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USE OF INTERFERENCE PASSBAND FILTERS WITH WIDE-ANGLE LENSES FOR MULTISPECTRAL PHOTOGRAPHY

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ABSTRACT

The aim of this study was to determine to what extent a constant spectral response can be obtained for wide-passband interference filters used with wide-angle lenses. We investigated the possibility of using the curvature of the lens surfaces to reduce the shift in the filter passband for large field angles and found that locating the filter on the proper surface will considerably reduce the shift of the passband.

Specifically, we determined the distribution of angles of incidence for full aperture pencils incident at several field angles on the second and fourth surfaces of the 90° Geocon IV, the 90° Paxar, and the 125° Pleogon. We then calculated the spectral transmittance of each lens when a wide passband interference filter was located on its second or fourth surface. We also calculated the degree of polarization introduced.

From the cases considered, we found that the tracing of an upper and lower marginal (rim) ray at maximum field angle is sufficient to determine the suitability of a surface, the criterion being that, the smaller the angle of incidence at the surface, the better. In addition, we found that, with the filter on the second surface of the Paxar, spectral transmittance changes with field angle were negligible and the modulation due to polarization was about 1%.

DESCRIPTORS: Interference filters, Multispectral photography, Polarization, Ray tracing, Wide-angle lenses

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INTRODUCTION

Optical Sciences Center Technical Report 25 (McKenney and Slater, 1968) discussed the need for passband interference filters in multispectral photography and described a method for their design. The design showed that it should be possible to fabricate sharply-defined passband filters for any central wavelength (400 to 900 nm) and any passband width (50 to 350 nm)--hence the name "accordion filter." The transmittance of accordion filters in the required passband was shown to be 2 or 3 times greater than that of the equivalent absorption filter. The result is a significant decrease in the T-number of a multispectral camera, sufficient in the Earth orbital case to improve the spatial resolution, under some circumstances, by a factor of 2.

Accordion filters share with all interference filters the drawback that, with changing angle of incidence, the shape and position of the passband also change. It is calculated that the position of the central wavelength shifts about 2% at a 20° angle of incidence. Photographs of typical terrain features, taken through an accordion filter, indicate that this shift is not detectable; however, under certain conditions the shift at 25° *is* observable. The question then arises as to how we can use accordion filters with wide-angle lenses to obtain, for example, multispectral photography of cartographic quality, as suggested by Badgley, Colvocoresses, and Centers (1968).

In this report we describe how, by coating the accordion filter onto an appropriate internal surface of a lens, we can greatly reduce the change in spectral content of the image-forming light with changing field angle. We outline the computational method developed and show how to apply it to three modern wide-angle aerial lenses. Detailed spectral response data are presented. We consider polarization effects and describe a simple way to select the most suitable lens surface.

TECHNICAL DISCUSSION

The requirement for obtaining constant spectral content across the film plane can be met exactly if we can find a surface of the lens upon which the angles of incidence at full aperture are distributed identically for all field angles. The range of the distribution of angles will determine to what extent this requirement can be met.

In considering the coating of lens elements, we imposed several restrictions to avoid possible problems. First, so as not to change the lens system, we considered using only the available lens surfaces. An interference filter coated on such a surface is thin enough not to affect the imaging characteristics of the lens. Second, we considered only uniform coatings, which simplifies the theoretical problem, and we considered only concave surfaces, which are relatively easy to coat uniformly and thus simplify the fabrication problem later. Third, since interference filters are highly reflecting for wavelengths that are not transmitted, we considered locating the filter on one of the first two lens elements only, in order to reduce the chance that off-band stray light would be scattered or reflected back through the filter at a high angle of incidence.

We started this study by evaluating some of the older, readily available designs of cartographic lenses. (See, for example, Stavroudis and Sutton, 1965.) Ray tracing of these lenses quickly indicated a serious mechanical vignetting problem. Typically, an old f/6.3 cartographic lens, such as the 45° semifield angle Metrogon, will vignette a full-aperture pencil at semifield angles greater than 35°; or, at full field, the lens will vignette until reduced in speed to about f/10. When coupled with the decrease in illuminance roughly proportional to $\cos^4$ of the semifield angle, the total decrease can amount to about three stops. A filter factor of 4 (two stops) can be introduced by some of the absorption filters used in multispectral photography. Thus, the T-number of such a lens may be T/36, which is generally too high for aerial or space applications.

We then obtained design data sufficient for our purposes for three aerial camera lenses, all illustrated on the opposite page: the Geocon IV lens (courtesy of Kollsman Instrument Corporation), the Paxar lens (courtesy of Pacific Optical Division of Chicago Aerial Industries, Inc.), and the 125° Pleogon lens (courtesy of Carl Zeiss, Inc.).

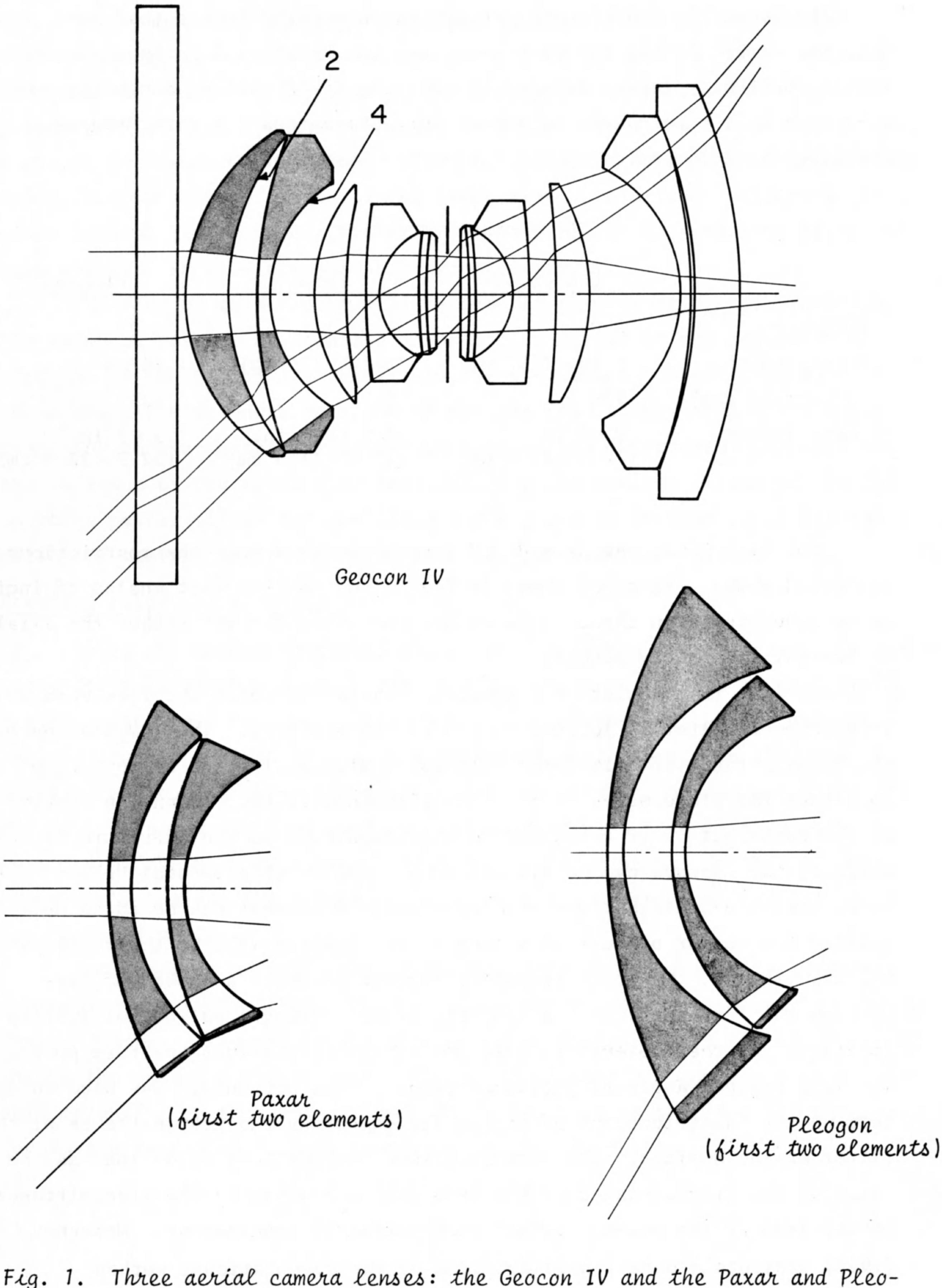


Fig. 1. Three aerial camera lenses: the Geocon IV and the Paxar and Pleogon (first two elements only).

The Geocon IV and Pleogon are precision mapping lenses that have come onto the market during the past year, and the Paxar is a reconnaissance lens. Four Paxar lenses mounted in modified KA-62 cameras are being operated as a multiband camera in NASA's Earth Resources Aircraft Program. Specific characteristics of the lenses are listed below.

Lens characteristics

	Geocon IV	Paxar	Pleogon
F/number	5.0	4.5	4.0
Focal length	6 in. (152 mm)	3 in. (76 mm)	80 mm
Full-field angle	90°	90°	125°
Image format	9 × 9 in. (22.9 × 22.9 cm)	4.5 × 4.5 in. (11.4 × 11.4 cm)	9 × 9 in. (22.9 × 22.9 cm)

For each lens, the second and fourth surfaces meet the restrictions discussed above. Also, as shown in Fig. 1, we can see that angles of incidence encountered on these surfaces are not excessive for either the axial or the full-field ray pencils.

We want to calculate the spectral transmittance of the lens when an interference filter is located on one of the surfaces. The computation of the transmittance of multilayer filters is straightforward at any angle of incidence for plane waves incident on plane substrates. When the curvature of the wavefront is of the same order of magnitude as the curvature of the surface, the surface can be divided into a number of elemental "plane" surfaces, and the contributions from each surface element can be added up. The greater the number of surface elements, the greater will be the accuracy of the calculation. We found it most efficient to trace a number of rays through the lens surface in a specific order. Using a polynomial fitting technique, we then determined what percentage of the full-aperture pencil lay in a certain angle-of-incidence range. This percentage was used to determine the "distribution" of angles for computing the transmittance of the filter on the surface. The "transmittance" of the lens is defined as the ratio of the transmittance of the lens with a coating to the transmittance of the lens if the coated surface were perfectly transparent. McKenney (1969) presents a detailed description of the computational method.

We assumed that the light incident on the surface is unpolarized. This is necessary because we did not keep track of each ray to be able to determine the plane of incidence. The assumption of unpolarized light is probably valid even for the polarized case also since there will be, for any angle of incidence, an "average" plane of incidence making the transmittance appear at the image plane as if the light were unpolarized. Assuming that, under unusual circumstances, it might be possible to observe some polarization effects, we will discuss such effects later.

The rest of this report will be devoted to presenting and discussing the computed results of locating an accordion filter on the second or fourth surfaces of the Geocon IV, Paxar, and Pleogon lenses. We will examine how the shape and wavelength position of the passband change with field angle, then show to what extent polarization changes are introduced. We will show that a trace of two meridional rays defining the maximum extent of the full-aperture pencil at the extreme field angle gives an indication of the suitability of coating a given lens surface with an accordion filter.

Passband shape and position

Using the method described above, we calculated the spectral transmittance for each of the three lenses, at full aperture and for several field angles, with the accordion filter on the 2nd and then on the 4th surface. The results are plotted in Fig. 2 on the following pages. In the case of 0° field angle, the shape and position of the passband of the accordion filter on the 2nd or 4th lens surface are compared with the passband shape and position of the same filter on a flat substrate at normal incidence. For other field angles, the passband shape and position are compared with that for 0° field angle.

For purposes of multispectral photography we are primarily interested in finding the smallest change in passband shape and position over the image plane. Clearly, the second surface of the Paxar represents the best case although the second surfaces of the Geocon IV and the Pleogon could be acceptable depending on the application. It is interesting that for all three lenses the second surface is preferred to the fourth.

GEOCON — SURFACE 2

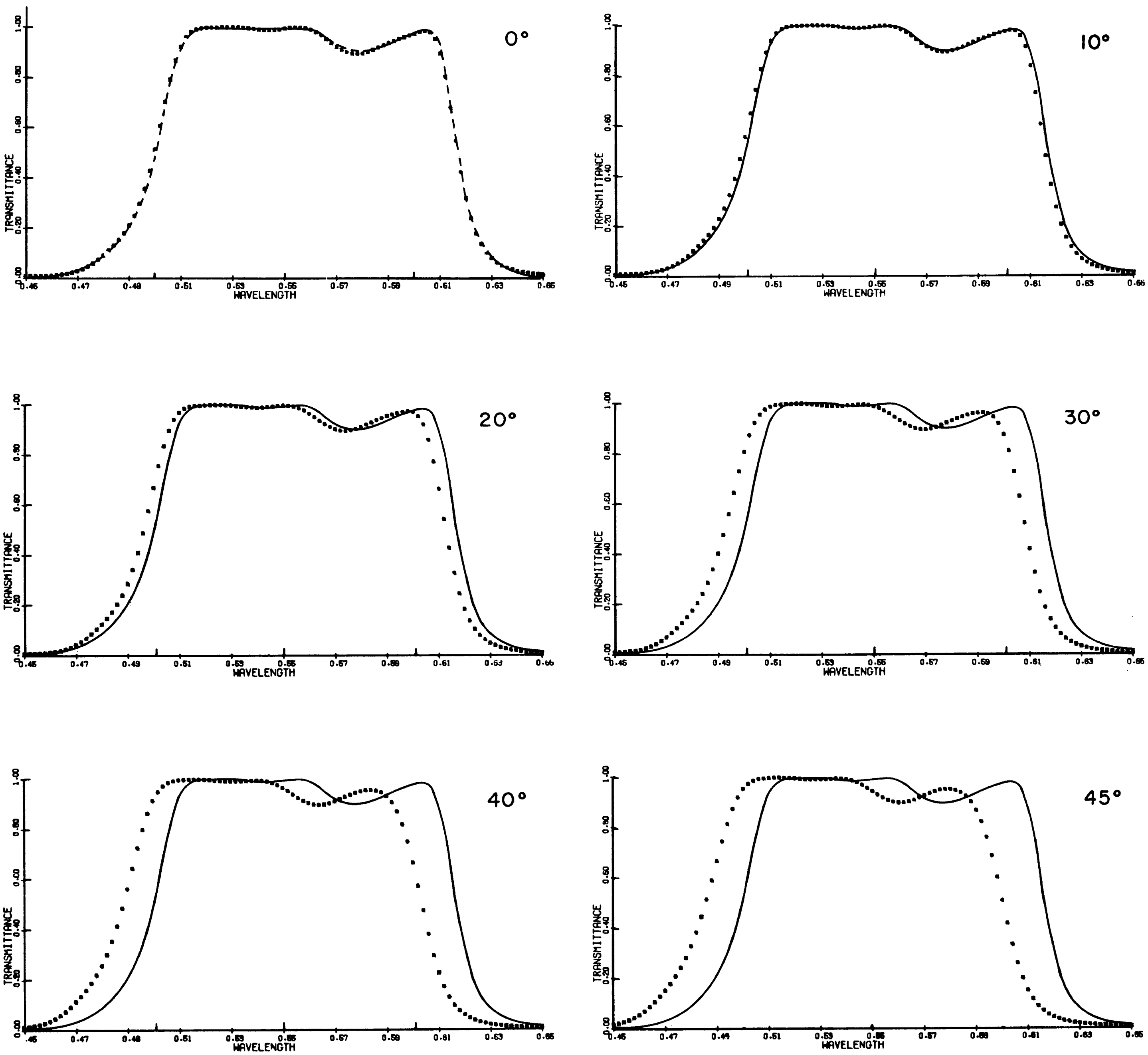
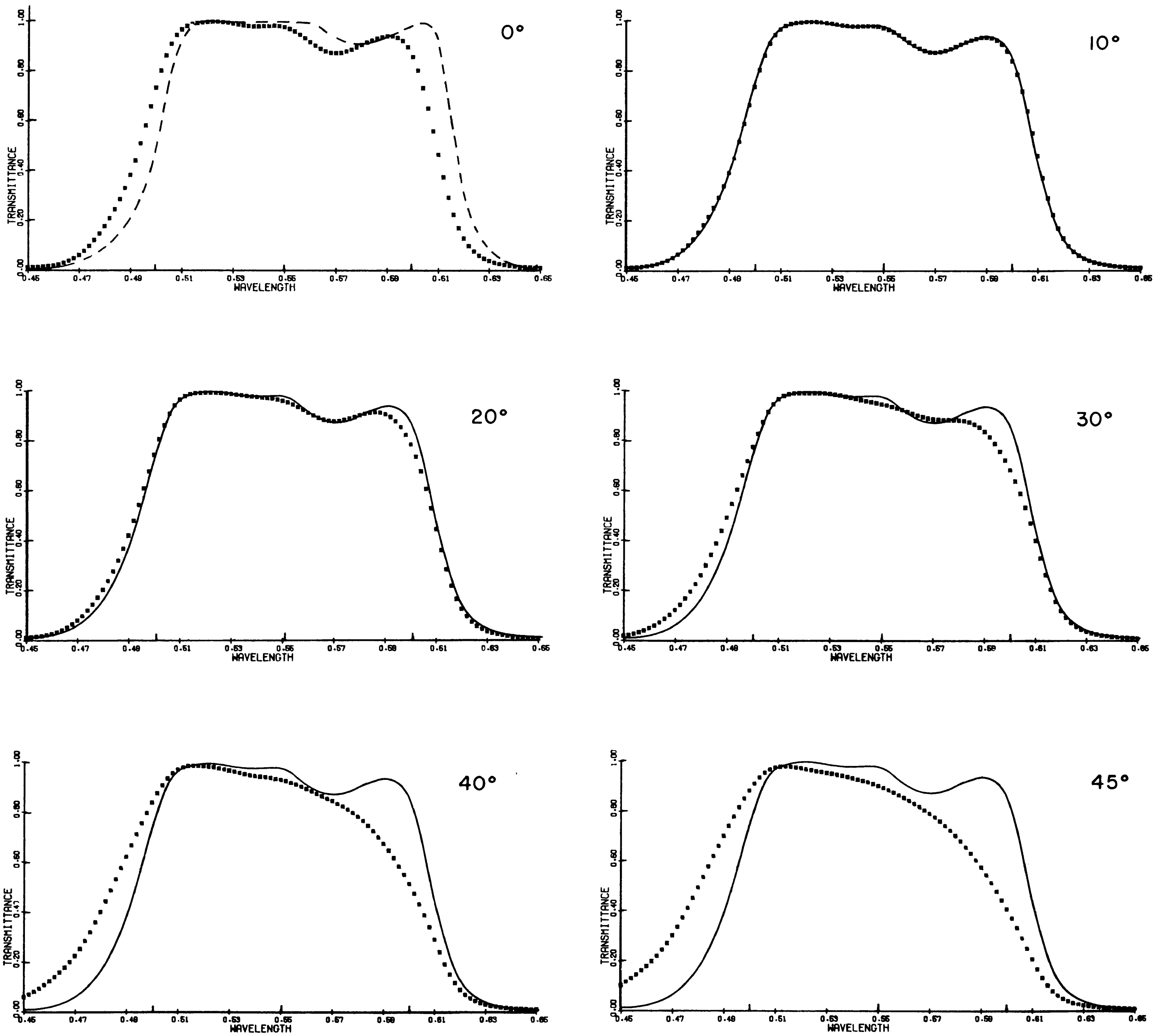


Fig. 2. These six pages show the spectral transmittance of an accordion filter located on the 2nd and on the 4th surfaces of the Geocon IV, Paxar, and Pleogon, for six semifield angles and for full aperture. (Wavelength scale is in μm.)

In the case of 0° field angle, the spectral transmittance of the filter on the lens surface (▪ ▪ ▪ ▪ ▪ ▪ ▪ ▪) is compared with the transmittance that would result if the filter were on a flat surface (---------) at normal incidence.

GEOCON — SURFACE 4



In the other five cases, the transmittance of the filter on the lens surface at the semifield angle indicated (▪▪▪▪▪▪▪▪▪) is compared with that at 0° (————) to indicate the shift of the passband.

PAXAR — SURFACE 2

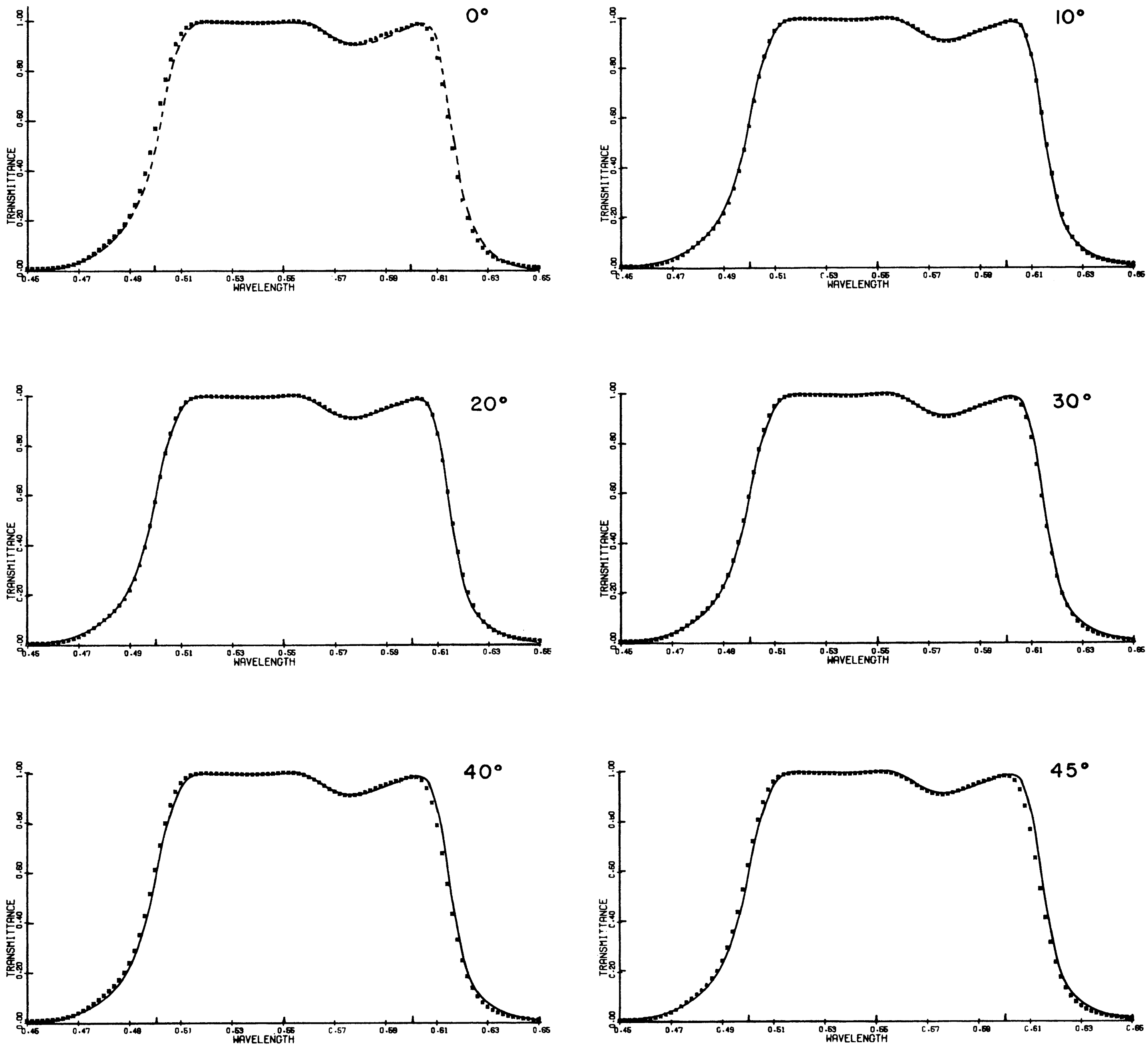


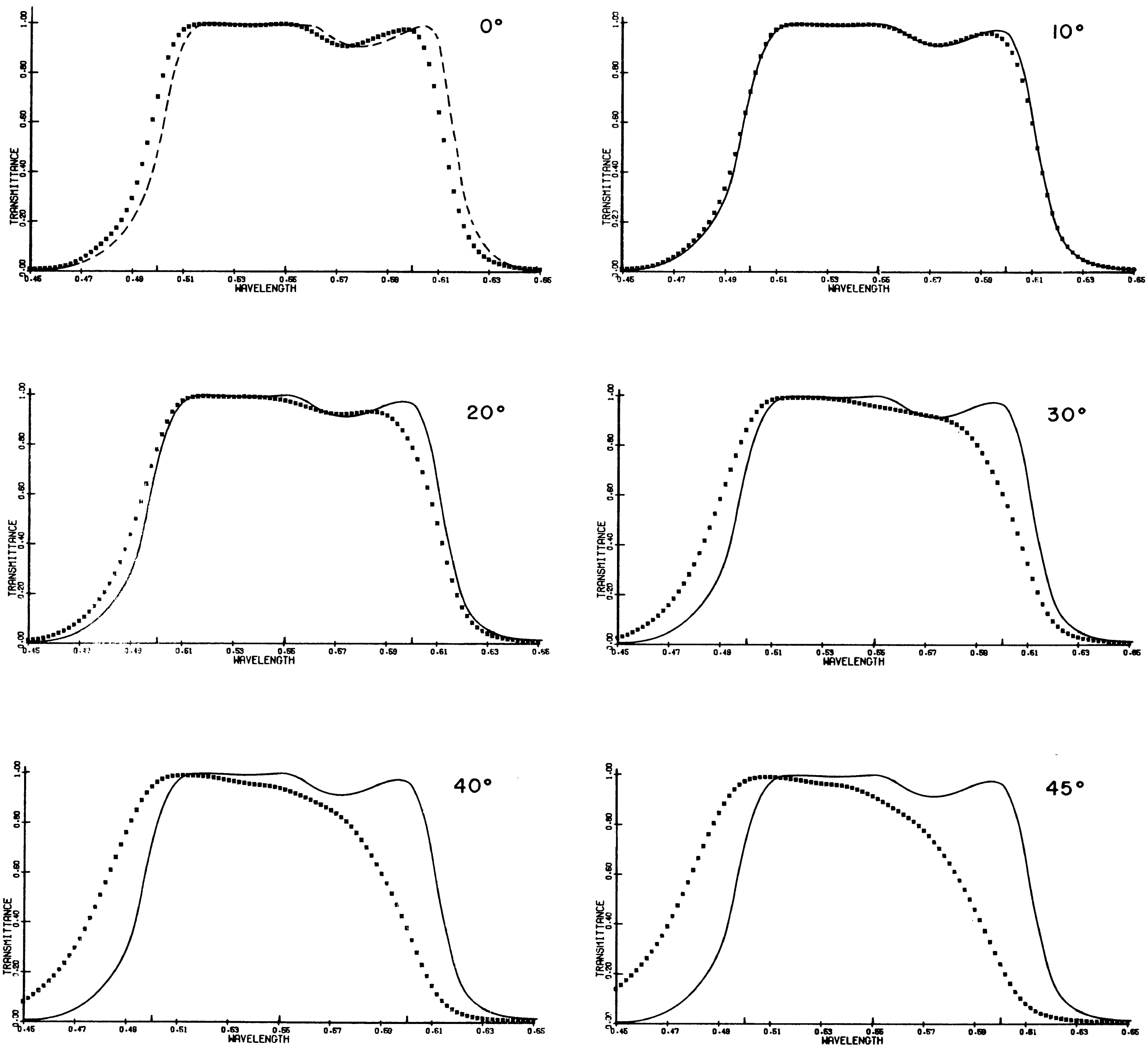
Fig. 2, continued

▪ ▪ ▪ ▪ ▪ ▪ ▪ Accordion filter on surface at semifield angle indicated

------- Accordion filter on flat surface, normal incidence

——— Accordion filter on surface at 0° field angle

PAXAR — SURFACE 4



PLEOGON — SURFACE 2

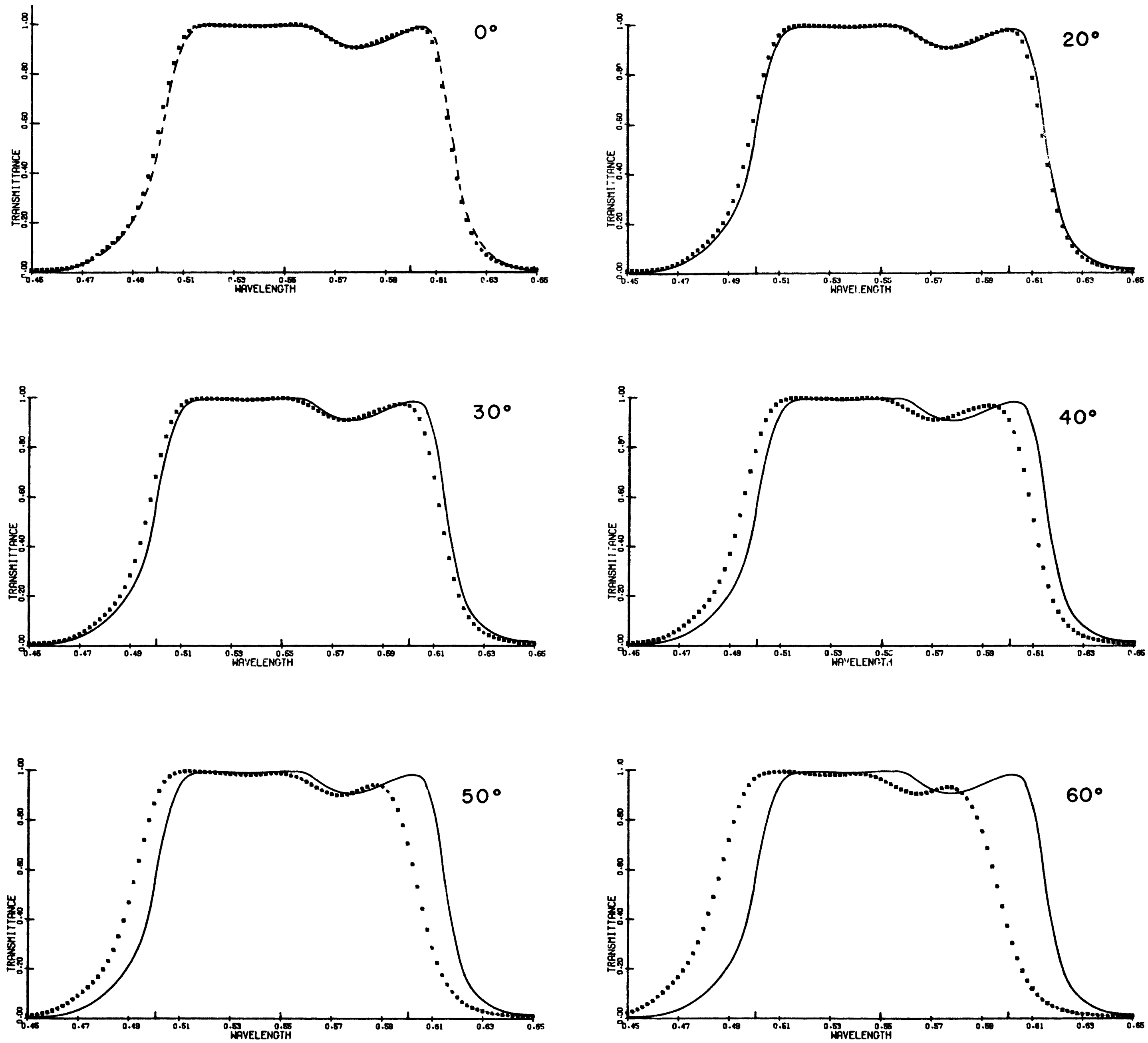


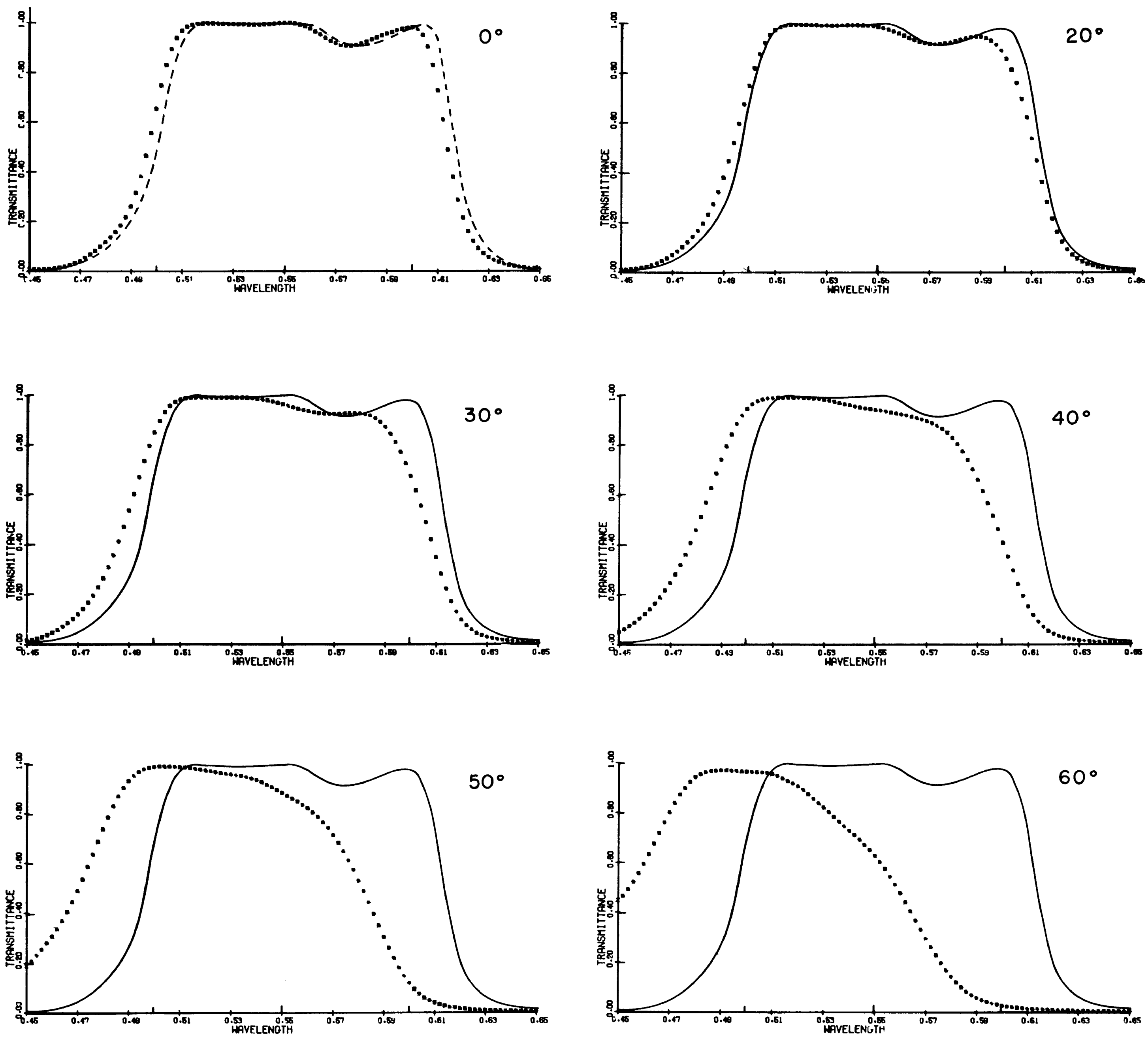
Fig. 2, continued

▪ ▪ ▪ ▪ ▪ ▪ ▪ *Accordion filter on surface at semifield angle indicated*

\- - - - - - - *Accordion filter on flat surface, normal incidence*

——— *Accordion filter on surface at 0° field angle*

PLEOGON — SURFACE 4



The graphs for the Geocon (pp. 6 and 7) indicate that the two surfaces modify the spectral transmittances in different ways. In the case of the second surface, the *shape* of the passband remains remarkably constant with change in semifield angle, while the passband *position* changes. In the case of the fourth surface, the *shape* of the passband changes noticeably, while up to 30° the change in *position* is small.

By reference to Fig. 3, below, we can quickly compare the shifts in the half-power points at the long wavelength cutoff of the filters. Again, the second surface of the Paxar is clearly the most suitable surface. The results for the Geocon illustrate an interesting point. Up to 30°, coating of the fourth surface is preferred to coating the second, but between 30° and 45°, coating of the second surface is preferred.

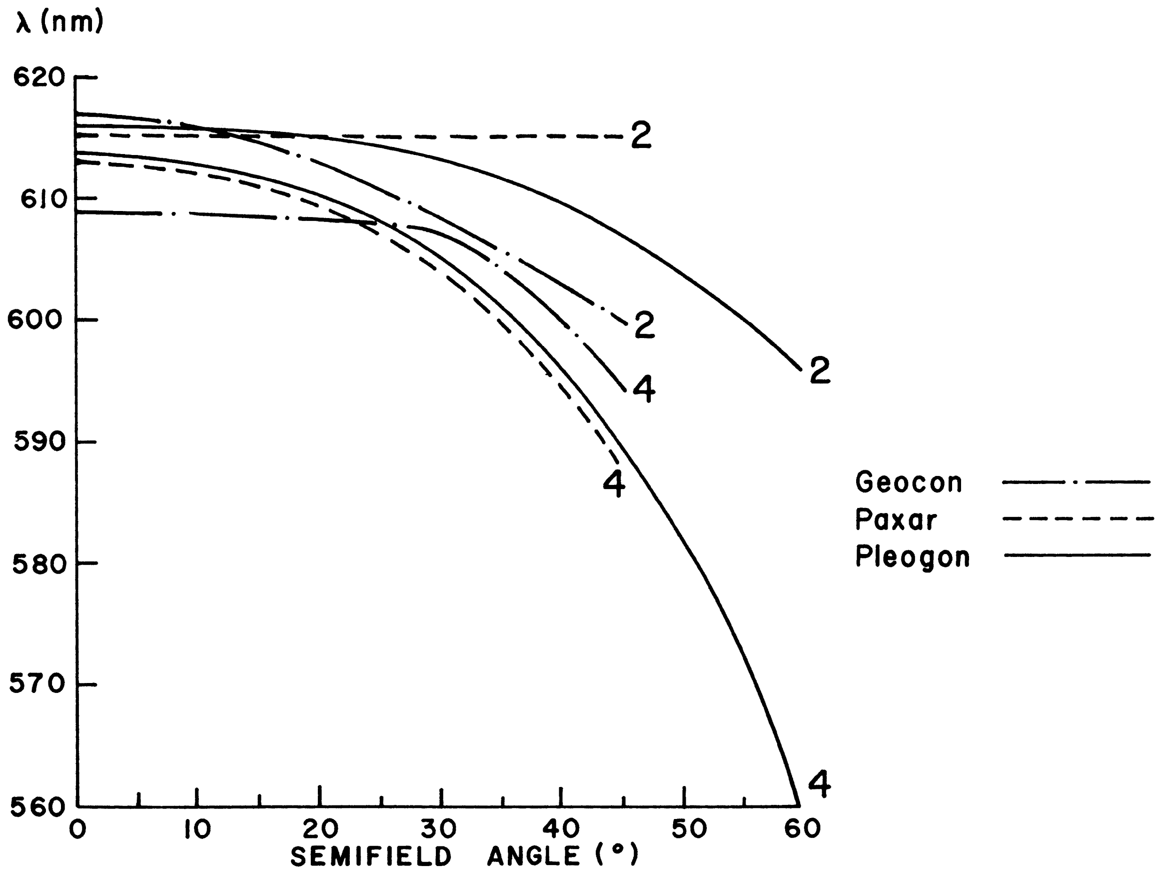


Fig. 3. Plots of λ against semifield angle for the 2nd and 4th surfaces of the three lenses; λ is the wavelength of the half-power point at the long-wavelength cutoff of the filter.

Polarization effects

Fig. 4 shows the wavelength difference for two extreme polarization components at the half-power points against the semifield angle for the two surfaces of each lens. The magnitude of the difference indicates possible variation in the spectral response over the film plane. Again, the second surface of the Paxar is preferable on this basis. It is also interesting to note the relatively high degree of polarization introduced by the fourth surface of the Geocon IV on axis. This is due to the relatively broad distribution of angles of incidence on this surface.

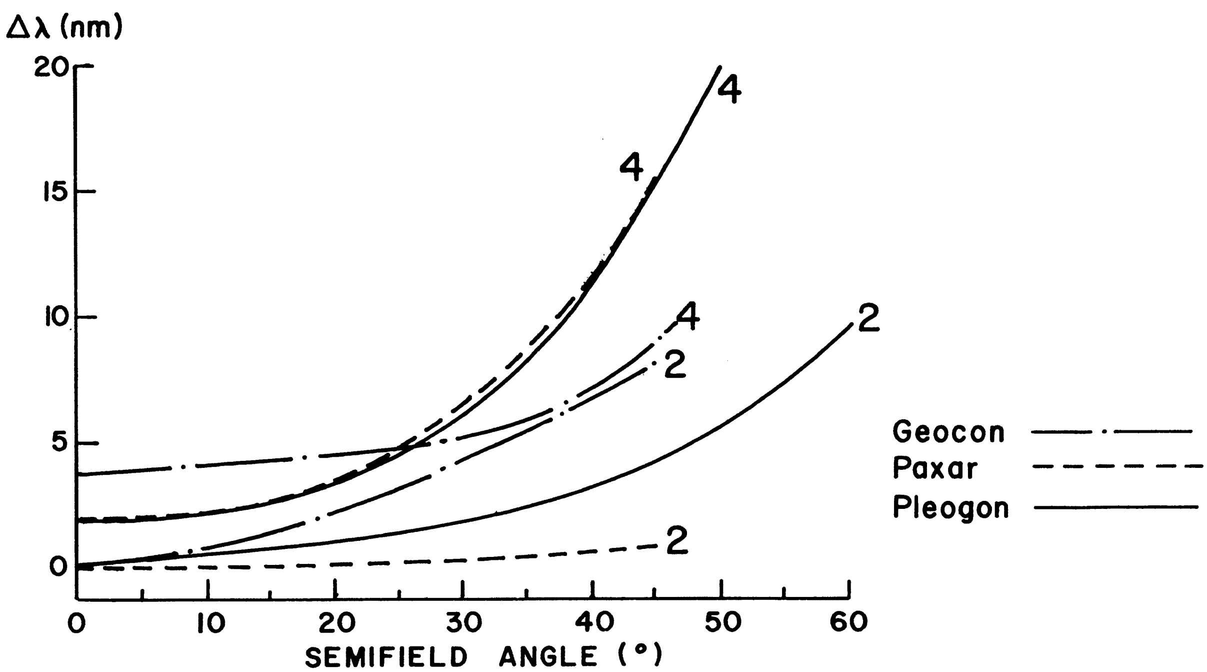


Fig. 4. Plots of Δλ against semifield angle for the 2nd and 4th surfaces of the three lenses; Δλ is the wavelength difference between the s and p half-power points at the long-wavelength cutoff of the filter.

Perhaps the most meaningful quantity that can be discussed for photographic applications is the percentage modulation. By this we mean the modulation of the total illuminance at an image point for an extreme change in polarization. At a semifield angle of 45°, the second and fourth surfaces of the Paxar give rise to modulations of 1.3% and 12.7%, respectively. On this basis, again, the second surface of the Paxar is preferred.

Determination of best surface by ray tracing

By ray tracing a lens, we can find the most suitable surface for coating with an accordion filter. In this study we used a computer program that determined the distribution of angles of incidence at a surface as a function of field angle. However, for the lenses considered, we found that, in place of this distribution, we could judge the suitability of a surface from a trace of an upper and a lower marginal (rim) ray. The criterion is simply that, at the maximum semifield angle, the smaller the angle of incidence at the surface the more suitable the surface. From the distribution of about 100 rays that were traced for each surface at each field angle, we compiled the table below, which gives the minimum and maximum angles of incidence for each field angle.

From the table we see that the second surface in all three cases is the best choice using the above criterion and that the Paxar, with its maximum spread of 12°, is preferred. The results based on this criterion are in complete agreement with those determined earlier from a detailed analysis of the problem.

Minimum and maximum angles of incidence

For semifield angle	Geocon IV		Paxar		Pleogon	
	2nd surface	4th surface	2nd surface	4th surface	2nd surface	4th surface
0	0-4	0-14	0-8	0-12	0-8	0-12
10	0-8	0-14	0-8	0-16	0-10	0-14
20	4-12	0-16	0-10	0-20	0-12	0-18
30	6-14	0-20	0-10	0-24	0-14	2-22
40	8-18	0-24	0-10	6-28	4-16	8-26
45	10-18	2-24	0-12	10-30	--	--
50	--	--	--	--	8-18	14-30
60	--	--	--	--	12-20	22-34

CONCLUSION

The results of this study indicate that some modern wide-angle aerial lenses can be used with wide passband interference filters if the filters are deposited uniformly on a selected lens surface. Of particular interest is the Paxar, four of which are being used with different Schott color filters in a multiband camera as part of NASA's Earth Resources Aircraft Program. It should be possible to improve the performance of this system, in terms of speed and spectral selectivity, by removing the Schott filters and coating each of the second surfaces with the appropriate accordion filter.

More generally, we believe that by tracing a meridional fan of seven rays across the full-aperture at the maximum field angle, we can select the best surface in a wide-angle lens for coating with an accordion-type filter. In the three cases examined in this study, we found that an upper and lower marginal ray trace was sufficient. The surface then selected is the one with the smallest value for its maximum angle of incidence.

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