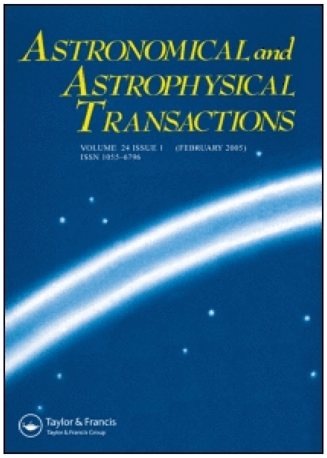

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A variable-focal-length telescope

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A special additional optical system (AOS) to develop any telescope into a zoom or a variable-focal-length telescope (variotelescope) is proposed. This system permits the telescope optics and detector (charge-couped device) to be matched in order to obtain the best resolution. An analysis of the resolution of the system consisting of the 'V-telescope and detector' is performed, and it is shown that the best way to match the optics and detector is to change the focal length, that is to change the image scale. The proposed AOS consists of two spherical mirrors: a large concave mirror and a small convex mirror. The AOS is illustrated by means of figures and tables.

Keywords: Telescope systems; Telescope optics; Charge-coupled device; Focal plain; Focal length

1. Introduction

There are many fields of astronomy and astrophysics where we can use different kinds of telescope, to resolve scientific problems. The prime aim of a telescope is to collect more light from a sky object without connection to its own optical scheme. Let us consider the basic optical schemes of telescope design in order to understand the main aims of our investigation. Most telescopes with mirrors have three basic optical configurations: a Newton or main telescope, a Cassegrain telescope and a Coudé or Nysmith telescope. Telescopes with a primary mirror of diameter more than 3 m usually enable observations to be made in the main focus instead of the Newton focus. A classical telescope which is constructed on an equatorial mount and usually has a third or 'tertiary' mirror that is located for direct light along the axis of rotation of the telescope is called a Coudé telescope. Telescopes using altitude–azimuth mounts have a similar focus called the Nysmith focus. The main property of the Coudé and Nysmith foci are to place the focal plane at a stationary point that is independent of the direction in which the telescope points. All large reflecting telescopes have a Cassegrain or Ritchey–Chrétien design and contain a central hole in the primary mirror. The light reflected from the secondary mirror passes through this hole, exits the telescope tube at the back of the primary and comes to the

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Cassegrain focus. Each of these optical configurations have a certain scale in their own focus plane, a set of search methods and corresponding apparatus.

In the last few years, charge coupled devices (CCDs) have been very widely used for recording the intensity in all spectral regions. Because of this facility we can combine the accurate measurement of each sky object and wide-field photometry. The resolution of the CCD sometimes does not match the certain scale of the telescope's focus plane which means that variable scaling is required since one of the properties of the CCD is to measure the star to at least 4 pixels. So, for the CCD, a very important aspect of observations becomes the agreement between the pixel size of the CCD and the scale of the image in a certain focal plane of a telescope. When there is agreement between the pixel size of the CCD and the scale of the image in the telescope, the most precise observations and highest efficiency of power usage of a telescope will be attained. However, such agreement is rarely realized and the introduction of additional optical elements or a reduction in the pixel size of the CCD to conform to these parameters is required. This leads to a worse signal-to-noise ratio in the telescope–apparatus system and a decrease in the effectiveness of the use and resolution of the telescope.

In this article we consider a new scheme for the design of a mirror telescope which has a large possibility for scaling in the focal plane without connection to a single- or multiple-elements telescope primary scheme. The modification consists of the addition of spherical mirrors. We called this a 'variotelescope' by analogy with vario-objectives that are widely applied in video and photographic cameras with zoom properties. It must be noted that it is possible to have a moving secondary mirror in all kinds of mirror telescope. This allows us to change the scale in the focal plane by small intervals by displacement of the focal plane. In suggesting this scheme we can change the scale by large intervals by moving the second, third and fourth mirrors.

The variotelescope allows us in many cases to design a more compact scheme for construction of both the telescope and the dome with less expense. Moreover our scheme enables us to improve the optical image of sky objects, to check observations which were carried out in other telescopes and to test apparatus before attaching them to a telescope on the other side with different parameters. Also, the scheme allows us to search for sky objects only by telescope scaling without including additional optical elements or a CCD. In this way we hope to standardize the design and to construct the scientific apparatus since large scaling by the telescope's mirror could be realized more easily.

2. Image for the assembled system of 'telescope optics and detector'

The main problem for astronomical observation is to match the telescope optics and detector in order to obtain the best resolution. That is why first of all we shall discuss the modern problem of the resolution. The resolution may be specified by a variety of options: the Airy disc size, the detector size associated with the detector pitch, etc. Also, it is necessary to remember that the resolution does not include the system noise or sensitivity. In a telescope system the optics and detector both have inherent resolutions, and the overall system resolution is a combination of these subsystems resolution. We shall not discuss the influences of the electronics and display, as they do not affect perceptibly the image quality if the optical system is well designed, that is if it is aberration free [1].

The resolution permits us to estimate the smallest target size T. The first approximation provides

$$t = \frac{T}{\ell}, \tag{1}$$

where t is the angular resolution of the system and ℓ is the distance from the system to the target. Sometimes it is more convenient to use the optical blur diameter B:

$$B = ft, \tag{2}$$

where f is the focal length of the telescope.

If the optics of the telescope are aberration free, the blur diameter B depends upon the optical F number. The detector size depends upon the detector selected. Also, if the telescope optics are not aberration free, B depends also on the aberrations of the optics, and the blur diameter B increases. The system consisting of the 'telescope and detector' is said to be detector limited, if B is small compared with the detector size. For large B the system becomes optics limited.

If the target is at infinity, it is impossible to use T or ℓ in equation (1) and it is necessary to provide the angular resolution t.

2.1 *Analysis of the resolution*

If the optics are not aberration free, it is necessary to use the Shade equation for the resolution [1] of the system:

$$b = \frac{1}{2\int_0^\infty |\mathrm{MTF}(u)|^2\,\mathrm{d}u}, \tag{3}$$

where MTF is the system's modulation transfer function, u is the spatial frequency variable with units of cycles per millimetre; b from equation (3) should replace B in equation (2). If the MTF increases, b decreases and the resolution 'improves'. The system resolution may be calculated from resolutions of the subsystems using

$$b \approx (b_1^2 + b_2^2)^{1/2}, \tag{4}$$

where b_1 is the resolution of the optics and b_2 is the resolution of the detector. Therefore it is possible to analyse the resolutions of the optics and detector independently.

2.2 *Estimating the resolutions of the optics and the detector*

The most popular measure of optical resolution is the size d of the Airy disc:

$$d_\lambda = 2.44\frac{\lambda}{D}f = 2.44\lambda F, \tag{5}$$

where λ is the wavelength, D is the diameter of the telescope optics, $F = f/D$ is the optical system F number and f is the focal length of the telescope. It is possible to substitute equation (5) in equation (3) to provide the optics equivalent resolution b_1:

$$b_1 = 1.845\lambda F. \tag{6}$$

Therefore approach used by Shade provides a resolution b_1 which is smaller then the Airy disc diameter.

The detector is specified by the number of pixels, detector size and detector pitch. If the detector MTF is substituted in equation (3), then

$$b_2 = d, \tag{7}$$

where d is the width of the detector's smallest element (pixel). Using equations (5), (6) and (7), we obtain

$$b = d[(1.845c)^2 + 1]^{1/2}, \quad c = \frac{\lambda F}{d}. \tag{8}$$

Obviously, as c decreases, b approaches d; that is, there is a detector-limited system. When $\lambda F/d$ is large, the system becomes optics limited. The designer can select the aperture size and focal length, using equation (8). For fast telescopes, F is about 1, and the theoretical limit of F is 0.5. Detectors are expensive and available in only a few sizes; that is, the choice is rather restricted. Therefore the best way for a designer to match the optics and detector is to change F, or the focal length of a telescope, that is to change the image scale.

2.3 *About the applications of charge-coupled device arrays*

In most cases, for astronomical observations, CCD are used. CCD arrays have detectors about 10 μm in size operating in the visible region of the spectrum, that is $\lambda = 0.5$ μm. Calculations show, if the F number is below 5, the resolution is not improved as the system is in the detector-limited region [1] and, if the F number is greater than 8, the optics resolution affects the discernible target size. (We always assume that the telescope optics are diffraction limited.) For film-based telescopes it is necessary to consider it is more detail, for example the graining of the film. This is not necessary with an electronic imaging system. Now that the size of detectors is being gradually reduced, this allows us to use faster telescopes with the best resolution. For example, replacing a 12 mm-format CCD (pixel size, 10 μm) with a 6 mm-format array (possible detector size, 5 μm) requires a reduction of 2 in the F number in order to maintain the same resolution. Only one equation describes the resolution of any telescope. If it is a long-wave infrared telescope with a detector of size 40 μm, the average wavelength for this spectral window is 10 μm, and the diameter of the Airy disc is about 24.4 F; these telescopes in most cases would be optics limited. Therefore a current long-wave infrared telescope system cannot provide the same resolution as telescopes with CCD for the visual region.

2.4 *Variotelescope design*

The system approach is to match the detector–optics combination. We can use optics that have a blur diameter that is less then 25% of the detector size, and better-quality optics do not provide better resolution. However, it is necessary to be very careful; if we use the same telescope optics and CCD with smaller detectors (and move into the optics-limited region), then aberrations may be unacceptable. Of course we match a camera system with a particular optics–detector combination. Another combination may not provide the desired performance; it may be necessary to use a telescope with another F number or a CCD with another detector size. It is very difficult to obtain a CCD with another detector size. Another problem, that is to match the telescope optics for a given detector size, is much simpler; by the addition of an optics system to our telescope we can obtain a telescope with the necessary F number, or a few F numbers to match a few detector sizes; that is a variotelescope should be designed.

Therefore our main aim is to design an additional optical system (AOS) for a telescope to develop it, that is to convert it into a telescope system with many different focal lengths, or different image scales (*i.e.* a variotelescope). It is the analogy of the well-known zoom

Table 1. The parameters of the two mirror system.

$r_1 = 60.778\,\text{mm}$	$d_1 = 100\,\text{mm} = -s$	$D_1 = 10.48\,\text{mm}$
$r_2 = 316.92\,\text{mm}$	$d_2 = -256.358\,\text{mm}$	$D_2 = 10.1\,\text{mm}$
$R = -42\,\text{mm}$	$d_3 = 365.62\,\text{mm} = s'$	$D_3 = 147\,\text{mm}$
		$D_4 = 3.2\,\text{mm}$

lenses used by amateurs [2]. Unfortunately zoom lenses are very complicated and have color aberrations; so apparently they cannot be used as an AOS for astrophysical observations. The best AOS for a variotelescope would be a simple mirror system, and in particular a system of spherical mirrors. A mirror system is preferable as it can be used over a wide spectral range, from far ultraviolet up to the infrared region. Of course the simplest mirror system is a single concave mirror but it has aberrations; therefore it apparently cannot be used as an AOS for a fast telescope. The second step is to investigate two-mirror systems, and in particular systems without aberrations (spherical, coma and astigmatism), that is anastigmats.

There are many two-mirror anastigmats; the simplest to manufacture is the Bowen system, which consists of two concentric spherical mirrors [3]. We designed an advanced Bowen-like system, that is not concentric and can be used for different distances of the object and image. Of course the magnification can also change, so the system may be used as an AOS for a telescope, turning it into a variotelescope. Also the distance to the mirrors can be different. The aberration correction can be very good except for the field curvature, which may be corrected by means of a Smith lens if necessary. A Smith lens can be manufactured from material that is transparent in a large spectral region, for example fused silica glass. Our AOS can reduce the focal length f of the telescope as well as increase f by turning the AOS to 180°.

The parameters of the two-mirror system are given in table 1. In table 1, r_1 and r_2 are the radii of curvature of mirrors, R is the radius of the field curvature, s is the distance from the object to the first mirror and s' is the distance from the last mirror to the image. The magnification m of the system $m = D_4/D_1 = 0.305$; if the system is reversed, the magnification $M = 3.26 = 1/m$. The hole in the concave mirror is 33 mm in diameter. d_2 is the distance between the mirrors, D_1 and D_4 are diameters of the object and image respectively, and D_2 and D_3 are the diameters of the main and secondary mirrors of the AOS.

It is possible to change m (and M) by gradually changing the distance d_1, s and s'. This can be seen in table 2. Also $R = -42\,\text{mm}$ is the same for all systems, as also is the diameter $D_2 = 10.1\,\text{mm}$ of the first mirror.

Table 2. The effect of changing m and M by changing the distance d_1.

d_1 (mm)	d_2 (mm)	d_3 (mm)	D_1 (mm)	D_2 (mm)	D_3 (mm)	D_4 (mm)	m	M
70	−260.25	362.63	7.36	10.22	155.0	2.87	0.39	2.56
100	−256.36	365.62	10.48	10.1	147.0	3.20	0.305	3.28
125	−254.03	367.66	13.1	10.1	140.0	3.23	0.258	3.87
150	−252.20	369.44	15.7	10.1	136.0	3.525	0.224	4.45
200	−249.69	371.94	20.96	10.1	130.3	3.724	0.185	5.4
250	−248.05	373.61	26.20	10.1	127.1	3.854	0.147	6.8
300	−246.91	374.81	31.44	10.1	124.9	3.946	0.125	8.0
350	−246.06	375.72	36.68	10.1	123.4	4.015	0.109	9.15

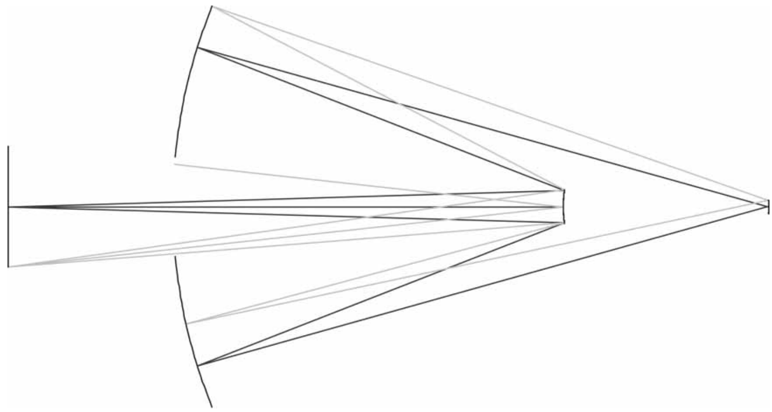

Figure 1. Advanced Bowen system of variable magnification; the first position. Magnification is 0.1.

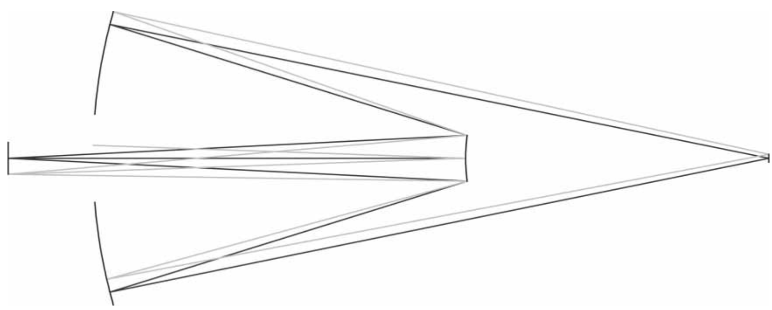

Figure 2. Advanced Bowen system of variable magnification; the second position. Magnification is 0.2.

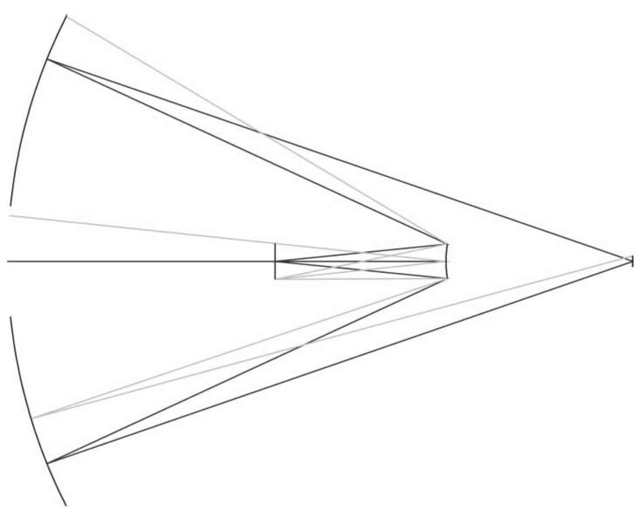

Figure 3. Advanced Bowen system of variable magnification; the third position. Magnification is 0.3.

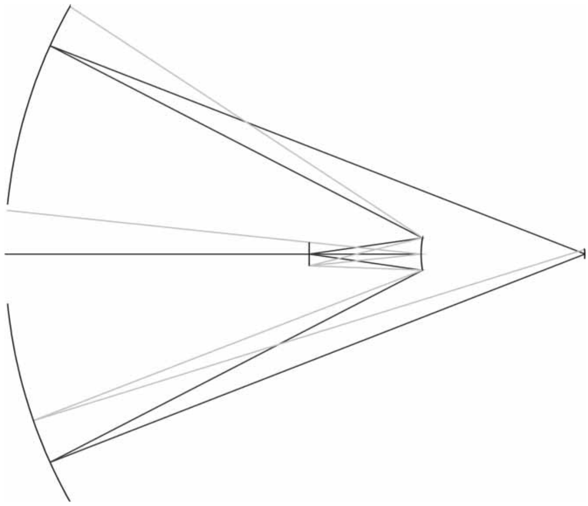

Figure 4. Advanced Bowen system of variable magnification; the fourth position. Magnification is 0.4.

Four typical layouts of the AOS are shown in figures 1–4; the telescope is not shown, and it can be situated on the left or the right-hand side.

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