Pomenis: A small portable astrograph for SSA

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ABSTRACT

The Steward Observatory SSA team developed the Pomenis Astrograph System as an alternative to more traditional narrow field of view small SSA systems. The astrograph is innovative with its fast optical design versus a traditional longer focal length found on commercial Cassegrain telescope that most "Raven class" systems are based on. Compared with other systems used for SSA, the Pomenis astrograph has an exceptionally wide 4.2°×4.2° field of view and a fast readout CCD camera. These features enable synoptic survey of the deep space satellite population several times per night. The aperture and focal length were carefully selected to achieve sensitivity relevant to synoptic GEO SSA with an integration time short enough to allow high precision astrometric reference using the streaked background stars. With its 7-color filter wheel, Pomenis also performs multi-color photometric screening of deep space satellites looking for anomalous behavior and can identify objects for higher fidelity measurements and study. Pomenis is housed in a unique trailer mounted enclosure, which enables the system to be deployed with minimal infrastructure, operated remotely and autonomously, and quickly relocated as required.

In addition to the SSA measurements described above, the astrograph is taking full-hemisphere night sky brightness (NSB) measurements in multiple color bands. These measurements will be compared to previously conducted each decade on Mt. Hopkins and Kitt Peak to study the increase in light pollution in southern Arizona. Pomenis will allow these measurements to be made on a more routine basis, and over a tighter spatial grid. This will facilitate our monitoring of the light pollution environment at the University's observatory sites and assess the impact of future development on the quality of the night sky. Additionally, Pomenis will be used for serendipitous astronomical surveys and to develop new techniques for precise photometric reduction over a wide field of view and high air mass.

1. INTRODUCTION

In response to the anticipated launch of Sputnik in 1957, the Smithsonian Astrophysical Observatory (SAO) was funded to develop and deploy an optical network to detect, track, and determine the orbits of Sputnik and those satellites that would follow. To support this mission, the SAO contracted Boller & Chivens to manufacture 12 Baker-Nunn Schmidt cameras. The Baker-Nunn telescopes used an innovative 51 cm three-element corrector lens assembly and 76 cm f/0.75 primary mirror. The very wide 5°×30° field of view was imaged onto a 25 cm segment of 55 mm wide cinemascope film [1, 2]. The Baker-Nunn telescopes would be deployed to form the first worldwide optical tracking network, and later the operational techniques would be adapted to the slower moving deep space satellites [3].

Other countries responding to the newly created space surveillance mission developed similar wide field of view photographic systems. The Russian AFU-75 camera designed by Lapushka and Abele at the Riga University was a 21 cm f/3.5 system with a 10°×14° field of view. The system was deployed to 15 sites worldwide. Later the same group developed the FAS camera, with a slightly larger 25 cm aperture and f/1.9 optical system with a 7°×10° field of view. The German developed Stellitenbeobachtungsgerät (SBG) significantly increased the aperture of foreign systems with its 42.5 cm f/1.8 system [4]. Perhaps the last of its generation, the Russian VAU finally matched the Baker-Nunn system's combination of aperture and field of view with its 50 cm f/1.4 system and 5°×30°. The VAU used a curved focal surface and a unique two-shutter system [4].

With the shift to electro-optical systems, initially with intensified silicon target cameras, and later with CCD imagers, it was no longer practical to cover the very large focal surfaces of the previous generation of satellite tracking cameras. The next generation of systems would have more modest fields of view that were matched to the relatively small imaging detectors of the day. To support these systems, significant development efforts focused on increasing the format size of intensified silicon detectors, ultimately leading to the original GEODSS Ebsicon camera with its 76 mm format [5, 6]. The small format size and high read noise of early CCDs slowed the adoption of CCD technology into SSA systems until the upgrade of the Moron Optical Space Surveillance (MOSS) system and the Deep STARE update for GEODSS in the early 1990s [7, 8, 9].

More recently, small commercial systems have been demonstrated by many groups, starting with the original Raven telescope system by AFRL [10]. These systems used commercial imagers with relatively small formats, and long focal length Cassegrain telescopes originally developed to serve the high-end amateur astronomer. Consequently, these systems adopted a “task-track” surveillance approach. Nonetheless, these systems were highly affordable and provided impressive sensitivity.

The Pomenis Astrograph takes a different approach. With Pomenis, we return to the wide field of view optical designs originally demonstrated by the photographic astrographs that were the foundation of early space surveillance. Suitable astrographs manufactured by Takahashi Seisakusho Ltd. with focal ratios as low as f/2.8 provide excellent image quality over a large 44 mm format. We combine the astrograph with a fast, large format commercial CCD camera and agile Paramount (MYT) equatorial mount. The relatively small aperture necessitates a different data collection protocol and *a priori* assumptions of a near-GEO satellite rate to achieve sensitivity approaching 16 magnitudes—but this is an acceptable compromise considering the total capital investment in the system, including the enclosure, is less than $60k. By allowing additional integration and by performing astrometrics relative to the streaked background stars, Pomenis will provide a search rate and sensitivity adequate for routine synoptic GEO space surveillance.

2. SYSTEM OVERVIEW AND PERFORMANCE

The design of a ground-based optical system to detect and track satellites is straight forward and based on a few simple principles. The systems are designed to detect unresolved objects illuminated by the sun against the background of the night sky. Even at a very dark site, the night sky is filled by diffuse background glow [11]. On a moonless night, the background is dominated by airglow in the upper atmosphere. In twilight, or when the moon is in the sky, Rayleigh scattering of sun and moonlight significantly increases the brightness of the background sky. Optical SSA systems are designed to optimize the detection of unresolved sources against this background by matching the pixel size and point spread function (PSF) of the satellite to the natural seeing limit of the sky and reducing sensor noise to a level so that the background sky noise is the dominant source of noise. Such a system is said to be “night-sky limited”. Thus, the performance of a ground-based optical SSA system is driven primarily by the night sky brightness at the site to which the system is deployed.

Satellites are discriminated by their relative motion to the background stars. A geosynchronous satellite, which is co-rotating with the earth, appears to be moving at 15 arcsec/s against the background stars, and the range of angular rates for near-GEO and graveyard objects span only a few arcsec/s relative to this motion. SSA sensors usually operate in one of two modes: (a) sidereal track, or (b) rate track. In the first mode, the telescope tracks at the sidereal rate, and the stellar background appears stationary on the focal plane. Satellites are detected by identifying short streaks in the image, or by the relative motion of the satellite between successive images. The optimal integration time for these systems is comparable to the pixel crossing time of the satellites of interest. The system provides a search capability unbiased (at least to first order) by the angular rate of the satellite. GEODSS (1 m f/2) and SST (3.5 m f/1) are examples of these systems. Because of the short integration times driven by the requirement for an unbiased search capability, the aperture of the telescope is large compared to a sensor operating in the task-track mode Figure 1 shows a typical Pomenis frame in sidereal tracking mode with a low earth satellite streaking across the frame. By design, the full format of the Apogee-Alta F9000 camera (36.7 mm square) oversamples the 44 mm unvignetted field of view of the telescope. Figure 2 shows a fully corrected long integration frame and the exceptionally high image quality of the Takahashi astrograph, which provides < 10 µm images over the entire 44 mm field of view.

In the second mode, the telescope is tracking at the anticipated rate of the satellite and the satellite appears as a near-stationary target. The astronomical background streaks relative to the near-stationary satellite. By tracking the satellite using an *a priori* element set or an accurate angular velocity estimate, the system can effectively integrate for a long period of time. In practice, the integration time is limited by the need to reference astrometrics to streaked background stars and to limit the contamination of field by long star streaks. In this mode, high sensitivity can be achieved with a modest telescope aperture, and the field of view of the system need only allow initial acquisition of the satellite based on the element set. These two factors enable designing a task-track system with modest commercially available small telescope and CCD cameras [10].

Figure 1. Low earth satellite streak across a typical Pomenis frame. The full 36.7×36.7 mm (51.9 mm diagonal) Apogee Alta F9000 camera format size is show, uncorrected for the slight vignetting of the field of view beyond about 44 mm.

The design approach for the Pomenis Astrograph is driven by a desire to have a system capable of synoptic GEO surveillance at a price point significantly under $100k. Performance at this price point forced a different approach to achieve the desired system performance. In this case, we adopted the approach of assuming *a priori* a near-GEO rate and allowing an integration time that would not compromise astrometric accuracy vs. our modest < 1 arcsec requirement. During a nominal integration time while tracking at GEO rates stars streak approximately 5 pixels. This data collection strategy allows Pomenis to use a commercial Takahashi E-180 Epsilon Astrograph. The E-180 astrograph optical-tube-assembly (OTA) has a 180 mm aperture, f/2.8 focal ratio, and provides high image quality over a 44 mm image circle. The requirement to keep star steaks under 5 pixels long limits our effective integration time to 1.65 s, achieves a target sensitivity of 16.3 m_v in a 20.5 m_v/arcsec^2 sky, and a metric accuracy of 0.5 arcsec with a 4.95 arcsec pixel using an affordable commercial system.

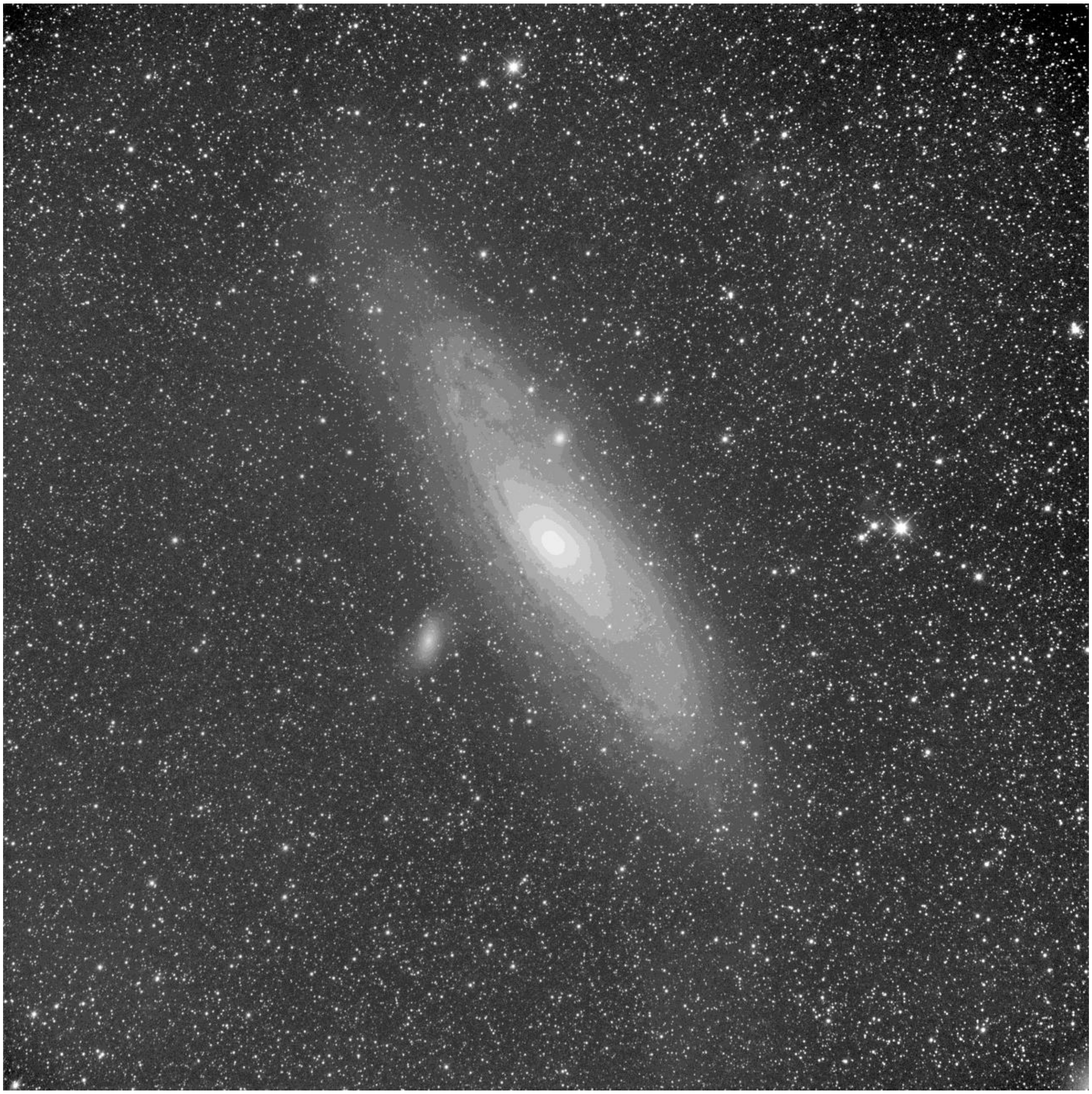

Figure 2. The Andromeda Galaxy (M31) and its satellite galaxy M32 in a co-added r', g', i' image showing the superior image quality of the Takahashi Astrograph.

As with most synoptic SSA systems, sensitivity can be traded with search rate. A well designed step-stare systems strives to closely match the readout time of the camera system to the step and settle time of the mount. Figure 3 shows the modeled search rate and sensitivity of Pomenis, and several other comparable systems, including systems integrated with COTS camera telephoto lenses, and the GEODSS Auxiliary telescope. Note that due to the data collection mode used for the astrographs, they operate at a point where they are providing the maximum sensitivity while still referencing the astrometric measurements to the streaking background stars. Potentially, sensitivity could be extended by integration beyond this point, but a separate shorter astrometric calibration frame would be required to provide an astrometric reference and contamination of the near-stationary satellite images by steaking stars would become a problem.

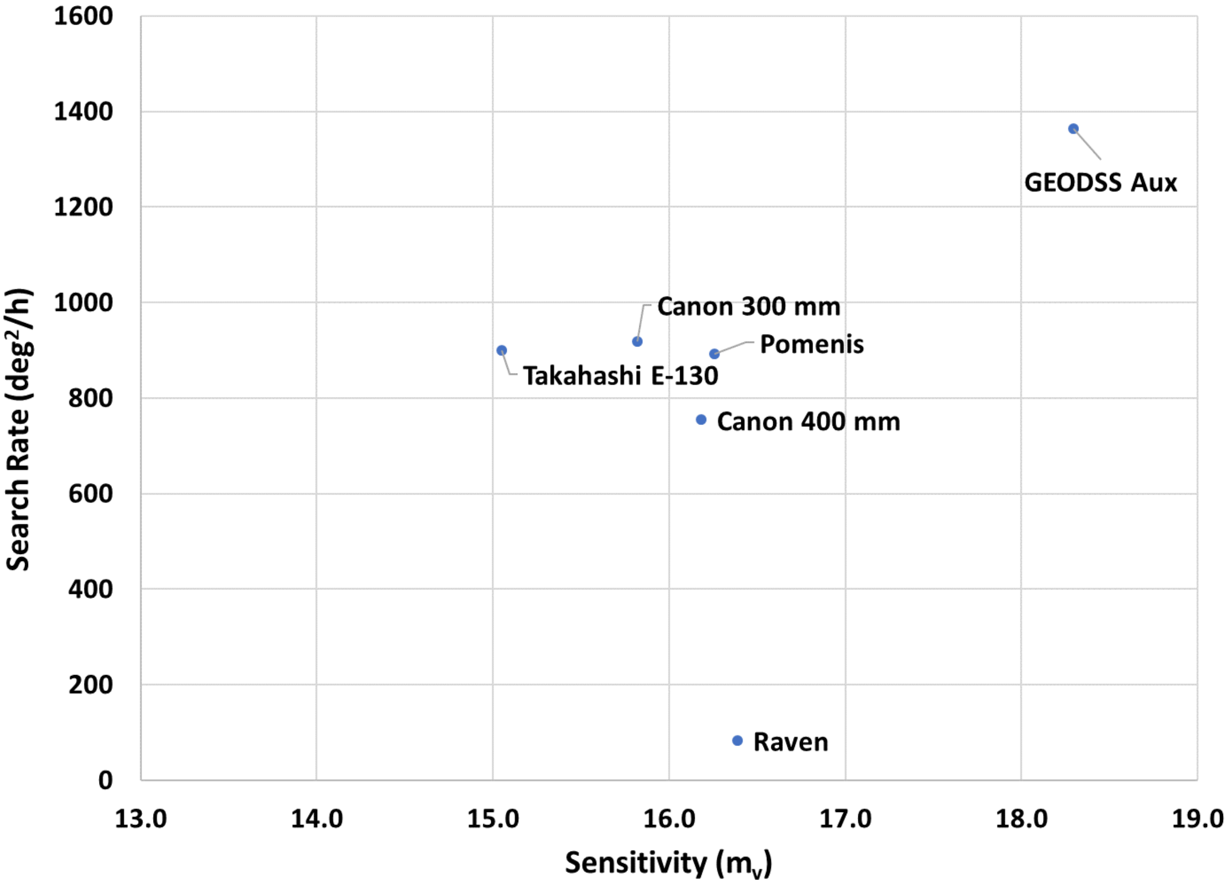

Figure 3. Search rate and sensitivity performance of Pomenis compared to other SSA Systems.

3. ENCLOSURE

Pomenis is more than just a telescope and camera system. The Pomenis Enclosure completes the system and provides environmental protection, infrastructure, and supplementary sensors to allow fully automated remote operations with a minimal footprint[1]. The enclosure is built atop an Airtow drop-deck utility trailer. This trailer features a hydraulic system which lowers the deck of the trailer to the ground when parked (see Figure 4). Removing weight from the wheels of the trailer and making broad contact between the ground and trailer frame provides exceptional stability without the use of outrigger jacks.

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[1] The Pomenis Astrograph is named after *Pomenis*, one of Actaeon's 48 greyhounds in Greek mythology. Greyhounds have excellent eyesight, allowing them to spot small animals at great distances.

Figure 4. The Dog House in its closed position prior to lowering the trailer bed into the operational position at the Mt. Lemmon site near Tucson AZ.

The roof of the enclosure is a clamshell style based on the Aqawan design used at Las Cumbres Observatory and elsewhere [16]. The roof opens with a compound motion that combines a lateral slide and horizontal rotation which maximizes available sky while minimizing outboard displacement (see Figure 5). By optimizing the geometry of the clamshell sections and mechanisms, the motion the roof is stable under gravity in both the open and closed positions. The opening at the vertex of the roof features four separate weather seals to keep water out. Inside the Dog House is an approximately 4.5 m^2 open area for setup of instruments. The frontmost area is partitioned for housing computers, control, and power equipment.

The entire system is powered via a 120VAC power inlet. Power usage is limited to 15A to maximize compatibility with available power sources. Power is provided via extension cord to a nearby building, generator, or solar array. Power is distributed using DLI Pro Switches, which allow remote monitoring and independent remote power cycling of all components. The Dog House has internal battery backups for all essential systems including computer, instruments, and roof mechanism. Network connection is provided via a ruggedized fiber optic cable.

The system can be remotely controlled and scheduled for semi-autonomous operations. In this mode the telescope performs scheduled observations while the control system monitors weather and power conditions. For instrument and environmental monitoring, the Dog House is equipped with internal and external CCTV cameras using a video server and integrating low light level cameras. A Boltwood weather station mounted to an external mast provides a robust weather system with no moving parts. In the event of inclement weather or power failure the system will safely shutdown and close. A high-efficiency air conditioner and heater unit maintains safe operating temperatures during the day and can pre-chill the instrument before nightfall

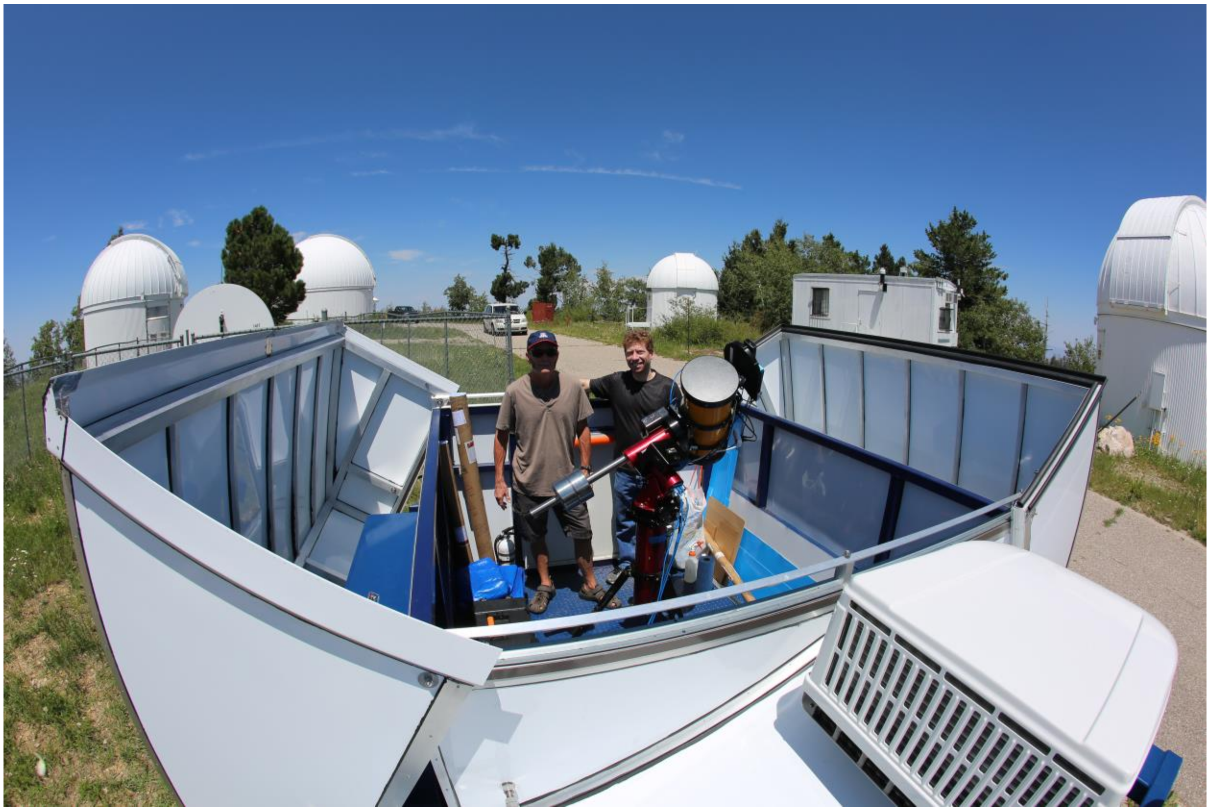

Figure 5. The Dog House in its open position showing the Takahashi E-180 Astrograph. The air conditioning unit can be seen in the foreground.

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4. CURRENT MEASURMENT PROGRAMS

Pomenis is continuing the commissioning process towards routine satellite tracking and routine satellite tracking is expected early in 2019. Currently, Pomenis is conducting night sky brightness (NSB) measurements at three University of Arizona astronomical site (Mt. Lemmon, Mt. Hopkins, and Kitt Peak). The same system attributes that make Pomenis an exceptional small synoptic surveillance system allow it to collect NSB measurements over the full visible hemisphere rapidly and in multiple color bands. These data sets will allow the University to monitor the evolving astroclimate at our sites and the impact of light pollution on the observatories. These measurements will be compared to previously conducted each decade on Mt. Hopkins and Kitt Peak to study the increase in light pollution in southern Arizona [12, 13]. As part of this effort, we are also collecting extensive measurements at low lunar elongations to refine models of the night sky brightness under challenging moonlit conditions. Pomenis is also equipped with two Unihedron SQM (sky quality meter) sensors, one co-aligned with the telescope, and a second fixed at the zenith, to provide data quality verification during the full-hemisphere collections.

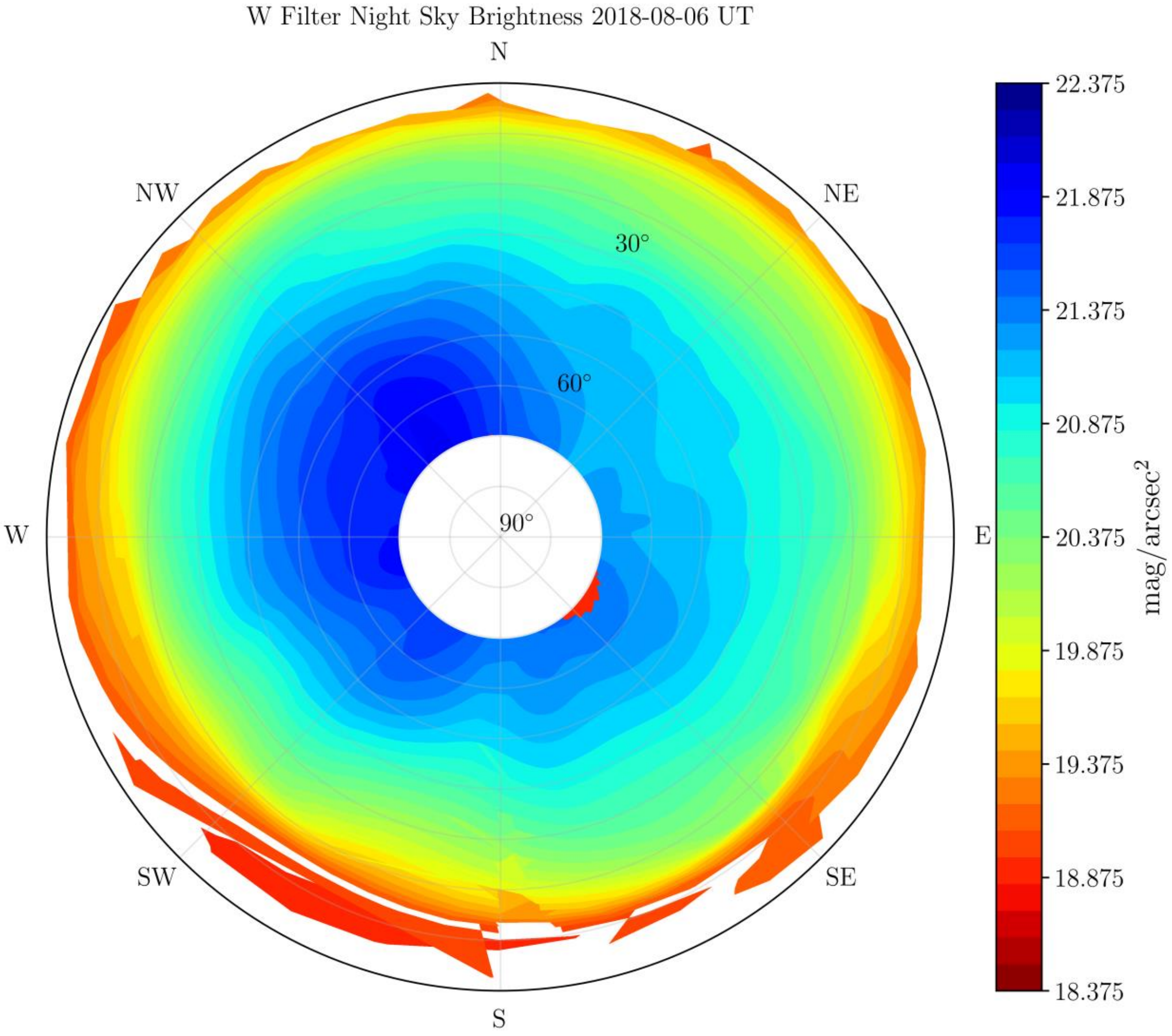

Figure 6. Full hemisphere night sky brightness measurement from Mt. Lemmon during our July 2018 campaign. The impact of Tucson SE-SW is clearly visible.

5. THE PATH TO LARGER ASTROGRAPHS

The Pomenis Astrograph is unique among the community of small COTS-based satellite tracking systems. The wide 4.2°×4.2° field of view, large format camera, and agile mount allows it to perform synoptic surveillance of near-GEO deep space satellites. The use of commercial components and the streamlined footprint enabled by the portable trailer mounted enclosure keep the total system cost at less than $60k. By making reasonable *a priori* assumptions about satellite angular rate, Pomenis can reach a sensitivity adequate to detect most payloads in GEO orbit, while keeping background star streaks short enough to support precision astrometry.

Pomenis demonstrates that small SSA systems can also operate synoptically and provide a significant search capability for brighter satellites. Nonetheless, Pomenis is limited by its aperture. To eliminate the *a priori* assumption of a near-GEO rate, an aperture closer to 40 cm is required [14, 15]. Ironically, such a system is nearly identical to the GEODSS Auxiliary telescope, which was closely based on the original GEODSS prototype system telescopes demonstrated by MIT Lincoln Laboratory. The prototype 14” folded Schmidt telescope had a field of view of 7 degrees. Unfortunately, with the original Ebsicon camera technology, the system did not have sufficient sensitivity to support routine catalog maintenance, and the telescopes were removed and surplused prior to the Deep STARE CCD upgrade. In the future, the combination of large format commercial CCD cameras and wide field of view astrograph telescopes offer an alternative approach to establishing and maintaining synoptic surveillance of deep space satellites in an affordable commercial system.

6. ACKNOWLEDGEMENTS

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