An Autonomous Geographically Distributed Ground Network that Scales

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ABSTRACT

The exponential growth in the number of resident space objects (RSO's) from commercial mega-constellations and the emerging role of space as a warfighting domain will stress capacity and timeliness of the existing Space Surveillance Network (SSN). This stressing condition arises from a scaling law mismatch between the exponentially growing number of RSOs and the linearly increasing number of sensors. This paper proposes a geographically distributed ground electro-optical telescope network that scales to large node count and presents prototype solutions implemented by the Aerospace Corporation. This network offers unique opportunities for military space, space domain awareness, and space traffic management.

1. INTRODUCTION

The "first space age" was ignited by the Russian launch of Sputnik 1 in October of 1957. The fierce competition between the United States and the Soviet Union to obtain and maintain space superiority created a contested domain. Most of the systems placed on orbit during this period were designed for military operations. In 1991 the Soviet Union collapsed, marking the end of the Cold War making the United States and it's Allies the winner of the "first space race". In 1991 Operation Desert Storm marked the first use of space capabilities as an integrated part of traditional military planning, logistics, and operations. The world watched as the United States used its space capabilities to provide systems precise targeting information and enabled the use of guided precision munitions with devastating results. The effectiveness of Operation Desert Storm spurred other nations to take note of the many advantages space offers and attempt to replicate US space capabilities. This marked a transition into the "second space age". At present, advances and innovation in space and sensing technology has made it possible for commercial companies and other countries other than the Unites States and Russia such as China, Member states of the European Union, Japan, Canada, and India to enter the space race. Specifically, commercial companies are competing to lower the cost of access to space and disrupt space-related industries. The proliferation of national and commercial stakeholders investing in space marks the start of a "third space race". Many nations are treating space as a warfighting domain, commercial companies are providing services once only available to the military, and commercial mega-constellations are emerging. Laws, regulations and norms of behavior are challenged to keep up with the rapid change. The resulting explosion of Resident Space Objects (RSOs) include space debris and spacecraft owned and operated by nations or independent commercial entities. These spacecraft can dynamically maneuver, requiring near real-time space surveillance for all Earth-to-Space, Space, Space-to-Earth and beyond Earth operations to establish attribution, ascertain intent, and ensure safety of flight. Such space surveillance must be persistent to identify, track, detect changes, and discriminate operational spacecraft from debris.

To address a portion of this problem the authors propose an innovative geographically distributed ground electro-optical telescope network that scales to large node count. This network is composed of a digital layer that addresses scheduling and data transport and a material layer that addresses physical ground terminals and their siting. Aerospace is developing both digital and material prototype implementations to demonstrate the scalability of this concept. The digital implementation is called Prime Focus, and utilizes cloud-native technologies to autonomously schedule and operate an arbitrary number of independent sensors. The material implementation is called Monocle, and utilizes a two-axis, fully enclosed and autonomously controlled gimbal for pointing and tracking. These autonomous, scalable digital and material implementations offer the opportunity to insert ground terminals on cell towers and operate these terminals remotely from data centers over the cell network. In this sense, Aerospace's prototype autonomous, geographically distributed ground network scales to arbitrary sensor count. This capability to scale the sensor network globally addresses issues of capacity and timeliness in the applications of Space Control, Space Domain Awareness (SDA) and Space Traffic Management (STM).

Example challenges addressed by the telescope network:

1. Operational persistence to enable RSO identification, tracking, discrimination, orbit regime changes, maneuvers and change detection
2. Worldwide coverage to augment commercial, civil, and military sensing capabilities
3. Active sensing via LIDAR
4. Ground-to-space free space-optical communications

The key to realizing a scalable, autonomous, geographically distributed electro-optic ground sensor network lies in establishing a scalable solution for each of four imperatives that currently limit the number of operational ground terminals. Section 2 describes these four imperatives, while Section 3 presents Aerospace's four prototype solutions. Section 4 offers a practical vision that merges these prototype solutions to form a geographically dispersed telescope network with five ground stations operated by a data center in El Segundo, CA that accepts observational tasking and delivers data products to the Unified Data Library (UDL)[9] and Warpcore[6].

2. FOUR IMPERATIVES FOR A SCALABLE ELECTRO-OPTIC GROUND ARCHITECTURE

There are four imperatives that a ground telescope network must address to enable scaling. Two are identified as digital, relating to the computational requirements imposed by the network and two are identified as material, relating to the physical realization and siting of the ground terminals.

1. ***Digital: Automated, real-time dynamic scheduling via network***
   Sensor scheduling is an M-sensor on N-target assignment problem, in which the number of possible assignments scales as $N!/(M![N-M]!)$ at any particular epoch, and extends indefinitely over time as sensors complete collects and are re-tasked. The combinatorial optimization problem scales factorially in the number of targets: a formidable computational scaling law that is illustrated by Figure 1. Target assignment is predicated on geometric and radiometric access from sensor to target and on real-time weather conditions at the ground sensor. Assignment may also require contemporaneous observations across multiple ground stations, handoff among ground stations, and may dynamically reprioritize both targets and sensors in response to events such as RSO maneuvers or ground station weather outages. These considerations demand an automated tasking system coordinating the ground stations in the telescope network: humans cannot be on the critical path for these decision loops.
2. ***Digital: Real-time data retrieval for decision support***
   Real-time data retrieval from the ground terminal is required to enable the feedback loop for dynamic, real-time tasking of the network. Modern instrumentation acquires data at rates that exceed the bandwidth capacity of geographically dispersed communication networks. Focal plane arrays with $>$100 Megapixels operating at frame rates $>$10 frames-per-second are currently available, and generate data at $>$ 2 GB/sec. Sustained transfer of these data from many collection nodes to an operations center for real-time postprocessing is impractical. This imperative demands an edge computing approach that processes these data at the ground terminal, extracting the relevant measurements and reducing the data load.

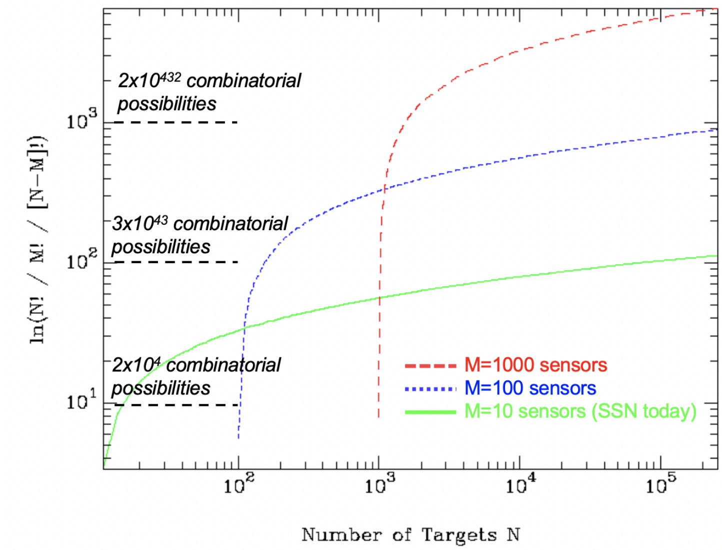

Fig. 1: *Combinatorial possibilities vs. number of targets N in the M-sensor on N-target scheduling problem. The steep increase in the number of combinatorial possibilities emphasizes the challenges of scheduling a telescope network as the Space Catalog grows to encompass* 10^5 *RSOs. Note that the y-axis displays* $ln(N!/M!/[N-M]!)$ *on a log scale. Optimal scheduling requires selection from the list of possible sensor-target pairings as sensors complete tasking and are re-tasked to observe a fresh target. Each selection that is considered must be evaluated for line-of-sight and radiometric access and for sensor weather outages. While this is manageable for the 10 electro-optical sensors in the current Space Surveillance Network, growth in the number of sensors rapidly proliferates the combinatorial possibilities. This necessitates the use of automated network scheduling algorithms to remove humans from decision loops.*

3. ***Material: Low-SWaP automated ground terminals***
   A geographically dispersed ground telescope network necessitates automated, low size, weight and power (SWaP), low-cost ground terminals for manufacturing, transport, installation, and sustained operation. Cost considerations dictate that the terminals in a scalable network must not require human staff to be present during operations. Applications like satellite laser ranging and free space optical communication that require laser transmission from the ground terminal levy the additional consideration of laser broadcast safety.

4. ***Material: Prolific insertion opportunities for installation throughout the globe***
   A geographically dispersed ground telescope network may control costs by reusing as much existing infrastructure as possible. Ground terminals require an insertion point offering power, network access, and sufficient physical security to preclude human interference. These insertion points must be available at a global scale to allow geographical diversity of the telescope network.

There are a number of geographically distributed telescope networks developed by academia[11], industry[5, 1], government[13], and international collaboration[18]. Each of these networks succeeds in addressing a subset of the above imperatives, but none comprehensively address all four.

3. DIGITAL AND MATERIAL PROTOTYPES AT THE AEROSPACE CORPORATION

To scale successfully, a distributed ground station network must address both digital and material aspects in an autonomous implementation. The digital aspect of this problem encompasses ingest of RSO targets for dynamic tasking by an operations center, allocation of observations to ground terminals for autonomous collection, and transport of observations via network back to the operations center where multi-sensor fusion is performed. Scalability of this digital solution is implemented through modern Development/Security/Operations (DevSecOps) techniques, cloud computing and cloud storage methodologies. These form the cloud architecture backplane on which the business logic of STM, SDA and Space Control resides. This business logic encompasses the radiometric and astrodynamics considerations underlying modeling and simulation, scheduling, and data processing algorithms. These considerations vary with the target and with the sensor's instrumentation package: imager, spectrograph, LIDAR, polarimeter, or other remote sensing methodology. It is useful to distinguish between cloud and business logic elements of the digital solution, as these activities engage personnel with different backgrounds and training.

A scalable solution to the material aspect of this problem calls for autonomous, low-SWaP ground stations that require minimal maintenance and afford ample opportunity to field these stations at diverse geographical insertion points. The material aspects of a scalable network emphasize manufacturability, environmental hardening, operationalization, industrial automation, servicing, and cost controls. These activities require an entirely different set of skills than those of the digital aspects above.

The challenge in developing and fielding a scalable ground telescope network lies in identifying scalable solutions across all of these disciplines. Aerospace is undertaking a pathfinding prototype development effort to evaluate scalable solutions for both digital and material aspects. The subsections below describe these prototype solutions, their current state of maturity, and paths forward to further their development.

3.1 Digital: Automated, Real-time Dynamic Scheduling via Network

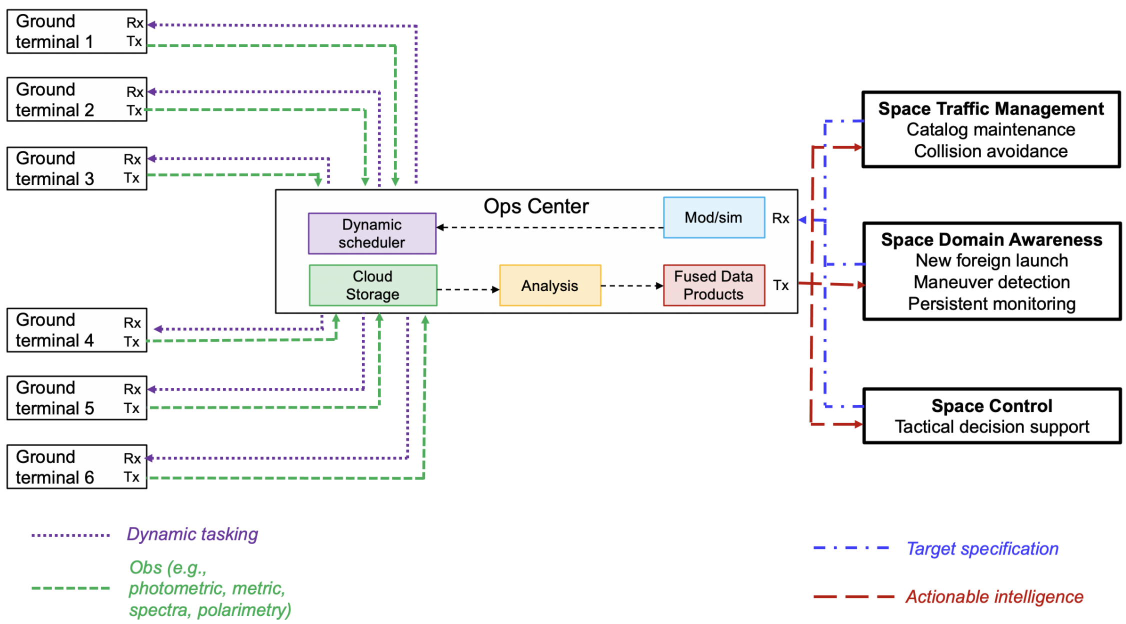

Fig. 2: *Architecture displaying a distributed ground telescope network interfacing to an operations center and driven by three user applications: STM, SDA and Space Control, depicted at far right in the figure. These users submit target lists to an operations center, which are analyzed for observability (blue mod/sim box), dynamically scheduled (purple scheduling box), and tasked to six ground terminals shown at far left of the figure. These ground terminals prosecute the observations and deliver data back to the operations center. Within the operations center, data are written to cloud storage (green storage box), analyzed (yellow analysis box), fused across the historical record maintained within the operations center (red fusion box) and delivered back to the user. This architecture emphasizes the dynamic, iterative nature of the interaction between multiple user communities and geographically dispersed telescope networks. Proliferation of the ground terminals at geographically dispersed sites increases capacity, increases windows of observability to any specific RSO, provides resiliency against weather outage, and reduces latency in servicing requests. This architecture does not currently exist.*

Figure 2 displays the overall architecture for a distributed ground network governed by an operations center responding to target specifications from users in the domains of STM, SDA and Space Control. Figure 2 represents an aspirational architecture that does not currently exist in the sense of the four imperatives described in Section 2.

Aerospace's scalable digital prototype for this architecture is called Prime Focus[4], and its automated processing pipeline is displayed in Figure 3. The Prime Focus prototype illustrates many of the elements identified in Figure 2: a ground station driven by an automated scheduler operating from user-specified target lists, writing observational data to cloud storage, and transmitting post-processed data to an external repository.

Prime Focus currently operates on a 24-hour cycle in which users upload target lists via webform, launching a series

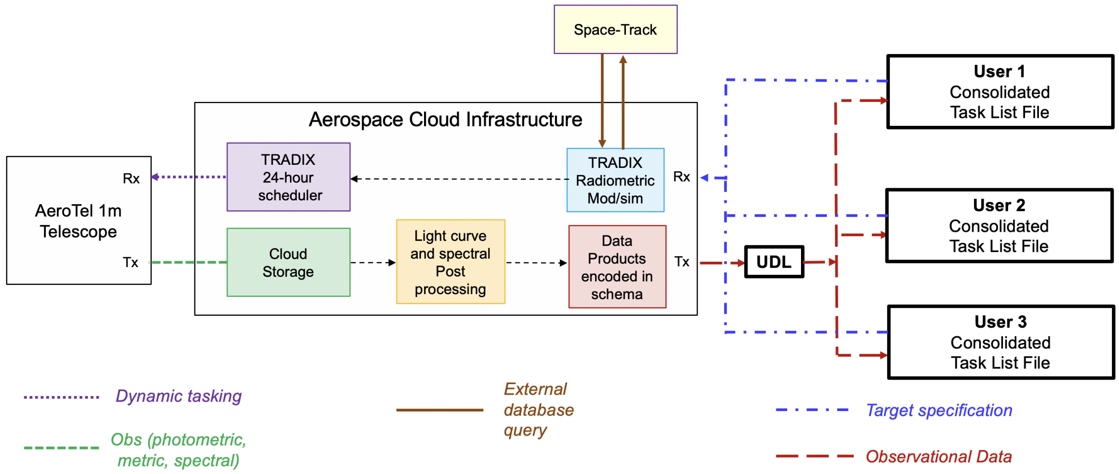

Fig. 3: *Aerospace's Prime Focus prototype architecture displaying a single-node telescope network based on the 1m AeroTel telescope in El Segundo, CA. This prototype accepts user-supplied Consolidated Task Lists (CTLs) via webform, represented at far right in the figure. Two-line element sets, SATCAT and Size records are downloaded (yellow Space Track box). Light curves are modeled using Aerospace's radiometric analysis tool TRADIX (blue mod/sim box). These light curves are processed to generate a 24-hour schedule that adheres to the OI 534-09 ruleset (purple scheduler box). Scheduled observations are issued over message bus to the AeroTel telescope for automated collection, at far left in the figure. The resulting observational data are written to Aerospace local cloud storage (green storage box), where they are processed (orange analysis box) and encoded (red encoding box) for upload to the UDL. Prime Focus is currently in integration & test, and the system is acquiring observational data on RSOs at regular intervals.*

of autonomous operations. Target information is downloaded from the Space Track catalog. Aerospace's radiometric analysis tool TRADIX is used to model target light curves. Scheduling algorithms employ these light curves to allocate time based on high signal-to-noise ratio observing opportunities. One scheduling algorithm uses the unclassified OI 534-09 category specification, in which observations are allocated based on a user-specified suffix rule. Additional scheduling algorithms are developed for specific instrument packages and observing campaigns. The schedule is regenerated upon each user-upload event, aggregating all target lists that have been submitted over the past 24 hours to produce a schedule that allocates time to all users until the schedule fills. The daily schedule is written to Aerospace cloud storage and scheduled observations are transmitted via message bus to AeroTel: a 1m telescope at the Aerospace General Offices in El Segundo. This telescope acts as a surrogate for the scalable material solution that is described in detail below. This telescope executes each observing request and writes resulting observational data to cloud storage. An important aspect of this design is the use of networked cloud storage to allow stakeholders throughout the Aerospace Corporation to inspect in real-time the scheduling, collection, and postprocessing results. This universal visibility greatly facilitates communication among staff and creates shared experience across the project. Data are post-processed to generate intermediate data products and are encoded for upload to external data centers such as UDL and WarpCore. Figure 4 illustrates sample Prime Focus pipeline products auto-generated during scheduling and collection.

The Prime Focus pipeline relies extensively on cloud-native computing architecture. The computing elements of this Pipeline are listed in Table 1. The project employs revision control, modern compilers, a continuous integration/continuous deployment system, Docker, Kubernetes, and AWS S3 cloud storage. This design helps to ensure scalability and reliability of the cloud computing/storage backplane. Currently four entirely independent scheduling and cloud storage pipelines are operating simultaneously on a continuous basis during integration and test. Any one of these pipelines may be utilized by the 1m telescope to obtain observing requests and report observations. This demonstrates scalability of the digital implementation to multiple sensors, each of which would operate using an independent pipeline.

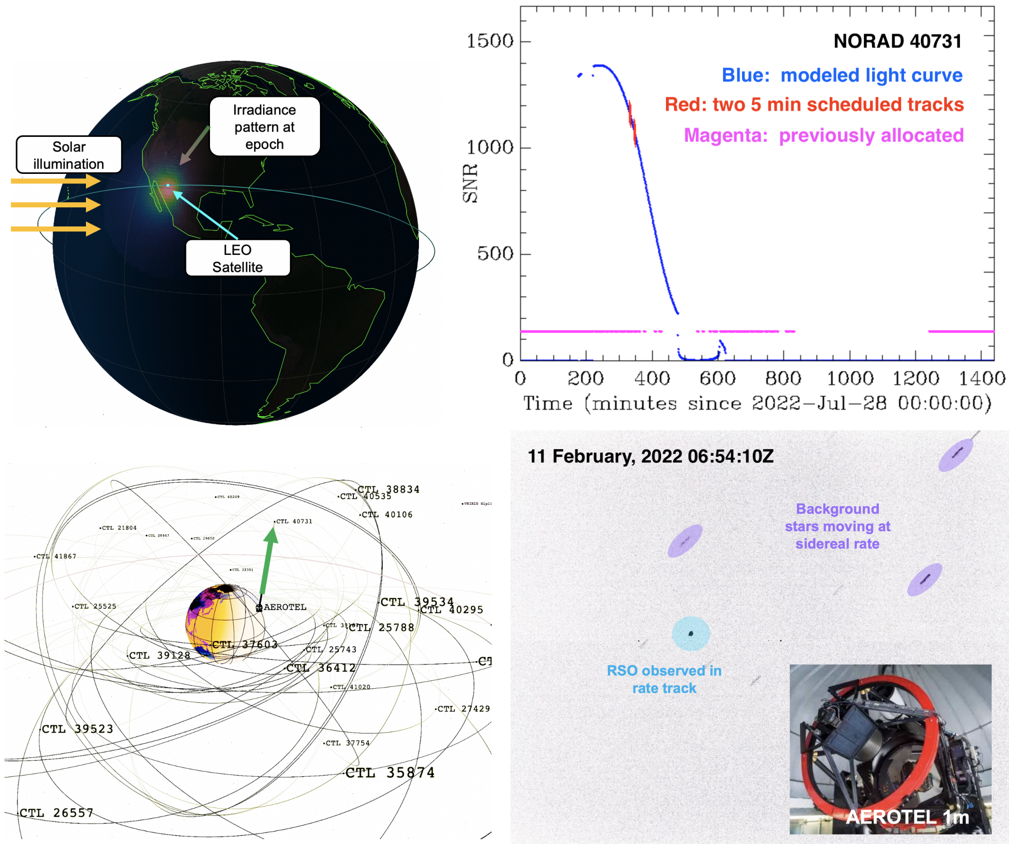

Fig. 4: *Elements of the Prime Focus automated pipeline. Upper left figure shows the geometric configuration and modeled irradiance pattern cast on the earth by a 1000km altitude LEO satellite at a specific epoch. The upper right panel displays the modeled light curve (i.e., SNR vs time) for an Atlas rocket body (Norad ID 40731). The automated scheduler evaluated observing opportunities for this target after most of the observing time had previously been allocated to other targets, as indicated in magenta. The automated scheduler identified and assigned two 5-minute blocks separated by at least 10 minutes, as indicated in red. The lower left panel displays the targets scheduled on the night of 28 July 2022. At the epoch captured in this panel, AeroTel was tasked to observe 40731, as indicated by the green arrow. At lower right a single AeroTel image acquired on Norad ID 37218 on 11 Feb, 2022. Highlighted in the image are the RSO (blue indicator) and several background stars (purple indicators) demonstrating rate tracking of this RSO.*

Table 1: Computing elements of the Prime Focus cloud-native pipeline.

Computing Element	Prime Focus Implementation
Revision control	Subversion
Operating system	CentOS 7
Compilers	gcc 8.3 - gcc 12.1
Message bus: protocol	RabbitMQ: JSON
Build system	CMake
CI/CD system	Jenkins
Build environment	Docker build container
Runtime environment	Kubernetes
Aerospace-internal cloud storage	AWS S3

3.2 Digital: Real-time Data Retrieval for Decision Support

Aerospace has developed and is now implementing an embedded algorithm to process rate-track imagery in real time. This algorithm offers several advantages over existing algorithms that post-process images sequentially. Aerospace's algorithm:

1. Performs stellar extraction to increase stellar sensitivity
2. Classifies stellar vs target photons to eliminate confusion among emitters in the field of view
3. Uses the target photons for real-time electro-optic feedback control and to increase target sensitivity
4. Provides an absolute estimate for target angular coordinates, analogous to the function of a star tracker
5. Performs the image analysis in real time via FPGA

An operation count on a Zynq processor supports 2k x 2k pixel image processing rates of 50 images per second. The data products delivered by the algorithm are the intensity and pixel location of the target and of each star in the field of view. This minimal set of output data yields a characteristic reduction in data load by a factor of order 10,000 relative to the original 2k x 2k imagery. Reducing the data load in this way enables transmission of SDA metric and photometric observations from the telescope to the data center without overwhelming the network bandwidth capacity.

This algorithm was envisioned at Aerospace in early 2022, and an embedded implementation has yet to be developed and demonstrated. Nevertheless, the scalability of this embedded algorithm to large node count is straightforward. FPGAs like the Zynq are available in single board computer (SBC) form factors at price points below $5,000. These SBC units may be emplaced at the ground terminal to perform real-time image processing for electro-optical feedback control of the pointing/tracking system, while reducing network load for transport of data to operations centers shown in Figure 2.

3.3 Material: Low-SWaP Automated Ground Terminals

Aerospace's scalable material implementation for a ground terminal is called Monocle[3]. This implementation employs a unique gimbal design developed specifically for autonomous telescopy. This design incorporates a two-axis Calotte dome and unifies the telescope pointing and tracking system and the dome steering system to minimize assemblies and SWaP. This allows the telescope optical tube assembly (OTA), drive system, and instrumentation to reside within the dome itself, with no opening to the external environment. There are substantial advantages to fully enclosing this hardware within an environmentally sealed, low-SWaP enclosure. The enclosed hardware is protected from contaminants, weather, and wind buffeting and may be baffled for stray light control. The interior of the enclosure may be thermally controlled via an external HVAC unit. There is no chimney effect from hot air rising out of a dome opening, which creates self-generated turbulence that degrades image quality[2]. Three generations of Monocles are shown in Figure 5 and a summary of the design advantages are listed in Table 2.

Aerospace has built a proof-of-concept v1 prototype with a 125mm aperture OTA in a 450mm diameter dome, shown in the center panel of Figure 5. This prototype exhibits a dome-to-aperture ratio of $\mathscr{R} = 3.6$: small compared to existing ground terminal designs. The compact design enables substantial reduction in SWaP and reduces loads on the pointing and tracking motion-control system. With the exception of the custom enclosure, the v1 prototype was constructed from COTS parts that are already commercially available for designs up to 1m aperture diameter. The prototype operates via wireless connection to SBCs resident within the enclosure. These SBCs accept commands and report telemetry and data products to a computer external to the enclosure. The SBCs run a Debian 9 OS and host control software written in C++ and compiled under GCC. All hardware is connected and controlled via USB. The prototype demonstrates an Internet-of-things approach to telescopy, in which the unit more closely resembles a wirelessly controlled appliance than a traditional telescope.

Components selected for the Monocle v1 prototype are at a high degree of technical readiness. The ring bearings and rotary encoders used within Monocle are high reliability and are employed in industrial applications: windmills, construction cranes and tank turrets. The load-bearing capabilities of the ring bearings in Monocle v1 far exceed requirements for electro-optical applications, while the inductive rotary encoders are designed to operate in environmental conditions far more adverse than those present in an enclosed dome. A flight-grade miniature GPS/IMU unit was mounted on the telescope OTA within the dome to geolocate the unit and for pointing reference during mount model calibration. Power slip-rings were used in the v1 design to eliminate cable wrap considerations. The v1 prototype used wireless communication with two industrial SBC's. This feature enabled the wireless, remote update and compilation of software resident on the SBC's, and was also employed for external command, control, and data retrieval from the prototype. These design choices demonstrated remote, autonomous operation over extended time periods with high reliability.

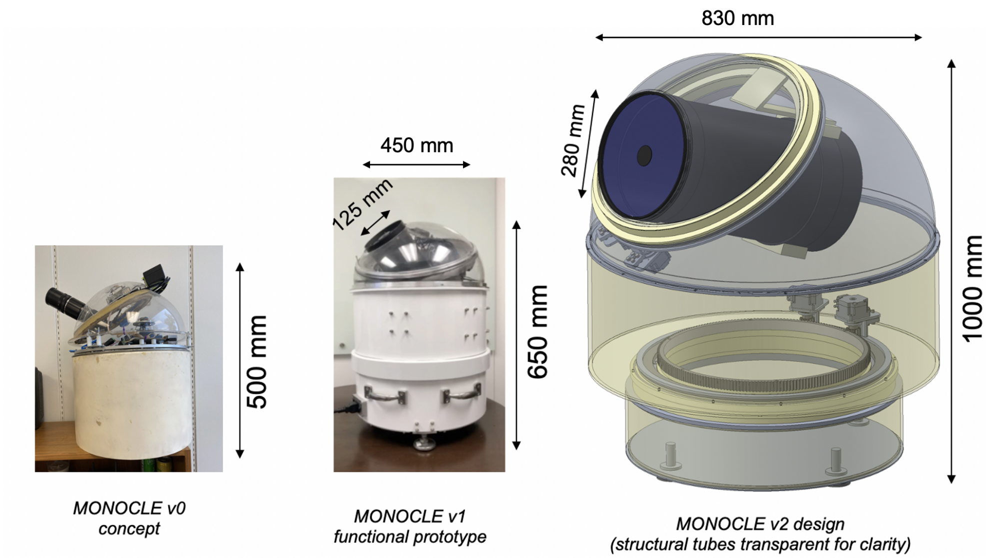

Fig. 5: *Three generations of Monocle. The left panel shows a v0 concept prototype built for display purposes. The center panel shows the v1 prototype, which demonstrated two-axis motion-control and autonomous operation. The right panel shows a design for a 280mm aperture v2 design containing a laser transmitter for satellite laser ranging and free space optical communication applications. The Monocle design exhibits an important laser safety feature in that there is a hardware limit on the elevation angle of the broadcast laser. This guarantees that laser broadcast is constrained to a cone above the ground terminal.*

Table 2: Design goals for ground terminals and Monocle's realization of these goals.

Design Goal	**As Implemented in Monocle**
1. Protection of telescope and instrumentation from weather, contaminants, wildlife	Telescope and instrumentation emplaced within sealed dome
2. Thermal control of telescope and optics for operation in diverse thermal environments	Sealed dome design permits temperature control via external HVAC system
3. Stray light suppression to reduce light pollution and mitigate laser jamming	Baffle mounting location on the optical tube assembly
4. Laser broadcast safety	Hardware limit precludes laser broadcast below limiting elevation
5. Minimization of wind loading on primary	Wind load transferred through the dome and into the base
6. Minimization of SWaP for transportability and fielding at remote sites	125 mm aperture prototype weighs 45kg, 450mm diameter dome, draws 35W during operation
7. Components chosen to minimize cost and schedule risk	Ring bearings, rotary encoders, optical tube assembly, single board computers, GPS/IMU, laser, fast steering mirror, slip rings and camera are commodity-off-the-shelf. Enclosure is custom.
8. Minimization of motion-control assemblies	Two-axis gimbal uses two rotating assemblies of the same design
9. Design scalable in aperture diameter	Design scales to aperture diameter of 1m
10. Tracks RSOs in all orbital regimes	Low-SWaP two axis gimbal design minimizes moment of inertia and mass under motion-control, enabling tracking rates for LEO and all higher altitudes

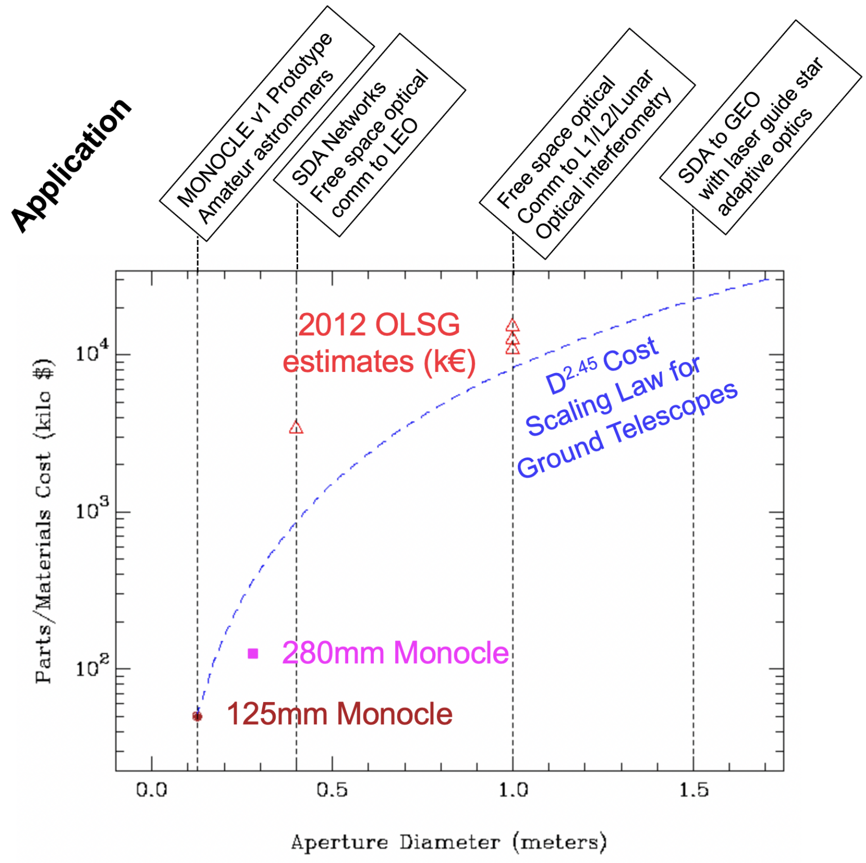

Fig. 6: *Parts and materials costs for Monocle v1 (as built), Monocle v2 (design estimate), and estimates from the 2012 Optical Link Study Group (2012 euros)[14]. The Monocle costs only encompass parts and materials, and do not include non-recurring engineering, installation, or operations costs. The Optical Link Study Group (OLSG) costs are published estimates drawn from the OLSG study. The plot displays the* $D^{2.45}$ *scaling law characteristic of ground-based telescopes[16]. The cost points for Monocle units are low relative to the OLSG estimates, and may scale more favorably than* $D^{2.45}$*. Listed across the top of the figure are SDA, telescopy, and optical comm applications at characteristic aperture design points.*

A 280mm aperture Monocle v2 design study for a satellite laser ranging unit was conducted in early 2022. A solid body rendering of this design is shown in the right panel of Figure 5. This design incorporated a 1.06 μm transmit laser and fast steering mirror housed within the enclosure. The design used the 280mm aperture as a laser receiver and for visible imaging to maintain pointing and tracking via the algorithm described in Section 3.2. This design incorporated significant improvements in the motion-control system over the v1 prototype, and further reduced the dome-to-aperture ratio to a value of $\mathscr{R} = 3$.

Aviation laser safety is an important consideration in transmitting from Monocle. Free space optical communication lasers operating at 1.5 μm are not considered an aviation hazard[7]. The ultraviolet lasers used to generate Rayleigh beacons for wavefront sensing of atmospheric turbulence are also not considered an aviation hazard[15]. Satellite ranging lasers tend to operate at higher power levels to ensure adequate return from the resident space object. These lasers may be aviation hazards, requiring additional safety measures.

Figure 6 displays the parts and materials cost scaling law vs aperture diameter. This plot quantifies the costs established via the Monocle v1 prototype and Monocle v2 design. This plot displays Monocle's favorable costing relative to ground station cost estimates from an Optical Link Study Group report[14] conducted in 2012. The plot also indicates that Monocle breaks the characteristic $D^{2.45}$ scaling law for telescope cost vs aperture diameter D. The Monocle prototype demonstration of low price points using COTS components in a low-SWaP form factor is a critical enabler for the manufacture of ground terminals at scale.

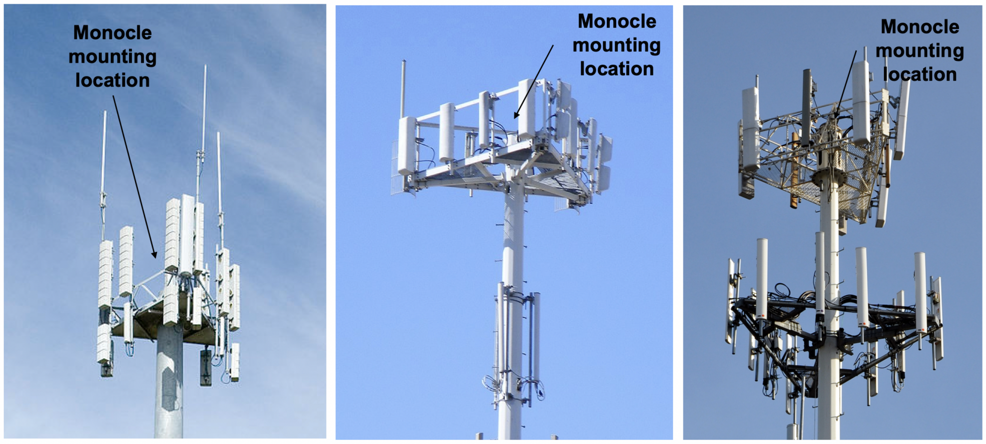

Fig. 7: *Examples of cell towers that could provide mounting locations for Monocle units. This mounting location does not interfere physically with existing hardware: antennae on these towers are side-facing, while Monocle would mount at the center of the platform atop the tower. This installation site offers power and network access, precludes human interference, enhances laser broadcast safety, reduces opportunity for laser jamming, and places the unit above the ground layer of atmospheric turbulence.*

3.4 Material: Prolific Insertion Opportunities for Installation Throughout the Globe

The final imperative for an automated, geographically distributed ground telescope network is to ensure a realistic path towards global insertion of ground terminals in a way that minimizes infrastructure costs while maintaining autonomy and low-latency communications for the ground terminals. The automated, low-SWaP design described in Section 3.3 above is key in enabling global insertion opportunities for these ground terminals using existing cell towers. This type of insertion point offers a number of advantages. Cell towers:

1. provide power, low-latency communication, and ensure physical isolation from human interference
2. are not owned by the cell carrier companies, but are instead owned by independent companies that rent mounting locations to the cell carriers for their equipment. These entities may be financially inclined to offer mounting sites for a new type of customer.
3. are ubiquitous throughout the world. There are approximately 300,000 cell towers in the United States and over a million towers around the globe.
4. elevate Monocle so as to improve laser safety. The Monocle design limits laser broadcast to lie above a limiting elevation angle, and emplacement on a tower further improves laser safety.
5. elevate Monocle above the first 50 meters of atmospheric turbulence, depending on the height of the tower. The characteristic strength of turbulence falls exponentially with altitude, so elevation of the ground terminal significantly mitigates image degradation from atmospheric turbulence.

For these reasons, cell towers offer an advantageous and scalable solution for a global telescope network. This element of the architecture has not yet been negotiated by Aerospace with cell tower companies. However, there is precedent for mounting electro-optical terminals on structures for free space optical (FSO) communications. For example, AstroTerra[8] and AOptix[10, 19] have fielded point-to-point FSO systems for bidirectional communication over horizontal paths. The Office of Naval Research has fielded a gimbaled system for FSO communication between Navy vessels[12]. These experimental efforts demonstrate the principal of mounting electro-optical systems on structures and stabilizing their pointing/tracking systems. The Monocle prototypes described in Section 3.3 above differ fundamentally in their design as two-axis pointing and tracking gimbals collecting on targets via active laser illumination or passive solar illumination. However, the operational model of placing these Monocle units on cell towers does not differ in character from deploying FSO terminals on towers, buildings, or ships.

As an alternative to cell tower installation, Monocle units may be installed in sites without any power and network connectivity by relying on solar panels and satellite internet antennae. The prototype unit in the center panel of Figure 5 draws 35W during operation. This power requirement can be met using a solar panel and rechargeable battery generator. Commercially available satellite internet links operate at data rates of order 100 Mbps. These rates are significantly lower than 5G's 20 Gbps data rates, but can still support dynamic tasking and observation retrieval at lower cadence.

4. SUMMARY

This paper has presented Aerospace's concepts and prototype development efforts for a geographically dispersed electro-optic telescope network that scales to large node count. Section 3.1 described Prime Focus as a prototype automated network scheduling and data transport layer hosted on a cloud-platform to ensure scalability to high-node count. The real time processing algorithm in Section 3.2 addresses real-time pointing/tracking control via electro-optic feedback while reducing data volume by a factor of order 10,000. The ground terminal prototypes in Section 3.3 display the many design advantages listed in Table 2 and establish favorable price points shown in Figure 6. Lastly, Section 3.4 argues for installation of Monocles on cell towers to realize global insertion opportunities using existing infrastructure. Collectively, the proposed architecture addresses each of the four scaling imperatives enumerated in Section 2.

Aerospace's proposed architecture displays unique features that ensure resiliency of the sensor network. Resiliency to weather outage is ensured by siting Monocles at geographically dispersed sites. Geographic dispersion and sensor proliferation limit the practicality of physical attack or cyber denial of service attacks: while any single node of the network may be vulnerable, the proliferation of dispersed nodes ensures continued operation of the network as a whole. Cyber attacks on a single node may aim to falsify observational data, but the proliferation of sensors may overcome this by identifying observations from the corrupted node as outliers. This type of resiliency has the character of distributed ledger technology (DLT), of which blockchain is a prominent example. DLT can be employed to decentralize decision-making through consensus without relying on a centralized authority[17]. This line of development devolves some of the analysis and data fusion from the operations center in Figure 2 to the automated peer-to-peer ground station network. This may be an attractive possibility in light of the combinatorial avalanche represented in Figure 1.

The option to redeploy Monocle units on an as-needed basis represents another unique feature of the proposed architecture that arises from the transportability and autonomy of the ground stations. Evolving geopolitical circumstances may dictate a concentration of sensors in a particular geographical region, and new circumstances may later call for deployment in a different region. New foreign launch, rising political tension, and active conflict are examples. Ships, planes, and tanks are able to redeploy as circumstances dictate, but current generation electro-optic telescopes cannot. Low-SWaP, low-cost Monocle units can be pulled from storage, transported, deployed for a period of service, and then decommissioned for storage.

The low capital and sustainment costs of Monocle create opportunities for iterative development that are not available from the current generation of electro-optic ground stations. At this particular time, rapid technological advances that could be incorporated into ground terminals are occurring in the fields of embedded processing, machine vision, and artificial intelligence. Beyond visible imagers, non-traditional sensors such as SWIR imagers, spectrographs, lidar, and polarimeters offer sensing modalities and data fusion opportunities that may provide a more refined assessment of RSOs. Incorporating new technologies and developing new instrumentation packages are labor-intensive, research-oriented activities that are not readily conducted on the small number of operational electro-optic sensors that compose the SSN. These activities benefit from widely available, low-cost ground terminals that will enable rapid iteration and experimentation by independent research groups and commercial entities. The three Monocle generations shown in Figure 5 emphasize the practicality of this iterative mindset. If the government standardizes on a ground terminal design and industry offers these ground terminals at price points characterized in Figure 6, universities and small businesses can afford to participate in this iterative development. This is the ground-based analogue to cube-sat standardization that allowed broader university and commercial engagement in the space sector.

Figure 4 presents an evolutionary path towards prototyping a ground telescope network that approximates the architecture shown in Figure 2. This concept integrates the Prime Focus and Monocle elements into a prototype geographically distributed telescope network. The figure shows a five element Monocle network geographically distributed over CONUS. Geographical sitings were selected from Aerospace corporate sites to host the ground terminals, providing

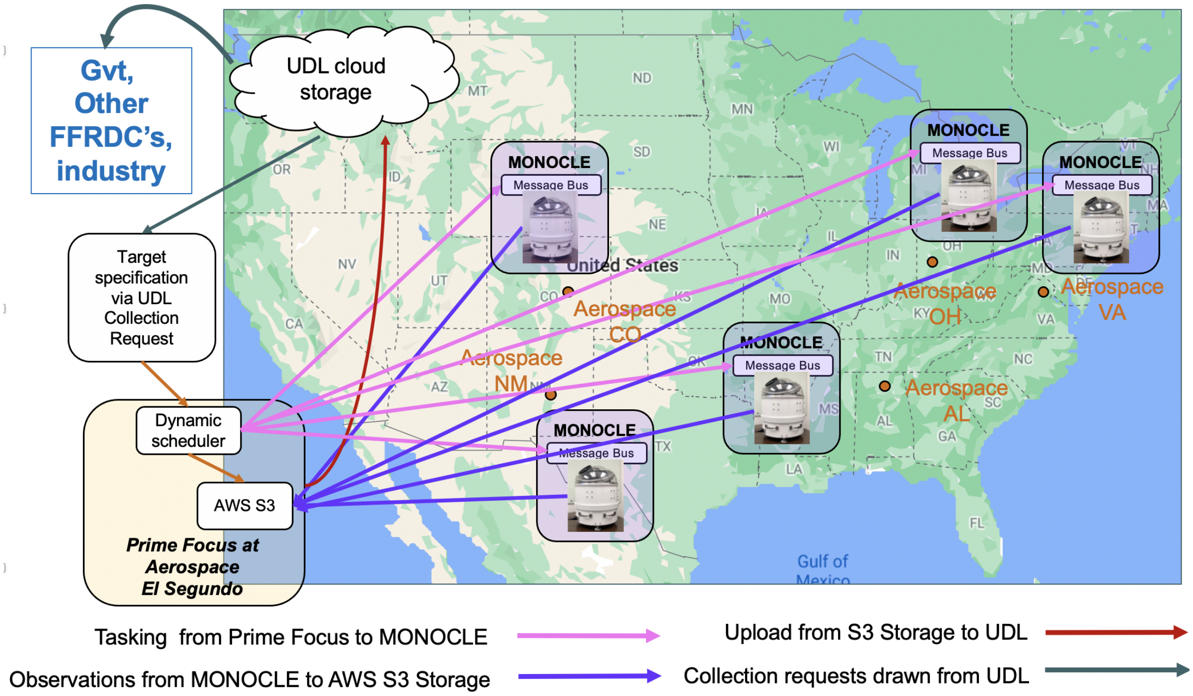

Fig. 8: *Notional geographically dispersed Monocle network utilizing existing Aerospace facilities across CONUS. These units may be emplaced on rooftops, scaffolding, or free-standing towers at Aerospace sites that are secured against human interference. The existing Aerospace intranet permits dynamic tasking and data retrieval to El Segundo: the site that currently hosts the Prime Focus pipelines and the AWS S3 cloud storage system. Prime Focus uploads data products to the UDL for distribution to government, FFRDC's and industry via the UDL. The UDL provides a collection request schema, which Prime Focus can retrieve at regular intervals to create a schedule of observations as described in Section 3.1 and illustrated in Figure 3. Implementation of a network like this creates meaningful opportunities for engagement across government, industry, academia and commercial sectors.*

power, ethernet, and physical security. This architectural choice postpones the need to negotiate for cell tower installation and retains the ground terminals in closer proximity to engineering staff that can troubleshoot issues. These sites are connected via the Aerospace intranet, allowing dynamic tasking and data transport over an existing network. Completing a prototype of this level of realism provides numerous opportunities for engagement by government, industry, academia, and FFRDC's: ground terminal hardware/instrumentation/embedded development, development of scheduling algorithms, usage analytics for load balancing, and experimental campaigns against RSO target lists. None of these activities are suitable for an operational sensor system like the SSN.

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