MULTIBAND CAMERA MONOGRAPH

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The primary intent of this monograph is to furnish the multiband experimentalist with a convenient source of current information on aerial photographic films, spectral filters, and optical-mechanical tolerances for multiband cameras. An account is given of the various types of aerial cameras emphasizing their advantages and disadvantages in multiband use. Some cameras specially assembled as multiband systems are described fully. Electro-optical and optical multiplexing techniques for multiband photography are discussed. Finally, some predictions are made concerning multiband cameras of the future.

The text of this monograph was initially written for inclusion as three chapters in a "Manual of Multiband Photography" coauthored by Dr. R. N. Colwell (editor) and Dr. E. F. Yost. Because of the high cost of reproduction of the many color photographs in the other chapters, the number of copies of the first edition of the manual will be limited. This is the reason for the separate publication of this monograph.

The author wishes to acknowledge with thanks the many useful discussions and data furnished by friends in government, industry, and university. In particular, he wishes to thank the Earth Resources Division at NASA Manned Spacecraft Center for their continued support of work on multiband cameras at the Optical Sciences Center.
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CHAPTER I. INTRODUCTION

Multiband photography has been employed as an aerial reconnaissance technique for about a decade. During its early development, and still to a large extent, the technique has been used experimentally and qualitatively as an aid to photointerpreters in the production, for example, of thematic maps. In recent years researchers such as Colwell and Yost have been attempting, using statistical methods, to determine to what extent quantitative data can be derived from multiband photography. This work has involved the spectroradiometric calibration of ground targets and camera systems and, in some cases, the colorimetric calibration of the viewing system.

Although significant progress has been made in interpreting and extracting information from multiband photographs, little progress has been made in improving the performance of multiband cameras. There are several reasons for this. First, with few exceptions, the films, filters, lenses, and cameras available for multiband work have not changed over the past 10 years. Second, these components, having been designed and marketed to meet other needs, are, as we might expect, not well suited to a specialized new technique such as multiband photography. Third, little attention has been paid to over-all design of multiband cameras, particularly in defining the optical-mechanical tolerances required.

For these reasons emphasis has been placed in the following text on discussions of (1) the results of recent developments, for example in wide pass-band interference filters, (2) the drawbacks of using off-the-shelf components, for example lenses not designed as a matched multiband set, and (3) the need for further research and development, for example in lens design and in sensitizing emulsions for a uniform response through the visible and photographic infrared. Hopefully these discussions will be instrumental in improving the performance of future multiband cameras.
CHAPTER II. FILMS AND FILTERS FOR MULTIBAND PHOTOGRAPHY

1. PHOTOGRAPHIC FILMS FOR MULTIBAND PHOTOGRAPHY

Multiband photography makes use of conventional aerial films; no special films have been developed. There are several manufacturers of aerial films, and although only the products of the Eastman Kodak Company will be mentioned here, it does not mean that the products of other companies are not as good or better. It does reflect the fact that Eastman Kodak manufactures a wide variety of aerial films and that detailed, relevant data on the films are readily available (see references, p. 17). For this reason, we will try to summarize only a few of the characteristics of aerial films that may be of interest to those working in multiband photography. A good general discussion of the photographic emulsion is found in Perrin (1965), and a discussion on color aerial films is found in American Society of Photogrammetry (1968).

Table 1 (foldout), assembled from parts of the Kodak "Manual of Physical Properties" and "Tech Bits" (see references), lists most of the film data of importance in multiband photography, particularly the resolving power, speed, spectral sensitivity, and base type.

New films are frequently introduced on the market. For example Kodak Infrared Aerographic Film 2424, with an emulsion similar to 5424 but slightly slower and on a 102-μm Estar base, has become available since Table 1 was compiled a year ago. Several film types not publicly listed by Kodak have been used in manned space photography. The following is a listing of such films; in most cases the use of a standard emulsion on a different base has caused the change in the name of the film type.

<table>
<thead>
<tr>
<th>Film type</th>
<th>Thickness and base type</th>
<th>Film type using similar emulsion</th>
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<tr>
<td>SO-168</td>
<td>64μm Estar</td>
<td>8442</td>
</tr>
<tr>
<td>SO-368</td>
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<td>2448</td>
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<td>SO-246</td>
<td>102μm Estar</td>
<td>5424</td>
</tr>
<tr>
<td>SO-164</td>
<td>64μm Estar*</td>
<td>3400</td>
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<td>SO-267</td>
<td>64μm Estar**</td>
<td>2405</td>
</tr>
<tr>
<td>2485</td>
<td>102μm Estar***</td>
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* The only difference between SO-164 and 3400 is the fast-drying (PX) backing for SO-164.
** Called Kodak Lunar Recording Film.
*** High-speed black-and-white film for lunar photography.
### CHARACTERISTICS OF KODAK AERIAL FILMS (revised)

<table>
<thead>
<tr>
<th>KODAK Film</th>
<th>Plus Type</th>
<th>Sensitivity</th>
<th>Base Type</th>
<th>Processing (s)</th>
<th>Acid Ester</th>
<th>Acetate Estar</th>
<th>Acetate Butyrate</th>
<th>Triacetate</th>
<th>Developed Sample</th>
<th>Gamma</th>
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<td>2401</td>
<td>ESTAR</td>
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<td>Dried Gel</td>
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<td>ESTAR</td>
<td>64</td>
<td>Dried Gel</td>
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<td>475</td>
<td>300</td>
<td>9.7</td>
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</table>

1. These indexes are for use with the KODAK Aerial Exposure Computer. KODAK Publication No. P-10, in determining the correct camera exposure for aerial (air-to-ground) photography. Aerial Exposure Indexes are not equivalent to, and should not be confused with, conventional film speeds intended for pictorial photography. An Aerial Exposure Index is defined as the reciprocal of twice the exposure (in meter-candle-seconds) at the point on the toe of the characteristic curve where the gamma = 0.6.

2. Photographically, the term "granularity" is an objective measurement that correlates with the subjective appearance of graininess. The root-mean-square (RMS) granularity value, as shown here, represents 1000 times the standard deviation in density produced by the granular structure of the material. The value is obtained when a uniformly exposed and developed sample is scanned by a densitometer having an optical system aperture of 820 and a circular scanning aperture 46a in diameter. The granularity value indicates the magnitude of the impression of graininess that would be produced if the sample were examined visually at a magnification of 12X. The RMS granularity data presented are for negative films having a net density of 1.0 (excluding the density of the support). For reversal materials, the RMS granularity values are obtained at a gross density of 1.0.


4. Without a filter.

5. With KODAK WRATTEN Filter No. 12.

6. A haze filter, such as a KODAK WRATTEN Filter HF-3, HF-4, or HF-5, is suggested.

7. A KODAK Wratten Filter No. 2E is used with this film.

8. A KODAK Wratten Filter No. 9B may be used if desired.

9. These data are tentative and subject to change without notice.

### TABLE I

Spectral Sensitivity Curves for D-2G Developer at D=1.0 above gross fog; except film type 2405, D=1.0, with DK-50 developer and the Color films.
An aerial exposure computer is available (Eastman Kodak, 1966) which is designed for use with Kodak aerial films and a few Wratten filters. Such factors as exposure, altitude, focal length, and ground speed can be used to determine the image motion on film. Also solar altitude angle, camera altitude, film and filter types, haze condition, and exposure time can be used to determine the F-number required.

**Panchromatic films**

These are black-and-white films sensitive to visible radiation out to about 720 nm. (The one exception is Super-XX, which is sensitive out to 680 nm.) At the extremes of the speed and resolving power range are type 2403 (Tri-X Aerographic) with an Aerial Exposure Index (AEI) (see footnote 1 on Table 1) of 250 and a low-contrast (1.6:1) resolving power of 22 cycles/mm, and type SO-243 with an AEI of 1.6 and a low-contrast resolving power of 205 cycles/mm.

In fact, neither of these films is likely to be used in space multi-band photography where films of medium speed and resolving power, such as Plus-X and Panatomic-X, will be more suitable. We should note that, if a wide range of scene luminances is to be encountered, Plus-X may be the best choice. For example, in a mission involving the photography of dark vegetated areas at dawn and dusk and ocean glitter patterns and ice fields at midday, we should choose Plus-X because of its wide exposure latitude of a million to one.

We should note that the spectral sensitivity curves are not included for all the black-and-white films listed in Table 1. This is because those which have approximately the same shape, such as Plus-X Aerographic, Plus-X Aerecon and Plus-X Aerial are represented by a single curve. The Aerial Exposure Index will indicate if there is any change in the average level of sensitivity from one similar film type to another.

**Infrared black-and-white film**

This film, type 5424, is sensitive to visible radiation and out to 900 nm although there is a dip in sensitivity around 520 nm. For IR
photography, Wratten filters Nos. 12, 25A, or 89B are usually used. The film without a filter has an AEI of 125. The resolving power at low contrast is 28 cycles/mm.

When using a filter that transmits largely (or in the case of the 89B, only) in the photographic infrared, it is advisable to redetermine the focus of the lens by making a through-focus series of exposures using the IR film and the selected filter.

Regular color film

Kodak makes several color reversal films and one color negative film, as listed in Table 1.

Recently a new color reversal film, SO-121, became available for high altitude photography. It has an AEI of 6 and a low-contrast resolving power of 80 cycles/mm.* This film was used in the photography of the Earth from Apollo 6 with notable success. All other color films produced by Kodak are balanced for low altitude photography. HF-3, HF-4, and HF-5 filters, or a combination of these (see Fig. 1), are required at high altitudes to reduce the high atmospheric luminance in the blue, which causes severe contrast and resolution reduction and also causes high altitude photographs to appear mainly blue. With SO-121, Kodak specifies the use of a strong haze-cutting filter, No. 2E, also shown in Fig. 1. If this filter is not used, the color balance in the developed transparencies will be incorrect.

Infrared color film

Ektachrome infrared aero film, type 8443 (Fritz, 1967), is a false color reversal film sometimes referred to as camouflage detection (CD) film because of its success in this application. The spectral response of the film with a Wratten 12 filter is shown in Table 1. Without a filter this film is sensitive to all the visible as well as the photographic infrared. The film gives a false color representation because the wavelength band from

* Eastman Kodak does not state how the resolving power of any of its color films varies with wavelength. The values quoted are for a black-and-white bar target illuminated under simulated daylight conditions.
Fig. 1. Haze-cutting filters for aerial color photography.
approximately 500 to 600 nm is reproduced as blue, the band from approximately 600 to 700 nm is reproduced as green, and the band from approximately 600 to 900 nm is reproduced as red.

We should note three facts about infrared color film. First, in spite of its name, two of the three wavelength bands fall in the visible. For this reason it is seldom advantageous to refocus the camera lens when this film is used with a Wratten No. 12 filter. Second, the overlap between the wavelength bands is even more pronounced than in the case of regular color film. Third, during storage, special precautions are necessary with respect to temperature and humidity both after manufacture and after exposure (Eastman Kodak, 1965b).

Why color films are not used in multiband photography

Although color films are superior to regular panchromatic films for mapping drainage, vegetation, soils, and culture (Anson, 1966), there are several reasons why their use is not a suitable alternative to the use of separate combinations of filter and black-and-white film as used in multiband photography:

1. The absorption characteristics of the dyes used in color films do not sharply define specific wavelength bands.
2. There is considerable overlap of the three wavelength bands.
3. The wavelength bands are fixed by the manufacturer.
4. As Sorem (1967) points out, the spectral response of color film is not flat but shows dips where the absorption cutoffs of the dyes cross. Sorem emphasizes that the color reproduction, whether it is in the camera film or in a print made from a camera negative, need not and almost never does have the same spectral characteristics as the original.

Radiation effects on film

In space multiband photography, where the film may be exposed to trapped radiation in the Van Allen belts or to ionizing radiation from solar flare activity, attention must be paid to shielding the film. Radiation effects
are generally negligible in aerial photography or photography from low altitude and low inclination Earth orbit. However, in high inclination or synchronous orbit, and in lunar and planetary missions, radiation effects can be severe, causing an increase in gross fog and granularity and a decrease in speed, gamma, and latitude of film.

A general rule on radiation effects is that the higher the Aerial Exposure Index of the film, the more sensitive is the film to nuclear radiation. It is unfortunate that relatively high Aerial Exposure Index films have to be used in multiband photography to offset the high filter factors involved.

The most detailed study of radiation effects on black-and-white aerial films is reported by Lewis and Watts (1965). Lamar (1967) reports on the effects of radiation on three color as well as nine black-and-white films. Both references tabulate data from laboratory irradiated film samples. Using data on radiation encountered in space (Valley, 1965), we can roughly predict the effect on film.

We should add two comments. First, all laboratory measurements have been made on film exposed to one type of radiation at a time, for example from monoenergetic electrons or protons. The possibility of a synergistic effect occurring, such as may take place in the space environment, has not been explored. Second, although radiation effects have not so far caused noticeable degradation in space photography, we need to exercise caution as space photography missions become more prolonged and when photography is conducted without the shielding afforded by the spacecraft walls.

2. Filters for Multiband Photography

In the following we will discuss the optical characteristics of filters for multiband photography, not the selection of passbands, which is outside the scope of this review. A good general discussion of filters is found in Scharf (1965), and a discussion on filters for color aerial photography is found in American Society of Photogrammetry (1968). The introduction of asymmetrical distortion by a before-the-lens filter which is slightly wedged is discussed on page 24.

Up to now, the worker in multiband 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 (see references: Corning, 1965; Eastman Kodak Company, 1965a; Schott and Gen., 1962). Corning and Schott produce colored glass filters although only Schott glass filters are made of optical-quality glass. In Schott filters the coloration is caused either by colored simple or complex ions in true solution or by submicroscopic colored crystals in the glass whose correct size is obtained by the temperature treatment of the glass. Most Wratten filters consist of organic dyes mixed in gelatin and lacquered for durability. These gelatin filters can be obtained from Kodak cemented between sheets of "B" glass, which is of adequate quality for most purposes but does not have sufficiently good surface for use with high performance systems of long focal length and large aperture. The Tiffen Optical Company markets a large variety of absorbing filters cemented between glass plates, and provided the filters for the Apollo 9 multiband camera.

Transmittance versus wavelength scans over the range 300 to 1000 nm for commonly used multiband filters are shown in Fig. 2. We should note that several of the visible passband filters transmit in the photographic infrared. Care must be taken to block the infrared transmittance with a low wavelength pass interference filter if these absorption filters are to be used with infrared-sensitive film. The transmittance versus wavelength scans for the Wratten filters used in the Itek nine-lens camera are shown in Fig. 17.

Absorption filters 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 multiband filter set, absorption passband filters have two additional undesirable characteristics:

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

(2) The passband cutoffs are not steep; this is particularly true for the long-wavelength cutoffs, resulting in a passband that is far removed from the ideal rectangular shape.

Interference filters have been considered (McKenney and Slater, 1968) for this application for three reasons:
Fig. 2. Plots of transmittance vs wavelength for Wratten filters commonly used in multiband photography.
(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 multiband work because:

(1) Filters of the width usually required in multiband photography (≥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 ignored the problem of designing suitable interference filters to replace absorption bandpass filters in multiband photography. Absorption bandpass filters were considered reasonably acceptable, for multiband photography was still in early development, and other problems such as multiband photointerpretation were more pressing. Filters became a major problem only when consideration was given to multiband photography of the Earth from low Earth orbit. Here the low efficiency of absorption bandpass 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 image blur. Should forward motion compensation (FMC) be unavailable—the first "Earth resources" orbital multiband cameras will have no provision for FMC—the amount of forward motion image blur can be reduced by a suitable choice of lens (high speed, short focal length) and film (high speed, low resolving power); however, the result is inevitably a loss in ground resolution compared with the case when a lower filter factor is available.

Comparison of absorption filters and interference filter designs

Typical passbands in the visible spectrum suggested for multiband photography are 440-580 nm, 500-620 nm, and 580-680 nm. In attempting to
isolate these passbands with Wratten or Corning* filters, we find at once that only in one case does the passband of the available filters 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. 3, 4, and 5. It is also noticeable that the short wavelength end of the passband generally shows a much higher transmittance than the long wavelength end, and that no high transmittance passband absorption filters exist in the red end of the spectrum. Thus, in the case of Fig. 5, we have to either 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, absorption filters isolate the required spectral passbands moderately well but not as well as desired.

A second serious drawback of absorption filters is their low over-all transmittance or high filter factor (see Figs. 3 and 4). A calculation for the dotted curve in Fig. 4 shows that the filter factor is about 9. In comparison, the interference filter designs 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. 4, 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 will 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. Now assume the camera is in a spacecraft orbiting the Earth and that the angular velocity of the camera with respect to the object is 50 mrad/sec. Assume also that the exposure time with a filter factor of 9 is 6 ms. The image smear is then 24 μm, and the resolving power is reduced to 30 cycles/mm. With a filter factor

---

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

Fig. 4. Comparison of Wratten absorbing filters with interference filter design required bandpass 500 to 620 nm.

Fig. 5. Comparison of Wratten absorbing filters with interference filter design required bandpass 580 to 680 nm.
of 3, the exposure time will be reduced to 2 ms and the smear to 8 μm, and 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 with 11% with the filter factor of 3.

Angular dependence of interference filters

The reluctance to use interference filters in multiband photography has been partly due, understandably, to the unavoidable change in passband shape and position with angle of incidence. The designs shown in Figs. 3, 4, and 5 show a shift which is roughly proportional to $(\cos \theta)^{1/3}$, where $\theta$ is the angle of incidence.

For angles of incidence (semifield angles) up to $20^\circ$, this $(\cos \theta)^{1/3}$ shift is a small factor, amounting to only 12 nm, or 2%, as illustrated in Fig. 6. The change in shape is hardly discernible. In our opinion, both are negligibly small; however, we will have to await field experiments to verify this.

* These calculations were made with the aid of the Itek Photographic Slide Rule.
The upper portion of Fig. 6 shows how the fields of view differ, for equal areal coverage, in strip and frame photography. Strip cameras are now comparatively little used; however, for the reasons mentioned on page 51, we think that they should be considered for use as multiband cameras. One relevant 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. 6. 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 semifield angles. For example, in the equivalent case of 27° semifield frame and 20° semifield strip photography, the percentage shifts are 5% and 1.4%, respectively.

Use of interference filters with wide angle lenses

Recently, McKenney and Slater (1969) investigated the possibility of using the curvature of a surface of a lens to reduce the shift in the filter passband for large field angles. They found that locating the filter on the proper surface considerably reduces the shift of the passband.

Specifically, they 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. They then determined the spectral transmittance of each lens when a wide passband interference filter was located on the second or fourth surface of the lens. The wavelength shift of the half-power point at the long wavelength cutoff of the filter is shown as a function of field angle and surface for the three lenses in Fig. 7. Obviously, the second surface of the Paxar is preferred but the second surfaces of the other lenses may be acceptable depending on the application.
Fig. 7. Plots of $\lambda$ against semifield angle for the 2nd and 4th surfaces of the three lenses; $\lambda$ is the wavelength of the half-power point at the long wavelength cutoff of the filter.
REFERENCES--CHAPTER II

American Society of Photogrammetry, 1968, Manual of Color Aerial Photog- 
raphy, ed. 1, American Society of Photogrammetry, Falls Church, Va.,  
550 pp.

Anson, A., 1966, "Color photo comparison," Photogrammetric Engineering  
32:286-297.

Corning Glass Works, 1965, "Glass color filters," Corning Glass Works  
Publication CF-3, Corning Glass Works, Corning, New York.

Eastman Kodak Company, 1961 to date, Manual of Physical Properties: Aerial  

Eastman Kodak Company, 1963 to date, Tech Bits, Eastman Kodak Company,  
Rochester, New York. (See, for example, "Characteristics of Kodak  
aerial films," Tech Bits #2, 1968.)

Eastman Kodak Company, 1965a, "Kodak Wratten filters for scientific and  
technical use," Kodak Publication B-3, Eastman Kodak Company, Rochester,  
New York, 77 pp.

Eastman Kodak Company, 1965b, "Kodak color films," Kodak Data Book No. E-77,  

Eastman Kodak Company, 1966, "Kodak aerial exposure computer," Kodak Publi- 

Eastman Kodak Company, 1967a, "Kodak aero-neg color system," Kodak Data Book  

Eastman Kodak Company, 1967b, "Kodak data for aerial photography," Kodak  

Eastman Kodak Company, 1968, "Applied infrared photography," Kodak Publica- 


Lamar, N. T., 1967, "Determining the effects of radiation on selected flight  

Lewis, J. C., and Watts, H. V., 1965, "Effects of nuclear radiation on the  
sensitometric properties of reconnaissance films," Technical Report  
APAL-TR-65-113, Air Force Avionics Laboratory, Research and Technology  
Division, Wright-Patterson AFB, Ohio, 94 pp.

McKenney, D. B., and Slater, P. N., 1968, "Filters for multispectral photog- 


CHAPTER III. OPTICAL-MECHANICAL TOLERANCES FOR MULTIBAND CAMERAS

1. REGISTRATION TOLERANCES

Some of the registration tolerances required for the camera system depend on which method we use to examine sets of multiband photographs. This is because, in optically or electronically analyzing the photographs, we can make corrections to compensate for some of the errors introduced by the camera system. For this reason we will begin by reviewing the various methods for conventionally displaying multiband data.

The simplest way of displaying a set of multiband photographs is to use a bank of projectors to superimpose the images on a screen. Different color and neutral density filters can be used with each projector so that density differences between the photographs can be displayed in a variety of color renditions. Unfortunately, this simple projection method usually introduces registration errors of its own, and the over-all spatial resolution of the superimposed photographs is low. One of the aims of a multiband viewer is to compensate for some of the registration errors introduced by the camera system. Such a viewer has been described by Yost and Wenderoth (1967). The Itek Additive Color Viewer is another example. Both of these viewers are expensive instruments, the first models of each costing $250,000 or more.

Another simple way of examining multiband photographs is to prepare contact color transparencies of each black-and-white photograph, using different spectral filters in the contact printer. The various color transparencies constituting the multiband set can then be superimposed and viewed directly or under magnification. This method does not allow registration errors introduced by the camera to be compensated. It does allow for the rapid dissemination of the black-and-white photography (often immediate analysis is essential), and the method is inexpensive.

An automatic method of examining multiband photographs involves extracting the data by scanning each photograph in the set using a microdensitometer. A density or exposure "signature" can then be generated additively or subtractively, and this signature can be compared with signatures of known ground features stored in a computer memory. It also has
the potential of removing some of the registration errors introduced by the camera. The extent to which this approach is feasible has not yet been established. However, the cost of the instrumentation is high.

We predict for the near future a rapid increase in the amount of multiband photography obtained as more extensive aircraft programs come into operation and further Earth orbital multiband experiments are inaugurated. There are perhaps a hundred groups in the United States alone, in government agencies, universities, and industry, who will be interested in evaluating this photography. Clearly a simple, inexpensive viewer is required that is capable of yielding high quality multiband reconstructions.

For this reason it is worthwhile mentioning a method currently under consideration by NASA which seems to embody most of the advantages of the above methods. Basically, it involves the development of a single viewing, registering, and printing unit, which we will refer to as the master projector, and a number of simple, inexpensive multiband viewers. With the master projector, a skilled operator will be able to superimpose the multiband imagery precisely, removing all the registration errors that can be compensated. The projector will then be used to print four (or more) black-and-white images alongside each other on a single piece of stable film (178-μm Estar base or perhaps glass plate). The film or plate with the four preregistered multiband images will then be duplicated and disseminated for use with simple multiband viewers.

Pending a detailed experimental study of the subject, we can only estimate the effect of misregistration on the information extractable from multiband photographs. We know misregistration causes color fringing similar to that seen in a maladjusted color TV picture or in a poorly printed magazine color reproduction. Fringing is irritating to the observer although, owing to his ability to discriminate the color images, he does not suffer as great a loss in spatial resolution as he would if the images were of the same color or simply in black and white. The exact amount of the loss depends in a complicated manner on the differences among the hues, saturations, and brightnesses of the colors involved.

The psychophysical nature of the problem coupled with the nonlinear characteristics of some of the causes of misregistration make it impossible to arrive at a single tolerance figure for a multiband camera. The approach
we will take in the following is to determine the tolerance for each cause of misregistration separately and to express the tolerance in terms of a decrease in multiband spatial resolution. We must be careful to remember that we are not here using the usual definition of spatial resolution. Multiband spatial resolution is the limiting resolution for which color fidelity can be maintained in a multiband reconstruction. This limit is the result of color fringing due to misregistration and/or spatial resolution differences between one multiband image and another.

A large number of causes can produce misregistration in a multiband camera system. We will deal here only with those that may persist in spite of good conventional optical-mechanical design and fabrication. Where applicable, we will indicate how tolerances can be ascribed to misregistration causes and how the multiband resolution of a combination of films is reduced when the misregistration is at the tolerance limit.

The causes of misregistration to be discussed are as follows:

1. Differences in image heights from one multiband photograph to another due to: differential asymmetrical distortion, chromatic variation in focal length, chromatic distortion, and lateral chromatic aberration. (Only chromatic variation in focal length can be corrected in a multiband viewer.)

2. The optical axes of the cameras are not parallel; i.e., there is a boresighting error (correctable in a multiband viewer).

3. Midpoints of the shutter exposures are not synchronized (correctable in a multiband viewer only in certain cases).

4. The film is not held flat in the focal plane of the lens (in general not correctable in a multiband viewer).

5. Differential film distortion is present (correctable in a multiband viewer when the film expands or contracts uniformly).

Those causes of misregistration which cannot be corrected in a multiband viewer are of especial importance to designers and users of multiband cameras.

Now we know that, if we have two identical photographic transparencies in contact, each having a spatial resolution of 100 cycles/mm, and we displace one with respect to the other by 10 μm (corresponding to the length of one cycle or one resolution element), the resolution of the contacted pair will drop from 100 cycles/mm to 50 cycles/mm in the direction of the displacement. We can use the following relationship to determine the resultant
multiband resolution, \( R_M \), for any displacement \( D \) in cycles/mm:

\[
R_M = \frac{R \cdot D}{R + D}
\]

where \( R \) is the spatial resolution of each transparency, assumed equal, expressed in cycles/mm.

Using the above relationship, we have drawn up Table 2 for handy reference in the discussion on registration. The first four columns list, in order, (1) values for resolution in cycles/mm for the camera lens-film combination, (2) the multiband resolution of the misregistered combination of films in cycles/mm, (3) three values for misregistration, namely 1, 0.5, and 0.25 resolution elements, and (4) the corresponding misregistration in micrometers. The fifth column will be referred to later.

**Table 2. Multiband spatial resolution as a function of misregistration.**

<table>
<thead>
<tr>
<th>Resolution, cycles/mm</th>
<th>Misregistration, in terms of --</th>
<th>Curve number when applicable*</th>
</tr>
</thead>
<tbody>
<tr>
<td>On each film</td>
<td>Of misregistered film combination</td>
<td>Resolution elements</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>7</td>
<td>0.5</td>
</tr>
<tr>
<td>10</td>
<td>8</td>
<td>0.25</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>20</td>
<td>13</td>
<td>0.5</td>
</tr>
<tr>
<td>20</td>
<td>16</td>
<td>0.25</td>
</tr>
<tr>
<td>40</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>40</td>
<td>27</td>
<td>0.5</td>
</tr>
<tr>
<td>40</td>
<td>32</td>
<td>0.25</td>
</tr>
<tr>
<td>60</td>
<td>30</td>
<td>1</td>
</tr>
<tr>
<td>60</td>
<td>40</td>
<td>0.5</td>
</tr>
<tr>
<td>60</td>
<td>48</td>
<td>0.25</td>
</tr>
<tr>
<td>80</td>
<td>40</td>
<td>1</td>
</tr>
<tr>
<td>80</td>
<td>53</td>
<td>0.5</td>
</tr>
<tr>
<td>80</td>
<td>64</td>
<td>0.25</td>
</tr>
<tr>
<td>100</td>
<td>50</td>
<td>1</td>
</tr>
<tr>
<td>100</td>
<td>67</td>
<td>0.5</td>
</tr>
<tr>
<td>100</td>
<td>80</td>
<td>0.25</td>
</tr>
<tr>
<td>120</td>
<td>60</td>
<td>1</td>
</tr>
<tr>
<td>120</td>
<td>80</td>
<td>0.5</td>
</tr>
<tr>
<td>120</td>
<td>96</td>
<td>0.25</td>
</tr>
<tr>
<td>140</td>
<td>70</td>
<td>1</td>
</tr>
<tr>
<td>140</td>
<td>93</td>
<td>0.5</td>
</tr>
<tr>
<td>140</td>
<td>112</td>
<td>0.25</td>
</tr>
</tbody>
</table>

*See Figs. 9 and 11.

We will simplify the discussion by assuming that any misregistration tolerance applies to a pair of photographs. Thus, when we refer to a misregistration of one resolution element, this implies that one photograph is displaced from the other by one resolution element in that region or at the point in question. If a multiband camera system produces four or more photographs,
we will assume that we are dealing with two or more identical pairs of photographs. Each pair of photographs will thus be misregistered by the same amount. In general, of course, this will not be the case: instead of all the photographs lying at the tolerance limit, some will fall within the tolerance limit. Discussing the problem in terms of identical pairs of photographs will give us the tolerance for the worst case.

**Matched image heights**

In this section we will deal with the optical causes of misregistration and assume that no other registration errors are present. The optical causes of misregistration will be discussed in terms of differential asymmetrical distortion, chromatic variation in focal length, chromatic distortion, and lateral chromatic aberration.

The result of each is that the change in image height with field angle will differ from one multiband photograph to another.

We should be careful to note here that we are not necessarily specifying a low value for the distortion of multiband lenses. (An exception would be if we wished to obtain multiband photographs of cartographic quality.) What we are specifying is that distortion differences should be small, and, when combined with small focal length and lateral chromatic differences, the resultant image heights should be the same from one multiband photograph to another.

Although in practice all four optical causes of misregistration are likely to be present to some extent, we will treat each separately, assuming the others are zero. This will give a clear idea how each contributes to registration errors. We will also discuss tolerances for chromatic variation in focal length and tolerances for distortion.

From the discussions beginning on pages 26, 28, and 30, it will be clear that we must design lenses specifically for multiband use to obtain the highest performance in terms of resolving power, F-number, and registration capability. Lenses designed for reconnaissance or cartographic purposes will inevitably fall short of meeting the special requirements of multiband lenses. A matched set of multiband lenses is presently being designed at the Optical Sciences Center. In addition, an attempt is being made to design a single multiband lens to yield matched imagery simultaneously in each spectral band.
**Differential asymmetrical distortion**—Lenses built to the same design and operating in the same passband may show some variation in distortion characteristics owing to slight errors introduced during alignment. Because of these errors, the radial distortion may not be symmetrical across any diameter in the image plane, and it may also change with azimuthal angle in the image plane. Tangential distortion is zero for the perfectly aligned lens, and, in the case of carefully aligned modern cartographic cameras, it usually does not exceed 5 μm, which for most purposes can be ignored.

**Distortion introduced by windows and filters**—Asymmetrical distortion can also be introduced by the presence of slight wedges in the filter and the window in front of the lens. In a complicated case we may have an antivignetting filter, a spectral filter, and a triple-pane window (for safety reasons in manned spacecraft). The distortion introduced by these five slightly wedged elements should be minimized by rotating each so that the individual wedges cancel each other as far as possible.

The angular deviations in the x and y direction $\delta_x$ and $\delta_y$ of a light ray passing through a prism of apex angle $\alpha$ has been shown (Shack, 1968) to be

$$
\delta_y = \alpha \left[ \frac{(n^2 - \sin^2 \phi)^{1/2}}{\cos \phi} - 1 \right] \cos \theta \cos \phi \sin \theta
$$

$$
\delta_x = \alpha \left[ \frac{(n^2 - \sin^2 \phi)^{1/2}}{\cos \phi} - 1 \right] \cos \phi \sin \theta
$$

where $\delta$ and $\alpha$ are small, $n$ is the refractive index of the filter or window material, $\phi$ is the semifield angle, and $\theta$ is an azimuthal angle in the plane of the prism measured from the line of greatest slope of the prism to the y axis.

In examining a set of multiband photographs, scene features at the center of the various frames are usually superimposed. Under this condition the radial, $\Delta R$, and tangential, $\Delta T$, image height differences introduced by a wedge in front of one of the camera lenses have been shown by Keenan (1969) to be given by:

$$
\Delta R = f [\delta_y \sec^2 \phi - \alpha(n-1) \cos \theta]
$$

and

$$
\Delta T = f [\delta_x \sec \phi - \alpha(n-1) \sin \theta]
$$
where $f$ is the focal length of the lens. Clearly $\Delta R$ is a maximum when $\theta = 0^\circ$ and when $\phi$ is the maximum field angle of the lens. For example when $\phi = 45^\circ$, $n = 1.58$, $f = 150$ mm and $\alpha = 20$ arc sec, then when $\theta = 0^\circ$ \hspace{1cm} $\Delta R = 21 \ \mu$m and $\Delta T = 0$

and when $\theta = 90^\circ$ \hspace{1cm} $\Delta R = 0$ and $\Delta T = 4 \ \mu$m.

Therefore, care has to be taken to orient in azimuth each window-filter-camera combination in a multiband array so that differential distortion between such combinations due to residual window-filter wedge is minimized.

---

![Figure 8](See text.)
The tolerances on differential asymmetrical distortion will be discussed on page 29.

Chromatic variation in focal length--A typical aerial camera lens is corrected over the wavelength range 500 to 700 nm. Beyond these limits the resolving power deteriorates. Furthermore, a plot of the effective focal length against wavelength for this type of lens is essentially flat between 500 and 700 nm; it changes slowly above 700 nm and more rapidly below 500 nm. Thus, if we were to use four filters of passbands 400 to 500 nm, 500 to 600 nm, 600 to 700 nm, and 700 to 900 nm with this lens, we might find that the effective focal length for the two intermediate passbands was 150 μm short of the position of the effective focal length for the two extreme passbands.

If the distortion characteristics of a set of such multiband lenses are identical, then, for the differential distortion between them to be zero, the focal lengths of the lenses, measured in the passbands for which they are to be used, must be equal. Thus, in the above example, the lenses for the blue and infrared, measured, say, in sodium light, would be 150 μm shorter in focal length than the lenses for use in the 500- to 700-nm region. Under these conditions the lenses would have matched focal lengths and zero differential distortion when operated in their respective passbands.

What we shall discuss next is the tolerance on the focal length match and how we might find a variation of, say, 150 μm in focal length in practice.

Tolerance on focal length match--The tolerance on matching the focal lengths of a lens array in a multiband camera system depends on:

(1) The loss in multiband resolution that can be tolerated when the picture formats are superimposed.

(2) The resolving power of the individual photographs.

(3) The semifield angle of the lenses.

Provided that each of the pair of lenses we consider has the same distortion characteristics, then the relationship we need is \( \Delta f \tan \theta = \Delta x \), where \( \Delta f \) is the difference in focal lengths, \( \theta \) is the semifield angle, and \( \Delta x \) is the shift in position of the image. This relationship and some of the values in Table 2 were used to construct the curves in Fig. 9. (The fifth column in the table gives the curve numbers.)
As an example, let us take the case of two 150-mm lenses of semifield angle \(45^\circ\) which yield a radial resolving power on film at this angle of 40 cycles/mm. Then let us specify that we need no less than 27 cycles/mm radial multiband resolution at this field angle from photographs taken simultaneously by the two lenses. From Table 2 we see that the maximum misregistration is 0.5 resolution elements, or 12.5 \(\mu\)m, and that the corresponding curve on Fig. 9 is number 4. From this curve the tolerance on focal length match is found to be 12.5 \(\mu\)m at \(45^\circ\). This and the other curves plotted on Fig. 9 can be used to determine the tolerance on focal length matching for different values of resolving power and/or semifield angle.

Returning to the discussion on page 26, we should note that it is possible to find focal length differences on the order of 150 \(\mu\)m in a group of about ten lenses even when extreme care is exercised in their fabrication and assembly. The center thicknesses, radii, and separations of the elements can be held to close tolerances; the difference in focal length seems to arise from the way the individual tolerances add or subtract from one assembled lens to another.
We can therefore use the following selection procedure. First we find two lenses whose focal lengths differ by 150 µm, to within the depth-of-focus tolerance of the lenses, say ±50 µm. Then we can achieve the precise registration tolerance of 12.5 µm by carefully adjusting the lenses, within their depth of focus, until their operational focal lengths are 150 µm different, to a tolerance of 12.5 µm.

A multiband projector operating at nominally 1:1 conjugates will allow compensation for small differences in the focal lengths of the camera lenses. For example, if one lens is of 150-mm focal length and another is of 153-mm focal length, one projection lens could operate at 1:1 and the other at 1.02:1 to equate the sizes of the projected images. This is readily accomplished by keeping the separation between screen and transparency fixed and adjusting the position of the projection lens. This slight change in projection lens conjugates is unlikely to change the resolution of the projected image even if a fast projection lens is used.

**Chromatic distortion**—Chromatic distortion is defined as the change with wavelength of the distortion characteristics of a lens.

A rapid and convenient method for measuring chromatic variation of distortion has recently been described by Tayman, Hull, and Washer (1968). The measurements were made with reference to the effective focal length of the lens for white light and consequently include the effects of lateral chromatic aberration and chromatic difference in focal length. The values reported enable the following maximum chromatic differences in image heights to be calculated for the measured lens:

- -68 µm for a blue-red color combination
- +30 µm for a blue-green color combination
- +54 µm for a green-red color combination

These image height differences are larger than acceptable for high resolution multiband photography. By a judicious choice of back focal length for each lens-filter combination it may be possible to reduce the above differences and at the same time maintain, or even improve, the resolution in each wavelength band.

Although the method referenced above provides a rapid measurement of chromatic image height differences for a single lens, a considerable amount of work is involved in determining the correct back focal lengths for
matching image heights of multiband lenses. Before proceeding with such tests, it is advisable to study the lens design data thoroughly to determine whether an adequate match can be realized for the various wavelength bands to be used.

*Tolerance on optical distortion*—For example here, let us consider two different radial distortions, as shown by the full and dashed lines in Fig. 10 for two otherwise identical, boresighted lenses. These distortion curves may represent two asymmetrical distortions, two chromatic distortions, or a combination of asymmetrical and chromatic distortion.

When simultaneous photographs are taken with these lenses and the photographs are superimposed at their centers, there will be 25-μm misregistration owing to differential distortion for semifield angles greater than about 35°. For cases when the resolving power of each pair of photographs is 10, 20, and 40 cycles/mm, we can immediately predict that the multiband resolution of each pair of photographs, when superimposed, is 8, 13, and 20 cycles/mm.

We should note that we cannot compensate differential distortion in a multiband projector.

![Graph showing radial distortion vs semifield angle](image-url)
**Lateral chromatic aberration**—Lateral chromatic aberration can be described as the radial displacement of the position of an image with wavelength or as chromatic change of magnification. In a well-corrected lens we would expect lateral chromatic aberration to be small but nevertheless of the same magnitude as the registration tolerances used in the previous examples.

The tolerance on misregistration due to lateral chromatic aberration can be calculated in the same way as the tolerance on focal length matching (see page 26), as both give rise to a change in magnification. The situation is complicated, however, because the change of lateral chromatic aberration with field angle is nonuniform. For example, we may encounter a $+10 \, \mu$m displacement of a green image from a red image at $20^\circ$ and a $-10 \, \mu$m displacement of a green image from a red image at $30^\circ$. Thus, in general, we will not be able to correct for lateral chromatic aberration in a multiband projector.

**Boresighting**

Unless the optical axes of the lenses in a multiband camera are parallel (we assume that the film surface is plane and orthogonal to the optical axis and that the scene is effectively at infinity), we will find that only a fraction of the area of the overlapped photographs will be in good register. The problem here is to determine how accurate the boresighting must be in order that good register is maintained over the entire area of the overlapped photographs and only a small loss in multiband resolution is sustained.

For two identical lenses whose optical axes are inclined to one another at a small angle $\theta$, we can derive the relationship

$$
\theta = \frac{\Delta x}{f \tan^2 \alpha}
$$

where $\Delta x$ is the amount of misregistration for a field angle $\alpha$ and $f$ is the focal length. Using this relationship together with the values from Table 2, we can plot the curves in Fig. 11 of boresighting error against half-field angle for 150-mm focal length lenses.
Again let us examine the case for two identical 150-mm lenses of semifield angle 45° and radial resolving power perpendicular to the flight direction and at full field of 40 cycles/mm. Let us specify that we need at least 27 cycles/mm radial multiband resolution at this field angle from superimposed photographs taken simultaneously by the two lenses. From curve 4 of Fig. 11, we find that for \( \Delta x = 12.5 \ \mu m \) the tolerable boresighting error is 0.083 mrad (17 arc sec). From Fig. 11 we can also predict that, if this tolerance is held, there will be less than 9% decrease in multiband resolution if the radial resolving power should increase to 80 cycles/mm at a semifield angle of 26°.

We should note that distortion has not been mentioned here, as the change in distortion over such a small angle is negligible. Further, boresighting error can be compensated in a multiband projector by tilting the projected images.

Fig. 11. Boresighting error vs semifield angle (see page 27 and Table 2).
Shutter synchronization

From time to time, tolerances on shutter synchronization for space multiband frame photography have been suggested (Badgley et al., 1968; Nicholson, 1967). In one instance (Badgley et al., 1968), a tolerance of ±1 ms was specified for 150-mm focal length cartographic cameras. This specification amounted to synchronizing the shutter of each camera so that the midpoint of each exposure coincided within ±1 ms. This is a severe tolerance, difficult to obtain with reliability and, in our opinion, not necessary in practice.

In discussing the problem here we will limit ourselves to an example of space multiband frame photography. For aerial frame photography and aerial or space panoramic photography the arguments are similar but the tolerances may differ substantially depending on the conditions of the specific case.

The tolerance on shutter synchronization is directly related to:

1. Loss in multiband resolution in the flight direction, in registering the overlapping portions of the photographs, due to the distortion characteristics of the lenses (assuming no attitude change between the exposures).

2. Loss in multiband resolution in registering the overlapping portions of the photographs due to attitude changes during the period of the exposures.

Effect of lens distortion on shutter synchronization tolerance--We cannot deal in general terms with this problem because of the wide variety of lens distortion characteristics encountered. We will, however, examine a hypothetical case of two identical lenses of 150-mm focal length, 90° total field, and with radial distortion, referred to the effective focal length of the lens* as shown by the full line in Fig. 10. Further, let us assume that the radial resolving power of the lens in the semifield range 40° to 45° is 40 cycles/mm.**

* This information can usually be obtained from the manufacturer, or it can be obtained from a lens test facility such as that at the National Bureau of Standards.

** For simplicity we will assume that the tangential distortion is negligible, as is often the case, and that the radial distortion is symmetrical across the field.
Now let us stipulate that the multiband resolution from two nadir photographs exposed at nearly the same instant through the two identical lenses has to be 27 cycles/mm parallel to the flight direction. From Table 2 we find that the tolerable misregistration is then half a resolution element, or 12.5 µm. However, from the assumed distortion curve, Fig. 10, we find that the maximum rate of change of distortion is about 35 µm/degree for extreme field angles.

If the cameras are mounted in a spacecraft moving at 7.8 km/sec around the Earth at an altitude of 156 km, then the nadir spacecraft rate is about 3°/sec. At 45° to the nadir, this rate is reduced to about 2°/sec. Thus, for the misregistration at a field angle of 45° to amount to 12.5 µm, the shutters on the cameras should be synchronized to 1/6 sec.

Characteristically, the rate of change of radial distortion with field angle decreases rapidly with decreasing field angle for a given lens. Thus, a tolerance calculated for an extreme field angle is likely to be more than adequate for smaller field angles. This is still likely to hold true if the resolving power increases severalfold toward the center of the format and if the same percentage degradation in the multiband resolution, due to lack of shutter synchronization, is specified across the format.

The combined values of resolving power and rate of distortion change, chosen in the above example, are perhaps unlikely to be encountered frequently in practice. Thus, we can say that a shutter synchronization tolerance on the order of ±0.1 sec, which can be readily obtained in practice, will usually suffice for frame multiband photography from Earth orbit. However, it should be emphasized that specific cases should be calculated using measured resolving power and distortion values referred to the focal length that yields the best average definition over the picture area.

We should note that in this case a multiband projector system cannot be used to correct the error because the error introduced is due to lens distortion whose rate of change varies nonlinearly with field angle.

Effect of attitude change on shutter synchronization tolerance--We will assume here that the multiband lenses are perfectly boresighted and that the spacecraft is changing in attitude (pitch, roll, and yaw) while nadir multiband photographs are being taken. Clearly, if the shutters are not synchronized, changes in pitch and roll will induce boresighting errors, and yaw will degrade the tangential resolving power.
We will assume spacecraft attitude rates of 0.9 mrad/sec in roll and 0.3 mrad/sec in pitch and yaw. We will take the same input values used in the preceding example for calculating boresighting error. The result for that example was that the tolerable boresighting error was 0.083 mrad. Therefore, for a roll rate of 0.9 mrad/sec the shutter synchronication tolerance is 0.09 sec, and for a pitch rate of 0.3 mrad/sec the tolerance is 0.27 sec.

As an example of a yaw calculation, let us take the case of two 150-mm lenses of semifield angle 45°, which yield a tangential resolving power of 20 cycles/mm. Then let us specify that we need no less than 16 cycles/mm tangential multiband resolution at this field angle from photographs taken time $t$ apart. The problem is to find $t$.

From Table 2 we know that the tolerable misregistration, $\Delta x$, is 12.5 $\mu$m. We also know that the semidiagonal length, $(k)$, of the format is 16.2 cm. If the yaw rate is $\dot{\theta}$ mrad/sec, then $t$ is given by

$$t = \frac{\Delta x}{2k\dot{\theta}}$$

which in this case is 0.26 sec.

We should note that tilting and rotating the projected images in a multiband viewer can compensate for errors introduced by attitude rates.

Lack of film flatness

When a vacuum platen is not used, we must be careful to check that the film is maintained in the focal plane of the camera. Surprisingly large departures from flatness can be encountered, sometimes exceeding the depth of focus of a lens of moderate F-number. Two methods for measuring film flatness for paper-backed films are described by Clark and Goff (1968). Repeatability under average conditions was ±25 $\mu$m and under the best conditions was ±5 $\mu$m for the more sensitive method. By making use of the limited depth of focus of a medium power microscope, accuracies of ±2 $\mu$m can be obtained on film which is not paper-backed. Care has to be taken that the film has come to temperature and humidity equilibrium before measurements to this accuracy are attempted.
The tolerances on film flatness can be established with the aid of the equation on page 26 when the distance from exit pupil to focal plane is substituted for f. Using 150 mm for this distance, let us assume we have 40 cycles/mm radial resolving power at a semifield angle of 45° and that we want to maintain a multiband resolution of 27 cycles/mm. The tolerable misregistration is then 12.5 μm. Let us take a special case where one film bends along a straight line from the center of the format (where the height differential is zero) to the edge (where it is 12.5 μm above the true focal plane). If the second film is held in the true focal plane, then the misregistration between the film and the edge of the field is 12.5 μm—the permitted tolerance.

Measurements on Hasselblad film magazines have shown that departures from film flatness can exceed 100 μm. Generally, the departure from flatness is present as a curl toward the lens along the sides of the film that decreases as the rollers are approached.

**Differential film distortion**

The lack of dimensional stability of film is a well-known problem to photogrammetrists. The problem is solved by the use of a reseau exposed on the film as the ground scene is being photographed. This is not a suitable solution, unfortunately, for multiband photography where two or more negatives must be in register. We will therefore examine the tolerances required for the environmental conditions such that adequate dimensional stability of the film will be maintained.

We will discuss film distortion in terms of reversible changes, due to changes in temperature and humidity, and irreversible changes encountered during the processing and the aging of the film. In practical multiband usage, only the differential distortion introduced by the combination of these reversible and irreversible changes is important. For convenience here, however, we will discuss reversible and irreversible changes separately.

In the following we will describe the properties of Estar base film only, as it is uniaxial and is dimensionally more stable than cellulose acetate butyrate or triacetate base films. Most of the films listed in
Film distortion due to humidity and temperature changes--The dimensional stability of film can be found in Eastman Kodak's data sheets (1961 to date) and conveniently in an Itek publication (1965). In this case we will consider the effect of changes of humidity and temperature on the dimensions of Estar base film of 22.9 cm x 22.9 cm image format. The manufacturer lists the following data, converted here for convenience to metric units:

Table 3. Coefficients of humidity and temperature change.

<table>
<thead>
<tr>
<th>Base thickness, μm</th>
<th>Coefficient of linear expansion</th>
<th>Humidity, % per °C</th>
<th>Thermal, % per % RH**</th>
</tr>
</thead>
<tbody>
<tr>
<td>64</td>
<td>0.00083</td>
<td>0.0035</td>
<td></td>
</tr>
<tr>
<td>102</td>
<td>0.00083</td>
<td>0.0025</td>
<td></td>
</tr>
</tbody>
</table>

* Measured at 20% RH between 21°C and 49°C.
** Measured at 21°C between 15% and 50% RH.

Let us assume we are using an array of identical 150-mm focal length cameras each having an image format of 22.9 cm x 22.9 cm. At the corner of the square format, assume that we have a radial resolving power of 40 cycles/mm and that the multiband resolution should not fall below 27 cycles/mm when picture formats from two cameras are superimposed exactly at their centers. The semidiagonal length of the format is 16.2 cm, and from Table 2 we find that the maximum misregistration tolerable is 12.5 μm. We therefore cannot tolerate a misregistration greater than 0.008%. Using this value we can then draw up the following table:

Table 4. Tolerance on humidity and temperature difference (see text).

<table>
<thead>
<tr>
<th>Base thickness, μm</th>
<th>Temperature, °C</th>
<th>Humidity, % RH</th>
</tr>
</thead>
<tbody>
<tr>
<td>64</td>
<td>10</td>
<td>2.3</td>
</tr>
<tr>
<td>102</td>
<td>10</td>
<td>3.2</td>
</tr>
</tbody>
</table>
These are fairly close tolerances, especially for spacecraft experiments whose immediate environment might undergo substantial excursions between the standby and operational modes. Care must therefore be exercised to ensure that, following a change in environmental conditions, all the films (in this case of 22.9 \times 22.9 \text{ cm image format}) in the cameras have returned to the same temperature and relative humidity, within the above tolerances, before multiband photographs are taken.

**Distortion due to processing, stretching, and aging of film**--Data and discussions on distortion caused by processing, stretching, and aging can be found in Eastman Kodak data sheets (1961 to date). The data published give the results of absolute measurements on one piece of film, whereas we are generally interested here in the relative or differential distortion introduced between several pieces of film. Although the magnitudes of these absolute changes will be much larger than any differential changes, they are nevertheless worth brief mention here.

Under three different processing and measurement conditions (see the above reference for details), 64-\mu\text{m}-thick Estar base film exhibited a dimensional change of \(-0.05\%, -0.02\%, \text{ and } +0.03\%\); the corresponding values for 102-\mu\text{m}-thick Estar base film were \(-0.03\%, -0.01\%, \text{ and } +0.02\%). For processing-accelerated and processing-longtime aging, the shrinkage of 64-\mu\text{m}-thick Estar base film was 0.07\% and 0.05\%, respectively; for 102-\mu\text{m}-thick Estar base film the shrinkage was 0.06\% and 0.03\%, respectively. Complete data are not available on the stretching of film when under tension in the camera and processor and during drying.

The absolute magnitudes of the above distortions are certainly large compared to the required registration tolerances. To render the differential distortions small, we have to ensure that adequate environmental safeguards are effected during the lifetime of the film.

The best solution to the film distortion problem is to record all the multiband images on the same film as in the four-lens camera described by Yost and Wenderoth (1967). Then differential distortion can occur only if the edges of the film experience different conditions from the center of the film. This situation can occur in rolled film because the edges of the film are first to reach equilibrium with a changed environment.

For other multiband cameras where several different rolls of film are used, meticulous care must be taken. To prevent stretching, the tensions the
various films encounter must be the same in the camera, processor, drier, and film reader. Ideally, there should be no temperature differential between the films from manufacture to storage of the negatives. Likewise for humidity, but this is more critical than temperature because of humidity hysteresis effects. The processing and drying of the films should be carried out under identical conditions.

We should note that we can compensate differential film distortion in a multiband viewer only if the films have expanded or contracted uniformly. The misregistration produced is then identical to that encountered with unmatched focal lengths (see page 26). If the film distortion is nonuniform and differs from format to format, then the result is similar to that of differential lens distortion and cannot be corrected in a multiband viewer.

Discussion of testing procedures

We must emphasize that the preceding discussion has, for convenience, treated the various causes of misregistration separately. In practice, all causes of misregistration will be present to some extent in any multiband system. From a set of multiband photographs taken from an aircraft or spacecraft it will, in general, be extremely difficult to diagnose which misregistration errors are limiting system performance. However, laboratory tests can be designed partially to isolate and thereby correct the errors. Most of these tests will also be needed in the initial assembly of the multiband array.

Boresighting error can be detected either by use of a large collimator or by making a time exposure of a star field. Shutter synchronization can be checked either electronically (by displaying the signals from photodetectors in the two image planes on a dual beam oscilloscope) or optically (by photographing a target moving at a known velocity in front of a stationary reference grid). Differential asymmetrical distortion can be determined by measuring the image height, corresponding to various field angles, on a collimator bank such as used at the National Bureau of Standards. These image heights should be the same, for all the lenses in the multiband camera, to the required tolerances. The distortion measurements should be made on
micro flat photographic plates to minimize film distortion and ensure a flat film surface. Focal length matching, conducted of course prior to system assembly, is also carried out conveniently using a collimator bank. Through-focus runs are made for several equally spaced field angles, and the plane giving the best average definition over the picture area is determined. The tolerable depth of focus is thereby known, and the area weighted average resolution (AWAR) can then be calculated if required in accordance with Military Standard 150-A (1959). In such testing, spectral filters are placed between the sources and targets in the collimators so that the above data are known for the passband with which the lens will be used. Preferably all-reflecting collimators should be used. If these are unavailable, a careful check should be made of refractive collimators in the infrared and particularly the blue where the performance may deteriorate and where slight refocusing may be necessary. Recently a preliminary post-flight calibration report was issued on the Apollo 9 multiband photography experiment S065 (Keenan and Slater, 1969).

2. **UNIFORMITY OF PHOTOMETRIC RESPONSE ACROSS THE FORMAT**

The uniformity of photometric response across the format (evenness of image plane illumination) is critically important in multiband photography. The degree of uniformity for the lens itself can be controlled within close limits by use of an antivignetting filter. Two problems, however, make it difficult to define a useful tolerance for the degree of uniformity required. These are (1) density changes in the photograph and (2) atmospheric backscatter.

**Density changes in the photograph**

Experimental data do not tell us how large a spurious change of density must be to cause erroneous photointerpretation. (Although adequately calibrated data are available, they have not yet been analyzed to the point of tolerance determinations.)

In regard to density changes, we have two guides to establishing a conservative value for the tolerance. First, a trained observer can discriminate density differences as small as 0.02. But, second, it is extremely difficult in the face of variations in film sensitivity and film processing to
maintain a tolerance this close. This second fact is likely to be the limiting factor in practice; in any case, the first one is not strictly relevant to the additive color display methods usually used in multiband photointerpretation.

Assuming a gamma of unity, we can express a change in density of 0.02 as a change in illumination level of 5%. For the lens alone, we can work well below this tolerance; for example, the antivignetting filter for the Kollsman Geocon IV lens holds the illumination level constant to 1% over 74° of the total field of 90°. Spectrophotometric data for the 152-mm Wild Aviogon and Universal Aviogon are given in an interesting paper by Duddek (1967), which presents spectral transmittance and relative illumination curves for the lenses. At F/8 the relative illumination in the image plane for the 152-mm Aviogon with antivignetting filter is about the same as that quoted above for the Geocon IV.

**Atmospheric backscatter**

There seem to be too few data on atmospheric backscatter for us to say that a uniform response is really what is needed.

This problem concerns the increase in atmospheric luminance encountered as the path through the atmosphere lengthens for more oblique angles of view. Studies are under way to investigate this effect in some detail (Meier, 1968). It is interesting to note that the latest Zeiss super-wide-angle aerial mapping lens, referred to as 125° S-Pleogon A 4/85, has an intentional amount, approximating \( \cos \theta \), of residual nonuniformity designed into the antivignetting filter. This means that the antivignetting filter allows the illumination at a semifield angle of 60° to be 50% of that on axis. Zeiss considers that the greater atmospheric path at 60° will approximately compensate for this change of 50%. Zeiss further points out that approximate compensation is all that can be accomplished easily in practice because, if the sun is not directly overhead, the change of atmospheric luminance with field angle will be radially asymmetric.
Discussion

The above considerations point to the possibility that multiband cameras should be of moderate field of view, for the following reason: the in-flight calibration of multiband cameras is carried out by photographing an area on the ground of known characteristics. Reference is then made to this calibration in the multiband photointerpretation of the unknown area. If the reference and the unknown areas are at different field angles, such that the reflected light from one is "diluted" by considerably more atmospheric luminance than the other, then the comparison of the two will be difficult and may give rise to an erroneous interpretation.

In summary, we can estimate that a useful tolerance on the uniformity of photometric response across the format is 10%. This in turn means that:

1. Film sensitivity and processing conditions should not vary by more than 0.02 in density or 5% in illumination level. This can be maintained only through extremely careful processing and the use of well-calibrated gray scales exposed alongside each frame.

2. The semiangular field of the multiband lenses should not exceed about 18°. This assumes that the cosine relation of atmospheric luminance holds. At 18°, then, if the lens exhibits no mechanical vignetting, the atmospheric luminance will not have increased by more than 5%.

We must emphasize that these are estimated values. Carefully conducted experiments and photointerpretation studies are necessary to establish this tolerance more exactly.

Verticality of multiband photography

The degree of verticality (where verticality is the angle between the optical axis of the camera and a line from the camera to the Earth's center) required of multiband photography is primarily determined by whether or not the photography is to be used to update existing maps. If it is not, and the photography is to be used for interpretation purposes only, then a criterion that can be used is that the degree of verticality should be such that the extreme field angle does not exceed 20°. For example, the optical
axis of a camera whose full field is 20° should not depart from the vertical by more than 10°.

If the multiband photography is to be used to update maps, then the tolerance on verticality is tighter. Colvocoresses (1969) has shown that, by properly scaling and rectifying the imagery, the errors caused by Earth curvature can be reduced to 50 m at a distance from nadir of 130 km and an altitude of 900 km. He goes on to show that, with a 1° angle to the vertical, a point in the corner of a 16° diagonal frame will be differentially displaced, in relation to the center of the photograph, by about 450 m. However, if the angle to the vertical is known, then optical or mechanical rectification can be performed on the imagery. Colvocoresses states that if the angle is known to 0.14° then, coupled with the residual curvature effect in rectification, the displacement error will amount to about ±53 m.

The extent to which one can depart from the vertical has not been calculated. However, we can guess that it might amount to about ±5°. The more important factor is the accuracy to which we know the error in verticality. From the above results it seems that an accuracy of 0.1° or better should be adequate for space multiband photography in the foreseeable future.
REFERENCES--CHAPTER III


Meier, H. K. (Carl Zeiss), 1968, Personal communication to the author.


Shack, R. V., 1968, Optical Sciences Center, Personal communication to the author.


CHAPTER IV. SYSTEMS FOR SPACE AND AERIAL MULTIBAND PHOTOGRAPHY

1. GENERAL

Multiband photographic experiments are being conducted as ground-based and aerial investigations to define the requirements for operational aerial and Earth orbital systems and to refine methods of multiband data handling and interpretation. It is not surprising, therefore, that the camera systems now in use, or proposed for future development, vary substantially in configuration and performance. On the one hand, simple single cameras with a filter wheel in front of the lens are being used for ground-based experiments. On the other hand, complex multilens cameras are being used for aerial multiband photography. Additionally, optically matched and boresighted conventional aerial reconnaissance cameras have been built for multiband photography. Designs of panoramic multiband cameras have been developed. In the future we may find arrays of cartographic or strip cameras used in a multiband mode.

For convenience, we will divide the wide variety of camera types that can be used in multiband photography into the following categories: conventional aerial cameras, multiband cameras, optical multiplexing cameras, optical-mechanical scanners, image tube cameras, and cameras using phototransistor arrays. Although not directly photographically recording, the last three systems operate in the photographic range as multiband sensors, and the imagery can be presented as a film record. A general discussion of sensors and data systems can be found (National Academy of Sciences, 1969) with emphasis on their use from Earth-oriented satellites.

A catalog of aerial reconnaissance and mapping lenses has recently been compiled (U.S. Air Force Avionics Laboratory, 1967). Catalogs of airborne photographic equipment (U.S. Air Force Avionics Laboratory, 1965), and photographic laboratory equipment (U.S. Air Force Avionics Laboratory, 1966) are also available. A particularly useful reference is a compilation of reconnaissance data by McDonnell Douglas (1968).

Rather than list conventional cameras in terms of F-number, focal length, format size, etc., we will compare on the following pages, their modus operandi, emphasizing particular features that are favorable or unfavorable for multiband photography applications.
2. CONVENTIONAL AERIAL CAMERAS

Cartographic cameras

Cartographic cameras are the easiest type of aerial camera to describe because they are all of the same general configuration. The distinctive characteristic of the cartographic camera is its high degree of distortion correction. Aerial photographs taken with modern 152-mm focal length 90° cartographic cameras, and measured with reference to the calibrated focal length of the lens, typically exhibit radial distortion of less than ±10 μm. The following additional characteristics are found in most cartographic cameras:

1. Total field of view across the diagonal is either 90° or 120°.
2. Format size is 22.9 x 22.9 cm.
3. F-number is between 5 and 6.3; T-number with antivignetting filter is about 10 for modern, and 20 for older lenses.
4. Camera has a between-the-lens shutter.
5. Fiducials for location of principal point of format are an integral part of lens cone.
6. Reseau and fiducial markers are exposed on film simultaneously with exposure of ground scene.
7. Camera has a vacuum platen.
8. Extensive flight and camera data are recorded alongside each frame.

The emphasis on wide field and freedom from distortion results in a lens of moderate F-number. With an antivignetting filter, the T-number is in the neighborhood of 10. Such a lens is therefore not well suited for multiband photography when the filter factor can easily exceed 3. This is particularly true of most modern cartographic cameras, which do not have provision for forward motion compensation. An exception is the recent Fairchild KC-6A camera described by Norton (1968), which utilizes film plane FMC with the Kollsman Geocon IV lens. Fig. 12 shows a cutaway view of the Geocon IV lens, and Fig. 13 shows FMC fiducials and other special features necessary in modern cartographic cameras.

We are also paying for wide field and freedom from distortion in terms of resolving power. The high contrast axial resolving power of modern mapping
Fig. 12. Cutaway view of Geocon IV aerial mapping lens (courtesy of Kollsman Instrument Corporation).

Fig. 13. Annotated photograph of the Fairchild KC-6A 150-mm aerial camera containing the Geocon IV lens.
cameras tested using operational films is found to be about 70 cycles/mm, while the area weighted average resolution (AWAR) is less than 50 cycles/mm, and sometimes 40 cycles/mm. These values compare unfavorably with those pertaining to reconnaissance cameras of the same focal length but smaller field in which AWAR values greater than 100 cycles/mm are common.

In summary, if we require multiband photography of cartographic quality, as has been suggested (Badgley et al., 1968), then, even for modest V/H ratios,* FMC must be employed to maintain the moderate resolving power of the cartographic camera. If cartographic quality is not required, other types of camera will yield higher resolving powers even without the aid of FMC.

The results of resolving power tests of seven cartographic cameras used with various color films have recently been reported (Tayman, Hull, and Washer, 1968). These results can be used to evaluate the lenses for multiband photography if the resolving powers of the color films are known for the wavelength bands used in the tests.

Frame reconnaissance cameras

In contrast to cartographic frame cameras, reconnaissance frame cameras come in a wide variety of configurations and consequently are hard to characterize briefly.

The frame reconnaissance camera is designed to operate with high resolving power and low F-number, and factors such as highly corrected distortion and wide field, in contrast to cartographic cameras, are generally of secondary importance. Other general characteristics are as follows:

1. Focal plane shutters are commonly used.
2. Total fields of view are generally in the range $10^\circ$ to $40^\circ$.
3. Fiducial markers are integral with the camera magazine, and reseaus are not used.
4. Vacuum platens are seldom used for film less than 12.5 cm wide.
5. Focal lengths range from a few centimeters to more than a meter; 15.2 cm and 30.4 cm are common.
6. Film widths range from 70 mm to 24.1 cm.

* Velocity, $V$, of camera carrier at height, $H$, above ground level.
Resolving powers of reconnaissance cameras also vary over a wide range, and values in excess of 200 cycles/mm have been obtained for cameras of 60-cm focal length recording on operational film.

We can make the general comment that reconnaissance cameras are better suited than cartographic cameras for aerial and space multiband photography. We pointed out on page 39 that when we are trying to identify objects by their spectral reflectance as well as their shape, we must maintain uniform photometric response over the image format. Providing the necessary uniformity for wide-angle lenses requires the use of an antivignetting filter in front of the lens. For the older cartographic lenses this necessitates a filter whose absorptance varies as \( \cos^4 \theta \), \( \theta \) being the semifield angle. But these lenses exhibit a significant amount of mechanical vignetting, at full aperture, over the outer 10° of the field. Thus the use of a \( \cos^4 \theta \) antivignetting filter is usually not adequate correction for older cartographic lenses used for multiband photography. Modern cartographic lenses require a smaller correction, about \( \cos^3 \theta \). This is because the design allows for coma to be introduced into the entrance pupil, which enlarges the area of the entrance pupil as the field angle increases. Mechanical vignetting is also reduced in comparison to older cartographic lenses. Nevertheless, for modern cartographic lenses of F-number about 5, the T-number with a \( \cos^3 \theta \) antivignetting filter is about 9. If one uses an ideal filter (that is, a filter giving unity transmittance throughout its passband) of 100-nm bandwidth, the filter factor for panchromatic film will be about 3, or we may say that the T-number has been increased to 16.6. The use of such a slow system in photography of the Earth from low orbit, or in some cases of aerial photography when high V/H ratios on the order of 50 mrad/sec are encountered, results in a system of poor resolving power (see page 12). Either the resolving power is limited by the forward image motion during the exposure, or fast film of low resolving power is used to shorten the exposure time and reduce the forward image motion.

Panoramic cameras

By virtue of its small instantaneous field of view, the operational resolving power of the panoramic camera is typically higher than 100 cycles/mm even for focal lengths of 60 cm. This, combined with its large angular
coverage (usually about $140^\circ$), accounts for the popularity of the panoramic camera in photoreconnaissance. Most panoramic cameras are equipped with FMC, which means that they can more readily accommodate the high filter factors associated with multiband photography than, for example, the conventional cartographic camera.

The two basic types of panoramic camera have the following characteristics in common: The film surface is curved along its length with the radius of curvature equal to the focal length of the lens. The instantaneous field is small, as the image falls onto a narrow slit immediately in front of the film, and the slit width, which is variable, governs the exposure; the slit length is equal to the film width. The difference between the two basic types is in the method of matching the velocities of film and image. In one, the lens and slit rotate and the film is stationary during the exposure; in the other, a prism rotates in front of the stationary lens at half the rate that the film moves past the stationary slit.

Both types of panoramic camera are described in the literature (Thompson, 1966, p. 47) as direct scanning (rotating lens and slit with stationary film) and rotating prism (stationary lens and slit, rotating prism and moving film). In addition, the various forms of distortions inherent in panoramic photography are described. These distortions are troublesome to the photogrammetrist although several methods have been developed to correct them fairly well during the printing process (Thompson, p. 154).

We will now describe two cameras developed recently and not mentioned in the Thompson reference; they are the 80-mm panoramic camera developed by Itek, referred to as the "optical bar," and the HP-307 panoramic camera developed by Hycon.

The 80-mm optical bar camera is illustrated in Fig. 14a and the camera configuration is sketched in Fig. 14b. Of interest in the design is that the image and film move in opposite directions during photography and that therefore the motions of both are continuous. The 80-mm, F/2.8 Schneider Xenotar lens is capable of dynamic resolutions in excess of 50 cycles/mm on Plus-X film. The angular coverage is $39^\circ \times 180^\circ$. The dimensions of the camera are $24 \times 33 \times 24.6$ cm high and the weight is 5.5 kg without film.

Fig. 15 is a photograph of the HP-307 panoramic camera. This is a conventional rotating lens system in which the film is stationary during exposure.
Fig. 14a. 80-mm Optical Bar Camera.

Fig. 14b. Camera Configuration.

Fig. 15. HP-307 panoramic camera.
The shutter slit and rotating lens are driven by the same motor, suitably geared, so that the rotational velocities of the slit and image are accurately matched. The weight when loaded with 72 m of 70-mm thin-base film is 4.5 kg. The operational resolving power of the system has been measured to be in excess of 100 cycles/mm on 3404-type film for an object contrast of 8:1.

Mechanically both the Itek and Hycon cameras are of simple, compact design, e.g., the Hycon camera includes only 15 moving parts. Thus both can be readily modified so that four or more cameras can be ganged together, using the same drive motor and gearing and the same electronics, to operate in a multiband mode.

Some preliminary experiments have been carried out by the U.S. Air Force using two F/5 HYAC panoramic cameras of 30.5-cm focal length manufactured by Itek. Different films and filters were used in the two cameras operating simultaneously. Further work along these lines is planned using HP-307 cameras.

Although panoramic cameras have several desirable features, there is some question as to whether their wide scan angle is of any real use in multiband photography. First, the ground resolution decreases as secant $\theta$, as the semifield angle $\theta$ increases (ignoring the curvature of the Earth, which increases the effect), and second, it is doubtful if the recorded tones of objects at high obliquity can be related to the tones of near-nadir objects. (See the discussion on page 40.)

**Strip cameras**

The continuous strip camera was developed in the 1930's and, since the KA-18A camera by Chicago Aerial Industries, no new strip cameras have been manufactured. A modified KA-51A framing camera with a 152-mm F/2.8 lens has been described, however (Gullicksen, 1967). The strip camera has some interesting features that make it appear well suited for multiband use:

1. For a given width of coverage, a smaller field angle is needed than in a frame camera. For example, the same area is covered with a $74^\circ$ strip camera lens as a $90^\circ$ frame camera lens. This is advantageous compared with the equivalent frame camera in three ways:
(a) The resolving power of the system is higher and the distortion lower.
(b) Without an antivignetting filter the photometric response is more uniform over the format.
(c) If an interference filter is used with the lens, the angular shift of the filter passband is less. (See page 14 and Fig. 6 in particular.)

(2) The slit in the focal plane of the camera can be contoured so as to compensate for lack of photometric uniformity across the film width. Thus the exposure of the system is increased at the edge of the field to match that at the center, whereas with the frame camera, the exposure (transmission) at the center is reduced to match that at the edge by an antivignetting filter.

(3) The film in the strip camera is moved past the stationary focal plane slit at a rate equal to the image motion. Forward motion compensation is thus built into the system.

(4) The strip camera has few moving parts, and these are continuous rather than intermittent as in other camera types. The camera is thus more reliable than others.

(5) Because of its simplicity, an array of strip cameras can be readily synchronized by driving them from a single shaft, thus the film rates in each camera are identical and the photography of an area (with perfect boresighting) is simultaneous.

(6) The photography is continuous so no film is wasted as in other forms of photography when a safety margin of overlap is introduced.

The design for the KA-18A is now many years old, and there is no question that the problems which beset that design, such as image expansion or contraction (owing to inaccurate matching of film and image speed), can be eliminated by employing modern design and fabrication techniques.

3. MULTIBAND CAMERAS

General

In the previous section of this chapter we have dealt with conventional
types of aerial cameras and pointed out their advantages and disadvantages when operated in a multiband mode. In this section we will describe a few of the camera systems which have been or are being developed specifically for multiband photography.

**Russian multiband camera**

One of the first multiband cameras described in the literature was designed and built in the USSR (Zaitov and Tsuprun, 1962). The camera, referred to as the "aerial photograph determiner," allows for the simultaneous photography of a ground scene on three different types of film and with three different spectral filters and exposures for each. Thus, nine simultaneously exposed photographs are obtained of the same ground scene, each photograph measuring 6 x 6 cm. The system consists of three detachable parts: the camera, a shutter mechanism, and a film magazine.

The camera consists of nine separate, light-proof compartments housing nine identical F/6.5 Industar-24 lenses of focal length 105 mm. In front of the lenses is a plate with openings over the lenses for nine different filters. A single focal plane shutter is used which covers all nine formats. Presumably, exposures are equated for the nine channels by F-stop changes or the use of neutral density filters, but this is not mentioned in the above reference. The magazine holds three supply and three take-up reels, each pair of reels having a capacity of 28 m of film. The take-up reels are connected by couplings to form a composite unit rotated by a single drive motor.

**Itek nine-lens multiband camera**

The Itek nine-lens multiband camera is the best known multiband camera in this country. Three of these cameras have been built, the first in 1962, and are now operated by the U.S. Air Force and NASA Manned Spacecraft Center as part of aircraft programs. The Air Force has used the camera in Project Vela Uniform, in geological studies related to the location of natural airstrips for emergency use, and for other purposes. NASA is using the camera on the Earth Resources Aircraft Program.
The main specifications* for the multiband camera are listed in Table 5. As with the Russian multiband camera, which it basically resembles, the Itek nine-lens camera consists of a camera body and a shutter and format assembly shown in Fig. 16.

The camera body fits directly to the camera mount, and the nine lenses are mounted on the lens mounting plate inside the cone section. The focal plane shutter and format assembly is built around a casting containing nine format openings, fiducial marker grooves and frame identification numbering markers.

The lenses used with the camera (see Table 5) are individually mounted on plates that are fastened and pinned to the camera body lens mounting, in accurate register with the fiducial markers. The transmittance characteristics of the filters attached in front of the lenses are shown in Fig. 17. Obviously these filters may be changed to meet different requirements in multiband photography.

A typical format opening is shown in Fig. 18. When the exposure is made, the edges of the photograph are marked by the inner edges of the format opening. The fiducial marks in the corners of the format are recorded in the photograph. Lines extended between opposite diagonal fiducial blades intersect the optical axis of the lens to a tolerance of ±25 μm. When the exposure is made, the arrowhead showing flight direction is also exposed. Similarly the band number is printed on the film through a transparent plaque bearing the band number. The F-numbers of the lenses are changed so that the same shutter time can be used on all nine exposures.

Either an LA-124A IMC magazine or an A9B magazine can be used with the nine-lens system. Both magazines need modifying to accept three separate film spools in place of the 24.1-cm film spool normally used. The magazine requires vacuum to keep the film flattened during the exposure period. When operated in the non-FMC mode, vacuum is applied to the platen after film advance. Vacuum is maintained during exposure and shut off automatically at the start of film transport. In the FMC mode, vacuum is continuously applied to the film during FMC action and the exposure period, and is shut off during the film transport period.

* These and other data related to the nine-lens camera have been supplied through the courtesy of Mr. C. B. Hazzard of the Itek Corporation.
Table 5. Leading particulars of Itek nine-lens 70-mm multiband camera

<table>
<thead>
<tr>
<th>Feature</th>
<th>Detail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lenses</td>
<td>152 mm, F/2.4 Leitz C106; or 152 mm, F/2.8 Schneider Xenotar</td>
</tr>
<tr>
<td>Angle of view</td>
<td>21°14' x 21°14'</td>
</tr>
<tr>
<td>Format</td>
<td>9 each, 57 mm x 57 mm</td>
</tr>
<tr>
<td>Film capacity</td>
<td>3 each, 70 mm x 76 m rolls</td>
</tr>
<tr>
<td>Resolution</td>
<td>26 cycles/mm to 53 cycles/mm depending on spectral region</td>
</tr>
<tr>
<td>No. of exposures</td>
<td>325 sets of 9 exposures each</td>
</tr>
<tr>
<td>Shutter type</td>
<td>Stainless steel focal plane with capping curtain</td>
</tr>
<tr>
<td>Shutter speeds</td>
<td>1/30, 1/60, 1/120 sec</td>
</tr>
<tr>
<td>Magazine type</td>
<td>A9B modified</td>
</tr>
<tr>
<td>FMC</td>
<td>2.5 to 125 mm/sec</td>
</tr>
<tr>
<td>Cycle rate</td>
<td>1.75 sec/cycle @ 1/30 sec, to 1.25 sec/cycle @ 1/120 sec</td>
</tr>
<tr>
<td>Operation</td>
<td>Remote, manual, or continuous pulse modes</td>
</tr>
<tr>
<td>Size (nominal)</td>
<td>41.6 cm (H) x 36.2 cm (W) x 37.9 cm (L)</td>
</tr>
<tr>
<td>Weight</td>
<td>Camera--23 kg; Magazine--18 kg; Control console--36 kg</td>
</tr>
<tr>
<td>Power</td>
<td>28 VDC 19A, 115 VAC 400 Hz 7A</td>
</tr>
<tr>
<td>Special</td>
<td>Takes 9 separate simultaneous pictures of a scene through</td>
</tr>
<tr>
<td></td>
<td>9 different film/filter combinations</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Band(s)</th>
<th>Spectral region (nm in steps of 50 ea.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-6</td>
<td>400-700</td>
</tr>
<tr>
<td>7</td>
<td>700-900</td>
</tr>
<tr>
<td>8</td>
<td>775-900</td>
</tr>
<tr>
<td>9</td>
<td>825-900</td>
</tr>
</tbody>
</table>

Fig. 16. Itek nine-lens multiband camera.
Fig. 17. Spectral transmittance of the Wratten filters used originally with the Itek nine-lens camera.

Fig. 18. Typical format opening in the Itek nine-lens camera.
The availability of FMC in the Itek nine-lens camera sets it apart from most others mentioned in this section. Because of the high filter factors encountered in multiband photography, particularly if absorption filters are used, exposure times are long and there is a real need for FMC. If FMC is not available we are restricted to low velocity-to-altitude ratios for multiband photography.

Yost's four-lens multiband camera

Yost and Wenderoth (1967) describe a camera that can take multiband photographs in four bands from 360 nm to 920 nm. A photograph of the camera is shown in Fig. 19. The Aero Ektar lenses were carefully selected to give as close an image height match from band to band as possible. A single focal plane shutter is used. Owing to the staggered arrangement of the lenses, the four photographs taken at one time have an aspect ratio of 2:1. The photographs can be taken either on four separate rolls of film or on a single roll, usually of infrared black-and-white film, simply by changing magazines. The advantage in using a single roll of film is that any set of four photographs on the roll is automatically in register in a viewer once the viewer has been adjusted to bring the first set into register.

![Fig. 19. Four-lens multispectral camera used for research.](image-url)
Yost's multiband camera, unlike many now in use, has been goniophotometrically calibrated. His multiband camera, together with the viewer he has designed to work with it, constitute a particularly fine system for research in aerial multiband photography.

Other multiband cameras

Several other multiband camera systems have been or are being developed to meet specific needs and are mentioned briefly below.

Panoramic multiband cameras--HYAC panoramic cameras, discussed on page 51, have been used in preliminary investigations. The U.S. Air Force is planning further work along these lines with HP-307 panoramic cameras.

Hasselblad multiband cameras--The U.S. Army Cold Regions Research and Engineering Laboratory has assembled four Hasselblad 500 EL cameras in an A11A aerial camera mount (Marlar and Rinker, 1967), for environmental analysis studies in arctic and temperate regions. The main advantages of this system are its small size and weight, choice of manual or automatic operation independent of external power, and its low cost.

In the Apollo 9 flight of March 1969, an array of four Hasselblads was attached, during flight, to the hatch window of the Command Module for Earth photography. A picture of the cameras and mount is shown on the cover. The lenses were 80-mm Zeiss Planars; some additional data are contained in Table 6.

Table 6. Apollo 9 multiband camera data.

<table>
<thead>
<tr>
<th>Wratten filter number</th>
<th>Film type</th>
<th>F/#</th>
<th>Focal setting</th>
<th>Exposure time</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>SO-180 (IR Ektachrome)</td>
<td>F/8</td>
<td>50'</td>
<td>1/250</td>
</tr>
<tr>
<td>25</td>
<td>3400 (Panatomic-X)</td>
<td>F/4</td>
<td>∞</td>
<td>1/250</td>
</tr>
<tr>
<td>58</td>
<td>3400 (Panatomic-X)</td>
<td>F/4</td>
<td>∞</td>
<td>1/125</td>
</tr>
<tr>
<td>89B</td>
<td>SO-246 (IR black &amp; white)</td>
<td>F/16</td>
<td>33'</td>
<td>1/250</td>
</tr>
</tbody>
</table>

A report by Keenan and Slater (1969) gives the results of the post-flight calibration and analysis of the cameras.
Those planning to use Hasselblad cameras in the future for multiband use should consider using selected Planar, F/3.5, 100-mm lenses. The new Zeiss lens exhibits very little distortion and may well be relatively free of chromatic variations in distortion and focal length. To exploit the high performance of these lenses, they should be used in photogrammetrically calibrated Hasselblad cameras, as described by Thompson (1969).

Multiband cameras at the University of Michigan*--Some of the pioneering work in multiband photography in this country was carried out at the University of Michigan under Project MICHIGAN sponsorship and remains classified. In 1963 a nine-lens system was mounted in a Graflex 10 x 12.7 cm camera body, and I-N type film emulsion was used on a glass plate (Project MICHIGAN Report, 1963). The glass plate was used because it permitted a better correlation of the nine images when they were later rescanned with a modified closed-circuit TV system. This, and later work (Hamilton, 1965), was directed toward testing spectral signature processing techniques for automatic recognition studies.

The University of Michigan has also made a 16-lens aerial camera using infrared aerographic film of 22.8-cm format size. Although this system was used in 1965, no results have been published.

Modified KA-62 multiband camera system--Chicago Aerial Industries has modified four KA-62 cameras for use as a multiband aerial camera system under a NASA contract. A fifth camera will be used for broadband photography.

The KA-62 aerial camera using a 76-mm F/4.5 Paxar lens is a reconnaissance camera covering a total field of 90°. A photograph of the system is shown in Fig. 20. The specifications for the modified multiband system are as follows:

(1) Resolving power: The area weighted average resolutions (AWAR) of the lenses filtered by Nos. 12, 57, and 25A Wratten filters should not be less than 50 cycles/mm, high contrast, on Plus-X film. Note that the cameras operationally use the Schott equivalent of these Wratten filters. The AWAR for the lens with a No. 89B filter should not be less than 50 cycles/mm, high contrast, on IR Aerographic film. The AWAR for the lens with a No. 47 filter should

* We are indebted to F. C. Polcyn, University of Michigan, for the following information.
not be less than 20 cycles/mm, high contrast, on Plus-X film.

(2) Differential distortion: The image height at any point in the field of any of the four lenses operating with the Nos. 57, 25A, 12, and 89B filters should not vary from the average value of these four corresponding image heights by more than 15 μm. With the No. 47 filter the image height should be within 0.1% of the above average.

(3) Uniformity of photometric response: The illumination level across the format to a semifield angle of 45° should not be less than 95% of the illumination level on axis.

(4) Focal length matching: The equivalent focal length of the four lenses should be within the depth of focus of the lenses when the lenses are used with Nos. 47, 57, 25A, and 89B filters.

Fig. 20. KA-62 camera to be modified for multiband applications. (Courtesy of Chicago Aerial Industries, Inc.)
Optical multiplexing is an interesting new approach to multiband photography. During exposure of black-and-white film in the camera, each color in the scene is multiplexed by a unique spatial carrier (analogous to the sub-carriers of radio telemetry). A true or false color reconstruction can then be made from the encoded black-and-white transparency by a novel additive color projection method involving the use of a spatial filtering system. A detailed theoretical treatment of the method can be found in Mueller (1969). Here we will describe the basic elements of the method, discuss how it works in practice, and add some comments on its performance.

Let us take, for example, the use of optical multiplexing to obtain a full-color reproduction of a simple scene consisting of a red barn, green field, and blue sky. In order to modulate the colors in the various parts of the scene spatially, we place a tricolor grating immediately in front of the film plane in an ordinary camera. The three sets of bars in the grating are at 60° to one another and are clear and cyan (passes blue and green and modulates red), clear and yellow (passes red and green and modulates blue), and clear and magenta (passes red and blue and modulates green).

The situation is sketched in the upper part of Fig. 21, where the original scene (A) is photographed on black-and-white film and modulated by the tricolor grating, shown at (B). The method used to obtain the color reconstruction of the scene is shown by the lower half of Fig. 21. Here a multiple light source array is placed in the focal plane of a collimator which illuminates the transparency (B). The multiple light source consists of three pairs of apertures illuminated with red, green, and blue light. The pairs of colors are oriented azimuthally so that the diameter joining the green pair is perpendicular to the modulation produced by the clear and magenta grating on the transparency; the red pair diameter is perpendicular to the modulation produced by the clear and cyan grating; and the blue pair diameter is perpendicular to the modulation produced by the clear and yellow grating. The radial position of each colored aperture is such that combined with the grating spacing, the effective wavelength, and the focal length of the field lens, the first order spectra fall on the optical axis. The zero and second order spectra fall outside the aperture of the projection lens. The
projection lens images the transparency (B) on a screen, as shown, or for additional magnification, an eyepiece is used. Now, the only light accepted by the projection lens from the parts of the transparency modulated by the clear and magenta grating is that from the green sources. Therefore, that part of the transparency, the green field in the original scene, will be illuminated only with green light in the final color-reconstituted image. By the same reasoning we can see that the barn and sky will be reconstituted in red and blue.

Fig. 21. Illustration of optical multiplexing as applied to multiband photography.
The photograph of the scene has thus been reconstituted in the original colors of the scene. The colors are saturated, however, which may not be the case in the original scene. To reduce the saturation and at the same time to increase the over-all brightness of the image, different amounts of white light from the zero order spectrum of the white light source can be introduced through a gray wedge. The three pairs of colored sources in the collimator focal plane are obtained by filtering white light. Obviously, the red, green, and blue filters mentioned for discussion purposes above can be replaced by wedge passband interference filters, and the photograph can be reconstituted in any combination of false colors. The brightness of individual colors can be changed by the appropriate insertion of gray wedges so that the reconstituted image can be viewed in any combination of hue, saturation, and brightness.

We will now list and comment upon some of the operational details and the present development status of an optical multiplexing scheme called TOC (Technical Operations Color) as supplied by Harvey (1969).

1. The resolution limit of individual color channels is lower than the black-and-white film's rated resolving power. This is because some of the film's storage capacity must be used to record the spatial carriers that encode the color data. Typically, Plus-X film which has a high contrast resolving power a little over 100 cycles/mm, when used with three 40 cycles/mm gratings, yields a final resolving power of 28 cycles/mm. Higher frequency carriers will yield correspondingly higher frequency imagery.

2. Theoretically the presence of the grating does not lower the speed of the system. This result has been confirmed experimentally and is due to the modulation supplied by exposure through the clear strips of the gratings.

3. The image reconstruction system, or viewer, is inefficient, as only the first order spectra are used. The image is not of sufficient brightness to allow for viewing on a large projection screen. Sufficient brightness is available when the scene is viewed through an eyepiece.

4. Tricolor gratings are now being stripped directly onto the emulsion. The advantage is that moving film FMC can now be employed if
necessary. The color gratings are dissolved off the film during processing.

(5) So far, the gratings produced have been limited to use with 35-mm film and have been of cyan, magenta, and yellow. For operational multiband purposes, gratings for 70-mm film and larger are required and an infrared grating is a necessity.

(6) The gratings in the TOC system can be made of absorption or interference filters. Interference filter elements have the potential for narrowband multiband photography.

(7) A new lens will have to be designed and built to get the best out of TOC when an IR grating is added. The problem is simply that of needing a moderately fast, high resolving power lens which covers the range 400 or 500 nm to 900 nm. Progress toward such a design is being made at the Optical Sciences Center.

TOC's simplicity and convenience in use and the small size and weight of the camera equipment compared with conventional multiband cameras make it worthwhile to consider for space and some airborne applications. As a single frame system, there is no problem with registration. In addition, as Keenan (1969) has noted, the system lends itself well to copying a multiband reconstruction produced in a master viewer. The TOC viewer could then be the inexpensive multiband viewer referred to on page 20.

5. **OPTICAL-MECHANICAL SCANNERS, VIDICONS, AND PHOTOTRANSISTOR ARRAYS**

**General**

In addition to cameras in which the image is recorded directly on film, there are three other basic forms of multiband sensors in which the image can be stored on either film or magnetic tape. Only brief mention will be made of these systems here, as we are concerned primarily with multiband sensors that record directly on film.

**Optical-mechanical scanners**

The most widely used nonfilm recording systems that can operate in the photographic range are optical-mechanical scanners. In these systems the
Image falls on a single photodetector or an array of photodetectors. The output signal from the photodetector(s) may be stored on magnetic tape or used to modulate either a light source from which a line scan is projected onto film or a cathode ray tube that can be photographed. The significant advantage of this type of system is the broad wavelength range that can be covered. Typically, all-reflecting optics are used; thus the wavelength range is limited only by the spectral sensitivity of the detector(s) and the transmission of the atmosphere. Several instruments exist that cover the range 0.3 to 15 μm. Another advantage of the optical-mechanical scanner is that the output signal is electrical, thus facilitating automatic data handling. The main disadvantage of this class of system is that the resolving power is lower than that of a photographic camera of the same size.

**Image tube cameras**

Plans call for a three-return-beam vidicon (RBV) multiband camera to be flown unmanned on an Earth Resources Technology Satellite at an altitude of 900 km in 1972. The camera will consist of three 126-mm, F/2.8 lenses of 16° diagonal field of view; three filters for the blue-green, red, and infra-red; and three 50-mm RBVs manufactured by RCA. The RBVs have a 25-mm square format and 6000 TV lines across each format that correspond to a resolving power of about 85 cycles/mm and a ground resolution no better than 100 m for high contrast terrain features. An electronically controlled focal plane shutter will be used.

The advantage to any image tube approach is that the complexities of either film retrieval or onboard film processing and scanning are avoided. Disadvantages with respect to film recording are that image tubes provide lower mensuration accuracy, have greater distortion, and are less uniform in sensitivity over the picture format.

These disadvantages are compounded if three vidicons are used in an attempt to obtain multiband photography as in the case of the Earth Resources Technology Satellite. For example, in this case the degree of misregistration among the three pictures has been estimated to be in excess of a hundred resolution elements as measured across their formats. Also, because of the variation in sensitivity across the formats, photometric accuracy or tonal fidelity is lost.
Baker and Slater (1968) have suggested using a single lens-image tube unit as shown in the following block diagram, Fig. 22. In this method, multiband imagery is obtained by rotating a filter wheel in front of the lens, and a high-speed scan is used to read out a set of sequentially filtered images. The high-speed scan, frame sequential mode, obviates registration errors, and, to a certain extent, the problem of nonuniform detector response. Further studies need to be carried out to determine the type of image tube most suitable for this mode of operation.

Fig. 22. Electro-optical multiband camera, simplified block diagram.

A vidicon can also be used in a multiband strip mode in which images of the same strip of ground in different wavelength bands are simultaneously presented alongside each other on a vidicon tube face. Such a system is under development at TRW Systems Group and is shown schematically in Fig. 23. The TRW system has been designed to operate with up to 60 different wavelength bands of about 5-nm bandwidth, the limit being set primarily by the energy available in each band and the scan time employed. The advantages of
this approach are the compact, lightweight configuration of the system and the fact that it does not contain any moving mechanical parts. Its main disadvantage is that of the low resolving power of vidicons. We should note that in determining the performance of the system from aircraft or spacecraft, the velocity-to-altitude ratio must be taken into account in conjunction with the read and erase time of the particular photoconductor used.

![Diagram of WISP](image)

*Fig. 23. Schematic of "Widerange Image Spectrophotometer" (WISP) as described by TRW Systems Group.*

### Phototransistor arrays

Phototransistor arrays, such as are now under development at Fairchild Space and Defense Systems, are likely to prove to be another form of high performance detector in the near future. The resolving power of these arrays is stated to be 35 cycles/mm and, with an extended blue response, the half peak values of the wavelength sensitivity curve for silicon lie at 450 nm and 1050 nm. Thus, silicon phototransistors have a more useful wavelength range for most multiband purposes than vidicons, which cut off in the infrared at about 850 nm. At present, work is progressing on fabricating multi-element chips in which rows of elements are staggered to achieve maximum resolution in a direction perpendicular to the rows. In this configuration, a moving image falls on the chip, which is sampled row by row in synchronism with the image motion—the technique being analogous to that employed in the conventional strip camera.
The most promising feature related to phototransistors is that, once the technology involved in building a multielement chip has been mastered, chips can be lined up to produce an array of any reasonable length. Arrays containing the equivalent of 50,000 to 100,000 TV lines are a possibility for the future. Further comparative advantages to vidicons are their higher sensitivity and considerably greater mensuration accuracy.
REFERENCES--CHAPTER IV


Keenan, P. B., 1969, Optical Sciences Center, Private communication to the author.


U. S. Air Force Avionics Laboratory, 1965, Airborne Photographic Equipment (3 vols.), U. S. Air Force Avionics Laboratory, Research and Technology Division, USAF Systems Command, Wright-Patterson AFB, RC 015200 (1), (2), and (3).

U. S. Air Force Avionics Laboratory, 1966, Photographic Laboratory Equipment (2 vols.), U. S. Air Force Avionics Laboratory, Research and Technology Division, USAF Systems Command, Wright-Patterson AFB, RC 014500 (1) and (2).


University of Michigan, Dec. 1963, Project MICHIGAN Quarterly Report, Willow Run Laboratory, Ann Arbor.


CHAPTER V, DIRECTIONS OF FUTURE DEVELOPMENTS

Aircraft multiband systems are now fairly numerous and, for experimental purposes, can usually be flown at low altitude to offset their limited registration capability. For these reasons and because of the present shortage of research and development money, there are few plans for the design and manufacture of further aircraft multiband systems. Thus it seems that future developments will be influenced most strongly by the requirements of remote sensing from space.

The present schedule for development and use of space multiband systems is as follows. In 1972, a three-return-beam vidicon system will be launched unmanned on the first Earth Resources Technology Satellite into a polar orbit at an altitude of 900 km for a one-year duration. In 1972, the first Apollo Applications Program flight will carry a high-quality photographic system, now under development, to an altitude of 400 km. The duration of this manned mission in low-inclination Earth orbit will be nine months. In the following years there will be follow-on ERTS flights which will probably carry modified versions of the earlier multiband system. By the latter half of the 1970's, NASA's plans call for the launch into Earth orbit first of space stations and then of space bases staffed by 10 to 100 scientists. The space station or base opens up the possibility of Earth scientists being able to study the film from a high performance multiband camera immediately after it has been processed (perhaps using a Bimat system) on board the orbiting vehicle.

Thus the general directions of future developments lie in the improvement of both photographic and electro-optical methods. We will now discuss more specifically what form these improvements will probably take starting with films and filters.

With regard to films, there are two innovations which, if made, could significantly improve the performance of multiband cameras. The first is to make available a higher resolving power infrared black-and-white aerial film. Kodak at present markets only fast IR black-and-white films of AEI ≥100 and resolving power little better than Tri-X. The emulsion has similar characteristics to type I-N emulsion used for spectroscopic plates and films. When used in a multiband camera, the IR band yields much poorer definition
than the other bands using Plus-X or Panatomic-X simply because of the inferior resolving power of the film. This is unfortunate since the greatest contrast differences often occur in the IR band; because of the film, the system cannot exploit them. There is no doubt that a slower IR film could be used: the Apollo 9 multiband camera in the IR band (defined by a Wratten 89B filter) was stopped down to F/16 at 1/250 sec; while in the green band (defined by a Wratten 58 filter) Panatomic-X was exposed for 1/125 sec at F/4 without any noticeable motion smear. The answer then seems to be to make a III-N or IV-N emulsion available on a 102 μm-thick Estar base as aerial film. The second improvement also relates to IR-sensitive film. When a single film is used with one or more lenses in a multiband camera, for example in optical multiplexing or in Yost's multiband camera, the performance of the system suffers because of the poor film sensitivity in the green. The solution is obviously to manufacture an IR-sensitive film with a flat spectral sensitivity between 400 or 500 nm to 900 nm; however, the possibility of achieving this type of sensitization is not known.

Recent design developments in spectral filters will improve the performance of multiband cameras in several ways. We discussed these design developments for interference passband filters in Chapter II, so we will only briefly outline their effect on multiband performance here. First, interference passband filters can be manufactured for any central wavelength in the range 400 to 900 nm and any passband width in the range 50 to 350 nm. Second, the cutoffs are sharper than those of absorption filters, thus improving spectral selectivity. Third, their efficiency is two or three times greater, which results in improved spatial resolution for aerial or space cameras encountering image motion limitations.

We will now conclude by discussing future possible advances in conventional multiband cameras, in optical multiplexing, and in electro-optical systems.

Conventional multiband cameras can be substantially improved by the use of lenses designed to give matched image heights for all bands and field angles. Up to now this has not been attempted, and the use of off-the-shelf lenses, although carefully selected, has not yielded the best results. The optical-mechanical tolerances of the camera bodies and magazines have also been inadequate. We should emphasize again that we need the precision of a
modern cartographic camera in terms of the optical properties of the filter (wedge angle, homogeneity of index, and planeness), the accurate location of the film plane with respect to the lens, film flatness, and film stability.

Frame cameras have been used for most multiband purposes up until now, but not always with vacuum platens as they should. Panoramic cameras, although easy to gang together when small, do not seem to offer any real advantage because multiband photographs taken at wide angles and at nadir cannot be correlated owing to the large difference in atmospheric path. The best solution to conventional multiband photography is the use of ganged strip cameras for the reasons outlined on pages 51 and 52. The drawback is that available strip cameras were designed many years ago and are of inadequate performance. Thus, to exploit the advantages offered by strip photography, a new strip camera would have to be designed and built incorporating recent advances in electronics, camera design, and fabrication techniques.

Optical multiplexing, as exemplified by Technical Operations Color (TOC), promises to be a convenient method for obtaining automatically registered multiband photographs. As we mentioned on page 63, the steps required to make this an effective multiband technique are first to include an infrared grating, second to use a lens designed to cover the entire spectral range 400 or 500 nm to 900 nm, third to produce the gratings on film at least 70 mm in width and preferably 12.7 cm in width. There is no doubt that optical multiplexing should play an important role in the future of multiband photography because of its advantages over conventional systems in size, weight, and comparatively loose optical-mechanical tolerances. The electro-optical analog of optical multiplexing also merits detailed study in the future. In this technique the scanning raster is rotated in 60° steps in synchronism with a rotating filter wheel, thus electronically forming the tricolor grating used in optical multiplexing.

Perhaps in electro-optical multiband photography we can expect the most rapid advances in the next few years. The design of the only system so far developed does not take into account the requirement of multiband photography that the images formed in the various bands have to be registered. The multiband performance will therefore be poor, but we can expect that in the next generation system this mistake will not be made again. Moreover, advances in image tube and in phototransistor array technology are being made at a
rapid rate. At present none of these detectors in an operational form has the information-packing efficiency of Plus-X film over an image format more than 25 mm square, but with the present rate of progress we need not expect that this situation will last for long.