The fundamental role of wide-field imaging in Space Situational Awareness

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ABSTRACT

National Space Situational Awareness (SSA) is fundamentally based upon surveillance of the variety of anthropogenic and natural objects moving in Earth Orbital Space (EOS): functioning satellites, derelicts, space debris, and naturally occurring objects. We define Earth Orbital Space is thus defined as the volume of space centered on the Earth within which Earth's gravitational potential affects the orbit (open or closed) of an object. Optical telescopes provide a significant fraction of all data for the surveillance of space, and virtually all data on GEO and related objects. Starting with an operational definition of *surveillance of space* (SoS), we discuss:

- The unique role of wide-field imaging in acquiring EOS surveillance data
- Detector-driven optical design of small, wide-field telescopes that produce data capable of providing high signal-to-noise images and tracks in the presence of detector and complicated background noise
- Multiple sky tracking and detector readout combinations to optimize object detection from LEO through GEO
- The approach to real-time image data processing capable of enabling immediate analysis and decision-making, as required.

Specifically, we describe the fundamental physics associated with the design of optical surveillance cameras based upon small aperture, wide field-of-view telescopes which we have designed. Critical performance issues include uncued detection of new and/or un-cataloged objects to faint limiting magnitudes (V > 14 at LEO), including initial trajectory determination, and the capability to survey large areas of the sky (such as the CONUS GEO belt of approximately 1800 sq. degrees) to faint limiting magnitudes (V ~ 18) every two hours. The goal is to convert these data into actionable information in very near real-time.

Initial data demonstrating and supporting our surveillance of space system designs and design goals are presented.

1. INTRODUCTION

Achieving Space Situational Awareness requires robust surveillance of space, utilizing a variety of techniques. Near-Earth space is critical to so many aspects of modern civilization that every practical technique should be used because collisions have catastrophic consequences. In short, because we need to know what is happening in Earth orbital space, we must observe as much of the 4π steradians of the sky as continuously as possible to discover, track and characterize active satellites, derelicts and space debris. We must also watch for activities that are potentially destructive, whether from malicious intent, negligence or chance. Wide-field optical imaging plays a fundamental role in this quest and stands ready to assume an even bigger one.

Acknowledging the importance and purpose of optical surveillance of space, J. T. McGraw and Associates, LLC (JTMA) has applied fundamental physics and astronomy to the mission of acquiring cued and uncued satellite observations with low-cost telescope systems that are capable of implementing affordable, persistent surveillance from 300 km to greater than 40,000 km. These data provide an important supplement to the data acquired by other space observation systems, together providing the information necessary to move towards the goal of a secure space environment for all peaceful purposes.

Since our last report [1] JTMA has made significant progress in implementing ground-based optical, affordable, persistent surveillance of space. Our prototype system of three small telescopes accomplishes many of the desirable elements of surveillance of space (SoS) by implementing JTMA precepts:

- Observe satellites ranging from LEO through GEO using telescopes with multiple-square-degree fields of view tracking at the sidereal rate so stars are point-like and satellites are distinguished as streaks
- Image at 1 Hz or faster frame rates on large-format CCDs to capture complete, accurately timed streaks from the lowest altitude, thus angularly fastest moving LEO objects
- Implement GPU-supported fast, efficient, faint streak detection, and analysis algorithms capable of interpreting them as trajectory information relative to astrometric stars in near real-time
- Real-time activation of another telescope to confirm and obtain additional same-pass trajectory data is enabled
- Cooperative operation of telescopes enables accurate parallax (range) determination out to GEO.

These capabilities have been demonstrated with our COTS prototype system. As a single example of implementation capability, our prototype system imaged the ANGELS super-GEO system and derived parallax (range) separation between the two components. A single observation is shown in Fig. 1.

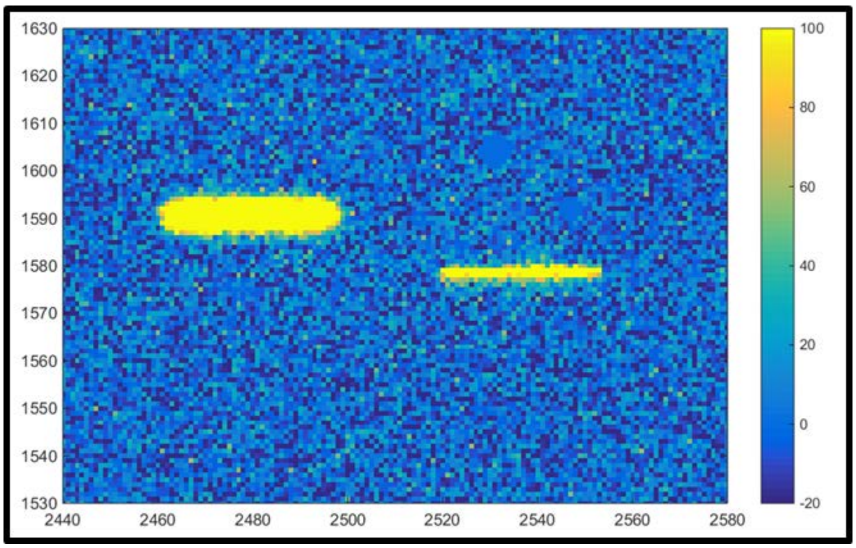

Fig. 1. Stamp from a 2° x 3° field showing the ANGELS bright rocket body and the fainter payload from 14 October 2014, when near optimum illumination. The payload is mag. 13.1 as a 60.4σ detection. The range difference between these GEO objects was resolved by parallax.

We describe our current status in implementing this portion of an envisioned global surveillance effort in support of Space Situational Awareness, including routine real-time identification of satellite streaks in wide-field images, and derivation of real-time trajectory data. We also describe design efforts to produce an optimized next-generation wide-field optical system and automated operation leading to “farms” of inexpensive telescopes [2] providing reconfigurable operations, including “space fences,” to survey orbital space from LEO altitudes to beyond GEO. We suggest that this effort significantly improves the community effort to secure space for military, commercial and research purposes.

Security, commercial, and scientific needs mandate accurate, complete, and cost-effective surveillance of space. In the US, a major responsibility for space surveillance resides with the Air Force. “The Air Force Space Command’s mission is to provide resilient and affordable space and cyberspace capabilities for the Joint Force and the nation.” [3] The related mission element of USSTRATCOM includes “to ensure US freedom of action in space and cyberspace.” [4] The AF 21st Space Wing has a broad charter, including space surveillance, and it operates a breadth of surveillance assets, including ground-based optical system such as the wide field GEODSS array. The mission of the 21st Space Wing is to “Provide and employ global capabilities to ensure space superiority to defend our nation and allies.” [5] These mission statements direct an outcome – they doesn’t specify the mechanism for attaining the required outcome. This paper establishes ground-based optical wide-field imaging as a fundamental, cost-effective, resilient mechanism for attaining a significant fraction of space surveillance, a cornerstone of space situational awareness.

Understanding the *purpose* of surveillance is a primary key to implementing correctly, effectively and efficiently the Surveillance of Space (SoS) and then assessing the effectiveness and efficiency of this activity as a mission element. Understanding of purpose is also a prerequisite to the design and implementation of surveillance systems and the suite of ground- and space-based detectors that enables the required functionality. Slightly modifying a modern definition for "surveillance" [6] provides a useful context for SoS:

> *The purpose of Surveillance of Space (SoS) is to detect and monitor the behavior, activities, and other changing characteristics of Earth orbiting objects for the purpose of influencing, managing, directing or protecting them*.

For various reasons, including passive solar illumination, well-understood telescope technologies, and realizable cost benefits, a significant element of a global satellite security system is based upon ground-based optical surveillance of space. The key feature of our surveillance system is implementation of many small near-COTS wide-field telescopes large enough to reach specified magnitude limits for LEO and for GEO, and small enough to cost but a few percent of the current generation of large, specialized telescopes. The wide-field capability and efficient, fast detection of streaks resulting from satellite motion set our systems apart from others that employ small telescopes. We have carefully assessed use of wide field of view telescopes for survey purposes. [7]

We describe the scientific bases for development of sensitive, wide-field telescope/detector systems to survey LEO/GEO space, recording the positions, ranges and motions of orbiting objects, including functioning satellites, derelicts and space debris, with the primary goal of protecting functional satellites from both random and directed threats encountered in the LEO/GEO environment.

There are several observational techniques that can be implemented with these well-designed small optical telescopes, deployed as arrays, to achieve significant optical surveillance. These include organized overlapping field observations yielding parallaxes for LEO terminator observations, and scanning modes of differently organized fields for rapid (two hour) repeated observations of CONUS GEO, for example. We review our survey techniques and specifically describe a wide field of view survey based upon detection of satellite motion-induced streaks that accomplishes many of the defined purposes of SoS.

2. GROUND-BASED OPTICAL WIDE-FIELD SURVEILLANCE – A PHYSICAL OVERVIEW

Having established the purpose for SoS, the issue becomes how best to implement ground-based optical surveillance to accomplish its purpose. To initiate design of an optical system to address surveillance we state and consider fundamental survey parameters and then iterate to a robust, cost-effective solution.

The key issue for surveillance is <u>detection</u> of satellites and debris. The signal-to-noise (S/N) of a detection can be quantified and used as one parameter to optimize telescope design decisions.

The Sun is the obvious SoS illumination source. It provides passive, exceedingly cost-effective (free!), broad-band, wide-field illumination of all of Earth Orbital Space (EOS), and is the obvious preferred illumination source for the vast majority of passive optical SoS. [8] We first develop efficient and effective dark sky SoS using the S/N of satellite detections as a primary parameter (for details, see [1]).

<u>Detection</u> of faint satellites requires imaging the largest possible signal - the solar photons reflected by the satellite - into the minimum number of area-format detector pixels, each of which has noise including the photon noise of the signal, the photon noise of the background illumination and the detector readout noise. That is, detection requires maximizing the signal to noise ratio, a *first step* of which is to simultaneously to put as many satellite photons and the optimum number of background photons onto each pixel of a low-noise detector. The telescope field scale on the detector, and the telescope optical bandpass must be optimized for satellite detection. Because of its COTS availability and widespread use for imaging the sky, we assume a silicon area-format detector (a CCD) for this preliminary throughput discussion.

Note that the function of a telescope is to map angles on the sky to positions on the detector. Thus, for a sidereal tracking telescope, a star will be imaged onto a few pixels in the focal plane, and the number of stellar photons in those few pixels increased linearly with the exposure time. By the same argument, the "sky background" is diffuse – every element of the sky radiates into all angles. Thus every angular resolution element on the sky illuminates every pixel in the detector. Clearly, a dark sky site and the use of bandpass filtering to exclude bright portions of the optical spectrum of the sky, while efficiently transmitting those wavelengths resulting from satellite-reflected sunlight, is essential to detectivity and the success of optical ground-based SoS.

At optical wavelengths (500 nm) the Rayleigh criterion indicates that a 0.5 m diameter telescope can resolve 10^{-6} radian or 0.2 arcsec, corresponding to a 0.4 m object at LEO and a 40 m object at GEO. Telescope resolution is ultimately limited to ~ 1 – 2 arcsec by Earth's atmosphere, so the majority of light from a satellite of physical size from CubeSats in LEO to the largest bus-based satellites in GEO will be contained in a 1 arcsec seeing-blurred PSF. Thus, in practice, to achieve the highest possible *detective* S/N, we design a surveillance telescope to put the PSF optimally into one pixel. This is a primary constraint on the CCD pixel size and the telescope field scale.

We state that the selection of a CCD detector drives the design process of our optical systems and our observing techniques, principally because detectors are expensive, and custom detectors are *very* expensive. Detectors have thus driven telescope design for more than a century. [9] At this point we seek detectors with the lowest possible readout noise, r_{Det}, pixel scale that matches the seeing-blurred PSF at the telescope site, the largest possible standard format, and the readout mode that achieves the framing speed required to obtain complete streaks on a single exposure for fast-moving LEO objects.

The one remaining issue involves limiting the optical bandpass onto the detector to optimize detection of solar-illuminated satellites. The major issue is that satellites are fabricated from multiple materials, each with a different wavelength dependent reflectance to sunlight. Additionally, because of satellite rotation, maneuvering and its orbital motion relative to our telescopes on Earth the materials from which satellites are fabricated will change the overall reflectance spectrum with time. While these changes are diagnostic for follow-up observations, the goals of detection for a wide-field survey require including as broad a detection bandpass as possible. The factors that impact specification of the broadband survey bandpass are: 1) the time-variable transmission of Earth's atmosphere, 2) the night sky spectral radiance caused by telluric emission, 3) the phase and direction of the moon from the survey field, 4) the transmission of the telescope, including all of its lenses and mirrors, 5) the spectral quantum efficiency curve of the CCD, and finally, 6) the bandpass-limiting filter that passes light from satellites, and eliminates or minimizes light from extraneous sources. An optical filter optimized for satellite detection has a bandpass of 380 – 725 nm.

Multi-bandpass observations of satellite are critical for satellite characterization. We here defer that function to other instruments, choosing to optimize detection of objects so that others can track and characterize them.

Conceptually, we have now designed a wide-field survey telescope. Modeling the satellite telescope throughput using the satellite point source S/N as the primary detectivity criterion enables progress towards optimized wide-field optical SoS.

3. OPERATION OF AN OPTICAL WIDE-FIELD SURVEILLANCE SYSTEM

Having described replicable wide-field telescopes, the operation of a prototype affordable, persistent surveillance system can be defined. From the outset this is a *space surveillance* system designed and optimized for this mission alone – it is not tasked for characterization – other telescopes provide this capability. The concept of persistent surveillance immediately implies that there is no *ab initio* difference between an uncued detection of a new (or recovered) object and routine catalog maintenance observations. In this sense, every wide-field observation is an uncued observation. This technique provides synoptic data and leads to statistical completeness, repeated observations leading to improved and updated orbital elements. In some respects, this is a new (or at least different) way of thinking about SoS, driven by the true survey nature of the project, the design of the surveillance telescopes, and the synoptic observations.

A useful adjunct of effective small telescope surveillance is the ability to deploy the same telescopes for theater-scale support. These systems are sufficiently robust that they will function in the field, and sufficiently inexpensive that they are expendable. [10]

Angular Domain

The angular areal extent of the celestial sphere is 4π steradians, or 41,253 square degrees, and satellites can appear in any of this angular area. The first driver for a useful SoS system is thus continuously to observe as much of the dome of the sky as possible – an obvious but seldom implemented criterion for a successful surveillance system. The second driver is to design the system to concentrate observations on high-value regions of space – the equatorial region for both LEO and GEO is an example.

We envision that at one telescope "farm," during sunrise and sunset twilight multiple telescopes will form a fully covered area of the sky. Once positioned, the telescopes will all track at the sidereal rate, maintaining the overlapping field geometry on the sky. All satellites passing through or in the survey cone for this configuration will be detected, and trajectory information will be generated for each in near real-time – within two seconds of detection. If a detected object has previously been measured, the current observations, referenced to UCAC4 astrometric standards, are flagged to update the orbit of the object, and record brightness information.

If the object is not cataloged, another telescope is tasked to go to a position provided by the uncued observation and acquire same pass data to refine the orbit sufficiently well that another telescope, perhaps in a different farm, can acquire the object and again upgrade the orbital parameters. For some orbits, the same farm might re-acquire the same object on its next orbit, and thus improve orbital elements. The goal is that once an uncued detection is made, the surveillance system will attempt create an initial orbital determination from multiple observations in the discovery orbit, or in closely spaced orbits.

In this overlapping field mode of operation pairs of telescopes will have a volume of space where their fields of view intersect, for which simultaneous observations in that volume will lead to an accurate parallax range determination. Real-time accurate range information will help with trajectory determination and rapid recovery of the object, and ultimately with orbit determination.

Because our goal is to provide surveillance of the nighttime sky using ground-based optical telescopes, each telescope should accurately point to designated angles on the sky. The required slew and track rates are determined by our analysis of the observing modes required to achieve accurate surveillance. The rates required to implement "all sky" surveillance are not extreme, and can be managed by high-end COTS telescope mounts and drives.

At any instant, the useful field of regard, the angular area accessible to a telescope, is a cone of 60° radius from the zenith, allowing observations through two airmasses or less (Fig. 3). In some instances, such as tracking an uncued discovery, the telescope should include a "guard ring" in zenith angle, enabling observations to three airmasses, or approximately 70° zenith angle or perhaps more. A viable limit is soon reached because in optical wavelengths light reflected from a satellite (or received directly from any star) is attenuated by scattering and absorption in Earth's atmosphere at a rate of approximately 15% per airmass, thus observations at greater than 60° zenith angle rapidly become unproductive.

Time Domain

Because EOS is continuously changing – satellites maneuver, they become active or dormant, orbits decay, new satellites are launched, and natural objects pass through it – SOS is time-critical, so the cadence for repeat observations has high priority. There are two drivers for EOS observing cadence: critical decision-making, and acquisition of crucial orbital data.

The entire purpose of surveillance is to provide the data and the information (these are two separate entities) that allow decision-makers to accomplish their jobs. Often the most critical decisions are time dependent: whether to move a satellite with a high probability of conjunction, how to monitor the motion and determine the final position of satellites in transfer orbits, whether to maneuver, de-orbit or park a malfunctioning satellite, and whether to take political or military defensive or offensive action to preclude the actions of bad actors, whether those actions are malicious or negligent. In extreme cases an argument for a one minute observation-to-action real-time response is appropriate.

The second driver for even higher cadence observational cadence is the necessity to derive accurate orbits for uncued detections. Our current observational experience emphasizes the fact that there are many objects orbiting in EOS for which there are no catalog entries available to us. Our observations thus always assume uncued detections, for which the most accurate possible orbits must be determined on the discovery pass, else the object cannot accurately be recovered on subsequent passes. In fact, for wide-field imaging, there is no real distinction between cued and uncued detections – cued detections are *a posteriori* selected because they have an accurate catalog entry. Our preferred technique for improving orbits for uncued detections is to determine a trajectory based upon the discovery observations assuming a circular orbit, and then in real-time cue another wide-field telescope to re-acquire the object, and in the process improve the orbital accuracy so that the object can accurately be re-acquired for some reasonable time into the future. In this case, the appropriate observation-to-action real-time response is a few seconds. With this response time a second telescope can be commanded to slew to a position at which it can re-acquire the uncued object and obtain sufficient orbital data to ensure an orbit accurate enough to be able to re-acquire the object over a window of opportunity of several days or more.

This uncued orbit determination reacquisition timescale is shorter than our estimates for decision-making, hence that timescale is accommodated by our same-pass orbit reacquisition observations.

The target SoS system thus requires observing all of viable Earth Orbital Space at a cadence of approximately one second. Note that this timescale and angular area is principally determined by LEO objects. Fast framing is required to obtain complete streaks on a detector, and to get multiple detections to unambiguously determine direction of motion.

From this set of considerations of time- and angular domain operation, we require a successful space surveillance system to:

1. Observe a wide field of view as continuously as reasonably possible
2. Do so with a cadence measured in seconds
3. And to limiting magnitudes of V ~ 14 at LEO to V ~ 18 at GEO.

4. SURVEILLANCE OF SPACE: SATELLITE STREAKS

Ground-based images generated as a result of SoS (as opposed to pointed observations) always contain streaks: if the telescope tracks a satellite, the satellite appears as a stationary image while background stars all streak at a rate determined by the satellite motion and motion of the telescope due to Earth rotation; if the telescope tracks stars, obviating their apparent motion, all satellites will create streak images. Hybrid techniques, for example tracking at approximate satellite rates, always produce star streaks, and usually satellite streaks, as well.

We are developing uncued SOS systems based upon tracking stars and allowing satellites to streak.

The status of our knowledge about objects in EOS is such that uncued discovery of debris, discovery of new satellites, rediscovery of catalog objects previously detected but for which orbital elements are no longer current, and detection of motion or change of state of active satellites dictates that we:

- continuously survey the largest angular area on the sky consistent with required detection limits,
- accomplish excellent astrometry, and when realizable including range (or orbital altitude), from which we derived accurate orbital elements allowing identification of satellites and updating of catalogs,
- provide accurate time-resolved radiometry providing object identification and status information,
- produce real-time notification of new or anomalous events, including discovery of new and recovered objects, and change of position or status of known satellites.

These are all features of the function of any full-service surveillance program. Based upon our development of telescope optics, detector utilization, streak detection and trajectory determination, JTMA has developed SoS strategies and techniques based upon tracking at the sidereal rate, and allowing all satellites to create streak images.

There are multiple positive aspects enabled by the decision to track stars. The first is the fundamental issue of correctly identifying orbiting objects. Tracking stars and allowing orbiting objects to streak effectively provides a unique radiometric signature for any natural or anthropogenic orbiting object. It produces a pseudo-point spread function which is the convolution of the telescope PSF - often an unresolved point - with the (vector) angular velocity of the object's image. A streak becomes the radiometric signature of an orbiting object, with the implication that acquired data must efficiently record streaks, and that quantifiably effective streak detection algorithms must be developed.

Another benefit of tracking stars is that the stars do not move in the image, thus providing the greatest possible image area uncontaminated by star images. With stationary stars, faint streak detection algorithms thus works with the largest possible angular area of the detector uncontaminated by (streaked) stars. This is important because any realization of a streak detection algorithm places a premium on the signal-to-noise ratio (SNR) included in the streak – and this technique provides the most stable and uncontaminated background for streak detection. The naturally-occurring background, including the stellar confusion limit at low Galactic latitudes, and unavoidable natural night sky illumination is the same as for an equivalent exposure time at any other tracking rate.

Tracking stars creates well-formed stellar images. These provide excellent PSF centroids for stars, which can be matched with astrometric catalogs, such as the USNO UCAC4 catalog. [11] This immediately provides fundamental data for the determination of orbital elements referenced directly to the International Celestial Reference System (ICRS). Standard geocentric orbital elements can be directly calculated on the basis of this astrometry.

Well-formed stellar images also provide precise radiometric calibration, because in a sufficiently large field of view images of many (~ 10 – 100) astronomically-defined radiometric standard stars will be recorded. The spectral range covered by stellar calibration is typically from 350 nm – 850 nm, enabling follow-up multicolor analysis of the satellite reflectance spectrum, if required.

When tracking stars the "effective PSF," or satellite signature, is an elongated streak. Several noise sources in silicon area-format detectors, "hot pixels" and cosmic ray events in particular, tend to be single or few pixel events, typically appearing as sub-PSF features in the image. These noise sources are rejected by algorithms that search for streaks as the kernel of the signal to be detected.

Tracking stars also obviates negative aspects induced into the survey problem by tracking satellites. Firstly, trying to detect orbiting objects against a background crenellated by structure from streaked stars is difficult simply because the background is changing at high frequency. While bright stars can be removed from the image, the photon noise from the star streak remains. More insidious is the presence of many faint stars near the sky background limit that are not removed from the image, adding additional background noise and obviating detection of the faintest orbiting objects. The stellar background is a function of Galactic latitude and longitude.

Meteors create streaks in tracked images, but these objects occur at altitudes of ~ 100 km. Thus these streaks are typically too long to be a satellite, and can easily be eliminated.

Finally, tracking a satellite is exceedingly useful for obtaining information about a single object, but this requires devoting a telescope to that single object. While certainly a valid measurement, this is not strictly a surveillance function, but rather a follow-up operation. Follow-up, confirming or characterization observations are a necessary critical function enabled and cued by the surveillance system, a function of surveillance on which we are currently engaged.

With sidereal tracking, all satellites produce streaked images. The streaks are essentially the unique PSF of the satellite, thus efficient algorithms for isolating and analyzing streaks relative to fixed stars can yield direction of motion and angular rate. These data allow estimation of a trajectory assuming a circular orbit. JTMA real-time analysis software produces this a trajectory which, for uncataloged objects, allows queuing another relatively nearby telescope to move to the appropriate place on the trajectory to reacquire the object and generate additional trajectory information. At the very least, the same-pass data can be used to estimate the next orbit reappearance of the object and the time- and angle-dependent error ellipse which, if of reasonable extent, allows reacquisition of the object, perhaps leading to an initial orbit determination IOD and, with repeated observations from the surveillance system, to a cataloged orbit.

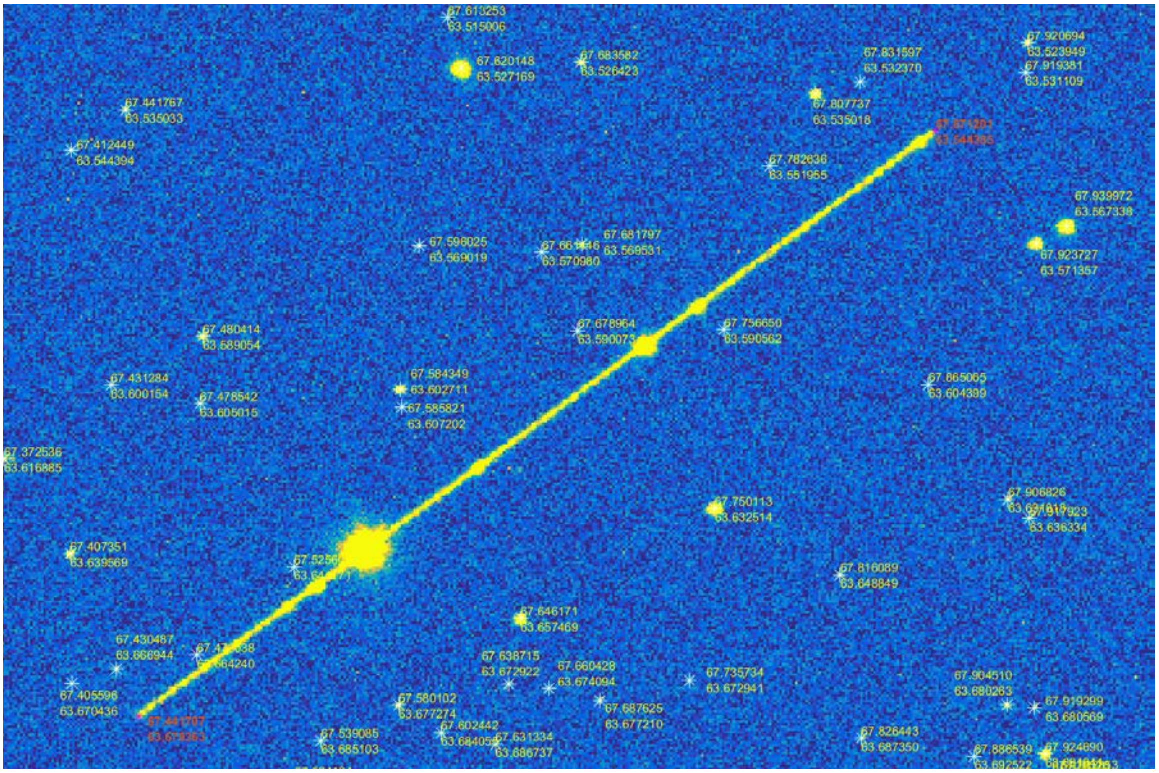

Fig. 2. This 3° x 2° image shows the complete 1 s streak of the AJISAI laser ranging satellite in its ~ 1500 km orbit obtained with the JTMA South Site. Several glints from this satellite are obvious. The catalog locations of other slower moving satellites detected in the field are marked. UCAC4 stars have been removed from the image, but their catalog positions have been used to locate the start and end point of this streak in ICRS coordinates. This track matches well the well-known orbit for this satellite.

The JTMA optical surveillance system includes provision for acquiring accurate parallax range, including upon object discovery, by pairwise separating coordinated telescopes along well-determined terrestrial baselines. By using multiple telescopes with overlapping survey volumes as a function of range, the streak image of a satellite can be observed simultaneously from two (or more) telescopes. While satellite parallax angles are large by astronomical standards, thus easily measured, it is the accuracy of the parallax measurement that provides useful ranges. This becomes possible for sufficiently accurate satellite streak observations made relative to multiple astrometric standard stars.

5. STATUS OF WIDE-FIELD SURVEILLANCE

Based upon this analysis of SoS, JTMA has implemented a testbed system of three small telescopes. Coordinated observations with these telescopes has demonstrated the utility and potential of wide-field surveillance techniques.

The geometry of the testbed system is shown in Fig. 2. The two eastern telescopes are Celestron 14-inch (355 mm) catadioptric systems with f/1.9 Hyperstar prime focus correctors and FLI Microline cameras with ON Semiconductor KAF-16070 4864 x 3232 interline transfer CCDs with 7.4 micron pixels. The interline transfer provides readout while integrating, yielding virtually continuous exposure on the sky, thus obviating the need for a shutter. The interline gates occult half of the CCD, however, though for streak imagery, the continuous exposure is of primary importance. These telescope produce useful fields of view of 3° x 2° with 2.23 arcsec pixels. Continuous exposures at 1 Hz cadence record complete streaks for satellites above approximately 500 km.

The telescopes are on Paramount MX mounts and are housed in AstroHaven clamshell dome. These are fully COTS facilities. The telescopes are synchronized to a GPS time base. Simultaneous observations with these two telescopes separated by a 27 km baseline provides useful parallax data out to GEO.

The third telescope is located at the University of New Mexico Campus Observatory. It is a 312mm f/5 AstroMak catadioptric system with a shuttered FLI camera providing a 1° x 0.75° FOV with an ON Semiconductor (formerly Kodak) 6303 full-frame CCD. This telescope is used for same orbit follow-up on detections made at the other two telescopes.

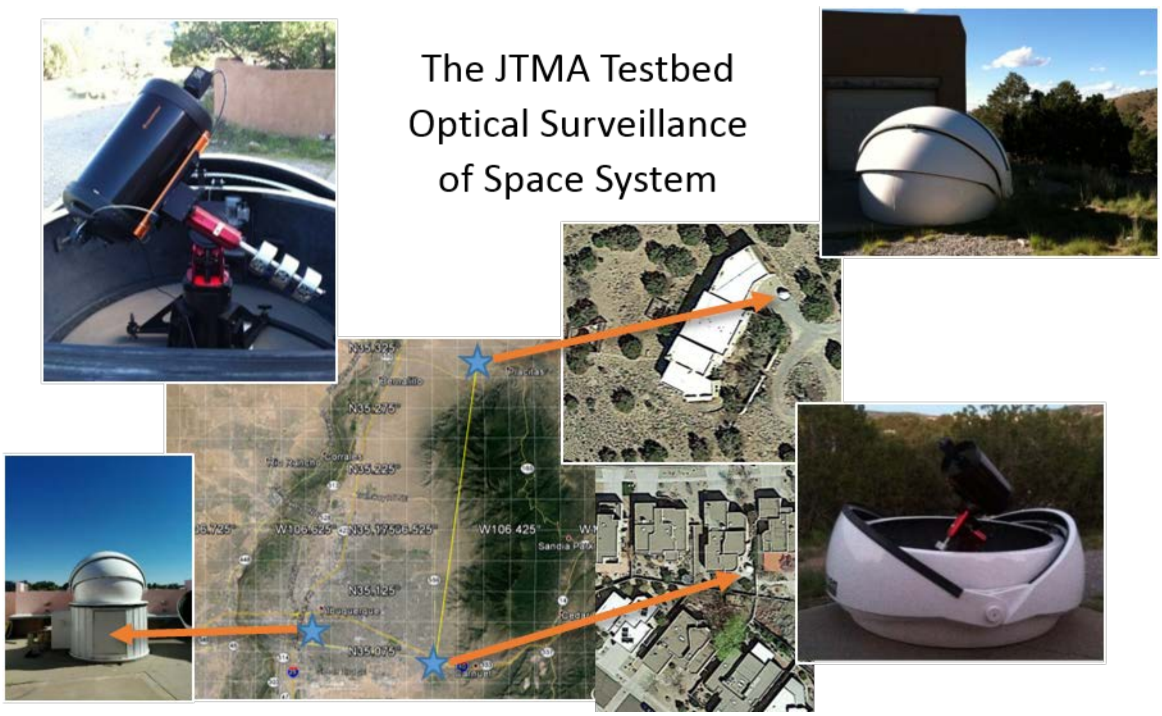

Fig. 3. The system of telescopes near Albuquerque, NM used as the JTMA testbed facility for wide field of view surveillance of space. The southernmost telescope is located in the Four Hills area of Albuquerque, and the northernmost in Placitas. The western telescope is used for same-orbit follow-up of satellites detected by the other two telescopes.

We show in Fig. 4 (upper panel) an easily detected streak from the OV1-5 satellite, a 1.5 m long, 0.6 m diameter cylinder at approximately 1050 km range with magnitude 7.3, while the lower panel shows a fainter streak from an uncataloged object at magnitude 11.8. Light blue squares in the lower panel indicate where stars were removed by astrometric matching to the field. The testbed systems successfully and efficiently detects streaks created by orbiting objects. An order of magnitude estimate is that in a two-hour terminator survey, principally for LEO objects, the system detects 300 – 600 streaks, some of which are multiple streaks from slower-moving objects.

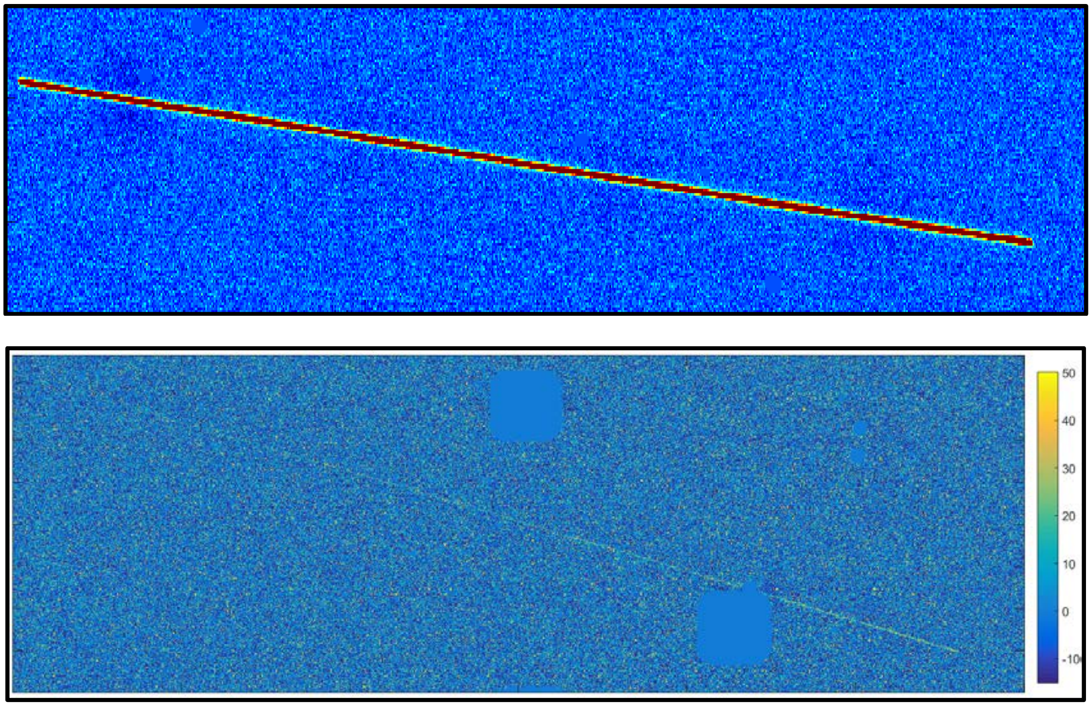

Fig. 4. Typical orbiting object streaks detected by the testbed system. The derelict satellite OV1-5 (upper panel) and an uncataloged object (lower panel).

Multiple streak images of the ANGELS rocket body and payload as shown in Fig 1 were analyzed for parallax distance. These satellites, in near-GEO orbits, were simultaneously observed by the JTMA testbed telescopes on two nights and, for one coordinated run, by the USAFA 0.4 m telescope. Fig. 5 shows time-resolved parallax measurements made by the JTMA testbed system along a circular orbit in an Earth-centered inertial (ICRS) coordinate system.

The one-sigma uncertainties on the parallax measurements made on the JTMA 27 km baseline are 82 km for the body, and 196 km for the fainter payload. The systematic mean separation of the orbits of the body and payload indicate that the measurement precision is photon limited, but that the accuracy of the parallax measurement is quite good. This is a clear indication that greater aperture would yield more precise and accurate parallax, in general.

Observations from one night made simultaneously at the USAFA by Dr. Francis Chun using the 0.4 m DFM telescope were also analyzed and found to be in excellent agreement with the JTMA measurements. Measurement residuals derived for the parallax between the JTMA Placitas and Four Hills sites separately yield one-sigma uncertainties of 10 km. The dependence of parallax uncertainty on baseline scales appropriately. Well-placed ground-based surveillance telescopes are capable of contributing to range determination, which in turn aids in initial orbit determination.

These on-sky faint-limit streak detections and the angular resolution (parallax) results show great promise for a well-structured, valuable implementation of optical SoS. JTMA will continue to develop, implement and test these optical techniques. For individual telescopes, intuition and our test results yield the same directions for future development: larger apertures, each covering larger fields-of-view. This is an expected result!

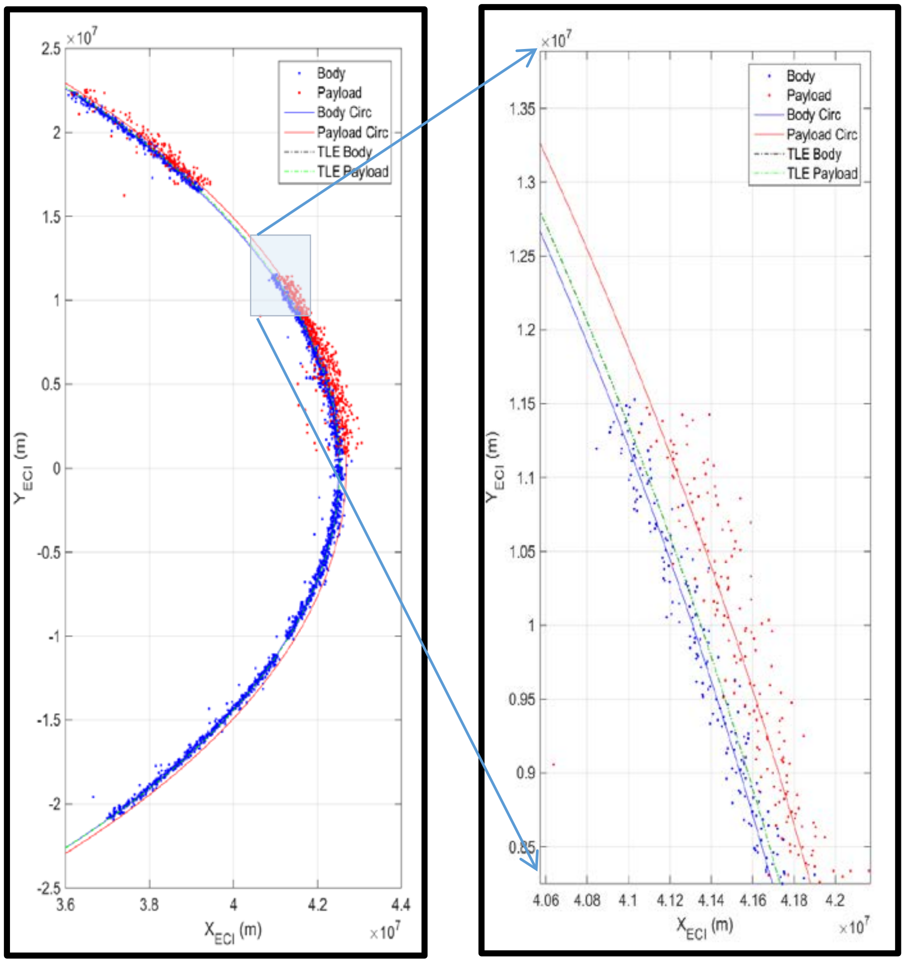

Fig. 5. Parallax measurements for part of the ANGELS orbit measured simultaneously by the JTMA 335 mm wide-field telescopes. Measurements are in the Earth centered ICRS coordinate system. The left panel shows part of the measured segment of the orbit. The segment of the measured orbit shown in the left panel, plotted as red (payload) and blue (body) dots, is shown relative to the calculated circular orbits for the payload and body as red and blue curves, respectively. The published TLEs for the payload and body are plotted as green and black dash-dot lines, respectively. The right panel shows an expanded view with individual one-second measurements resolved.

We show in Fig. 6 the FOV of the current 355 mm JTMA testbed telescopes compared for reference to the commercially produced 400 mm USAFA telescope with its 1k x 1k 14 µm pixel detector. The large increase in angular area is due to the mission driver to cover large areas of the sky with optically fast telescopes, and thus inclusion in the optics of a prime focus corrector that produces a f/1.9 focal ratio. This image graphically demonstrates the major goal of our research and development of wide-field optical surveillance. The ratio of areas between the JTMA and the commercial standard USAFA telescope is a factor of 150.

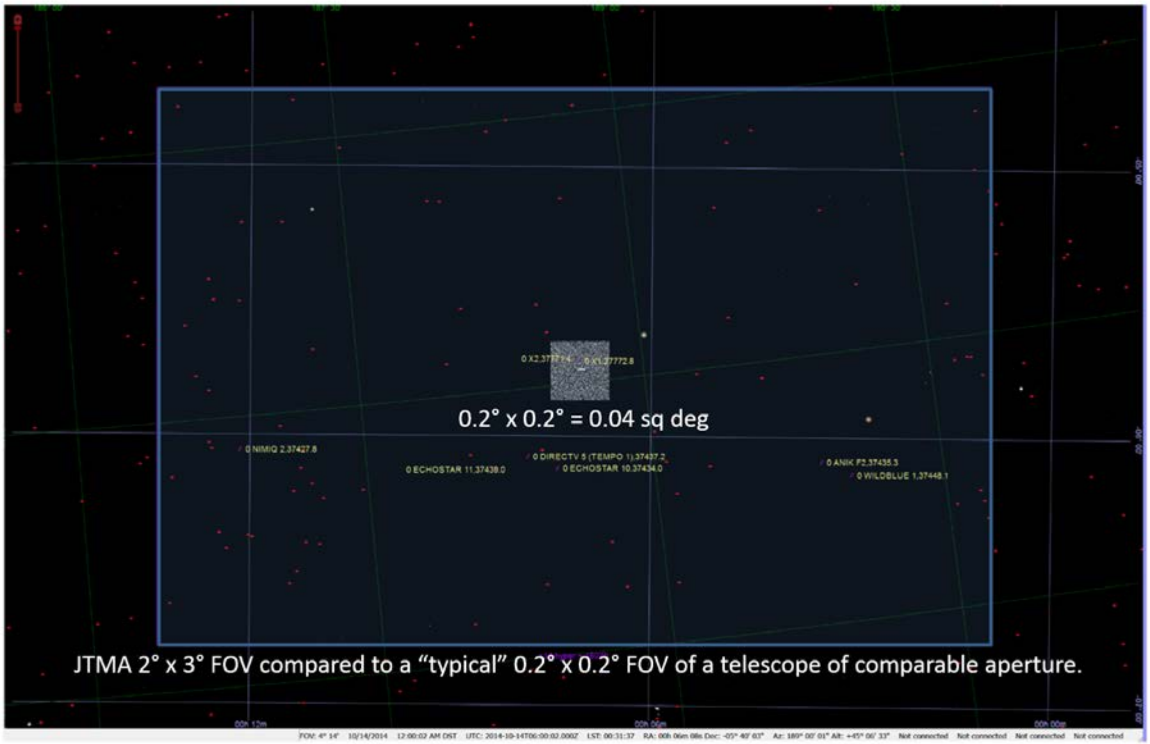

Fig. 6. The JTMA philosophy is to conduct SoS with wide field of view telescopes. This is illustrated by a comparison between the USAFA 0.4 m telescope with a 1k x 1k 14 µm pixel CCD, shown as the 0.2° x 0.2° white field at the center. The blue outline represents the 2° x 3° field of view of the 355 mm catadioptric telescope with a f/1.9 Hyperstar prime focus corrector and a 4864 x 3232 7.4 µm pixel CCD. Operated at one frame per second, this telescope produces more than 7,000 images or 230GB of raw data at each ~ 2 hour terminator observing session.

Our next steps in optical design will be to increase both the aperture and the field of view of the basic SoS telescope. We have underway implementation of a new prime focus focal reducer (PFFR) designed by Mark Ackermann, which will be incorporated into another COTS 355 mm diameter telescope for incremental test and development. The areal field is shown as the inner boundary of Fig. 7. The areal ratio of this field of view relative to our “benchmark” 0.4 m telescope is a factor of 215.

Informed by test with this follow-on instrument currently being implemented, the next step will be detailed design of a production SoS wide-field telescope with a ~ 0.5 m primary matched with an Ackermann-designed prime focus focal reducer to a standard e2V 4k x 4k pixel CCD detector. The larger aperture will add more than 0.4 magnitude to the detection limit. The areal extent of the field of this telescope is shown as the outer boundary in Fig. 7. This field referenced to our 0.4 m benchmark is a factor of 325.

The Ackermann prime focus focal reducer design is shown in Fig. 8. This figure illustrates the degree of sophistication and optical efficiency embedded in these designs. It is the merger of optics, detectors, and software, informed by more than three decades of experience merged into a philosophy that enables the progress towards affordable, persistent surveillance of space reported here. We assert that this source of data and information is a useful contribution to Space Situational Awareness.

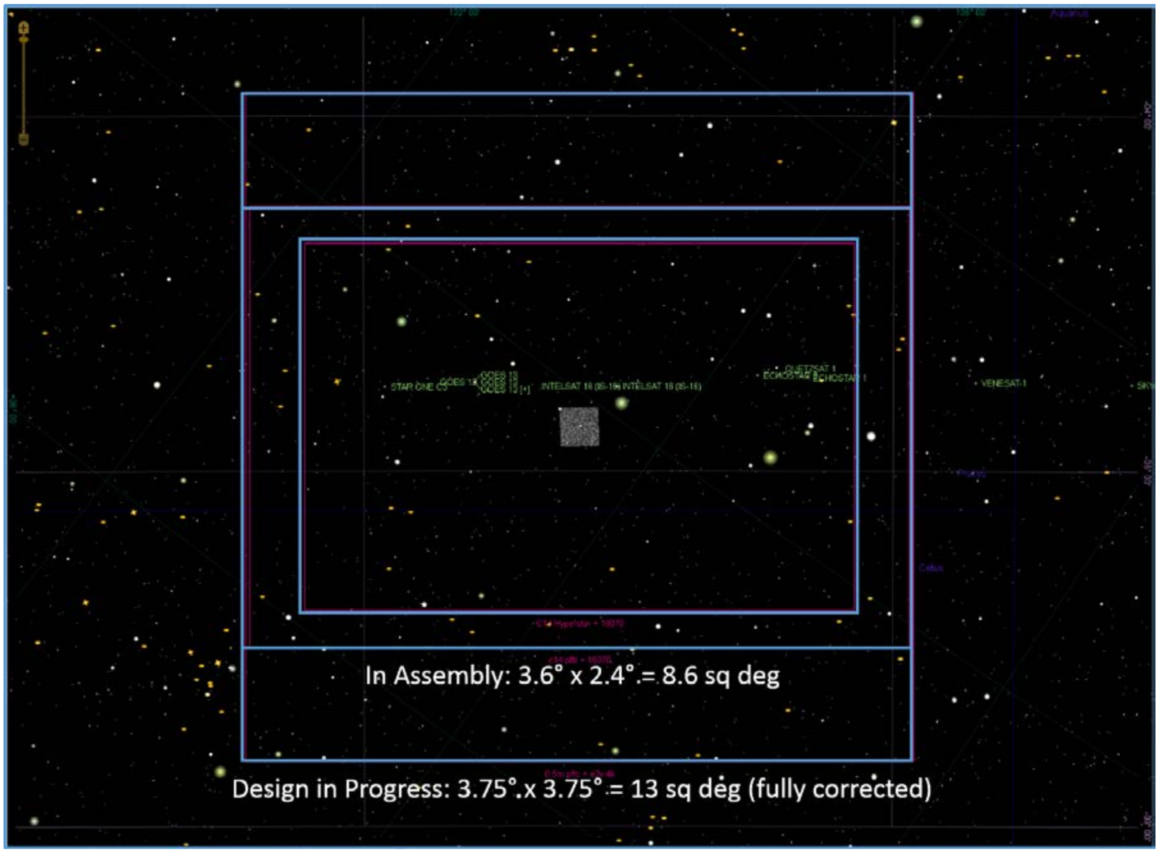

Fig. 7. Fig. 6 is replicated here as the innermost blue box. The prototype 355 mm telescope with new prime focus focal reducer is shown as the 3.6° x 2.4° box, covering 8.6 square degrees on the sky. The ~ 0.5 m telescope with Ackermann prime focus corrector, which is now under design, will have a 3.75° square, fully corrected field of view, covering 13 square degrees of the sky. These are viable designs for persistent surveillance of space.

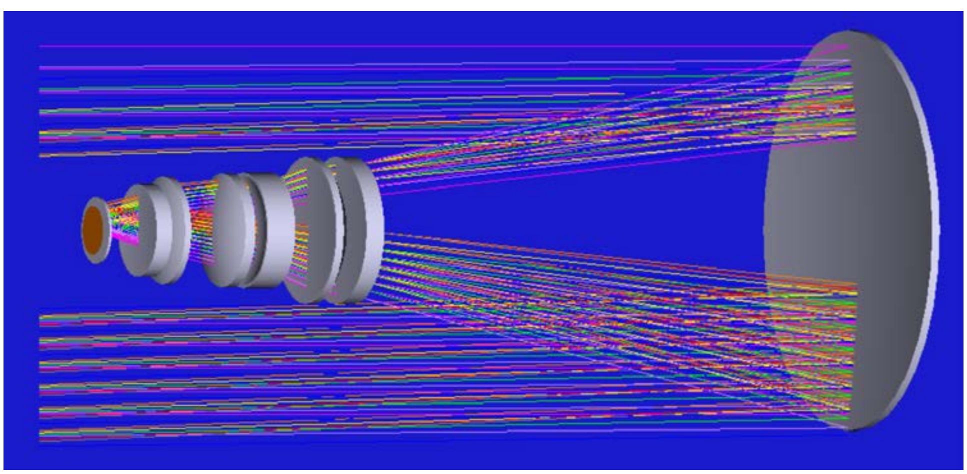

Fig. 8. Design layout for the Ackermann prime focus focal reducer being implemented into the next generation of 355 mm survey telescope. Note that the aperture stop for this design is on the first lens of the corrector, not at the primary. The relatively small diameter of this design and optimally coated optics makes it very efficient of light.

6. CONCLUSION

For more than a decade the three principals of JTMA have explored various aspects of optical surveillance of space. We have advocated optical surveillance as being valuable, efficient and cost effective. With recent AF SBIR funding a COTS prototype SoS system has been built and operated to good effect. A summary of current progress is:

1. We've designed and implemented a COTS wide-field survey system with instantaneous FOV of six square degrees and single-telescope capability of observing hundreds of square degrees of the sky each night to magnitude 12-13 at LEO and 16 at GEO. Systems under development will push this to 14 and 18+ respectively.
2. Satellite streak detection has been developed as an optimum technique for searching, locating and providing first-order dynamical information for satellites, including wide-field coverage for uncued detections.
3. The current prototype systems each produce typically 300 – 600 detections in a two-hour terminator observing session, demonstrating a very high production rate useful for catalog maintenance functions, as well as object recovery and uncued detections.
4. Efficient streak detection and real-time trajectory determination enables same-pass follow-up observations to improve the trajectory allowing rapid progress toward initial orbit determination.
5. The functionality of this prototype system will be greatly enhanced by research enabling replicable telescopes with greater light grasp – larger primary mirrors – and wider fields of view provided by a combination of a faster primary mirror and innovative focal reducer/corrector design. These design efforts are underway.
6. The prototype telescopes operated together have demonstrated useful parallax (range) measurements.
7. System deployment designs to enable wide coverage of the sky, both for LEO and GEO observations (and everything between), as well as parallax measurements when useful, and same-pass follow-up when necessary are underway. These system designs also include redundant observational capability to minimize effects of bad weather.
8. The heritage of the JTMA instrumental development has been and will continue to be cost-effective (COTS) survey instrumentation. Useful, highly capable survey instrumentation developed in this mode has been demonstrated.

It is asserted that cost-effective, persistent and highly capable ground-based optical surveillance of space is being demonstrated by these reported and continuing developments.

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