The sky at one terabit per second: Architecture and implementation of the Argus Array Hierarchical Data Processing System

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ABSTRACT

The Argus Optical Array is a synoptic survey observatory, currently in development, that will have a total collecting area equivalent to a 5-meter monolithic telescope and an all-sky field of view, multiplexed from 900 commercial off-the-shelf telescopes. The Array will observe 7916 deg² every second during high-speed operations (m_g ≤ 16.1) and every 30 seconds at base cadence (m_g ≤ 19.1), producing 4.3 PB and 145 TB respectively of data per night with its 55-gigapixel mosaic of cameras. The Argus Array Hierarchical Data Processing System (Argus-HDPS) is the instrument control and analysis pipeline for the Argus Array project, able to create fully-reduced data products in real time. We pair sub-arrays of cameras with co-located compute nodes, responsible for distilling the raw 11 Tbps data rate into transient alerts, full-resolution image segments around selected targets at 30-second cadence, and full-resolution coadds of the entire field of view at 15+-min cadences. Production of long-term light curves and transient discovery in deep coadds out to 5-day cadence (m_g ≤ 24.0) will be scheduled for daytime operations. In this paper, we describe the data reduction strategy for the Argus Optical Array and demonstrate image segmentation, coaddition, and difference image analysis using the GPU-enabled Argus-HDPS pipelines on representative data from the Argus Array Technology Demonstrator.

Keywords: Argus Optical Array, pipelines, image subtraction, GPU computing, data management

1. THE ARGUS OPTICAL ARRAY: PHASED PROTOTYPING OF A DEEP MULTIPLEXED SURVEY

The Argus Optical Array will be a massively-multiplexed optical observatory, designed for synoptic time-domain observations. We are currently undertaking a phased prototyping process, evaluating hardware for an eventual 900-telescope array which would provide comparable collecting area to a 5-meter monolithic mirror telescope. By using a large array of 200-mm, commercially-available telescopes, this collecting area can be spread out over an 8000 sq. degree field of view, enabling simultaneous monitoring of O(10⁷) stars and galaxies. The full survey description and science justification for the Argus Optical Array is given in Ref. 1, and an updated mechanical and optical design can be found elsewhere in the Proceedings.² A full treatment of the general utility of multiplexed array observatories relative to monolithic systems for high-speed sky surveys can be found in Ref. 3.

The first stage in this process, the 9-telescope Argus Array Technology Demonstrator (A2TD) based on the design concept of the Evryscopes,⁴,⁵ was completed in 2021. A2TD is described in full elsewhere in the Proceedings.⁶ A2TD provides a lab-local test bed for rapid prototyping of control systems, data management, and other enabling technologies for Argus Array array, including a novel automated polar alignment and single-axis tracking drive,⁷ on-sky testing of climate control systems,⁸ mechanical and structural support.⁹

The second stage of development, Argus Pathfinder, will contain 38 telescopes, enabling it to survey the seasonal northern sky between declinations of −20° and 72° every night. Pathfinder will observe at 30-second

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cadence, with a $5 - \sigma$ limit of $m_A = 19.6$ in single images, where $m_A$ is the magnitude in a wide passband ranging from 350 nm to the blue edge of the Fraunhofer A line and O$_2$ telluric band at 750 nm. This depth is equivalent to $m_g = 19.1$ or $m_r = 18.3$ under dark sky conditions. Argus Pathfinder will be the first iteration to be deployed to a dark site, the Pisgah Astronomical Research Institute in Rosman, NC.

The Argus Array observing strategy, used at all stages of instrument development, uses a ratcheting approach to build up sky coverage over the course of a night. The instrument tracks the sky in 15 minute intervals, each of which concludes with a rapid slew back to the next field position, defined by the pointing of the meridian of the array. Two observing cadences will be used: a standard survey with 30-second exposures, and a secondary fast survey at 1-second cadence. In both cases, the dead time between consecutive images is sub-millisecond, with images read out to an internal camera buffer before transfer to a control computer over USB3.0.

Table 1 contains the system parameters of Argus Pathfinder and the Argus Optical Array instruments, including properties of the dataset.

| Argus Pathfinder (Q3 2022) | Argus Optical Array |
|---------------------------|---------------------|
| **Telescopes** | 38x Planewave 203 mm F/2.8 (combined 1m-class equiv.) | 900 x Planewave 203 mm F/2.8 (combined 5m-class equiv.) |
| **Detectors** | 61 MPix Sony IMX455 sCMOS | 61 MPix Sony IMX455 sCMOS |
| | 1.7e- RN and 80 $\mu$s dead time > 90% QE at 475 nm | 1.7e- RN and 80 $\mu$s dead time > 90% QE at 475 nm |
| **Field of View** | 9 sq. deg per telescope | 9 sq. deg per telescope |
| | 344 sq. deg instantaneous | 7916 sq. deg instantaneous |
| **Nightly Sky Coverage** | 19,370 sq. deg. (15 minutes per night) | 19,370 sq. deg. (2-10 hours per night) |
| **Pixel Sampling** | 1.38 arcsec/pix | 1.38 arcsec/pix |
| **Site** | North America Pisgah Astronomical Research Institute | North America Pisgah Astronomical Research Institute |
| **Exposure Time** | 1 second high-speed | 1-second high-speed |
| | 30-second base-cadence | 30-second base-cadence |
| **Wavelength** | Wide-band (350-750 nm) | Wide-band (350-750 nm) or alternating g', r' |
| **Pixel Count** | 2.3 GPix | 54.9 GPix |
| **Mosaic Image Size** | 4.7 GB | 110.1 GB |
| **Nightly Raw Data** | 180 TB (high-speed) | 4.3 PB (high-speed) |
| | 6 TB (base-cadence) | 145 TB (base-cadence) |
| **Throughput at 92% duty cycle** | 464 Gbps (high-speed) | 11 Tbps (high-speed) |
| | 15.5 Gbps (base-cadence) | 367 Gbps (base-cadence) |

Table 1. Survey and dataset parameters for the Argus Pathfinder and Argus Optical Array instruments. Data types assume 16-bit pixel data.

With its 54.9 GPix combined mosaic imager, the Argus Optical Array will produce 4.3 PB of raw data per night when observing in the 1-second cadence mode, and 145 TB per night at base cadence, numbers that are comparable to the entire data sets of the many data-rich astronomical surveys currently operating. The prototype Argus Pathfinder system, containing 38 telescopes, will produce accordingly less data, but still up to 180 TB per night at 1-second cadence, 24% more than the full Array at 30-second cadence. To reduce this data into an event stream of astrophysical transients, long-term lightcurves, and image data products requires both a physical compute architecture capable of the necessary throughput and a performant software pipeline.
In this paper, we introduce the Argus Hierarchical Data Production System (Argus-HDPS), the unified control and analysis pipeline for the Argus Optical Array project. In Sections 2 and 3, we describe the science and engineering requirements of the system. In Section 4, we outline the data flow and physical compute hardware underlying Argus-HDPS. In Section 5, we describe the algorithms and implementation status of the pipeline. Finally, in Section 6, we summarize and present pipeline performance results on data from A2TD.

2. SCIENCE REQUIREMENTS AND DATA PRODUCTS

Transient alerts and images are produced at multiple effective cadences, using coaddition to perform deep searches for slow-rising transients at timescales out to 5 days. To minimize data backlog and support rapid community followup of transient events, HDPS must produce alerts and reduced images within cadence for cadences less than 1 day; i.e., 30-second images must be reduced and alerts generated within 30 seconds. As the data rate slows for longer, multi-day coadds, sub-cadence latencies can be achieved using daytime operations.

Full-frame images from the full Argus Optical Array will be prohibitively large to store, requiring up to 145 terabytes per night at 30-second cadence and 4.3 petabytes per night at 1-second cadence. To support long-term retention of image data, HDPS must reduce incoming images into pre-defined data products, including:

1. Images, segmented into $13.7 \times 13.7$ arcminute sky regions.
   (a) Full-resolution segments (HEALPix$^{10}$ NSIDE=256) at base cadence, cached locally for at least 5 days
   (b) Full-resolution segments, coadded at 15-minute to 5-day cadences
   (c) Sparse full-resolution segments, containing transient detections and pre-selected science targets
   (d) Low-resolution segments with $10 \times$ reduced resolution (13.8 arcsec/pixel).

2. Transient alerts, distributed via community brokers
   (a) From single images, at both 1- and 30-second cadence
   (b) In deep coadds, up to 5 days

3. Photometric light curves
   (a) Transient sources: from image subtraction, sequentially released via alerts
   (b) Detrended long-term lightcurves for an input catalog of $O(10^7)$ sources

Reduced image data from Argus, including deep coadds, sparse full-resolution images covering science targets, and low-resolution 13.8-arcsecond per pixel images of the entire sky, will be stored long-term and made available publicly.

The production of long-term photometric light curves, containing tens of trillions of photometric measurements across a five year survey, is a unique challenge among the Argus Optical Array data products. Removing systematics from the lightcurves inherently depends on long-term trends in time, and for this reason, we elect to produce precision lightcurves in periodic data releases, rather than within the observing cadence. Per-epoch photometry, however, will be produced in real time, using the pipelines we have developed for the Evryscopes. Calibrated and detrended lightcurves for pre-selected science targets will be generated and released on a schedule.

3. ENGINEERING GOALS

Analysis and control pipelines are a long-term investment in the project, and scalability in software instrumentation will enable rapid iteration of the physical instrument and continuity towards the full Argus Optical Array. In addition to the science-driven goals above, we are developing Argus-HDPS with the following engineering goals:

1. Scalability and adaptability from the prototype stage to the 900-telescope Argus Optical Array
2. Integration between the control system and analysis system to minimize latency and intermediate storage requirements
3. Maintainability of the codebase, using standard version control,∗ dependency management,† and automated
testing‡ tools
4. Reliability for long-term operation and production of a stable dataset, including hardware-in-the-loop
testing of cameras and focusers

Particularly at the current stage, adaptability to a heterogeneous instrument has been essential to enable rapid
prototyping while navigating the supply chain constraints early in the prototyping process, and will remain an
important feature of HDPS to support long-term evaluation of telescopes and cameras with Argus Pathfinder.
Between the A2TD and Pathfinder instruments, Argus-HDPS includes support for two camera manufacturers
(Atik Cameras§ and QHYCCD¶), five camera models, and two telescopes with associated focusing hardware (the
Celestron‖ RASA-8 and a custom Astrograph from Planewave Instruments∗∗)

4. SYSTEM ARCHITECTURE

To meet the science and engineering goals of the Argus Optical Array, while coping with data rates into the
terabit-per-second regime, we use a converged data collection and analysis pattern, in which images are reduced
into data products within the observing cadence. In Figure 1, we present a flowchart of the basic components of
Argus-HDPS, including the core processes and data products.

Integration between hardware control and data analysis systems is essential for reliable data caching and
storage management, and for latency optimization at the fastest cadence. HDPS uses a modular software
architecture for hardware control, based on a stable contract between core system components (optical and
mechanical control, weather and instrument state monitoring, and pipeline instances), defined using HTTP
APIs.

4.1 Camera Control

Each camera is directly connected to a camera command (CC) compute node capable of reducing its data in
real time. We have developed Argus-HDPS wrappers for the vendor-supplied camera SDKs from Atik Cameras
and QHYCCD, which abstract the basic functions of the cameras to a standard, shared Python API. Each CC
node communicates with state machine processes exporting this API using an internal socket server. To
minimize latency, camera control processes copy the image data, along with corresponding metadata, directly
into a shared memory object store (Apache Plasma††), from which images are written to disk on a rolling basis.
Cameras attached to each CC node can be controlled collectively using an asynchronous HTTP API by the
instrument control system. The control system can control an arbitrary number of CC nodes (19 for the full
Argus Optical Array).

4.2 Compute Nodes

CC nodes are standard many-core x86 rack-mounted servers, co-located with the instrument. Individual cameras
connect to the CC nodes via USB 3.0 and high-density PCIe expansion cards. CC nodes will each be equipped
with a GPU for image analysis. GPU requirements are primarily driven by memory size and bandwidth; in
addition to the images themselves, each camera has a corresponding set of calibration frames (darks, flats, bad
pixel masks, plus intermediate background and noise maps) and reference frames, which must also be transferred
to the GPU at the start of each ratchet. Each compute node is also equipped with ~50 TB of local storage for
temporary caching of full-frame data at 30-second cadence, and enough RAM to cache data at 1-second cadence
for up to one minute.

*https://git-scm.com
†https://python-poetry.org
‡https://pytest.org
§https://www.atik-cameras.com
¶https://www.qhyccd.com
‖https://www.celestron.com
∗∗https://planewave.com
††https://arrow.apache.org
Figure 1. Pipeline components, processes, and data products for the Argus Optical Array.
5. PIPELINE IMPLEMENTATION

Once each full-frame image has been recorded in the in-memory object cache, analysis is delegated to analysis processes. Each analysis process pre-allocates the relevant reference and calibration frames on the CC node’s GPU resources at the start of each pointing. CMOS image calibration, source detection, and resampling to the HEALPix grid are done directly on the GPU, and source catalogs are transferred to system memory for cross-matching and astrometric fitting on the CPU. In the current implementation, image subtraction and coaddition are also done on the CPU.

5.1 Image Management

The highest-data-rate components of Argus-HDPS are those which interface with with the full-resolution 61-MPix images from the cameras. These images are both unwieldy to access, with 122 MB file sizes that incur a disk read penalty on the order of the exposure time, and require external indexing via a database to be searchable in space or time. To support these standard usage patterns, we have developed a hierarchical, equal-area storage system for Argus Array data, inspired by, but distinct from, the Hierarchical Progressive Survey (HiPS) format described in Ref. 11.

In the full-frame images, we perform standard image calibrations (dark subtraction, flat fielding, masking of bad pixels) and fit an astrometric solution using a custom high-speed solver. The ArgusSolve astrometry algorithm is based on the quadrilateral hashing$^{12}$ and the iterative fitting.$^{13}$ Combined with an optimized implementation in Python, a one-directional mapping from celestial to pixel-plane coordinates for full-frame images can be produced in $\sim 100$ milliseconds. A full WCSLIB$^{14}$-compatible FITS header can optionally be generated for the full-frame image in $\sim 5$ s.

5.1.1 Image Segmentation

Each full-frame image is reprojected into equal-sky-area tiles (based on the HEALPix$^{10}$ pixelization scheme with NSIDE=256), providing 786,432 potential 13.7$\times$13.7 arcminute sky regions across the celestial sphere, of which 58.6% will be observable by a Northern Hemisphere Argus Optical Array. The resulting segment images are stored in a structured tree of directories, grouped based on membership of each segment in the hierarchy of HEALPix tiles with NSIDE=4,16,64. Grouping the directories in this way is done to minimize the number of files per directory. Within each directory, images are stored per-night as multi-extension cubes in a FITS-like format modified to support 16-bit float data. Given a time and sky position, this scheme allows the path for a given spatial/temporal image tile to be uniquely determined without an external index, while maintaining a number of files on disk that is manageable with standard filesystems.

5.1.2 Sparse Image Segments

Each set of image segments for a single full-frame image is approximately the same size as the original data; however, each image tile can be further partitioned and selectively compressed. We have developed a “stamping” procedure, in which “minipix” segments of each image tile (at a higher HEALPix level, corresponding to NSIDE=16384) not containing science targets (either those detected in image subtractions or pre-cataloged by the science team) are set to zero and the resulting image compressed. To minimize the impacts on serendipitous science cases, full resolution images at base cadence will be cached at least up to the longest coaddition epoch (5 days), and low resolution maps, at a pixel scale of 13.8 arcsec per pixel, will be saved for the whole sky. The compressed sparse and low-resolution segment images combined take up $\sim 5\%$ the storage space of the full-resolution segments.

5.1.3 Deep Coaddition in Sky Segments

Because the full-resolution image tiles are pre-aligned to a fixed HEALPix grid, coaddition is greatly simplified. Coaddition on Argus sky tiles is optimized for point-source detection using a per-image matched filter, which is the statistically optimal method for background-limited images.$^{15}$ Figure 2 shows a deep coadd of a set of 30$\times$30-second exposures, made using the algorithm described in Ref. 15. These images were collected from a site local to our UNC-Chapel Hill lab, so the achievable depth is not representative of median performance at a dark-sky site; however, the 5-$\sigma$ limiting magnitudes of $m_g = 17.8$ at 30s and $m_g = 19.8$ at 15 minutes are
reproducible from the same calculation we use to predict dark sky performance, given typical sky brightness for a moderately-dark suburb ($m_V \approx 19$ per sq. arcsec). We reduced the images in Figure 2 using the Argus-HDPS GPU/CPU pipeline, including image segmentation, reprojection, and astrometry.

Figure 2. A 15-minute coadd of data from a Celestron RASA8 node of A2TD. Full-frame images from each sensor are reprojected into HEALPix segments, which are then used for further analysis tasks (photometry, image subtraction, and coaddition.)

5.2 Transient Alerts

Argus Pathfinder will produce transient candidates at a rate of approximately one million per night, and the full Argus Optical Array could meet or exceed the alert rate of the Rubin Observatory. Transient detection is performed using image subtraction in the reprojected HEALPix image segments, leveraging long-term coadds as reference frames. We have implemented two different algorithms for image subtraction in Argus-HDPS, and both will undergo long-term on-sky evaluation with Argus Pathfinder: the ZOGY algorithm described in Ref. 16 for image subtraction at base cadence and in deep coadds at 15-minute cadence or greater, and the direct image subtraction method we previously developed for the low-latency transient discovery pipeline for the Evryscopes,17 for real-time operation in 1-second cadence data. Figure 3 shows an image segment with a simulated transient source, a reference image, and subtraction images made using both subtraction algorithms.

In collaboration with the Arizona-NOIRLab Temporal Analysis and Response to Events System (ANTARES),18,19 we are prototyping a public transient alert system for low-latency release of candidates from the Argus Optical

Figure 3. Per-tile image subtraction near an injected transient source with a 5-$\sigma$ peak significance, using both the high-speed direct subtraction algorithm of Ref. 17, and the ZOGY algorithm.

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Array. To maximize utility and ease of use for the community, we are adopting the evolving community standard of streaming serialized alert packets via Apache Kafka.‡‡

5.3 Light Curves

Full evaluation of the expected precision of lightcurves from the Argus Optical Array will be made using data from Argus Pathfinder; however, initial results from A2TD nodes indicate that sub-percent performance may be achievable, at least on short timescales. Figure 4 shows the RMS vs magnitude for 900 stars during a single 15-minute ratchet at 30-second cadence, before and after three iterations of detrending using the SYSREM algorithm, which achieves \( \sim 7 \) mmag performance at the bright end.

6. PIPELINE PERFORMANCE AND SUMMARY

We are developing Argus-HDPS, an integrated instrument control and data analysis system for the Argus Optical Array, which uses asynchronous HTTP connections to orchestrate observation and analysis tasks across multiple control servers that pair optical/camera control with edge GPU computing capabilities for minimal latency. For current prototyping stages, all analysis will be completed on a single x86 server; scaling to a full 900-telescope system can be accomplished linearly with the addition of 19 additional control servers. This system enables a low-latency sharing of instrument state with an O(1000) camera array, and allows for images to enter the analysis pipeline within 100 ms of camera readout. We have demonstrated real-time image data product generation, using a custom high-speed astrometric solver and GPU-based reprojection of sensor-plane data to produce equal-area image segments, which are then coadded and subtracted for transient detection at both single-image cadence and in deep coadds. Public data release of imaging and transient alert data from the Argus Optical Array is planned, and will be publicly prototyped after a commissioning period.

Table 2 presents the average compute time for the image segmentation and analysis pipeline stages, measured using a representative 36-core test server and an NVidia RTX 3090 Ti GPU. Source detection, astrometry, and segmentation to the HEALPix grid are completed in an average of only 27 milliseconds on the GPU, which can be shared sequentially by many cameras to generate image data products in real time, even at 1-second cadence. CPU-based image subtraction is possible within cadence by parallelizing the direct subtraction at the segment level; however, a GPU implementation is in development.

‡‡https://kafka.apache.org/
### GPU Timing

| Step                                                      | Time   |
|-----------------------------------------------------------|--------|
| 61-MPix image copy to GPU                                 | 16 ms  |
| Calibration                                              | < 1 ms |
| Median-filtered background map                           | 1.7 ms |
| Source detection                                          | 6.1 ms |
| Image segmentation and resampling to HEALPix grid        | 3.2 ms |

### CPU Timing (single-threaded)

| Step                                                      | Time                                      |
|-----------------------------------------------------------|-------------------------------------------|
| Source de-duplication                                     | 7.5 ms                                    |
| Astrometric solution                                      | 190 ms (95 ms with cached distortion terms)|
| Image segments written to storage (modified FITS-format)  | 475 ms                                    |
| Minipix stamping and low-resolution image generation      | 300 ms (batch reduction)                  |
| Direct image subtraction (1-second cadence)               | 20 ms per tile                            |
| ZOGY image subtraction (30-second+ cadence)               | 1400 ms per tile                          |

Table 2. Average timing results for key processing steps in Argus-HDPS.

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