Lens systems for sky surveys and space surveillance

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ABSTRACT

Since the early days of astrophotography, lens systems have played a key role in capturing images of the night sky. The first images were attempted with visual refractors. These were soon followed with color-corrected refractors and finally specially designed photo-refractors. Being telescopes, these instruments were of long-focus and imaged narrow fields of view. Simple photographic lenses were soon put into service to capture wide-field images. These lenses also had the advantage of requiring shorter exposure times than possible using large refractors. Eventually, lenses were specifically designed for astrophotography. With the introduction of the Schmidt-camera and related catadioptric systems, the popularity of astrograph lenses declined, but surprisingly, a few remained in use. Over the last 30 years, as small CCDs have displaced large photographic plates, lens systems have again found favor for their ability to image great swaths of sky in a relatively small and simple package. In this paper, we follow the development of lens-based astrograph systems from their beginnings through the current use of both commercial and custom lens systems for sky surveys and space surveillance. Some of the optical milestones discussed include the early Petzval-type portrait lenses, the Ross astrographic lens and the current generation of optics such as the commercial 200mm camera lens by Canon. We preview our astrograph designs for commonly available CCD detectors.

1. INTRODUTION

Telescopes are usually built to address specific scientific questions, with angular field of view and image resolution being the usual primary design parameters. Two examples at the extremes of angular field size are: 1) efficient small-field observations of individual objects at high angular resolution for identification and characterization, and 2) wide-field surveys for clustered, diffuse or moving objects. Specific telescope designs often originate with the proponents specifying, at least qualitatively, the most important of the parameters that will result in a telescope that fulfills a particular mission. The requirements for a wide-field survey are markedly different from those for resolved imaging.

Astronomers in the mid-nineteenth century used the combination of a new detector – the photographic plate – and refractive cameras to accomplish wide field sky surveys that enabled discoveries which fundamentally changed our understanding of the universe. The heritage of those wide-field refractors, starting from portrait cameras, provides insight about today's designs of wide-field surveys for astronomy and Space Situational Awareness (SSA).

We briefly discuss the design parameters for a wide-field survey telescopes and lenses and contrast those with the physical characteristics that define a resolution-limited imaging telescope, such as those equipped with adaptive optics (AO), which provide a different type of SSA data.

The lessons learned from this foray into history are:

- Good designers know their past, think broadly about current problems and future solutions, and synthesize those solutions in optimal, extensible ways.
- Refractive elements in optical systems are not to be disdained. While surface reflection and transmission losses occur, and chromatic aberration is introduced, a century and a half of design expertise has gone into development of extremely capable refractive lens designs, and we can capitalize on that.

- Refractive telescopes can provide exquisite images over very wide fields and should be considered as candidates for certain SSA wide-field surveillance observations.

1.1 Fundamental telescope design – wide-field imaging

The practical telescope planning process usually starts with specifying all of the real factors (some of which are unknown or unrecognized at the outset) that are required for a successful, science-driven telescope. This process must include the fundamental parameters of the telescope and its detector system, and is also must include "matching" the telescope and its detector suite to the sky – the objects and object density, as well as the all-important background, and the expected detector noise sources, such as readout noise. If innovative focal planes play a role, their performance must be evaluated.

Design of successful telescopes starts with analysis of fundamental geometric optics defined by the planning process, and then evolves as the aberrations associated with real and manufacturable optics are evaluated. The design process must address the fundamental field angle dependent aberrations – which are termed "fundamental" for a reason! They cannot be ignored, especially for wide-field designs. They must be incorporated into the design process, and they ultimately limit telescope performance. Reflective surfaces have aberrations produced by figure and orientation, while refractive optics introduce chromatic aberrations. The image quality as a function of field angle becomes a primary metric for wide-field telescopes.

The design effort is carried out with highly capable software, usually ray tracing programs that allow both design and optimization and provide excellent predictions of telescope imaging performance. Most telescopes designed and built over the past three decades have used ray tracing as the principal design tool. Ray tracing is fundamentally straightforward [1]. Specified or randomly generated rays described by three direction cosines propagate through the system and are stopped, refracted or reflected at interfaces. The interface rules for reflection and refraction are:

$$r = i; reflection$$
$$n_1 \sin\theta_1 = n_2 \sin\theta_2\, ; refraction\ (Snell'sLaw)$$

For reflection, the angle of reflection relative to the normal of the reflecting surface at the point of incidence of the incoming ray is equal to the angle of incidence relative to the normal, with the incident ray, reflected ray and normal all being coplanar. For refraction θ_1 and θ_2 are coplanar with the normal of the refracting surface at the point of incidence and the amplitude of refraction is given by the ratio of the indexes of refraction of the materials on the respective sides of the optical interface. Refractive elements thus provide the advantage of three degrees of freedom in the design process: the curvature of the two optical surfaces of the optical element and the index of refraction of the material, while reflection provides one degree of (achromatic) design freedom. The thickness of refractive elements often plays only a minor role and is frequently not counted as a degree of freedom.

Since the earliest days of astronomy with optical instruments, there has been a type of telescope that was "in vogue" on differing timescales. The timescales are associated with development timescales for new optical systems, detectors, and the presumed, therefore funded, needs of the observers of the celestial sphere. For example, astronomical use of portrait lenses with photographic plates shows the wisdom of the astronomers of the mid-1800's to adapt a commercially developed product to image the sky, resulting in fundamental discoveries such as the dusty interstellar medium [2].

1.2 A Tiny Tutorial

The three fundamental parameters characterizing an optical/infrared telescope are the diameter of the entrance pupil D, the effective focal length, EFL, and the focal ratio, f/number [3]. The design scale factor for these parameters is the characteristic broadband or monochromatic wavelength, λ, of electromagnetic radiation being measured. The larger the diameter, D, the greater the collected flux. The longer the effective focal length, EFL the greater the image scale in the focal plane (pixels/arcsec), and the larger the focal ratio, the smaller the angular field of view. These three parameters are related:

$$f/number = EFL / D.$$

The preliminary design evolution of a telescope is basically the analysis of triangles – a telescope converts angles on the sky to angles resolved at the focal plane as displacements.

The first fundamental parameter, the focal plane image scale, s, provided by an optical system of EFL mm is given by

$$s = 1/EFL\ [rad\ mm^{-1}] = 206{,}265/EFL\ [arcsec\ mm^{-1}]:$$

which specifies the mapping of angle into focal plane displacement.

The second fundamental parameter of telescope specification is its angular resolving capability. The characteristic angular resolution of a telescope pupil (here assumed circular) is the Fraunhofer diffraction pattern of the entrance pupil evaluated at wavelength λ [4][3]. The intensity diffraction pattern, an Airy pattern, results from superposition of electromagnetic radiation which propagates as a wave through the pupil. The familiar shape of the Airy pattern is described by a special function, the Bessel function of the first kind of order unity, applicable to circular boundary value analyses. The angular resolution, defined as the (angular) distance from the peak of the diffraction pattern to the first dark ring is:

$$\sin\theta = 2 \times \frac{1.916\lambda}{\pi D},$$

where the factor 1.916 results from evaluating the argument of the Bessel function for the first zero of this function, $J_1(2m)$, which occurs for m = 1.916.

For small angles

$$\theta \cong \frac{1.220\lambda}{D}\ [radian] = 2.516 \times 10^5 \frac{\lambda}{D} [arcsec],$$

the familiar Rayleigh criterion for evaluating the angular resolution of a circular optic. The Rayleigh criterion is also often used to characterize the resolution of a pair of objects imaged by an optical system because this length places the intensity maximum of a star in the first diffraction minimum of another.

The third fundamental parameter for application-driven telescope design is the angular field of view on the sky provided by the telescope. This is primarily determined by the focal ratio of the telescope. For a detector of given physical size, a shorter focal ratio will image a greater solid angle of the sky on that detector, but at the expense of less angular resolution per pixel.

We now have the fundamental parameters to estimate the zeroth order parameters of a telescope. Fig. 1 illustrates the physical bases of these fundamental parameters with a specific example. Fig. 1 shows that the longer the EFL, the larger the focal ratio and the less light is concentrated into a pixel in the focal plane. Thus long focal length systems are "slower" than smaller focal ratio "fast" systems because it will require a longer integration time on the scene to acquire the same total signal per pixel as provided by the faster optical system. Note that the fundamental focal plane resolution element for both telescopes observing at the same wavelength, 500 nm in the optical, as a specific example, is the same: $\theta = 0.126$ arcsec. The one difference between the systems is that the EFL for the upper system is 1 m, whereas the EFL for the lower is 2 m resulting in an f/1 upper and an f/2 lower system subtending different angular scales in the focal plane. Assuming a solid state detector with 9 µm square pixels, the f/1 system pixels will subtend 1.86 arcsec, while the f/2 system pixels subtend 0.93 arcsec. The f/1 system thus is capable of focusing four times more light into a pixel than is the f/2 system, illustrating why telescopes requiring brighter images are designed with faster focal ratios. Note that this means four times the background per pixel, as well! Similarly, for a given detector the faster optical systems image more of the sky in a single exposure. The detection limit of the faster system is, in general, fainter for the faster system for equal exposure times. The faster system, because of its pixel scale, cannot resolve detail on the angular scale of the telescope resolution element. (In this example, neither can the f/2 system, with pixels subtending 0.93 arcsec while the telescope delivers 0.126 arcsec resolution!)

In fact, this example also demonstrates that by choosing a detector with specific pixel size, p, and specifying the pixel resolution, s - a usual procedure in preliminary design of a telescope - the required effective focal length, EFL, of a telescope can be determined. For example, a sky survey project might *a priori* determine that one 9 µm (0.009 mm) pixel should subtend 1.5 arcsec. This statement provides a starting point for the effective focal length of the instrument

$$EFL = 1/s = 0.009 * (206265/1.5) = 1237.6\ [mm].$$

As we proceed with mission-driven telescope design we should seek solutions with effective focal length of about 1.2 m. Usually the EFL, as well as the other initial parameters of a telescope, evolve somewhat as mission requirements are re-examined and knowledge of design complexity and cost is included in the preliminary design considerations.

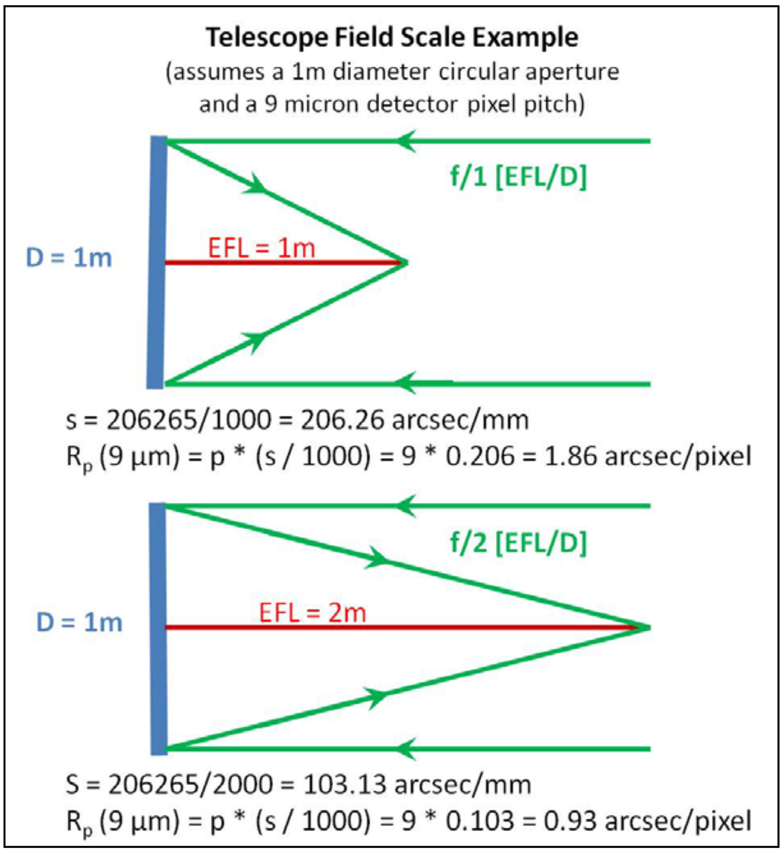

Fig. 1 provides a specific comparison of two schematic telescopes differing only in their effective focal lengths, EFL, and thus their f/ ratios. The diameter, D, of each pupil is defined as 1 m. The upper panel shows the imaging geometry for a telescope of f/1, that is, an EFL of 1 m. The lower panel shows the geometry of an f/2 telescope, with an EFL of 2 m. The field scale, s, and the pixel resolution in arcseconds, R_p, is calculated for a detector of pixel pitch p = 9 µm for each case.

The most significant issue relative to these fundamental telescope parameters, especially for wide-area sky surveys, is that they can be combined with knowledge of the size of the (seeing blurred) image and the sky brightness in the bandpass(s) to be observed to define an "optimal" telescope based upon the signal-to-noise (S/N) achievable for faint objects. In general, larger telescopes and longer integration times result in fainter limiting magnitudes for point-source (i.e. unresolved) images. Moving object surveys, for example meteor or uncued satellite detections, have integration times limited by the rate of motion of the objects, and the instantaneous field of view should be as large as possible to maximize the detection rate. These objects are imposed upon the (appreciable) background light of the sky. That background light is subject to the same statistical fluctuations imposed by random arrival times of individual photons at a pixel as are the photons arriving from an object to be detected in the presence of this noise.

The background is a significant and often limiting source of noise. Seeing-limited telescopes, with resolution limited to ~ 1 arcsec, and for which larger telescope diameter and focal ratio results in no further isolation of point images on the background, have an optimal diameter and focal ratio determined by the signal-to-noise (S/N) of faint images on the appreciable background.

The background is the limiting design factor for ground-based, wide-field telescopes. The background fills the entire field of view of the telescope and every point in the field radiates uniformly into every angular resolution element of the detector. For a background radiance B [W $m^{-2}\theta^{-2}$] in the observed optical bandpass, the sky brightness in a single resolution element is proportional to $B\theta^2D^2$. Integrating for time *t*, the background signal is $Bt(\theta D)^2$ with consequent noise $\sqrt{Bt}$ (θD). The point-source signal is proportional to tD^2, yielding a signal-to-noise ratio

$$S/N \propto \frac{(tD)^2}{\sqrt{tB}(\theta D)} = (D/\theta)\sqrt{t/B}.$$

Thus obtaining optimal (or acceptable) S/N for a survey telescope involves optimizing the telescope diameter with respect to the (variable) site seeing, the (variable) site sky brightness, and the (often externally dictated) integration time (cf. [5]).

The resolution requirements and tradeoffs for terrestrial wide-field surveys are fundamentally different from those for high angular resolution observations. A major goal of adaptive optics (AO), for example, is to recover the diffraction limited performance of a telescope observing through a turbulent atmosphere. A requirement of an AO or space-based system is thus that the detector pixel spacing resolves the diffraction pattern. Many references dealing with AO describe telescopes that recover a major fraction of the fundamental angular resolution of the telescope [6]–[8], thus requiring that the detector record that detail.

For wide-field imaging systems, this requirement is replaced by the requirement to angularly resolve closely spaced seeing-blurred point source images in conditions determined by the distribution in time of astronomical seeing. Observing through Earth's turbulent atmosphere results in time-dependent modulation of individual seeing-limited point source images, thus this resolution criterion is only statistically determined.

Deriving a criterion for the required angular resolution of a (terrestrial) wide-field survey thus depends almost totally on the seeing conditions at the telescope site. Bally et al. [9] have empirically determined a useful resolution of 2.2 pixels per angular seeing profile, often taken as the modal FWHM seeing for the site, or some percentage of that histogram (e.g. the seeing encountered 10% of the time at the site). This criterion results from application of the sampling theorem to the statistical FWHM of the seeing-blurred PSF. For wide field surveys involving moving objects, this criterion can be further relaxed to match the pixel size to the seeing blurred PSF.

Thus, a narrow field AO system designed to match the pixel pitch of a detector might require pixels that subtend ~ 0.05 arcsec, while for a terrestrial wide-field imaging system a pixel might subtend ~ 0.5 arcsec. Thus, a detector applied to a wide-field system might easily subtend 100 times more sky than the same detector used on an AO system designed to resolve diffraction-limited detail in the image.

And then there are optical aberrations waiting to spoil your day [3]. The considerations discussed thus far "get us into the ballpark" with respect to telescope design. The real design efforts involve obviating the effects of optical aberrations. The fundamental (Seidel) aberrations are:

- Spherical aberration
- Coma
- Astigmatism
- Distortion
- Field curvature
- Chromatic aberration

Note that these are fundamental aberrations arising from the physics of the function of lenses and mirrors that must be eliminated and/or balanced in the design effort. Spherical aberration and coma, for example, respectively result from the reflection or refraction at a surface arising from the geometrical definition of a spherical and a parabolic surface. Chromatic aberration results from refractive elements (generally glass) having wavelength-dependent index of refraction.

To the fundamental telescope detector and atmospheric properties discussed above, a wide-field survey telescope must survey the largest reasonable area on the sky to the required limiting magnitude. The metric for this requirement is usually the “throughput” characterized as the *etendue* or “AΩ product” - the product of the effective area of the telescope pupil, A, and the observed solid angle on the sky, Ω [3]. The etendue results from conservation of radiance from the source through the properly designed optical system. For initial design purposes the “raw” etendue can be estimated as the product of the area of the primary pupil and the solid angle subtended by the field of view on the sky. For wide field surveys, big etendue is way better!

2. IN THE ERA OF ASTROGRAPHS

A particular type of astronomical telescope, the astrograph, is of current interest because previously these telescopes successfully repeatedly surveyed large fractions of the sky with remarkable scientific impact.

The name “astrograph” is a modern English concatenation of the Greek “astro-“ derived from “astron,” star, but properly constellation, or “stars strewn across the sky,” and the Greek “graphos,” “to draw” [10]. Thus an astrograph “draws” the stars (natural or artificial) strewn across large areas of the sky.

Astrographs represent “tours de force” in optical design and matching of detectors to the optical systems. Their unique ability to survey large fractions of the sky in single exposures make them particularly useful as examples of telescope design and as benchmarks for addressing optical surveillance of the sky to support Space Situational Awareness (SSA).

The driver for camera designs, including astrographs, was the invention and refinement of the detector – the photographic plate. Modern photography based upon dry plates or films that could be stored prior to use and would remain stable over long periods of time traces its history to the work of French inventors Joseph Niepce and Louis Daguerre in the era 1827 – 1839 [11][12]. It was astronomers Johann von Maedler and John Herschel who in 1839 publicly used the word “photography” applied to this process, showing that from the earliest history of the process astronomers were searching for techniques – detectors – that could record the sky. It was John Herschel who, based upon his experiments, proposed the use of silver chloride in the manufacture of photographic plates [13]. In 1879 the dry photographic plate allowed photographers to prepare and store emulsions for later exposure, and the images formed on these plates were stable and persistent, allowing copies to be made from a single negative plate. In 1889 George Eastman invented a flexible film base for emulsions, and photography exploded as an accessible, useful technique.

Portrait lenses designed to record scenes and events on photographic plates, which have image resolution ~ 10 μm, were naturally adapted to observation of the night sky. Lens systems principally designed for portraiture are listed here. Virtually all of these lens systems have their own literature, much of which is web accessible. All of these lenses have been used for astrophotography! It is this suite of lenses that first enabled surveys of the nighttime sky.

<u>Milestones in Lens Design</u>

- 1841 - Petzval Portrait
  - Bruce Telescope, Willard Lens, Bache Lens, Draper Lens
- 1866 - Rapid Rectilinear
- 1887 - Double Gauss
  - Aerial lenses in Ballistic Cameras supporting early SSA
- 1890 - Protar
- 1893 - Cooke Triplet
  - Metcalf 10-inch, Lowell-13-inch (Pluto discovery lens)
- 1896 - Planar
- 1899 - Celor
  - Led to Ross Astronomical Lens

- 1899 - Unar
- 1900 - Heliar
- 1902 - Tessar
- 1931 - Sonnefeld

2.1 Astronomical Astrographs

Fig. 2 shows the nearby galaxy Messier 31 as imaged by astronomer E. E. Barnard on 26 August 1889 [14], [15], nearly 125 years ago. Barnard and other astronomers recognized the “nebular” nature of M 31, but the idea that it was an external galaxy much like our Milky Way was still 50 years in the future. Astrographic images of the Milky Way led to the understanding of our Galaxy as a flattened system of stars, discovered nebular regions of large angular extent, later recognized as gas and dust concentrated in the central plane of our disk-like Galaxy, and observed smaller nebulae on the sky leading to the current inventory of planetary nebulae and supernova remnants in the Milky Way and the “fuzzy patches” later resolved as other galaxies. Certainly our understanding of astronomy improved when astronomers could examine “the broader view” of the celestial sphere!

Fig. 2. Messier 31, the Andromeda Galaxy, photographed by E. E. Barnard on 26 August 1889 using the Lick Observatory Willard lens [16], a variant of the Petzval portrait lens design. The width of this image subtends more than 10 degrees on the sky.

Development of lenses for both portraiture and for astrography was evolutionary, with design improvements driven by the necessity for minimizing aberrations and consequently producing higher resolution and lower distortion over wide fields of view. Figure 3 shows the simple optical layouts of the Petzval Portrait lens and the Triplet Lens. Both lenses use elements fabricated of crown and flint glass to minimize chromatic aberration while attaining the required optical power from each lens assembly.

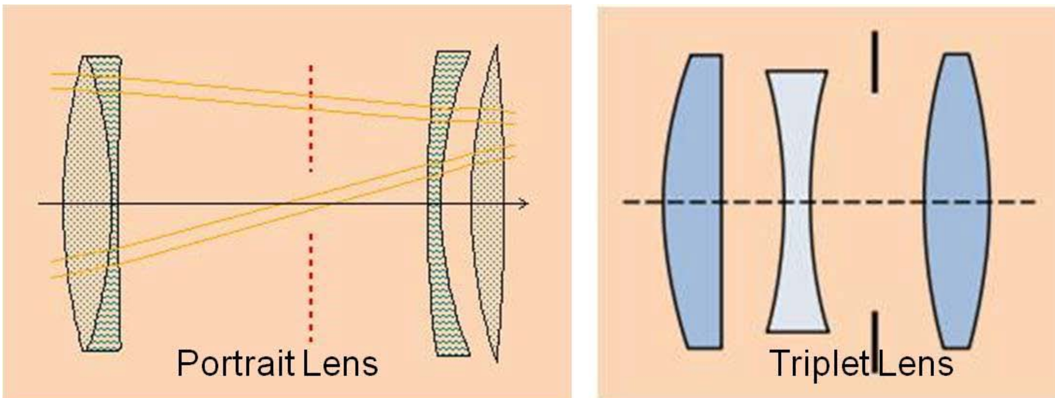

Fig. 3. The left panel shows the optical layout of the portrait lenses first used in astrographs. This exemplifies the optics of the Willard Lens, commercially produced for portraiture. The first and fourth positive (converging) elements are fabricated from crown glass while the negative (diverging) second and third elements are flint glass. The right panel shows the generic triplet that has evolved into commercially produced versions used today, such as the Cooke Triplet. This system used positive crown glass elements with a central negative flint glass element to minimize chromatic aberration.

Further evolution, with slightly increased optical complexity, is illustrated by the derivation from the Triplet Lens of three related four-lens systems, the Sonnenfeld-Vierlinser [17], Ross Astronomic [18] and Tessar [19] lenses, shown in Fig. 4.

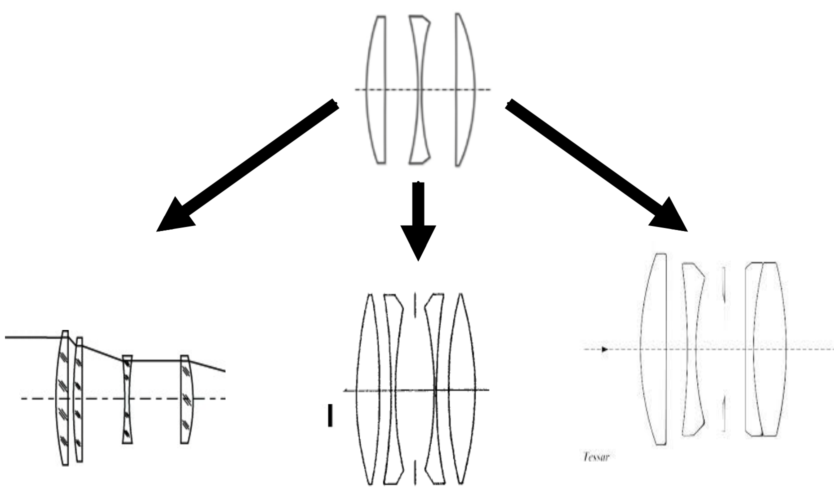

Fig. 4. The Sonnenfeld-Vierlinser, Ross Astonomic and Tessar (left to right) lenses evolved as variants of the original Triplet Lens. This illustrates the ongoing spawning of new designs from old. Each of these versions of the triplet lens maintains the “crown-flint-crown” glass sequence to minimize chromatic aberration with new surfaces used to minimize spherical aberration in the quest for higher image resolution, color correction, and larger undistorted fields. (Technically, the Tessar evolved from the Zeiss Unar, a design with four separate lenses.)

The Bache camera was based on a Petzval-type portrait lens. This was the camera that first imaged the Horsehead Nebula in the Orion Complex, shown in Figure 5. This discovery was a significant observation that supported the idea that dust in nebulosity absorbed light, and that the dark structures in star-forming regions were not the "absence of stars," but rather clouds of dust so optically thick that little to no background light could be seen. We now know that it is the dark regions of gaseous nebulae (H II regions) in which new stars are, in fact, in the process of formation.

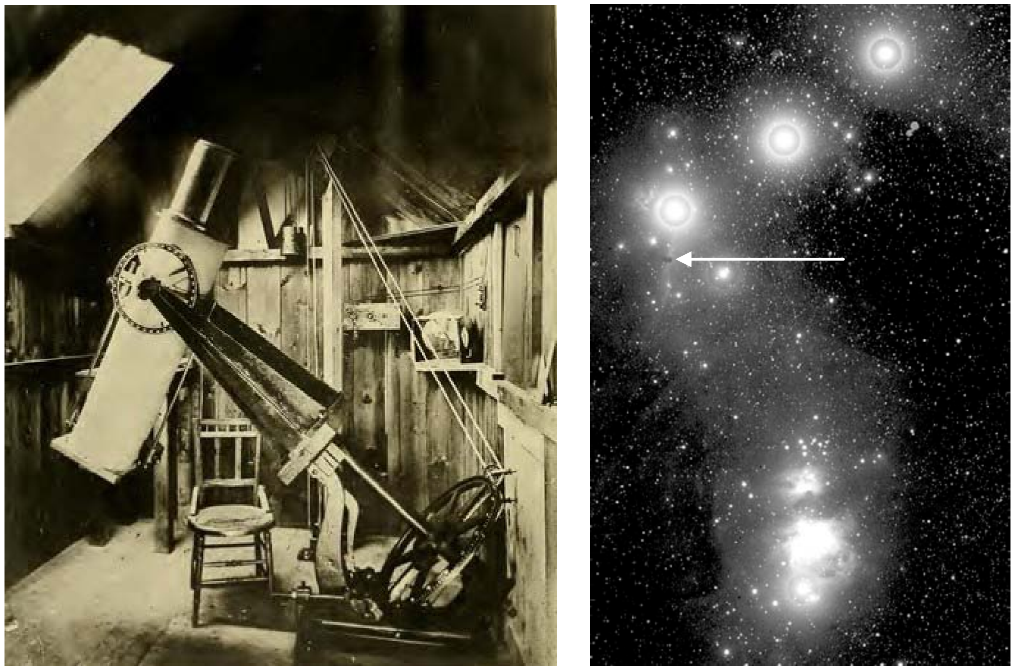

Fig. 5. Williamina Fleming used the Bache portrait lens from Cambridge in 1888 to observe the Horsehead Complex [20]. The three bright stars at the top of this image are the belt of Orion in this familiar winter constellation. The Horsehead Nebula, just below Alnitak, is marked with an arrow. Note the bright photographic halation rings surrounding bright stars in this image.

This observation illustrates the capability of wide-field photographic imagery to provide data leading to detection of subtle but exceedingly important new features in the night sky. The fundamental discovery of obscuring dust mixed with the gaseous interstellar medium led to today's understanding of the composition of the material and the environment of regions of new star formation.

The first of the "icy worlds" of our solar system, Pluto, was discovered at Lowell Observatory using the 13-inch Cooke Triplet telescope, shown in Figure 6, which used 14-inch x 17-inch photographic plates [21]. Wide-field images were obtained in the ecliptic, informed by astrometric data on Uranus and Neptune indicating the possible presence of "Planet X." Hour-long exposures were pairwise searched by eye using a blink comparator to look for an object with the appropriate motion to be a distant planet. In the era of astrographs, this was the normal technique for motion detection, including the barely perceptible proper motions of stars. On 18 February 1930 Clyde Tombaugh made the first detection of Pluto[21]. The mean apparent visual magnitude of Pluto is 15.1 and at its brightest its apparent visual magnitude is 13.56 [22]. This attests to the nascent detection ability of a 13-inch wide-field astrograph with photographic plates used as detectors to detect faint moving objects.

This then-new world is now defined as the first "dwarf planet" of our solar system. However, by Legislative Memorial Pluto remains a planet in New Mexico, where Clyde Tombaugh was for many years a professor in New Mexico State University in Las Cruces.

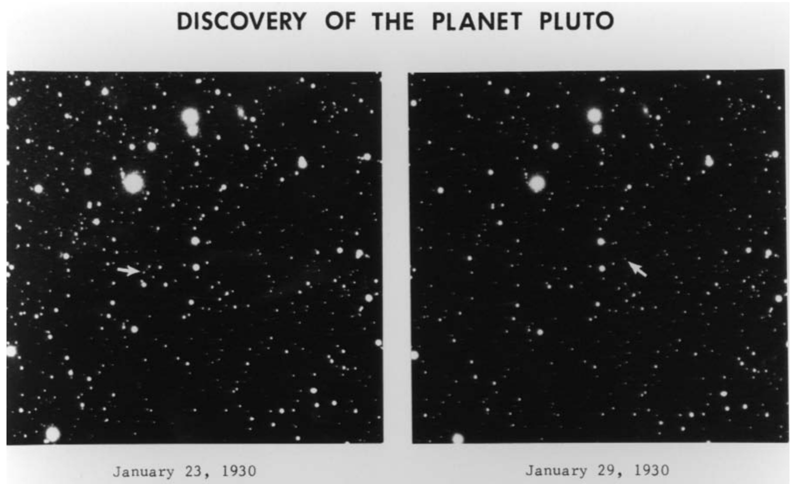

Fig. 6. The 13-inch Cooke Triplet, the "Pluto Lens," at Lowell Observatory in Flagstaff. Photographic plates of the ecliptic were compared to discover the world Pluto by its motion across the sky. Small portions of the discovery plates from 23 and 29 January 1930 are shown to illustrate the detection of motion of this faint object.

The Era of Astrographs is an era in which fundamental instrumental innovation led to discoveries that defined our understanding of the universe today. The wide-field imagery of the Great Nebula in Andromeda, a long-recognized celestial object, the nature of which was unknown, illustrates that new and improved technology - sensitive, wide-field observations of the sky - lead to knowledge, and more importantly, understanding, of objects in our night sky. Similarly, discovery of the Horsehead Nebula demonstrates that resolution of detail in the wider scene leads to new understanding leading to increased awareness that enables understanding on a broad scale. Dust-obscured lanes in galaxies, the nebulae and the structures in them are now understood as star-forming regions and, as a result of the bright newly formed stars, as luminous tracers of spiral galaxy structure. The detection of motion of faint objects is clearly demonstrated by the heroic work of Tombaugh and his Lowell Observatory colleagues in discovering the new world, Pluto.

3. IN THE NEW ERA OF ASTROGRAPHS

Our discussion thus far demonstrates that Space Situational Awareness is not a new concept – we simply need to evolve new technology to take advantage of technological improvements and address new requirements

Astrographs have evolved in just this way. Approximately a century after astrographs were first implemented, the advent of the space age created the necessity to track Sputnik and its successors, as well as the rockets that launched them. The necessity to ensure holding the "high ground of space" put new pressures on imagery of the sky – especially wide-field imagery. Many space science and geodetic research programs are also supported by terrestrial tracking of Earth-orbiting satellites [20].

Many of the first satellite tracking cameras were adopted from aerial camera lenses on fast-tracking mounts. An example is the Russian AFU-75 satellite camera based upon the Uran-16 aerial objective [23]. This highly capable seven-element, 210mm aperture, 736mm focal length lens provided a 10 x 14 degree field of view. The AFU-75 camera was replicated and distributed to more than 25 locations worldwide. This and similar other distributed surveillance networks demonstrates the utility for economical, efficient replication of cameras that can function as a network to establish near-continuous coverage of the sky.

New cameras designed specifically for satellite tracking were developed, principally in the decades of 1960 – 1970. These include the 300mm aperture, f/3, nine element French Antares camera which produces an 11 degree field of view with very high image quality [24][25]. The 300mm aperture, f/2.5, EFL 750mm, 10 element German BMK-75 satellite camera produces an impressive 19 degree field of view, reportedly with very low distortion and 5µm spot sizes (FWHM) [26].

Current era astrographic lenses include the commercially available Canon 111mm aperture, f/1.8 lens that provides a 12.35 degree field of view with high image quality. A 65mm aperture, 180mm EFL Nikon lens providing an 11 degree field of view has also been used for astrography. Both lenses have been incorporated into multi-lens configurations on a single mount for wide-field radiometry of stars to discover transiting planets. These surveys have been highly successful.

The University of New Mexico has recently produced designs for astrograph lenses, again detector driven as was the original astrograph 125 years ago! The first is driven by the wide availability of silicon detectors in 35mm camera format. The 100mm aperture, 200mm EFL lens produces a 43mm diameter field of view which accommodates an unvignetted 35mm detector. This lens provides very high image quality across the bandpass 400nm – 850nm, as shown in Fig. 7.

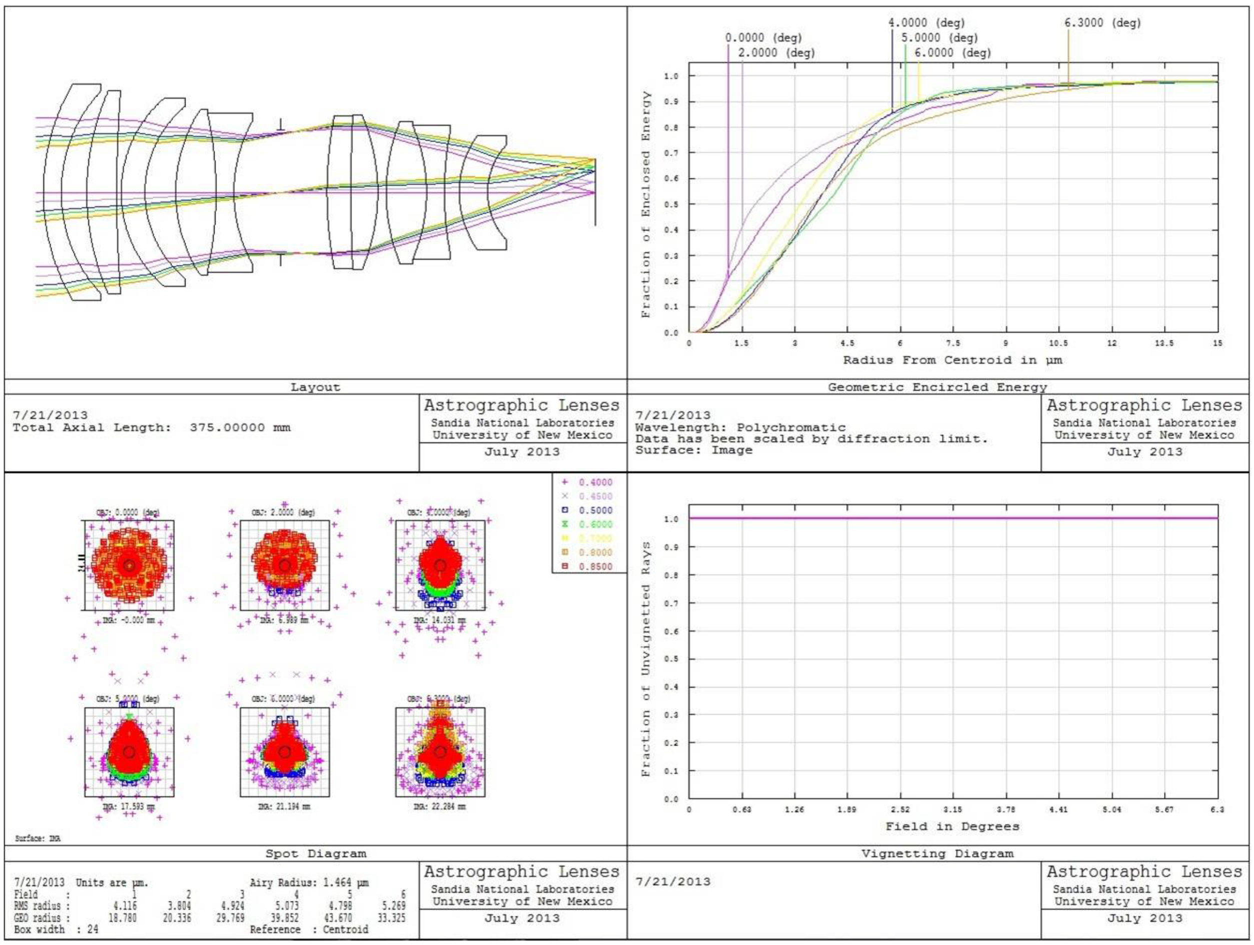

Fig. 7. New 200mm focal length lens designed for use with 35mm format detectors. Upper left is the optical layout diagram in which half-field angles to 6.3 degrees are color encoded. The upper right panel shows encircled energy. Spot diagrams as a function of field angle are shown in the lower left panel, where wavelength from 400nm to 850nm is color encoded relative to a 24µm square and the field angle is specified above each box. The vignetting curve is shown in the lower right panel.

The second design is driven by the advent of the 95mm square STA-1600 CCD with 9µm pixel pitch [27]. This design provides full illumination over the entire detector – vignetting is virtually nil. The 300mm aperture, 750mm EFL system operates at f/2.5 with very high image quality over the entire field, as shown in Fig. 8.

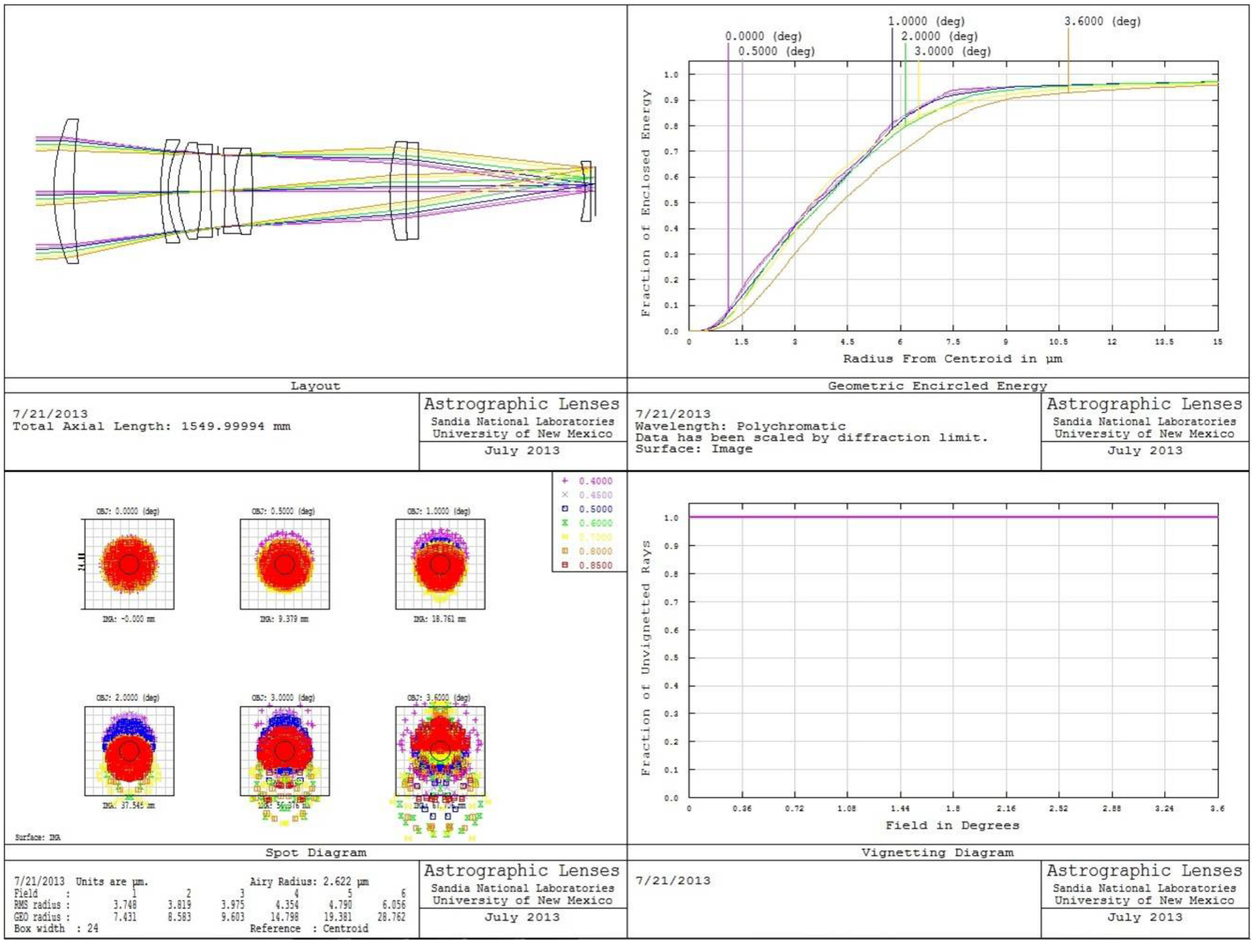

Fig. 8. New 300 mm aperture, f/2.5 lens designed for use with the Semiconductor Technology Associates 1600 CCD, a 10,560 x 10,560 device with 9µm pixels. Upper left is the optical layout diagram in which half-field angles to 3.6 degrees are color encoded. The upper right panel shows encircled energy. Spot diagrams as a function of field angle are shown in the lower left panel, where wavelength from 400nm to 850nm is color encoded relative to a 24µm square and the field angle is specified above each box. The vignetting curve is shown in the lower right panel.

Both of these lenses can support effective and efficient surveillance of space. The 200mm lens with 35mm commercial detectors is especially useful when replicated and operated for (nearly) all-sky monitoring. The 300mm lens with STA-1600 CCD detector is exceedingly effective in high accuracy, fast moving object imagery. As for all optical systems described here, these designs, driven by the practical and scientific needs of surveillance of space, incorporate and are made possible by the generated knowledge, techniques and technologies of the past.

4. SUMMARY

The purpose and intent of this paper is to continue to understand alternatives for the surveillance of space and consequently attaining the required levels of space situational awareness. We suggest that these goals can best be met in a technological sense by incorporating innovative elements, all of which will have demonstrable roots in the past. Starting from that basis, we suggest that thinking broadly about solutions to problems and requirements, learning or at least achieving perspective from the past, synthesizing multiple technologies as necessary - as has always been done, and defining current “optimal solutions” to today’s vision of our problems. In the area of optical surveillance of space, “old fashioned” refractive systems with “modern” CCD detectors perform exceedingly well, and may have a role as a connected, “intelligent” wide-field surveillance system for new objects and configurations, target characterization and astrometry, and detection of faint moving objects, including those in high angular rate orbits.

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