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EVALUATION OF A COMPACT CASSEGRAIN OPTICAL SYSTEM

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EVALUATION OF A COMPACT CASSEGRAIN OPTICAL SYSTEM

S.G. Garner, R.A. Joyce and R.P. Johnson

ABSTRACT(U)

A small Cassegrain optical system, with mirrors manufactured on an in-house aspheric surface generator, has been tested using visible radiation. The optical system performance was found to be limited by the relatively poor quality of the finish on the mirrors. It was also found that the design had to be modified to reduce stray light to acceptable levels, which reduced the effective aperture and degraded the diffraction limited resolution of the design. The resulting design may be suitable for those seeker applications requiring relatively low angular resolution from a small aperture, and in which small size and light weight are of paramount importance.

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1. INTRODUCTION

In an earlier study on possible component options for an imaging infrared (IIR) anti-ship seeker head(ref.1), it was suggested that a Cassegrain optical system offered some advantages over competing designs in terms of equipment weight and volume. A principal constraint limiting IIR seeker design is the lack of space available in a weapon seeker head and a Cassegrain reflecting system was favoured because of the compact nature of the folding geometry. As a follow up to the initial study, a small Cassegrain system was designed(ref.2) and manufactured to test the validity of the design and to evaluate the capability of an in-house aspheric surface generator used to shape the optical components.

The results of the initial evaluation of the experimental wide-field Cassegrain optical system, using visible band radiation, are presented in this paper. It was found that the predicted resolution of the system was not obtained, apparently due to optical surface imperfections. Completely effective stray light shielding was found to be difficult to achieve, highlighting a fundamental problem in the implementation of practical wide-field Cassegrain optical systems. The shielding required to reduce the stray light to moderate levels resulted in a significant reduction in the clear aperture of the optical system, degrading the theoretical diffraction limited angular resolution of the system. Other aspects of image quality, such as contrast and distortion were not studied in any detail, since scattered light problems were found to dominate the performance of the system.

2. DESIGN AND MANUFACTURE

The initial specifications for the Cassegrain design were as follows.

- f.o.v. 175 mr (10^{o})
- Optical speed f:1
- Two reflecting elements
- Minimal aberrations

After the initial design study(ref.2) it was found that the full 10^{o} f.o.v. could not be achieved with an acceptable angular resolution. The final design was based on aspheric surfaces for the primary and secondary mirrors and the specifications were:

- Optical speed f:1
- f.o.v. 100 mr (6^{o})
- Primary mirror diam. 60 mm
- Secondary mirror diam. 36 mm
- Angular resolution better than 1 mr over f.o.v.

The Cassegrain components were manufactured using an in-house aspheric surface generator (ASG). This process involved mirror blank design, rough machining and heat treatment, finish machining, profile assessment, smoothing, surface plating, surface stress relief, polishing, reflective and hard coating

The surface profiles of the mirrors were tested with a Zeiss 3 axis co-ordinate measuring machine and it was found that the ASG was producing an rms profile error of 3-5 μm at a pitch of 3mm, which was thought to be due to the combined effects of bearing roundness errors and ballscrew drunkeness. These errors were expected to be repeatable for a given tool path, and therefore could possibly be compensated for by modifying the cutting data. However, in view of extra time and cost involved, this process was not attempted on the set of mirrors manufactured for the initial evaluation.

The optical elements are shown in the following figure.

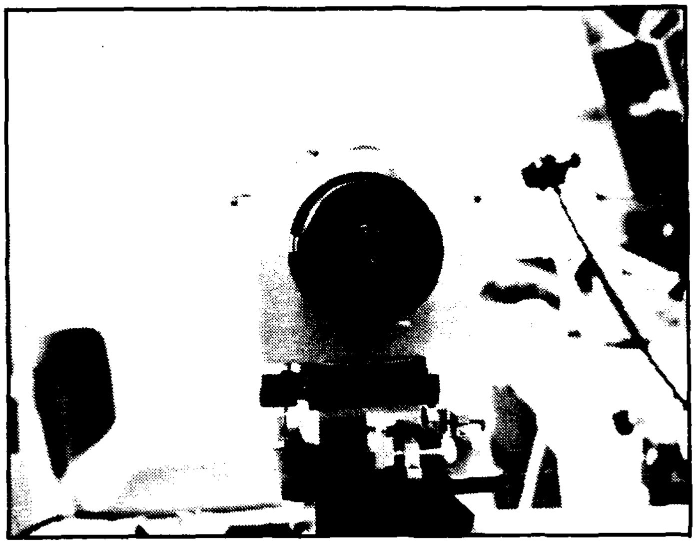


Figure 1. The optical assembly

3. CASSEGRAIN EVALUATION

3.1 Discussion

The Cassegrain optical system is reflective, so testing was carried out in the visible region of the electromagnetic spectrum. The results of this testing were expected to give an indication of the overall imaging performance of the design.

As the initial testing progressed, it was noted that the optical performance of the system was dominated by the following factors;

a. the hand polished surfaces were visibly of inferior quality and the performance of the underlying geometry could not be properly assessed,

b. stray light reaching the detector could not be reduced to moderate levels without significant alterations to the original design, which reduced the clear aperture of the optics, and

c. the required stray light shields considerably reduced the clear aperture of the optics, limiting the achievable resolution.

Consequently, the testing process was modified to account for these factors and to assess their impact on the practical implementation of the original design.

3.2 Technique

The image quality of the Cassegrain system was tested by placing a CCD detector chip at the image plane and displaying the image on a TV monitor for focusing and image assessment. Images were permanently recorded using a thermal video printer. The alternative approach of using transfer optics to relay the image from the image plane to the exterior of the optics assembly would possibly have allowed the use of an IR imager for performance assessment. However, this was impractical with simple optical components, due to the small f number of the system and the close proximity of the image plane to the secondary mirror. Appropriate transfer optics would have required a major design effort to ensure that they did not introduce aberrations and diffraction effects that could have masked some of the characteristics of the Cassegrain system.

In order to place the detector at the focal plane, a Phillips CCD video camera (type LOH 0600/00) was modified by separating the detector chip from the camera housing (figure 2). The detector chip was then replaced by a detector die mounted on a 20 mm ceramic disk which could be passed through the 30mm hole in the centre of the primary mirror and positioned at the image plane. The modified camera and the optical assembly are illustrated in the following figure.

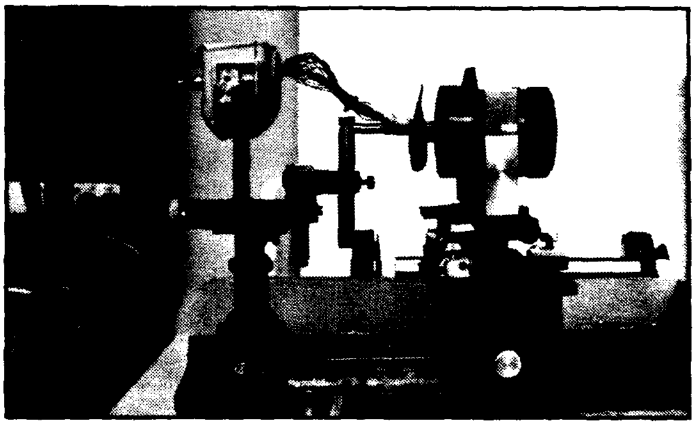


Figure 2. Camera modifications

The detector chip was connected to the camera electronics with 220mm lengths of unshielded wire. This arrangement gave minor problems with noise, but the image quality was adequate for testing the optical system. The detector was placed on the end of a 100mm stalk, and the Cassegrain optical system and the stalk were then mounted on a short optical rail. The mountings gave vertical adjustment and the stalk allowed two way adjustment in the horizontal plane, providing controlled centring and focusing of the image on the detector. Finally the rear of the Cassegrain was shielded, to prevent stray light from entering.
It was also necessary to attenuate the light falling on the detector as the camera was saturating in daylight conditions. Neutral density filters were placed in front of the detector to provide control over the incident light level without upsetting the geometry of the optical system.

3.3 Stray Light

Initial testing revealed that a significant amount of stray light was falling on the detector, reducing image contrast to unacceptable levels. Stray light is an inherent problem in a wide field Cassegrain system, particularly one with the image plane between the optical elements.

The field from which direct stray light may reach the detector in a Cassegrain system is illustrated in the following figure.

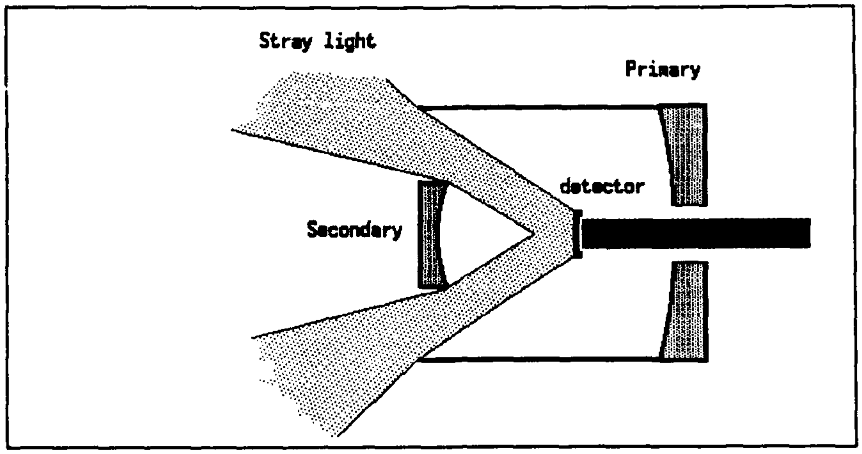


Figure 3. Direct stray light on the detector

Since the stray light markedly reduced the image quality, further investigations into methods for reducing stray and scattered light were carried out to determine whether or not the design could be modified to produce acceptable image contrast.
Three approaches were investigated.

3.3.1 Addition of an external conical light shield (figure 4)

Varying lengths of black cone shielding were fitted to the Cassegrain system to eliminate light that was falling directly onto the detector and also to intercept most of the light falling onto the walls of the housing, which was acting as a scattering source. With a 450 mm cone

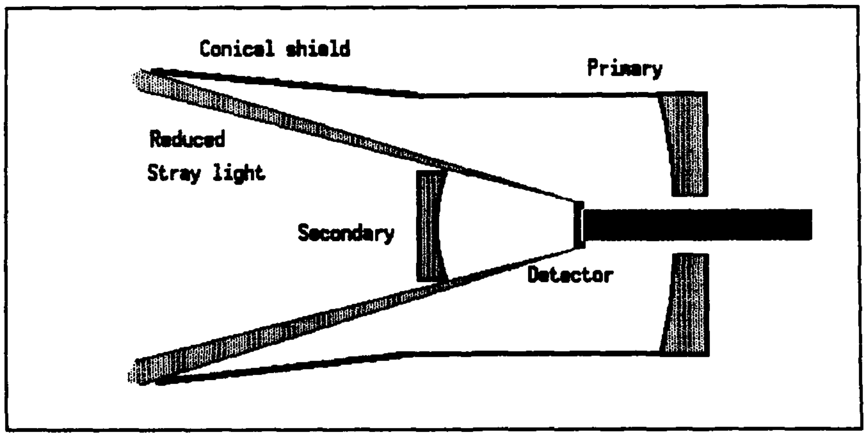


Figure 4. External baffle

fitted, the image contrast was as high as any achieved. Of course, the addition of an external shield to the end of the Cassegrain system is not practical for use in a seeker because of the limited space available.

3.3.2 Combined internal shielding (figure 5)

A cylindrical light shield placed around the secondary mirror was most effective at stopping direct stray light from hitting the detector. This baffle, in combination with a baffle around the detector to reduce scattered light, provided relatively effective overall shielding from direct light and internally scattered stray light. However the baffle around the secondary intercepted some of the image forming radiation, thus reducing the clear aperture.

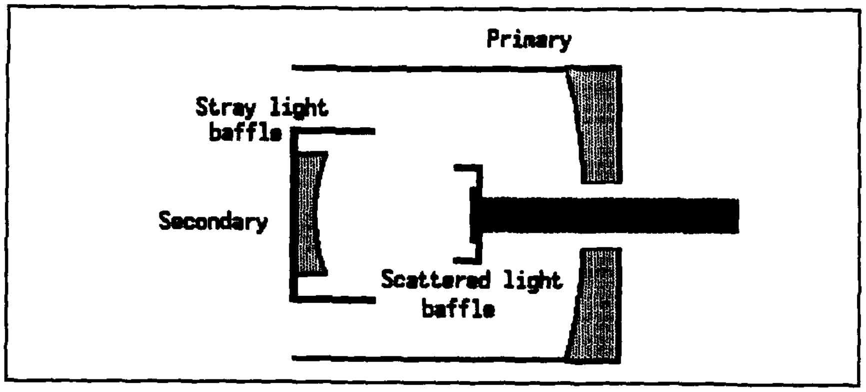


Figure 5. Combined shield

3.3 Angular Resolution

The resolution of the optical system was tested using a 1x1m square resolution test chart at varying distances up to 60m. Limiting resolution was assessed by noting the angular spacing of the test chart bar patterns that could just be resolved by visual inspection of the TV image. A typical image is shown below.

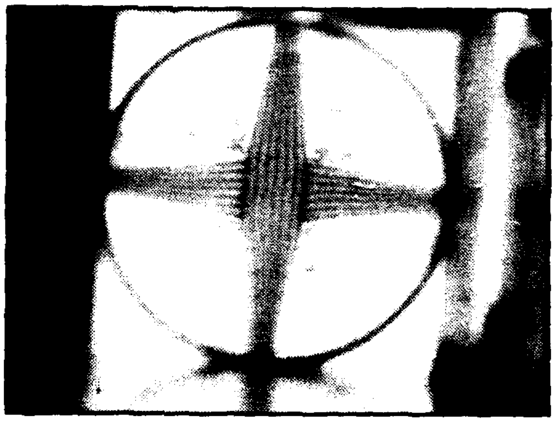


Figure 6. Typical test pattern

The visible band resolution was found to be in the vicinity of 1.5 to 4mr over the 4.2 x 5.6° field of view. This does not meet the design goal of 1 mr over the field of view and is consistent with the order of magnitude of the angular irregularities in the optical surface profiles of 3-5 μm at 3 mm pitch. It is below that generally required of a practical optical design.

The other aspect of the modified design that contributes to the resolution is diffraction due to the annular input aperture. An analysis of diffraction due to the system aperture is presented in Appendix I, in which it is shown that the reduction in aperture due to the stray light shielding reduces the achievable resolving capability of the optical system such that the best possible result is around 0.52 mr at 10 μm wavelength. This would be a significant limitation in an optical system with high quality mirrors.

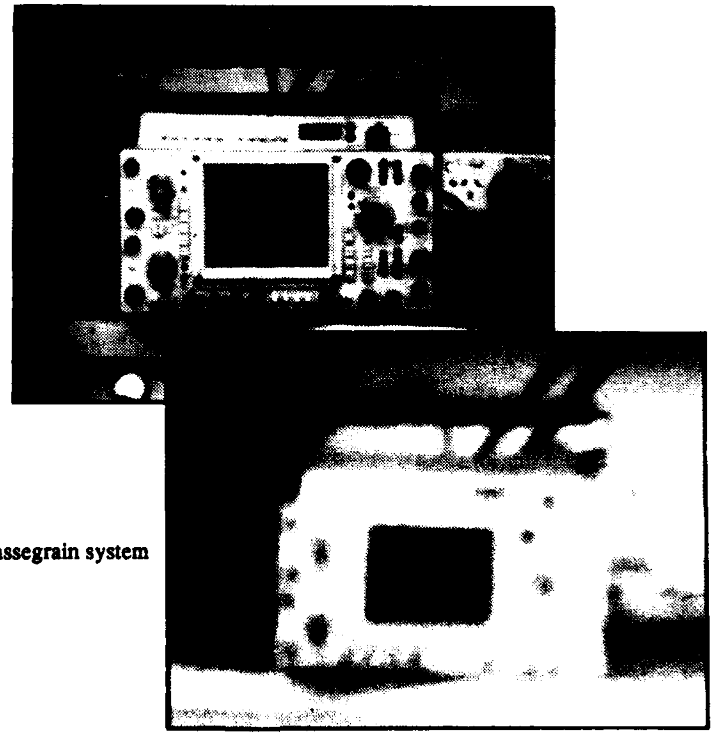
3.4 Distortion

Variations of magnification over the field-of-view lead to distortion in the image. The system was tested using a regular square test pattern and displayed no obvious distortion.

3.5 Overall image quality

The quality of images produced by the demonstration Cassegrain optical system is illustrated in the following figure. These images were produced under typical laboratory ambient lighting conditions with overhead fluorescent lights and with full internal shielding of the Cassegrain system. It was noted that the image quality degraded noticeably under conditions where more direct light fell on the optical system, and in outdoor conditions with natural sunlight and a bright sky, it was not possible to produce recognizable images without an external shield on the optical system.

conventional lens



Cassegrain system

Figure 7. Typical image quality

4. DISCUSSION AND CONCLUSIONS

The two main effects that limited the performance of the Cassegrain optical system were the surface finish of the mirrors and direct and stray light falling onto the detector.

The technique of using visible band radiation to test the performance of IR optics could not be applied to the experimental Cassegrain design, due to excessive surface faults in the mirrors. The effect of these faults on IR performance was not assessed. A detailed investigation into the quality of the experimental optical system will require either an order of magnitude reduction in the mirror surface faults to allow visible band testing, or the development of a true IR image quality assessment facility.

The chosen optical configuration places the focal plane between the primary and secondary mirrors to achieve a low aberration image. It was found that this arrangement resulted in excessive levels of stray light due to the exposure of the detector to both direct and scattered extraneous radiation. Baffles were devised to partially overcome the stray light problem, but at the expense of restricting the optical aperture of the system, resulting in a predicted increase in diffraction related image defects. The effects of diffraction on image quality are subtle, but become increasingly important as the wavelength increases. Regardless of the quality of the optical surfaces or the geometrical design, diffraction will limit the resolution of the restricted aperture Cassegrain optical system to around 0.5 mr at 10 μm. This is a fundamental limitation that cannot be overcome by design or fabrication improvements.

The reflecting optical system studied has the inherent advantages of small size and light weight and may have adequate resolution for some applications. However, if an application calls for maximum resolution from a small aperture, it is recommended that careful consideration also be given to the performance of competing refractive designs. Many of the limitations of the Cassegrain configuration, particularly in the area of scattered light, are not as severe with refracting optics. Where the primary requirement is for minimum size and weight, combined with a relatively narrow field-of-view and moderate angular resolution, a Cassegrain design may be suitable, and it may be the only option where the requirement is for a long focal length system to fit into a small volume.

5. ACKNOWLEDGEMENTS

It is a pleasure to acknowledge the contribution of Mr R.L. Larsson who modified the TV camera to operate with the external detector. Optical surfaces were prepared and mounted under the guidance of Mr S.J. Passmore, and Dr O.M. Williams provided the optical design information.

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3. Born, M. and Wolf, E. "Principles of Optics". Pergamon, 1980

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APPENDIX I

DIFFRACTION FROM AN OBSTRUCTED APERTURE

The final baffle structure is shown to scale in the following figure. The clear aperture is reduced to an annulus with an internal diameter of 44 mm and an external diameter of 60 mm.

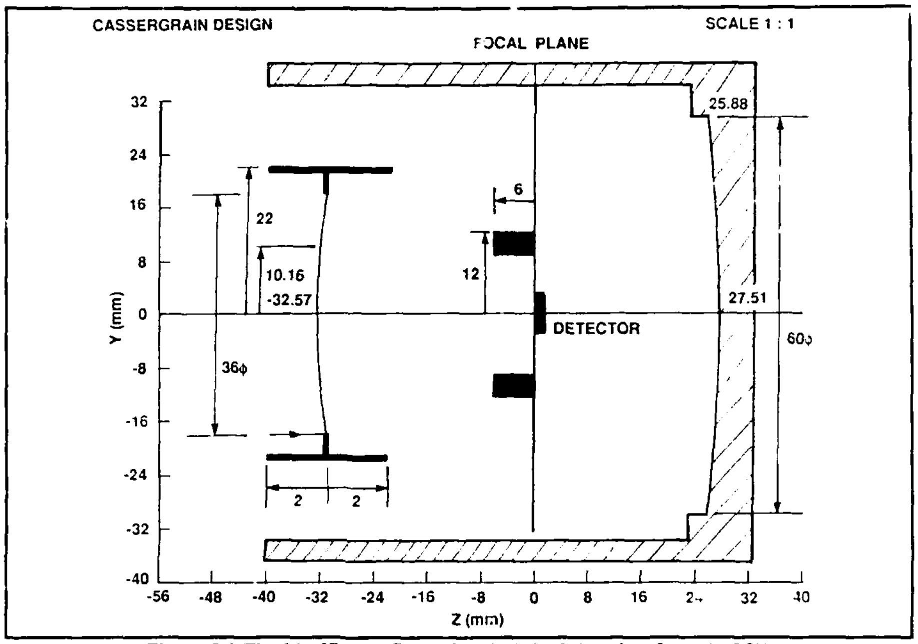

Figure I.1 Final baffle configuration (original drawing from (ref.2))

The distribution of energy in the focused image may be assessed by considering a point source on axis. The distribution of energy in the image may be derived (eg Born and Wolfe (ref.3)) for the obstructed aperture and for an on-axis point source;

$$\frac{I}{I_o}=\frac{1}{(1-\varepsilon^2)^2}\left[\left(\frac{2J_1(ka\omega)}{ka\omega]}\right)-\varepsilon^2\left(\frac{2J_1(k\varepsilon a\omega)}{ka\omega}\right)\right]^2 \tag{I.1}$$

where ε is the ratio of the inner radius to the outer radius,
k is the wavenumber of the radiation,
a is the outer radius and ω is the angle from the optical axis.

The intensity distribution in each ring of the diffraction pattern may be integrated over the area of the ring, providing an indication of the fraction of the total target flux falling in the various rings of the diffraction pattern as in the following table;

TABLE I.1 DISTRIBUTION OF FLUX IN DIFFRACTION PATTERNS

Configuration	Distribution of energy		
	1st ring	2nd ring	3rd ring
obstructed aperture	22%	25%	20%
clear aperture	84%	7%	3%

From this it can be seen that the obstructed aperture results in the spread of energy from a point source into the higher order structure of the diffraction pattern. In an IR seeker, signal-to-noise ratio, and hence detector performance, is likely to be highly dependent upon the collection of as many target photons as possible. In order to collect a major proportion of point target flux, the diffraction pattern for the Cassegrain system will need to be sampled out to at least the third ring. An appropriate measure of the angular resolution is therefore the angle to the third minimum, rather than the conventional Rayleigh criterion of angle to the first minimum. For the design proposed, this sets the angular resolution at approximately 0.26 mr at 5 μm and 0.52 mr at 10 μm. Although this resolution may be adequate for many applications, it is considerably worse than the 0.2 mr at 10 μm achievable with a clear aperture of the same diameter.

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