A 1.2m Deployable, Transportable Space Surveillance Telescope Designed to Meet AF Space Situational Awareness Needs

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ABSTRACT

Recent years have seen significant interest in optical-infrared (OIR) space surveillance capabilities to complement and supplement radar-based sensors. To address this legitimate need for OIR sensors, the Air Force Research Laboratory has been working on several projects intended to meet SSA requirements in practical, fieldable and affordable packages. In particular, while the PanStarrs system is primarily an astronomy project, their well-designed telescope(s) will have substantial SSA capability, but the system, based on four 1.8m apertures on the same mount, will be a fixed location asset. For world-wide deployment, we are studying a smaller "PanStarrs derived" system which would be replicable and inexpensive. A fixed set of telescope arrays would provide substantial SSA search and monitor capability. These telescopes are also designed to be deployed in pairs in a standard cargo container package for theater SSA.

With a 1.2m aperture and a 4.5deg FOV, each telescope would have the same étendue as its big brother PanStarrs telescope, but with image quality optimized for space surveillance rather than astronomy. The telescope is even scaled to use production PanStarrs focal plane arrays. A single 1.2m system has almost the same search rate for dim targets as any other system in development. Two such telescopes working together will exceed the performance of any SSA asset either in production or on the drawing boards. Because they are small they can be designed to be replicable and inexpensive and thus could be abandoned in place should the political climate at their deployment sites change for the worse.

1. INTRODUCTION

According to Emil Faber, "Knowledge is good." In the field of Space Situational Awareness (SSA), Emil would tell us that "more knowledge is more good." Many of the staples of modern life are enabled or significantly enhanced by space systems. Communications, entertainment, weather forecasting, agriculture, energy exploration and defense all are critically dependent upon the proper function of space systems.

The efficient use of space requires knowledge of the space environment. Satellites are fragile objects and even though "space is big," there exist a multitude of threats such as orbital debris, close passing meteoroids and even other satellites with hostile intent.

To be aware of what is in orbit, we need to monitor the space environment. This requires sensors. The space surveillance community is now searching for the appropriate suite of sensors that fully supports SSA by providing the information leading to the knowledge necessary for intelligent decision-making whether dealing with space debris, the status of a commercial satellite, or the initial moves in an attack upon the world's space assets.

Research on sensors with sensitivities ranging across the electromagnetic spectrum, active or passive illumination, space- or ground-based, and with other significant considerations also included, such as implementation and operational costs, has been addressed for years. The issue of specifying an appropriate sensor suite has been brought to a head, however, by identification of new threats for which we must prepare, and the initiation of significant funding to implement and integrate SSA.

1.1 Precepts of Space Situational Awareness

In this paper we report on a small part of our efforts to bring sense and sensibility to one small part of the evolution of SSA. There are some precepts that are worth stating:

- The sensors that support SSA will not reflect "business as usual."
    - There will be a suite of sensors including space- and ground-based instruments.
    - Radar and optical-infrared (OIR) sensors (and others) will be included.
    - Passive observations and active illumination will be enabled.
    - New sensors with new capabilities must be developed.
    - With a growing SSA grid, sensor implementation costs must reflect good benefit-to-cost ratio.
    - With a growing SSA grid, operational costs may be more important than implementation costs.
- There is a great deal to be learned and synthesized from former and current research and development with respect to synthesizing the appropriate suite of sensors.
    - There exists more than 400 years of telescope design expertise, for example.
    - NIH (not invented here) has no useful role in SSA
- Implementing secure SSA requires serious people to solve serious problems.
    - Synthesis of information from multiple sensors types in the suite should be thought out prior to or in conjunction with funding and implementing a sensor type.
    - Leadership of the SSA implementation effort requires initiating and funding competing ideas, especially ideas that could lead to new, cost-effective, robust sensors for SSA.
    - Leading SSA implementation requires that at some point the best ideas from some groups might need to be merged with the ideas of others.
    - Leading SSA implementation requires that leaders demonstrate intelligent and effective decision-making about the sensor suite to be implemented well before space surveillance data ever arrives from the sensors.

The basic issue we discuss here is that because OIR sensors will be part of the space surveillance network, it is important to design and implement sensors – telescopes – that provide useful and possibly unique information, but are cost-effective in implementation and operation.

1.2 Optical-Infrared Ground-based Surveillance of Space

The aspect of SSA we address here is OIR space surveillance. This requires a wide field of view (FOV) telescope, but does not require the ultimate in image quality, because the space debris, meteoroids and satellites we seek all move or have unique signatures. Our basic precepts are:

- Ground-based sensors are cheaper to design, build, implement and operate than space-based systems.
- Ground-based systems should be "pushed" to derive as much information as possible, leaving space-based systems to accomplish what they do best.
- Because the telescopes operate through Earth's atmosphere, individual point spread functions (PSF) will be "seeing blurred."
- The telescope optics must emphasize wide field of view while accommodating a seeing-blurred PSF of nominally 1arcsec.

Our approach is first to survey optical designs, in general, and then to select the wide-field designs that can possibly address the space surveillance mission. While there are a host of optical design parameters that must be analyzed to assess the utility of a design, for the purposes of this paper we describe the utility of a design with but two parameters. The FOV is characterized by calculating the diameter of the field at which the aberrated image degrades to 1 arcsec, and the image quality is described by the rms 80% encircled energy diameter of the images within that FOV.

The optical designs we investigated are basically all of those used or proposed for astronomical survey applications. They are best characterized by the number of mirrors in the system, because all the optical systems we considered are reflectors, almost always with refractive correctors.

The reason this exercise is important is that the number of optical surfaces represents the degrees of optical freedom in achieving the goal of a very wide FOV and adequate imaging. We thus expect telescopes with more mirrors and more refractive correcting elements to perform better in the space surveillance application. Of course, as the surface count mounts, so do fabrication costs and often operational costs to keep more complicated optical systems aligned and functioning. In addition, optical design remains something of an art. Some design families achieve excellent wide-field capability with relatively few elements, while other families provide surprisingly good images. Balancing wide FOV, pretty good images, operational complexity and total cost is at the heart of our investigation.

Some global precepts will apply to all the designs we considered. Firstly, because we specify a wide FOV, the secondary obscurations in these telescopes will be large, typically 30% - 35% by area. Secondly, for application to SSA, we can trade image quality for field of view because there is no need to multiply sample the final point spread function. Considering that atmospheric seeing conditions at many locations are typically one arcsecond, exquisite optical aberration correction is not necessary. Optics producing spot diagrams on the order of 1 arcsec diameter will usually be sufficient.

Finally, the étendue and throughput of small telescopes can rival that of large telescopes. The implication is that for fixed dollars, we should invest in many small telescopes rather than a few large ones.

Thus, even with the impending demonstration of the DARPA 3.5m Space Surveillance Telescope (DSST), it is not clear that this is the instrument the Air Force or the nation needs as a prototypical SSA sensor. It is very large and expensive and requires a fixed facility with substantial infrastructure. To monitor global activity, the Air Force would require four or five more such systems. This represents a huge investment and it is not clear that this approach is best.

1.3 <u>An Alternative Consideration of OIR Space Surveillance</u>

Our research drives us to present an alternate approach. We believe that the Air Force mission of SSA requires a modest number of small, transportable OIR SSA observatories. These telescopes have greater information generation capability than fewer large telescopes, plus they are mobile and are more nearly "field instruments." They could be located around the world in friendly places and moved if necessary. With the correct choice of telescope design, each such observatory could exceed the performance of the DARPA SST at a fraction of the cost, could be strategically located or tactically relocated, and result in more information and more knowledge. Rather than being locked into fixed facilities, transportable SSA assets make more sense.

In this paper we present results of a study examining what type of OIR system(s) should be adopted for a transportable SSA observatory.

2. BACKGROUND

Ever since the former Soviet Union launched the first artificial satellite, Sputnik, on 4 October 1957, it has been important to know what is orbiting the earth, its operational characteristics and status, where it is and what parts of the planet it will pass over next. This has come to be known as Space Situational Awareness or SSA.

2.1 <u>The Tools of Space Situational Awareness</u>

Over the past 50 years, a number of tools and techniques for monitoring earth-orbiting satellites have been developed and experienced gradual evolutionary improvement. These tools consist of two basic systems; radar for monitoring low earth orbit, and optical systems for monitoring higher orbits. The details of these systems are beyond the scope of this paper but an excellent discussion of the overall Space Surveillance Network (SSN) can be found in the text by Vallado [1].

The topic of this paper is that of improved tools for optical-infrared (OIR) SSA. At present, this is principally accomplished by the three sites making up the GEODSS [2] network and the Morón Optical Surveillance System (MOSS) located at Morón Air Base Spain [3]. MOSS is the newest of the assets but the smallest in aperture. The GEODSS network is relatively old and somewhat limited in capability. It has been substantially upgraded over the years, but the current environment requires a very significant increase in capability over the present, and achieving such an increase will require new optical and detector systems.

2.2 <u>The Perception of Need</u>

Over the past 50 years, a number of trends have evolved which have conspired to make the SSA problem significantly more difficult. Not all these will be discussed here and not all are important to the subject of this paper. The most significant of the trends however have a direct impact on present considerations.

The first trend is that of an ever increasing number of space launches and the continuing accumulation of space debris. Every piece of space debris needs to be detected, tracked and cataloged. Each piece is important because of the damage it can cause to operational space systems. At the present time, something on the order of 8,000 pieces of space debris are actively tracked, but the true number of derelict space objects is much higher. Items as small as a chip of paint can cause significant damage to space systems [4], but nothing this small can be tracked or even detected.

The second trend is that some space systems have become smaller. In the past, electronics were bulky and required significant power, and the only way to make a satellite with any significant capability was to make it large. This required large launch vehicles which made venturing into space the purview of wealthy countries. Today microelectronics are extremely compact and capable with relatively low power consumption. Very capable low earth orbit systems are being developed by universities and are no larger than a shoe box. As the trend continues, it is anticipated that a significant number of small satellites will populate the skies making detection and tracking more difficult.

Another trend has to do with the types of detection and tracking systems making up the SSN and how they have evolved. Historically, new approaches to SSA sensor systems have been limited and at times viewed as competitive rather than complementary. This resulted in a basic two sensor family approach to SSA architecture which has a number of limitations that have slowly come to be viewed as significant.

Radar systems are very large and expensive to upgrade and operate. They are used for detection and tracking of objects in LEO but due to power limitations have a lower bound on the size of objects which can be tracked and an upper bound on the maximum altitude at which they are effective. Unfortunately, these systems, while very capable, are large, often fixed, high-value assets which begin to appear as questionable investments when faced with a multitude of realistic asymmetric threats.

For high orbit objects, optical techniques are used. The principal method is optical change detection where one images a patch of sky several times and looks for what has moved. To guarantee all objects with certain orbital parameters will be imaged, detected and tracked, a leak-proof search strategy is required. Key elements of this strategy are the instantaneous area coverage of a single image frame, integration time for each frame and the time required to move from one location on the sky to another. At present, it is thought that the GEODSS system is not capable of detecting and tracking faint, small objects in GEO or HEO with a leak-proof optical fence. Hence, there exists the perception that a new system to replace GEODSS is required.

In addition to limitations of GEODSS, there are other “holes” in the SSA approach. There are no dedicated OIR systems to perform a blind search for dim objects in LEO. With all the arguments regarding the prowess of radar systems not withstanding, there remains the need for optical systems to augment, complement, and when necessary, substitute for radar systems. A properly designed OIR system has the advantage of being much smaller, less expensive and easier to locate in remote parts of the world.

Another problem with the current system of systems is the possible lack of capability to detect and track objects in geosynchronous transfer orbits (GTOs). Objects in GTOs are usually moving too fast to appear in a detectable

Doppler bin for radar systems, and too fast for GEO and HEO leak-proof search strategies to guarantee detection. This often results in objects unexpectedly appearing in GEO.

2.3 A Possible Solution

Since 2003, the Air Force has studied the problem of optical SSA under a program known as the Air Force Space Surveillance Telescope (AFSST) [5]. AFSST was never envisioned to be a single telescope or even a small constellation of large and expensive telescopes. Rather, the AFSST study was an effort to look at what types of optical systems were required world-wide to provide an OIR-only SSA capability for space objects in all types of orbits. The problem of blind satellite detection and tracking at LEO is much more difficult than for higher altitudes and therefore requires different approaches, hence the idea of a system of highly replicable telescopes rather than one large, complicated, expensive design replicated only a few times around the world.

The overall problem of optical SSA is too large for a complete discussion in this paper. Therefore, we limit ourselves to the simpler problem of optical systems for detecting and tracking satellites in high orbits. This is the task presently assigned to the GEODSS network and the problem addressed by the DARPA Space Surveillance Telescope (DSST) [2, 6-7]. Because this is a well-defined optical system, we compare search rates for our alternative sensors to the DSST "baseline" telescope, a proxy for which is discussed by Ackermann and McGraw [10].

Recognizing that the GEODSS network cannot meet all the demands of providing the SSA required for both civilian and military space operations, DARPA initiated their Space Surveillance Telescope (DSST) project. Cost-performance concerns with the DSST project have been expressed numerous times, but the project persists on a path which will provide a measured improvement in capability at a very significant price [8-10]. The most significant concerns with the DSST are that it is a large, extremely expensive, fixed facility; that it includes questionable design choices which limit its capability; and that it can easily be replaced with a modest number of smaller and far less expensive systems [10].

The alternative to the DSST approach is smaller aperture systems which can easily be transported to any friendly location on earth. Here we consider systems with apertures in the range of 1.0m to roughly 1.5m. Telescopes of this size could be designed into transportable containers and shipped, trucked or flown to remote locations when required. If built sufficiently inexpensively, many copies could be purchased and put into operation thereby improving world-wide coverage. Also, if sufficiently inexpensive, the systems could be relocated, abandoned or destroyed in place if the political climate at the deployment location were to change.

In between these two extremes lie a number of civilian astronomical facilities which could be replicated and used for SSA, if necessary. They would still have the disadvantage of being fixed facilities, but having been built by civilian astronomers (on a budget), they are likely to be much less expensive than the DSST. Examples of extremely capable civilian astronomical projects include PanStarrs [11], the Dark Energy Survey [12], the Discovery Channel Telescope (DCT) with prime focus corrector (PFC) [13], and the Large Synoptic Survey Telescope (LSST) [14].

2.4 The Search for a Better Solution

Small aperture telescopes are very attractive from a cost and size point of view but cannot be serious contenders unless their search rate and sensitivity are in some way comparable to the larger telescopes. Fortunately, a number of studies have shown that small telescopes with very wide fields of view are in many cases more capable than larger telescopes. For fainter targets, in the 18 to 21 visual magnitude range, two or more small telescopes can share the observational task and equal the performance of a single larger telescope at a fraction of the total cost. This approach is that adopted by the PanStarrs project with the single exception that the eventual four-aperture PanStarrs system will have all telescopes in a common mount. The approach proposed here is to have one telescope complement the next by observing a different patch of sky. In this way, the longer integration time required for the smaller scope on each patch of sky is more than offset by having two or more large patches of sky imaged at the same time. This approach is developed in references [8-10,15]. Also, a recent paper by MIT Lincoln Laboratories explores the same concept, but they examined small telescopes (0.6m aperture) to augment the larger telescopes rather than replace them [16]. Their analysis clearly shows that smaller aperture and wider FOV systems have significant application to the SSA problem. Here we propose slightly larger apertures (1.0m to 1.5m) with very wide fields and transportable observatories in an effort to completely replace large and overly expensive fixed-site SSA telescopes.

3. DESIGN OPTIONS

Throughout the remainder of this paper, for comparative consistency we consider only designs with an aperture of 1.2m. This was selected somewhat arbitrarily by simply scaling the PanStarrs optical design by two thirds. This aperture is, however, well within the range of 1.0m to 1.5m discussed above. For the purposes of this paper, we have simplified the problem of comparing multiple parameters for these systems by reporting the angular field of view (in degrees) and the angular diameter of the point spread function (in arcsec) encircling 80% of the energy.

3.1 One Mirror Approaches

There are no known single mirror catoptic solutions providing high image quality over a wide image field. Correction of aberrations requires a low-power refractive group known as a prime focus corrector (PFC). Depending upon the application, these can range from two lenses with all spherical surfaces to as many as seven elements with one to four surfaces of conic or aspheric figure. Image quality is a complex function of the focal ratio and surface contour of the mirror, the maximum diameter of the lenses relative to the diameter of the mirror, chromatic bandwidth and field of view. Typical examples of state-of-the-art prime focus correction are provided by the DCT PFC [13] and the DES PFC [12]. Figs. 1-3 show the optical design for prime focus correctors considered for this study.

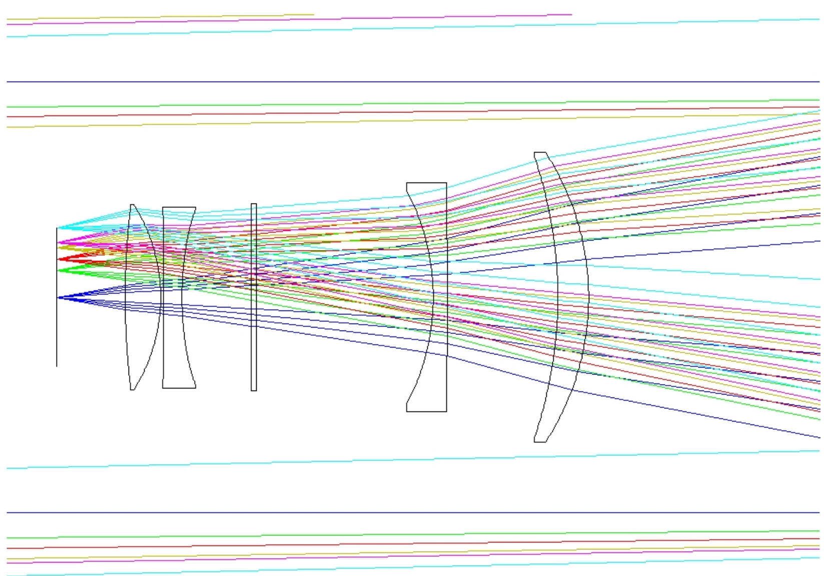

Fig. 1. 4 lens (3 asphere) prime focus corrector SST
producing 1 arcsec spots over a 2.5deg field at f=2.85.

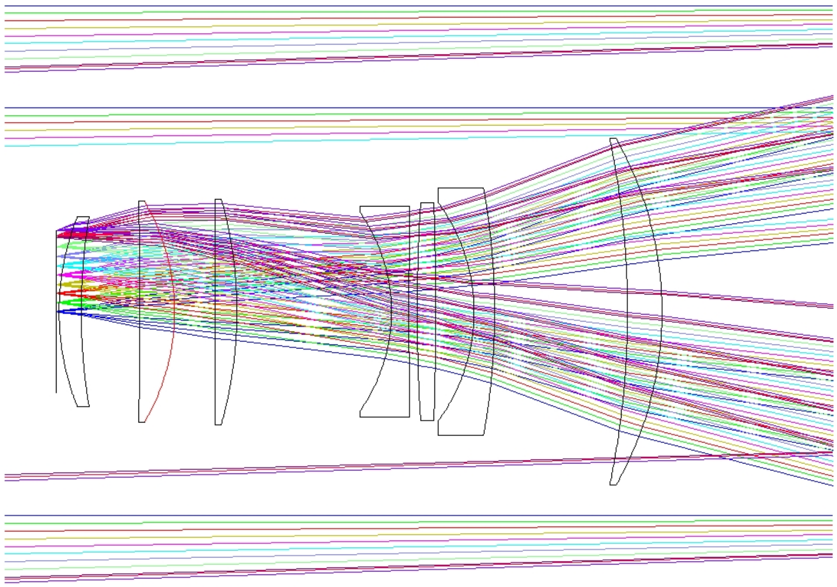

Fig. 2. 7 lens (4 asphere) prime focus corrector SST
producing 0.8 arcsec spots over a 3.5deg field at f=2.54.

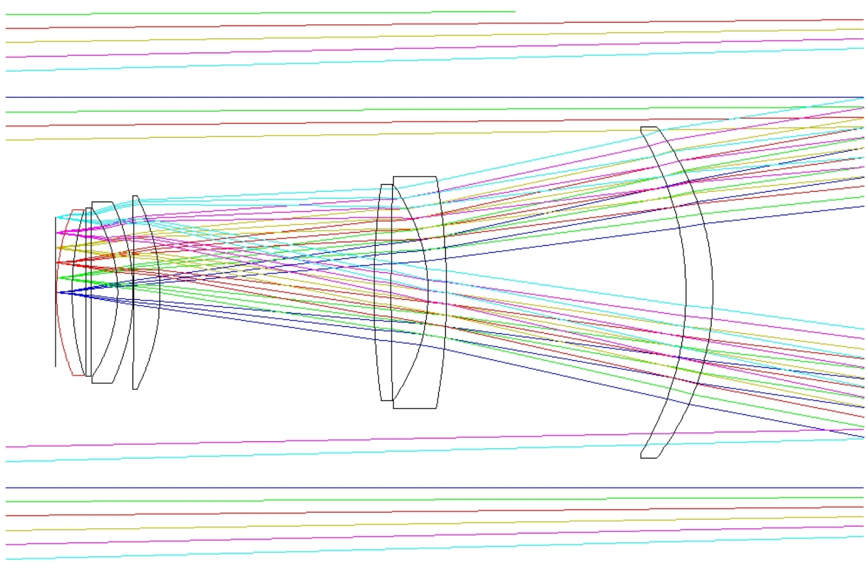

Fig. 3. 6 lens (all spherical) prime focus corrector SST
producing 0.85 arcsec spots over a 3.0deg field at f=2.9.
(Modification of design by Terebizh [17])

Catadioptric systems with full aperture refractive correctors frequently have extremely wide fields of view but usually have curved focal surfaces. Designs such as the Schmidt, Maksotov, Richter-Slevogt, and Baker-Nunn are excellent examples. Attempts to flatten the focal surface normally result in narrower fields or degradation in image quality. The Automated Patrol Telescope at the University of New South Wales in Australia is an example of a flattened Baker-Nunn [18]. Image quality is respectable but the field was narrowed to roughly 5deg. The Phoenix telescope on Maui is another example of a flattened Baker-Nunn. Phoenix has a much wider field but image quality is unknown [19]. Generally, such systems have tube lengths on the order of twice the focal length, making them physically very long.

3.2 Two Mirror Approaches

Several two-mirror wide field configurations were analyzed. The two-mirror systems tested were dominated by various realizations of the ubiquitous Ritchey-Chrétien design. The classical Ritchey-Chrétien design optimizes a two-mirror system for wide-field performance by using hyperbolic figures on the primary and secondary. In general, these systems perform well for the space surveillance task.

3.2.1 Folded Prime Focus Corrector

One option for reducing the length of prime focus systems is to include a fold mirror which can be flat or of a flat aspheric figure. The disadvantage is that the fold mirror necessarily increases obscuration. Examples of folded PFC systems include ROTSE [20] and the University of Arizona SpaceWatch system [21]. Because performance is generally similar to the PFC systems discussed above, no examples are presented here.

3.2.2 Field-Corrected Schwarzchild Aplanats

Two forms of these aplanats were analyzed, the famous Ritchey-Chrétien form and the much less well known Couder form.

3.2.2.1 Ritchey-Chrétien Form

The classic Ritchey-Chrétien (RC) and the modified quasi- or super-RC variants are known for producing wide field images. Modifications of the RC form were selected for several recent wide-field survey telescopes including the VST [22], PanStarrs [11], and the SkyMapper project [23].

A number of RC variants were considered for this study. Most were of the super-RC form where the mirrors had both conic and general aspheric corrections. Refractive field correctors ranged from simple three lens designs to systems with up to five lenses. Sample designs with general aspheric mirrors are shown in Figs. 4-7.

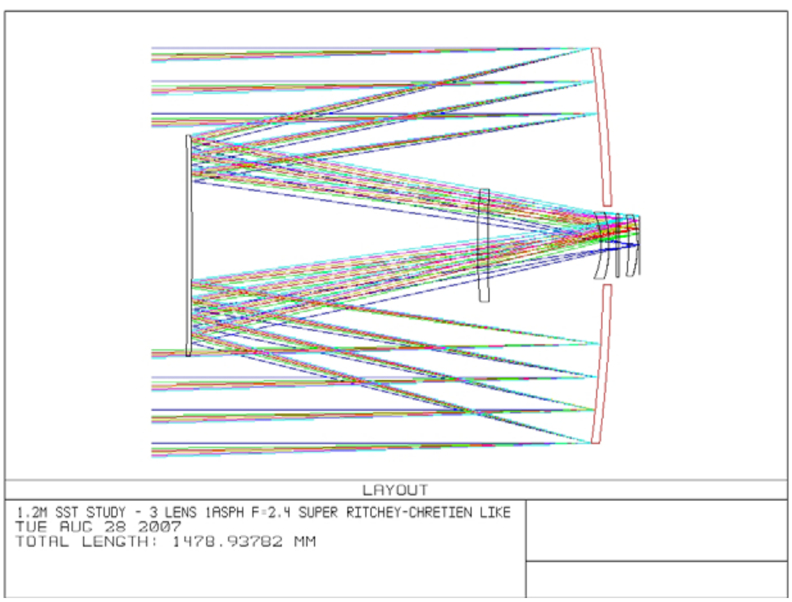

Fig. 4. 3 lens (1 asphere) corrector for Super-RC SST producing 0.8 arcsec spots over a 3.5deg field at f=2.4.

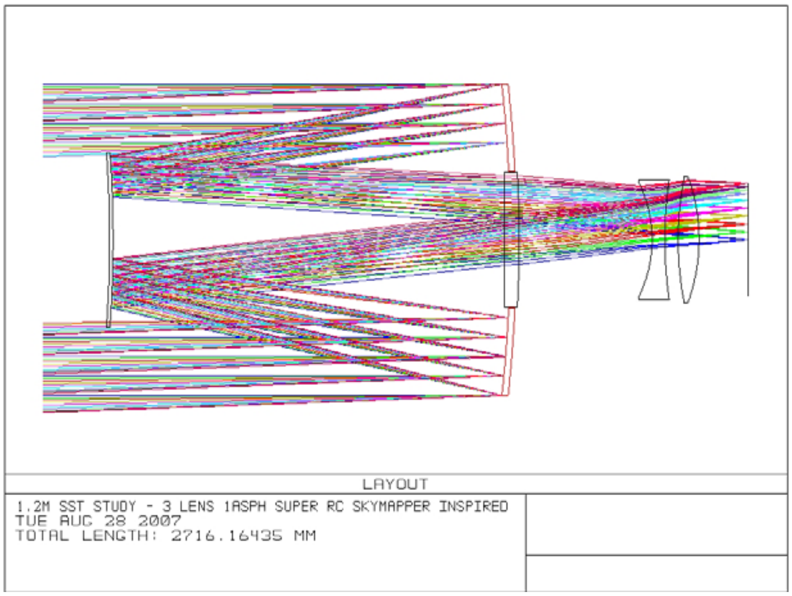

Fig. 5. 3 lens (1 asphere) corrector for Super-RC SST
(designed after the SkyMapper survey telescope)
producing 0.63 arcsec spots over a 4.3deg field at f=4.8.

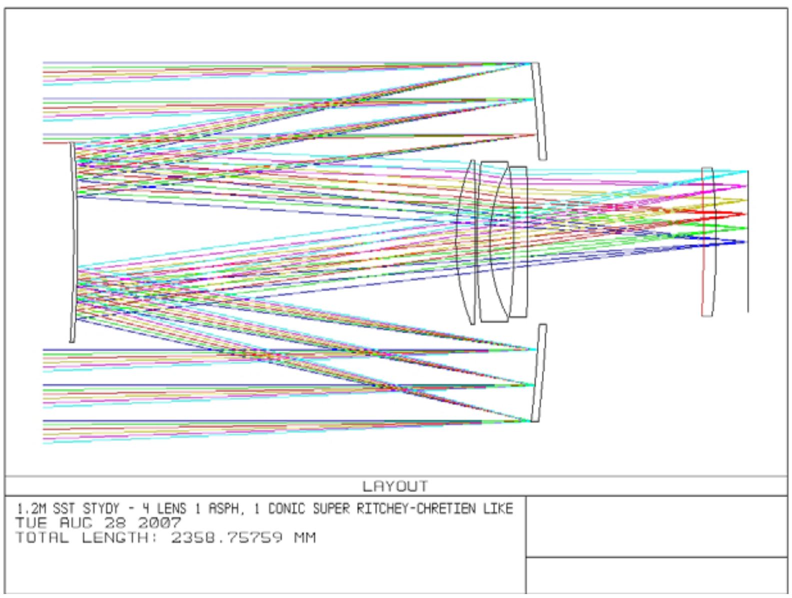

Fig. 6. 4 lens (2 asphere) corrector for Super-RC SST
producing 0.74 arcsec spots over a 5.0deg field at f=4.44.

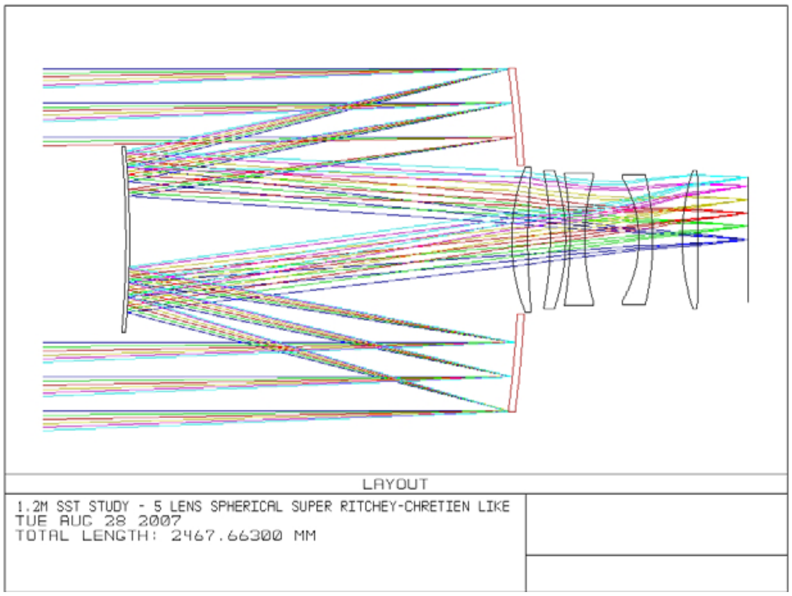

Fig. 7. 5 lens (all spherical) corrector for Super-RC SST
producing 0.84 arcsec spots over a 4.65deg field at f=4.44.

In addition to super RC designs with general aspheric mirrors, two designs were examined with simple conic mirrors. These are considered classic RC systems even though the curvatures and conic constants will not allow the telescopes to perform without the corrector lenses. Examples are shown in Figs. 8 and 9. Fig. 8 is particularly interesting because nearly identical performance was obtained with the simple conic mirrors as for the super-RC design shown in Fig. 5. The simple RC design resulted in a significant change in the lens shape, but overall performance was maintained. The reason for pursuing the classic RC designs is that it was thought alignment and fabrication would be easier.

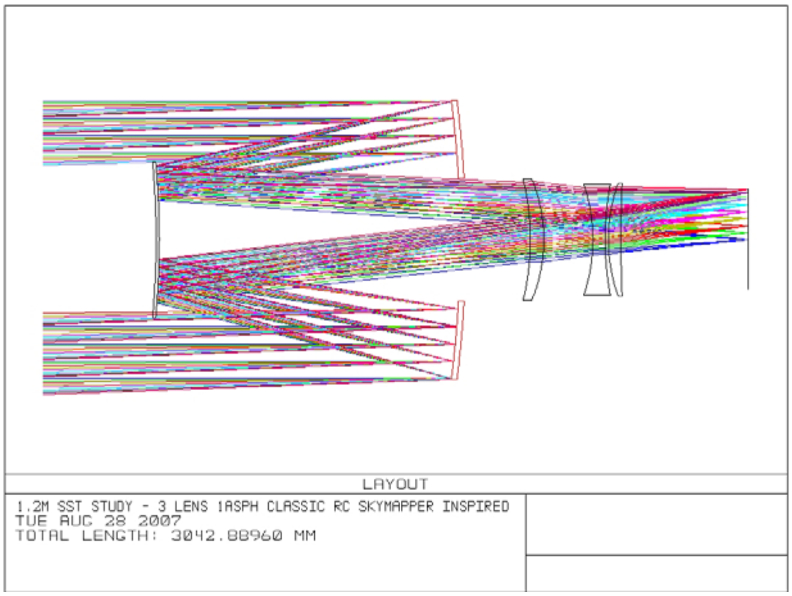

Fig. 8. 3 lens (1 asphere) corrector for classic-RC SST
(designed after the SkyMapper survey telescope)
producing 0.63 arcsec spots over a 4.3deg field at f=4.8.

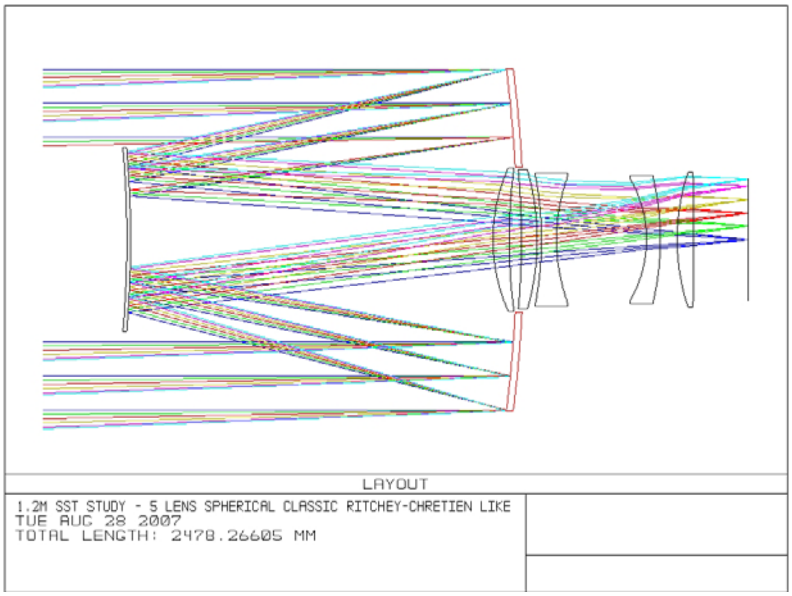

Fig. 9. 5 lens (all spherical) corrector for classic-RC SST producing 0.87 arcsec spots over a 4.5deg field at f=4.44.

3.2.2.2 <u>Couder Form</u>

The Couder is the least known of the Schwarzchild aplanats. When encountered, people often think one has accidentally misspelled coudé. It is known that DARPA investigated the Couder at one point before selecting their current Paul-Willstrop design, but discarded the Couder because it was "really long and wants to stay that way [24]." The Couder can, however, be made short, if necessary, and the field flattened at the same time. Fig. 10 shows the layout for a very short, wide-field Couder examined as part of this study.

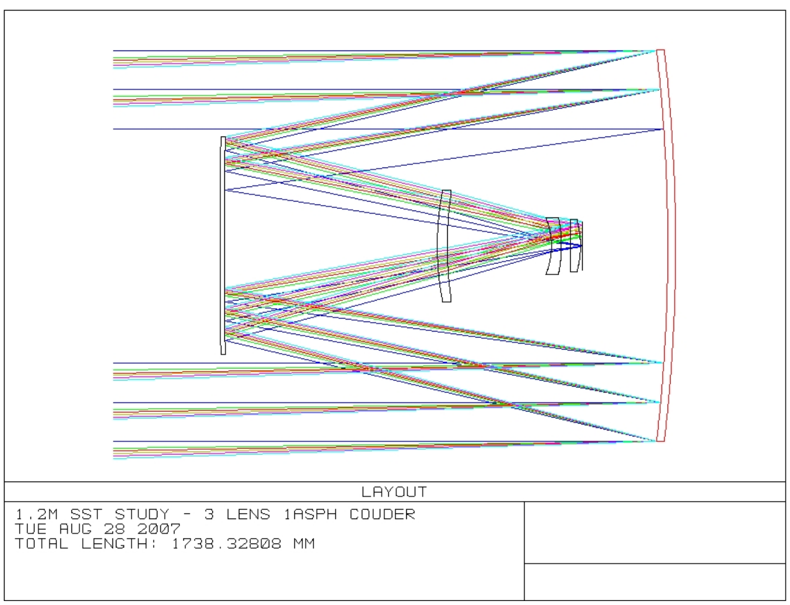

Fig. 10. 3 lens (1 asphere) corrector for Couder SST producing 1 arcsec spots over a 3.5deg field at f=2.0.

3.2.3 Two-Mirror, Three-Reflection Systems

An unusual category of two mirror telescopes are those where the primary mirror is used twice. These are sometimes known as two mirror three reflection telescopes (2M3RT) and other times are referred to as modified Paul designs. The true 2M3RT has one figure on the primary and uses it as both the primary and secondary. There are telescope designs which advertise two mirrors and three reflections but figure the primary with an inner and outer zone, thereby producing a three mirror system where the primary and tertiary are monolithic [25]. Here we consider only the true 2M3RT design. Fig. 11 shows one such design with a four lens corrector. Other designs feature from three to five lenses with one or more aspheric surfaces.

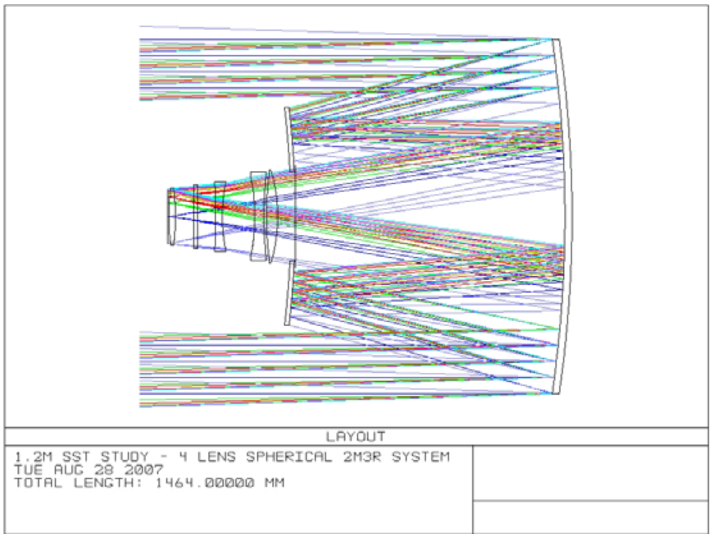

Fig. 11. 4 lens (all spherical) corrector for two mirror three reflection SST producing 0.68 arcsec spots over a 3.5deg field at f=2.5.

3.3 Three Mirror Approaches

While there exists a number of unusual three mirror optical telescope designs, the only one given serious consideration here is the basic Paul layout. We examined three mirror systems with focal ratios ranging from f=1.0 to f=2.0, all with flat focal planes. Examples are seen in Figs. 12-15.

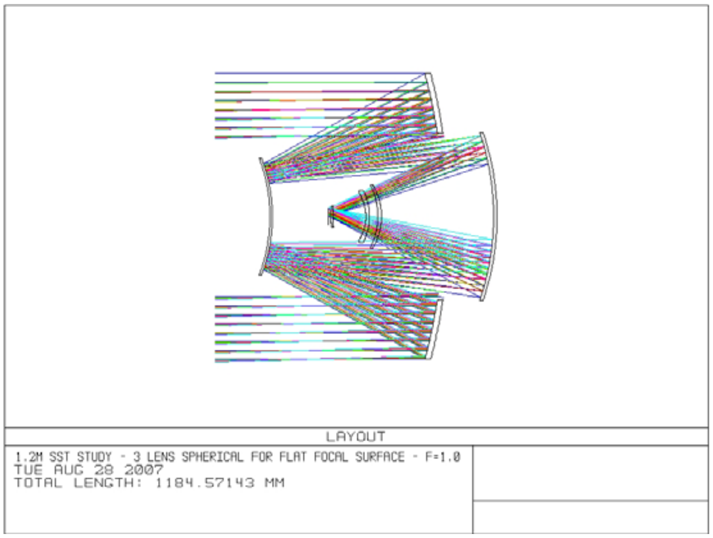

Fig. 12. 3 lens (all spherical) corrector for Paul-type SST producing 0.65 arcsec spots over a 3.5deg field at f=1.0.

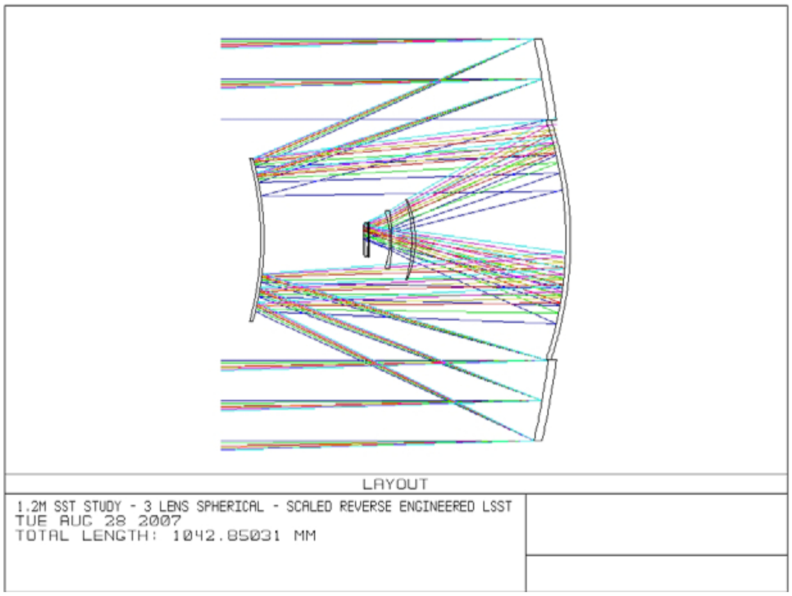

Fig. 13. 3 lens (all spherical) corrector for Paul-type SST producing 0.49 arcsec spots over a 3.5deg field at f=1.25.

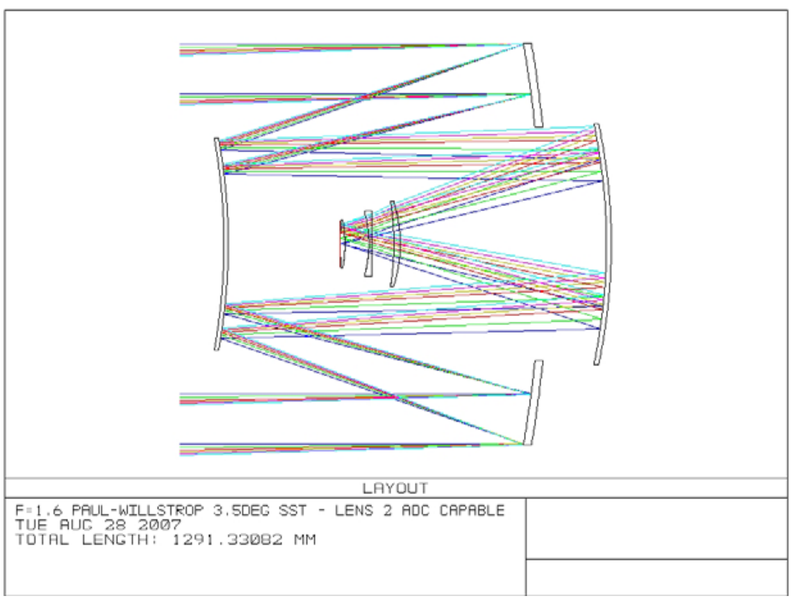

Fig. 14. 3 lens (all spherical) corrector for Paul-type SST producing 0.95 arcsec spots over a 3.5deg field at f=1.6. Lens 2 in this design is plano concave and could be used as a tip-tilt type atmospheric dispersion compensator.

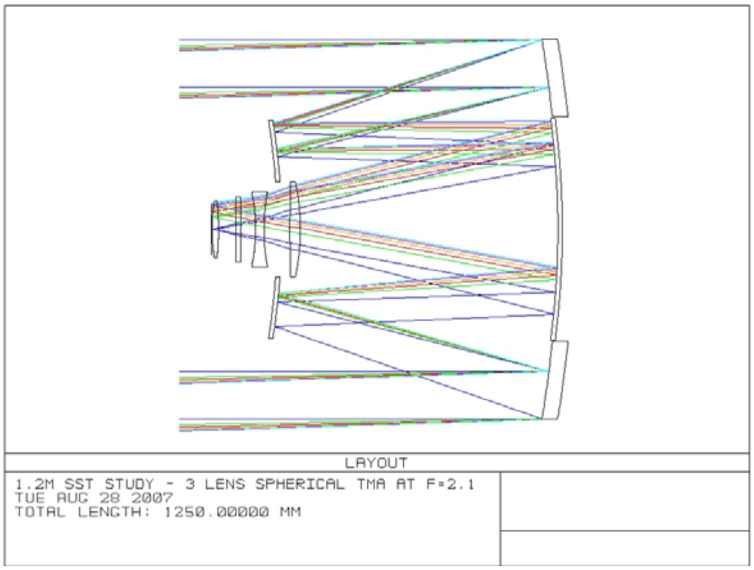

Fig. 15. 3 lens (all spherical) corrector for Paul-type SST producing 0.85 arcsec spots over a 3.62deg field at f=2.1.

3.4 Four Mirror Approaches

Four mirror axially symmetric optical designs are capable of very wide-fields with flat image surfaces, but generally suffer from complex aspheric surfaces and significant obscuration. The design performs extremely well and is capable of scaling to much larger apertures. The greatest problem with the four mirror design is that it will produce pristine images without refractive correctors. Introducing the necessary dewar window and possibly an optical bandpass filter tends to destroy image quality. The design shown in Fig. 16 features a thin aspheric plate as the dewar window and no other refractive components.

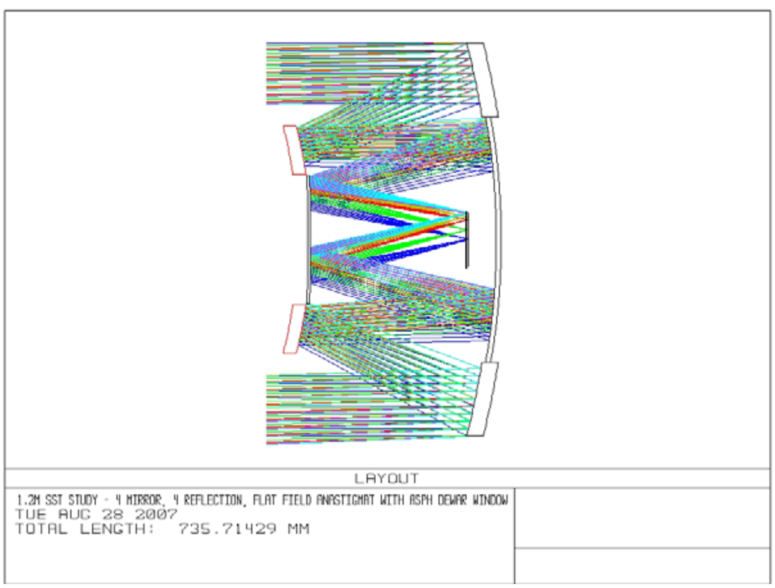

Fig. 16. Single aspheric plate dewar window on four mirror, four reflection SST producing 0.85 arcsec spots over a 4.1deg field at f=1.89.

4. PERFORMANCE OF SELECTED DESIGNS

Figs. 1-16 present sixteen out of more than thirty designs considered for a small aperture space surveillance telescope. While the optical search rate for each was calculated for comparison against other designs, none of those data are presented here because there are simply too many designs to consider.

Some of the designs need to be set aside as they simply are too complicated or would be expensive to fabricate and difficult to align and operate. Some of the designs are set aside because they are simply too close to other designs which were kept. Still other designs were set aside even though they remain very interesting. For example, the PFC design in Fig. 3 is extremely capable and incorporates an all-spherical corrector, making it less expensive to build and easier to align than competing designs. It might be useful for a larger telescope, but in the 1.2m aperture range, many of the RC-type systems offer a wider field with a more compact overall system.

To keep the analysis tractable, from this point forward we limit ourselves to consideration of only four systems. Three systems are in one form or another RC type Cassegrains with wide-field refractive correctors. The fourth system is a new design with an all-spherical corrector. It is currently being evaluated for performance *versus* ease of manufacture and alignment.

The designs will be compared with one another in terms of their sky search rate computed as a function of target visual magnitude. Details of the calculation technique are presented elsewhere [10]. What is important to note here is that all systems were calculated with similar input data.

For comparison purposes, performance calculations will include the approximated search rate for the DARPA SST [6]. These values were derived from unclassified, unlimited release information regarding the DARPA project. Additional details are available elsewhere [10].

4.1 <u>The Designs</u>

Four systems of more than 30 analyzed appear to provide wide FOV with acceptable image quality and an optical design that supports inexpensive fabrication, replication and robust field operation. These four systems are described here.

4.1.1 <u>5.0deg, 4 Lens Super RC</u>

This is the design seen in Fig. 6. The primary and secondary mirrors are aspheric with both conic constants and higher order corrections. The obscuration ratio is 32% (by area). The corrector is all of fused silica and includes two aspheric surfaces. Image performance is exceptional considering the field, but alignment will not be trivial. This design is thought to be somewhat expensive to manufacture and test relative to its aperture.

4.1.2 <u>4.5deg, 5 Lens Simple RC</u>

This is the design seen in Fig. 9. The primary and secondary mirrors are simple conics. The obscuration ratio is 29.5% (by area). The corrector is all of fused silica and all surfaces are spherical. Image performance is extremely good considering the field and alignment should be no more difficult than a classic RC. This design is thought to be inexpensive to manufacture and test.

4.1.3 <u>4.3deg, 3 Lens SkyMapper Derived RC</u>

This design was loosely based on that of the SkyMapper survey telescope [23]. While the detailed SkyMapper design has not been published, sufficient information is available to follow the basic approach. It appears to be an unusual and very effective variant of the traditional RC Cassegrain. While SkyMapper itself was designed for a 3.4deg field, we were able to push the design to 4.3deg and maintain excellent performance.

Strangely enough, the same performance is achieved by designs shown in both Figs. 5 and 8. The design in Fig. 5 has more complicated mirror surfaces with both conic and higher order corrections. Therefore we continue here with the design seen in Fig. 8. This optical system features simple conic mirrors. The obscuration ratio is 31.5%

(by area). The corrector is all of fused silica and has only one aspheric surface. Overall this design is thought to be slightly more difficult than the 4.5deg design but cost about the same because it has two fewer lenses.

4.1.4 <u>5.3deg, New Design with All Spherical Corrector</u>

This is a relatively new design being pursued specifically for its ease of manufacture. The current design produces 1.3arcsec diameter image spots over a 5.3deg field with obscuration less than 35%. The design contains more than one type of glass but great care was taken to avoid exotic and expensive materials in the corrector.

4.2 Performance

Performance is compared in terms of search rate *versus* visual magnitude. All calculations assumed a 6:1 signal to noise ratio. CCD quantum efficiency was 85% for all systems except the notional DARPA clone which used a value of 75%. All systems were assumed to have a single frame area equal to that of a hexagon inscribed within the light circle with the exception of the notional DARPA clone which used an inscribed rectangular array with an area of 5.8 square degrees. All systems were assumed to slew at a rate of three degrees per second and require two seconds to settle. All calculations assumed a series of three images in a given location before moving on. All calculations assumed a sky brightness of 18^{th} magnitude per square arcsec. All calculations assumed CCD pixel size was approximately matched to the PSF but that the image spot falls on the corner joining four pixels (worst case).

Calculated performance is seen in Figs. 17-19. All figures contain the same data but have their scales changed to emphasize fainter magnitudes. The last trace listed in the legend in each figure is the calculated search rate if two of the 5.3deg all spherical telescopes were working together.

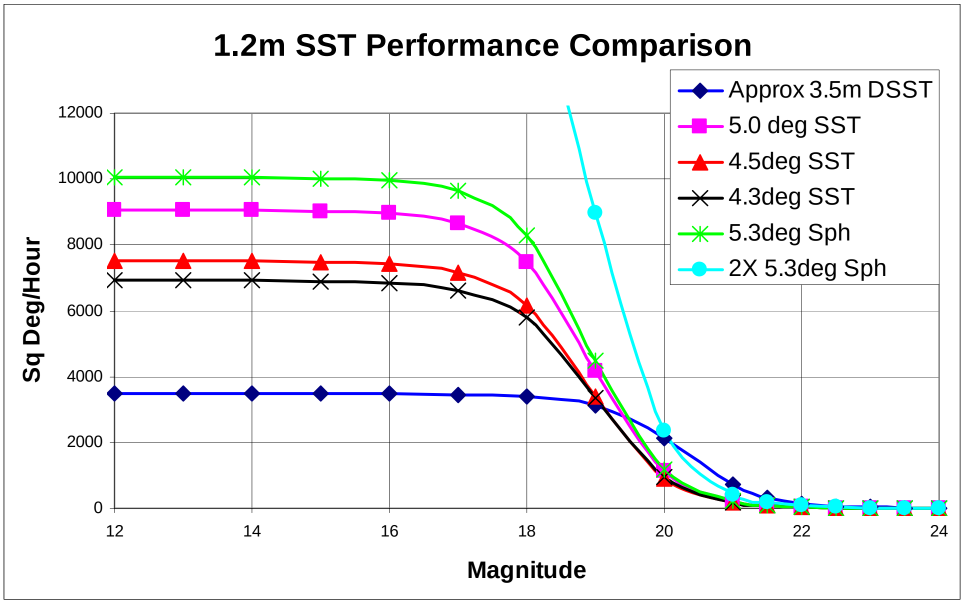

Fig. 17. Calculated performance for the various 1.2m SSTs.

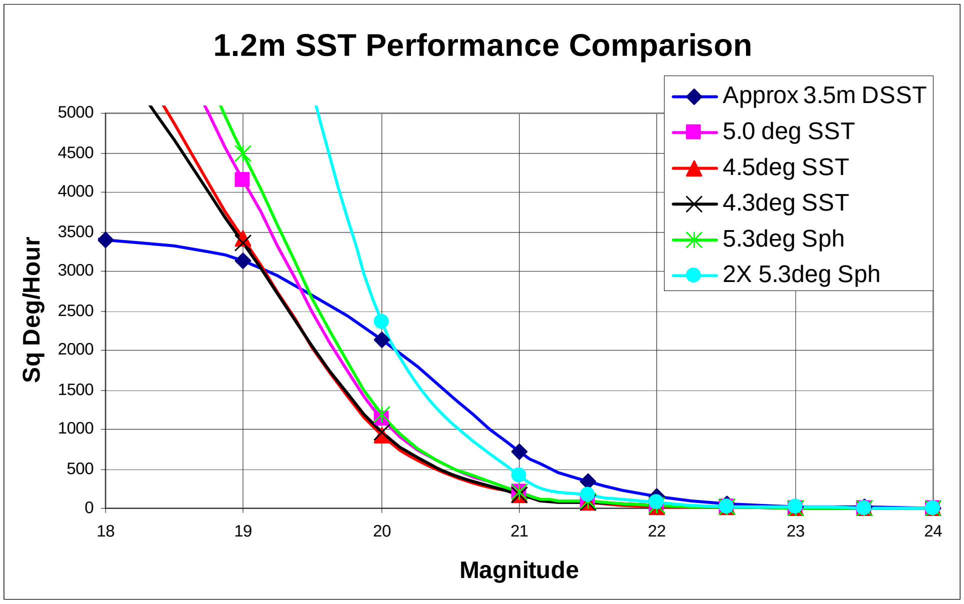

Fig. 18. Calculated performance for the various 1.2m SSTs.

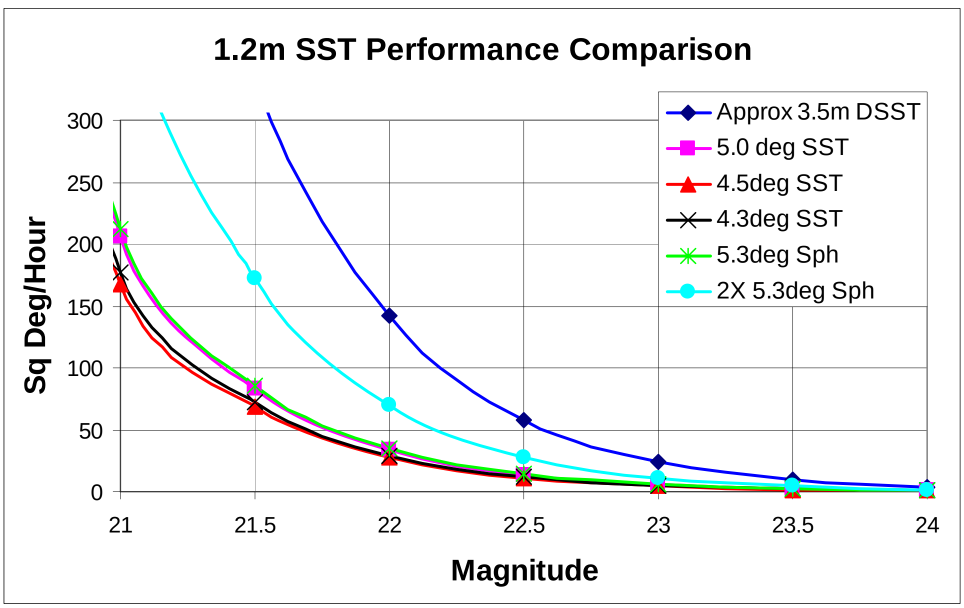

Fig. 19. Calculated performance for the various 1.2m SSTs.

Calculated performance data clearly show that for bright targets, all of the various 1.2m SST concepts have exceptional search rate. For objects fainter than roughly magnitude 19.5, all of the smaller telescopes are exceeded by the larger 3.5m system. At some point, there is no substitute for aperture. It is, however, possible to use multiple smaller systems to equal or exceed the performance of the larger telescope at all magnitudes. Even if four of the 5.3deg systems were required, their cost would still be substantially less than a single 3.5m telescope.

5. SUMMARY

We have examined a substantial number of telescope optical designs with the hope of finding an ideal design for a modest aperture space surveillance telescope. The goal was to show that small telescopes which can be relatively inexpensive, have sufficient performance that they could be considered as serious alternatives to proposed expensive, fixed-site, 3.5m aperture systems.

The 1.2m aperture systems perform extremely well, trading aperture for sky coverage. The significant advantage of the 1.2m systems is that they can be engineered into transportable containers which can be shipped, flown or trucked to remote locations everywhere, thereby providing an affordable world-wide network. Being transportable, the systems could be moved if the political climate changes, or if there is a greater need for their capability at another location. Also, being inexpensive, the systems could be abandoned or destroyed if necessary without significant loss.

Designs for three telescopes with 1.2m aperture and fields in excess of four degrees across were presented and analyzed. Each design has its advantages, but the widest field system had the highest calculated performance. An interesting 5.3deg field system with spherical corrector was also considered. That telescope has lower image quality but is still capable of very high search rates. Having an all spherical corrector, this telescope would be significantly less expensive to build, test and align than any of the others considered to date.

6. REFERENCES

[1] Vallado, D.A., Fundamentals of astrodynamics and applications, Microcosm Press, 2001.

[2] US Air Force Fact Sheet, Ground-Based Electro-Optical Deep-Space Surveillance, http://www.af.mil/factsheets/factsheet.asp?fsID=170

[3] US Air Force Fact Sheet, Morón Optical Space Surveillance (MOSS) System, http://www.peterson.af.mil/library/factsheets/factsheet.asp?id=4742

[4] Gutierrez, Sidney M., US Astronaut, personal communication.

[5] McGraw, J.T., Ackermann, M.R., Air Force Space Surveillance Telescope: Final Report, AFRL-DE-PS-TR-2007-1074, final report for contract FA9451-04-C-0203, University of New Mexico, 2007.

[6] Space Surveillance Telescope, DARPA Tactical Technology Office, http://www.darpa.mil/tto/programs/sst.htm

[7] Grayson, T.P., Curved Focal Plane Wide Field of View Telescope Design, SPIE Vol. 4849, page 269, 2002.

[8] McGraw, John T., Ackermann, Mark R., Martin, Jeffrey B., Zimmer, Peter C., The Air Force Space Surveillance Telescope, Proceedings of the 2003 AMOS Technical Conference, also published as Report No.: SAND2003-3226C, Sandia National Laboratories, Albuquerque, NM (USA), September 2003.

[9] Ackermann, M. R., McGraw, J. T., Zimmer, P. C., Golden, E., Optical Design Trade Space for the Air Force Space Surveillance Telescope, Proceedings of the 2005 AMOS Technical Conference, September 2005.

[10] Ackermann, M.R., McGraw, J.T., Large-Aperture, Three-Mirror Telescopes for Near-Earth Space Surveillance: A Look from the Outside In, presented at the 2007 AMOS Technical Conference, to be published in the proceedings of the 2007 AMOS Technical Conference.

[11] PanStarrs Telescope Project website, http://pan-starrs.ifa.hawaii.edu/public/home.html

[12] The Dark Energy Survey Project website, http://decam.fnal.gov/.

[13] Discovery Channel Telescope Project website, http://www.lowell.edu/dct/

[14] LSST Project website, http://www.lsst.org/lsst_home.shtml

[15] Ackermann, Mark R., McGraw, John T., Martin, Jeffrey B., Zimmer, Peter C., Blind Search for Micro Satellites in LEO: Optical Signatures and Search Strategies, Proceedings of the 2003 AMOS Technical Conference, also published as Report No.: SAND2003-3225C, Sandia National Laboratories, Albuquerque, NM (USA), September 2003.

[16] Lambour, R., Pearce, E., Ferner, S., Rork, E., Trujillo, P., Decew, A., Hopman, P., Small Aperture Telescope Augmentation Study, Sixth US/Russian Space Surveillance Workshop, August 22-26, 2005, Proceedings edited by P. K. Seidelmann and V. K. Abalakin. Available on the web at http://lfvn.astronomer.ru/report/0000015/ssw_3_3/index.htm

[17] Terebizh, V.Yu. 2004, "A Wide-field Corrector at the Prime Focus of a Ritchey-Chrétien Telescope," Astronomy Letters, **30**, 231-240 (in Russian), 200-208 (in English).

[18] Carter, B.D., Ashley, M.C.B., Sun, Y.S., Storey, J.W.V., Redesigning a Baker-Nunn camera for CCD imaging, Proceedings of the Astronomical Society of Australia, Vol. 10, No. 1, P. 74-76, 1992.

[19] Law, Bryan, *et al*., Phoenix Telescope at AMOS: Return of the Baker-Nunn Camera, SPIE Vol. 4836, pp. 119-129, 2002.

[20] Akerlof, C.W., *et al*., The ROTSE-III Robotic Telescope System, arXiv:astro-ph/0210238v1, 10 Oct 2002.

[21] McMillan, R. S., M. L. Perry, T. H. Bressi, J. L. Montani, A. F. Tubbiolo, and M. T. Read. 2000. "Progress on the Spacewatch 1.8-m Telescope and Upgrade of the Spacewatch 0.9-m Telescope." Abstract in ***B.A.A.S.***, **32**: 1042.

[22] Mancini, D., *et al*., The VST Project: Technical Overview, SPIE Vol. 4004, pp. 79-90, 2000.

[23] Rakich, A., Blundell, M., The SkyMapper wide field telescope, SPIE Vol. 6267, electronic, 2006.

[24] Pearce, E., MIT Lincoln Laboratories, email personal communication.

[25] Viotti, R. F., La Padula, C. D., Vignato, A., Lemaitre, G., Montiel, P., Dohlen, K., Two-mirror, three-reflection telescopes as candidates for sky surveys in ground and space applications. The MINITRUST: an active optics warping telescope for wide-field astronomy, SPIE Vol. 4849, pp. 377-383, 2002.