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GROUND-BASED TELESCOPES FOR THE OBSERVATION OF SPACE DEBRIS.

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ABSTRACT

Large cameras for detecting space debris present special requirements in their design. Some newly designed or modified, fast, wide-angle optical systems should satisfy them. Possible designs include a prime-focus corrector giving 1.5°s field of view. However, the successful surveying of the debris population requires the deployment of a number of such telescopes, with a corresponding cost for replication and subsequent operation and maintenance. The use of metal mirrors, a tripod tube structure and other features in the telescope should minimise those costs. A CCD detector would be mounted at a prime or Cassegrain-type focus. The wide field of the telescope may be filled by a mosaic of CCDs, using special device packaging and machining.

1. INTRODUCTION

Satellite mission planning requires statistics of the space debris population in order to assess satellite operational lifetimes and collision risk. To determine such statistics, observations of objects larger than the shieldable limit (~1cm) are necessary. Because the debris population evolves, observations are required now and indefinitely into the future.

An Earth-based sensor has many advantages for this work. The sensor may have a large aperture, it is easily upgraded and repaired, and it will never become part of the debris population.

However, detecting small particles in orbit is difficult because of their long range and high angular velocity as seen by an Earth-based sensor. Objects which were fragmented by an explosion or which have been exposed to radiation may have low albedos, further reducing their visibility.

Debris in LEO and GTO orbits are visible from a particular site on Earth when they are above the horizon, sunlit, and the observer's sky is dark. These conditions are only met occasionally for a given orbit, so much observing time is needed to map the populations in all orbital regimes. GEO objects are only visible from a range of geographic longitudes, so telescopes must be deployed around the Earth so that all GEO longitudes are observable.

Thus, to detect faint objects requires large aperture telescopes; the need to sample large areas of sky requires many telescopes with wide fields of view.

Although interesting "spot samples" of the debris population may be obtained with existing astronomical telescopes[1], prolonged observing campaigns on these telescopes may be unpopular with the scientific communities which funded and expect to use them.

Hence, we consider special-purpose, ground-based telescopes for observing space debris which could also observe Earth-crossing comets and asteroids.

Targets for the optical design exercise are derived from consideration of four performance criteria:

- detection of centimetre-sized debris,
- wide field of view,
- compatibility with solid-state detectors, and
- competitive complexity and cost

Taken together, these represent a fairly unusual requirement in that existing optical design concepts are only marginally suitable. However, the pressure of research aims in ground-based astronomy has led the Royal Greenwich Observatory to develop a number of optical designs for telescopes with fields of view of around 1°. Four systems are found to be particularly relevant. We describe and review the capabilities of these designs and report our results.

Metal mirror technology has been studied at University College London and we discuss the potential advantages of metal mirrors and a tripod-supported prime-focus CCD mosaic.

On the basis of these and related studies we propose designs for a global network of four to eight telescopes, optimised for detection of space debris.

2. SENSOR REQUIREMENTS

The development of sensor systems is driven by three *main* requirements which we examine below.

2.1 Minimum detectable diameter

The debris population may be divided into three size categories:

- **I** routinely radar trackable (>0.5m)
- **II** small enough to be shielded against (<1cm)
- **III** between these two limits.

The category III size is a performance hurdle: sensors must be able to detect debris of this size.

We use the signal environment model from Crowther *et al*[2] to determine the minimum aperture suitable for the detection of category III debris.

Table 1 shows the noise equivalent diameters for debris in LEO (sampled at 750km) and GEO as a function of telescope diameter assuming a 40% overall sensor efficiency, a good astronomical site, and a 375nm sensor passband.

To detect debris with sizes down to the shieldable limit clearly requires telescopes of 2+m diameter.

2.2 Field of view

Sky coverage is an importan. If an accurate demography is to be obtained then a survey must complete before the population which it is measuring changes. Rapid gathering of data is also required to study the evolution of newly formed debris clusters following a fragmentation event.

When LEO orbits are observed from the Earth's surface, the angular coverage (θ) along an orbit for a telescope of field of view (Φ) is approximately $h\Phi/(R_e+h)$ where h is the orbit height and R_e the radius of the Earth. For h=600km, a 1° diameter sensor field of view (Φ) is minified to ~0.1° in terms of its along-orbit coverage: the *effective* field of view of a telescope (θ) is thus much less than that its designed value (Φ).

For GEO observations, minification is less of a problem: $\theta \sim 0.8\ \Phi$. However, debris must still be above the observer's horizon. The range of GEO longitude which is visible from a site is a function of site latitude, as shown by the Table 2
For a survey zone 30° wide in GEO latitude, a sensor on a site with 75% clear nights would require a mapping rate of >14 sq°/night (or >1.5 sq°/hour) to finish a single-pass survey within a year. Orbit determination requires a multi-pass survey with much higher mapping rates only possible with large aperture telescopes working at fast focal ratios. Mapping rates >5 sq°/hr (corresponding to a triple-pass survey) will require multiple telescopes per site.

2.3 Detector matching

The choice of detector for debris sensors is straightforward. A basic figure of merit (ε_d) is the product of the detector's quantum efficiency (QE) and the solar spectrum (I_{sun}), integrated over the useful wavelength range of the detector:

$$\varepsilon_d = \int QE(\lambda)\, I_{sun}(\lambda)\, d\lambda \qquad \text{(Eqn 1)}$$

Using this criterion, the thin CCD gives superior performance to any photocathode-based imaging system. Neither thermal noise nor read-out noise are significant enough in state-of-the-art CCDs to disaffirm this conclusion. Development of CCDs is leading to monolithic devices which have a large number (>10^6) of pixels offering large field angles (ϕ) using a small number of CCDs in a mosaic.

However, the monolithic nature of large CCDs imposes a requirement on telescope design: engineering of the detector system is simplified if the focal surface of the optical system is flat.

Telescope diameter	NEDcm LEO	NEDcm GEO
1m	3.3	16.
2	2.3	12.
3	1.9	9.8
4	1.6	8.7

Table 1 Noise equivalent diameters (cm) for sensors as a function of telescope diameter; debris are assumed to have an albedo of 0.1. LEO observations conducted with a staring sensor. GEO observations used blind-tracking at the GEO rate but assumed a residual 1"/s debris motion.

site latitude	max zenith distance 75°	90°
0°	132°	162°
22°	128°	160°
45°	110°	154°
56°	84°	150°
67°	nil	128°

Table 2. GEO longitude coverage as a function of site latitude, for maximum sensor zenith distances of 75° and 90°

3. OPTICAL DESIGNS

A number of optical designs has been developed subject to the following guidelines:

1. A camera with 1.5 to 3.0 metres aperture.
2. A relative aperture of about f/2.5 to f/3.5.
3. A field of view of 1.0° to 1.5° diameter.
4. Wavelength coverage of ~400nm, with a short wavelength limit ~400nm to 450nm.
5. Theoretical aberrations over the whole wavelength range at one simultaneous focus to be less than ~0.5" total spread. This rather tight target allows for additional image spread to occur due to temperature changes, defocus, misalignments, etc. and will result in lower engineering costs. (The telescope may operate unattended.)
6. Preferably an external, accessible focal surface with a mechanical arrangement capable of supporting a large detector system with electronics. Accessibility is not required for routine operations but is important for efficient commissioning and maintenance.
7. A flat focal surface - though this is only marginally preferred.

An aberration-corrected prime focus is considered. The accessibility is superior to the normal Schmidt, and published prime-focus corrector lens designs can be improved upon in either field or aberrations. The other systems considered are relatively fast and compact two-mirror systems. Conventional two-mirror (Cassegrain and Ritchey-Chrétien) systems are not generally fast enough. It is, however, feasible to design a reducer lens to be applied to those foci. Although that approach has not yet been followed in relation to the present project, such a lens will be large and complicated and may limit the performance.

Some all-reflecting systems are potentially interesting in this applications. Willstrop [3] describes such a very compact telescope with a field of 3.0° diameter. However, a field of 1.0° to 1.5° is probably too small for those optical systems, and the conventional Schmidt, to become competitive in this project. A particular feature of most very wide-field systems is the size of the central obstruction or other masking of the primary mirror, typically 50 per cent by area. Also, those systems have internal foci which are less accessible than a prime focus. If compactness becomes the overriding need, it can probably be met with the Bowen-Vaughan system described below.

Current research in ground-based astronomy makes some technical demands which are similar to those of the present work. Fields of view of 1° or so include some hundreds of potentially interesting galaxies and stars, and astronomers are developing new instrumental techniques to enable simultaneous spectroscopy of large numbers of such objects. Thus we have some familiarity with the problems, having studied similar systems in relation to the 4.2m William Herschel Telescope on La Palma, the forthcoming GEMINI project for two eight-metre telescopes, other large telescopes, and some smaller instruments for particular research programmes.

An exercise has been carried out to review the capabilities of these (largely new) designs in relation to the above numerical aims for the present project. Four designs are discussed here:

(1) the prime-focus corrector lens giving a field of view of 1.5o with an hyperboloid primary mirror.
(2) the prime-focus corrector lens giving a field of 1.1o with a paraboloid primary mirror
(3) the Bowen-Vaughan camera and
(4) the Cassegrain-Schmidt Survey Camera.

3.1 The 1.5° prime-focus corrector lens for an hyperboloid

Richardson *et al.* [4] described a three-element prime-focus corrector lens giving a field of 1° diameter with the primary mirror of a Ritchey-Chrétien telescope. It used one aspheric surface, represented by a polynomial. We have developed a modified version for the present application (actually from a different starting point). The f-number is similar to that of Richardson *et al.* (f/3.58) but the field of view with the present design is 1.5° in diameter, and the aspheric surface is a concave ellipsoid. (This aspheric surface is not considered prohibitive. The manufacturing tolerances expressed as surface slopes are much less severe than for a Schmidt corrector plate. The ellipsoidal figure provides a convenient optical test at its geometrical foci.) The rear element is formed of fused silica, which gives a small improvement in aberrations, and the centre element is computed to lie relatively near the front element. The lens is illustrated in Fig 1.

It is anticipated that in due course the design will be modified to include an atmospheric dispersion compensator (ADC), possibly in the front two elements, and their proximity should help that development. The central obstruction is only about 4% by area. The aberrations are shown in Fig 2. The conventional distortion at the edge of the field is 1.4% in the pincushion sense, and the field of 1.5° corresponds to 285mm diameter.

3.2 The 1.1° prime-focus corrector lens for a paraboloid

This lens is based on the unpublished design used for the prime-focus corrector lens for the William Herschel Telescope. It can incorporate a compensator for atmospheric dispersion, of a known design but not shown here. Used in conjunction with an f/2.5 primary mirror, the aberration-corrected beam in the example illustrated in Fig 3 has a relative aperture of f/3.0
and aperture of 3.0 metres. As before, the focal surface is flat. The lens gives small aberrations, mainly less than 0.3" over an unvignetted field of 1.1° and the required wavelength range. The distortion is again 1.4% in the pincushion sense, and the field of 1.1° corresponds to 171mm diameter.

3.3 The Bowen-Vaughan camera

The third relevant system is the Bowen-Vaughan camera [5]. Rather few telescopes using this concept have been built, and none so fast as that described here. Although giving reasonably good aberrations (see discussion below), a large aspheric secondary mirror and an aspheric corrector plate are needed. Sky baffles are necessary to avoid direct sky light passing through the hole in the primary mirror to the detector - the baffles pose no particular problems in this application.

Despite the possible additional complexity posedby the secondary mirror, this system should be entered into the final evaluation process. It combines the shortest tube length with a very accessible focus.

An example has been computed for an aperture of 3.0 metres, operating at f/3.1. The field of view is 1.1° in diameter and the designed wavelength range is also the same as in the other designs. The optics are illustrated in Fig 4. The relatively short tube length is apparent. It may be seen that the corrector lens lies close to the hole in the primary mirror, although there is some flexibility in the design as regards this position. The central obstruction is about 25% by area. The image spread is mainly within about 0.25" diameter and the distortion is only about 0.1%.

3.4 The Cassegrain-Schmidt Survey Camera

The basic Schmidt Camera has a variant which incorporates two mirrors and is usually referred to as the Cassegrain Schmidt. It provides a fast focus behind the primary mirror. The overall length of the telescope tube is shorter in relation to the focal

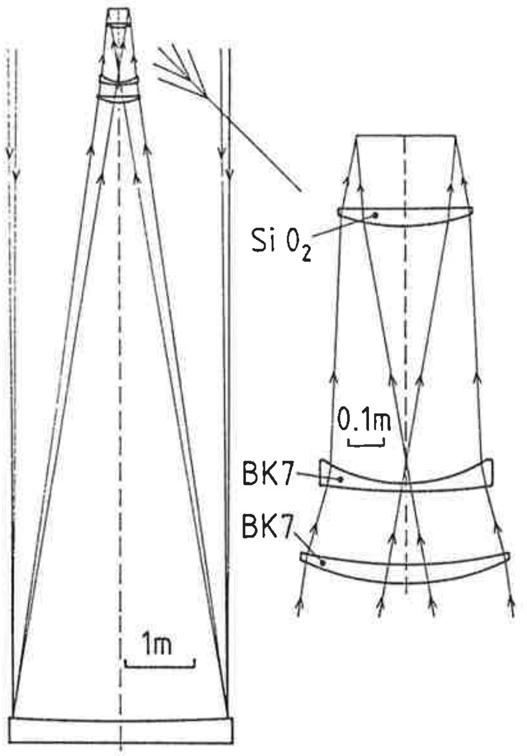

Fig 1 The three-element corrector for a hyperboloid mirror giving a 1.5° field of view.

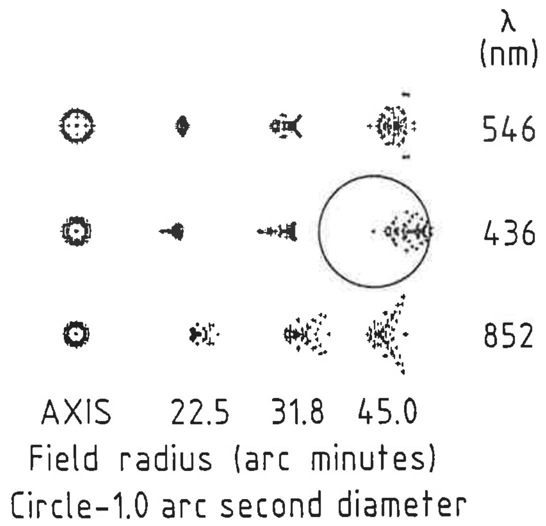

Fig 2 Aberrations of the system of Fig 1.

length than the basic Schmidt. The two mirrors are spherical.However, in its simple form, the Cassegrain Schmidt has various problems. First, aberrations vary strongly with wavelength. Second, the focal surface is curved. There is a central obstruction of about 25% by area, similar to that of the Bowen-Vaughan system discussed above.

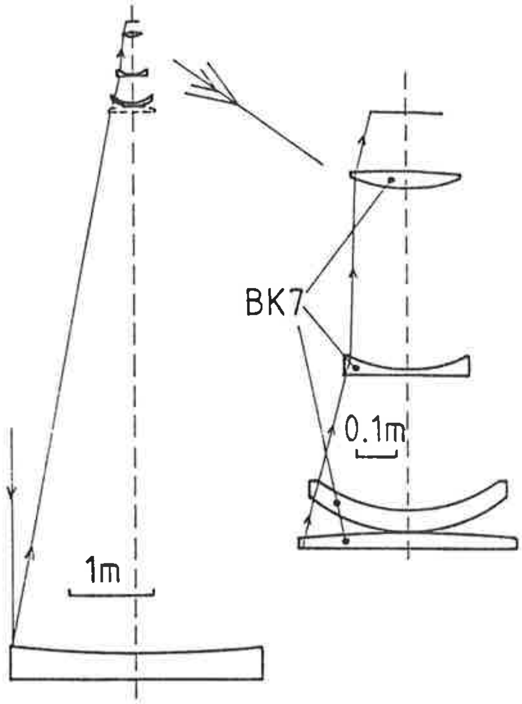

Fig 3 The four-element corrector for a paraboloid

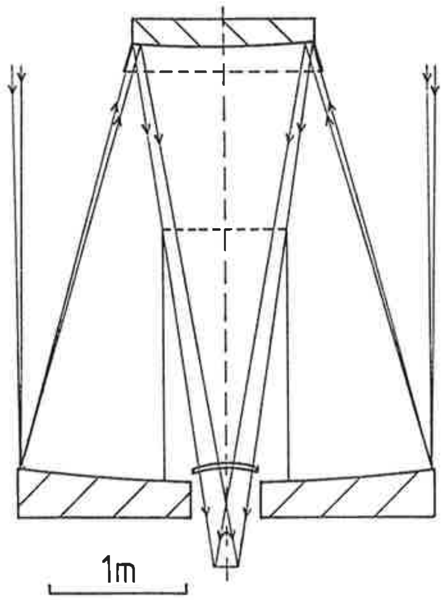

Fig 4 The f/3.1 Bowen-Vaughan camera.

Our development has three aspects:

(i) The corrector plate of the Cassegrain Schmidt is achromatised by implementing it as a cemented doublet.
(ii) A subsidiary lens is applied, in the form of a meniscus, close to the focus. This provides additional correction of some aberration terms (notably the Petzval sum), but also serves as the entrance window of the cryostat needed for the detector system. Thus, there are no additional air-to-glass surfaces.
(iii) The focal surface is constrained to be flat.

The example operates at f/3.25 and is illustrated in Fig 5. Aberrations have a total spread less than or approximately equal to 0.5". This system is intrinsically capable of wider fields of view, with the result that the aberrations are almost independent of the field position. Correspondingly, the field could be extended if required. The system is effectively distortionless and the images are stationary with respect to wavelength.

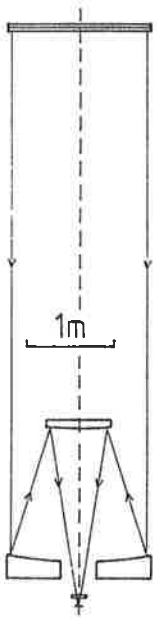

Fig 5 The Cassegrain-Schmidt Survey Camera.

The size of such a camera will be limited partly by the availability of optical glass blanks for the corrector plate in the necessary sizes. A diameter of 1.5 metres seems feasible. The inclusion of an ADC is likely to be more complicated than in the other systems discussed.

The performance of these systems tends to exceed the strict requirements of the problem, and they therefore have the capability of further development or exploitation in various ways: a larger field, faster primary mirror, relaxation of tolerances, and freedom for the addition of an ADC with reduced concern for any aberrations that introduces.

4. TELESCOPE PHILOSOPHY

We envisage a telescope which is relatively simple in mechanical terms, with few optional or interchangeable facilities. Many details which are necessary for an astronomical observatory will be unnecessary. Once assembled on a remote site, it will be expected to operate for long periods with little adjustment and throughout its life with no routine changes of function. Probably, a number of similar telescopes will be produced. It may be convenient for parts to be interchangeable, or to be reproducible to the necessary accuracy for direct fits.

5. TELESCOPE STRUCTURE

The function of the telescope structure is to maintain alignment of the primary mirror and detector, in the presence of a variable gravity vector and wind buffeting. This is conventionally achieved by a space-frame telescope tube (such as the Serrurier truss). The central secondary mirror or prime-focus apparatus is usually supported from the top of the tube by thin, edge-on vanes which are in the beam. The space debris application is not so stringent as conventional astronomy, particularly in the diffraction characteristics of the telescope or in infrared emissivity. Thus it is not necessary for the the central supports to consist of thin vanes. Furthermore, we do not require interchangeable top-ends to feed different foci. Only one of the possible systems has a secondary mirror, which would usually be relatively massive but for which a light-weight technology could be considered. Therefore, we consider a simplified and economic structure which may be more appropriate than a Serrurier truss.

In this proposed structure, most of the mass of the telescope is contained in the primary mirror, its support system and cell. The cell also houses the altitude bearing assembly of the mount. The detector and prime-focus corrector lens assembly are mounted in a barrel which is supported off the perimeter of the primary mirror cell by a tripod. The tripod has much less mass than a complete telescope tube. Alternatively, the central structure of corrector lens etc can be mounted on a central tube, as proposed by Meine[6].

The telescope mount could be either of the alt-az or alt-alt configurations. The latter is mechanically convenient for a compact telescope such as we propose, and also avoids the singularity at the zenith which is a feature of the alt-az.

6. METAL MIRRORS

The mirror substrates for conventional telescopes are usually of zero or low expansion materials, and the telescope structure of metal. Temperature-induced de-focus is handled by servo control of the position of the secondary mirror or prime-focus detector, introducing the need for an extra mechanism, electronics and software.

We propose an alternative concept for the space-debris telescopes: manufacture of the telescope entirely in aluminium alloy, including the mirror. The expansion or contraction of the structure will be compensated by a corresponding change in the focal length of the mirror. Temperature differentials within the aluminium alloy structure should be small in view of its good thermal conductivity (although this question should be studied). The detector assembly may be permanently bolted-down and should remain in focus despite temperature changes.

Other consequences of using a metal primary mirror have recently been reviewed by Rozelot *et al*.[7]. Putative advantages include lower risk of breakage, simplified thermal control and enhanced use of active optics, and most probably lead on to lower mass and cost. (Active optics are not called for in the present work.) The reduction of "mirror seeing" with no need for air conditioning, etc, is certainly helpful. (Mirror seeing is the degradation of angularresolution caused by a temperature difference between the mirror and ambient air.)

A metal mirror should be less demanding than glass in ways which are appropriate for the type of facility envisaged. It is easier to attach to, and easier to handle. Conventional machining processes should be useful when more than one telescope is made to one design. The figure of a metal mirror is generated on a numerically controlled machine. (Machines exist up to at least eight metres capacity.) The mirror is already aspheric before nickel plating and optical polishing; successive mirrors produced to the same design will be interchangeable even if produced on different machines.

7. MOSAIC CCDs

A CCD package in a mosaic of CCDs has six degrees of freedom: three rotational plus the three cartesian coordinates of the centre of the active area. The ideal mosaic would locate the individual devices in all six degrees of freedom, so that the pixel-arrays are contiguous between devices with a precision of one tenth of a pixel. However, this is extremely difficult and expensive to realise. In general, each degree of freedom which can be relaxed enhances the precision which can be achieved in controlling the others which can not.

Optically, the critical parameter is the depth of focus and the impact which this has on the co-planarity (or the approximating to a defined focal surface) of the mosaic. This means that three degrees of freedom are most critical - Z (parallel to the optical axis) plus the rotations about X and Y. The other three degrees of freedom govern positioning in the focal plane or surface. If these are not controlled to around one tenth of a pixel, they may as well be relaxed entirely, since the data will have to be re-binned during analysis onto a single rectilinear grid anyway. We believe that this is the best approach, and it opens the way for a simple method of assembling the mosaic which avoids the need for complex adjustments of device alignment. This has been discussed with the UK EEV company and is described below.

The first stage concerns the CCD packages themselves. These are normally ceramic. During manufacture, the unceramised package is machined then fired. This tends to distort the package, the underside of which may be tens of microns from flat. We propose to obtain the packages from the manufacturer before they mount the dice (bare silicon chips) and diamond-machine flat the undersides. A small blind hole will be machined centrally into the underside of each device, so that a threaded stud projecting downwards from the package may be located and cemented in place. The packages will then be returned to the manufacturer who will cement the dice in place.

The process of cementing introduces errors of piston and tilt in location of the dice; errors which may amount to tens of microns. Our strategy for handling these is to position each CCD package on an optical flat surface, then determine the height of each corner of the active area above the flat by optical metrology (*eg* using a precision microscope). A separate wedge-spacer can then be diamond-machined in copper for each CCD in order to compensate for the piston and tilt error of that device. The devices can then be assembled on a copper platen also diamond-machined flat. The threaded studs will pass through holes in the wedges and the platen, in order that the devices may be retained with spring-loaded nuts. By this means, the mosaic can be assembled and disassembled for replacing defective devices, with no adjustments required.

8. COMMENTARY

Large aperture, wide field telescopes are required to efficiently sample the space debris population because of its low surface density and the faint irradiances of the smaller members of the population. A number of telescopes, globally distributed, is required to sample GEO debris and provide a high enough mapping rate to adequately sample LEO population evolution. Using the optical designs we have described combined with the advantages of metal mirror and CCD mosaic technology, a global telescope network is feasible at minimal procurement and operational cost .

9. ACKNOWLEDGEMENTS

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