Multiple observing modes for wide-field optical surveillance of GEO space

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ABSTRACT

Very wide field of view optical sensors with silicon detectors are being used in multiple survey modes by J. T. McGraw and Associates to provide persistent, affordable surveillance of GEO space to faint limiting magnitudes. Examples include:

- classical staring mode with typical integration times of seconds provided by multiple co-directed sensors to provide a deep mosaic of tens of square degrees per exposure to faint limiting magnitude
- step-and-stare observations of several second integration time from which a continuous, overlapped, mosaicked image of GEO space can be provided
- time-delay and integrate (TDI) imagery obtained by driving the telescope in declination and stepping the telescope in the E-W direction, which produces repeated, overlapping (if desired), synoptic images of GEO space

With current 350 mm diameter optics, detection limits for concentrated observations (e.g. “neighborhood watch”) detection limits of magnitude 18 are achieved, and for uncued survey the detection limits are fainter than magnitude 16.

Each of these techniques can employ multiple telescopes to obtain search rates in excess of 1000 square degrees per hour, allowing complete uncued CONUS GEO surveillance to +/- 15 degrees latitude every two nighttime hours. With appropriate placement, sensors could provide complete coverage of GEO to these limiting magnitudes at the same survey rate.

At each step of the development of this unique capability we discuss the fundamental underlying physical principals of optics, detectors, search modes and siting that enable this survey, a valuable adjunct to RF, radar, GEODSS and other optical surveys of GEO space.

1. INTRODUCTION

We have developed and implemented potentially transformative techniques for ground-based, affordable, persistent surveillance of space. These techniques include cost-effective, replicable sensors capable of wide-field imaging of the nighttime sky to faint limiting magnitudes characteristically approaching 18th magnitude at GEO and 15th magnitude at LEO. This is accomplished using wide-field optical systems providing multi-square degree images at a characteristic cadence of a few seconds per exposure. A single sensor built upon a COTS 350 mm diameter telescope and mount, a commercially available area-format detector, and high-performance desktop computing is described. This system can survey the entire CONUS GEO belt (3600 square degrees) twice per night with arcsecond angular resolution to magnitude 17.5, corresponding to an object at GEO approximately 0.6m in diameter. Positional and brightness data for detected objects are generated and reported in real-time.

Because the system design is extensible and replicable, faster cadence, parallax range measurement, and (especially) weather avoidance is enabled by adding additional telescopes to the global network. Additionally, the performance of individual sensors can be more than doubled by adding additional detectors in a wider field of view optical configuration based upon the same telescope, but with a different prime focus corrector or prime focus focal reducer.

Current optical surveillance techniques are largely object-driven: positions for objects of interest are sent to telescopes for confirming and updating observations. This mode of optical surveillance remains supported by our sensors, but in survey mode all imaged objects to the detection limit are detected and reported, potentially obviating the need for queued individual observations of objects, and certainly enabling graceful growth of object databases!

An analogy between radar and optical surveys exists: Radar, inherently a wide-field survey technique, uses phase coherence at long wavelengths (relative to light) to construct an "all-sky" target map (~ hundreds of square degrees), identify objects, track them, and report on them in real-time. Our optical techniques acquire multiple wide-field images (~ degrees), which we use to create an image mosaic over timescales of minutes to create a very wide-field image (~ 100 degrees), in which we identify every image above a S/N threshold to determine position to arcsecond accuracy and S/N-limited brightness estimates, and report on them in real-time.

Our imaging techniques allow passive generation of a mosaicked "all-sky" image – or any other useful image configuration, such as the "rectangular" GEO belt. From the image we derive position, motion, and brightness for every object above a S/N threshold ~ 6, and report the object's parameters in real-time. The final output of this technique is the list of objects derived from the images, and their time, position, and brightness parameters to be used for updating a catalog, or for creating new entries. New entries are then subject to future correlation and confirming follow-up observations from multiple data sources.

True surveillance is data driven and anticipatory. The sensor array we describe here, deployed at multiple locales worldwide, is capable of providing continuous time-resolved images of every object from LEO through MEO to GEO at or brighter than our faint limiting magnitude. This provides a potentially transformative capability for the surveillance of space. We here describe the context, instrumentation and techniques that enable this new mode of surveillance.

2. CONTEXT

Human activity occurs on land, on the sea, in the air, and in space. Associated with these domains is a volume of activity, with space representing by far the largest of the four! The value of human activity in space, the most recently opened of these domains, is immense and continues to increase. Thus, the security of space increases in importance and value, as well.

The fundamental elements of security are persistent surveillance and intelligence. Thus, security depends upon the completeness of surveillance of the volume of the activity, and surveillance of space, in turn, requires affordable persistence with multiple sensor types.

Because of the immense economic value and strategic importance of each of the domains of human activity each has been and will continue to be a conflict arena. Thus, we learn from history that detecting potential threats in space will continue to be the most effective deterrent to impending space-based global conflict. If pressed to warfare, surveillance is one of the most significant element of decisive, effective action.

Optical surveillance of space (SoS) is a powerful component of the global, multi-sensor surveillance system providing information upon which to base Space Situational Awareness (SSA) and other security and safety of flight activities. A principle benefit of optical survey techniques at GEO is that the sun passively provides ~ 1350 W m^{-2} irradiance at the Earth's distance, and the energy distribution is strongly peaked in the optical region of the spectrum. Thus, for passive surveillance, the source (our sun) is ideal, provided compensation for absorption and scattering in Earth's atmosphere, including weather, is incorporated into the surveillance network design.

3. CONSTRAINTS AND SOLUTIONS

Using the Sun as the illumination source implies some constraints:

- to achieve the best possible signal-to-noise (S/N) for detections, and for faint object detectivity, in general, observations are obtained at night
- the S/N of each detection depends upon atmospheric extinction, including clouds

- because of the Sun/Earth/Moon geometry of our solar system, there exist predictable times when optical detection becomes more difficult: e.g. operations near the bright moon, and Earth occultation of GEO objects.

There exist techniques to obviate or minimize the effect of each of these constraints. The sensor can be optimally chosen to provide the most efficient and effective surveillance possible. As one example, the detector should have high quantum efficiency from approximately 400 – 700 nm to achieve high S/N relative to the terrestrial and celestial backgrounds. The readout noise should be as low as reasonably possible. Readout noise and "sky" background noise are the principal determinants of the S/N of any satellite observation. The noise associated with the night sky background and the detector readout noise, compared to the brightness limit determined to be necessary for each orbital domain surveillance (e.g. 18^{th} magnitude at GEO, 14^{th} magnitude at LEO) determines design parameters such as the diameter of the FOV, the detector angular pixel size and the readout time. Optimizing the detective S/N is, in fact, a primary area of expertise that we've applied to the design and implementation of sensors, some results from which we've described at AMOS [4, 8].

Resolution of the constraint imposed by weather is straightforward: observe simultaneously from two or more sites, with each site located in a different predominant weather system. This requirement speaks directly to the "cost-effective" condition on our sensors and facilities. If a new sensor that meets or exceeds all detection requirements can be fielded for a fraction of the cost of a current sensor, a customer could field two sensors to obviate weather and/or provide additional, complementary or supplementary data, and still save money. Similarly, observing from multiple sites helps to obviate some of the Earth occultation effects.

Finally, when imaging satellites, they move against the background of stars. Alternative observing modes have been used to acquire optical satellite data. The first technique is to have the telescope mount track at the sidereal rate and let the satellites create streaked images. The second technique is to use stationary telescope mounts, resulting in both stars and satellites forming streaked images. A third technique is to track at a chosen satellite rate, which results in a stationary satellite image, but with all the stars, and possibly other satellites in the image, creating steaked images.

We choose to track at the sidereal rate and let the satellites streak. The fundamental rationale is to keep images containing satellites as "clean" as possible. An astrometric catalog (currently UCAC4) is used to identify stars to the limiting magnitude of the image, and remove the stars them from the image prior to calculating the background across the image. Far fewer image pixels are removed in this technique than if stars were allowed to streak. The star positions also provide the coordinate reference for determining the satellite position and motion. The satellite brightness can be compared to stars of known brightness to make radiometric measurements.

Finally, cost is always a constraint! Cost-effectiveness for optical surveillance of space derives in large measure from valid judgement about vendors and sources for sensor systems. JTMA uses COTS hardware and software whenever possible. These components are, however, always implemented using our own optical designs, operated under our own physical models, and data are acquired and analyzed with our own software.

That is, we first research available COTS options for optics and hardware because there exist excellent designers, opticians, machinists and programmers who service the lucrative high-end amateur astronomy community. In fact, professional astronomers are utilizing COTS elements to accomplish forefront astronomical research (e.g. Mark Ackermann's poster, this meeting). Thus, we investigate potential vendors, and often engineer our sensors to use available COTS optics, mounts, cameras, filters, observatory control software, etc., provided these products meet our specifications for implementing a forefront sensor. Establishing a robust, known supply chain is a requirement for designing and implementing a capable COTS-based system of sensors for SoS.

Based upon our knowledge of COTS astronomical hardware, we assume *a priori* that a sufficiently capable optical system (for example) exists for our purposes. Requirements are defined by detailed examination of the surveillance problem to be addressed, trade-space analyses, and supplemental design by our optics expert. We research potential vendors of optical system that potentially meet our requirements. If proven suitable, purchasing the COTS systems with no non-recurring design costs, or worse, hiring an optics designer to start *ab initio*, makes our sensors highly cost-effective relative to the current norm. And this technique bolsters the economy and rewards design and fabrication excellence in fields of interests to us.

4. Optical Surveillance of GEO

For several years the authors, now collectively J. T. McGraw and Associates, LLC (JTMA), have presented at AMOS various physics- and astronomy-based techniques for affordable, persistent optical SoS. Topics addressed include wide-field telescope designs[1], [2], innovative operation of detectors[3], [4] useful survey strategies[5], [6], [7] and real-time survey operations[8], all principally based on COTS products[9]. A component of SoS at GEO, for which optical surveillance is particularly useful, is enabled by balanced application of these fundamental physics techniques.

Current optical observations in support of SoS are, in part, made by classical Newtonian, Cassegrain or Schmidt-Cassegrain telescopes with effective focal length and detector pixel size chosen to resolve (or nearly resolve) the point spread function (PSF) of a star. One use for these telescopes is to observe the sky at a position and time, usually specified by a TLE, provided by an aggregator or customer of the telescope operator. The image information derived from the observation is returned to the operator or customer for reduction and analysis with respect to the observed position, time, rate and angle of motion. Other well-known satellites, considered to be orbital (and perhaps radiometric) standards (e.g. GPS), are observed to vet the other observations. These observations are vital to the maintenance of orbital information about the observed targets.

Based upon our definition of “surveillance,” there is another mode of SoS based upon wide-field imaging that we have implemented: synoptic wide-field surveillance.

A classical astronomical telescope produces an image of the sky typically somewhat less than a degree in angular extent, represented in our analogy (Fig. 1) as a segment of a parking lot surveillance camera image.

Fig. 1. Classical telescope image of an object.

This image tells us that there is a car legally parked in the “visitor” parking lot. The visible windows, taillights and tires appear in good condition. The white license plate, with a bit more information about the state or area, can tell us something about the “home” locale of the car. Everything is normal!

A wide-field image of the parking lot of angular extent considerably greater than a degree, Figure 2, provides crucial additional information deriving from the image itself, but also from the relationships among the cars, and the wide-field image is more likely to show interrelationships and coordinated behavior, as well as many tens of times more information about activity in the parking lot under surveillance.

For example, we can immediately note that no scofflaws have parked in the Fire Lane. The near-field cars are all legally parked, each car in its “slot” with good separation. With persistence we can see if the same cars are parking in the visitor spaces repeatedly, either because they are very good customers, or because employees are using the visitor lot so they don’t have to traverse the distance to the more distant parking lot with its assigned slots. The streets are clear, all is well … though the “mud prints” ahead of the second car from the right look interesting.

The principal difference between Figures 1 and 2 is the area encompassed. Surveillance of larger areas provides more information of different types and importance. Multiple time-resolved images provides valuable historical and predictive information.

This homily parallels the JTMA developments in wide-field surveillance of space. Time-resolved, wide-field imagery provides more useful information relative to the defined surveillance of space function. The wide-field images enable new object discovery, and a view of the environment of any targeted satellite. The multi-degree wide images obtained by our telescopes includes multiple GEO satellites, for example.

Fig. 2. A wide-field image provides true surveillance of the parking lot. This image provides information about multiple vehicles, relationships amongst the vehicles, and is observation of any interloper entering the parking lot.

Much of the optical SoS imagery done from Earth utilizes classical astronomical telescopes, typically designed to resolve the seeing-blurred point spread function, resulting in smaller fields-of view from telescopes with rather high f/ratios. Typical astronomical telescopes thus have sub-arcsecond pixel resolution and fields of view measured in arcminutes on the sky. There are, of course, counter-examples: Schmidt cameras, GEODSS, the Baker-Nunn systems, which cover multiple square degrees on the sky, but also have rather low throughput, poor image scale match to solid-state detectors, field-dependent aberrations, and often curved focal surfaces. The predominant telescopes used today for ground-based SoS remain higher f/ratio, smaller field of view instruments.

These telescopes are typically employed to provide pointed observations to confirm the presence of an orbiting object, and to improve its orbital elements, among other possible measurements. While making excellent observations of cataloged objects, they are not optimum for discovering previously uncataloged orbital objects. In the homily above, their FOV is not wide enough to observe multiple objects per image, or the environment of the target object.

5. A Paradigm Shift: Uncued Persistent Surveillance of Space

The techniques developed by JTMA are driven by rapid re-visit imagery to a faint limiting magnitude over a substantial fraction of the sky. We optimize the system throughput, the etendue or $A\Omega$ product for the telescope, simultaneously with the number of images per second, determined by detector and background noise statistics. This allows continuous exposures at high cadence and low noise from which satellite images can be extracted.

Instead of thinking of optical SoS as a large number of discontinuous “postage stamps” as provided by classical astronomical telescopes and acquired at directed positions, our techniques instead observe large areas of the sky (multiple square degrees per image) in uncued mode to the same (or fainter) limiting magnitudes as the classical telescopes. The analogy with the parking lot example is obvious – more useful and actionable surveillance information is contained in the large, continuous, image.

Because our wide-field survey attains the same (or fainter) limiting magnitude than the classical astronomical telescope observations, all of the classical, queued observations are included in the wide-field data set, plus everything that we didn't know was there, or objects simply not on the priority observing list for the queued mode observations. We obtain a broader vision of space with which to accomplish true SoS.

An example of one large-area survey technique is the surveillance of the CONUS GEO belt. Note at the outset that this example can be extended to all of the GEO belt with appropriate placement of our sensors. The CONUS GEO belt subtends 120 degrees E-W and 30 degrees N-S, or 3,600 square degrees centered N-S on the projected declination of the GEO orbits.

The design of the survey depends upon the field of view of the sensor and the imaging format of the detector. At present JTMA is operating two detectors, a 4864 x 3232, 7.4 micron pixel interline transfer CCD, which provides readout while integrating at the cost of about 50% obscuration (effectively, quantum efficiency), and a 2048 x 2048, 11 micron pixel sCMOS device. Because the emphasis on a GEO survey is to detect small objects at 36,000 km, the lower readout noise sCMOS device is the detector of choice even though it has a smaller format.

The telescope is a Celestron C-14 – a 14-inch (355 mm) diameter catadioptric telescope operated with a Starizona HyperStar prime focus corrector to provide an effective focal length of 684 mm. This yields a field scale of 3.32 arcsec per pixel at the detector. The 2048 detector pixels subtend a field of view of 1.8 x 1.8 degrees, or 3.53 square degrees on the sky per exposure. This telescope is shown in Figure 3.

Fig. 3. A JTMA SoS sensor based upon a C-14 telescope with a HyperStar prime focus corrector and CMOS detector mounted on a Taurus English fork mount.

An exposure time of 6.4 seconds provides an optimum S/N per image with a detection limit fainter than magnitude 17.5, with the noise principally dependent upon the photon shot noise per pixel generated by the sky background and the detector readout noise. The Software Bisque Taurus mount provides a slew/settle time between exposures of 3.0 seconds. The total dwell time for an image is thus 9.6 seconds.

The survey technique for this sensor is then to obtain an image, move in an optimum direction to the next image center and acquire another image, *et seq*.

The CONUS GEO belt mosaic requires 1020 images, and 9792 seconds (2.72 hours) to complete with one sensor. With focus and overlap overheads, this sensor can complete an imaging survey of the CONUS GEO belt in three hours. Thus, a single JTMA sensor, as currently configured can accomplish two full GEO belt surveys per clear night. This corresponds to a survey rate for a single-detector sensor, including observing overheads (e.g. focus) greater than 1000 square degrees per hour.

A simulation of a 40-image subset of a GEO Belt survey obtained from the JTMA test facility in New Mexico is shown in Fig. 4.

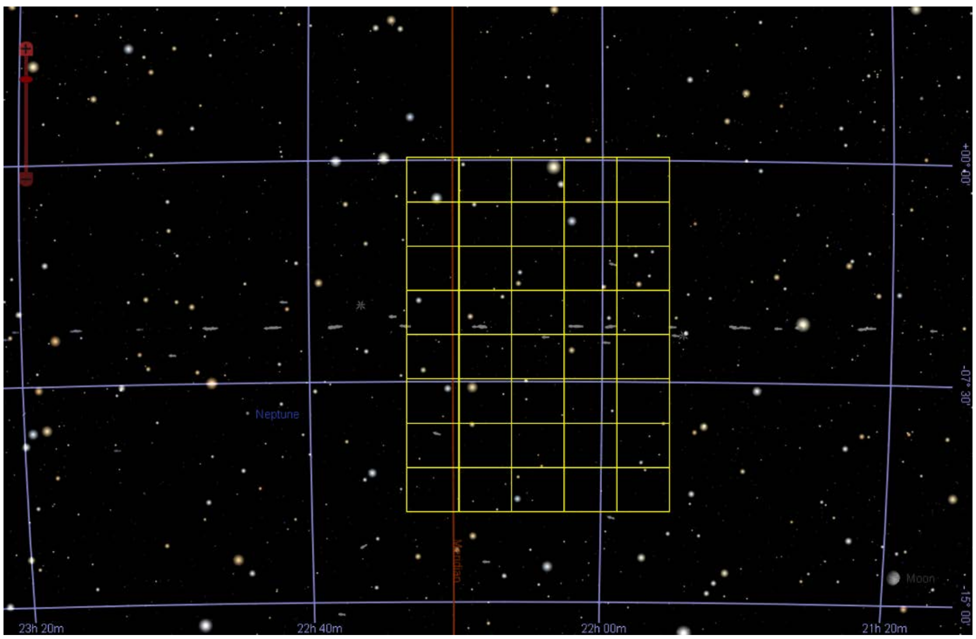

Fig. 4. 40 frames of a simulated survey of CONUS GEO from New Mexico using the sensor shown in Fig. 3. Each square subtends 3.53 square degrees on the sky and the 40-image subset covers 142 square degrees. This 4% segment of the CONUS GEO belt is acquired in 6.4 minutes, including telescope slew/settle time. A series of images across the middle of this image at declination ~ -5° appear as "dashes." These are the locations of GEO satellites in the mid-plane of the GEO belt as observed from latitude of +35°. The observing sequence, starting at the northwest (upper right) image, is to proceed south, step east and then step north, *et seq*. This sensor surveys the sky to magnitude 17.5 or fainter at a rate greater than 1000 square degrees per hour.

There exist techniques to increase the survey rate based upon 300 mm – 500 mm diameter primary optics. A prime focus focal reducer (PFFR) designed by Ackermann has been fabricated, installed and tested on a C-14 telescope (Fig. 5). Using the interline transfer CCD detector this optical configuration yields a 3.6° x 2.4° field of view covering 8.6 square degrees on the sky, or 40% more sky area than the HyperStar PFC on the same telescope, and with markedly reduced vignetting. JTMA is conducting additional trade-space analyses and on-sky testing of survey capabilities of multiple telescopes, leading to future development of new complementary and supplementary sensors for the global surveillance system we envision.

Fig. 5. Ackermann-designed prime focus focal reducer mounted on a C-14 with prime focus corrector plate removed. The pupil for this unique system is on the first corrector lens, not, as is usual, at the primary mirror. This system produces a 3.6° x 2.4° FOV on a KAF16070 interline transfer CCD in a Finger Lakes Instruments camera.

Excellent optics design capability allows JTMA to optimally image and detect the information brought to the focal plane by an optical system.

- Edge-butted mosaics of detectors can cover larger areas of the sky and obtain better angular resolution per pixel, as needed.
- For frame transfer CCD detectors time-delay and integrate readout provides optimal on-sky detection, especially for N-S scans, which are, by definition, on great circles on the sky.
- For detectors with significant readout structure at the edges, such as CMOS devices, sparse arrays with one detector-width "gaps" in the focal plane can prove efficient for some applications.

Other specialized configurations are enabled by very wide field optical systems, as well.

6. Summary

The optical survey operation described here produces uncued observations over large fractions of the sky. Here we've discussed GEO, in particular. With different observing strategies, but identical physical configurations, JTMA wide-field sensors can produce complete surveys to appropriately faint limiting magnitudes at satellite altitudes ranging from LEO to GEO and beyond, track transfer orbits, and perform neighborhood watch functions. The sensors are very versatile and easily configured to carry out these different missions.

There is no requirement that observations made with JTMA sensors be uncued! Sensors described here can be programmed to carry out targeted observations of objects, and those tasks are made easier and more secure because of the wide fields of view on all our sensors. With FOVs larger than two degrees (four square degrees on the sky), there will never be doubt about whether the target was just missed, as can happen with smaller FOV telescopes, or whether it really wasn't where it was predicted to be!

In a recent interview, then Lt. Gen. Raymond described space surveillance as “a little data limited,” and he expressed the goal of “making sure we have the right data necessary to make decisions.”

We agree with these statements and add that the SoS effort cannot have the “right” data if it is data starved, and that adding information to any compilation of SoS data requires a systematic, planned approach. Mechanisms to achieve this are underway, under development, and being invented, re-invented or improved at this time. It is the goal of JTMA to provide a significant fraction of accurate SoS data that can be timely and straightforwardly integrated into the appropriate data bases. In fact, the logical thread running through the JTMA AMOS papers, from the outset of our involvement, is to contribute significantly to the optical portion of SoS data.

There are four significant statements embedded in this paper:

1. JTMA has developed techniques and sensors capable of synoptically surveying large areas of the sky with high fidelity, accuracy and known uncertainties.
2. JTMA can ultimately provide these data based upon a globally dispersed system of affordable, replicable sensors.
3. The primary, but not only, operational mode of our sensors is an uncued, wide-field survey.
4. Statements and ideas reported will be questioned until demonstrations are made and the results are known.

The most common query we expect concerns the use of wide-field surveillance. The anticipated first issue is that “we just aren’t used to doing it that way.” This is absolutely legitimate, and we invite our colleagues to discuss with us the issues we raise in these papers. That is, in fact, a primary purpose of AMOS and the inclusion of JTMA papers!

It is globally acknowledged that space surveillance systems track only a small fraction of objects known to be in Earth orbital space. Radar is excellent at surveying near-Earth space (LEO, and MEO), and somewhat less capable at larger ranges, primarily due to the $1/R^4$ loss of transmitted power with distance. While queuing of radar observations occurs, it is inherently an uncued survey system because it is capable of detecting and tracking any object of appropriate angular size (physical size as a function of range). Thus, the concept of uncued observations is not unknown to the SoS community.

JTMA sensors are an excellent adjunct to radar at MEO, GEO and beyond, and in transfer orbit tracking. It is a useful adjunct at LEO (and beyond) because there is no significant instrumental modulation of detectivity over angle in the surveyed volume of the sky. (Except for clouds, of course.) In short, all SoS sensors are vital to continued observation in support of secure use of space. The optical capability we propose to implement will support current efforts, but the uncued, synoptic portion of the survey is capable of systematically building the catalog of tracked and identified Earth-orbiting objects for years to come.

Bringing space surveillance data bases current with inclusion of more of the untracked objects in Earth orbital space is daunting, but certainly not impossible. Thank goodness such a large fraction of the AMOS attendees are by nature, training, and mission, dauntless!

7. Acknowledgements

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