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INTERFERENCE FILTERS FOR MULTISPECTRAL PHOTOGRAPHY

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ABSTRACT

A new type of interference filter is described, which can readily be designed for any central wavelength (400 to 900 nm) and any passband width (50 to 350 nm). These filters provide sharper cutoffs and greater efficiency than conventional absorption filters, and total transmittance in the required passbands is shown to be 2 or 3 times greater, resulting in shorter exposure times and consequently about a twofold increase in spatial resolving power for early space multiband photography experiments.

Several configurations of multiband camera systems are considered, and qualitative comparisons are made regarding variation of spectral response as a function of both field of view and polarization of incident light.

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I. GENERAL

Introduction to multispectral photography

Multispectral photography* concerns the identification or discrimination of objects within a scene by taking photographs in several wavelength bands in the visible and photographic infrared. The photographs are then projected in register onto a viewing screen through different colored filters. The resulting composite multicolored image can be of considerable benefit to the photointerpreter, both in the rapid screening of large quantities of data and in the detailed study of small areas of critical importance.

We know that a color photograph, taken of a colorful scene, contains more information than the equivalent black-and-white photograph. A good conventional color photograph realistically portrays the color of a scene to the observer. It can do this because of the careful balance between the spectral responses of the three layers in the film which are sensitive to three broad, overlapping regions of the visible spectrum.

Emulsions can be sensitized to wavelengths in the near infrared out to about 900 nm. These were found several years ago to be important in military photoreconnaissance because they could be used to identify camouflaged sites. The reason for this can be found by comparing the low infrared reflectances of camouflage materials (dead foliage, camouflage paint, green plastic sheet, etc.) with the high infrared reflectance of live foliage. The use of color infrared film (which presents the photographic IR as red, red as green, and green as blue) was a further help to the photointerpreter, as camouflaged areas show up more readily as color differences than as shades of gray. Earth scientists found many important applications for conventional and

*Also referred to as spectral-zonal photography, multiband photography, or spectrophotography.

IR color film, and groups in Russia and the USA proceeded to determine the merits of multispectral photography as an extension of color photography.

In using color IR film the step had already been made of improving discrimination at the expense of color fidelity. It was felt that more information and better discrimination could be obtained by choosing wavelength bands in the visible and photographic infrared that were more selective, i.e. narrower and without overlap, than the dyes used in color film emulsions. The photographic images, on black-and-white film, could be projected in register onto a viewing screen through different spectral and neutral density filters. The color balance of the composite projected image could thus be changed at will. Density differences between the various projected transparencies would show up as color differences in the composite image. These color differences would be more marked than those on color film and would offer a considerable improvement over the discrimination provided by the different shades of gray in black-and-white photography. A few additive color viewers working on this principal have been built. These demonstrate the diagnostic potential of multispectral photography. In their present state of development, however, they have increased rather than decreased the time needed for photointerpretation.

Attempts are now being made to obtain quantitative data from sets of multispectral photographs. For example, microdensitometer scans of the multispectral images of a given scene can be compared in a computer with scans of known ground features such as agricultural and forestry areas. It is hoped that such a comparison will allow different crops to be identified automatically. Such data as crop vitality and soil moisture content might also be obtained.

It is interesting to note that several different types of camera systems are being used in multispectral photography. For example, one USAF group is planning to use 3-inch-focal-length panoramic cameras for multispectral photoreconnaissance; another is using a nine-lens frame camera primarily for geological studies. University groups are using four-lens and nine-lens frame cameras, and one group is using a standard Speed Graphic camera in studies of ground-to-ground multispectral photography. Strip multispectral photography and behind-the-lens filtering onto multiple image planes are being considered. NASA is using an aircraft-mounted nine-lens frame camera and is planning several low earth orbit "Earth Resources" missions in which four or six multispectral cameras will be used, perhaps in one case using wide-angle mapping cameras.

The filter problem

One of the outstanding problems in multispectral photography lies in the selection of the best set of filters for a particular study, say of agricultural areas. Another is the selection of filters for an orbital mission, for example when the same filter set has to be used for studies in such diverse subjects as agriculture, geology, and oceanography. Up to now, the worker in multispectral photography has been severely limited in the choice of filters available to him. The only suitable bandpass filters have been absorption filters of the Corning, Schott and Wratten types. These can be obtained for only a few regions in the visible spectrum, and furthermore, the width of each is fixed. Besides these two basic limitations, which have hampered the search for an optimum filter set, absorption bandpass filters have two additional undesirable characteristics:

(1) Their efficiency is low; typically their peak transmittance is less than 0.60 (60%).

(2) The bandpass cutoffs are not steep. This is particularly true for the long-wavelength cutoffs, resulting in a bandpass which is far removed from the ideal rectangular shape.

Interference filters were considered for this application for three reasons:

(1) When made of dielectric thin films, they exhibit very small loss due to scattering and absorption.

(2) They can be designed and built for any central wavelength in the visible and photographic infrared.

(3) The cutoffs can be made very steep.

Until now, however, interference filters have been rejected by those involved in multispectral work because--

(1) Filters of the width usually required in multispectral photography ($\gtrsim$100 nm) were unobtainable.

(2) The central wavelength and the shape of the passband change with angle of incidence. This effect becomes increasingly pronounced as the angle of incidence increases beyond about 10°.

For some years researchers neglected the problem of designing suitable interference filters to replace absorption passband filters in multispectral photography. This was because, with multispectral photography still in early development, other problems, such as multispectral photointerpretation, were more pressing and absorption passband filters were considered reasonably acceptable. Filters became a *major* problem only when consideration was given to multispectral photography of the earth from low earth oribt. Here the low efficiency of absorption passband filters (their high filter factor) means that little of the available energy is incident on the film plane. This necessitates long exposure times, which, coupled with the high angular velocity of the spacecraft, can cause substantial forward image motion. In the event that forward motion compensation (FMC) is unavailable* the amount of forward motion image blur can be reduced by a suitable choice of lens (high speed,

*The first "Earth Resources" orbital multispectral cameras will have no provision for FMC.

short focal length) and film (high speed, low resolving power), but the result is inevitably a loss in ground resolution compared to the case when a lower filter factor is available. It was because of the low efficiency of absorption filters and the future possibilities of multispectral photography from orbit that the work described here was initiated.

Comparison of absorption filters and interference filter designs

We will preview here some of the results to be described later in this report in order to emphasize the advantage of the interference over the absorption filter.

Typical of the passbands in the visible spectrum suggested for multiband photography are 440 to 580 nm, 500 to 620 nm, and 580 to 680 nm. In attempting to isolate these passbands with Corning,* Schott, or Wratten filters we find at once that only in one case does the passband of the filters available fall in the center of the required passband. In most cases the transmittance of the filters rises steeply at the short wavelength end of the passband and tails off slowly at the long wavelength end. These characteristics show up clearly in Figs. 1, 2, and 3, and it is also noticeable that the short wavelength end of the passband generally shows a much higher transmittance than the long wavelength end. We should also note that no high transmittance passband absorption filters exist in the red end of the spectrum. Thus, in the case of Fig. 3 we either have to ignore the requirement for the 680 nm cutoff or work with the very unsatisfactory filter shown as the dotted curve.

We may conclude that as a class, then, absorption filters isolate the required spectral passbands moderately well but not as well as desired.

*Corning filters cannot be used with a camera because they are not manufactured of optical grade glass. However, they can be used as part of the condensing system in a multiband projector or viewer.

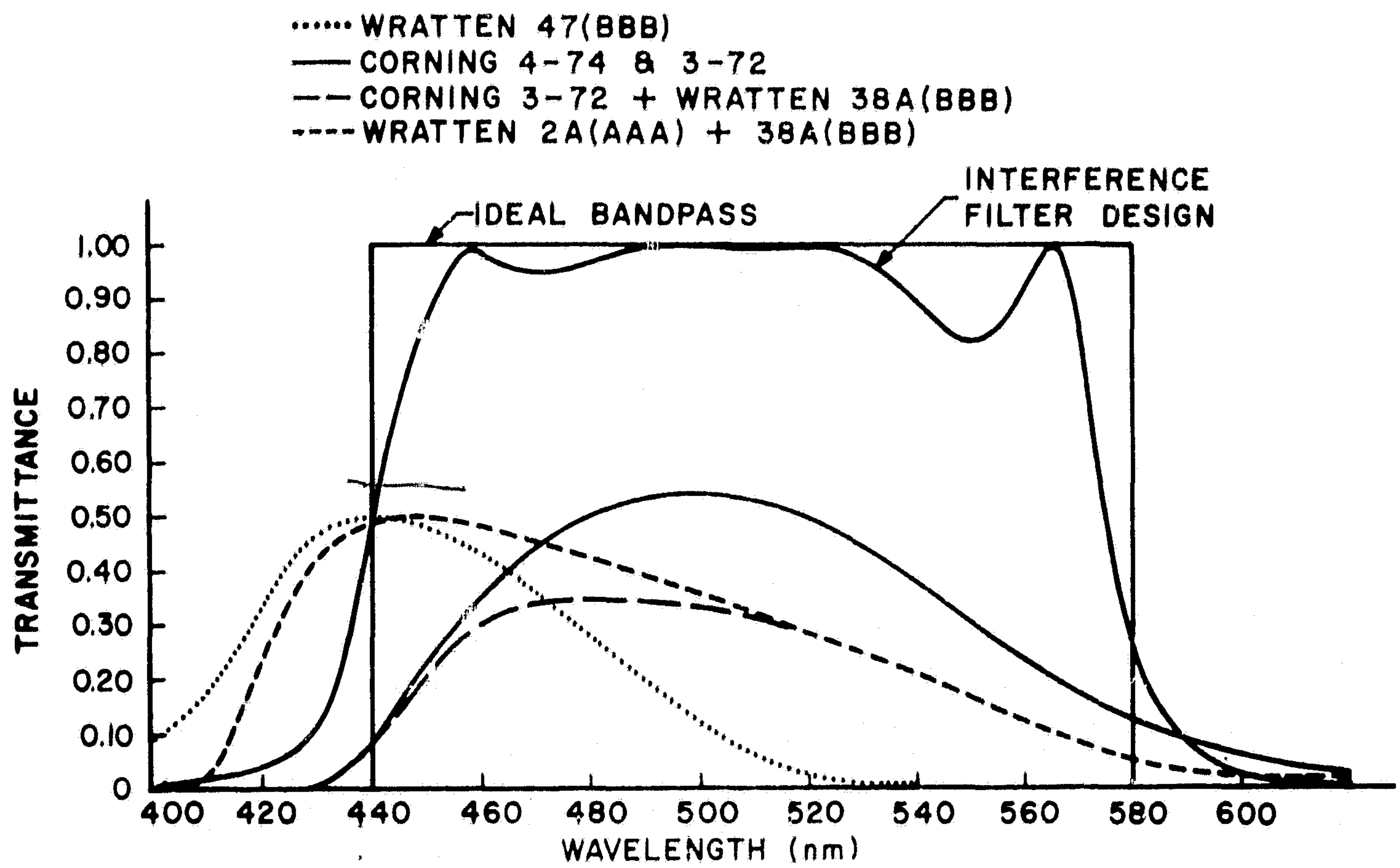

Fig. 1. *Comparison of Wratten and Corning absorbing filters with interference filter design; required bandpass 440 to 580 nm*

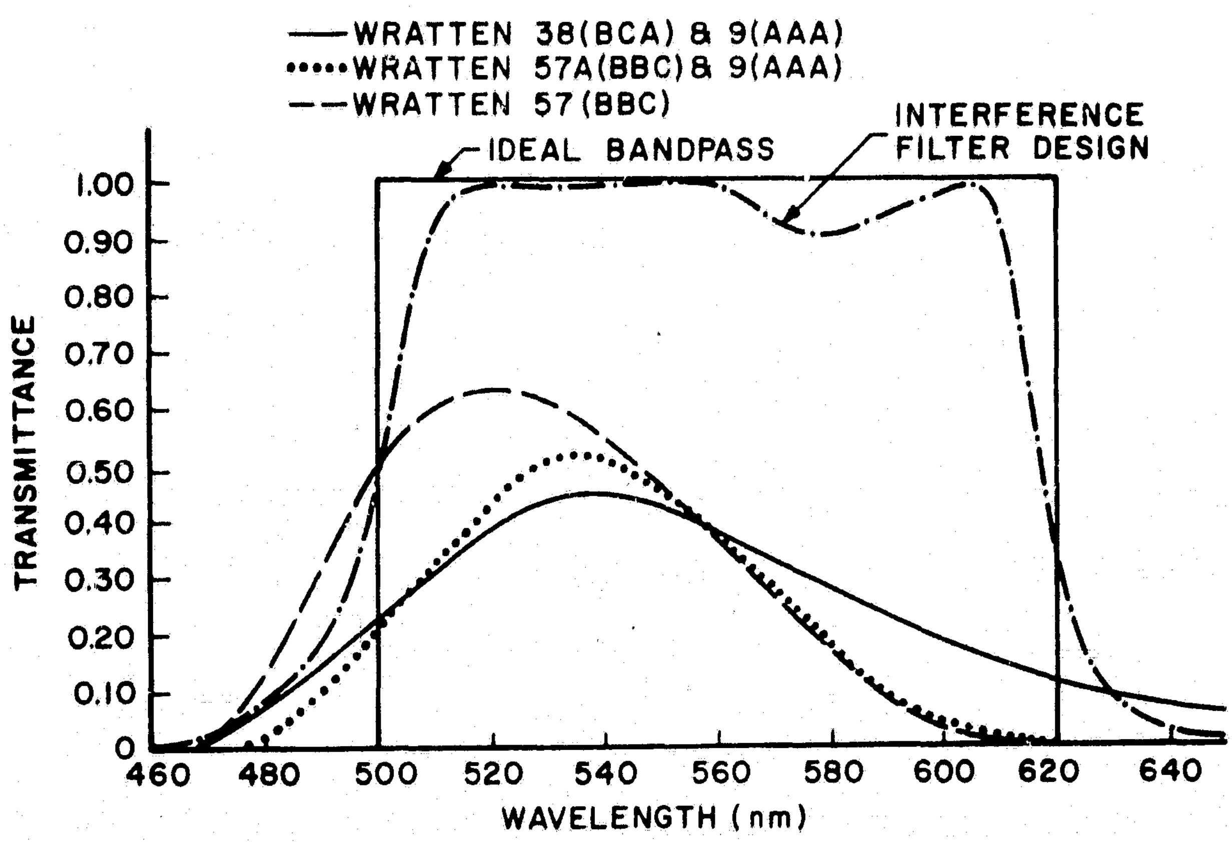

Fig. 2. *Comparison of Wratten absorbing filters with interference filter design; required bandpass 500 to 620 nm*

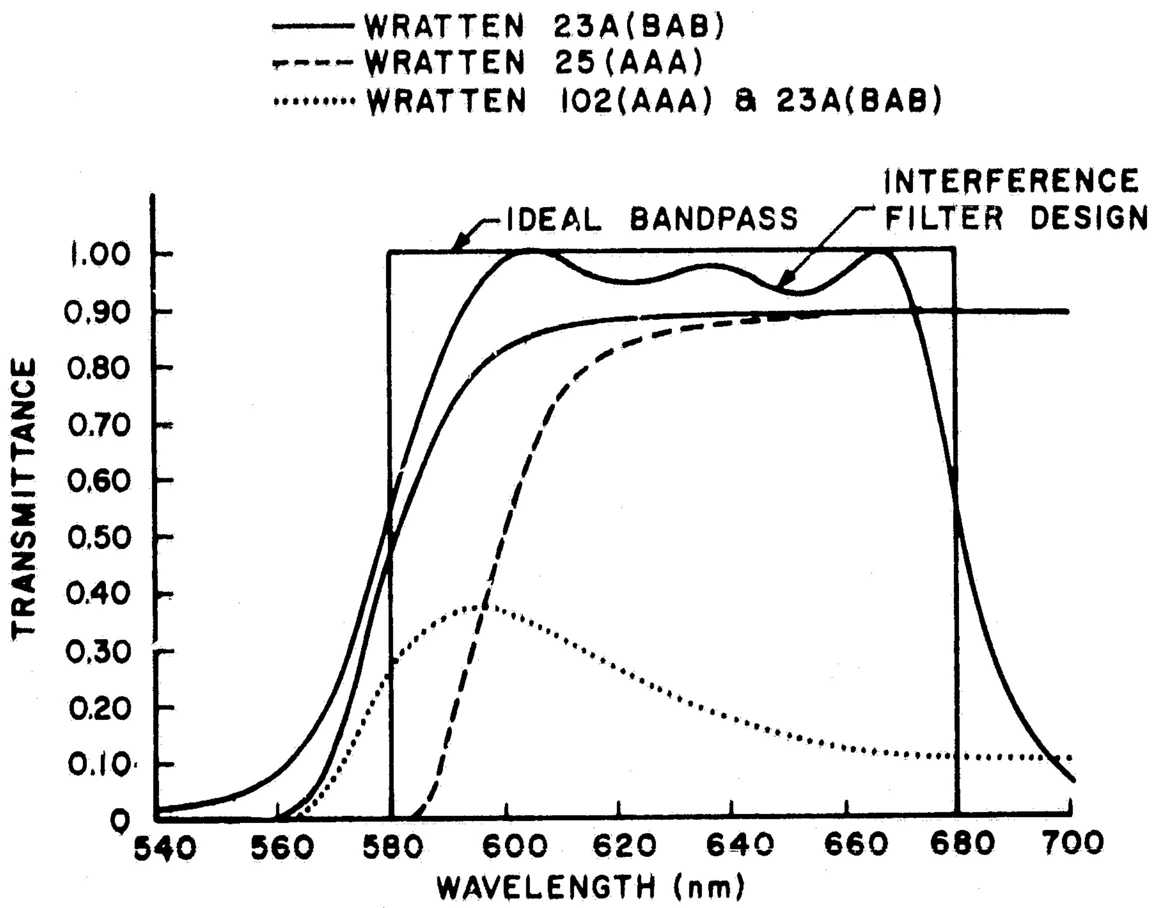

Fig. 3. Comparison of Wratten absorbing filters with interference filter design; required bandpass 580 to 680 nm

A second serious drawback of absorption filters is their low over-all transmittance or high filter factor. This is also shown clearly in Figs. 1 and 2. A calculation for the dotted curve in Fig. 2 shows that the filter factor is about 9. In comparison, the interference filter designs were to show a maximum calculated transmittance greater than 0.9. If the fabricated filters were to show a transmittance of 0.8, then, for the design shown in Fig. 2, the filter factor would be about 3. Thus the gain in filter factor in this case, in using an interference rather than an absorption filter, is a substantial factor of 3.

To illustrate the importance of this decrease in filter factor, we take the specific case of a diffraction-limited f/5 lens of focal length 80 mm recording an object of contrast ratio 2:1 on Plus-X film. If the camera is stationary with respect to the object, the resolving power on film is about 56 cycles/mm. (These calculations were made with the aid of the Itek Photographic Slide Rule.) Now let us assume the camera is in a spacecraft orbiting the earth and the angular velocity of the camera with respect to the object is 50 mrad/sec. Let us also assume that the exposure time with a filter factor of 9 is 6 milliseconds. The image smear is then 24 nm and the resolving power is reduced to 30 cycles/mm. With a filter factor of 3, the exposure time will be reduced to 2 milliseconds and the smear to 8 nm. Under these conditions the resolving power will be 50 cycles/mm. As a percentage, the resolving power has dropped by 46% with the filter factor of 9 compared to 11% with the filter factor of 3.

Angular dependence of interference filters

The reluctance to use interference filters in multispectral photography has been partly due, understandably, to the unavoidable change in passband shape and position with angle of incidence. The designs shown in Figs. 1, 2, and 3 show a shift that is roughly proportional to $\cos^{1/3}\theta$, where θ is the angle of incidence.

For angles of incidence (semi-field angles) up to 20°, this $\cos^{1/3}\theta$ shift is a small factor, amounting to only 12 nm or 2%, as shown in Fig. 4. The change in shape, as we shall see later, is hardly discernible. In our opinion, both are negligibly small; however, we will have to await field experiments to check that this is true.

On the upper part of Fig. 4 we show how the fields of view differ, for equal areal coverage, in strip and frame photography. Strip cameras are now comparatively little-used; however, for several reasons (discussed in a NASA manual on multiband photography, now in press, authored by R. N. Colwell, P. N. Slater, and E. F. Yost), we think they should be considered for use as multispectral cameras.

One reason is that, for the same areal coverage, a smaller field of view is required than in frame photography. The gain is obvious from the 100% area line in Fig. 4, The field angles for the same areal coverage are 16° and 11° for frame and strip photography, respectively. The corresponding percentage shifts in the long-wavelength cutoff of the filter are 1.4% and 0.7%. Furthermore, it is clear that this gain will become more marked for larger semi-field angles. For example, in the equivalent case of 27° semi-field frame photography and 20° semi-field strip photography, the percentage shifts are 5% and 1.4%, respectively.

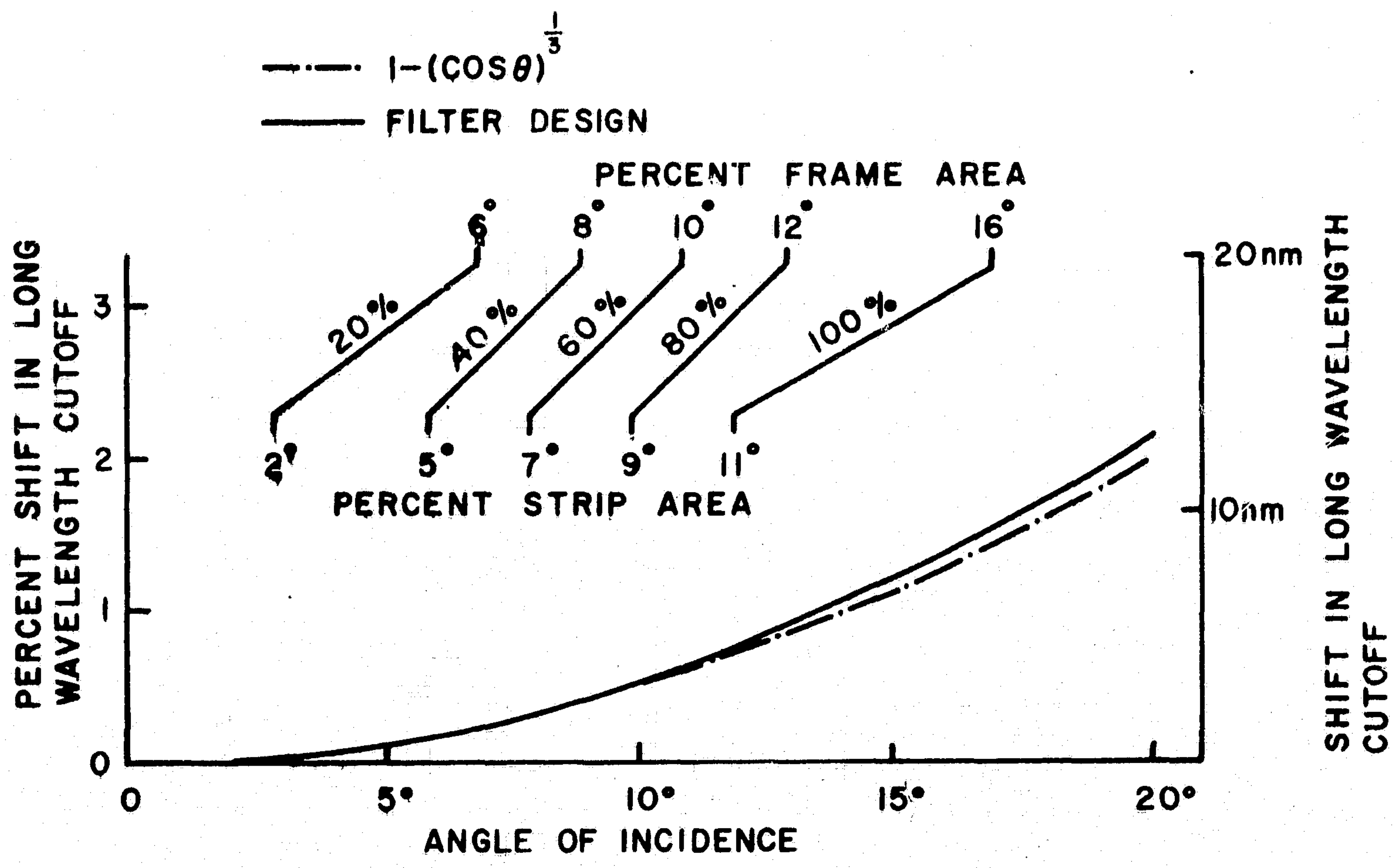

Fig. 4, Variation of cutoff shift with angle of incidence.

II. FILTER DESIGN BACKGROUND

For multispectral photography, the interpretation of photographs would be greatly simplified if a filter could be designed which had the following characteristics: 100% transmittance in the passband with no transmittance in the stopbands; infinitely sharp transitions from opaque to clear at the cuton and cutoff wavelengths; and no change in these characteristics with a change of the angle of incidence on the filter. In Section III we will discuss a method which has been used to design a filter which represents a substantial step from Wratten filters toward the highly idealized specifications outlined above. The necessity of this design effort is indicated below.

In many applications, the tolerances on the half-width of the filter (the ratio of the full-width at half maximum transmission to the central wavelength $\Delta\lambda_{\frac{1}{2}}/\lambda_o$) are large. We try to produce the "narrowest filter," or a broad filter that transmits "green" or "red." For multispectral photography the half-width must be accurately controlled (in fact we speak more of the cuton and cutoff wavelengths than of the filter half-width). For this preliminary investigation, we have been investigating filters with half-widths ranging from 0.15 to 0.26. We have tried to design a filter whose half-width can be varied over wide ranges with a minimum amount of redesign.

Two filters of so-called conventional design might be considered for this application. (1) A multiple-cavity filter can be designed to have a bandwidth of about 0.15 to 0.20. Such filters are available commercially. In general, the background rejection is poor (in the visible spectrum), and precise control of the bandwidth is difficult to achieve in practice. (2) Another possibility is to use two filters, a high- and a low-pass (frequency) combination. Although the passband could be controlled in this manner, such difficulties as multiple reflection ghosts and a relatively low transmittance ($\sim$0.80) in the passband make this approach undesirable.

Putting the entire design in a single stack is desirable since this will minimize reflection losses and problems with multiple reflections. Epstein (1952) took such an approach in designing a multilayer stack consisting of a high-pass stack and a low-pass stack matched to the substrate by an appropriate triple-layer stack. The idea is attractive, but the shape of the passband is poor and the background rejection in that particular design is unacceptable.

Our approach was similar to Epstein's. Originally we hoped to find two stacks that could be coupled together easily to produce a clean passband whose width could be varied simply by varying the thicknesses of the two stacks. We will refer to such a filter as an accordion filter. Our initial attempt to design an accordion filter was to simply place together two stacks whose spectral transmittance was high in the region of the passband. The result is shown in Fig. 5.

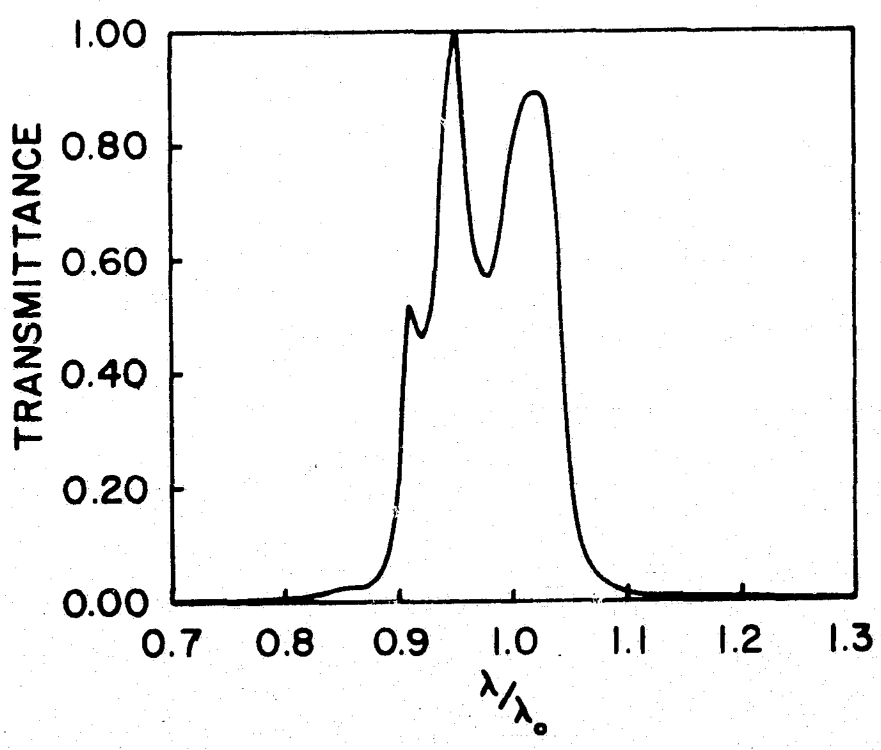

Fig. 5. Calculated transmittance of an unmatched high-pass:low-pass filter.

This clearly indicates the need for the systematic design approach which is outlined in the next section.

An alternative approach of designing through use of the thin films automatic correction program was discarded because of the difficulty involved in making filters with layers of nonequal thicknesses. Our basic philosophy has been to find a design which not only has all of the desired features but which can be made easily.

III. THE DESIGN OF ACCORDION FILTERS

The accordion filter is shown schematically in Fig. 6a. It consists of two multilayer stacks of different thicknesses whose basic function is to reflect the light on the long and short wavelength sides of the passband. The only two stack configurations considered in this study are standard high- and low-pass stacks, shown schematically in Figs. 6b and c. These were selected because of their simplicity, relatively wide use in other applications, and symmetry. The latter quality makes them suitable for analysis on the basis of Herpin theory (Herpin, 1947).

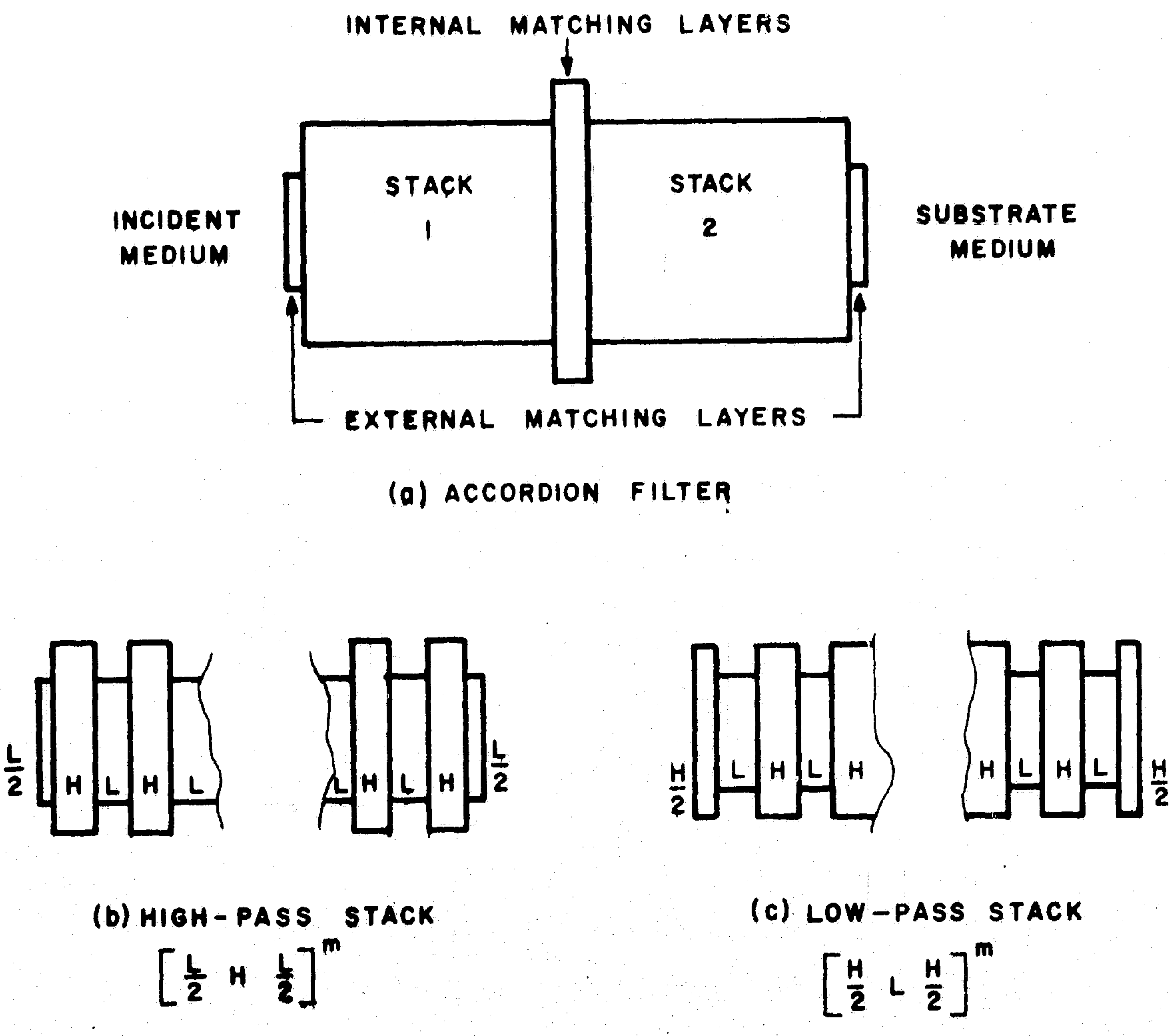

Fig. 6. The basic accordion filter and its elements.

The first step in the design procedure is to find the properties of the individual stacks: (1) the Herpin equivalent indices and thicknesses and (2) widths of the high reflection bands (HRB's). The thicknesses of the two stacks are then chosen to make the edges of the HRB's correspond with the desired filter half-width. Some small changes in the location of the HRB's must be made in the final design stages to achieve the exact bandwidth, as this bandwidth will depend to a small extent on the types of matching layers chosen. The scaling of the general design is visualized more easily when the results are plotted against relative frequency on a logarithmic scale. The filter passband can be centered on a frequency scale by centering the HRB's at

$$\sigma_1 = \sigma_o\left(\frac{1 + \Delta\sigma/2\sigma_o}{1 - \frac{1}{2} W_H}\right) \tag{1a}$$

and

$$\sigma_2 = \sigma_o\left(\frac{1 - \Delta\sigma/2\sigma_o}{1 + \frac{1}{2} W_H}\right) \tag{1b}$$

where σ_o is the center frequency of the accordion filter, $\Delta\sigma/\sigma_o$ is its desired passband width, and W_H is the width of the HRB (Young, 1967):

$$W_H = \frac{4}{\pi} \sin^{-1}\left(\frac{1 - n_a/n_b}{1 + n_a/n_b}\right) \tag{2}$$

where n_a and n_b are the indices of the two materials in the high-pass or low-pass stacks.

Since the Herpin equivalent index and limiting HRB width depend on the basic period and not on the number of periods, the second step in the design process is to select the number of periods to be used in each stack. The number of periods is best chosen with consideration of the required rejection outside the passband. The rejection will be greater for a stack with more periods. Ideally, one would like this number to be very large, but a compromise must be made for practical considerations. The most commonly used materials for the visible portion of the spectrum are zinc sulfide (H) and cryolite (L). Because of film stresses which inevitably build up in the deposition process, the number of layers must be limited. These two materials can be deposited in alternating layers to a limit of about 60 quarter-wave-thick layers. A more reasonable limit might be 35 to 40. The largest number of layers possible should be used when sharp filters with good background rejection are required. The filters investigated have either 13 or 15 layers in each stack ($m = 6, 7$ in Fig. 6b and c), for a total of 29 or 33 layers. This number of layers seems to be a good compromise between high rejection in the stopbands and practicality.

Third step in the design procedure is to select two stacks and couple them together. We demonstrated above that simple spectrophotometric considerations are insufficient for this purpose. A more fruitful approach has been to design on the basis of the Herpin equivalent indices and thicknesses. This allows us to reduce each stack to a single layer whose index and thickness are strongly a function of wavelength. The equivalent indices for low-pass stacks and high-pass stacks have been plotted in Figs. 7 and 8, which represent only two of an infinite number of possible stacks. The hatched areas indicate the limiting region of the high reflectance band where the equivalent index is undefined in this context. The matching layers are chosen so as to anti-reflect the interfaces between the stacks themselves and the external media. A lossless filter over the entire passband would be the result of a perfect

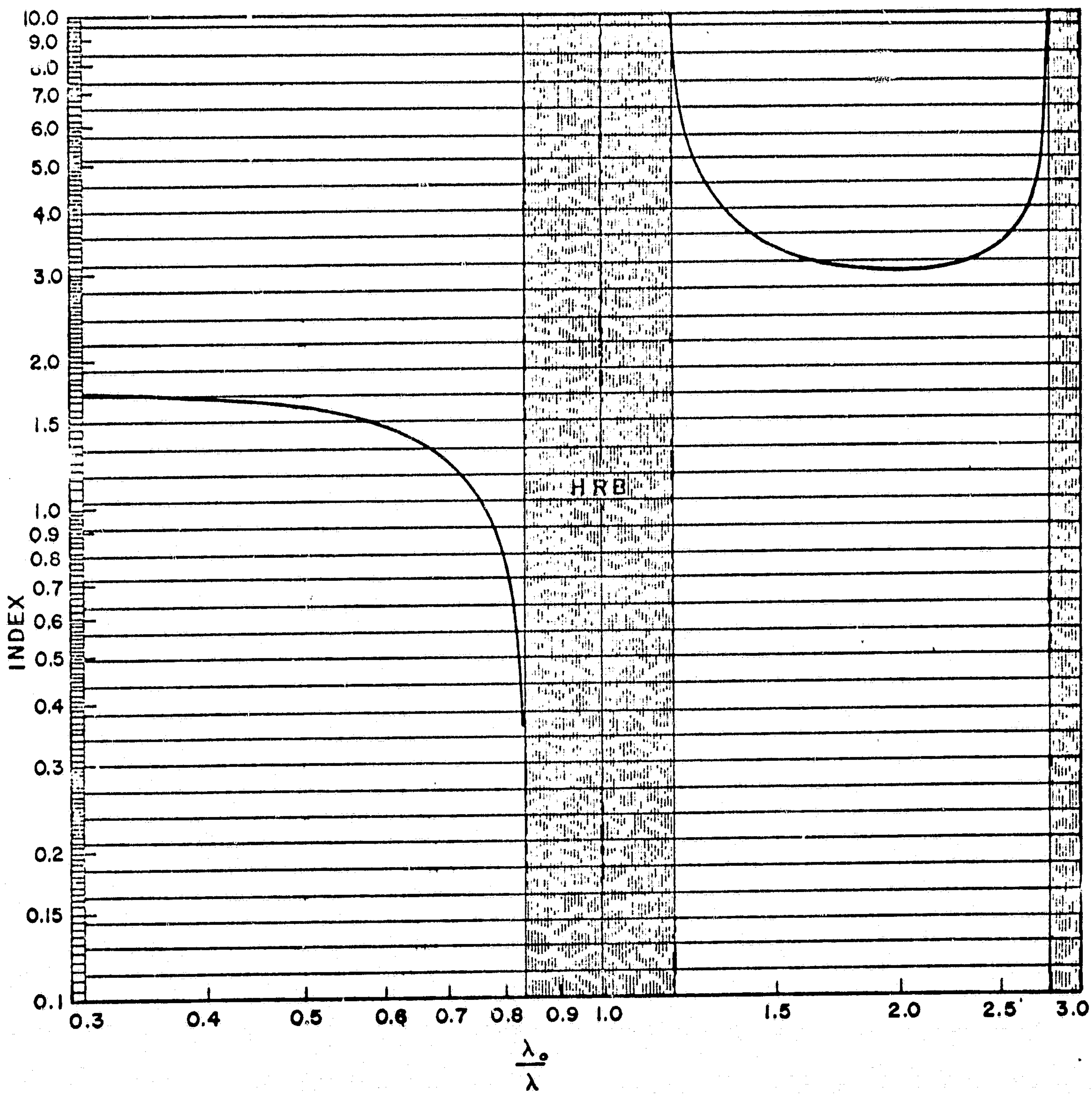

Fig. 7. The Herpin equivalent index of a low-pass stack (H/2 L H/2).
See also packet in rear of report.

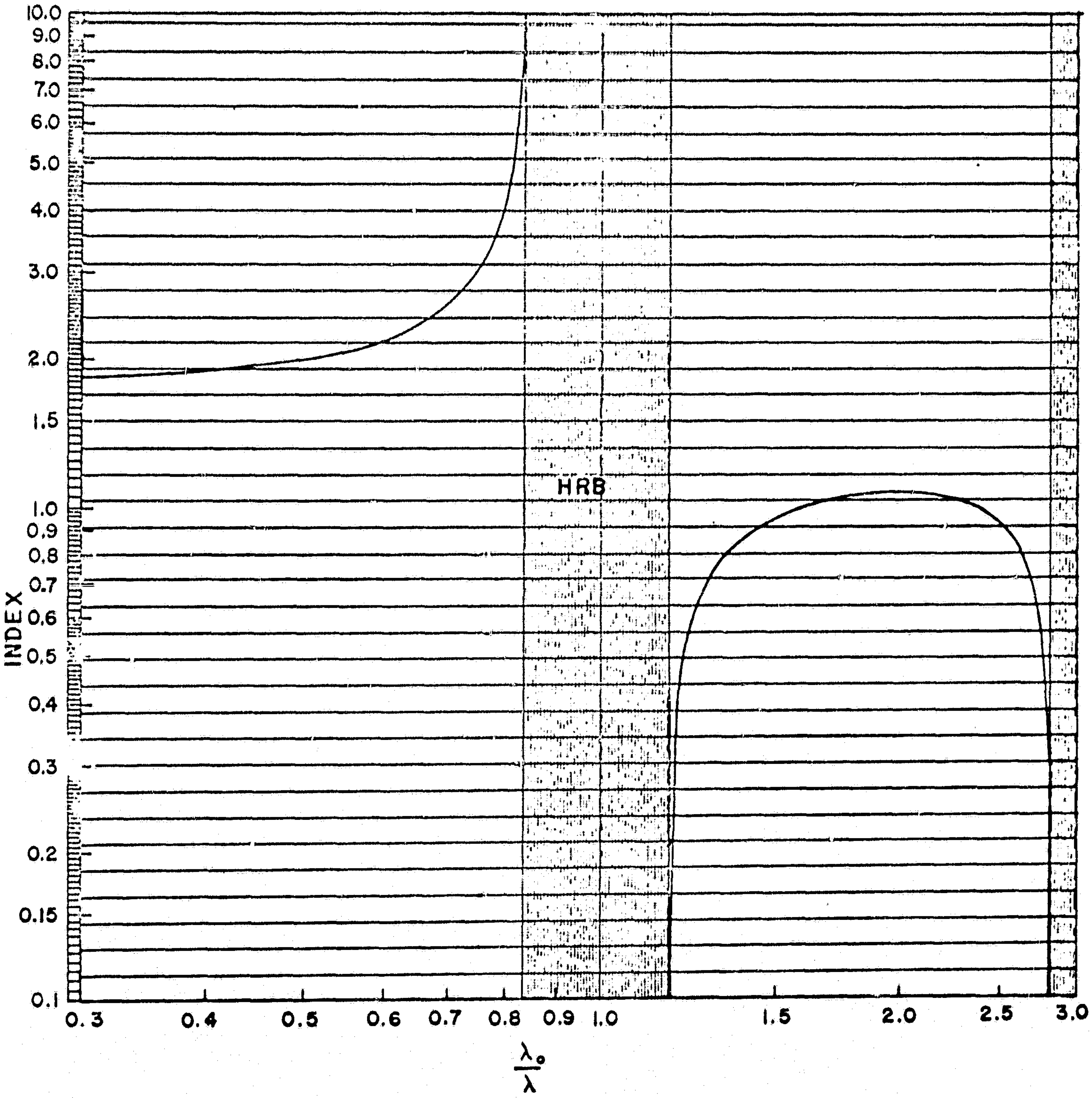

Fig. 8. The Herpin equivalent index of a high-pass stack (L/2 H L/2). See also packet in rear of report.

matching job. The large dispersion of the indices renders this a difficult task. It has been found that the task of finding a matching layer (or layers) is easier when two stacks are selected whose dispersion is in the same sense. The simplest matching layer is a single quarter-wave-thick layer which will anti-reflect the two media in the center of the passband. The refractive index of such a matching layer is just the geometrical mean between the two external media of indices n_j and n_k:

$$n_{film} = \sqrt{n_j \cdot n_k} \quad . \tag{3}$$

The indices of quarter-wave layers which will satisfy Eq. (3) at the center of the passband have been calculated as a function of the relative band separation (roughly proportional to filter width) for high-pass:high-pass and low-pass:low-pass combinations with glass ($n = 1.52$) for both the incident and substrate media. These are shown in Figs. 9 and 10, respectively, where n_M is the index of the internal matching layer and $n_{H'}$ and $n_{L'}$ are the indices of the external layers. These two designs are:

$$G\ H'\ \{\lambda_1(L/2\ H\ L/2)^m\}\ M\ \{\lambda_2(L/2\ H\ L/2)^m\}\ L'\ G \qquad (\lambda_1 < \lambda_o < \lambda_2) \tag{A}$$

and

$$G\ L'\ \{\lambda_1(H/2\ L\ H/2)^m\}\ M\ \{\lambda_2(H/2\ L\ H/2)^m\}\ H'\ G \qquad (\lambda_1 < \lambda_o < \lambda_2) \tag{B}$$

respectively. We found it quite remarkable that the values did not change appreciably. We further noted that the values for design (B) were very close to those for existing materials (ZnS:2.3, ZrO_2:2.10, and MgF_2:1.38). For

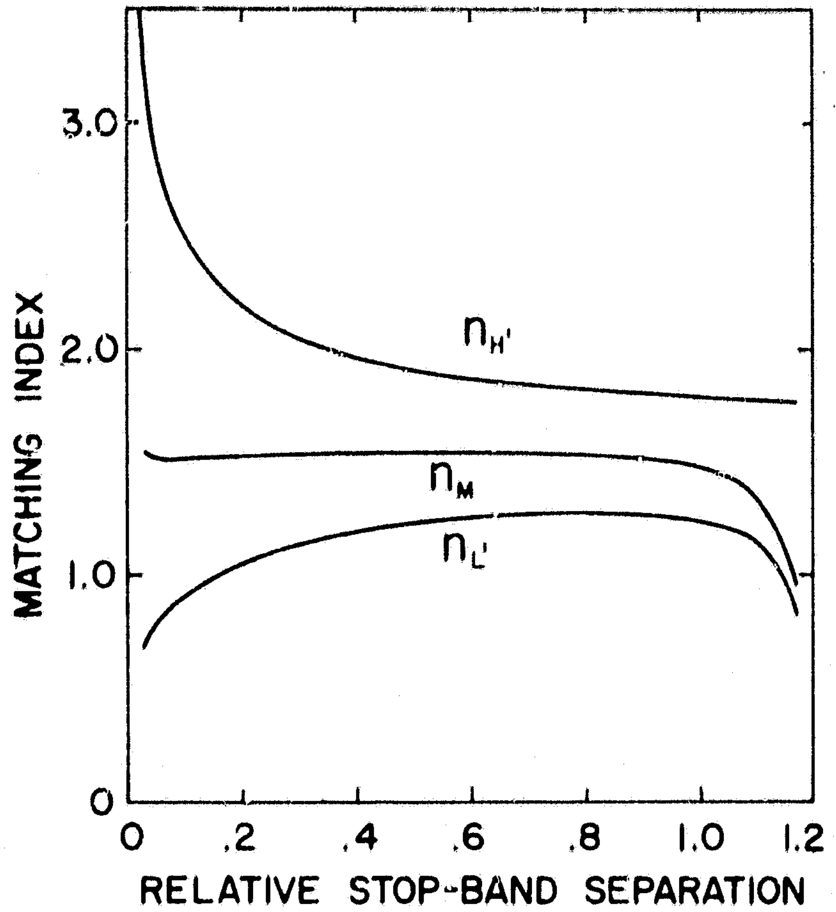

Fig. 9. Matching layer indices for high-pass:high-pass accordion filters.

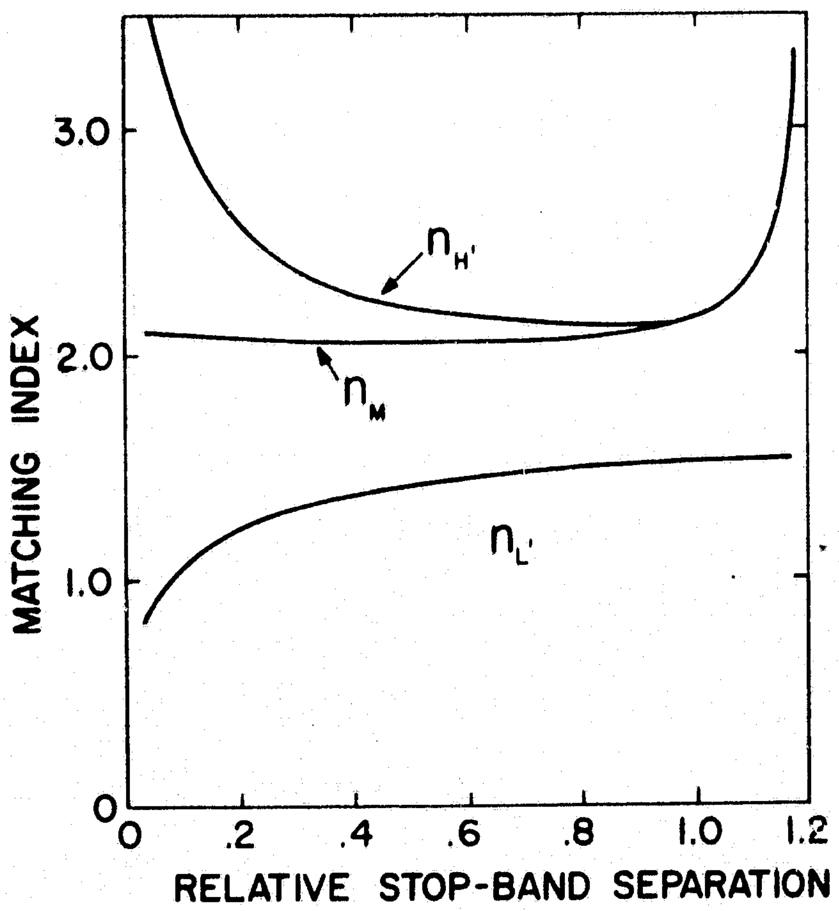

Fig. 10. Matching indices for low-pass:low-pass accordion filters.

this reason our attentions were confined to the low-pass:low-pass construction. The transmittances of three such filters are shown in Fig. 11, where the only changes in the designs were the values of λ_1 and λ_2 in (B). We have therefore found a simple design whose width can be varied almost at will with only a few calculations required (Eqs. (1) and (3) only). When two media are matched by a layer whose index is different from that of Eq. (3), the loss by reflection increases only slowly with increasing mismatch. For this reason, a layer with a constant index (i.e., a real single layer) has been found to be an effective matching layer for a wide range of passband widths.

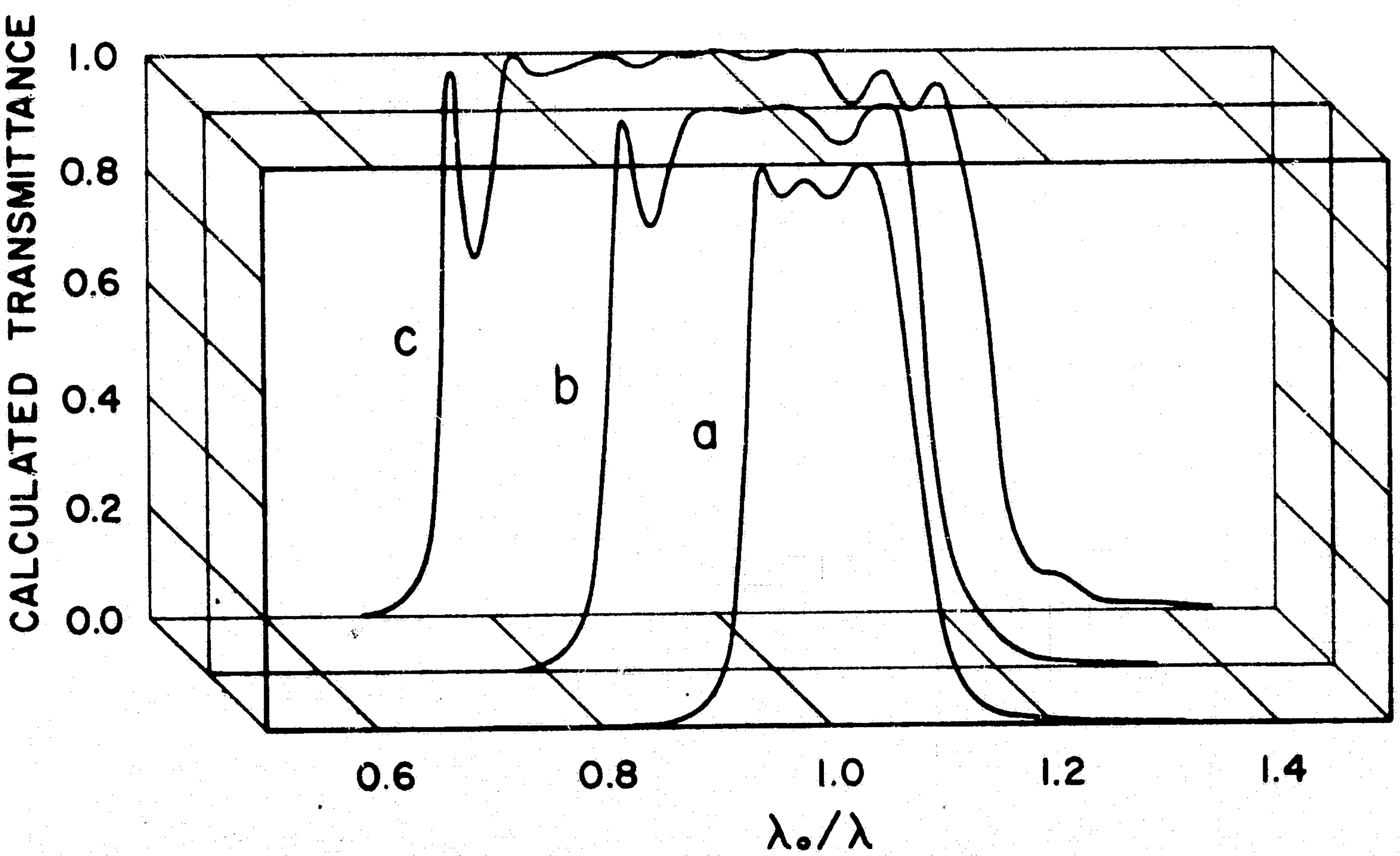

Fig. 11. Calculated transmittance of three low-pass:low-pass accordion filters with (a) $\lambda_1 = 0.7623\ \lambda_0$, $\lambda_2 = 1.2785\ \lambda_0$
(b) $\lambda_1 = 0.7152\ \lambda_0$, $\lambda_2 = 1.3853\ \lambda_0$
(c) $\lambda_1 = 0.6580\ \lambda_0$, $\lambda_2 = 1.5700\ \lambda_0$

We shall now examine another example of an accordion filter in detail. Fig. 12 shows the calculated transmittance for one with a half-width of 0.30. This represents a considerable improvement over the Wratten filters (Figs. 1-3) and is not too much different from the ideal. The most objectionable features are the two small transmission dips in the passband near λ_0/λ = 0.90 and 1.05. That these appear is not surprising since the matching was done at the center of the passband ($\lambda_0/\lambda \approx 1$).

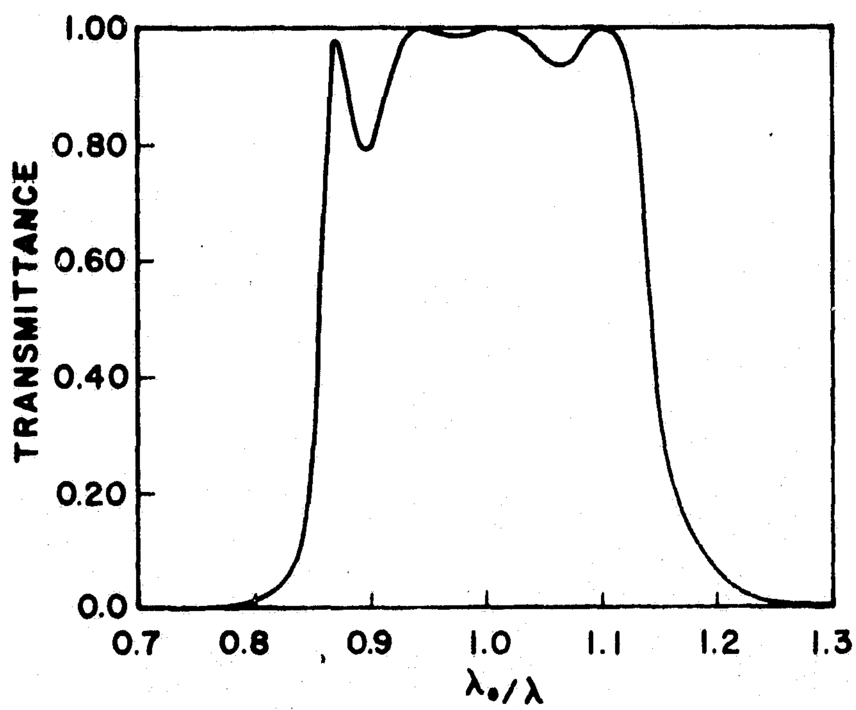

Fig. 12. The transmittances of a 30% wide accordion filter.

Their occurrence is explained by reference to Fig. 13, which shows the Herpin equivalent indices N_1 and N_2 for (a) the low-pass:low-pass construction and (c) the high-pass:high-pass construction. We have also plotted the indices $n_{H'}$, $n_{L'}$ and n_M which would be required for the three matching layers in each case to be able to achieve an "ideal" design. A minimum transmittance will

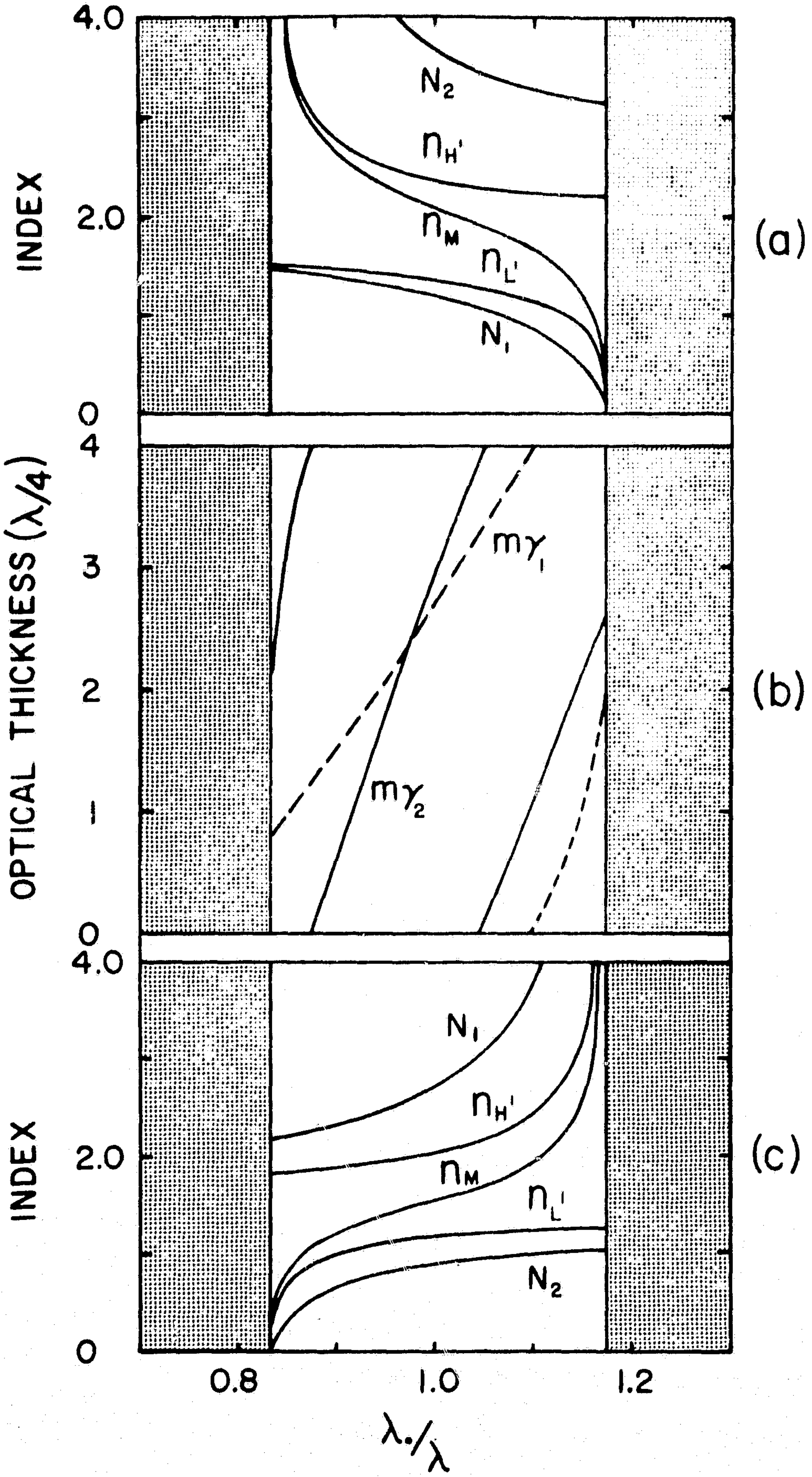

Fig. 13. *The equivalent indices N_1 and N_2 and thicknesses $m\gamma_1$ and $m\gamma_2$ for (a) low-pass:low-pass and (c) high-pass:high-pass accordion filters. The indices $n_{H'}$, n_M, $n_{L'}$ are those required for a perfect match over the passband and are described more fully in the text.*

occur when the equivalent thickness of the stacks is an odd multiple of $\lambda/4$. The equivalent thicknesses are plotted in Fig. 13b, where we see that these conditions exist in the regions where the transmittance is a minimum.

We have found that the design procedure outlined above can be greatly simplified by using graphical techniques, owing to the relative insensitivity of the design to small changes in the indices of the matching layers. We have plotted the equivalent indices of low- and high-pass stacks in Figs. 7 and 8, respectively. The purpose of the unusual scales is to allow the calculations described above to be done more simply. These figures have been reproduced on transparencies which can be found in the back flap. An accordion filter can be designed with these in a three-step procedure: (1) Select the values of the indices of the incident medium and the substrate medium and select the stacks to be used. (2) Mark out the cuton and cutoff wavelengths on the logarithmic λ_0/λ scale of the transparencies on a separate sheet. Laying the transparencies on this sheet with the edges of the HRB's in the proper positions will give the relative values of the wavelengths λ_1 and λ_2 for the two stacks under $\lambda_0/\lambda = 1$ for each stack. (3) At the center of the passband, the indices required for the matching layers can be read from the logarithmic scale at the left. The value is found at ½ the distance between the two curves for n_M (the linear scale allows us to merely count boxes), and the values of the indices of the external matching layers are ½ the distance from the value of the respective medium index to the proper line.

The real value of the transparencies lies in their power to demonstrate the reason for selecting two stacks whose dispersion is in the same sense. A collection of similar transparencies for stacks with different index ratios and different symmetrical period configurations would allow us to investigate a large number of other designs before actually calculating them.

IV. PROPERTIES OF MULTISPECTRAL ACCORDION FILTERS

In Section III, we described in general how accordion filters could be designed for any reasonable bandwidth so that the transmittance would be high in the passband. In this section we shall discuss the general properties of the accordion filters that have been designed specifically for multispectral applications. The designs of the filters for the three passbands given in Section I (Figs. 1, 2, and 3) are shown in the table below. The calculated transmittance was shown previously in Section I for light incident normally on the filter. Although these filters are not exactly "ideal," they do represent a sufficient improvement over Wratten filters at normal incidence.

Accordion filter designs

Fig.	Band (nm)	Design	λ_1(nm)	λ_0(nm)	λ_2(nm)
1	440-580	G L' $\{\lambda_1(H/2\ L\ H/2)^7\}$ M $\{\lambda_2(H/2\ L\ H/2)^7\}$ H' G	362.0	500.4	682.7
2	500-620	A $\{\lambda_1(H/2\ L\ H/2)^7\}$ M $\{\lambda_2(H/2\ L\ H/2)^7\}$ H' G	411.3	553.6	730.0
3	580-680	G L' $\{\lambda_1(H/2\ L\ H/2)^7\}$ M $\{\lambda_2(H/2\ L\ H/2)^7\}$ H' G	477.2	626.0	806.0

$n_A = 1.0$; $n_G = 1.52$; $n_{L'} = n_L = 1.38$; $n_{H'} = n_H = 2.30$; $n_M = 2.10$;
$4(nh)_{L'} = 4(nh)_M = 4(nh)_{H'} = \lambda_0$

These filters have 32 or 33 layers and could be made from commonly used materials by vacuum evaporation. This number of layers will yield a mechanically stable filter which should survive small temperature excursions and the types of environment encountered in high-altitude flights and low-orbital space flights (based on past experience in the laboratory). An estimation of the difficulty of making these filters will require further computations and experimental investigation. The fact that many of the layers have the same optical thickness is one of the strongest points in favor of these designs.

As mentioned previously, the passbands change shape and position when light is incident at angles other than normal. The optical properties of an interference filter are determined in part by the thicknesses of the layers. These thicknesses control the phase differences between the many multiply-reflected beams which interfere constructively or destructively to build up the passband. When the angle of incidence is changed, all path differences will change, causing the passband to shift. It is easy to show that the optical path difference between rays reflected from the front and back sides of a plane parallel layer is proportional to the cosine of the angle between the ray in the medium and the surface normal. Thus a film becomes effectively "thinner" as the angle of incidence increases, and the passband will shift toward shorter wavelength. This phenomenon is unavoidable with interference filters. Similar phenomena are not observed in Wratten filters since the passband is controlled by the absorption of dyes whose properties are not dependent on the direction of light.

We shall now look in detail at the properties of the filter shown in Fig. 2 for normal incidence. In a camera which is photographing a distant object, each point in the image plane represents light which is incident on the lens in a nearly parallel bundle. The passband shown in Fig. 2 would therefore represent the response on the optical axis for a system with a filter in front of the lens. Other angles of incidence θ will represent the response of the system in a circle of radius f ($\tan\theta$), where f is the focal length of the system. From our discussion, if the passband shifted from red to blue, color film of a "white" scene would show a red center with concentric rings gradually changing color to green, blue, etc. The calculated amount of shift of the long wavelength band edge was shown in Fig. 4. The transmittance of this filter at three angles of incidence is shown in Fig. 14.

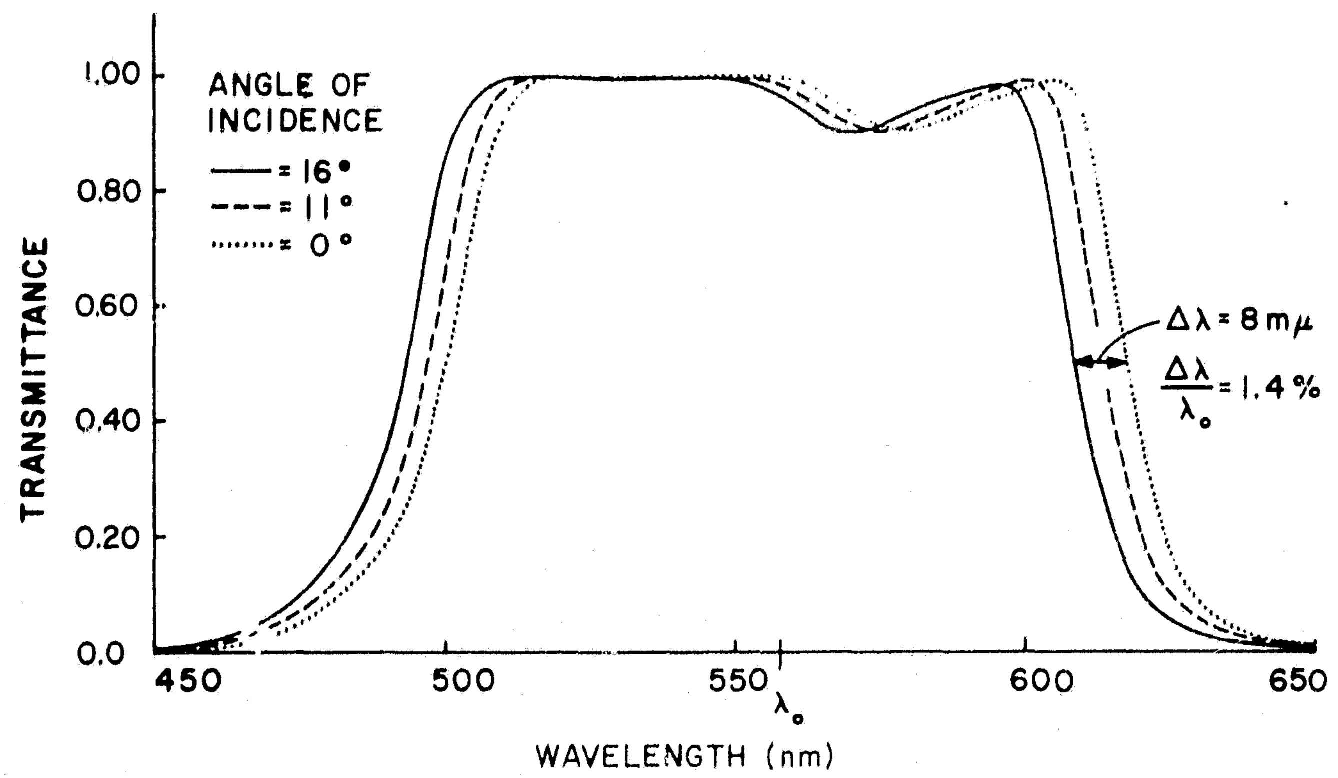

Fig. 14. Transmittance calculated for three angles of incidence.

We notice that any change in the shape of the passband is virtually undiscernible, and that the shift of the passband is very small in relation to the passband width. Such shifts would be difficult to observe in practice with photographic recording of typical ground scenes. With narrower bandwidths, it is possible that such shifts would be outside the region of the passband and could cause considerable difficulty in the interpretation of multiband photographs.

We have limited our discussion to angles of incidence less than 20°. The use of interference filters at larger angles of incidence brings up several problems that can further confuse the interpretation of results. One of the most difficult problems is the difference in filter response with polarization of the incident light. The reason for this can be explained quite simply by noting that the polarizing angle (Brewster's angle) is being approached for angles of incidence larger than 20°. This means that one component of the polarization will be reflected much more strongly than the other. The combination of films getting "thinner" and reflecting power changing gives the passbands shown in Fig. 15 for light incident at 45° on this same filter.

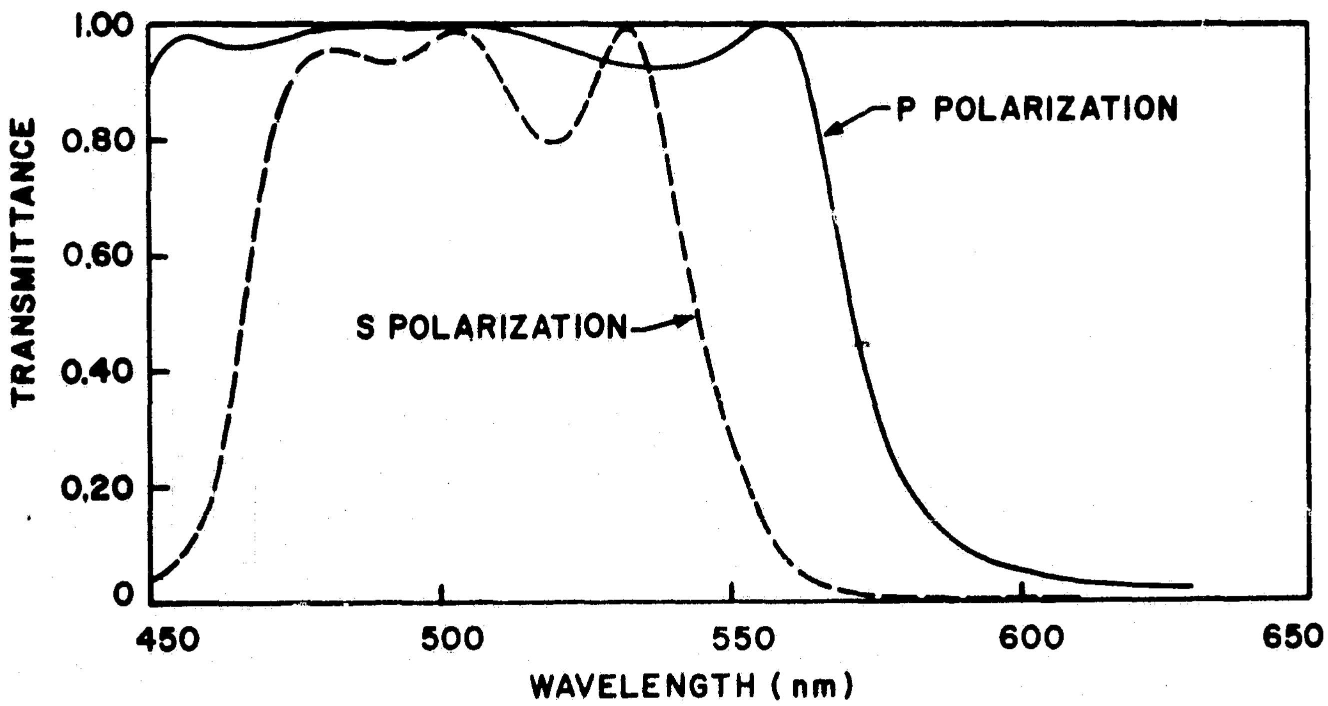

Fig. 15. Transmittance at 45° angle of incidence of a "normal incidence" accordion filter.

The passband has shifted noticeably from its original position (500 to 620 nm), and the bandwidth is different for the two polarizations. If the incident light were unpolarized, the resulting passband would be the mean of the two curves, giving a band with a greater width for transmittances less than 0.5 than near the top of the curve. Simply changing the thicknesses of the layers will not help the polarization problem since the polarizing angle is not related to the thicknesses. This is shown in Fig. 16, where the thicknesses were adjusted so that the passband at 45° would be in the "same" position as at normal incidence. This is the basis of the "graded thickness" filter, in which the layers are intentionally deposited in a nonuniform manner. (This is done in just the opposite way from which the well-known antivignetting filters are made for wide-angle cameras.) Because of problems one would expect to have in the interpretation of photographs taken through filters at angles of incidence greater than 30°, we do not recommend their use.

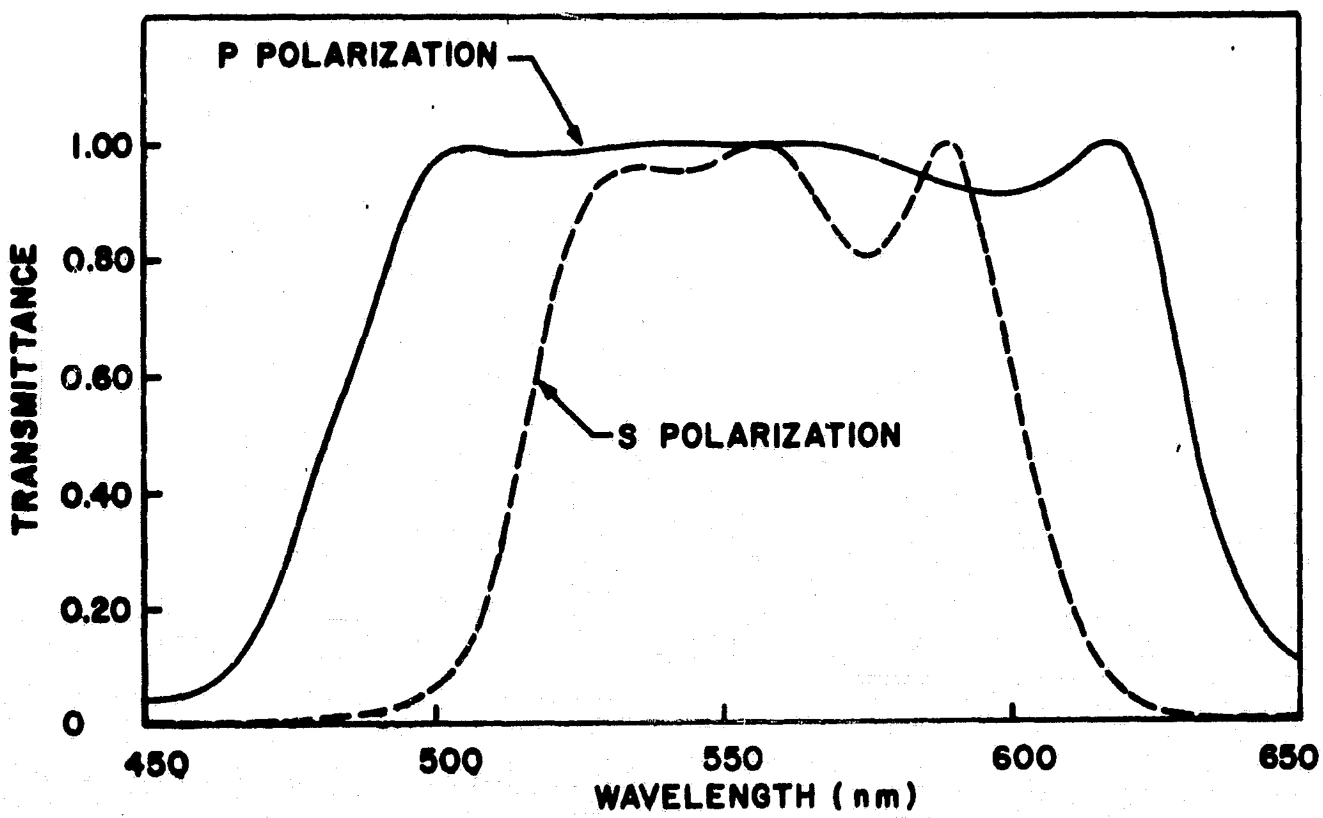

Fig. 16. Transmittance at 45° angle of incidence of an accordion filter whose thicknesses are effectively a quarter-wave thick at 45° angle of incidence.

V. NEW INSTRUMENTATION TECHNIQUES

The before-the-lens filter designs described so far in this report are suitable for use with frame or strip cameras having total fields less than about 40° and for any type of panoramic camera. They are inadequate for wide-angle frame and strip cameras or for simultaneous behind-the-lens filtering purposes. We now discuss these two cases in some detail because of their importance in multispectral photography.

Filters for wide-angle cameras

For some purposes, it is advantageous to have a combined mapping-and-multispectral camera system, usually necessitating coverage of a 90° total field. It seems unlikely that the design principles discussed earlier can be extended to yield *flat* before-the-lens filters for cameras of such wide field. The best solutions to filtering wide-angle cameras would seem to be the use of graded before-the-lens filters or filters deposited on a suitable inner concave surface of the lens.

Graded before-the-lens filters.--These filters were discussed in Section IV. The undesirable shape of the passband and the problems encountered because of polarization effects were pointed out. For these reasons, this type of filter does not warrant further discussion.

Filters deposited on an internal surface of the lens.--In a preliminary analysis of the designs of cartographic lenses, we have generally found that a suitable internal surface exists for the deposition of a passband interference filter. Our criteria are that the surface is near the front of the lens, that it is concave, and that the angles of emergence of all rays do not exceed ±20° in angular spread. In order to determine this third quantity, we traced two full-aperture pencils through the lens, one axially and the other at a semi-field angle of 45°.

For some of the older cartographic lenses whose designs are given in the literature (Cox, 1964; Stavroudis and Sutton, 1965) we found the desired limited angular spread. Modern cartographic lenses appear similar to each other in their general configuration, and we hope that our preliminary analysis of the Geocon IV (design details courtesy of the Kollsman Instrument Corporation) may be representative of many others. The analysis showed that, on one of the concave surfaces near the front of the lens, the angular spread of the emergent light was less than 30°.

We are indebted to Mr. G. W. Wilkerson for this analysis. We are currently developing a general computer program to evaluate the spectral response of filters deposited on internal surfaces of lens systems. This program will calculate the spectral content of the image-forming light at any chosen field angle on the format. Thus, the spectral response of the lens-filter combination will be known for any field angle.

Behind-the-lens interference filters

Behind-the-lens filtering is important in experiments that use a single image-forming lens instead of several to conserve weight and volume. Behind-the-lens interference filters may be either normal to the optical axis following a stepping 45° mirror or inclined to the optical axis (dichroics). The former arrangement allows multispectral photographs to be taken sequentially; the latter provides simultaneous multispectral photography. In aerial or space applications, simultaneous photography in the various wavelength bands is desirable for reasons related to lens distortion and attitude rates (Colwell, Slater, and Yost, 1968) and also because vibration is not introduced.

Behind-the-lens filters normal to the optical axis.--The spectral performances of before- and behind-the-lens filters, normal to the optical axis, differ in that the former vary only with field angle, whereas the latter vary with both field angle and f-number. For a given lens, the variation in angle of incidence across a behind-the-lens filter is greater than the variation across a before-the-lens filter. In addition, the before-the-lens filter does not degrade the image-forming properties of the lens, whereas the behind-the-lens filter introduces every aberration but field curvature.* Although these degrade the image-forming properties of available lenses, it should be possible to design lenses with residual aberrations sufficient to cancel those introduced by the filter.

In summary, the main disadvantages of behind-the-lens filters normal to the optical axis are that they do not provide simultaneous multispectral photography and that, in contrast to before-the-lens filters, they cannot be used with available lenses without degrading image quality. They may be a better choice than before-the-lens filters if space is at a premimum or if moderate f-number, moderate field, and low angular resolution can be tolerated.

Behind-the-lens dichroic filters at 45° to the axis.--Dichroic filters are usually deposited either on a glass plate or along the diagonal surface of a cube. In both cases the filter is placed at an angle to the optical axis, commonly 45°. The tilted glass plate introduces the same aberrations listed before (see footnote). However, because the plate is tilted, the aberrations (except for spherical and longitudinal chromatic aberration) are no longer symmetrical with respect to the optical axis. A cube dichroic filter introduces the same aberrations but in a symmetrical form so that they can be compensated by suitably designed camera lenses.

*That is, spherical aberration, coma, astigmatism, distortion, and longitudinal and lateral chromatic aberration. Actually the aberrations are introduced by the optical thickness of the substrate and not by the interference filter, which is only a few μm thick. For aircraft and space use, pellicle substrates are too fragile, and it is necessary to use glass substrates on the order of 1 cm thick for a 5 cm diameter.

The main disadvantage of the cube dichroic filter is not the amount of aberration it introduces but the fact that it acts as a polarizing filter (as does the tilted glass plate) and is more sensitive to variations in angle of incidence than is a filter normal to the optical axis. The latter problem becomes more severe with larger angles between the optical axis and the normal to the filter, with lower f-numbers, and with wider lens fields.

Behind-the-lens dichroic filters at <45° to the axis.--The problems enumerated above can be ameliorated if the dichroic filter is oriented at less than 45° to the axis. Several such systems have been considered for color television in a paper by van Doorn, de Lang, and Bouwhuis (1966), which discusses the filter problem in detail.

We are examining a double pentaprism arrangement which seems to offer a good solution to the problem for moderate field of view photography. One layout of the system is shown in Fig. 17. The characteristics of the system are as follows:

(1) The dichroic surfaces make an angle of 22.5° with the optical axis.

(2) The total field of the system cannot exceed 10°, or the prisms will become huge.

(3) The solid cemented arrangement has obvious advantages over other designs discussed previously (van Doorn, de Lang, and Bouwhuis, 1966).

(4) For a 10° total field, the range of angles of incidence on the dichroic surfaces is from 12.5° to 32.5°.

In regard to item 4, since the angular range does not pass through 0°, the dichroic filter can be designed so that the required passband is obtained for an angle of incidence of about 23° corresponding to a 0° field angle.

Mr. Wilkerson is presently designing a lens for this system. The problem of designing a lens to work well with a long glass path in image space is difficult because of the large amount of lateral color compensation required.

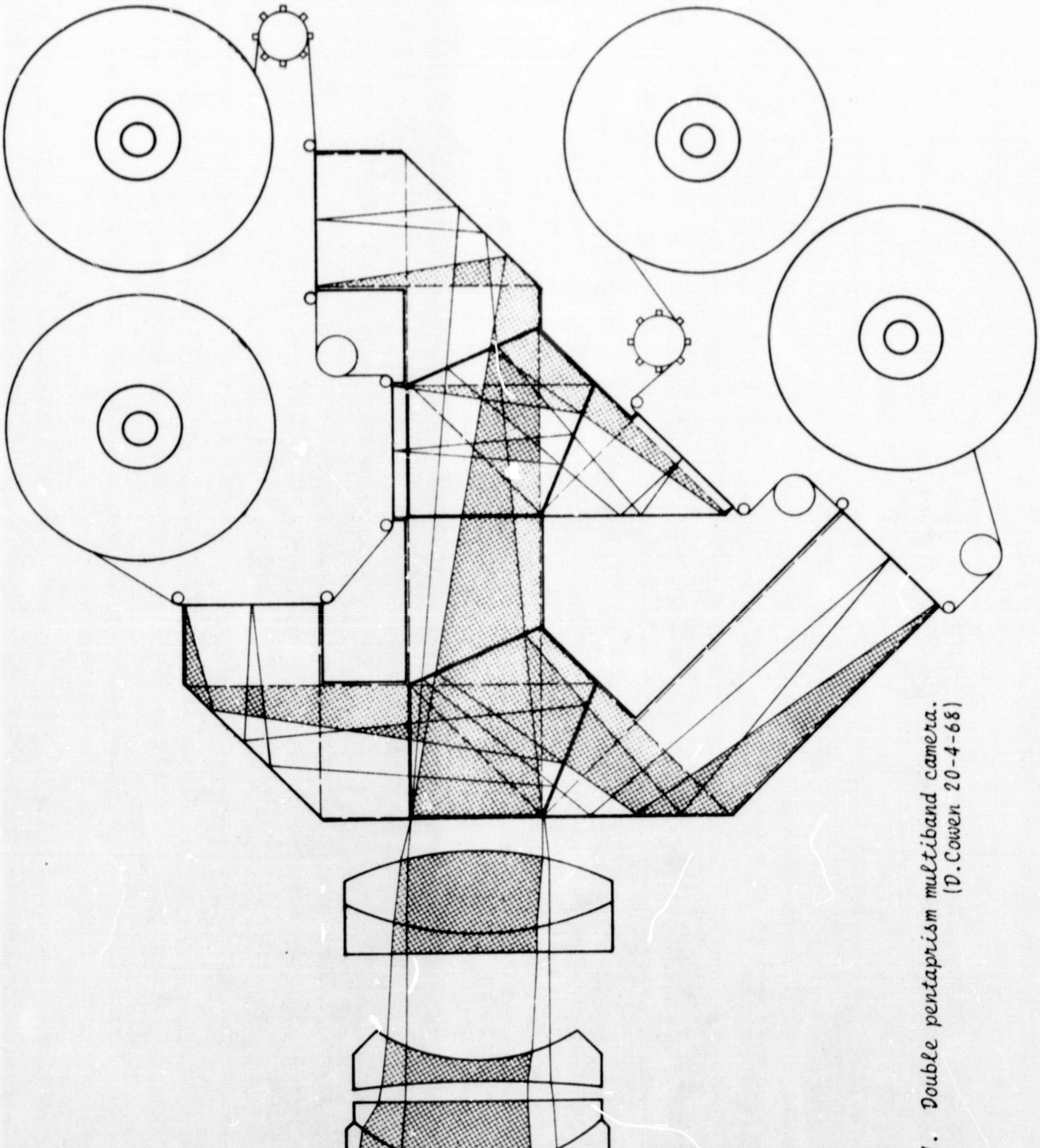

Fig. 17. Double pentaprism multiband camera.
(D.Cowen 20-4-68)

Furthermore, the wavelength range for the lens is from 400 to 900 nm, each image plane covering about 100 nm. Wilkerson's approach is to use the substitution parameter routine of the Jet Propulsion Laboratory's version of the Los Alamos Scientific Laboratory lens design program. Using this substitution routine, he will optimize the design with regard to all five required wavelength bands simultaneously.

VI. SUMMARY

Designs of flat before-the-lens "accordion" interference filters exhibit several advantages over conventional absorption passband filters: The position and width of the passband can be selected over a wide, continuous range of values. The short and long wavelength cutoffs are sharp. The transmittance is high and consequently a reduction of about three in filter factor can usually be expected over the equivalent absorption passband filter.

The disadvantage of the before-the-lens accordion filter is that it is limited to use with lenses of less than 40° total field because of passband shift with increasing angle of incidence. Work now in progress indicates that this limitation can be overcome by coating a suitable surface of one of the lens elements.

Further work is planned to investigate multi-format single lens cameras. Studies are being made of dichroic filters at 45° to the optical axis and of a double pentaprism arrangement using dichroic filters at 22½° to the optical axis. Unique lens design problems encountered with these behind-the-lens filters are being tackled using substitution techniques in an automatic lens design program.

A new computer program is being developed to calculate the spectral transmittance of optical systems that incorporate interference filters in nonparallel light. Use of such a program will allow us to evaluate the possibility of coating a lens element, for instance, and to evaluate the properties of behind-the-lens dichroic filters.

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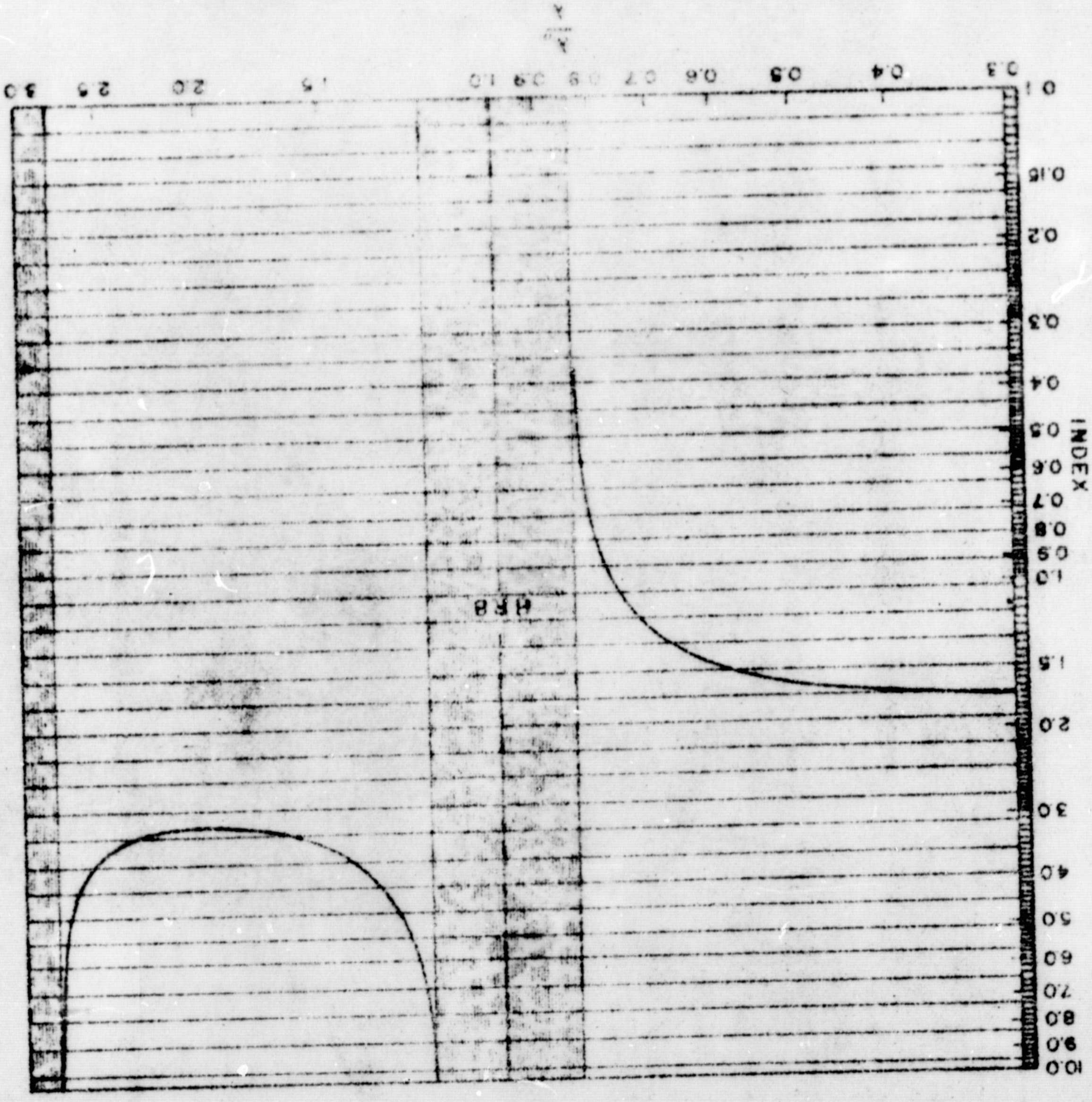

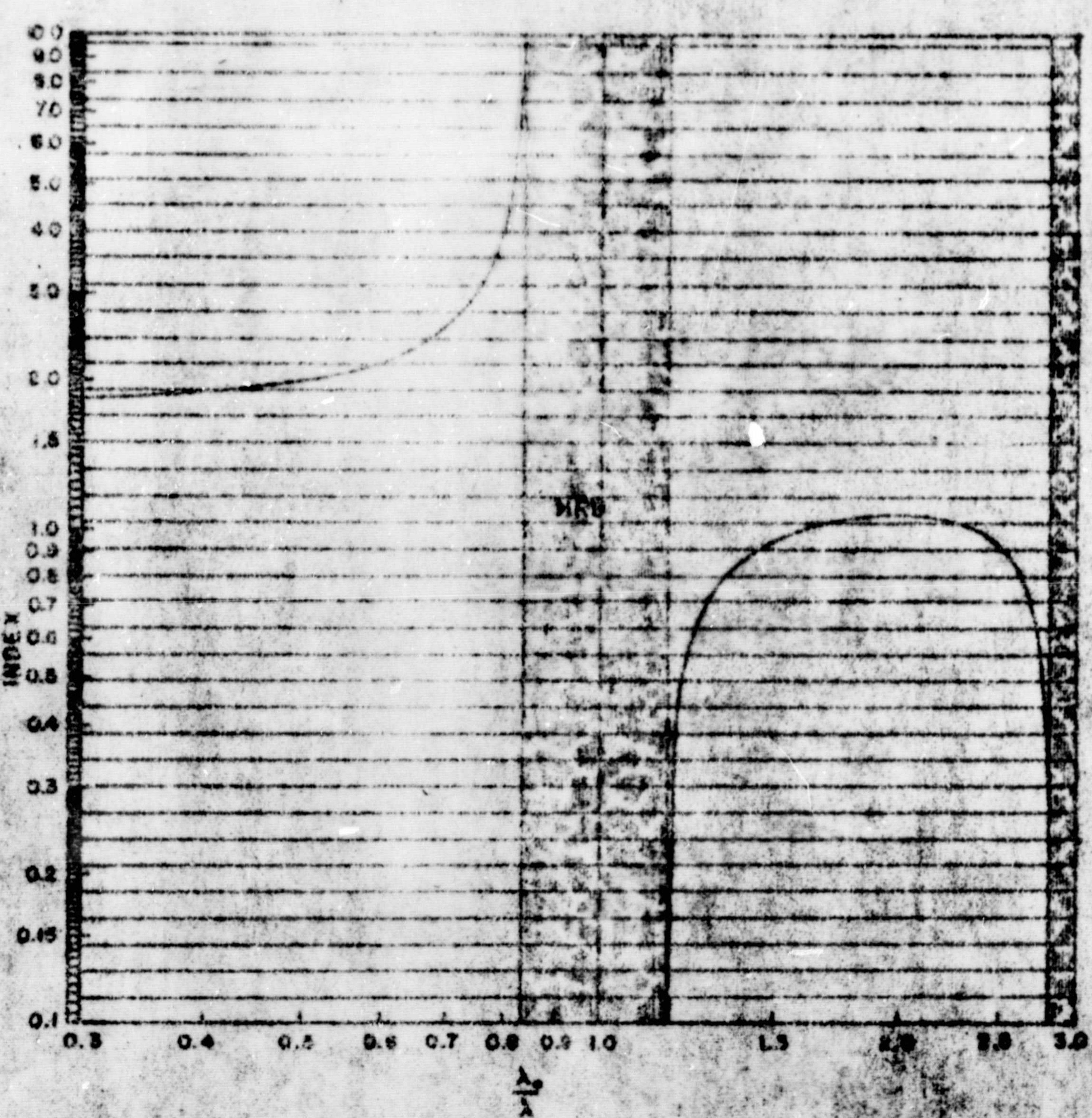
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