R. H. WIGHT
Fairchild Camera and Instrument Corporation
Syosset, L.I., NY 11791

An Advanced Optical Objective Lens

The development of a high-performance, ultra-wide-angle lens is described.

ABSTRACT: *A low-distortion objective lens was required to cover a 140-degree field-of-view with good resolution, high speed and relative illumination, and broadband (silicon sensor) spectral response. The development philosophy adopted and the results obtained are discussed together with potential applications to photogrammetric requirements.*

INTRODUCTION

THE OBJECTIVE LENS described here was originally designed for use in an electronic camera which incorporated an array of silicon charge coupled device (CCD) sensor chips in its focal plane. The camera system was intended to perform a "real-time" aerial reconnaissance function by sensing and simultaneously transmitting pictorial information about the area being overflown. Goals for this sytem included good resolution, wide angular coverage, and minimum electronic bandwidth.

These goals could be met simultaneously only by minimizing signal redundancy. This required minimization led logically toward the selection of the "strip" type of camera, which has no redundancy at all. However, no lens forms were known which could cover a 140 degree wide field-of-view with the needed speed, relative illumination, low distortion, resolution, and spectral coverage. Reverse telephoto "fisheye" lenses were of course well known, as were standard cartographic objectives of up to 120 degrees coverage. The very high distortion in the former type precluded its use because ground resolution would suffer greatly at the edges of the field of view. (It follows from the fact that the sensor array has a fixed pitch that, even if the lens resolved well at the edges of the distorted edge-compressed image, the system could not.) Standard cartographic lenses on the other hand would not provide, in a single example, the needed field-of-view, relative illumination, and optical speed.

One potential answer appeared to lie in the work done by Hugues[1] on wide angle lenses incorporating a parabolic surface. Two drawbacks existed, however. First, the Hugues work had not been carried to angles greater than 90 degrees; second, a lens of the form reported would be so large as to preclude its practical use at the focal length (approximately 1.3 inches) needed to work with the sensor array.

Preliminary design work demonstrated the probable practicality of designing and manufacturing a variant of this type of lens to meet the electronic camera goals shown in Table 1. Mr. Thomas I. Harris (Optical Research Associates) was consequently engaged to perform the optical design task.

UNUSUAL DESIGN CONSIDERATIONS

SPECTRAL CORRECTION

The broad spectral sensitivity of the silicon sensor demanded a lens of equally broad spectral coverage. This coverage significantly exceeds that normally incorporated into a photographic objective lens design, the spectral region covered being from 400 to 1100 nanometers. The relative weighting

PHOTOGRAMMETRIC ENGINEERING AND REMOTE SENSING,
Vol. 52, No. 8, August 1976, pp. 1049-1055.

TABLE 1. LENS DESIGN GOALS.

Effective Focal Length	1.3 Inches
Relative Aperture	f/4
Field of View	140 (±70) Degrees
Spectral Range	400–1100 Nanometers*
Axial Transmittance	80 Per Cent
Relative Illumination	50 Per Cent
Distortion	Minimized
Image Quality	50 Per Cent Modulation at 40 lp/mm to 60°
Overall Length	10 Inches

* Weighted in accordance with Silicon CCD response.

used in the design process and subsequent performance analysis is illustrated in Figure 1. The relative weights ascribed to specific design wavelengths also are given on the performance prediction illustrations.

The required broad spectral correction resulted in the use of glasses having anomalous partial dispersions in order to obtain apochromatic performace throughout the field-of-view. The high level to which chromatic correction was taken is shown by the high overall resolution performance obtained.

BEAMSPLITTER PROVISION

The sensor array chip geometry made it physically impossible to butt one chip against the next to form a continuous line in the image plane. A beamsplitter was therefore introduced into the image space to allow half the chips to be mounted on one side and half on the other in an interdigited way to form an "optically butted" continuous strip.

LENS FORM DEVELOPMENT

It became apparent relatively early on the lens design process that the Hugues parabolic surface would have to be replaced by an elliptical surface if the required angular coverage and overall length values were to be achieved. Whereas departure from the parabolic surface reintroduced astigmatic and distortion contributions which had been eliminated in the classic form, these were within the bounds correctable within the remainder of the system. The resultant lens form was the eight component (16 element) design illustrated in Figure 2.

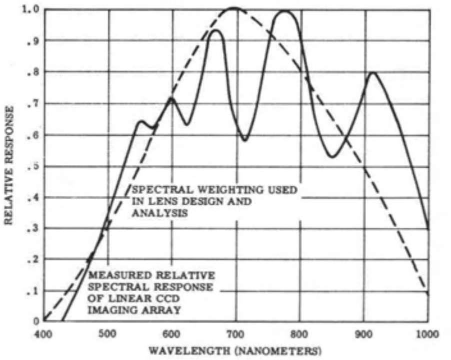

FIG. 1. Spectral correction.

DESIGN PERFORMANCE ANALYSIS

The completed design was thoroughly analyzed with respect to Modulation Transfer Function (MTF) across the field-of-view, relative illumination, and distortion. These results are summarized in subsequent Figures 3 through 13 as follows:

- MTF data at field angles of 0°, 15°, 30°, 45°, 60°, and 70° are presented in Figures 3 through 8.
- Utilizing the required modulation data for type 3401 film, the on-film resolution prediction was made with the results shown in Table 2.
- The high level of relative illumination achieved through the use of the pupil-coma introducing elliptical element is illustrated in Figures 9 through 11.
- Whereas the lens is not "distortionless" in a photogrammetric sense, the distortion is very low compared to a "fisheye" lens of comparable angular coverage. This is shown in Figures 12 and 13.

REDUCTION TO PRACTICE

Upon completion of the design, the lens was fabricated. (The finished lens is shown in Figure 14.) Because of the very close tol-

TABLE 2. PREDICTED "ON-FILM"* RESOLUTION.

Field Angle	Resolution (Line Pairs/mm)	
(Degrees)	Radial	Tangentiel
0	70	70
5	70	65
10	70	65
15	70	65
20	70	60
25	65	60
30	55	60
35	50	60
40	50	60
45	50	60
50	60	50
55	60	50
60	60	45
65	70	40
70	70	30

* 3401 Film, high contrast #25 filter cascade of lens MTF and 3401 AIM curves with allowance for manufacturing tolerances.

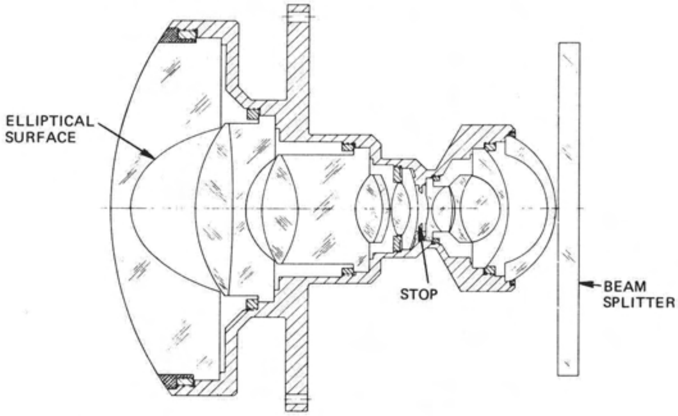

FIG. 2. 1.3-inch *f*/4 wide angle low distortion lens.

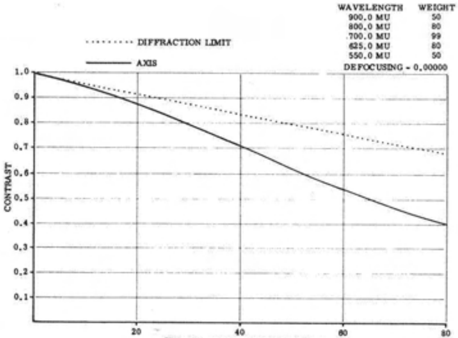

FIG. 3. MTF on axis.

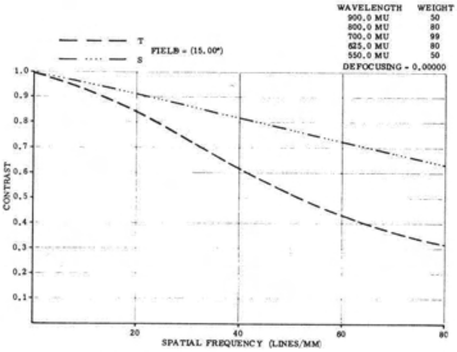

FIG. 4. MTF 15° off-axis.

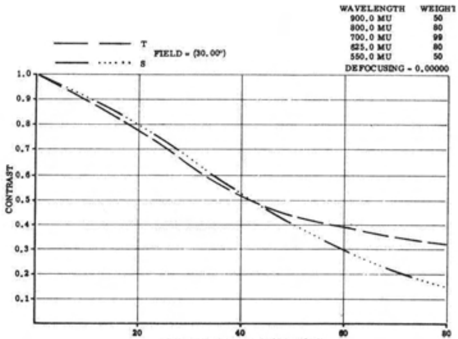

FIG. 5. MTF 30° off-axis.

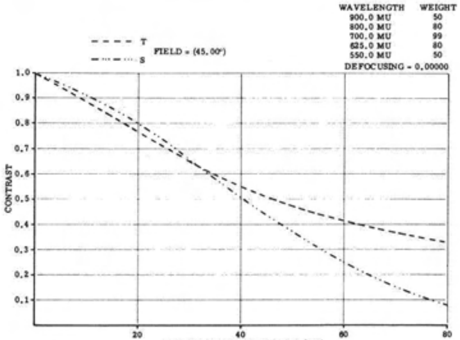

FIG. 6. MTF 45° off-axis.

erances established as necessary during the design process, both melt recomputation and "as manufactured log" re-evaluations were necessary. In the former, exact glass constant data were used in establishing the prescription given to the optical shop. In the latter, the measured characteristics of the fabricated elements were used to optimize element spacings for best overall performance.

It is this use of the re-optimization of element spacing that makes possible the fabrication of the elliptical surface to within feasible tolerance. Without resort to this technique, lens performance usually would be seriously impaired.

While the objective was not intended for photographic application, and therefore contained no shutter mechanism, an experimen-

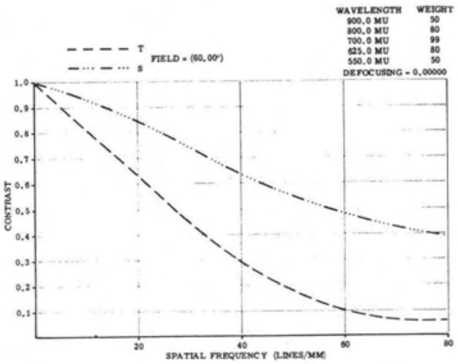

Fig. 7. MTF 60° off-axis.

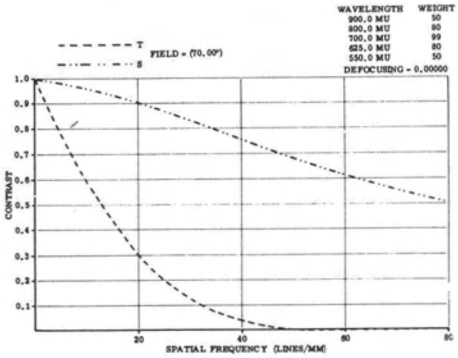

Fig. 8. MTF 70° off-axis.

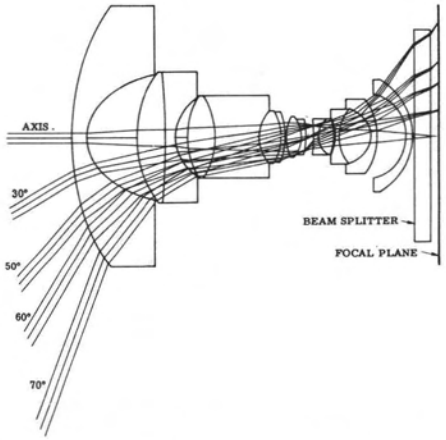

Fig. 9. Ray trace showing expanded pupil of 1.3-inch $f/4$ wide angle low distortion lens.

tal film focal plane was put in place and some exposures made. One such picture is shown in Figure 15.

Implications for Photogrammetry

The lens form has several features which recommend it for potential application to photogrammetric use. These include:

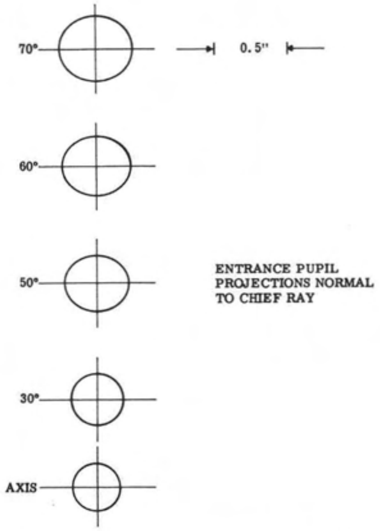

Fig. 10. Entrance pupil projections.

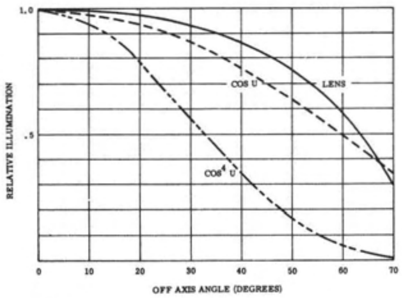

Fig. 11. Relative illumination.

Wide Angular Coverage. A 140-degree diagonal cartographic lens could very significantly reduce the amount of flight time required for a given coverage. Scaled to fill a 9 inch × 9 inch format, the subject lens would have a focal length of approximately 2.3 inches.

Wide Spectral Coverage. This would allow use of both color film and infrared film without re-focus of the camera.

High Optical Speed and Relative Illumination. At $f/4$ the objective can perform well over a range of scene illuminations. The already low rate of illumination fall-off with angle could be reduced sensibly to zero by use of radiant gradiant filter with a corresponding loss in "speed" of two "stops."

Low Distortion. At the focal length required to fill a 9 inch × 9 inch format, the calibrated distortion of the lens would be approximately ± 3,000 micrometers. While this is sufficiently high to cause difficulty with "analogue" reduction equipment, precise knowledge of the distortion at any point in the field-of-view makes data reduction by compu-

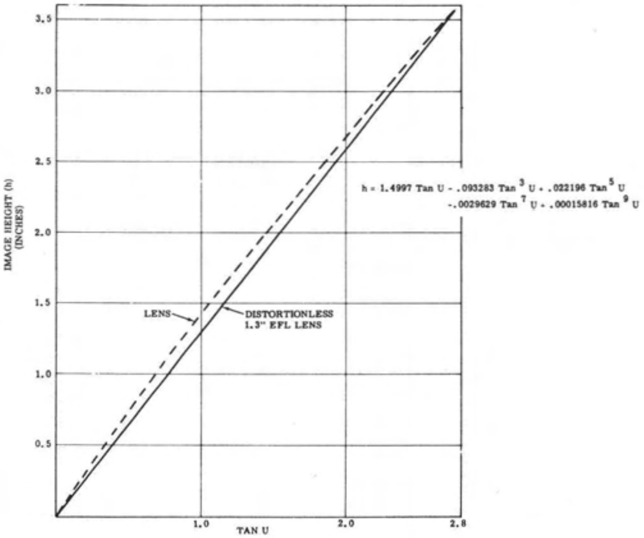

Fig. 12. Distortion data.

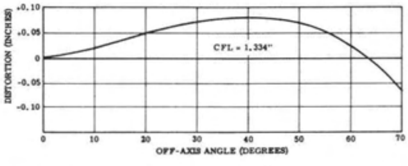

Fig. 13. Calibrated distortion.

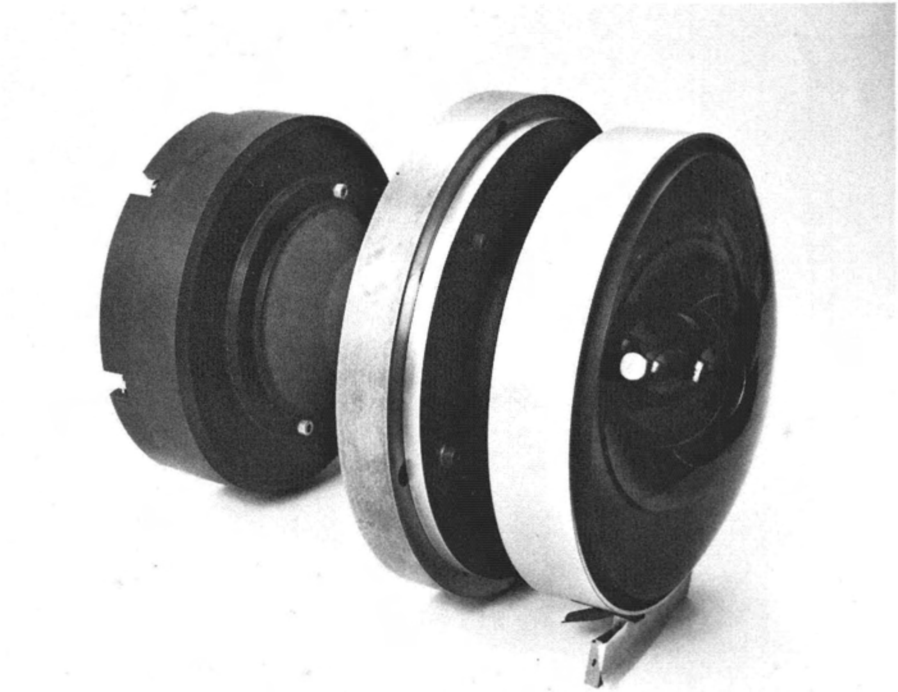

Fig. 14. 1.3-inch *f*/4 wide angle low distortion lens.

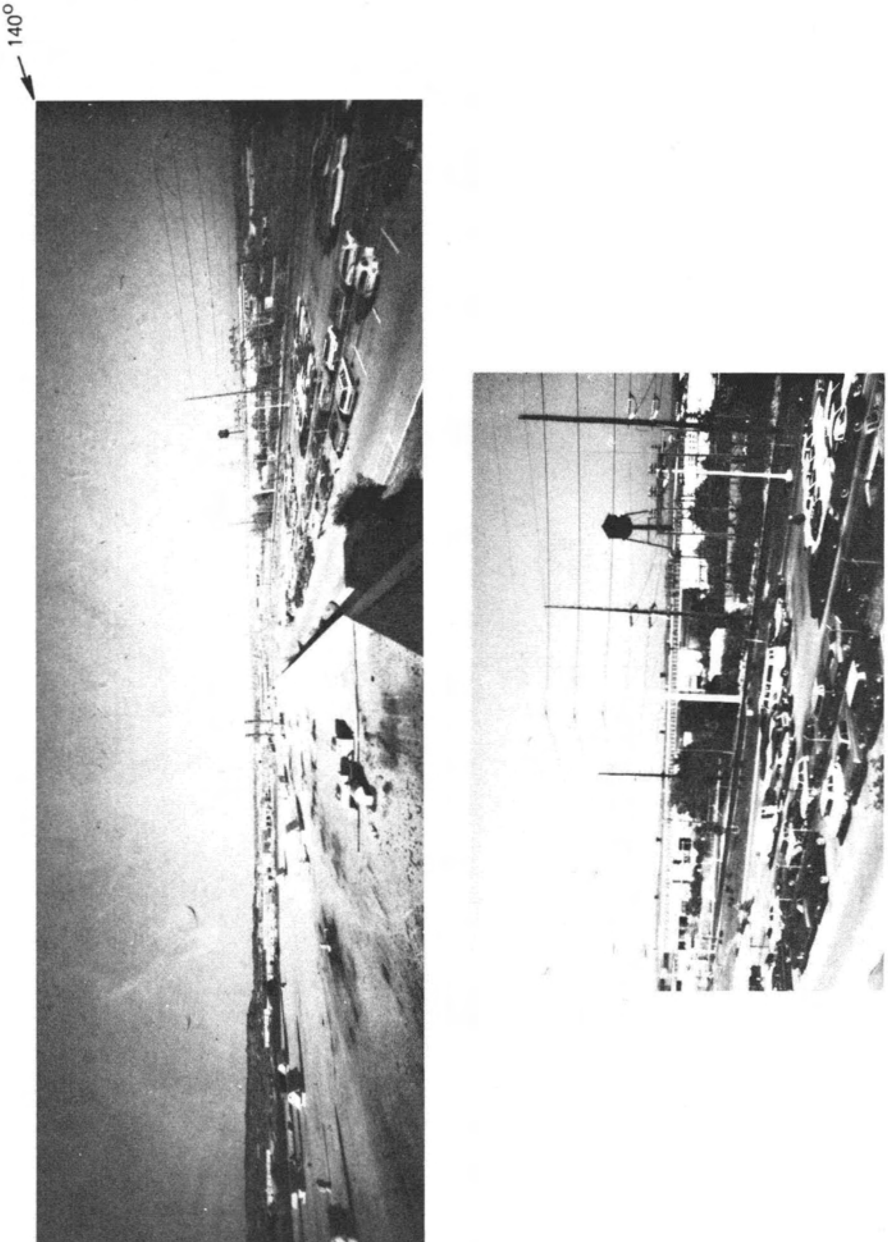

FIG. 15. 140° photograph and enlargement.

ter in an analytical photogrammetric system practical. The accuracy to which the distortion in a photograph taken with the lens can be known is greatly improved by the fact that what served the electronic camera as a beam-splitter, is optically just a plane-parallel piece of glass in the optical path. This can be used in cartographic applications to support a *reseau* pattern in contact with the film at the instant of exposure.

AN OPEN QUESTION

As the results presented have shown, a new, high-performance, ultra-wide-angle objective lens form having potential applications to photogrammetry has been successfully developed. In this sense, the lens constitutes a solution looking for a problem. Ultimately its utility will be driven by economic factors. Will or will not the extended coverage, speed, etc., provide an ultimate reward to the user which can justify a change to new equipment? That answer cannot be self-generated by the lens developer alone. It must come from the photogrammetric community.

Your considered comments will be appreciated.

REFERENCES

1. Hugues, Ed., "Objectifs photographiques grand-angulaires utilisant une surface parabolique", *Japanese Journal of Applied Physics,* Vol. 4, Supplement 1, 1965, *Proceedings of the Conference on Photographic and Spectroscopic Optics,* 1964.

CALL FOR PAPERS
4th CANADIAN SYMPOSIUM ON REMOTE SENSING

The 4th Canadian Symposium has been scheduled for May 16, 17 and 18, 1977, in Québec City, Québec. The Department of Lands and Forests of the Province of Québec will host the meeting, which is sponsored by the Canadian Remote Sensing Society of the Canadian Aeronautics and Space Institute and other professional societies and government departments.

The Symposium will examine Remote Sensing as a vital and mature technology which embodies conceptual problem definition, technologica development, and proven application. It hopes to demonstrate the wide applicability of particular sensors and interpretation algorithms in a way which enhances our appreciation of the interdependence of processes on the earth's surface, its water bodies and in the atmosphere.

Those wishing to present a paper at the 4th Canadian Remote Sensing Symposium are asked to send a detailed, comprehensive summary of 250 words (in English or French) no later than *September 30, 1976,* to the address given below. Since selection of papers to be presented at the meeting will be based upon this summary, it must include an outline of the problem, methods used in its solution, and results obtained. Papers accepted for presentation will be refereed prior to publication in the Symposium Proceedings. Papers may be presented in either English or French.

Dr. J. Kruus
Technical Program Chairman
4th Canadian Symposium on Remote Sensing
Canada Centre for Remote Sensing
2464 Sheffield Road
Ottawa, Ontario
K1A 0E4