Large-Aperture, Three-Mirror Telescopes for Near-Earth Space Surveillance: A Look from the Outside In

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Abstract

In this era when Space Situational Awareness (SSA) is a national priority and optical-infrared telescopic sensor development is underway, cost-benefit analyses of competing approaches are necessary and appropriate. The DOD is presently investing in a new three-mirror telescope for SSA. At the same time, the Air Force, various universities and private research organizations are either studying or building wide-field telescopes with similar capabilities, but in most cases, at a significantly lower cost. Much of the expense for the DOD system appears driven by certain design choices which were thought necessary to fulfill the mission. Design details which would allow an independent analysis have not been published and no public comparison with other approaches is known to exist. Most telescope designs however, can be closely approximated from their optical configuration and imaging performance specifications.

An optical designer will tell you that field curvature is one of the five monochromatic aberrations. The fact that one DOD development effort considers field curvature a design feature immediately draws attention to the project. This coupled with the paucity of published information and the very high development cost make a closer examination necessary before decisions are made regarding production of additional units.

This paper examines the likely design and performance of a proxy telescope intended to find NEOs, compares and contrasts that telescope with similar, but lower cost on-going projects, and examines the wisdom of reproducing such a telescope and placing multiple copies around the globe. The study primarily concentrates on performance measured in terms of search rate in square degrees per hour *versus* object visual magnitude. Other considerations such as cost, transportability, availability of replacement components ease of installation and maintenance of alignment are also considered.

1 Introduction

This paper attempts to examine the performance of a 3.5m aperture, 3.5deg field of view, f=1.0, three mirror anastigmat telescope designed for rapid and sensitive search for earth orbiting satellites. Such a system is currently being built by the DOD. At present, very little information regarding the design of this telescope is available in the open literature. This makes an assessment of their approach difficult. Rather than argue over the merits of this program, we instead take the available information and design a similar system intended for finding near earth crossing objects (NEOs) such as asteroids and comets. We then compare performance of our telescope with other wide-field systems being built by universities and private research organizations.

2 Background

The DOD is presently in the late stages of developing and fielding a 3.5m, wide-field telescope for space situational awareness monitoring [1]. The system is frequently referred to as the Space Surveillance Telescope. Here we refer to it as the DSST. This telescope includes a number of interesting design features but is very expensive in comparison to other systems currently in development. While the finished telescope will most certainly be a capable space monitoring asset, it is not clear that it will be cost effective or that it will be what is really needed for space monitoring. Unfortunately, few details of the DSST project are available thereby making an independent assessment difficult.

Throughout development, the DSST team has relied on a group of astronomers, optical designers and space survey experts to guide their progress. While this is commendable, the group is most notable for individuals and organizations not represented. For example, no one from the Air Force Research Laboratory (AFRL) was included. Also, we note that the principal investigator from the CTI project, the only large-aperture (1.8m) Paul-Baker type telescope ever fielded, was included [2].

Early in the DSST development, the program manager published a paper discussing the curved focal plane telescope [3]. The paper argued the merits of using a curved focal plane for wide-field space surveillance applications. Stated advantages included higher image quality, faster focal ratios, eliminating the need for refractive correction optics and supporting a wider field of view. Initially, the arguments appear convincing, but as one considers the volume of published literature on wide-field optical telescopes, detectors and space object detection, the convenience of using a curved focal plane begins to diminish.

The DSST project claimed that the curved focal plane was necessary to improve image quality without the use of corrective optics. They cite designs published by Willstrop in which a curved image surface three mirror anastigmat system demonstrates extremely high image quality with spot diameters on the order of 0.1 arcsec, while a similar design with a flat focal plane was only capable of image quality on the order of 0.3 arcsec [4]. They also claimed that to further decrease focal ratio and improve image quality, a curved focal surface was required. Such claims are difficult to accept when one considers existing optical designs for wide-field telescopes with extremely fast focal ratios and flat focal planes. Rakich has published extensively on the complete design space for three mirror systems and includes a discussion of flat-field designs [5]. Terebizh recently published an all reflective design for an 8.4m, f=1.25, 3.0deg FOV system [6]. Many other designs exist, some with all spherical optics.

It is interesting to note that curved focal surfaces are not new, as optical telescopes have been plagued with their presence for centuries. In most systems, careful selection of element powers or the addition of refractive components corrects the field curvature. In modern times, the imaging sensor of choice is the CCD (or CMOS FPA). Until recently, these have all been flat, thereby requiring telescope image fields to be flat. DARPA is developing special thin CCDs which can tolerate some deformation to support a surface of compound curvature [7]. It remains to be seen whether this technology becomes generally accepted or is viewed through the lens of history as a technical curiosity. The DSST effort has however, suggested that this innovative design feature will allow the elimination of complex refractive components [3,8]. The realization of such claims remains illusive as the limited knowledge available regarding the DSST suggests that it still has at least two corrector lenses, and the paper proclaiming improved performance [8] actually demonstrates worse performance from the telescope with the curved focal surface. Careful examination of the plot scales in this paper [8] reveal that the flat focal plane design performs significantly better.

While some would claim that the ability to image on a curved focal surface is an innovative design feature, two gentlemen from the history of optical telescope design have another way of describing field curvature. Both Philip Ludwig von Seidel and Karl Schwarzschild describe field curvature as an aberration [9].

If the DOD were only building a single demonstration telescope, the DSST might only be considered an expensive technology demonstration, but with the stated position that they want the Air Force to fund 4-5 more identical telescopes to complete a world-wide constellation, questioning the wisdom and value of the DSST becomes imperative [10-11].

Without additional information, it is impossible to perform an exact evaluation of the DSST. However, aside from proprietary details of optical design, telescopes are simple imaging radiometers. Achieving an accurate approximation of their performance is not difficult. In this paper, we combine information provided by the DOD and others, with known optical techniques to achieve a representative DSST design. Since we are not in the business of finding earth-orbiting satellites, we instead design our system for finding near earth-crossing asteroids and other objects sometimes referred to as NEOs. The two problems are extremely similar so that a telescope system optimized for finding NEOs would also be highly-optimized for finding artificial satellites. Finding NEOs is however, mostly the concern of civilian astronomers, and therefore does not require access to DSST project information. Our telescope will be known as the NEOSST.

3 Developing The NEOSST Design

3.1 What is Known from DOD Sources?

Our NEOSST will be designed to be similar to the DSST. This requires knowing as much about the DSST as possible. The telescope is known to have a 3.5m aperture and is of the Paul-Baker design [1,3]. They refer to this as a Mersenne-Schmidt similar to Willstrop [12], but the design is more properly known as a Paul-Willstrop. The telescope will have a curved focal plane and was originally thought (or designed) to have a 3.0deg field of view (FOV).

3.2 What is Known from Other Sources?

The DSST is believed to operate at a final focal ratio of f=1.0 [13-14]. The design is of the Paul-Willstrop family with the tertiary mirror located behind the primary, but the tertiary is relatively close to the primary compared to the dimension of the aperture [14]. The system appears to use two corrector lenses [14] although it is possible that there is also a curved window in physical contact with the curved CCD focal surface array [8].

It is known that the telescope will be located on the White Sands Missile Range. Seeing conditions are likely to be the same as those experienced at similar internal continental sites. For example, typical seeing at the McDonald observatory is on the order of 0.9-1.0 arcsec [15]. The Discovery Channel Telescope will be located at Happy Jack in northern Arizona, another internal continental site. Mean seeing at Happy Jack is also on the order of 0.9 arcsec [16]. With such seeing conditions, it is likely that the designers would decide to roughly match pixel size to the total point spread function (PSF) to maximize sensitivity. With assumed 1.0 arcsec seeing and a 3.5m focal length, typical 15mm pixels would give a good match to the final PSF realized at the zenith.

3.3 Known and Estimated Design Parameters

An official DOD presentation discussing the DSST and curved CCD technology shows a picture of a rectangular array made from 12, 3-edge buttable CCDs which appear to be 2k x 4k arrays [17]. They are arranged in a rectangular grid giving 12k x 8k pixels. An image of this array taken from the presentation is seen here in Fig. 1. For a 3.5m focal length telescope, this rectangular array does not fit the light circle as lots of pixels are lost at the edges. If however, the FOV is increased to 3.5deg, this array almost perfectly makes an inscribed rectangle. Unfortunately this only uses about 5.8 square degrees of a possible 9.62 square degree light circle, but difficulties in tiling the curved surface with rectangular CCDs are likely to be part of the reason such an array was chosen.

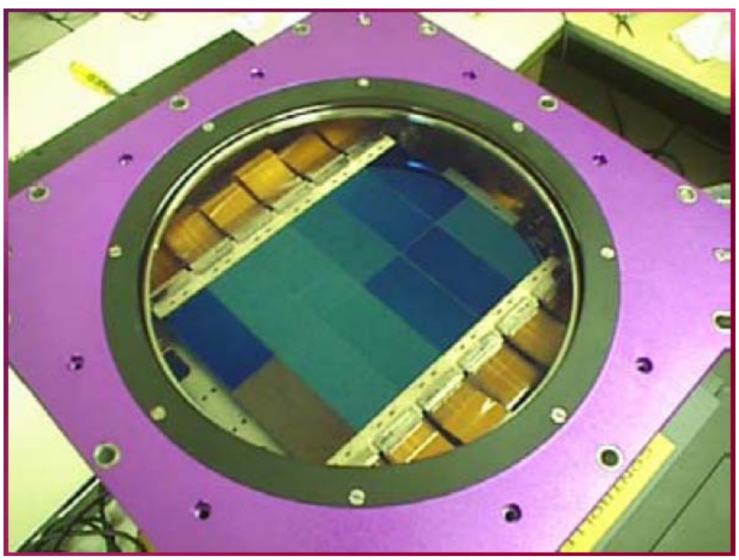

Fig 1. Assumed to be the 8k x 12k pixel curved focal surface array for the DSST [17].

3.4 The NEOSST Optical Design

To the greatest extent possible, the NEOSST will use the above parameters and attempt to achieve a similar wide-field space surveillance telescope designed for NEO detection and tracking. Design work was facilitated with the Zemax commercial optical ray-tracing package [18]. A number of relatively similar design approaches were considered before arriving at what we use as our final NEOSST system. Most of the design variations dealt with the relative placement of the mirrors, diameter of optics other than the primary, surface figures and obscuration ratios.

The NEOSST design is shown in Fig. 2. It features a 3.5m aperture, a 3.5deg FOV and a focal length of 3.5m. While it was very tempting to design out the curved focal surface, our NEOSST design includes a curved image surface. Detail of the two lens corrector system and focal surface are shown in Fig. 3.

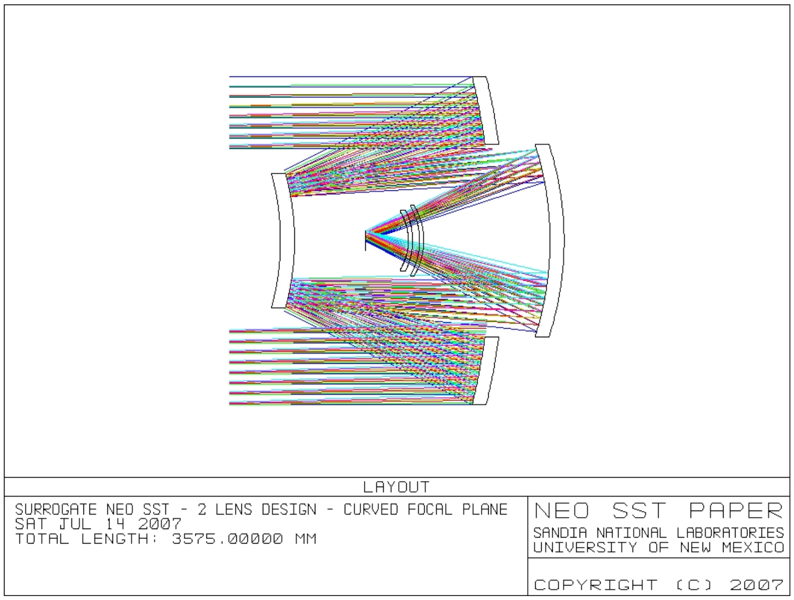

Fig 2. Optical layout of the NEOSST.

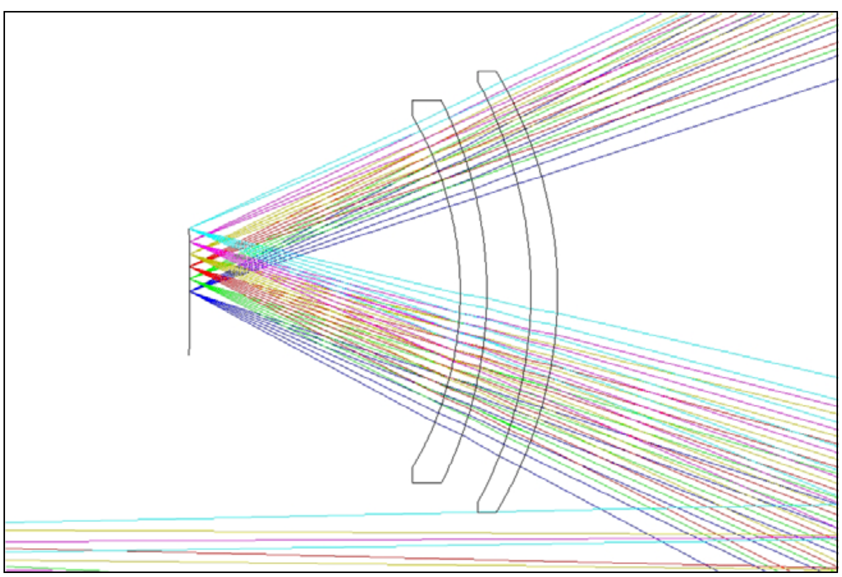
Fig 3. Layout detail of the corrector and curved focal surface.

3.5 Possible Variations of the NEOSST Optical Design

Throughout development of the NEOSST design, a number of variations were considered and pursued to some length. Three such variations are presented here. The first has a flat focal plane and is seen in Fig. 4 with detail seen in Fig. 5. The second has a curved focal plane with a more conventional three lens corrector system and is seen in Fig. 6 with detail presented in Fig. 7. The final variation uses the laminate focal surface window configuration as seen in Fig. 20a of reference [8]. This design could not be made to perform well. Most optical systems which produce high quality images without optics near the focal surface will suffer significant image degradation once refractive components like dewar windows and filters are introduced. That is likely what happens with this design approach. The design is seen in Fig. 8 with detail in Fig. 9. Performance of these design variations will be discussed in a later section.

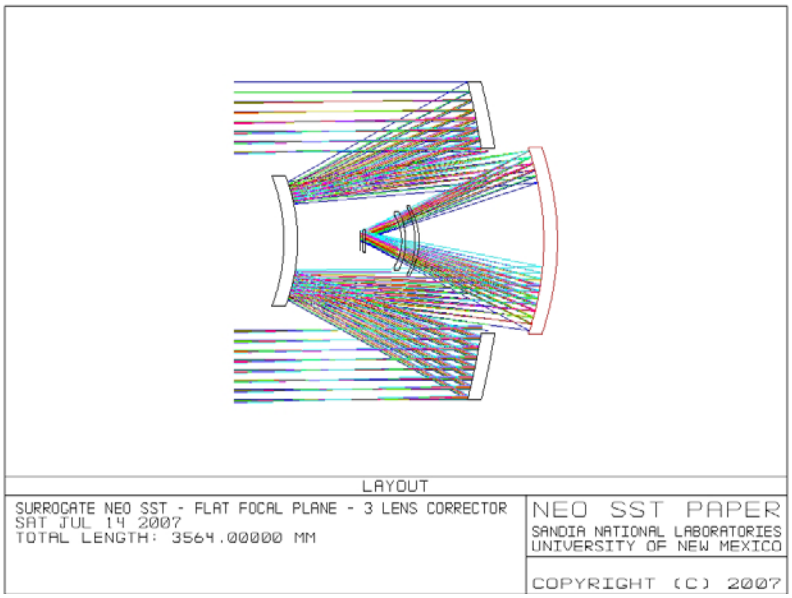

Fig 4. Optical layout for surrogate NEO SST with flat focal plane.

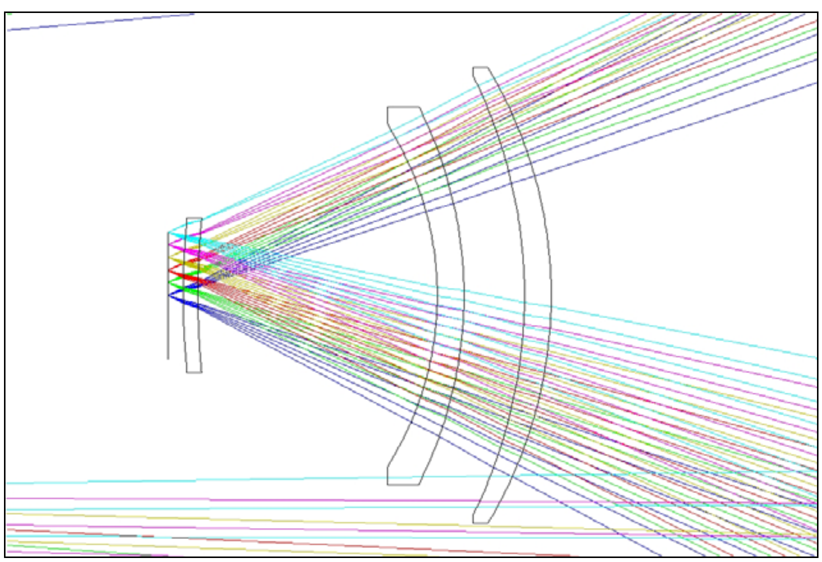
Fig 5. Detail for Surrogate NEOSST with flat focal plane.

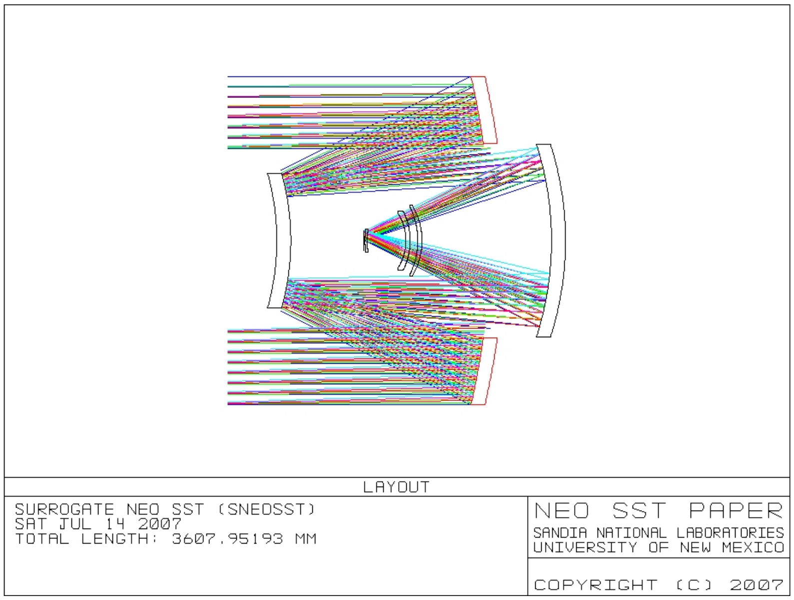

Fig 6. Alternate NEOSST with three lens corrector and curved focal surface.

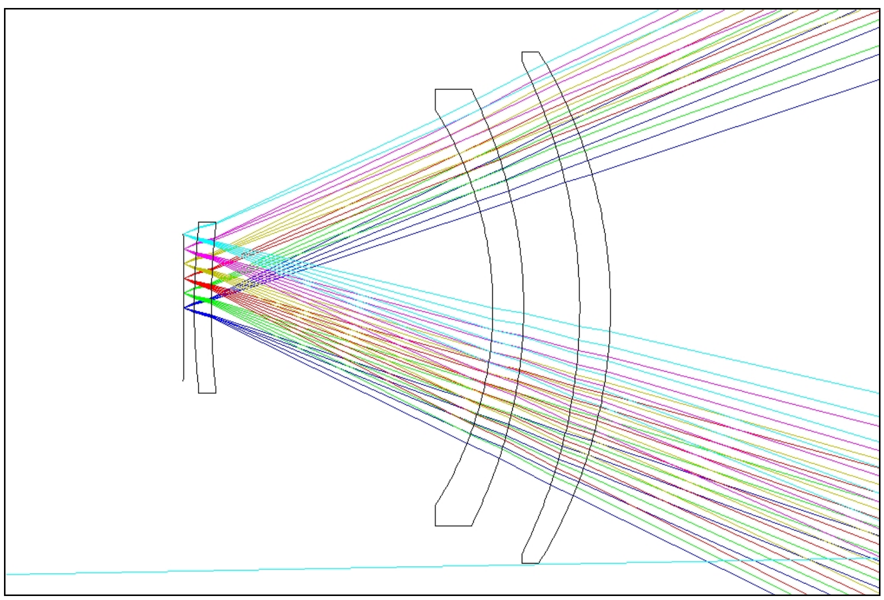

Fig 7. Detail for the alternate NEOSST with three lens corrector and curved focal surface.

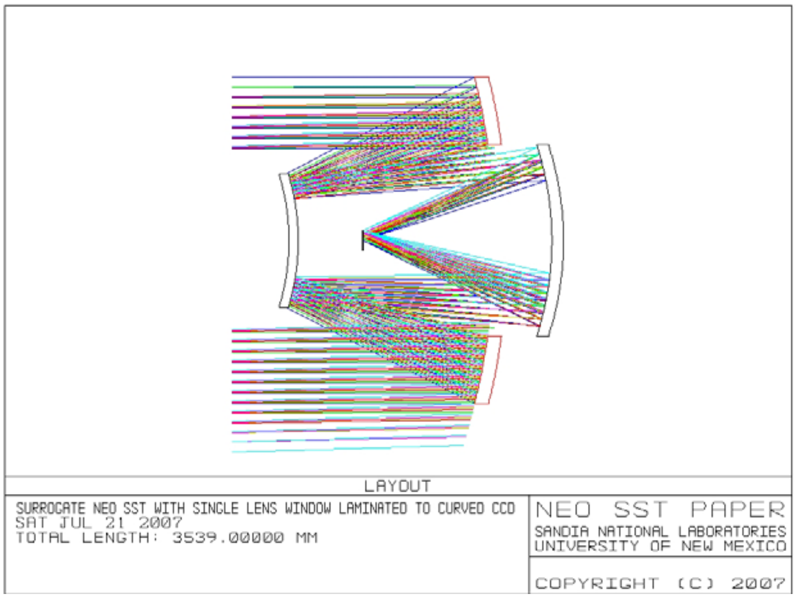

Fig 8. Alternate NEOSST with single lens
corrector laminated with curved focal surface CCD
(as suggested in reference [8]).

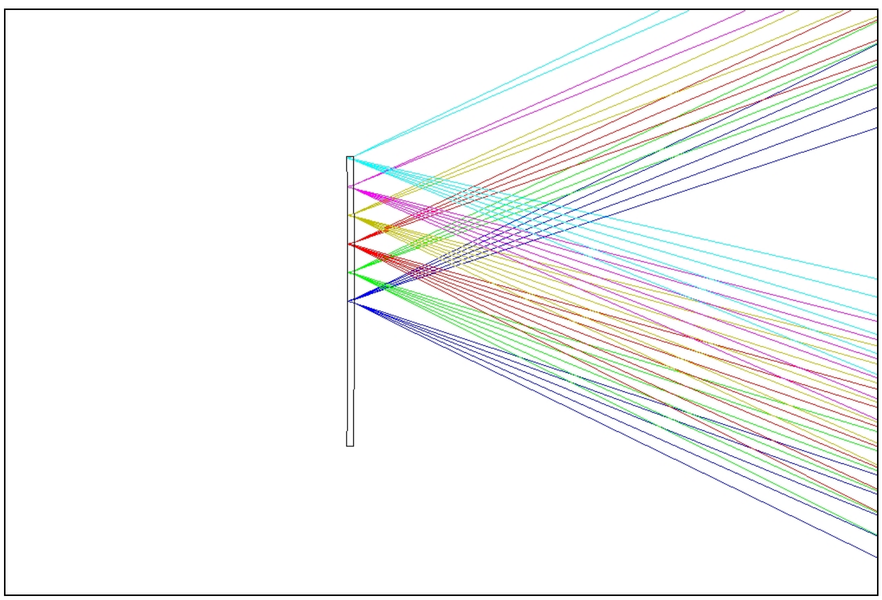

Fig 9. Detail for alternate NEOSST with single lens
corrector laminated with curved focal surface CCD.

4 A Discussion of Alternative System Designs

If it were necessary to build an extremely sensitive, high search rate NEO finder, should one follow the lead of the DSST or are there better alternatives? This is a fair question and one which needs to be answered before the decision to fund 4-5 more DSST systems is made. As this paper is about the NEOSST design, we do not want to launch off into a large exploration of optical telescope design space. Some of that work has already been done [19] and results of more recent work are the subject of another paper [20].

To present some quick results, we have identified three alternative telescope systems already in design or in production. These are PanStarrs [21] being built by the Institute for Astronomy in Hawaii, the Discovery Channel Telescope [16] (DCT) being built at Lowell Observatory by a consortium of interested parties (including the Discovery Channel), and the Large Synoptic Survey Telescope [22] (LSST) still in the early stages of development.

PanStarrs uses a super Ritchey-Chrétien design optimized to produce very high image quality over a 3.0deg FOV. Their telescope has a 1.8m aperture but will eventually have four such apertures ganged in a common mount. The focal plane array uses orthogonal transfer CCDs and has a mosaic large enough to cover almost the entire image circle. Ideally the image is an inscribed hexagon which allows easy tiling of the sky for survey operations. The area of the inscribed hexagon is slightly larger than 5.8 square degrees.

The DCT is a 4.2m multipurpose telescope capable of being converted from an f=6.2, field corrected Ritchey-Chrétien, to an f=2.3 prime focus instrument with a 2.0deg diameter light circle. We are interested in the prime focus option because it covers the larger field. The system is currently under construction in northern Arizona with an estimated total cost in the $30M-$35M range.

The LSST is still in the planning stages. When operational it will have an 8.4m aperture and a 3.5deg FOV. The optical design is that of a Paul-Willstrop, similar to the DSST, but it operates at a more reasonable focal ratio of f=1.25 and has a flat focal plane. The LSST design could have been scaled down to 3.5m with a cost in the neighborhood of $30M. Such a design would have had a flat focal plane and been capable of supporting an inscribed hexagonal focal plane array for sky coverage on the order of 7.96 square degrees. It is thought that one of the designers of the DSST was a member of the LSST optical review team so it is likely that the DSST project had access to the LSST design [23]. A scaled LSST would have performed at least as well as the DSST, but at a much lower cost.

Of course, the unspoken secret of the curved focal plane technology, in general, is that the extremely thin CCDs necessary for bending have limited quantum efficiency at the red end of the spectrum. Their quantum efficiency is slightly less than typical thinned and back illuminated CCDs. The scaled LSST design with its flat focal plane could take advantage of the very latest fully-depleted CCDs with significantly higher quantum efficiency in the 800-1100nm region. These CCDs are too thick to be curved. To build the most sensitive NEOSST possible, we want thick CCDs with enhanced quantum efficiency in the 800-1100nm spectral range. The rationale for using curved CCDs with their lower quantum efficiency is difficult to understand.

To a large extent, the search rate capability of any telescope is determined by its étendue, or the product of the aperture area and the imaged field. While there are other factors such as quantum efficiency, the stability of the mount and the ability to scan to a new position and settle into place, but the single greatest factor will be the étendue. Often when encountered, the reported étendue includes the full aperture and full image circle. Here we report the étendue which includes the actual image area and accounts for obscuration and approximate optical transmission.

The effective étendue for the systems is shown in Table 1. Twin DCTs and quad PanStarrs are also included. The twin DCTs could be built for the published budget of the DSST. Table 1 clearly shows how twin DCTs easily eclipse the DSST, even if the DSST had a full inscribed hexagonal focal surface array. The quad PanStarrs is included for a fair comparison. Table 1 also shows that the quad PanStarrs surpasses the DSST as being built, and compares well with the DSST if it were ever equipped with a full hexagonal focal surface array. The LSST is clearly the system to beat, but with a price tag on the order of $300M it would not be the most practical solution to our problem.

Table 1: Comparison of Étendue for the DSST and potential alternate approaches.

System	Imaged Field (sq deg)	Aperture (m)	Transmission (fraction)	Etendue
LSST - Full Hexagon FPA	7.96	8.4	0.6	264.67
Twin DCT PFCs - Full Hexagon FPAs	2.6	4.2	0.85	61.24
DSST - If Equipped with Full Hexagon FSA	7.96	3.5	0.6	45.95
Quad PanStarrs - Full Hexagon FPAs	5.85	1.8	0.7	41.68
DSST - As Being Built with Rectangular FSA	5.9	3.5	0.6	34.06
DCT PFC - Full Hexagon FPA	2.6	4.2	0.85	30.62
PanStarrs - Full Hexagon FPA	5.85	1.8	0.7	10.42

Our NEOSST system will have an étendue similar to the DSST.

While the LSST is extremely interesting, it clearly is in a class by itself and will be excluded here from further consideration. The single PanStarrs is at a bit of a disadvantage with its smaller aperture but is continued in the comparison because the basic design has significant potential for smaller and less costly telescopes than our 3.5m NEOSST.

5 Performance of the NEOSST

5.1 Imaging Performance

The imaging performance for the NEOSST is more than adequate for the intended NEO search instrument. PSF root mean square (RMS) diameters are on the order of 0.5 arcsec which guarantees that the telescope will be seeing limited at all but the best astronomical imaging sites. The spot diagram is presented in Fig. 10, a graph of RMS spot radius is presented in Fig. 11 and a plot of encircled energy is presented in Fig. 12.

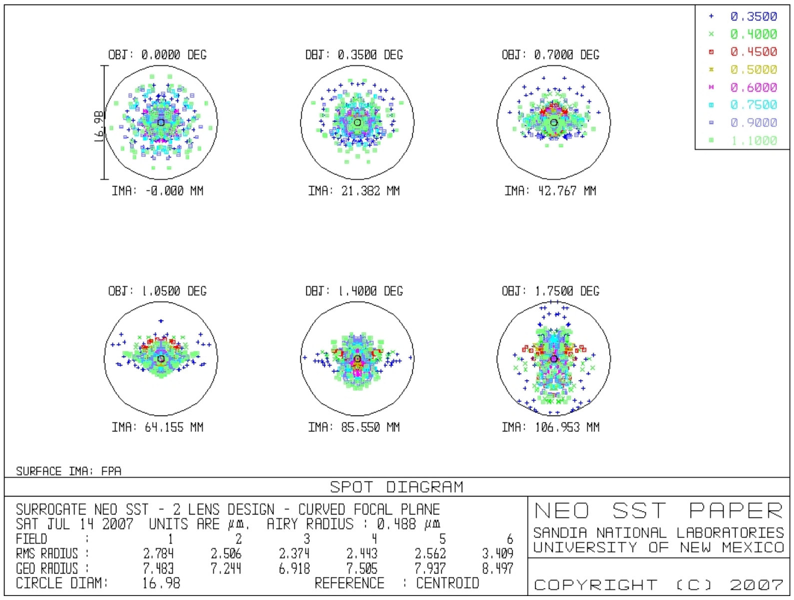

Fig. 10. Spot diagram for the NEOSST.

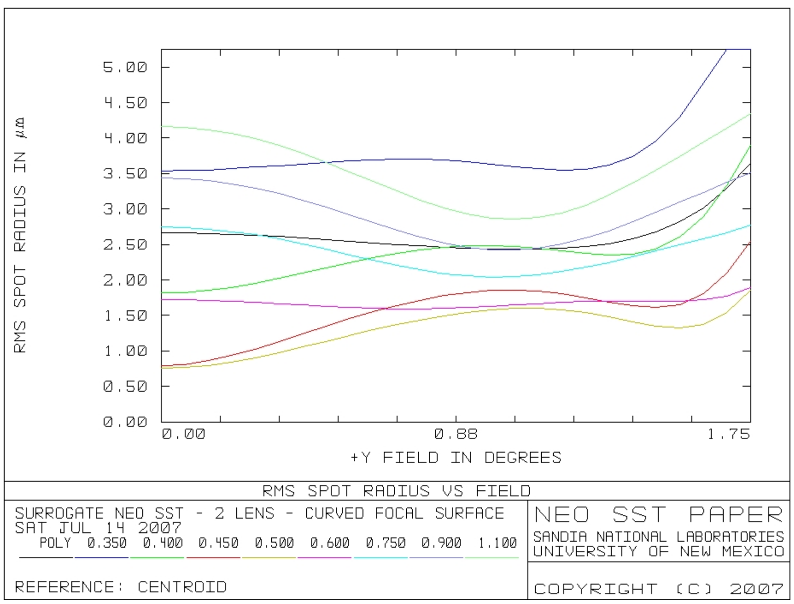

Fig. 11. RMS spot radius for the NEOSST.

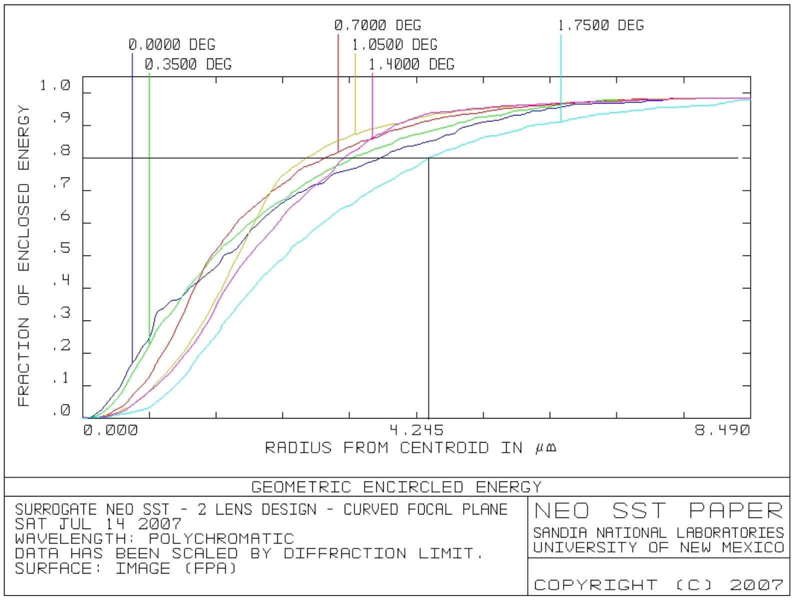

Fig. 12. Encircled energy graph for the NEOSST showing 80% of the energy falls into a circle of diameter slightly greater than 0.5 arcsec..

5.2 Imaging Performance of NEOSST Design Variations

Imaging performance of the alternate NEOSST designs is mostly similar to the selected two lens design with the exception of the final design with the laminate dewar window and focal plane copied from Fig. 20a in reference [8]. This system could not be made to perform. It is unknown if the DSST team has been successful in developing a high performance design with the laminate window, but the authors here could not make it work. From examining the graphs in reference [8], it appears as the authors of that paper could not make the approach work either.

Here, image performance is presented as spot diagrams for the three lens flat design in Fig. 13, the three lens curved design in Fig. 14, and the laminate design with curved focal surface in Fig. 15.

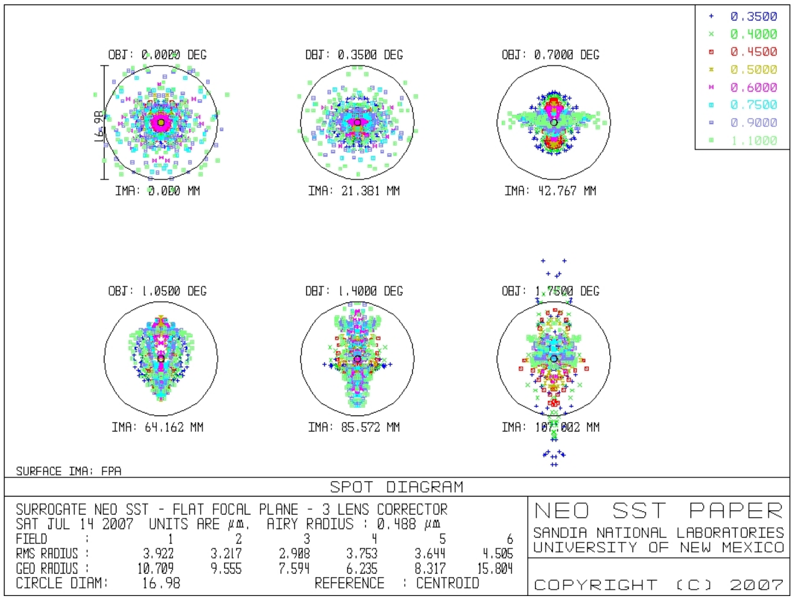

Fig. 13. Ray-traced spots for the three lens surrogate NEOSST with flat focal plane.

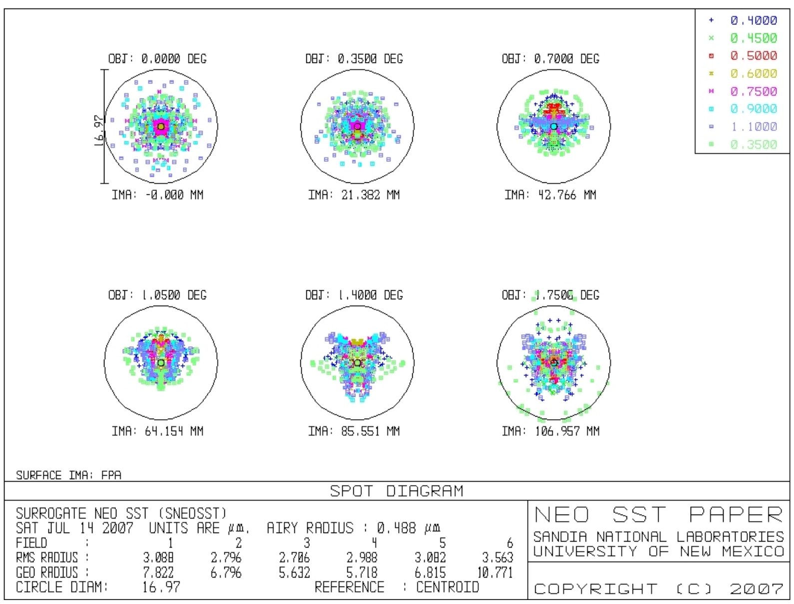

Fig. 14. Ray-traced spots for the three lens surrogate NEOSST with curved focal surface.

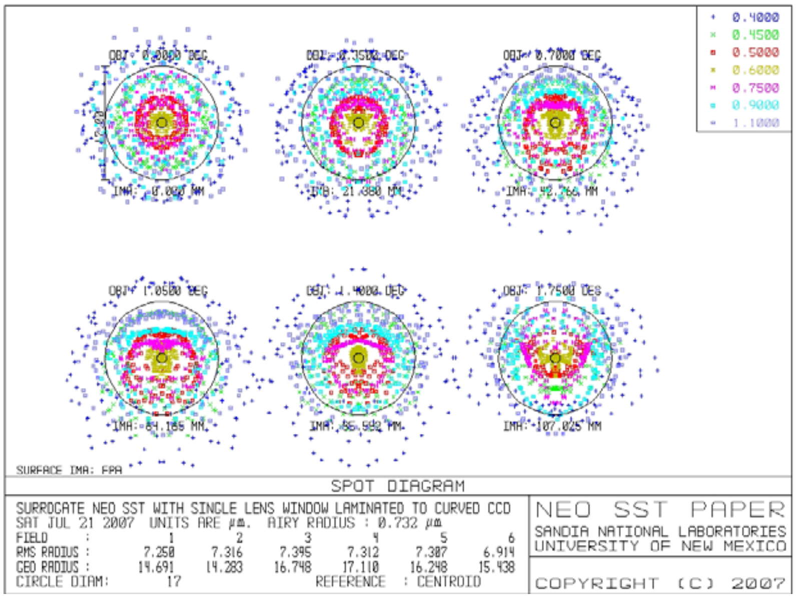

Fig. 15. Ray-traced spots for the laminate dewar window and curved CCD surrogate NEOSST.

5.3 Search Rate for the NEOSST

Calculation of the rate at which our NEOSST can search for low-visibility asteroids and comets follows from standard radiometric principals and has been described elsewhere [24]. This approach was used for similar calculations with results reported in other papers [19,25-26]. Several details of these calculations are very important and difficult to convey in a short paper. For objects brighter than roughly 18th magnitude, the calculations are very straightforward and not particularly sensitive to the placement of the image spot in the focal plane array. For very dim targets, the search rate calculated depends strongly on factors such as read noise, dark current, sky brightness, pixel size and the placement of the image spot on the pixels themselves. If the object spot is directly in the center of a pixel, one could calculate a much higher search rate than if the image spot were located in the worst possible location, the corner joining four pixels.

In this paper we have assumed that the pixels are sized roughly to match the point spread function (including atmospheric effects). The pixel sizes used for the various systems are presented in Table 2. When calculating search rate, we have used the worst possible configuration with the image spot split equally between four adjoining pixels. Read noise was assumed to be seven electrons for all CCDs and dark current was assumed to contribute 0.1 electron per pixel per second. Sky brightness was 20th magnitude per square arcsec and the minimum reliable detectable signal to noise ratio was six to one. Each optical system was assumed to be capable of slewing at a rate of three degrees per second and require a total of two seconds to stop and settle. Some might argue that this is unrealistic for the longer optical systems featuring the prime focus correctors, but if designed properly, this should be an attainable goal. The giant LSST will be operating within similar parameters when completed.

Table 2: Pixel Sizes for Telescope Systems. The larger pixels required for the PanStarrs and DCT systems might be arrived at through 2 x 2 binning of smaller pixels prior to read operations (to minimize read noise).

2L-Curved SNEOSST	Full Hex SNEOSST	Single PanStarrs	Quad PanStarrs	Single DCT PFC	Dual DCT PFC
15μm	15μm	34μm	34μm	40μm	40μm

Others investigators will most certainly calculate slightly different search rates, particularly for the faintest targets. This is understandable given the sensitivity of the calculations to the various input parameters. Here we have presented our inputs and discussed the calculation process. We make no attempt to match other calculations, only to calculate all systems with the same inputs and same constraints. Search rate results for the very dim magnitudes should be viewed and compared with caution.

One factor which differs for the various telescope systems is the CCD quantum efficiency. Curved CCDs were assumed to have a maximum QE of 0.75 while flat CCDs achieved a maximum QE of 0.85. The bandpass for the calculations was 500nm wide, centered at 700nm.

Fig. 16 presents the search rate for the two lens NEOSST with the curved focal plane array. The search rate was calculated for three cases. The worst case (used elsewhere in this paper) has the image spot sharing a minimum of four pixels as if the spot were centered at the corner where four pixels intercept. The two-pixel calculation gives results as if the image spot were on the line separating two pixels. The best case is where the image spot is centered on a single pixel.

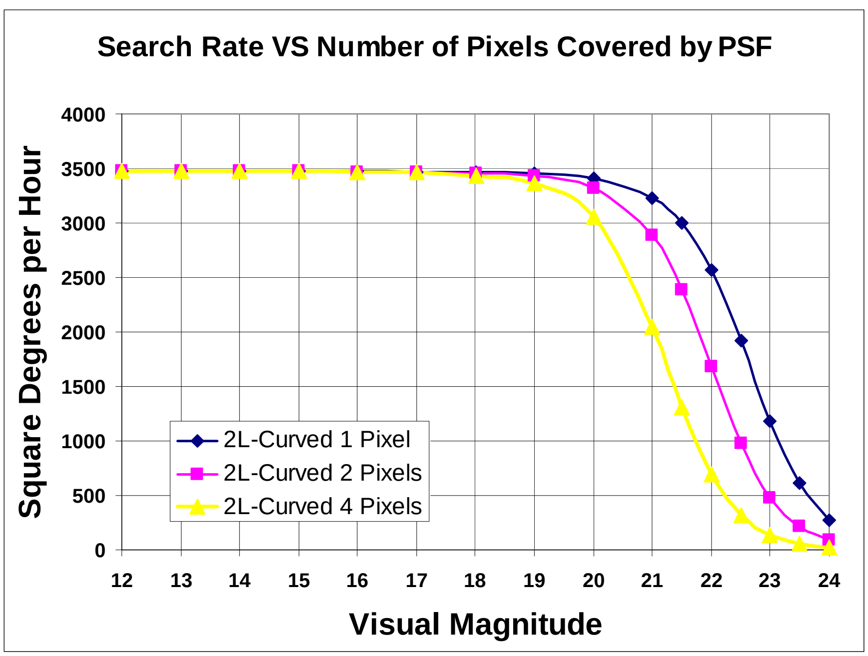

Fig. 16. Search rate calculations for the NEOSST.

Fig. 16 clearly shows the impact of spot placement on search rate. Because it is impossible to guarantee where an image spot will appear on the CCD array, worst case conditions must be considered.

5.4 Search Rate Comparison with Other Systems

The worst-case search rate for the NEOSST telescope compared with other systems is presented in Fig. 17. As discussed above, the comparison includes a total of three telescope designs with two variations each. In Fig. 17, we see that the NEOSST variation with a full inscribed hexagon focal surface array has the greatest search rate for most magnitudes. This should come as no surprise as this variation has the greatest overall étendue. If we were to actually build a NEOSST like system to search for NEOs, we would find some way to use the entire light circle. Most likely this would require making the focal surface flat.

Surprisingly, most of the systems considered perform about the same. The single PanStarrs is at a significant disadvantage in aperture and field of view compared with the NEOSST but it has a higher throughput and therefore achieves close to the same search rate at brighter magnitudes. For dimmer targets, the single PanStarrs falls off a bit more quickly, but the quad PanStarrs performs better than the NEOSST and almost as well as two DCT PFCs working independently.

The DCT with prime focus corrector appears as the lowest performance system but the comparison is not entirely a fair one. The DCT PFC was never optimized for space object search. The field can be pushed out to beyond three degrees with loss of image quality but as designed, the DCT is intended for astronomical research. Two DCT PFC systems, which could be purchased for the published budget for the DSST, perform as well as the baseline NEOSST at brighter magnitudes, and much better at the faintest magnitudes.

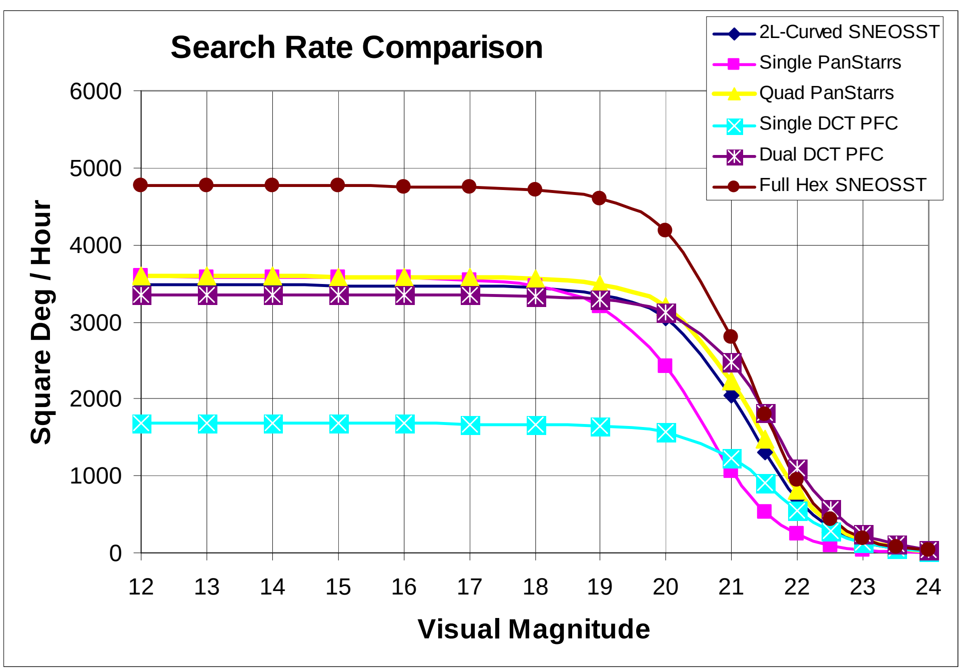

Fig. 17. Comparison of search rates for three telescope systems with two variations each.

6 A Question of Value

6.1 Is the NEOSST the Best System for Finding NEOs?

Is the NEOSST the best system for finding NEOs? The analysis suggests that that the NEOSST design is not optimal for finding NEOs. Other system designs are better suited for finding NEOs. The NEOSST performs well, but its performance is equaled or exceeded by other, more easily produced systems.

The NEOSST with the full hexagonal focal surface array performs much better than the standard NEOSST, but there remains the difficulty of tiling the curved focal surface with rectangular CCDs, even if they are curved. Eventually the attempt to project a rectangular grid onto the spherical surface will result in gaps in the mosaic array. While gaps are present in any mosaic array, they are normally uniform across the array. On a curved array, the gaps would necessarily change in width as a function of position.

As stated above, the easiest way to produce a NEOSST with a full hexagonal array would be to flatten the focal surface. The DSST team suggests that the curved focal surface was necessary to improve performance. With the available information, the authors of this paper cannot conclude that the curved focal surface was anything other than a design choice. It does not appear as though it was a requirement.

6.2 Is the NEOSST worth $65M?

Is the NEOSST worth the $65M (or more) cost to develop it? This is a difficult question as development of a new system costs more than production of an existing design. However, virtually all telescopes used for astronomical research world-wide are unique systems and all have scaled development costs significantly less than that of the DSST. If one were willing to spend $65M on a single site SST project, the lower risk, higher performance alternative would have been to build two identical DCT PFC systems. If greater performance were required, the systems could have been optimized for a much wider field. Prime focus corrector designs with three degree fields have been demonstrated by Terebizh [27].

6.3 Does it Make Sense to Build More NEOSSTs?

Does it make sense to build additional NEOSSTs for a world-wide constellation to completely monitor the night sky, 24 hours a day, 7 days a week, 365 days a year? If the NEOSST is not the best system for the job and the NEOSST is of higher cost in comparison to alternatives, it is difficult for the authors to conclude that it would be wise to build more such systems.

6.4 What are the Alternatives?

What are the alternatives? Many people will point out that it is easier to criticize something than to improve it. In the case of the NEOSST, there are several ways to improve it. First, it should be built with a flat focal plane and the CCD array should cover the largest possible inscribed hexagon. Second, it would make more sense to produce a smaller system with a greater field of view. This could be done with three mirror telescopes but could more easily be accomplished with a less complex design such as a two-mirror field corrected Schwarzschild aplanat (Ritchey-Chrétien or Couder), or a very wide-field prime focus corrector which could be folded, if necessary, to reduce overall length.

7 Summary

In this paper we have attempted to examine the performance of a space search telescope designed to find near earth objects (NEOs) such as asteroids and comets. This telescope was designed to be as close a replica of the DOD Space Surveillance Telescope (presently being built) as possible because the problems of finding NEOs and satellites are very similar, and the DSST project has advertised that their approach was specifically selected to maximize sensitivity and search rate.

Our analysis suggests that such a telescope is a viable option for finding NEOs. Clearly, such a telescope design will perform. However, the analysis also suggests that the telescope contains a number of design choices which limit its performance and appear only to result in a considerable increase in cost. Designs for astronomical telescopes currently under construction could have been adapted to the space surveillance problem with either greater performance at similar cost, or equal performance at a lower cost.

If we were to build a NEO search telescope today, we would not follow the three mirror anastigmat, curved focal surface array approach. There appear to be much better ways to solve the problem. If we were in need of a world-wide constellation of telescopes dedicated to finding NEOs, we most certainly would not build multiple copies of the three mirror anastigmat, curved focal surface telescope.

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