

# An Overview of Wide-Field-Of-View Optical Designs for Survey Telescopes

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## Abstract

While large aperture telescopes are highly desirable for their enormous light grasp, smaller telescopes are increasingly pressed into service as wide-field survey instruments to aid in the search for near earth objects, satellites and space debris. Various optical designs are found throughout the technical literature but not all represent truly capable wide-field survey instruments and the search to find such designs is time consuming without any guarantees of its completeness. Here we present an overview of wide-field optical designs suitable for survey instruments in the ½ meter class aperture range. The size is small enough to be affordable for many less well funded research programs, yet large enough that when coupled with a modest CCD mosaic, the resulting system represents a capable survey instrument. Many optical designs exist with each having its own strengths and limitations.

## 1. Introduction

Wide-field astronomical sky survey work dates back to the mid 1840s, shortly after the invention of photography [1]. Early survey instruments were nothing more than cameras and the optics were early camera lenses. Some of the better known optics were made by Voigtlander and Petzval [2]. As the technical characteristics of photography improved, larger versions of camera lenses were custom built for use as dedicated sky survey instruments. Six and ten inch Voigtlander lenses were somewhat common. One of the best known large survey instrument from the early 1890s was the 24 inch Bruce Telescope, a simple four-lens Petzval-type refractor [3]. (Note: During this early era, such lenses were measured by their focal length and not their aperture.)

Interest in telescopes as sky survey instruments improved slightly in the early 1910s with the invention of the Ritchey-Chretien telescope [4]. The optics improved again in 1922, when Violette published details of a refractive aberration corrector for the Ritchey-Chretien optical system [5]. Before this time, refractive correctors were not well known, but were in use as chromatic correctors and field flatteners on refractor telescopes [2, 6].

The 1931 introduction of the Schmidt Camera optical system forever changed astronomical sky survey work [1]. For the first time, a practical system of modest aperture and high image quality was available with an extremely wide field of view. The basic Schmidt and its many variations are still in use today. They are however limited to apertures less than about 1.25 meters due to the need for a full aperture refractive corrector.

In 1935, Maurice Paul adapted the Mersenne corrector of 1636 [7, 8] to form a three-mirror imaging telescope [9]. The resulting optical design was anastigmatic over wide fields of view, with the only limitation being that it resulted in the image being produced on a convex spherical surface. Flat field variations of the Paul system were developed by

Willstrop [10] in the 1980s, but resulted in some loss of either image quality or field of view. More recently, refractive correctors have been adapted to the Paul optical design, thereby allowing it to achieve very wide fields of view while imaging on to a flat focal surface. A modified version of the Paul system is currently in use on the DARPA sponsored Space Surveillance Telescope (DSST) (with a curved focal surface) [11], and is planned for use on the Large Synoptic Sky Survey Telescope (LSST) with the technically superior flat focal plane [12].

Most sky survey work is still accomplished by smaller projects with significantly less funding. They typically use instruments with apertures of less than 1 meter and frequently strive for wider fields of view. Often these efforts use abandoned Schmidt and Baker-Nunn optical systems, adapting them for flat-field imaging with CCDs [13-15]. Other surveys build custom instruments. The optical designs pursued for smaller survey instruments frequently reflect the optical interests of their designer. Unfortunately, not all designs are created equal and it is not clear that many of the smaller survey efforts engage in a sufficient trade-space analysis.

In this paper, we attempt to take a look at the available choices for modest aperture survey instruments with the hope that this information will benefit those developing sky survey instruments in the future. As we are developing no sky survey instruments of our own at this time, the information presented should be less prone to influence by any specific design preferences.

## **2. Background**

Within the last fifteen to twenty years, the interest in sky survey work has increased significantly. Be it to find potentially hazardous objects (PHOs), near earth objects (NEOs), space debris, or for space situational awareness, the optical goals are very similar. These systems are more than large camera lenses. They seek to image fields ranging from as narrow as 1 deg, to as wide as 9 degrees with apertures ranging from a few hundred millimeters to over 8 meters in diameter.

Recent examples of large aperture (greater than 1 meter diameter) survey instruments, either in-service, or in the planning or development phase, include a wide variety of optical systems. A quick look at the telescopes from 11 representative efforts is presented here. The list contains no surprises. Essentially all of the well known optical systems are included.

- a) The QUEST project used the Palomar Oschin Schmidt camera. It featured a 1.25 meter aperture and imaged a square 4 x 4 degrees [16].
- b) The SkyMapper project is using a custom 1.3 meter wide-field Ritchey-Chretien optical system [17]. It features a novel 3-lens corrector design and images a circle 3.4 degrees in diameter.
- c) The PanStarrs project has their first optical assembly in operation. Known as the PS-1, the telescope is a custom 1.8 meter wide-field super Ritchey-Chretien

optical system. It features a modification of a classic 3-lens Wynne-type corrector and images a circle 3.0 degrees in diameter [18].

d) The Sloan Digital Sky Survey uses a 2.5 meter Ritchey-Chretien optical system featuring a Gascoigne-type corrector system using an aspheric plate and field flattening lens [19]. It is capable of producing a 3-degree diameter light circle (2.5 degrees in imaging mode).

e) The T250 ACTUEL telescope is currently in development for the Observatorio Astrofísico de Javalambre at Teruel Spain. It will be a 2.5 meter aperture Ritchey-Chretien system with a 3.0 deg field of view, operating at a focal ratio somewhat faster than the Sloan telescope [20-21].

f) The DSST is nearing completion and subsequent first light [11]. The design is a modified Paul optical system sometimes known as a Mersenne-Schmidt. It features a 3.5 meter aperture with a 3.5 degree diameter field of view and operates at a focal ratio of f/1.0. It has an unusual curved focal surface.

g) The Dark Energy Camera (DEC) for the Dark Energy Survey (DES) will use the existing 4 meter Blanco telescope. The new prime focus corrector features five lenses and will image a field 2.1 degrees in diameter [22].

h) The Discovery Chanel Telescope will eventually include a prime focus corrector of six lenses. The 4.2 meter aperture telescope will image a field of 2.0 degrees diameter [23].

i) The San Pedro Mártir Observatory is pursuing two 6.5 meter aperture telescopes that will be known as the SPM-Twins [24]. The wide-field telescope is currently planned to be of Cassegrain configuration and feature a 4- or 5-lens corrector, producing an image field of 1.5 degrees diameter.

j) The 8.2 meter aperture Subaru telescope is being upgraded to include a very ambitious prime focus corrector capable of imaging a field of 1.5 degrees diameter [25]. Constraints such as the availability of large glass and the limited diameter of the largest correcting lens make development of the Hyper Suprime Camera an unprecedented effort.

k) The LSST will feature an 8.4 meter aperture Paul optical system including a 3-lens corrector [12]. The telescope will image a field 3.5 degrees in diameter onto a flat focal surface at a focal ratio of f/1.24.

Although less well known, a number of survey efforts with telescopes of aperture one meter and smaller are either in development or in process. Examples of a few such survey instruments are given in the list below.

l) The well known Ground-based Electro-Optical Deep Space Surveillance (GEODSS) program actually consists of two different types of telescopes. The smaller is a Schmidt-camera of 375mm aperture. It is believed to image a field of 6 degrees diameter [26].

m) The Las Cumbres Observatory project includes a distributed network of telescopes. The smaller survey instruments are of 400mm diameter and of a commercial aplanatic Schmidt-Cassegrain configuration [27]. Depending upon the detector in use, they image fields as large as 40 x 40 arc minutes.

- n) The International Scientific Observers Network (ISON) includes ten observing sites world-wide with a significant number of different telescopes. One telescope appearing at all sites is the RST-220, a Richter-Slevogt configuration system modified by Valery Terebizh to image a field as wide as 6 degrees diameter. The 22cm aperture telescopes normally image fields of 4 x 4 degrees [28].
- o) The US Naval Observatory Robotic Astrometric Telescope (URAT) project planned to field a series of 850mm aperture telescopes designed for wide-field (4.5 degrees diameter) imaging with near zero distortion and near perfect image quality [29]. Fabrication of the first telescope was halted with completion of the primary mirror. The optical design was a highly optimized Richter-Slevogt Cassegrain that included both full aperture and sub-aperture refractive correctors.
- p) The larger GEODSS telescopes are of 1 meter diameter and image a field of 2.1 degrees diameter. They are essentially folded prime focus systems using a 3-lens corrector [26].
- q) The Canadian One Meter Initiative (OMI) is working to field a 1 meter aperture survey telescope in Canada. The design features a very wide-field prime focus corrector, imaging a field of 3.11 degrees diameter. The corrector requires four lenses with one of special glass and one with an aspheric surface [30].

The two lists of survey instruments presented above largely span the commonly known optical design space. There are however other design options, and for any specific survey application, some design characteristics are ideal while others could prove detrimental. Selecting the best optical design requires an examination of the optical design space for each application. A good example of a survey program that performed a trade space analysis is that of the URAT effort [29]. They have published several papers discussing the optical design space considered. Most of the designs are full aperture catadioptrics, but the effort did consider at least one refractor. Noticeably absent from their published considerations are conventional Ritchey-Chretien systems and prime focus correctors. It is not known if these were considered. As the URAT survey did feature very demanding image quality requirements, it is possible the team dismissed approaches they thought were less likely to prove successful without detailed consideration.

### **3. Characteristics of Survey Telescopes**

Survey telescopes are by definition, wide-field of view systems. For a true telescope, fields of view are normally less than about 10 degrees. There exist a few designs that go wider with small apertures, but these are generally the exception. Systems based on camera lenses often go much wider and are not considered as telescopes here. Refractor telescopes are a special case that will only be touched on here. For most purposes, telescopes include at least one reflective surface.

One characteristic of wide-field systems is that they have large focal planes. For axially symmetric optical designs (or near symmetric systems with a flat fold mirror), the optical system necessarily includes some form of obscuration. For prime focus systems, the image surface itself forms the obscuration. For Cassegrain-like systems, the secondary mirror will normally be the defining obscuring element. If we consider only the image

surface for the moment, then the obscuration ratio can be calculated from the system Lagrange Invariant. For a given system with aperture area  $A_p$ , and field of view defined by an imaging solid angle,  $\Omega_{FOV}$ , the Lagrange Invariant is defined as the product,  $A_p \Omega_{FOV}$ . The brightness theorem teaches that this value will be constant throughout the optical system. If the area of the focal surface is smaller than the aperture and represented by the area  $A_{FPA}$ , then the solid angle of the light bundle converging on the focal surface will be larger than the solid angle defining the system field of view, by a ratio of  $A_p/A_{FPA}$ . We can use this information to calculate the minimum system obscuration ratio.

For any on-axis reflective system, the minimum obscuration ratio, expressed as the area of the focal plane array divided by the area of the aperture ( $A_{FPA}/A_p$ ) can be shown to be approximately equal to the ratio  $\theta_{FOV}^2/\theta_{FPA}^2$ , where  $\theta_{FOV}$  is the angular diameter of the system field of view, while  $\theta_{FPA}$  is an angular diameter of the light bundle converging onto the focal plane array. For systems with a field of view less than about 10 degrees, we can use the small angle approximation and derive an alternate expression for the obscuration ratio as

$$Obscuration\_Ratio = \frac{A_{FPA}}{A_p} = \theta_{FOV}^2 (f/\#)^2$$

This equation more clearly shows the relationships. The minimum obscuration ratio increases with the square of the field of view, and with the square of the system focal ratio ( $f/\#$ ). In real systems, the obscuration ratio is larger than this ideal value as other elements such as corrector lenses, possibly secondary or tertiary mirrors, fold mirrors, the dewar, and possibly a shutter, introduce additional obscuration. For Cassegrain systems, this obscuration ratio is somewhat related to both the secondary magnification ratio and the field of view, while for a prime focus corrector, this obscuration ratio is often four to nine times as large as that caused by the focal plane array alone. Unfortunately, there are no simple relationships describing obscuration ratios for specific systems as individual cases are highly dependent upon the exact field of view, the number of corrector lenses, materials and the nature of aspheric surfaces. A total of 50 published optical designs were examined to look for trends in the final obscuration ratio and attempt to relate it to the design, the focal ratio or the field of view, but no clear trends emerged. Each design proved somewhat unique.

Another feature of wide field of view optical telescopes is that they necessarily require refractive corrector elements. (We are for the moment excluding a small number of purely reflective systems such as a reflective Schmidt camera.) Any trade space analysis for telescopes must consider the availability of glass in large size blanks. This often has the effect of limiting the types of optical systems and the fields of view that can be considered. Such practical considerations played a significant role in the design of the prime focus corrector for the Hyper Suprime camera. For most smaller applications, large elements of common glass types are not an issue, but the more exotic types of glass such as special low dispersion materials are usually only available in smaller pieces with limited total thickness. For example, a favorite low dispersion glass for apochromatic

refractor telescopes, and some prime focus corrector applications is S-FPL53 from Ohara. This material is normally produced in strips 160mm wide and 40mm thick. Anything larger requires a very costly special order and simply might not be available at all.

The study of wide field of view optical systems is nonetheless a lesson in refractive corrector designs. Significant insight into the functional limitations of various telescope approaches and corrector concepts can be obtained through performing a trade space analysis for a given survey telescope.

A final characteristic of survey telescopes is that the large focal planes require even larger dewars and sometimes optical shutters. These components can contribute significantly to overall obscuration and might make an otherwise ideal design impossible. Certain telescope designs adapt better to dewars and shutters than others. Such topics will be considered in the next section where we discuss the characteristics of different optical design families.

#### **4. Characteristics of Optical Design Families**

When considering possible telescope designs for survey instruments, only a few real choices exist. The telescope can be a refractor, a full aperture catadioptric, or a corrected reflector utilizing anywhere from one to four mirrors. Systems with more than four mirrors are possible but such designs are rarely encountered and are usually not suited to survey instruments. Here we consider design choices for system apertures up to 1 meter diameter.

##### *Refractors:*

Refracting telescopes are nearly ideal for systems with apertures less than about 150mm. They have zero obscuration and you do not lose light on reflecting surfaces. Chromatic correction can however be difficult and require either a large number of elements, special glass types, or an optical design that is physically longer than its actual focal length. The URAT project considered a refractor of 600mm aperture and a focal ratio of  $f/6$ , but it required special glass and was only optimized for a spectral bandwidth of 100nm [29]. A 400mm aperture  $f/9$  alternative was designed by the authors and can be built with a single, readily available, but expensive  $\text{CaF}_2$  blank.

Typical refractors used for survey work will have apertures of 100-400mm, focal ratios of  $f/4$  to  $f/7$  and fields of view up to 9 degrees diameter.

##### *Catadioptrics:*

Full aperture catadioptrics are ideal for smaller telescopes as large blanks of common glass types such as BK7 or fused silica, are available in sizes up to about 1.5 meters diameter. Many design choices such as the Schmidt, Baker Reflector Corrector, Maksutov, Houghton (Richter-Slevogt), Hamilton and Baker-Nunn are known and many feature all or mostly spherical optics. Fields of view in the 5-7 degree range are possible while imaging onto flat focal surfaces, but obscuration can be an issue for designs with single powered mirrors.

Typical full aperture catadioptric systems designed for survey work will have apertures of 300mm or more. If equipped with a single powered mirror, they will have focal ratios ranging from  $f/1$  to  $f/5$  and fields of view ranging from a few degrees up to as wide as 10 degrees. Obscuration becomes a significant issue and often a flat fold mirror will be used to move the detector, shutter and dewar out of the optical path. When equipped with two powered mirrors as in a Cassegrain configuration, focal ratios are generally in the  $f/2$  to  $f/5$  range with fields of view up to about 6 degrees diameter.

#### Single Mirror Reflectors:

Single mirror systems are all basically modifications of the prime focus corrector concept. The primary mirror directs light towards the front of the telescope where a collection of anywhere from one to seven lenses will correct the geometric aberrations while trying not to introduce chromatic aberration. For wide fields of view, the designs can become quite complex and expensive.

Typical single mirror systems will have apertures up to 1 meter diameter, operate at focal ratios in the range of  $f/2$  to  $f/4$  and image fields ranging from 1 degree to 5 degrees diameter. Although less common with larger apertures, very small aperture systems might include a flat fold mirror to move the detector package out of the collection aperture.

#### Two Mirror Reflectors:

Two mirror systems come in many configurations, but here we consider only those from the extended Cassegrain family, ignoring designs of the Couder, Schwarzschild and Gregorian type. Two mirror systems are well known to professional astronomers and used extensively for systems with apertures as large as 10.4 meters [31] and fields of view in excess of 3 degrees diameter [17]. For small aperture survey systems, the same designs can be readily adapted.

Typical Cassegrain-form small aperture survey telescopes will have apertures up to 1 meter diameter and fields of view as wide as 4.5 degrees. These systems will generally operate with focal ratios in the range of  $f/3$  to  $f/6$  and have correctors with anywhere from 2 to 5 lenses.

#### Three Mirror Reflectors:

Axially symmetric optical systems with three powered mirrors are much less common in ground-based astronomy. Very few systems are known to have been built. A few small aperture systems were built by Willstrop for demonstration purposes, but those systems are generally not in use for routine survey work [10]. McGraw built a 1.8 meter aperture system in the early 1980s and used it for narrow-field survey work, but the system is no longer in operation [32]. The Paul optical design can nonetheless be adapted to use for smaller aperture survey work. The main disadvantage of the approach for smaller apertures is that the obscuration ratio is generally significant. For large aperture systems where there are fewer alternatives due to the limited availability of large glass correctors, the Paul system makes more sense.

If adapted to small aperture survey work, Paul optical systems would range in aperture from about 500mm up to 1 meter diameter. Focal ratios would be in the range of f/1 to f/3 and fields of view would be typically in the 3 to 5 degree range.

Four Mirror Reflectors:

Systems with four or more mirrors are encountered infrequently. For axially symmetric configurations, the two most likely designs to be found are the double pass Cassegrain (direct view), and the reimaged Cassegrain. The double pass Cassegrain as a purely reflective instrument is achromatic and anastigmatic and images onto a flat image surface. Adding filters or even a dewar window degrades performance and the central obscuration is enormous. The reimaged Cassegrain is much more practical but optically more complex. It forms an intermediate image after the Cassegrain optics and reimages this focal position onto a final focal plane.

The double pass Cassegrain is capable of fields of view up to about 6 degrees and generally operates at focal ratios in the f/1.5 to f/2 range. The reimaged Cassegrain is much more flexible than the double pass Cassegrain and can image fields as wide as 7 degrees at focal ratios as fast as f/1.0.

The following table summarizes typical parameters for smaller aperture survey telescopes.

System Configuration	Typical Focal Ratios		Typical Fields of View	
	Low	High	Low	High
Refractor	f/4	f/7	2 degrees	9 degrees
Single Mirror full Aperture Catadioptric	f/1	f/5	1 degree	9 degrees
Two Mirror full Aperture Catadioptric	f/2	f/5	1 degree	6 degrees
Single Mirror Prime Focus Corrector	f/2	f/4	1 degree	5 degrees
Two Mirror Cassegrain Focus Corrector	f/3	f/6	1 degree	4.5 degrees
Three Mirror Paul-Type System	f/1	f/3	1 degree	5 degrees

## 5. Commercial Telescope Designs

When considering telescopes for small survey applications, it is reasonable to first turn to the commercial world to see if readily available off-the-shelf components can be adapted. Such commercial items come in an exceptionally wide variety of sizes and configurations and are likely to be much less expensive than production of a few custom optical systems. For this study, we examined the world of readily available commercial telescopes. We limited our consideration to those systems that could be purchased by a well funded backyard astronomer or a university research program. Essentially, this consisted of



standard catalog items. Results of the survey are presented in figure 1 below. There we plotted the field-of-view for these commercial systems against their aperture.

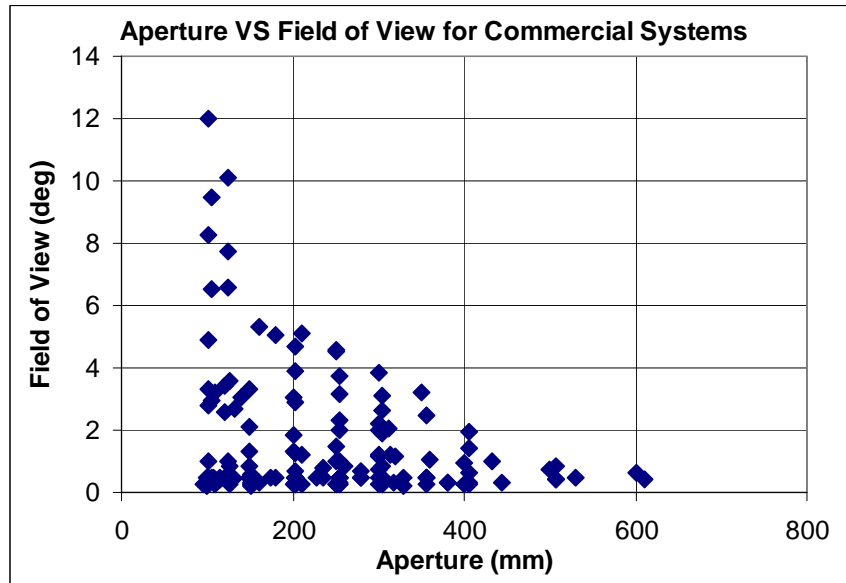


Fig. 1. Plot of Aperture VS Field-of-View for commercial telescopes.

What is striking about the data presented in figure 1 is that the majority of commercial telescopes exist in the lower left of the plot. The region to the upper right is completely devoid of available systems. Unfortunately, most modest aperture survey programs would benefit from telescopes with characteristics that would be plotted in the upper right corner of figure 1. No such systems are available on the commercial market.

This is not to say that commercial telescopes are unsuitable for survey work. There were a few telescope examples that would be attractive for smaller aperture survey efforts. The Takahashi FSQ-106, 106mm aperture, 9 degree field of view Petzval type refractor offers substantial wide-field performance. The Officina-Stellare Veloce RH-300 astrograph has a 300mm aperture and 3.8 degree diameter field of view. The telescope is of the Hamiltonian medial design family, folded in a Cassegrain-like configuration. Ceravolo offers a high quality 300mm Corrected Dall-Kirkham astrograph with a 2 degree field of view. Other isolated examples could be described, but the basic message would not change. Systems with apertures on the order of 500mm and fields-of-view on the order of 5 degrees are not available. Unfortunately systems with these characteristics would be ideal for most small aperture surveys.

## 6. Optical Designs from Major Astronomical Telescopes

Following the example of the previous section, we examined a total of 40 optical systems used at major observatories. In figure 2, we present a plot of field-of-view as a function of aperture.

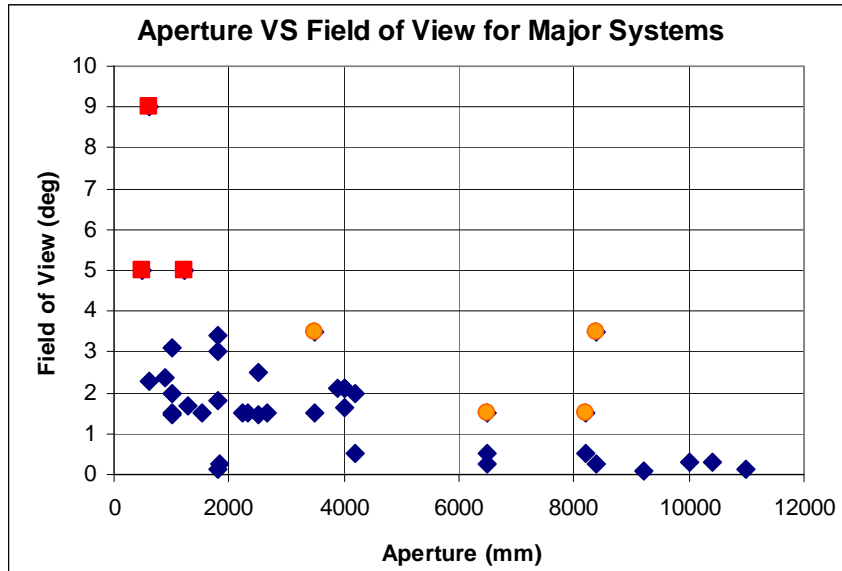


Fig. 2. Plot of Aperture VS Field-of-View for major telescopes.

This plot shows the same basic characteristics as that in figure 1, with a few notable differences. First, as a general rule, major systems do not operate with as wide of fields as smaller systems. This is simply the result of scaling where spot size changes with aperture, but the diffraction limit is fixed by the focal ratio. Second, there are a few systems that appear to exhibit abnormally wide fields of view for their aperture. The first one is at 600mm aperture with a 9 degree field of view. This is the International Concordia Explorer Telescope (ICT-T), an f/1.125 Schmidt system being built for observations from the South Pole [33]. Another unusual telescope is found at 3.5 meter aperture and 3.5 degrees field of view. This is the DARPA SST [11]. Even with the unusual curved focal surface, the system still stands out for its potential performance. The third system is at 8.4 meter aperture and 3.5 degrees field of view. This is the LSST [12]. When operational, this will be the “mother of all survey telescopes.” The final example is at 8.2 meter aperture and 1.5 degrees field of view. This system is the Hyper Suprime camera for Subaru [25]. Most of the other systems follow a trend similar to that seen for commercial systems. Wider field systems generally have smaller apertures. While some of the major systems might be candidates for scaling to apertures of less than 1 meter, none would really prove to be a standout except for the ICE-T which needs no scaling.

## 7. Optical Designs Used for Some Smaller Surveys

There are at present three excellent examples of modest aperture telescopes being used, or being built for wide field-of-view survey instruments. The first of these was mentioned above, 600mm Schmidt camera for ICE-T [33]. This system is somewhat unusual. While essentially a classic Schmidt camera, the telescope features two corrector plates and a three element cemented lens group for field flattening. It is designed to image a field 9 degrees wide, but will record a rectangular image 4 x 8 degrees. Two systems are being built, one optimized towards the blue end of the spectrum and the other

for the more red wavelengths. The basic design could easily be adapted to a more general survey mission. The optical layout for the ICE-T is shown in figure 3. The use of two aspheric plates in place of the traditional single Schmidt plate was first proposed by Linfoot in 1955 [34].

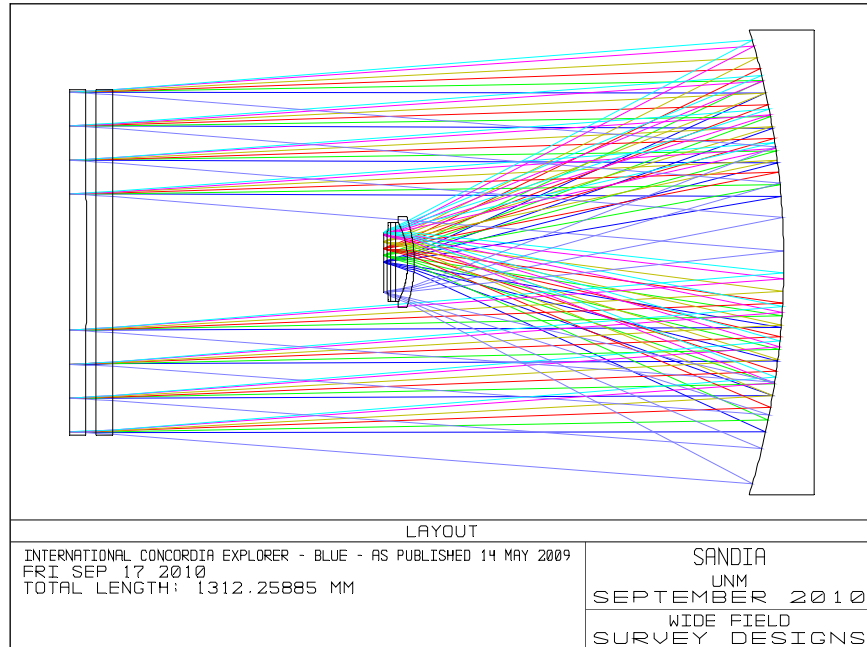


Fig. 3. 600mm ICE-T Schmidt Camera

The second system presently being developed is the Chinese Antarctic Schmidt Telescope [35]. It is actually a collection of three identical Schmidt-like cameras. The systems will have a 500mm aperture and image a field of 4.14 degrees diameter at a focal ratio of  $f/3.17$ . The optical design is really not a Schmidt camera but a variant of the Schmidt concept known as the Baker Reflector Corrector [7], which is then varied yet again. The Baker Reflector Corrector is very rarely encountered. The only two known examples are the Seyfert Telescope at the Dyer Observatory [36] and the Elizabeth Telescope in South Africa, sometimes known as the Cape Telescope [37-38]. The Chinese version is modified to have the corrector out front of the focal surface (probably for thermal reasons), and the primary mirror was allowed to acquire a hyperbolic figure. An approximate layout for the AST3 is shown in figure 4.

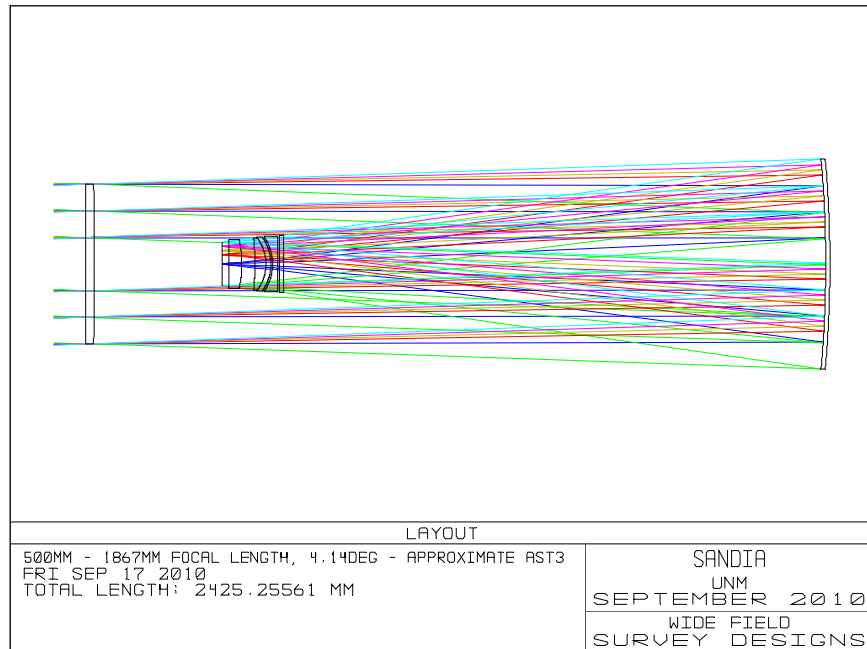


Fig. 4. Approximate AST3 Baker Reflector Corrector

The final system presently in use as a survey telescope is the 220mm aperture RST-220 of the ISON network [28]. While being slightly smaller than the previous two examples, it is included here as it was optimized for a field as wide as 6 degrees and can easily be scaled to an aperture of 500mm. The basic Richter-Slevogt (Houghton) optical system was modified by Valery Terebizh for wider fields by increasing the separation between the two full aperture corrector lenses [39]. The optical design is very simple and easy to fabricate, align and operate. An approximate optical layout for the RST-220 is shown in figure 5.

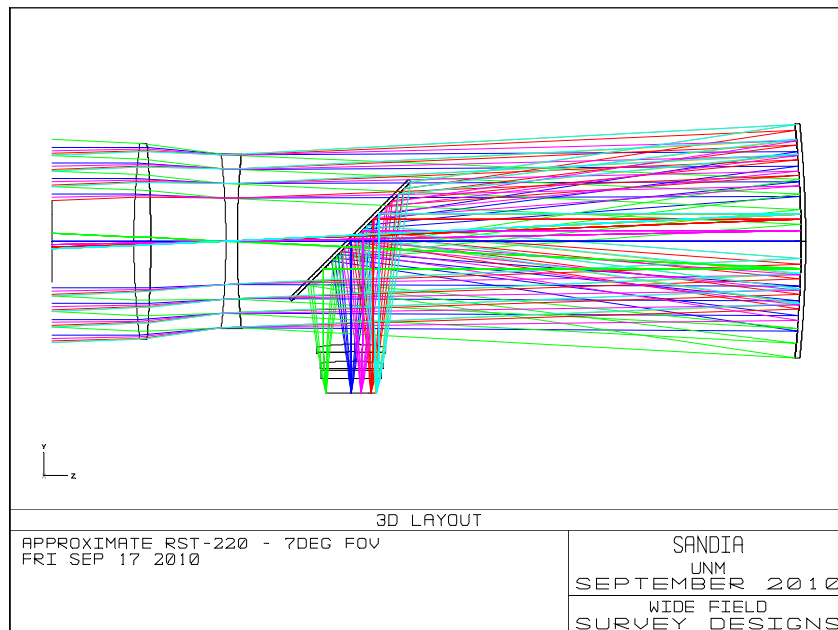


Fig. 5. Approximate RST-220 optical system.

## 8. Other Designs for Smaller Survey Telescopes

Seven other sample optical systems are shown to show help illustrate the content of the design space available for smaller aperture survey instruments. Each system is scaled to an aperture of 500mm and normally images a field of 4.5 to 5.2 degrees, depending upon the system. Each system is capable of placing most of the ray traced optical energy into a  $9\mu\text{m}$  square pixel.

The first system is a classic Baker Reflector Corrector modified with a more complex corrector before the focal plane and a fold mirror to place the detector package out of the optical system. This is shown in figure 6. At first look, the corrector design appears to be of the form used by Peter Wise [40] for his NeWise line of commercial telescopes, but the design is in fact very different. The Wise design uses a spherical mirror, and a negative lens group before the fold mirror with a positive lens group after the fold mirror. The present design uses afocal lens groups in both locations and a hyperbolic primary mirror. This astrograph represents an original design developed by the authors.

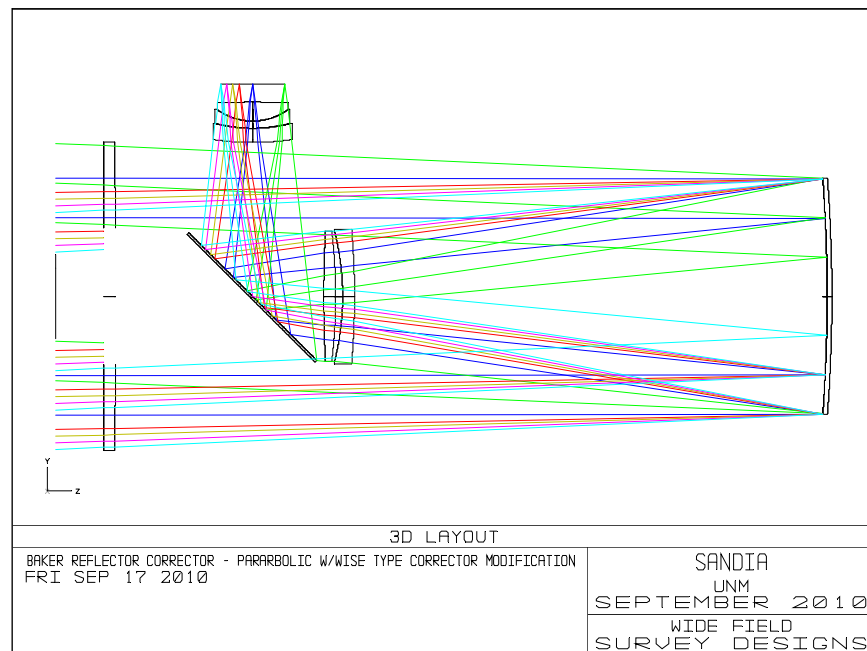


Fig. 6. Modified Baker Reflector Corrector System

The second system is a modified Maksutov, sometimes referred to as a New-Maksutov or NewMak. It features a split meniscus corrector. This system produces better image quality than either the modified Richter-Slevogt, or the classic Maksutov. The lens curves are more gentle than those used in the Maksutov, thereby making the NewMak easier to manufacture. The only drawback relative to a classic Maksutov is the use of two corrector lenses. The NewMak is an original design developed by the authors.

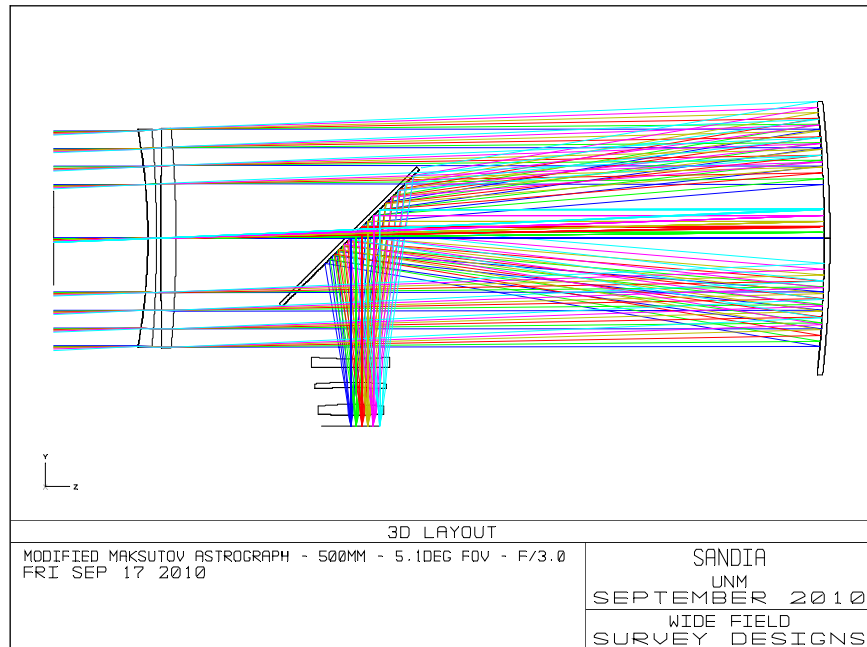


Fig 7. New Maksutov Optical System

The third optical system is a modified version of the classic Hamilton [41]. It is an unfortunate fact of history that this design is known as a Hamilton, based on the 1814 British patent issued to W.F. Hamilton. The design was actually developed by Sir Isaac Newton but never published [42-43]. Dating to the year 1672, Newton's design has since been analyzed and found to be both achromatic and aplanatic, it requires only a single glass type and was within the manufacturing capabilities of 17<sup>th</sup> century opticians. Had Newton published this design, it is likely that it would have significantly changed astronomy over the following two centuries.

The design presented here is highly modified from Newton's original concept. The light path is allowed to pass through the front lens twice, once in each direction, resulting in a significant departure from the Newton/Hamilton design. Here, we also use an angled fold mirror and a small corrector group just before the focal plane. This design is an original development of the authors.

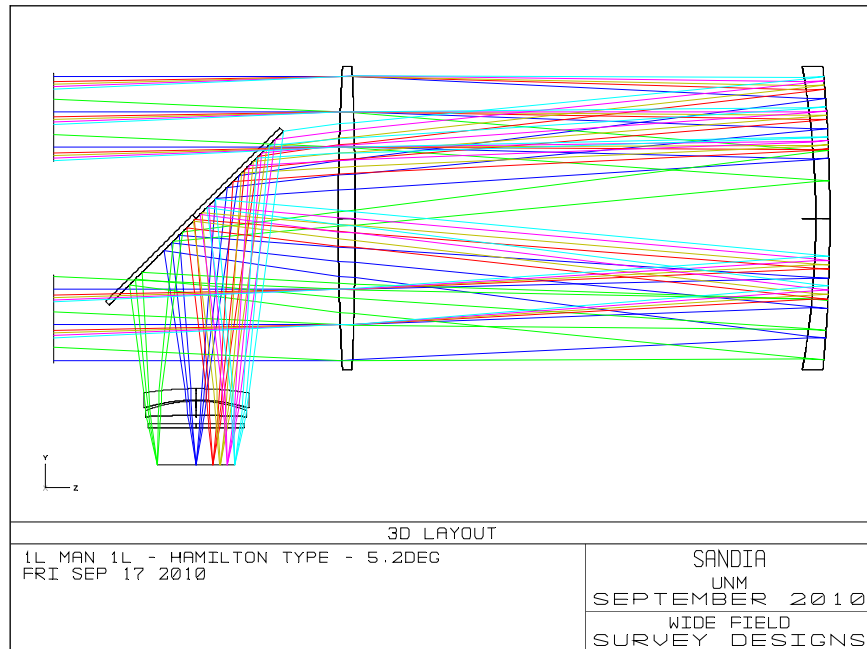


Fig. 8. Modified Hamilton system.

The fourth system shown is a simple prime focus corrector. The design features a hyperbolic primary and a five lens corrector with all spherical surfaces. No exotic glass types were used in the design. The optical layout is shown in figure 9.

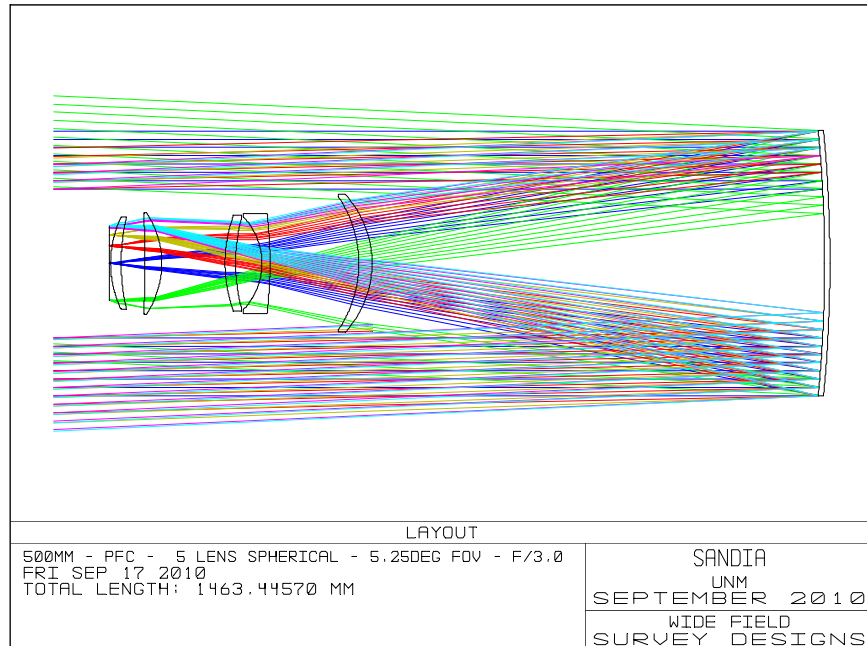


Fig. 9. Prime Focus Corrector

The next design is a super Ritchey-Chretien with a three lens corrector. It is optimized to produce images over a field of 4.5 degrees. The design is loosely based on the SkyMapper system [17]. The optical layout is shown in figure 10.

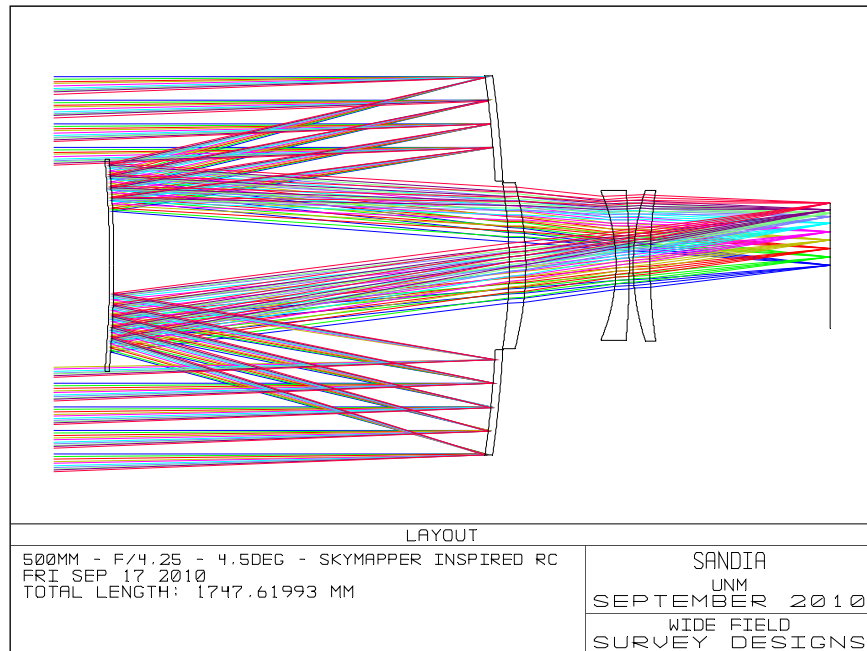


Fig. 10. Small aperture super RC survey telescope.

Three mirror anastigmats such as the Paul are possible in this aperture range, but generally result in greater obscuration than necessary given the fields of view. The following example shows a 500mm aperture Paul with a 4.6 deg field of view.

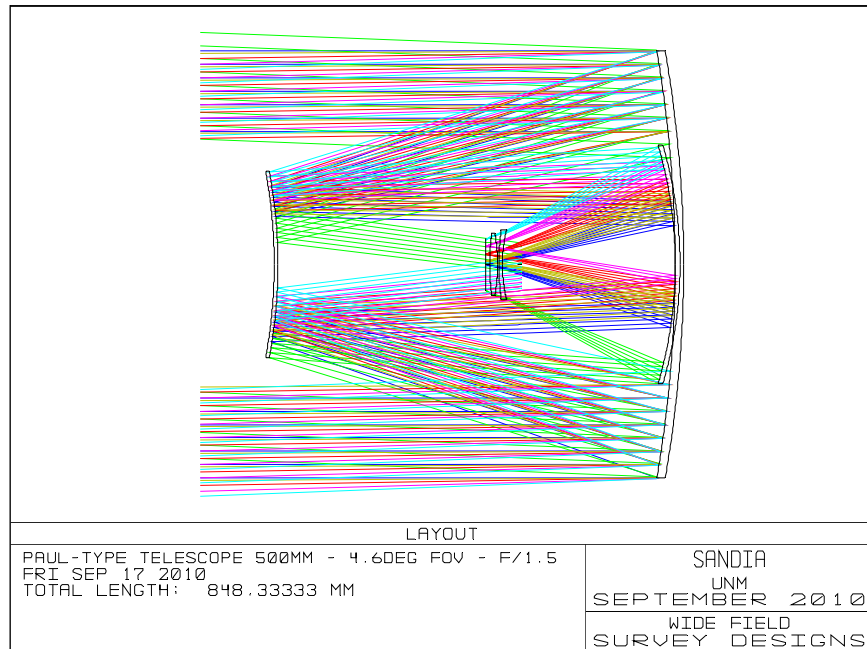


Fig. 11. 500mm Paul system.

What is highly interesting about the Paul and its variants is that it is capable of producing achromatic and anastigmatic images onto a curved focal surface using only mirrors. The



unfortunate result is that the inclusion of any refractive optics, such as a dewar window or filter, results in degraded images. It is therefore necessary to include refractive correcting elements whether one designs for a flat or a curved focal surface. What is interesting however, is that if a system is designed for a flat focal surface, it is possible to change the correcting optics and produce an image on a curved focal surface, with nearly identical image quality, without having to refigure the mirrors. The converse is also true. It is possible to start with a system optimized to produced images on a curved focal surface, and redesign the corrector to produce nearly identical image quality on a flat focal surface. Again, this is accomplished without modification of the mirrors. The corrector designs are somewhat complex, but easily within current manufacturing capabilities. Such a corrector would allow changing a telescope such as the DARPA SST from curved focal surface, to a flat focal plane, without loss of image quality or field of view.

The final system presented here has one of the widest practical fields and the design can easily be scaled to larger apertures. This design is a reimaged Cassegrain. It requires four mirrors and has substantial obscuration, but produces sharp images across a 7 degree diameter field at a focal ratio of f/1.0. The optical layout is seen in figure 12. The basic reimaged Cassegrain can be scaled to 3.5 meters aperture to produce a simple space surveillance telescope with a 3.5 degree field of view, imaging at f/1.0 and having three of the four mirrors of spherical figure. This is an original design by the authors.

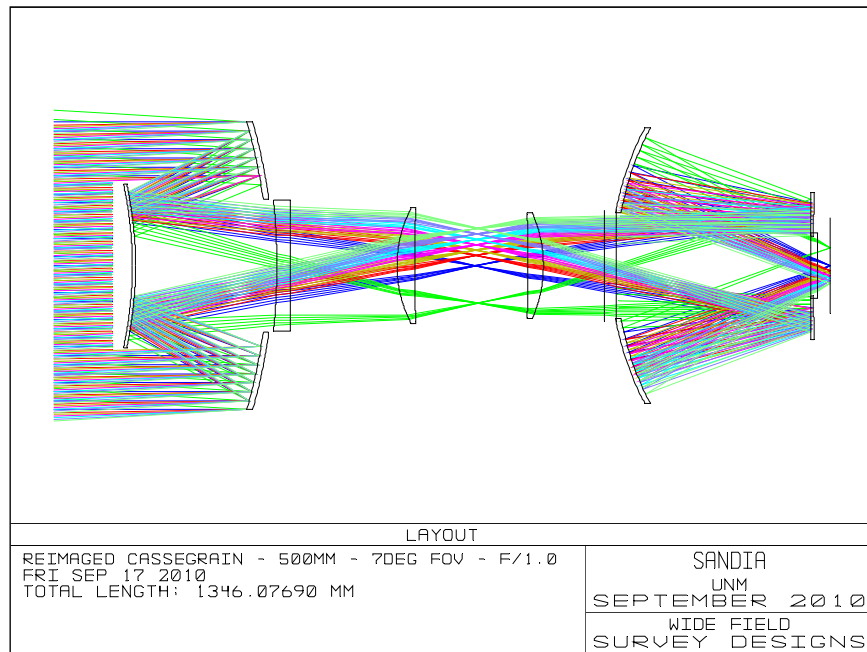


Fig. 12. Reimaged Cassegrain

## 9. Summary

The optical design trade space for small aperture survey telescopes is extremely rich. It contains scaled versions of all the larger aperture survey instruments, as well as a number of unique designs that can only be realized with smaller apertures due to the necessary size of refractive components. Unfortunately, that portion of the design space featuring

apertures in the range of 500mm to 1 meter diameter, with fields on the order of 5 degrees diameter or larger, is largely unexplored. Three designs in process or already in the field were identified as the only known entries into this part of the design space at this time. To complement these designs, we provided seven additional design, all of which fit into this largely unexplored part of the design trade space.

It is hoped that the information provided in this paper will find use helping to guide some future sky survey project during its early planning stages.

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