A Large Spectroscopic Telescope for Space Object Identification

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Abstract

A transportable, medium-aperture telescope with a segmented spherical primary mirror might find use as a spectroscopic space object identification tool. Systems with spherical primary mirrors are easier to produce, easier to align and easier to keep in alignment but image quality suffers greatly thereby placing significant demands on corrector optics. We present the design of an improved corrector for spherical primary telescopes. This design is novel, simple and adapts equally well to post prime-focus applications or to Cassegrain-form systems with spherical primary and spherical secondary mirrors.

1. Introduction

The tools of space situational awareness (SSA) include ground-based optical systems for detection, tracking and characterization of space objects. Characterization techniques include imaging, phase angle dependent photometry and spectroscopic observation.

Spectroscopy is a powerful tool but requires either large apertures or long integration times as the photons are dispersed by wavelength. For global SSA, low-cost, transportable assets would be preferred, but such would require new, more practical optical designs.

2. Background

On October 3rd, 1957, space systems were the objects of fiction and dreams. On October 4th 1957, with the launch of Sputnik [1], artificial satellites became an unknown reality. Over the past 51 years, space systems have found their way into almost every aspect of daily life. With more nations looking towards the military, social and economic benefits of space systems, awareness of what objects are in space, where they are, where they are going and what they are doing is critical.

An important part of SSA is space object identification (SOI). Objects must be identified to understand their function and to help resolve ambiguities when objects appear close and become misidentified. One tool useful for SOI is spectroscopy, but spectroscopy introduces unique demands for observing systems which differ from simple temporal photometers [2].

Modest aperture telescopes can be used to characterize satellites by observing their change in photometric brightness as a function of solar phase angle. Recording spectra, particularly dense spectra, spreads the available photons across hundreds, potentially thousands of wavelength bins. This necessarily requires longer integration times, larger apertures, or both.

3. A Spectroscopic Telescope for the Air Force

As the world-wide utilization of space increases, SSA will grow in importance. With this growth, interest in SOI will increase as well. It is believed that an affordable and practical spectroscopic system for SOI will be of interest to the global space community. Such a system would need to be replicated at a number of locations around the world. Rather than large, expensive fixed installations in locations with potentially changing social, economic and political climates, low-cost, transportable systems would likely be the better choice.

A large monolithic mirror would be a poor choice for a transportable telescope. Rather, such a system would most likely require some form of segmented primary which could be quickly disassembled or folded into transport configuration. While there are options for segmenting an aspheric primary, the need to quickly align the mirrors upon deployment, cost considerations and the demands of maintaining the figure of an aspheric mirror, suggests that a spherical primary would be a better choice. Spherical mirrors however present their own set of problems. A compact, short focal ratio telescope would require a fast spherical primary. The spherical aberration from such a mirror would be enormous necessitating correction.

The technical literature contains many designs for large telescopes with spherical primary mirrors. An excellent review of the literature can be found in reference three. Each design corrects the image over some practical field, but the design approaches vary widely and not all would be applicable to a robust, deployable spectroscopic telescope. One option would be to use a post prime focus type corrector on an articulated or fixed (Arecibo type) spherical primary mirror. The other option would be a Cassegrain form telescope.

The best example of a post prime focus spectroscopic telescope with a spherical primary mirror is the Hobby-Eberly Telescope (HET) at the McDonald Observatory in Texas. This telescope was actually once called the Large Spectroscopic Telescope [4]. The HET is an Arecibo type telescope where the primary is fixed in elevation at all times and fixed in azimuth during an observation. Tracking is accomplished by moving the spherical aberration corrector at the front of the telescope. Originally the HET was configured to drive a small number of fibers, but with the VIRUS instrument and the wide-field corrector (WFC), the telescope will drive a large integral field unit (IFU) fiber bundle [5]. The South African Large Telescope (SALT) is the sister to the HET [6]. SALT presently has a wider field with substantially better image quality but this will change when the WFC is complete.

It is possible to use a flat fold mirror to shorten telescopes of the post prime focus configuration. This was proposed for one design variation of the Overwhelmingly Large (OWL) telescope [7]. With the fold mirror, tracking can still be accomplished by moving only the corrector, or the full telescope can be articulated for tracking if desired.

At present, there are no large Cassegrain-form spectroscopic telescopes with spherical primary mirrors. A modest number of such designs are available in the literature, but without exception, they require relatively large, highly aspheric convex secondary mirrors. An initial assessment suggests that the cost and complexity of a large convex, aspheric secondary mirror would mostly negate the benefits and savings of a spherical primary. Wilson [8] presents the design for a wide-field spherical primary system. This design exhibits excellent image quality but relative to the primary aperture, the three remaining mirrors represent large aspheres. As most ELT projects are aiming for significantly smaller fields, the relative size of the corrector optics will shrink, but complexity remains high. A good example of such a spherical primary ELT concept is being considered by the 42m European ELT program [9]. Even with complex expensive designs, Cassegrain-form telescope have advantages in terms of physical length, over all focal ratio and pointing and tracking.

The most significant problem with developing a large spectroscopic telescope with spherical primary is the corrector optics. Existing and published designs are simply too complex.

4. The Improved Spherical Aberration Corrector

The solution to the problem of a practical, transportable, spectroscopic telescope with spherical primary is the improved spherical aberration corrector (ISAC) [3]. This is a highly innovative and extremely unusual corrector in that it uses only three surfaces but four reflections. It is adaptable to post prime focus applications such as for telescopes like SALT and the HET, and can be used with a flat fold mirror such as in the one OWL concept. ISAC is also readily adaptable to Cassegrain-form telescopes with spherical primary and spherical secondary mirrors. In this spherical-spherical Cassegrain configuration, the cost and simplicity advantages of the primary are also realized with the spherical secondary.

Without the use of adaptive optics, and when driving optical fibers, extremely high image quality is not required. Rather, it is only necessary for the optics to concentrate the light sufficiently that local seeing conditions dominate the point spread function. This allows reducing complexity further from ISAC designs intended for true imaging applications. The designs presented below contain only one aspheric surface in the entire optical system. Even so, image performance is really exceptional, particularly for the Cassegrain-form telescope.

The designs presented are adjusted to operate at a focal ratio of f/6. While some would argue that this is too slow for optical fibers and that focal ratio degradation will result in lost light, a properly designed system will perform as well as a telescope with a shorter focal ratio. While there will be some focal ratio degradation when driving the fibers at f/6, if this degradation is characterized and the spectrometer designed to be fed at this reduced focal ratio, there will be no loss relative to a telescope with a faster focal ratio. However, if desired, the ISAC designs can be adapted to focal ratios as fast as f/4.

Another point is that the designs presented below do not include an atmospheric dispersion compensator (ADC). An ADC should be included for working more than a few degrees away from the zenith. Many ADC designs are available and could be optimized into the system.

A system aperture of 4m was selected as being large enough to collect sufficient light to drive a spectrometer, yet small enough that it could be realized with a transportable, segmented spherical primary mirror. A likely design would consist of six hexagonal segments with a characteristic face to face dimension of 1.5m. In either system, the maximum diameter of the corrector optics is 480mm. The full imaged field is 6 arcmin. This is more than sufficient for spectroscopy of satellites.

<u>Post Prime Focus Spherical Primary Spectroscopic Telescope with ISAC</u>

The post prime focus design is seen in Figure 1, with Figure 2 showing detail of the corrector optics. Mirror 3 is the only asphere in the entire system. It has 4^{th} and 6^{th} order correction terms. Figure 3 presents the point spread function showing the spots well within a one arcsec diameter circle. Figure 4 shows the diameter for 80% encircled energy is 0.33 arcsec. The optical prescription for the system is presented in Tables 1 and 2 in Zemax format.

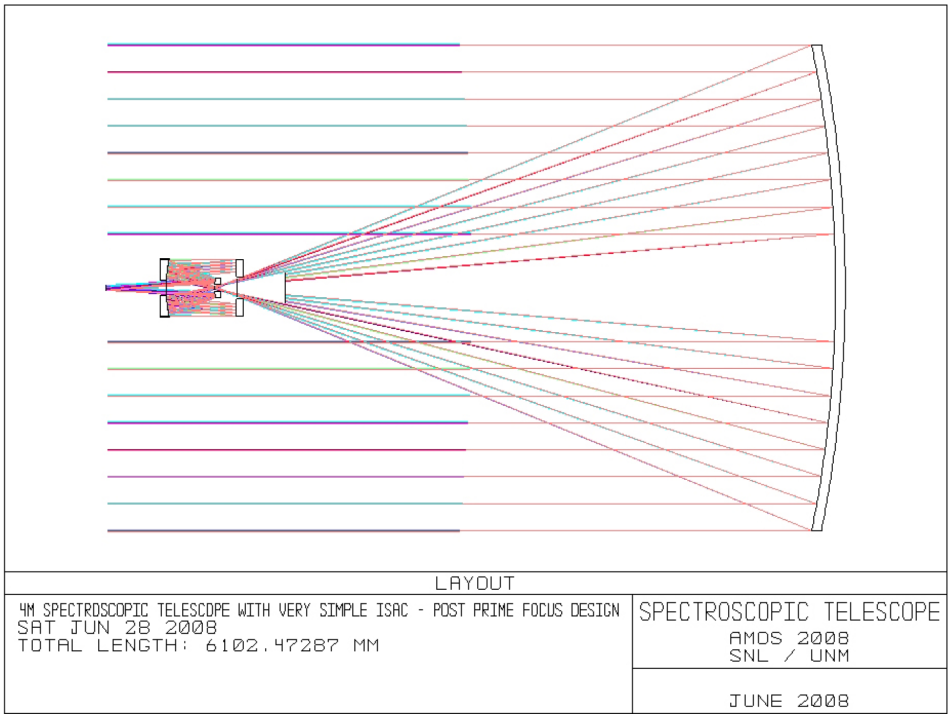

Fig. 1. Post prime focus telescope with spherical primary and ISAC corrective optics.

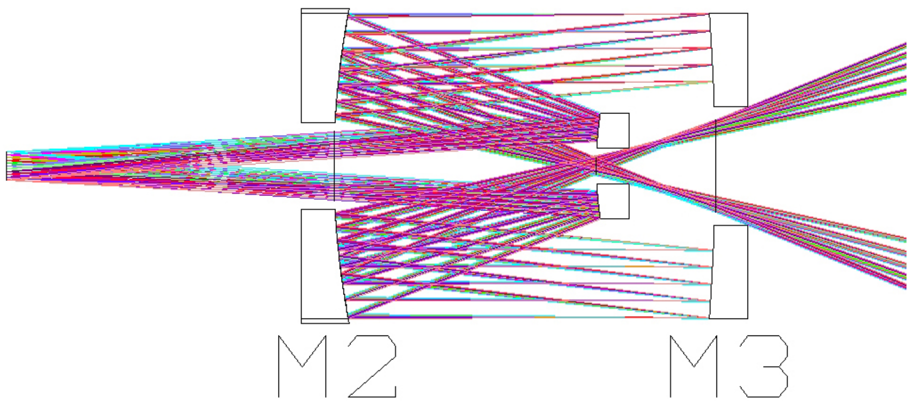

Fig. 2. Detail of corrector from Figure 1.

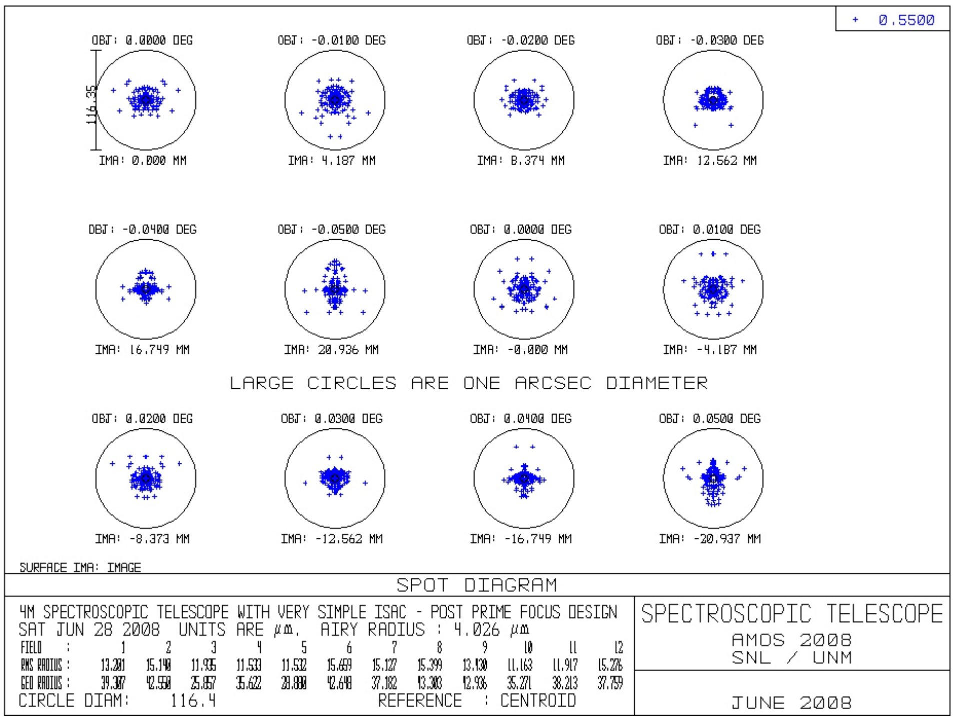

Fig. 3. Point spread function for post prime focus version of the spherical primary spectroscopic telescope with ISAC

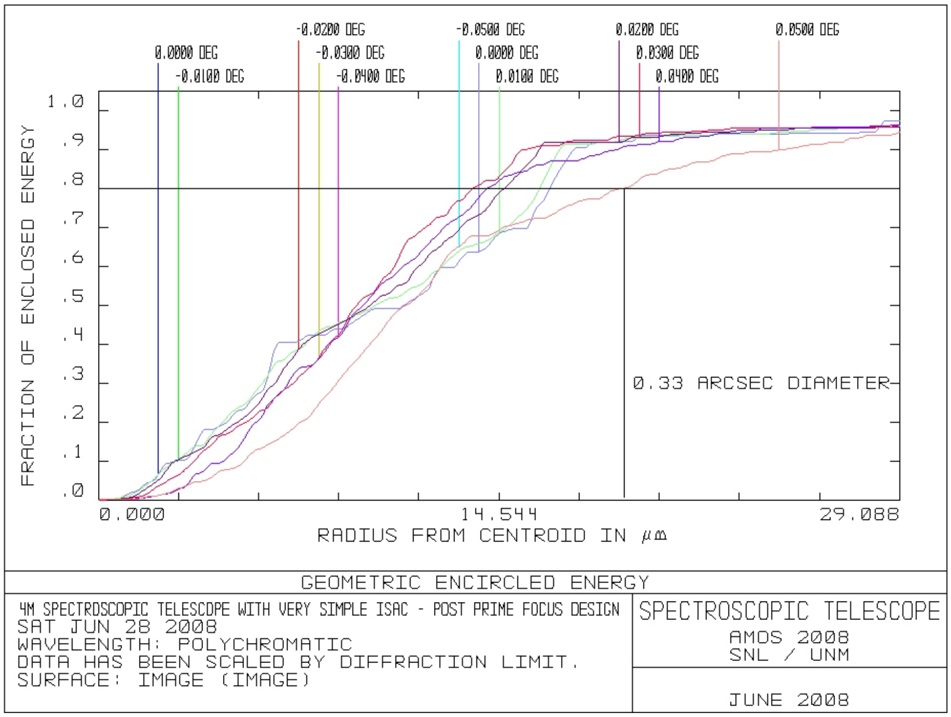

Fig. 4. Encircled energy plot for post prime focus version of the spherical primary spectroscopic telescope with ISAC

Table 1. Optical prescription (Zemax format) for post prime focus version of the spherical primary spectroscopic telescope with ISAC.

#	Type	Comment	Radius of Curvature	Thickness	Glass	Diameter	Conic
0	STANDARD		INFINITY			0.0000	0
1	STANDARD		INFINITY	6000.0000		0.0000	0
2	STANDARD	M1	-10400.0000	-4540.3316	MIRROR	4000.3389	0
3	STANDARD	BAFFLE	INFINITY	-400.0000		240.0000	0
4	STANDARD		INFINITY	-181.6544		140.7061	0
5	STANDARD		INFINITY	-400.3667		27.0792	0
6	STANDARD	M2	1230.7977	400.3667	MIRROR	480.0000	0
7	STANDARD		INFINITY	181.6544		0.0000	0
8	EVENASPH	M3	-2398.0748	-181.6544	MIRROR	465.0848	0
9	STANDARD		INFINITY	-400.3667		0.0000	0
10	STANDARD	M2 AGAIN	1230.7977	400.3667	MIRROR	464.8000	0
11	STANDARD	M4	514.3641	-400.3667	MIRROR	160.0000	0
12	STANDARD		INFINITY	-500.1134		107.0279	0
13	STANDARD	IMAGE	INFINITY	0.0000		41.8769	0

Table 2. Aspheric terms for surface 8 in Table 1.

#	Type	Comment	Glass		A2	A4	A6
8	EVENASPH	M3	MIRROR		0	7.2383E-10	2.9339E-16

Cassegrain-form Spherical Primary Spherical Secondary Spectroscopic Telescope with ISAC

The design for the Cassegrain-form telescope with spherical primary and spherical secondary is seen in Figure 5, with Figure 6 showing detail of the corrector optics. Mirror 4 is the only asphere in the optical system. It has 4^{th} and 6^{th} order correction terms. Figure 7 presents the point spread function showing the spots well within a one arcsec diameter circle. Figure 8 shows the diameter for 80% encircled energy is 0.21 arcsec. The optical prescription for the system is available in Tables 3 and 4 in Zemax format.

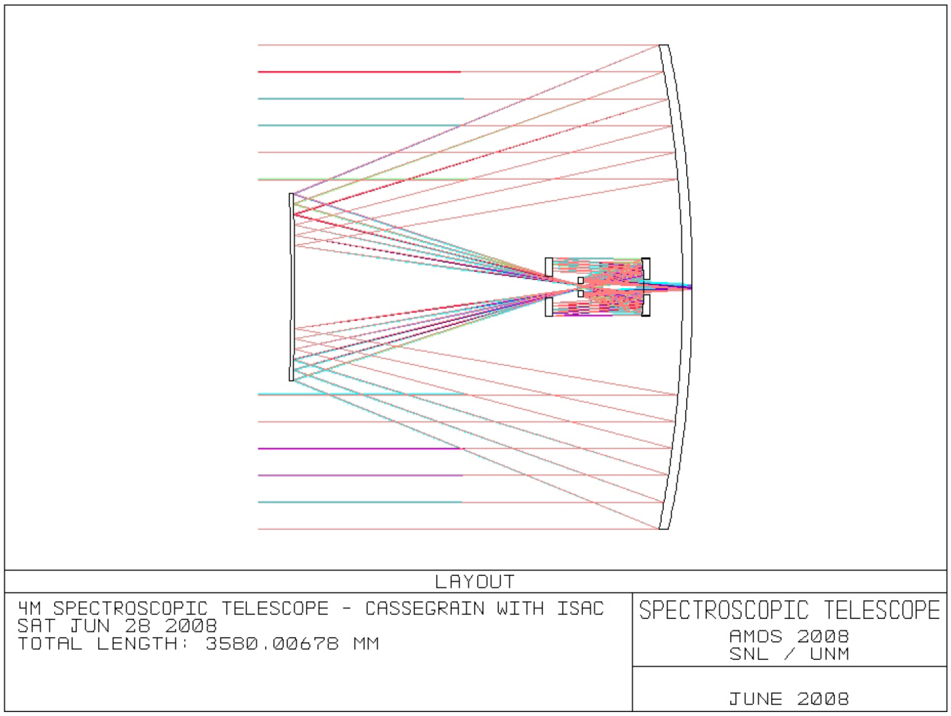

Fig. 5. Spherical primary spherical secondary
Cassegrain-form telescope with ISAC corrective optics.

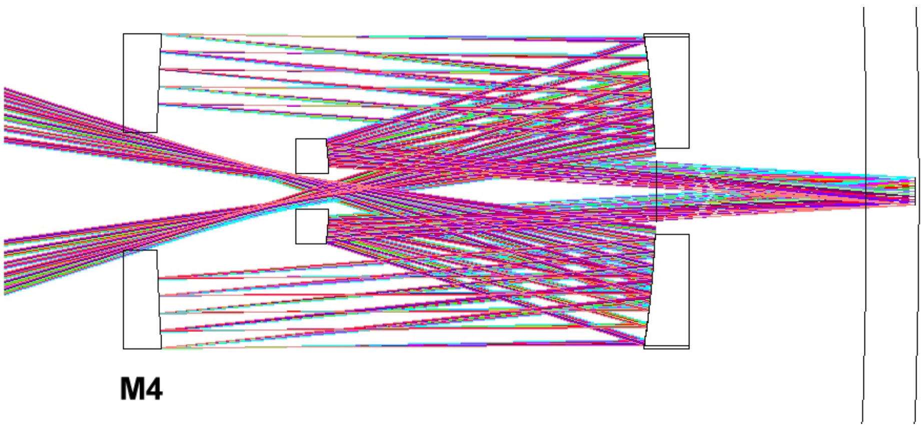

Fig. 6. Detail of corrector from Figure 5.

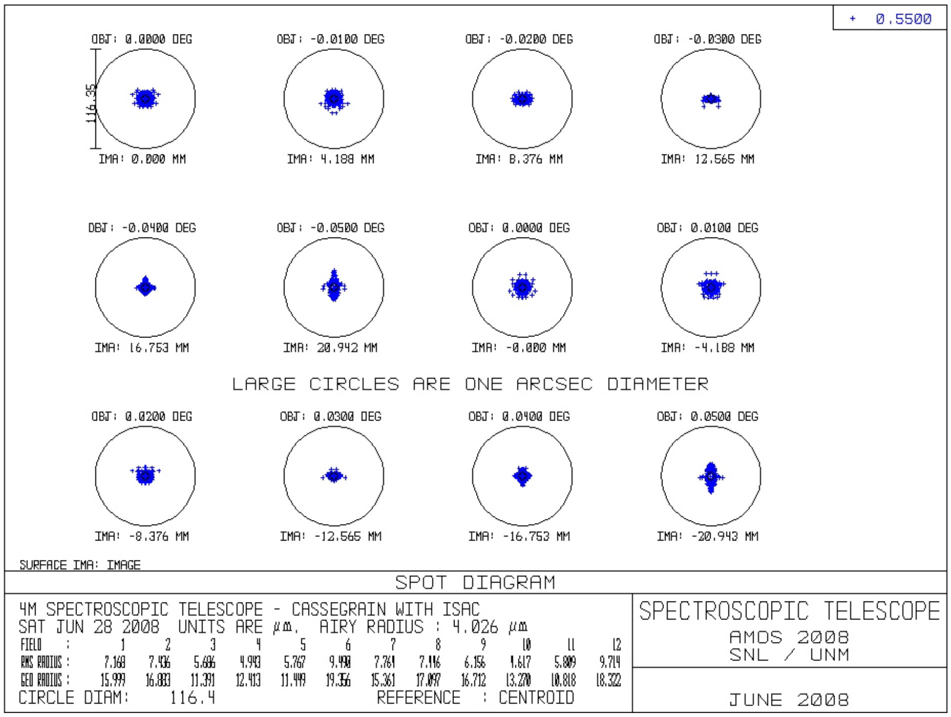

Fig. 7. Point spread function for the Cassegrain-form of the spherical primary spectroscopic telescope with ISAC

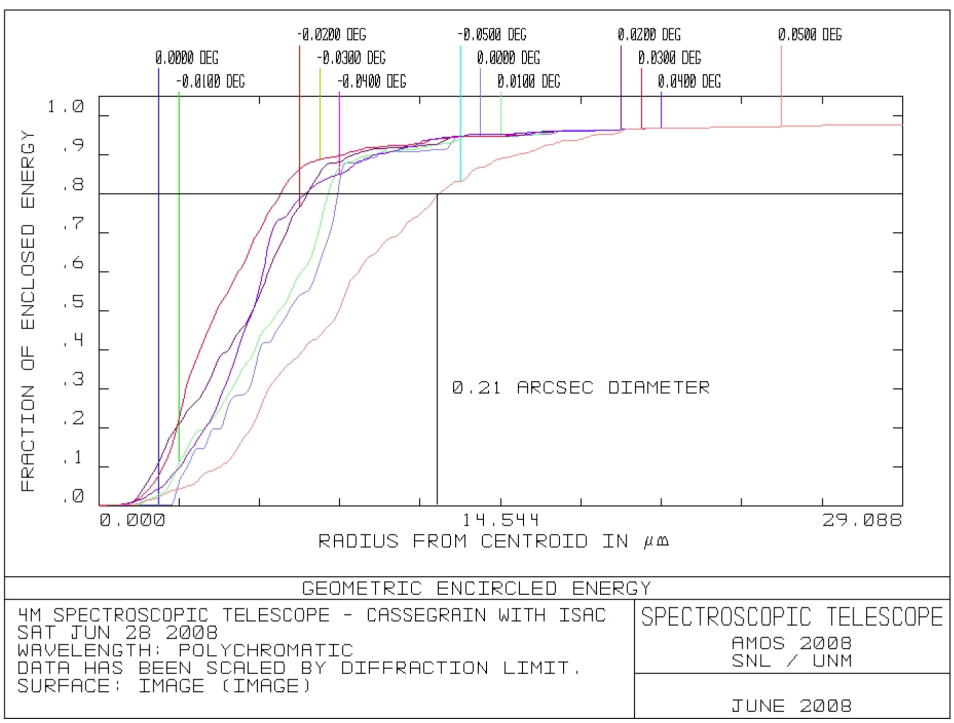

Fig. 8. Encircled energy plot for the Cassegrain-form of the spherical primary spectroscopic telescope with ISAC

Table 3. Optical prescription (Zemax format) for the Cassegrain-form of the spherical primary spectroscopic telescope with ISAC.

#	Type	Comment	Radius of Curvature	Thickness	Glass	Diameter	Conic
0	STANDARD		INFINITY			0.0000	0
1	STANDARD		INFINITY	3500.0000		0.0000	0
2	STANDARD	M1	-10400.0000	-3200.0000	MIRROR	4000.3389	0
3	STANDARD	M2	-20800.0000	1340.0000	MIRROR	1544.0373	0
4	STANDARD	BAFFLE	INFINITY	400.0000		0.0000	0
5	STANDARD		INFINITY	644.5269		0.0000	0
6	STANDARD		INFINITY	496.3932		0.0000	0
7	STANDARD	M3	-1547.3495	-496.3932	MIRROR	480.0000	0
8	STANDARD		INFINITY	-262.8072		0.0000	0
9	EVENASPH	M4	2927.2696	262.8072	MIRROR	480.0000	0
10	STANDARD		INFINITY	496.3932		0.0000	0
11	STANDARD	M3 AGAIN	-1547.3495	-496.3932	MIRROR	468.7335	0
12	STANDARD	M5	-659.6060	496.3932	MIRROR	160.0000	0
13	STANDARD		INFINITY	393.4065		93.8117	0
14	STANDARD	IMAGE	INFINITY	0.0000		41.8706	0

Table 4. Aspheric terms for surface 9 in Table 2.

#	Type	Comment	Glass		A2	A4	A6
9	EVENASPH	M4	MIRROR		0	-4.6438E-10	-1.7894E-16

Comparison with Other Approaches

Both spherical primary spectroscopic telescope designs require a three mirror corrector with one of the mirrors a general concave asphere. The significant advantage of these designs is the spherical primary and the relatively small diameter of the single asphere. There are however other telescope designs which should be considered. These include the Ritchey-Chrétien (RC), a relayed Ritchey-Chrétien (RRC), the Dall-Kirkham (DK), the Pressman-Camichel (PC), the classical Cassegrain (CC), the Harmer Cassegrain (HC), the Lovejoy Cassegrain (LC) and the Gregorian to name a few. The Gregorian is not considered further due to its length and similarity to the CC and RC. Various incarnations of the RRC are found in the literature but not considered further in this paper. The remaining systems are all of the Cassegrain form. Each will produce an image on a curved surface unless a refractive field flattener is used. All designs except the RC require a refractive field corrector. All systems were considered with a maximum secondary diameter of 1.5m. Primary-secondary separation was adjusted to give the highest image quality. Refractive correctors were limited to two lenses and a maximum diameter of 400mm. Table 5 reviews the physical characteristics of each system considered. Surfaces which are exactly parabolic are so identified rather than listing them as simple conics.

As seen in Table 5, the disadvantage of more conventional approaches to a large spectroscopic telescope is that each requires at least on aspheric surface and some designs require two. Both the aspheric primary and aspheric secondary mirrors are thought to be significant disadvantages of the more conventional approaches. Refractive field correctors represent an additional complication for most systems and are a limiting factor when attempting to scale to very large apertures. RMS image spot diameter (in arcsec) for each design is compared in Table 6, with performance for the Cassegrain-form system with ISAC included.

Table 5. Mirror configurations for Cassegrain-form telescopes.

Design	Primary	Secondary
Ritchey-Chretien	Conic	Conic
Dall-Kirkham	Conic	Sphere
Pressman-Camichel	Sphere	Conic
Classic Cassegrain	Parabola	Conic
Harmer Cassegrain	Parabola	Sphere
Lovejoy Cassegrain	Conic	Parabola

Table 6. RMS spot diameter for various telescope configurations.

System	Arcsec
Ritchey-Chretien	0.0337
Dall-Kirkham	0.0577
Pressman-Camichel	0.0444
Classic Cassegrain	0.0301
Harmer Cassegrain	0.0678
Lovejoy Cassegrain	0.0548
ISAC Post PF	0.1940
ISAC Cassegrain	0.0978

Table 6 clearly shows that over a 6 arcmin field, the various corrected Cassegrain configurations produce smaller spots than either ISAC design, but at the expense of a large aspheric primary, a large aspheric secondary, or both. Also, all of the classic forms require corrective lenses with the sole exception of the RC due to the relatively narrow field of view. In typical applications without adaptive optics, optical fibers will likely be fed with a beam diameter on the order of one arcsec. For this application, the ISAC designs have more than sufficient image quality for the final point spread function to be seeing limited. For a transportable system with segmented primary mirror, the spherical primary has significant advantages in terms of cost, setup and alignment. For apertures much larger than four meters, a spherical primary becomes even more important. If necessary, significantly higher image quality can be achieved by replacing the two spherical corrector mirrors with either conics or general aspheres [3].

5. Summary

We have presented the optical design for two simple telescopes which could easily be adapted for spectroscopic observation of artificial earth-orbiting satellites. Each telescope uses a 4m spherical primary mirror and a highly simplified version of the improved spherical aberration corrector (ISAC) with a single aspheric surface. The Cassegrain-form telescope has both spherical primary and spherical secondary mirrors. The optical designs are sufficiently simple that these telescopes should be ideal candidates for a transportable spectroscopic SOI system.

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