30th Space Symposium, Technical Track, Colorado Springs, Colorado, United States of America
Presented on May 21, 2014

EXPLORATION OF WIDE-FIELD OPTICAL SYSTEM TECHNOLOGIES FOR SKY SURVEY AND SPACE SURVEILLANCE

Primary Author
Mark R. Ackermann, University of New Mexico, mackerm@unm.edu
Coauthors
Rex R. Kiziah, United States Air Force Academy, rex.kiziah@usafa.edu
J. Douglas Beason, Universities Space Research Association, doug@dougbeason.com
Peter C. Zimmer, University of New Mexico, zimm@lodestar.org
John T. McGraw, University of New Mexico, mcgraw@lodestar.org

ABSTRACT

During the past twenty-five years, there has been significant development of optical telescopes dedicated to wide-field surveys of time-dependent deep space phenomena, slow-moving near-earth objects (NEOs) and fast-moving earth-orbiting space debris. While telescope fields of view have gradually increased, a single technical approach has not emerged as the dominant design. Useful designs range from single mirrors with refractive prime focus correctors, to complex and more expensive three-mirror systems. When implemented as an operational system, each of these designs has strengths and weaknesses, and no single approach appears ideal for all situations, but some approaches tend to be more generally applicable than others. To design an effective wide-field telescope for sky survey or space surveillance, it is necessary to systematically examine all components of the problem and potential solutions. Simply designing an optical system with high image quality or wide field of view is not sufficient. It is necessary to carefully match the characteristics of the optical system (layout, aperture, focal ratio and modulation transfer function) with those of the observing site (sky brightness, transparency, seeing and elevation), the detector (pixel pitch, quantum efficiency, read rate and read noise), and the observing program (target brightness, target motion, observing strategy and feature extraction software). In this paper, we examine the characteristics of complete system solutions for detecting deep-space objects, NEOs, and earth-orbiting space debris; and we compare these characteristics with the recently fielded Space Surveillance Telescope.

INTRODUCTION

Space systems are critical for national defense and of high importance to the global economy. The first artificial satellite was nothing more than a simple radio beacon, but quickly, nations realized that radio beacons could be replaced with transponders and satellite-based communication was borne. Beyond communication, satellites were quickly developed for monitoring weather, intelligence and science.

Today, dozens of nations operate satellites for both military and economic purposes. The global economic impact of space systems and related services was slightly in excess of $304B for calendar year 2012[1]. At present, there are approximately 1000 active satellites on orbit ranging in complexity from simple cube satellites to multi-billion dollar remote sensing satellites such as the Hubble Space Telescope. With an approximate average replacement cost of $200M each, this represents a capitalization of $200B for the spacecraft and approximately $75B more for replacement launch costs[2]. Clearly, the global economic importance of space systems is enormous.

Most spacefaring nations have only a few satellites. They are often used as a stimulus for economic development and seen as a source of national pride. A small number of countries own and operate most of the current space systems. Over the coming decade, it is estimated that over 1000 new satellites will be launched, with most of these ending up in either low earth orbit (LEO) or geosynchronous earth orbit (GEO)[3]. With approximately 1000 active satellites presently on orbit (and more than 7000 inactive satellites and related pieces of space junk), space is crowded, or to quote the current government vernacular, space is congested, competitive and contested.

To safely operate space systems, it is necessary to know what objects are on orbit, where they are at any particular time and where they are going. Even though space is enormous, the desirable orbital regions are relatively small and the potential for collision between objects is real. In February of 2009, an active Iridium satellite collided with a deceased Cosmos satellite in LEO[4]. The resulting debris cloud contains hundreds of objects large enough to be tracked and potentially thousands of smaller objects that are still large enough to disable another spacecraft. The surveillance and monitoring of objects in orbit is known as space situational awareness (SSA). This is an essential activity for the safe, cooperative and productive use of space.

While a variety of systems are useful for SSA, ground-based optical telescopes are the tools of choice for monitoring objects in high earth orbits (HEO) such as GEO, Molnaya and Tundra orbits. These optical telescopes are similar to those used by astronomers who monitor the skies for potentially hazardous NEOs such as passing comets and asteroids. Watching the sky for NEOs is important as relatively small comets and asteroids are potentially hazardous, having enough energy to cause large scale destruction if they were to collide with the earth and strike an urban area. In February 2013, a meteor entered the earth's atmosphere and exploded over the Russian city of Chelyabinsk[5]. The damage was relatively light as the meteor did not actually strike the ground, but it proved to be a total surprise, having approached the earth without being sighted. The danger of NEOs is real, and, at present sky surveys provide the only possibility for warning.

When examining the ground-based optical telescopes used for SSA and sky surveys around the world, one quickly finds a myriad of designs and system approaches. While one would expect telescopes designed and built by various groups to have some differences, the variety of hardware in use is significant. Not all the systems are ideally suited to the survey work they attempt to conduct.

This paper presents a systematic examination of the trade space available to developers of optical telescopes for SSA and sky survey applications. This trade space includes optical systems, detectors, site characteristics and data processing algorithms. We begin with background information on SSA and planetary defense sky surveillance with a discussion of proven observational techniques for each. This is followed with a brief discussion of a subset of existing telescopes designed or adapted for either sky surveillance or SSA. Moving beyond this background information, we examine the systems engineering and trade space issues for ground-based optical survey instruments and then present information on new technologies that may be adapted to the problem.

BACKGROUND

Approaches to Ground-Based Optical Sky Surveys

The practice of ground-based optical SSA and NEO search have a number of similarities in that the object is to detect dim point sources of light moving against the fixed stellar background. The two disciplines are however different as satellites move on much shorter time scales and are therefore easier to detect during a single observing session.

Sky Surveys for NEOs

The earliest sky survey efforts occurred during the late 19th century. With the development of practical photographic plates, astronomers soon realized that they could use telescopes to photograph astronomical objects. The first successful astronomical photographs were made of the sun and the moon in the mid-1800s. The early photographic plates were relatively insensitive and only useful for very bright objects. Improved plates were developed towards the end of the 1800s thereby making astrophotography of stars practical. Astronomers quickly realized that these plates could be used with portrait lenses from studio cameras to capture wide angle images of star fields[6]. This was the birth of the modern sky survey work. The earliest sky surveys were conducted to develop star charts and catalogs of stars.

When searching for asteroids and comets, the general technique is to use the telescope in sidereal track mode to photograph wide fields of stars. Over the course of a couple of weeks, the procedure is repeated at least two more times. The images are compared to find any objects that are moving. Before the use of charge-coupled device (CCD) electronic image detectors, the images were recorded on film. Comparing images to look for moving objects was done on a device known as a blink comparator[7]. This is the technique that was used to look for the planet Pluto. Today with CCD sensors, the images are recorded electronically and can easily be subtracted one from another, to look for objects that have moved.

The telescopes used for NEO search are quite varied in design and configuration but generally share the common characteristic of imaging a wide field of view. While there is no standard instrument, Schmidt cameras tend to find frequent use as they are optically fast and can image wide fields on CCDs and very wide fields on film. A typical Schmidt system will have an aperture on the order of 15- to 30-inches and can easily image a five-degree wide field using a CCD detector.

One of the better-known NEO search efforts is the Catalina Sky Survey (CSS)[8]. Up until 2013, the CSS was using three instruments. These included the 1.5-meter reflector on Mount Lemmon in Arizona, the 28-inch Schmidt camera on Mount Bigelow in Arizona and the 20-inch Uppsala Schmidt at Siding Springs Observatory in Australia. The 20-inch Schmidt was retired in 2013.

The Mount Lemmon reflector is used at prime focus. It was imaging a field of 1.1 x 1.1 degrees but was recently upgraded to image a field of 2.24 x 2.24 degrees. This upgrade required both a larger detector and changing the prime focus optics from being a simple corrector to one that also introduced some focal ratio reduction. The Mount Bigelow Schmidt was also recently upgraded from a field of 2.86 x 2.86 degrees to one of 4.4 x 4.4 degrees. This upgrade required a larger CCD and a small change in the optics used to flatten the image field.

Sky Surveys for SSA

Space situational awareness started in the early days of the space age, just after the Soviet launch of the Sputnik satellite. Individuals in both the U.S. and Soviet Union equipped with optical binoculars helped to track the satellite[9]. As this approach did not provide quantitative data, cameras were soon put into service.

The first satellite tracking cameras were repurposed ballistic cameras that had been developed to track ballistic missiles. These cameras were themselves repurposed military surplus aerial photographic cameras. The normal mode of operation was for the camera to track the stars while the satellite would streak across the frame.

By knowing the start and stop times of the exposure, the satellite position could be determined by comparing it with the stellar background. A popular camera in the west was the BC-4 ballistic camera[10]. In the early days of the space program, these were positioned at dozens of locations around the globe as shown in Exhibit 1.

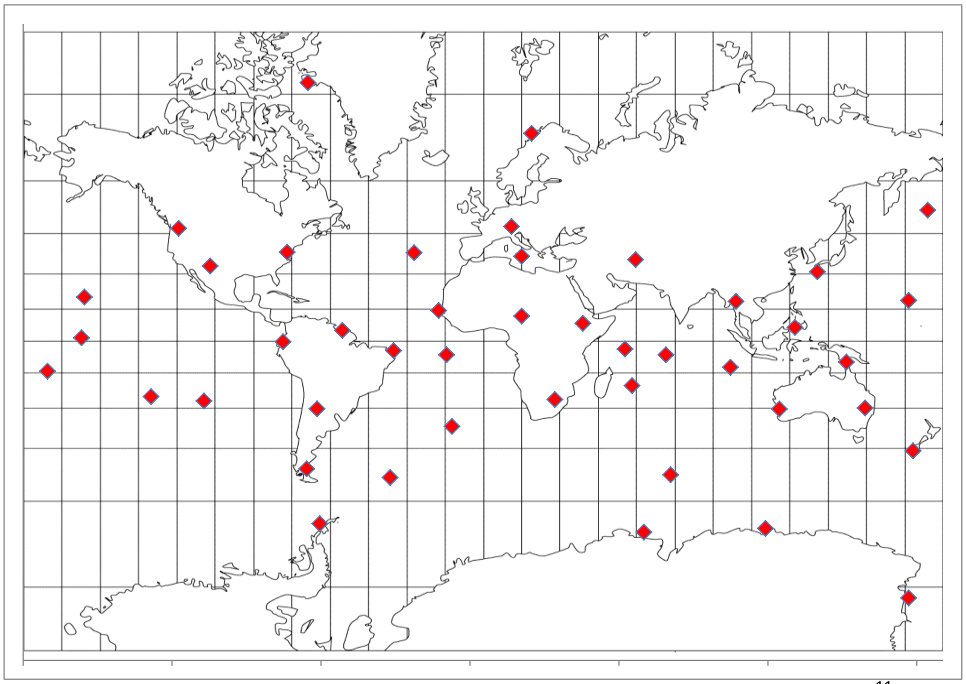

Exhibit 1. Location of observing sites equipped with BC-4 ballistic cameras[11].

The various lens-based ballistic cameras had apertures in the 100-250mm range and focal ratios in the range of f/2 to f/5. While they were useful for early satellite observations, they were not as sensitive as required for capturing the streaks of fast-moving satellites in LEO. Astronomical meteor cameras were tried and found to be useful, but few existed and they were otherwise being used for meteor research. The solution was for the government to build the now famous Baker-Nunn camera. This was a special purpose satellite tracking camera with a 500mm aperture, an f/1 focal ratio, and it could image a patch of stars 5-degrees by 30-degrees. A total of 18 cameras were deployed world-wide, with 12 being operated by the Smithsonian Astrophysical Observatory and six being operated by the Air Force. The final deployment sites are shown in Exhibit 2. Some cameras were moved to more favorable observing locations partway through their service life.

While film-based SSA was useful, significant time was required to develop the film and then measure the location of satellite streaks within the images. A faster and more efficient system was required as the longer-term solution. Initial work with the light sensing tubes from television cameras proved useful for astronomy and the technique was eventually developed and refined for SSA work[12]. In the U.S., this work led to development of the Ground-based Electro Optical Deep Space Surveillance (GEODSS) system.

GEODSS telescopes have a 1-meter aperture and an f/2.15 focal ratio. They were originally designed to image a 2-degree diameter field on to the input face of an 80mm diameter image tube. The images were captured electronically and could be processed on computers[13]. GEODSS quickly proved to be much more effective than the Baker-Nunn cameras which were soon retired. During the late 1990s, the GEODSS telescopes were upgraded to use modern CCD cameras. The new cameras were 3x-4x more sensitive and allowed the telescopes to detect space objects as much as 2 magnitudes fainter. Today, GEODSS is the workhorse of U.S. ground-based optical SSA, with three sites (Socorro NM, Maui and Diego Garcia), each equipped with three telescopes.

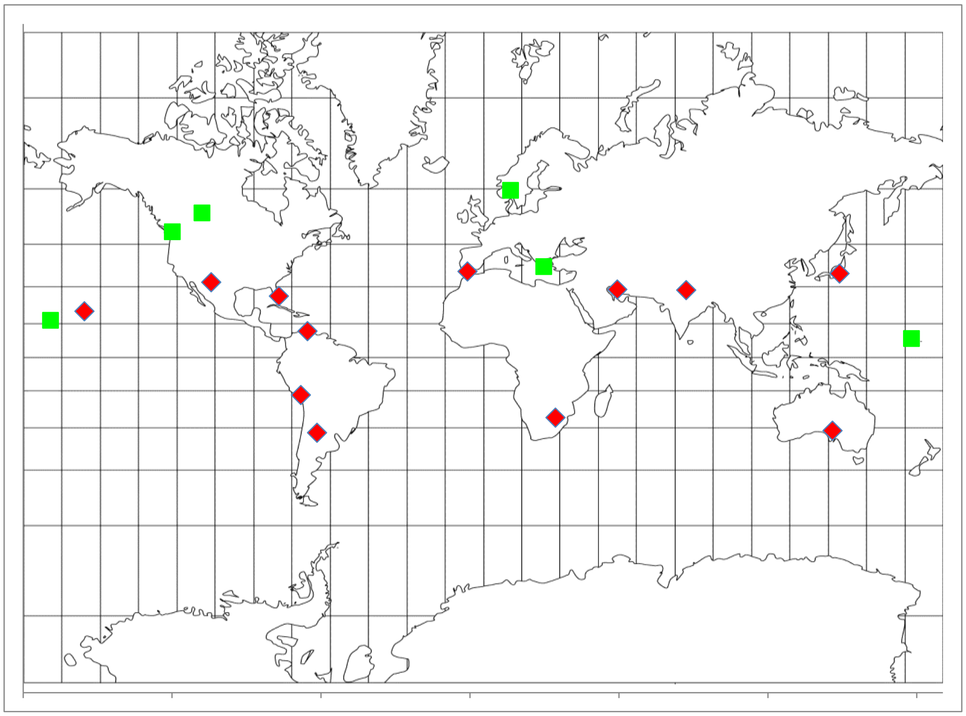

Exhibit 2. Baker-Nunn camera locations. SAO sites (red) and military sites (green)[14].

While GEODSS is a rugged and reliable system, there are too few sites and too few telescopes to provide global SSA coverage. As satellites have become somewhat smaller, and with the proliferation of small pieces of space debris, the 1-meter aperture of GEODSS is now insufficient to detect some of the very faint, high altitude objects that are required for more complete SSA. To address these deficiencies, the Defense Advanced Research Projects Agency (DARPA) began development of the next-generation ground-based optical SSA system in 2002[15]. This was known as the Space Surveillance Telescope (SST). The SST began testing in February 2011 and is currently being moved from New Mexico to a final deployment location in Western Australia.

The SST has a 3.5-meter diameter aperture and a 3.5-degree diameter field of view. It features a three-mirror Mersenne-Schmidt design which is capable of wide-field imaging with fast focal ratios[16]. To achieve the necessary performance, DARPA chose a curved focal surface design and proceeded to develop special curved CCD detectors. The curved CCDs were selected to eliminate the requirement for large and expensive lens-type corrector optics seen in other telescope designs. To date, only one SST has been built.

In other parts of the world, the general approach to ground-based optical SSA developed along similar paths to that followed in the U.S., but there are some significant differences as well. Only a few nations pursue any form of SSA and only the U.S., Russia and China have significant programs. The Russian activities are better known in the west than those of China; hence, only Russian work is briefly discussed here.

The Russians initially used ballistic cameras and followed these with development of specialized film-based satellite tracking cameras such as the AFU-75 and the VOW[17]. Their third generation systems were designed to use television tubes similar to the approach followed in the U.S. for development of GEODSS. The Russian electro-optic system is known as Okno and is located atop a mountain near the city of Nurek in Tajikistan. For a variety of reasons, Okno took decades to fully bring on line and with its television tubes, is considered by some to be outdated. It is highly likely that the various telescopes that make up the Okno system will soon be upgraded to use CCD cameras.

The fourth-generation Russian systems are very different from the U.S. approach. Rather than develop a small number of extremely expensive, government-owned telescopes, the Russians have pursued a private network consisting of a large number of small aperture telescopes deployed world-wide. This system is known as the International Scientific Optical Network (ISON)[18]. While these small telescopes are not as sensitive as the U.S. SST, they do provide complete global coverage, and ISON is presently adapting a small number of larger Soviet-era telescopes for SSA. These larger systems will provide SST-level sensitivity but will not have the same search rate.

Other Sky Surveys

Not all sky surveys are looking for objects that move. A Number of surveys look for time dependent astronomical phenomena such as planets occulting distant stars, variable stars and active galactic nuclei. These instruments also image wide fields of view and compare images taken at different times, but it is only necessary to look for fixed objects that change in apparent brightness and not for things that move. Examples of such sky surveys include the SuperWasp[19] effort and the Dark Energy Survey (DES)[20]. SuperWasp uses two sites, each equipped with eight CCD cameras using commercial 200mm camera lenses. One site is on the Canary Islands while the other is located in South Africa. The DES project recently upgraded the 4-meter Victor Blanco telescope in Chile for wide-field prime focus imaging. This project images fields of 2.1-degrees diameter through different filters to obtain low-order spectroscopic image information. The tools and techniques associated with this type of sky survey will not be discussed further in this paper.

Examples of Ground-Based Optical Sky Survey Instruments

Telescopes are available in a myriad of optical configurations. At some point in history, almost every conceivable configuration has been developed and adapted for sky survey observations. Six examples that largely span the design space are presented here.

Palomar Oschin Schmidt Camera

The Palomar Oschin Schmidt Camera is the largest Schmidt system in the U.S. It features a 48-inch aperture corrector plate and a 72-inch diameter primary mirror. When used with curved photographic plates, the f/2.5 optical system could easily image a field of 9.5 x 13.3 degrees[21]. More recently, the camera was modified with a field flattening lens and equipped with CCD sensors to electronically image a field of 5.7 degrees diameter. The Oschin Schmidt was originally used to map the northern hemisphere sky, helping to form one of the most complete, non-digital star catalogs. The project was known as the Palomar Observatory Sky Survey.

NEAT Prime Focus Camera

The earliest reflecting telescopes used a single mirror. For more than 100 years, the largest telescopes in use were single-mirror reflectors. Gradually they were replaced, first with giant refractors and then with Cassegrain type two-mirror telescopes. The problem with a single mirror is that it introduces significant aberrations when used for even modest fields of view. In 1913, Sampson published a paper describing how a single mirror could be combined with three lenses for wide-field imaging at prime focus[22]. The concept did not catch on initially but in recent years, prime focus correctors have become quite popular.

The Near Earth Asteroid Tracking (NEAT) Survey originally placed a camera at the focus of a GEODSS telescope, but when that became unavailable, the Air Force developed a focal reducing prime focus corrector for a 1.2-m telescope that was available on Maui. The NEAT corrector both reduces the primary mirror focal ratio from f/3 to about f/2 and also corrects the image over a 2-degree field of view[23].

SkyMapper

SkyMapper is a 1.35-m aperture survey instrument located at the Siding Springs Observatory in Australia. The telescope comes from a modification of the Cassegrain design family, with two mirrors and three corrector lenses[24]. The optics are relatively simple with low fabrication and alignment tolerances. SkyMapper features a very wide field of view of 3.4 degrees. It is used to map the southern skies across six color bands. The basic design would also allow SkyMapper to function as an effective and relatively inexpensive SSA telescope provided the camera were upgraded for more rapid image readout.

Space Surveillance Telescope

The Space Surveillance Telescope (SST) was briefly introduced above. It is included here as it represents the only current survey instrument relying on three mirrors to form the final image. The SST operates at an amazingly fast focal ratio of f/1[25]. The problem with high-speed, wide-field telescopes is that the primary mirror introduces significant aberrations that must be removed with corrective optics. In the case of the SST, these corrective optics include two large and fast mirrors and three lenses. The large corrective optics introduce significant obscuration which reduces the overall system efficiency. For the 3.5-m SST, these obscurations combined with other losses to reduce the light collection capability to that of less than a 2.8-m aperture telescope. The SST images a field of 2 x 3 degrees onto a CCD mosaic of 8k x 12k pixels with a 15um pitch. Even with the system light loss mechanisms mentioned above, the SST is extremely sensitive and able to search wide fields of sky very quickly.

SuperWasp

SuperWasp is a lens-based wide-area survey looking for extra-solar planets. The survey is based out of the United Kingdom, but observing facilities are located on the Canary Islands and in South Africa. Each site features a single mount with eight co-mounted cameras, each pointed at a slightly different location on the sky. The cameras use 200mm focal length, f/1.8 commercial camera lenses manufactured by Canon. The lenses feature significant high image quality but also have significant light falloff from center of the field to the corners of the image. Each camera has a CCD sensor with 2k x 2k pixels on a 13.5um pitch. The combination of detector and lens allow each camera to image a 7.9 x 7.9 degree patch of sky[26].

Houghton-Terebizh

The VT-78a telescope was designed by the Russian physicist Valery Terebizh for the ISON project. The VT-78a has some lineage to previously published optical designs, but also includes a number of novel features that make it quite unique. The optical system features three full-aperture lenses out front to precondition the optical beam.

The image is formed by two spherical mirrors in a Cassegrain configuration. With a 192mm aperture and a 300mm focal length, the system images a field of 7.1 x 7.1 degrees onto a 4k x 4k detector with 9um pixels[27]. This telescope is used widely throughout the ISON project, and, in some cases, four are collocated on a single mount.

SYSTEMS ENGINEERING FOR SKY SURVEY INSTRUMENTS

Before investigating new technologies for sky survey instruments, it is prudent to examine the problems of SSA and NEO search from a systems engineering perspective. The survey does not consist simply of a telescope and sensor. Rather, any sky survey is dependent upon a number of factors, some of which the instrument designer can control and some that cannot be controlled. These factors conveniently fit into four groups; site characteristics, optical characteristics, sensor characteristics, and characteristics of the observing program.

Site characteristics are the most difficult to control. They include atmospheric seeing conditions and sky brightness. The seeing can be critical to some observing programs as it results in an increase in image spot size or point spread function (PSF) which reduces the sensitivity of the overall instrument. All sites experience variations in seeing conditions. Site survey work is required to understand the expected average seeing and the likely variations about this average. Short of selecting a new site, little can be done to control site seeing. The one exception is if the seeing is dominated by low altitude turbulence. On some sites, building a taller containment structure helps elevate the telescope out of the most turbulent air.

Sky brightness is another site characteristic. The background glow of the atmosphere resulting from lights at nearby cities and facilities contributes to noise and works to limit system sensitivity. In general, very little can be done about sky brightness. It is important to note that historically, light pollution only gets worse. When selecting a site, it would be useful to consider what the sky conditions will be in the decades to follow.

The physical characteristics of available CCD sensors represent the second most difficult set of parameters to control. For large survey efforts with significant budgets, it is often possible to have detectors custom made and thereby optimized for the particular observing activity. For most survey efforts, custom CCDs are too expensive and it is therefore necessary to select from those readily available. While modern sensors include both CCDs and complimentary metal-oxide semiconductor (CMOS) technologies, here we only consider CCDs. CCD characteristics include the pixel size, quantum efficiency, read noise and dark current. There are a number of other characteristics having less impact on overall performance that are not considered here.

The pixel size needs to be appropriately matched to the overall system PSF (which includes optics and atmospheric seeing). How one appropriately matches these two is, however, open for some interpretation. For imaging applications, it is important to achieve proper spatial sampling of the PSF to achieve maximum image resolution. For most imaging applications, this quickly reduces to Nyquist sampling the PSF, or, putting a minimum of two pixels across the expected PSF dimension.

For non-imaging applications where the goal is to achieve maximum sensitivity, it is best to size the pixel to match the expected PSF. The problem with this approach is that image spots will fall randomly on the CCD array and one cannot guarantee that all important spots will be perfectly centered on a single pixel. In most cases, the PSF will be shared by more than one pixel, with a worst case situation occurring where the PSF is exactly centered on the corner of a pixel and the light is shared equally among four pixels. If the pixels are large, they capture more background photons from the sky and if they are too small, they capture less light from the object of interest. Careful analysis is required to optimize the pixel size for a given application.

The sensor quantum efficiency (QE) describes how efficient the CCD is at converting photons of a given wavelength to electrons. High quality scientific CCDs will have a QE greater than 90% across a wide range of useful wavelengths. Commercial grade, front-illuminated CCDs will have lower QE values, typically 60% in their prime wavelength range. A higher QE results in improved sensitivity. Lower QE sensors are normally much less expensive.

Read noise provides an indication of how much extra noise is introduced into the signal for each and every pixel in the image. Read noise directly impacts system sensitivity. It is often dependent upon the rate at which pixels are read out from the device with higher read rates resulting in greatly increased read noise. Typical scientific CCDs will have read noise values of 3-4 electrons RMS (root mean square) at low read rates and 10-12 electrons RMS at high read rates. Lower quality CCDs have much higher read noise. The CCDs for the SST have a read noise of 18.6 electrons RMS which is thought to be quite high, considering that these were custom CCDs[28].

Dark current is the final CCD characteristics of interest. This is a measure of how many electrons per second one can expect to leak into a pixel thereby partially contaminating the image. High-quality CCDs are normally operated at very low temperatures where the dark currents are almost imperceptible. Some CCDs have higher dark current rates. The CCDs for the SST have an average of 2-electrons per pixel per second dark current[29]. This value is very high and is thought to result largely from physically bending the CCDs to accommodate the curved focal surface.

When designing a new instrument, the characteristics of the optical telescope are perhaps the easiest to control, even if they are expensive. When adapting an older telescope for a new observing mission, less control exists, but auxiliary optics are often used to modify the telescope characteristics for a better match with the expected observing program and available detectors. Telescope characteristics include the optical layout, aperture, focal ratio, obscuration, field of view and image quality as represented by the point spread function.

Many choices exist for the basic optical layout. Here we focus on traditional reflecting telescopes where the primary mirror provides most of the image forming optical power. Lenses are used to correct aberrations closer to the detector, but there are no full-aperture lens as seen in catadioptric type telescopes. The basic configurations to select from are shown in Exhibit 3. These include a single mirror with prime focus correcting lenses, a folded prime focus system that is identical to the first with the exception of a flat folding mirror, the two-mirror Cassegrain type telescope that has a convex secondary mirror, and the three-mirror anastigmat approach as was pursued for the SST. Both the prime focus options and the three-mirror anastigmat are capable of wide fields of view and small focal ratios, but the prime focus approach results in lower central obscuration.

The system aperture is a relatively simple choice but one that has significant impact on cost, image scale, focal ratio and field of view. Larger apertures require larger facilities and larger corrector optics. Overall system and facility costs have been found to scale approximately proportional to the telescope diameter raised to the 2.7 power[30]. Even small reductions in aperture can result in significant cost reductions. Aperture also directly impacts system sensitivity. In terms of visual magnitude (which is a logarithmic scale), large changes in aperture usually result in only small changes in the limiting visual magnitude. For faint objects, it is highly desirable to have as large an aperture as possible.

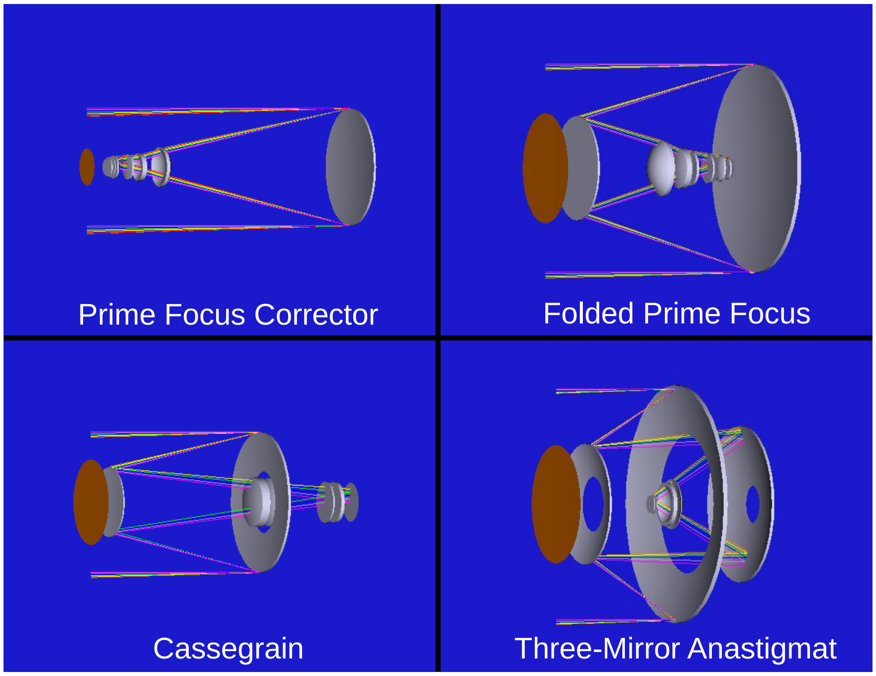

Exhibit 3. Optical layout options. The red disk seen on each layout shows the extent of the central obscuration.

The system focal ratio has a significant impact on overall cost and complexity. Fast systems result in short optical assemblies and therefore, smaller and less expensive facilities. However, optical aberrations are nonlinear functions of the inverse focal ratio. Faster telescopes become complex very quickly, and complexity drives cost.

System obscuration and field of view are directly related to one another and partially dependent upon optical layout and focal ratio. While faster optical systems result in smaller final images, they also require larger corrective optics. Different optical designs tend to experience a sweet spot in the trade space where the overall system offers the best combination of less complex optics, small image size and lower obscuration. The exact optimum point is generally found through trial and error.

Image quality is the last characteristic of the optical system that can be controlled. Many optical designers seek to achieve the highest possible optical quality, but it is important to match the system optical performance with the observing mission, site observing characteristics and detector characteristics. It makes no sense to design an expensive system that is theoretically capable of diffraction limited images if the local atmospheric seeing will limit the final image quality to 2-arc seconds. In such cases, lower image quality can be tolerated from the telescope with a significant savings in cost and complexity. Similarly, it makes no sense to place tiny point spread functions onto a detector with large pixels. As discussed above under detector characteristics, it is important to match the final image quality to the detector.

The final group of system characteristics are defined by the collection mission and observing strategy. This group includes such parameters as the mount slew and settle rates, integration time, tracking, image processing, detector read rate, search rate and limiting magnitude. The mount slew speed and settle time are very important for SSA where one wants to cover as much of the sky as possible within a given observing session. For NEO search, the integration times are much longer so slew rate and settle time are less important. Telescopes such as the SST and GEODSS were designed for high slew rates and rapid settling times. Most civilian astronomical telescopes are not intended for such high duty cycle operations. Integration time, when combined with a number of other system characteristics, determines the overall system sensitivity. Longer integration times provide for greater sensitivity but at the expense of a lower search rate. However, for targets that are moving, there exists an optimum integration time, beyond which sensitivity actually decreases. For SSA work, the optimum integration time is determined by how long it takes the image spot from a satellite to move off a single pixel. For NEO search, the spots are essentially motionless during reasonable length exposures and this is not a concern.

For a telescope such as the SST, one can easily calculate the optimum exposure time for a satellite moving across the sky while the telescope tracks the stars. A calculation of this sensitivity is shown in Exhibit 4. This information comes from a publically released DARPA publication and is assumed to be for the system operating in what DARPA describes as a non-operational mode[31]. In this Exhibit, the dark blue trace represents the sensitivity as a function of time for observing stars in sidereal track mode. The purple/pink curve is for a satellite in a GEO orbit, moving at a relative rate of 15 arcsec/sec. One can see that the sensitivity for such an object first increases with time, peaks and then decreases.

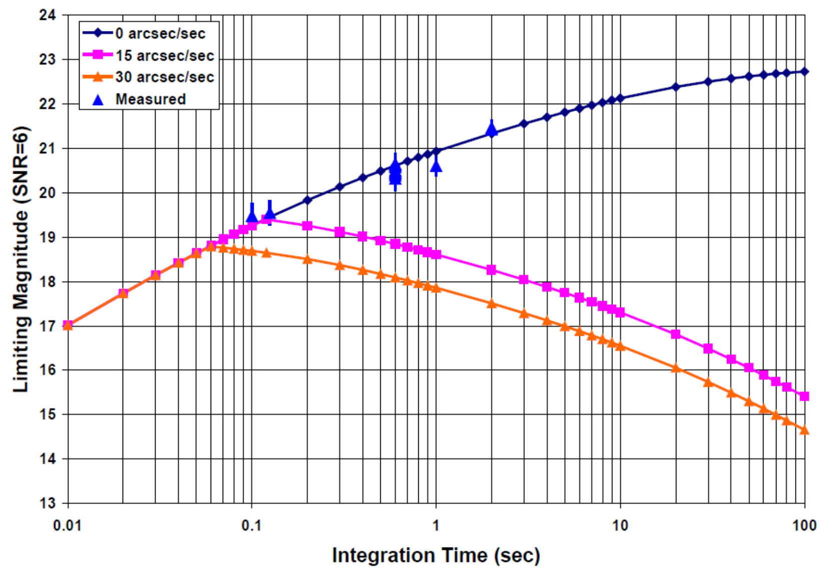

Exhibit 4. DARPA calculation of SST sensitivity.

The overall system search rate is a function of detector read rate, integration time, slew rate and the number of frames required per location on the sky before moving on. A lot of assumptions go into any such calculation. This combination of parameters is described by some as the observing strategy and by others as the search strategy. There are no perfect answers for how to observe and search, but it can be demonstrated that some search strategies are more effective than others. In general, one can achieve higher sensitivity or a greater search rate but not both at one time. For targets that are moving across the field, the integration time is fairly well fixed, so search rate then becomes a function of read time, slew rate and the number of frames taken at each location.

The calculated sensitivity for the SST is based on an image processing technique where one makes several exposures at the same location and then does a frame-to-frame comparison (in the form of a subtraction) to look for moving objects. A problem with this approach is that it tends to increase image noise as even when subtracting frames, the noise adds in quadrature. There are other processing techniques where the noise is treated differently. The results are a higher signal to noise ratio for similar exposures and search rate. One such technique has been developed at the University of New Mexico (UNM). Details of the approach and algorithms are beyond the scope of this paper, but results showing a comparison of sensitivity and search rate for the frame to frame technique will be provided later. The mathematical techniques used to calculate sensitivity, signal to noise ratio and search rate are well documented in the technical literature[32].

REFERENCE DESIGNS

For reference purposes, we present the optical designs for both GEODSS and the SST. These will be used later to calculate performance for comparison against new optical approaches.

GEODSS Reference Design

The GEODSS optical layout is shown in Exhibit 5. While the GEODSS design is often described as being a Richey-Chrétien system, the secondary mirror is actually spherical. The corrector requires four lenses, all of spherical figure and made from common glass types. Optical performance is shown in Exhibit 6 with system sensitivity shown in Exhibit 7. For all exhibits presented below showing sensitivity calculations, the red trace shows the sensitivity for stars in sidereal track mode while the black trace shows the sensitivity for a satellite moving at a relative rate of 15 arcsec/sec.

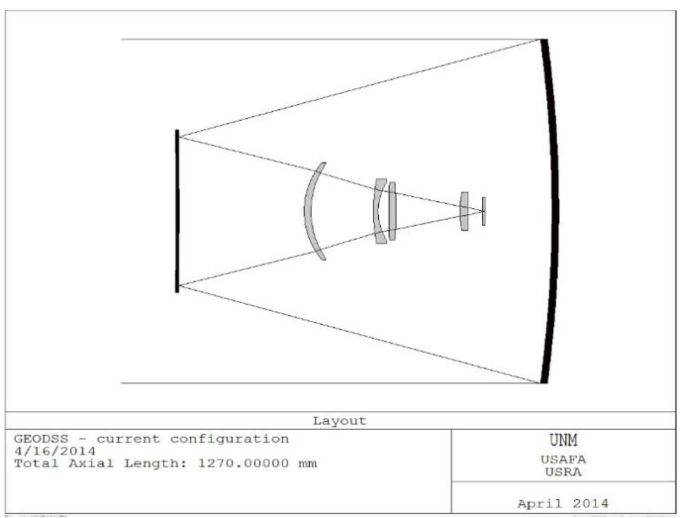

Exhibit 5. GEODSS reference design

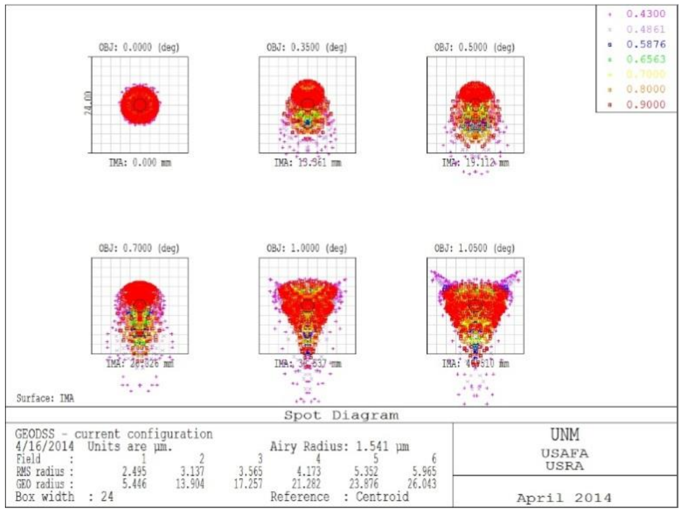

Exhibit 6. GEODSS spot diagram. The boxes are representative of the actual 24µm pixels.

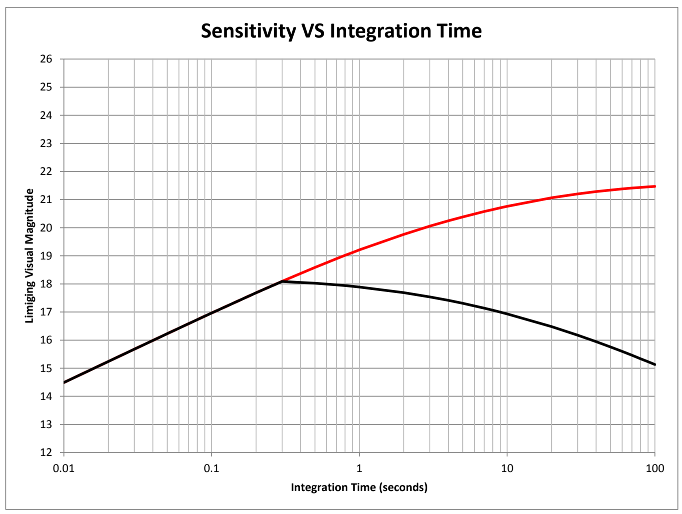

Exhibit 7. GEODSS calculated sensitivity.

SST Reference Design

The SST optical layout is shown in Exhibit 8. The corrector requires three lenses with one having an aspheric surface. All lenses are made from common glass types. Calculated optical performance is shown in Exhibit 9 with calculated system sensitivity shown in Exhibit 10. Note these calculations accurately reproduce the DARPA published sensitivities shown in Exhibit 4.

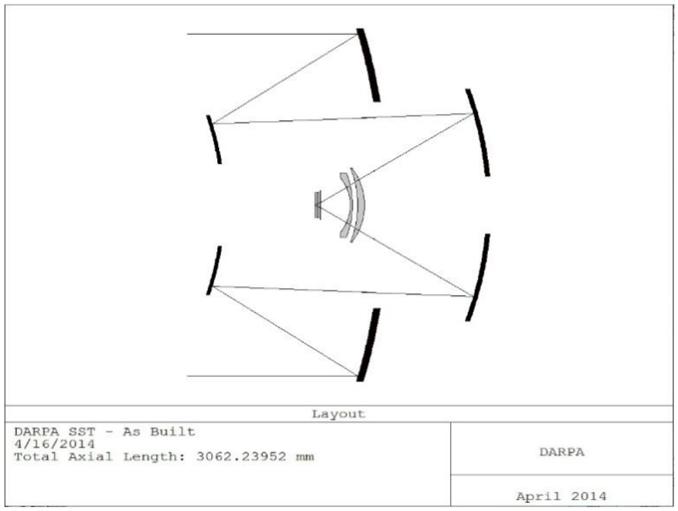

Exhibit 8. SST reference design

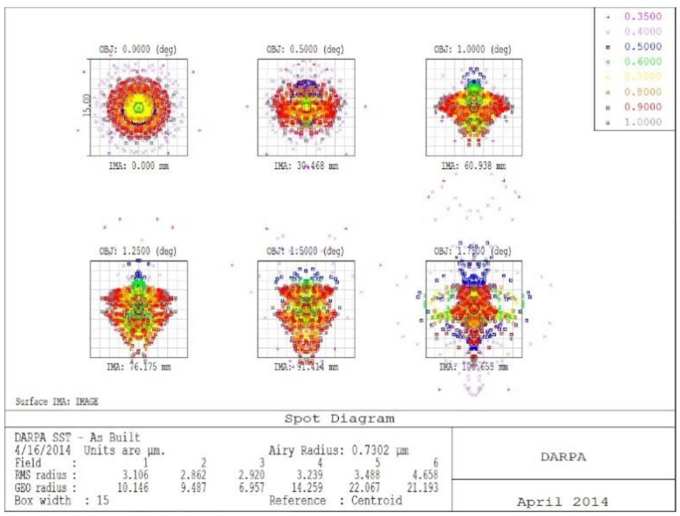

Exhibit 9. SST spot diagram. The boxes are representative of the actual 15µm pixels.

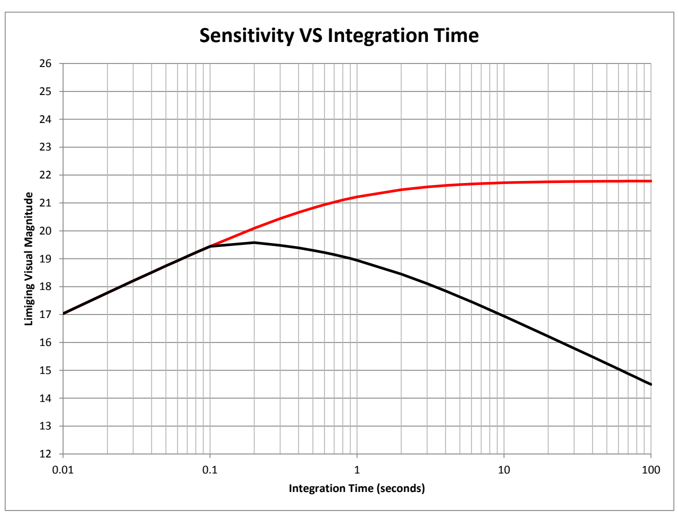

Exhibit 10. Calculated SST Sensitivity

NEW OPTICAL DESIGNS

Six new optical designs are presented for comparison against the two reference designs. The first two designs are based on the existing GEODSS primary mirror and can therefore be thought of as potential GEODSS upgrades. The third design is based on an enlarged version of the existing SkyMapper telescope currently operating in Australia. The fourth design is based on an existing, surplus parabolic mirror left over from the original Multiple-Mirror Telescope (MMT) project[33]. The last two designs are new prime focus space surveillance telescope concepts that may be thought of as possible low-cost alternatives to the SST. In each design presented, the corrector lenses are designed to use readily available types of glass such as BK7, fused silica, F2, LLF1 and CaF_2. All lenses can be made from materials available off-the-shelf. No special production is required for exotic glass or larger material blanks. For brevity, sensitivity calculations are only provided for the SSA mission and only show targets in GEO, moving at 15 arcsec/sec relative to the stars.

Wide-Field GEODSS Upgrade - Folded Prime Focus

The first design is based on the GEODSS system. It uses a folded prime focus corrector configuration. The secondary mirror is flat. The folded design was selected to allow this optical configuration to fit within the current GEODSS system envelope. The layout is shown in Exhibit 11, with spot diagrams shown in Exhibit 12 and sensitivity presented in Exhibit 13. The corrector requires seven lenses, but all have spherical surfaces and the system images a field of 3.5 degrees diameter.

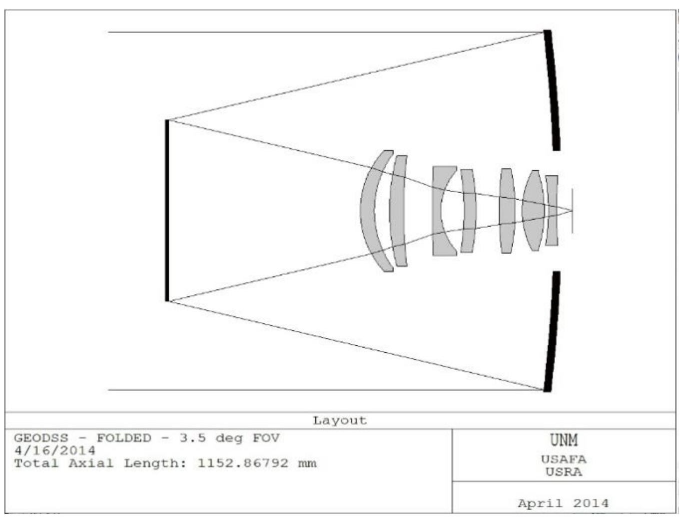

Exhibit 11. Layout for wide-field GEODSS upgrade.

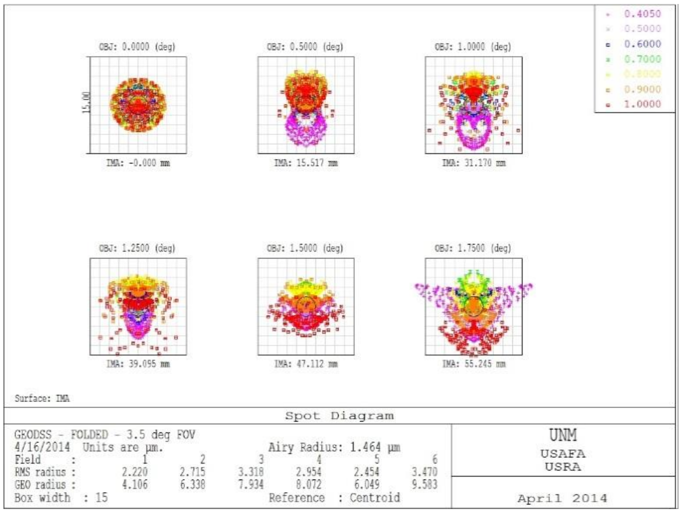

Exhibit 12. Spot diagram for wide-field GEODSS upgrade. The boxes are representative of the recommended 15µm pixels.

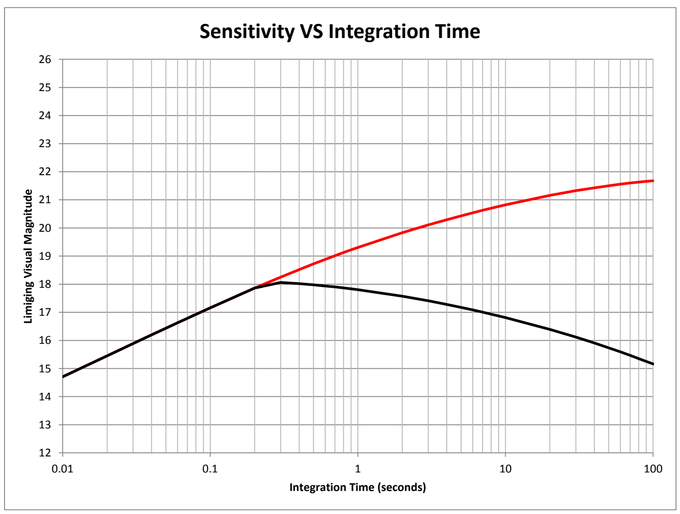

Exhibit 13. Calculated sensitivity for wide-field GEODSS upgrade.

Very Wide-Field GEODSS Upgrade - Prime Focus

The very wide-field GEODSS upgrade is also based on the existing GEODSS primary mirror. This system uses a straight prime focus corrector and achieves a corrected field of 4.5 degrees diameter. The seven lens corrector uses all spherical optics. This design is longer and would therefore require some mechanical modifications of the GEODSS systems. The optical layout is seen in Exhibit 14, with spot diagrams in Exhibit 15 and sensitivity shown in Exhibit 16.

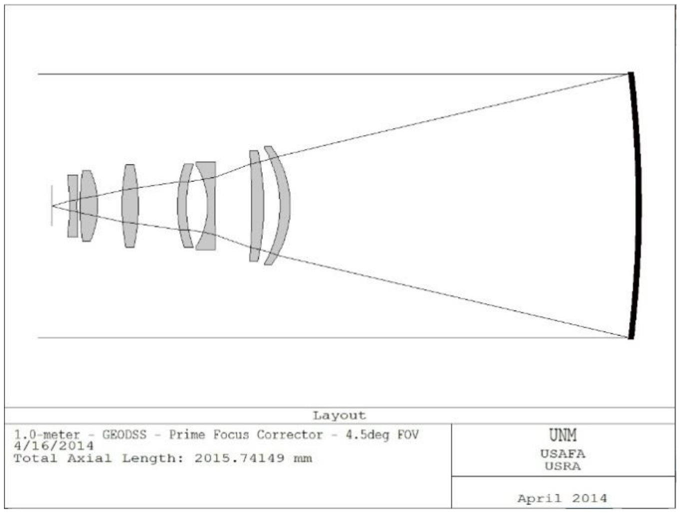

Exhibit 14. Layout for very wide-field GEODSS upgrade.

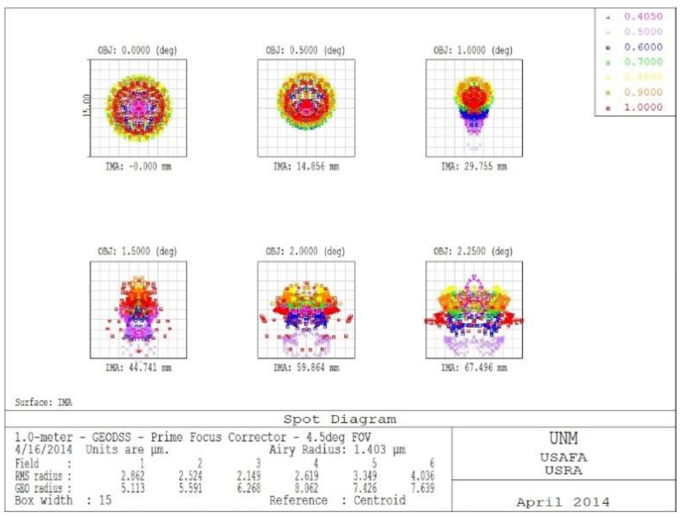

Exhibit 15. Spot diagram for very wide-field GEODSS upgrade. The boxes are representative of the recommended 15µm pixels

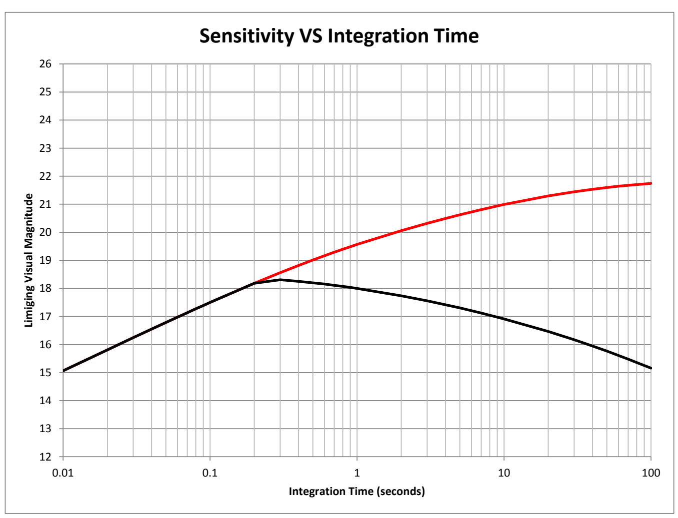

Exhibit 16. Sensitivity for very wide-field GEODSS upgrade.

SkyMapper Derived Cassegrain

The third system is based on the 1.3-m SkyMapper telescope in Australia but with the system enlarged to a 1.95-m aperture and the field of view increased from 3.4 to 3.5 degrees. The first lens of the corrector includes a mild aspheric correction on one surface. This design was included to show that fast optics are not required for SSA. This telescope has a final focal ratio of f/4.8. The drawback of a slower optical system is that the focal plane array and corrective lenses become proportionally larger. For this system, the largest lens is approximately 780mm diameter. This however compares well with the largest lens in the SST being 750mm diameter. The optical layout is shown in Exhibit 17, with spot diagrams in Exhibit 18 and system sensitivity approximately shown in Exhibit 19.

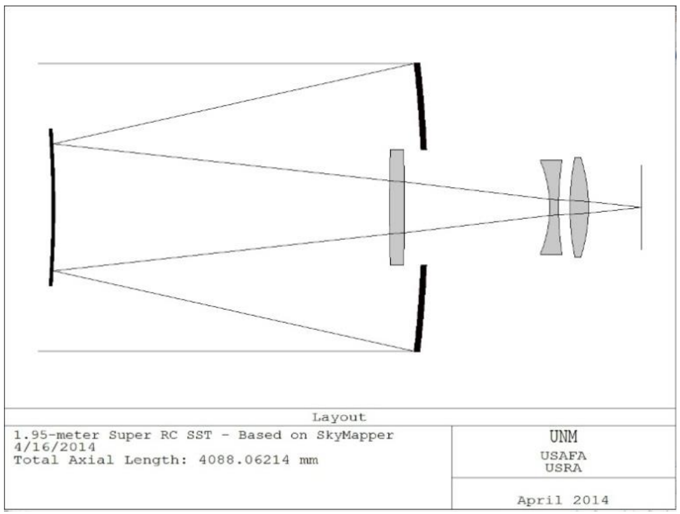

Exhibit 17. Optical layout for 1.95-m SkyMapper.

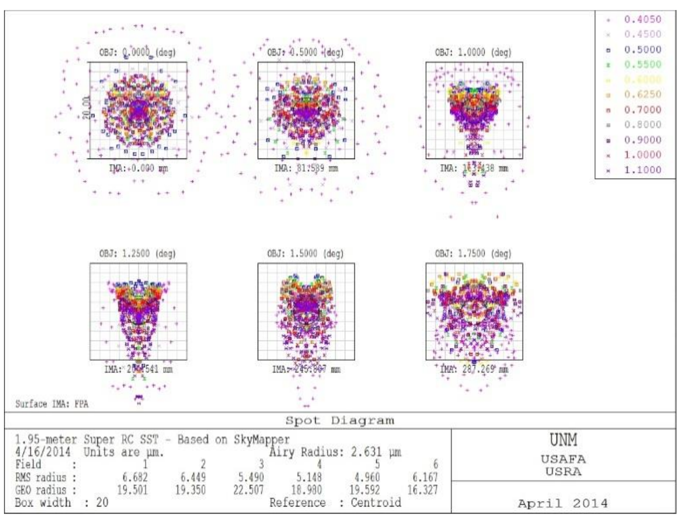

Exhibit 18. Spot diagram for 1.95-m SkyMapper. The boxes are representative of the recommended 20µm pixels.

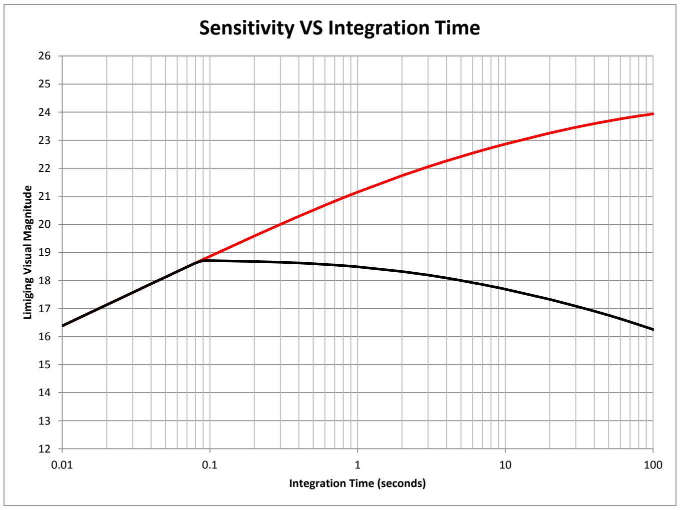

Exhibit 19. Sensitivity for 1.95-m SkyMapper**.**

Repurposed 1.8-m MMT Mirror

The fourth design was developed to provide an option for very rapid development of a new SSA capability. The original MMT telescope included six 1.8-m diameter mirrors that featured parabolic surface figure and an f/2.7 focal ratio[34]. At least five of these mirrors are known to be in crates and available for immediate use. This design includes a novel reflective focal reducer and images a field of 2.0 degrees diameter at a final focal ratio of f/2.14. All lenses and the secondary mirror have spherical figures. The optical layout is shown in Exhibit 20, with spot diagrams presented in Exhibit 21 and sensitivity shown in Exhibit 22.

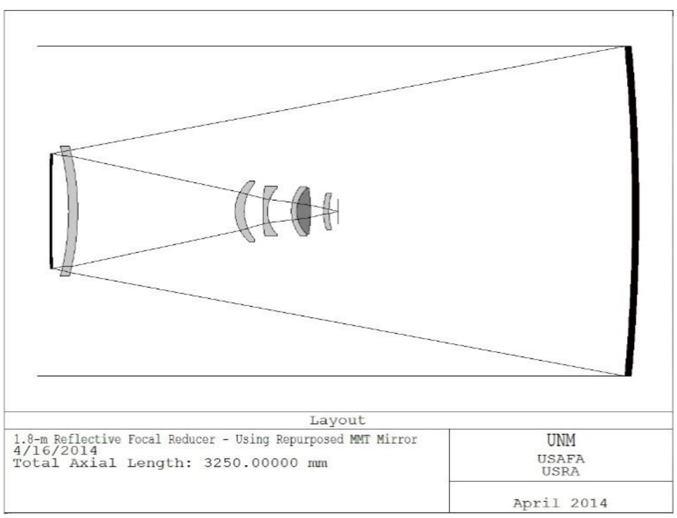

Exhibit 20. Optical layout for repurposed MMT mirror.

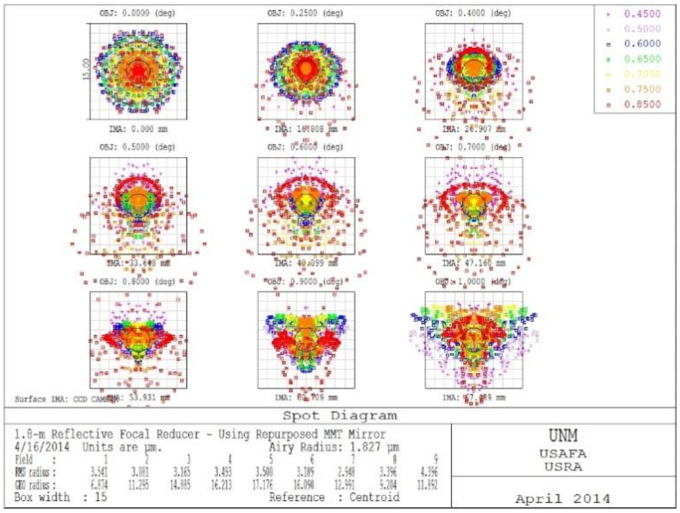

Exhibit 21. Spot diagram for repurposed MMT mirror. The boxes are representative of the recommended 15µm pixels.

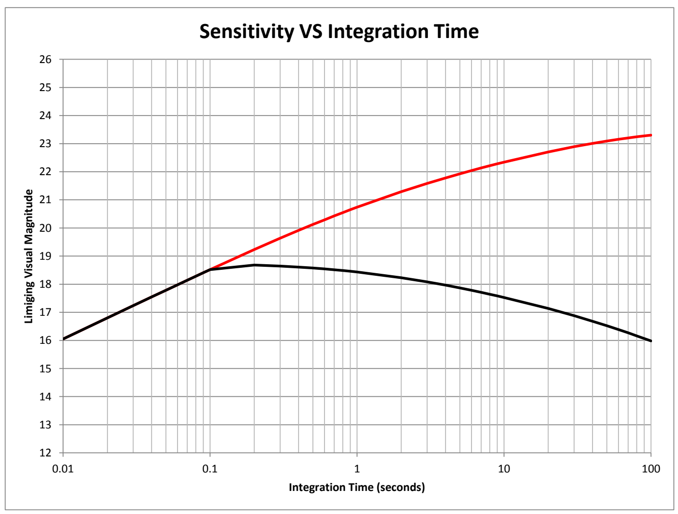

Exhibit 22. Sensitivity for repurposed MMT mirror.

Prime Focus System with 2.0-m Hyperbolic Primary

The fifth system is a prime focus design using a relatively small 2.0-m diameter mirror. It was designed to show that a small telescope with enhanced image processing algorithms could approximately equal the performance of the SST as built and demonstrated. The primary mirror has a simple hyperbolic figure. The corrector requires six lenses, three of which have surfaces that include both conic figures and a sixth order aspheric correction term. The optical layout is shown in Exhibit 23 with the corresponding spot diagram shown in Exhibit 24. The sensitivity shown in Exhibit 25 is calculated using the frame to frame subtraction technique as described above. The modified algorithms have greater sensitivity. These results will be discussed in the performance section presented below.

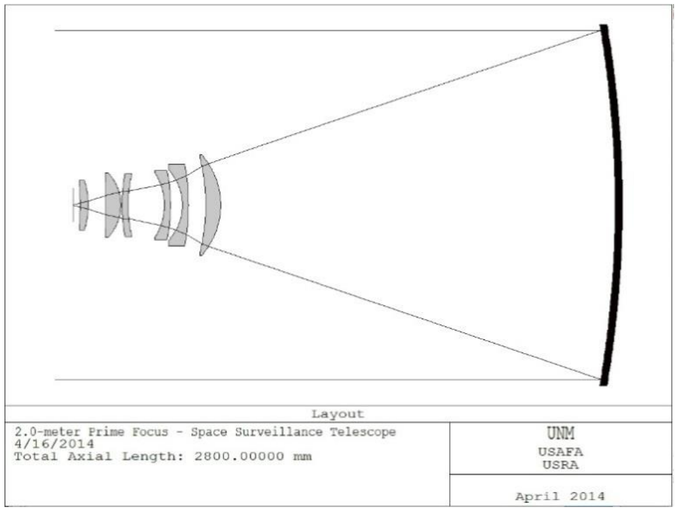

Exhibit 23. Optical layout for 2.0-m prime focus system.

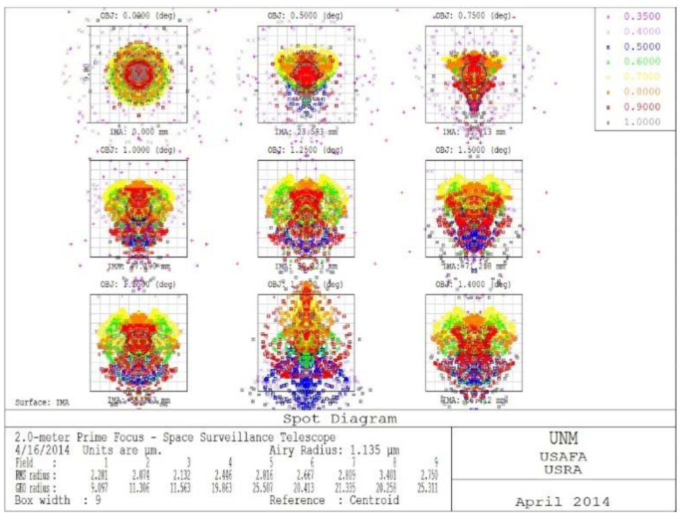

Exhibit 24. Spot diagram for 2.0-m prime focus system. The boxes are representative of the recommended 9µm pixels.

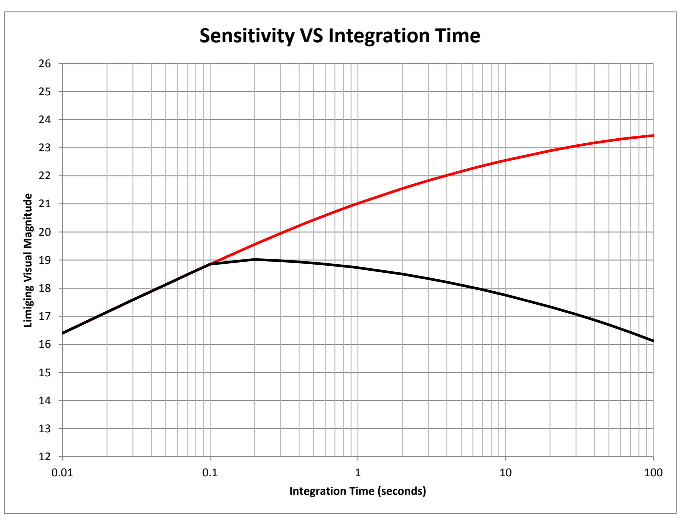

Exhibit 25. Sensitivity for 2.0-m prime focus system.

Prime Focus System with 2.9-m Aspheric Primary

The final system also uses a single mirror and a prime focus corrector. This system was sized to exactly match performance of the SST as built and as it was designed to operate. The single mirror approach is significantly less complex and will therefore reduce cost as compared to the SST. The telescope is also significantly smaller and will therefore be much less expensive. This telescope was designed to compete with the SST on a photon per photon basis at the focal plane. It does not collect as many photons as the SST aperture, but it uses them more efficiently and can therefore match the larger and more expensive SST performance. The optical layout is shown in Exhibit 26, with the spot diagram shown in Exhibit 27 and sensitivity shown in Exhibit 28.

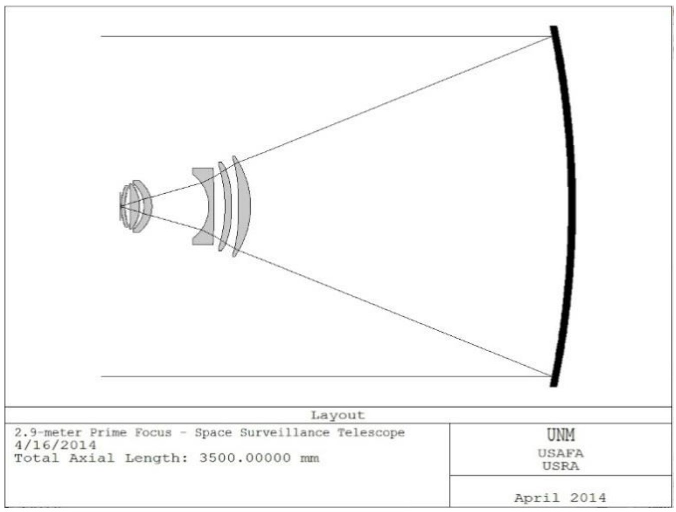

Exhibit 26. Optical layout of 2.9-m prime focus system.

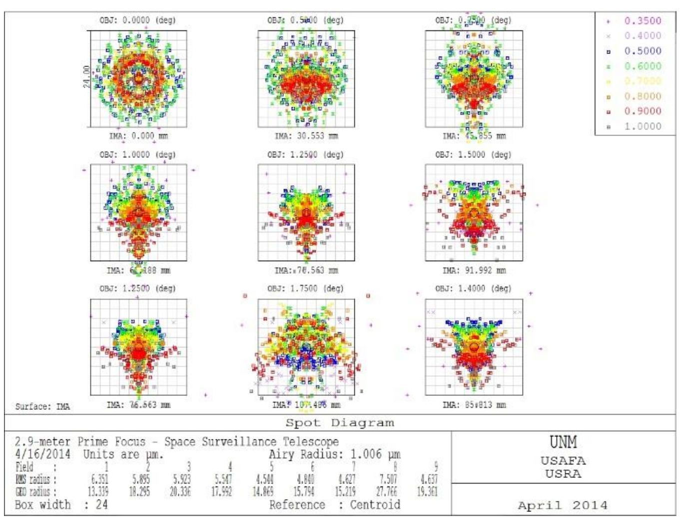

Exhibit 27. Spot diagram for 2.9-m prime focus system. The boxes represent 24µm pixels.

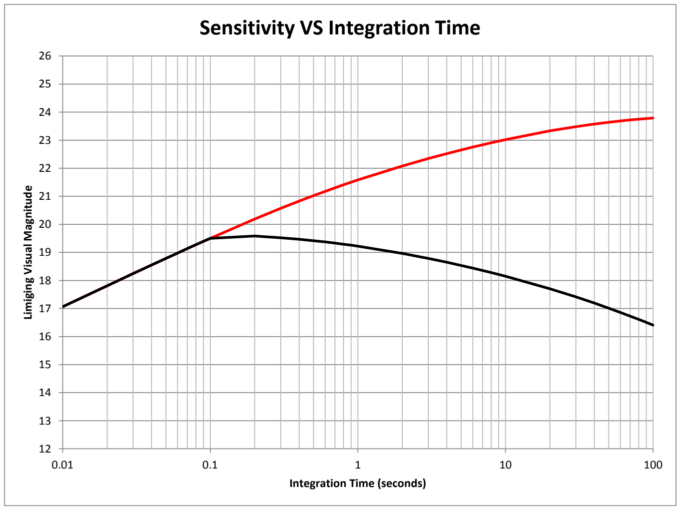

Exhibit 28. Sensitivity for 2.9-m prime focus system.

PERFORMANCE COMPARISON

To compare performance of the six new optical designs with the two reference designs, we follow rather standard approaches to calculate the radiometric sensitivity and search[35]. Maximum integration times are determined by the system optics, detector and target motion. With this integration time, other system parameters are used to calculate search rate in square degrees per hour.

For the frame to frame subtraction method of image processing and target detection, the sensitivity and search rate are plotted in Exhibit 29. Performance of the SST is shown as the red square. The GEODSS reference design is shown as the green triangle. The other six systems are shown as black triangles and identified with text boxes. Note the 2.9-m system performs identically to the SST. The marker for this system is plotted slightly above that for the SST and is difficult to see in the Exhibit 29.

The two GEODSS-based options were included to show the potential performance for an upgraded GEODSS system. They produce roughly the same sensitivity but with a much higher search rate. These options were not intended to be SST competitors.

The design based on the 1.8-m MMT mirror was included to show what could be achieved with a readily available mirror. The mirror is not at all optimum for use as an SSA instrument, but with proper corrector optics, it provides GEODSS-like search rates with about a 0.7 magnitude improvement in sensitivity.

The 1.95-m Cassegrain system based on the enlarged SkyMapper design shows better sensitivity than GEOSS though that should be expected with the larger aperture. The system also shows a much higher search rate as it has a wider field of view.

The 2.0-m prime focus design provides a search rate similar to SST and has a sensitivity approximately half a magnitude lower. This is very impressive performance for such a small system when compared against the 3.5-m aperture SST. The 2.9-m prime focus system was designed to compete with the SST photon per photon. The calculations show that it achieved almost the exact same sensitivity and search rate. Having only one mirror and being smaller, it would however be significantly less expensive.

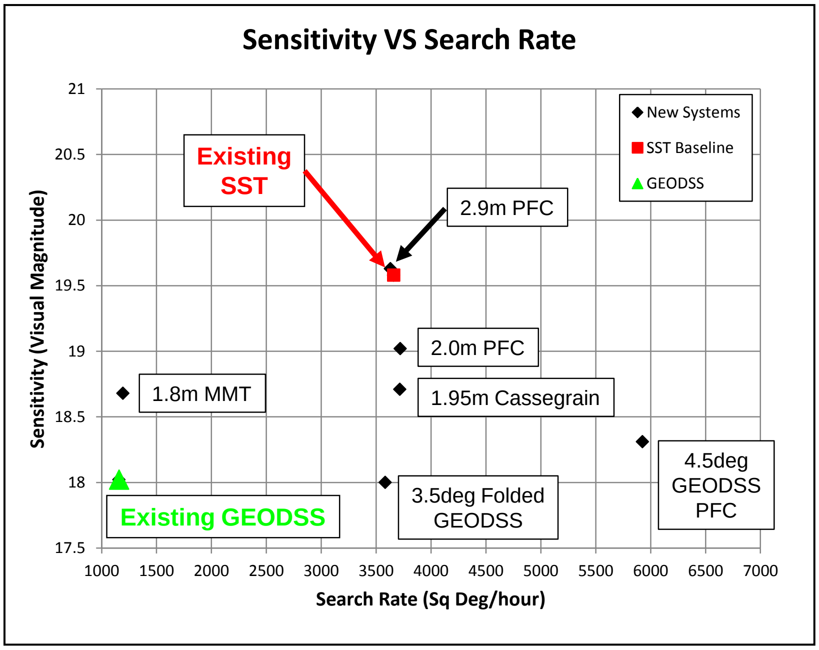

Exhibit 29. System performance comparison for standard target detection algorithms.

When using the new processing algorithms developed at UNM, performance for the various systems changes significantly. These algorithms have been demonstrated on small telescopes; they are not theoretical. The performance for all seven systems shows an improvement in both search rate and sensitivity. The new performance is plotted in Exhibit 30. The marker for SST performance has not changed as it is unclear if these algorithms can be adapted to SST images. Note that the 2.0-m prime focus system now exceeds SST sensitivity and search rate. Note that the sensitivity and search rate for SST are calculations based on academic assumptions as outlined in the literature[36]. The performance of SST in operational modes of use is unknown.

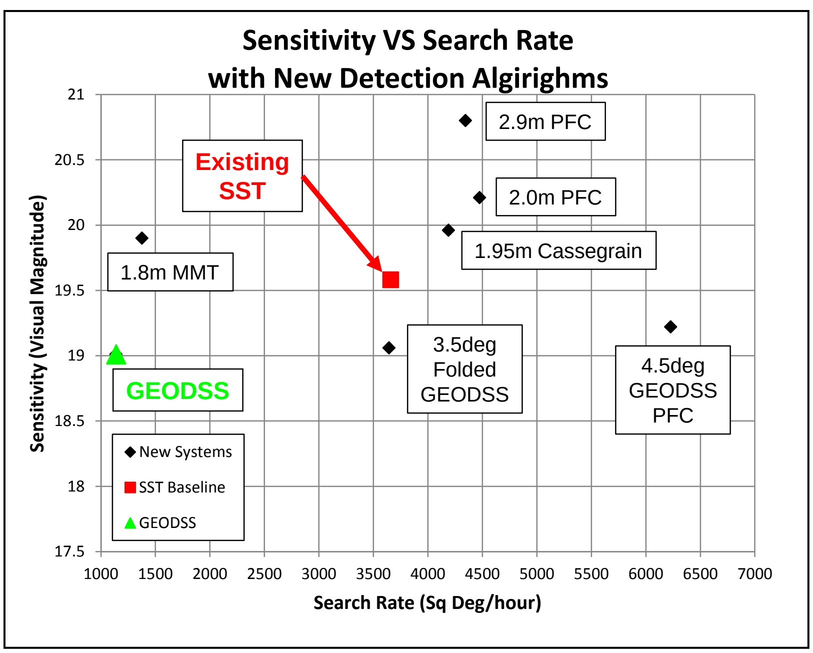

Exhibit 30. System performance comparison using advanced processing algorithms.

WHY NOT BUILD MORE SSTS FOR SSA

The SST is already built and has demonstrated exceptional performance. The design is proven. It is fair to ask why one would not simply build more copies of the SST. The answer to this question is straight forward. The SST performs exceptionally well, but represents a high cost approach. The original SST budget was $65M. Unofficial publications show that the final system cost on the order of $110M[37]. A review of congressional records shows FY2002-FY2014 expenditures for the system in excess of $160M in current year dollars[38].

When comparing SST against large telescopes that were built by civilian astronomical organizations during the same period of time, the results support the view that SST is a high cost approach. The Discovery Channel Telescope (DCT) has a 4.2-m aperture and was built in Arizona for a total cost of $54M (2012 dollars)[39,40]. The system does not move as fast as SST and has a smaller field of view but it also has a larger aperture. The Visible and Infrared Survey Telescope for Astronomy (VISTA) was built during the same period by the European Southern Observatory (ESO)[41]. VISTA was designed and assembled in Europe, then shipped to Chile for installation with a total cost of $56M (2012 dollars)[42]. VISTA has a 4.02-m aperture. It does not move as fast as SST and with only a 1-degree diameter field, does not survey as fast as SST, but VISTA is also an infrared telescope thereby making it inherently more expensive to design and build.

The potential cost for any of the six systems proposed is difficult to determine without a detailed study. Here, it is only possible to apply approximate models that account for size scaling and optical complexity[43]. Based on these models, estimated system costs are provided in Exhibit 31.

System Description	Cost Range	
	Low	High
Wide-Field GEODSS Upgrade - Folded Prime Focus		$1.25M
Very Wide-Field GEODSS Upgrade - Prime Focus		$1.25M
SkyMapper Derived Cassegrain		$20M
Repurposed 1.8-m MMT Mirror	$10M	$15M
Prime Focus System with 2.0-m Hyperbolic Primary	$15M	$20M
Prime-Focus System with 2.9-m Aspheric Primary	$30M	$50M

Exhibit 31. Estimated System Costs

While there is a temptation to argue that SST was built as a military system and is therefore going to be more expensive, it is important to point out that SST was actually built more like a civilian system. The computer networks do not feature military grade security. The telescope was built and delivered without spare parts and the system was not designed to be rugged, reliable or easily maintained. In fact, the SST design requires the telescope to be largely disassembled to remove the primary mirror for recoating and the SST was built without a mirror recoating capability on site. It is also tempting to argue that the cost to produce additional copies of the SST will be lower than the development cost. This is most likely true, but public presentations suggest the replacement costs are on the order of $100M per copy. No matter what the cost, SST is complex and optically inefficient. Alternate designs are smaller, more efficient and less complex. As a result, alternate designs should be less expensive and represent a better value.

The SST represents a magnificent feat of modern optical engineering, but as a practical SSA instrument, it is less than optimal. Rather than transition the SST to an operational status at its demonstration location in New Mexico, it is being moved to Australia at an approximate cost of $20M. The Australian government will spend tens of millions of dollars to build the observatory structure and put the telescope back into operation. The SST will be located at the Harold E. Holt Naval Station on the west coast of Australia[44] at an elevation of approximately 50m. The last major state-of-the-art astronomical instrument to be installed at an elevation below 1000 feet was the giant 40-inch refractor at the Yerkes Observatory near Williams Bay Wisconsin. This occurred in 1897. During the intervening 117 years, no major instrument has been installed at so low an elevation.

SUMMARY

This paper presents a systematic look at the problem of SSA, briefly discusses the related problem of NEO search, and develops six new, practical optical approaches for ground-based optical systems. The optical approaches provide a good sampling of the potential design trade space, including options with a single mirror and two mirrors. Two systems were intended to be GEODSS upgrades. They perform extremely well for their aperture sizes but cannot approach SST-level sensitivity. Two systems were included simply to further explore the design space. The final two systems were included as serious alternatives to the SST. They demonstrate that smaller systems can compete with SST head to head, but at a much lower cost, and that a much smaller system can compete with SST when used with improved processing algorithms. The SST demonstrated an important new capability for the U.S. Air Force and also demonstrated interesting new technologies. While the SST is known to perform extremely well, it is complex, inefficient and expensive.

REFERENCES

[1] The Space Report 2013, Space Foundation, Colorado Springs, CO (2013).

[2] Result calculated from published data: SATELLITES TO BE BUILT & LAUNCHED BY 2022, WORLD MARKET SURVEY, Forecasts to 2022, 2013 Brochure, Euroconsult (2013).

[3] SATELLITES TO BE BUILT & LAUNCHED BY 2022, WORLD MARKET SURVEY, Forecasts to 2022, 2013 Brochure, Euroconsult (2013).

[4] T.S. Kelso, Analysis of the Iridium 33-Cosmos 2251 Collision, AMOS Technical Conference (2009).

[5] D.A. Kring, Chelyabinsk Air Burst, Lunar and Planetary Information Bulletin, Issue 133, USRA, May 2013.

[6] E.E. Barnard, Monthly Notices of the Royal Astronomical Society, Vol. 50, p.310 (1890).

[7] A. Franknoi, The Discovery of Pluto: Generally Unknown Aspects of the Story, PASP, Astronomy Beat, Number 23, May 18, 2009.

[8] E.J. Christensen, The Catalina Sky Survey, Lunar and Planetary Laboratory, November 2013.

[9] L. Campbell, SAO Special Report #6 (1957).

[10] J.E. Durrenberger, SPIE Journal, Vol. 2, 8th SPIE Technical Symposium, Los Angeles CA, 8 AUGUST 1963.

[11] NASA Directory of Observation Station Locations, Volume 2, November 1971.

[12] W.A. Hiltner, Stars and Stellar Systems, Volume II: Astronomical Techniques, University of Chicago Press (1962).

[13] W.J. Faccenda, GEODSS: PAST AND FUTURE IMPROVEMENTS, The MITRE Corporation (2000).

[14] NASA Directory of Observation Station Locations, Volume 2, November 1971.

[15] T.P. Grayson, Curved Focal Plane Wide Field of View Telescope Design, SPIE Vol. 4849 (2002).

[16] SST Fact Sheet, DARPA, http://darpa.mil/uploadedImages.content/our-work/TTO/programs/sst/factsheet tab fiund.jpg, accessed August 2013

[17] А.Б. Бельский, НОВЫЙ ПОДХОД К РАЗРАБОТКАМ ОПТИКО-ЭЛЕКТРОННЫХ СРЕДСТВ МОНИТОРИНГА ОКОЛОЗЕМНОГО КОСМИЧЕСКОГО ПРОСТРАНСТВА, Оптический журнал, Том 76, № 8, август 2009.

[18] I.E. Molotov, Pulkovo cooperation of optical observers-the first two years of the project PulKon, International Scientific Conference “Earth Observation space objects,” Zvenigorod (2007).

[19] R.A. Street, SuperWASP: Wide Angle Search for Planets, ASP Conference Series, Vol 294, pp. 405-408 (2003).

[20] H.T. Diehl, The Dark Energy Survey Camera (DECam), FERMILAB-CONF-11-442-AE-PPD (2011).

[21] R.G. Harrington, The 48-inch Schmidt-type Telescope at Palomar Observatory, PASP, Vol. 64, No. 381, p.275 (1952).

[22] R.A. Sampson, On correcting the field of a Newtonian telescope, Monthly Notices of the Royal Astronomical Society, Vol. 73, p.524-527 (1913).

[23] J.L. Africano, Deep-space satellite observations using the near-Earth asteroid tracking (NEAT) camera at AMOS, SPIE Vol. 4490 (2001).

[24] A. Rakich, The SkyMapper wide field telescope, SPIE Vol. 6267 (2006).

[25] SST Fact Sheet, DARPA, http://darpa.mil/uploadedImages.content/our-work/TTO/programs/sst/factsheet tab fiund.jpg, accessed August 2013

[26] R.A. Street, SuperWASP: Wide Angle Search for Planets, ASP Conference Series, Vol 294, pp. 405-408 (2003).

[27] В.Ю.Теребиж, Объектив VT-78a, http://www.terebizh.com/V.Yu.T/pictures/vt-78a/, accessed April 2014.

[28] SST Fact Sheet, DARPA, http://darpa.mil/uploadedImages.content/our-work/TTO/programs/sst/factsheet tab fiund.jpg, accessed August 2013

[29] SST Fact Sheet, DARPA, http://darpa.mil/uploadedImages.content/our-work/TTO/programs/sst/factsheet tab fiund.jpg, accessed August 2013

[30] A.E. Whitford, GROUND-BASED ASTRONOMY, A TEN-YEAR PROGRAM, National Academy of Sciences-National Research Council, Washington DC (1964).

[31] T. Blake, Utilization of a curved focal surface array in a 3.5m wide field of view telescope, AMOS Technical Conference (2013).

[32] M.R. Ackermann, Affordable Options for Ground-based, Large-aperture Optical Space Surveillance Systems, AMOS Technical Conference (2013).

[33] J.M. Beckers, The Multiple Mirror Telescope, Telescopes for the 1980s, pp. 63-1 28
Annual Reviews Inc. (1981).

[34] J.M. Beckers, The Multiple Mirror Telescope, Telescopes for the 1980s, pp. 63-1 28
Annual Reviews Inc. (1981).

[35] M.R. Ackermann, Affordable Options for Ground-based, Large-aperture Optical Space Surveillance Systems, AMOS Technical Conference (2013).

[36] M.R. Ackermann, Affordable Options for Ground-based, Large-aperture Optical Space Surveillance Systems, AMOS Technical Conference (2013).

[37] T. Brinton, DARPA Space Telescope Will Track Objects in Geostationary Orbit, Space News, April 29, 2011.

[38] RTD&E Budget Office. FY 2012-FY 2015 PE 0603285E and PE 0603287E RTD&E Budget Items for Space Surveillance Telescope. DARPA, 18 Mar. 2014.
<http://dsearch.dtic.mil/search?site=rdds&client=rdds&output=xml_no_dtd&proxystylesheet=rdds&proxycustom=%3CADVANCED/%3E>.

[39] J.C. Hall, First Light from the 4.2-meter Discovery Channel Telescope At Lowell Observatory, American Astronomical Society, AAS Meeting #221 (2013).

[40] Cost data provided by the Discovery Chanel Telescope Project (2013).

[41] J. Emerson, The Visible and Infrared Survey Telescope for Astronomy (VISTA): Looking Back at Commissioning, The Messenger, ESO, March 2010.

[42] G. van Belle, The Scaling Relationship Between Telescope Cost and Aperture Size for Very Large Telescopes, SPIE Vol. 5489 (2004). Reported in CY2003 dollars. Inflates to approximately $56M in CY2012 dollars.

[43] M.R. Ackermann, Affordable Options for Ground-based, Large-aperture Optical Space Surveillance Systems, AMOS Technical Conference (2013).

[44] United States and Australia Advance Space Partnership, Department of Defense News Release, Press Operations, Release No: 895-12, November 14, 2012.

