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Multiband Cameras

Requirements, tolerances and recent developments.

INTRODUCTION, REQUIREMENTS AND TOLERANCES

THE PAST FEW years have seen a steady increase in the use of multiband photography in remote sensing accompanied by the development of many different types of multiband cameras. We will be discussing some of the requirements of multiband cameras and a few of the more interesting specialized systems, including some presently under development. Cameras on the commercial market are not included.

In multiband photography, a camera records a number of images of a scene through several spectral filters. Commonly the imagery is converted into black-and-white positive transparencies, which are illuminated through a second set of spectral filters and brought into register to form an additive color display. In other instances the various images are scanned and the outputs are operated on simultaneously or sequentially in analog or digital processors. In any event we are dealing with a comparison of signals, the registration of which governs the spatial resolution of the recombined imagery. We have called the spatial resolution of the recombined imagery *multiband spatial resolution* and defined it as the limiting resolution for which spectral fidelity is maintained in a multiband recombination. This limit is the result of *color* fringing due to misregistration and/or spatial resolution differences between one multiband image and another. According to this definition, the multiband spatial resolution of any perfectly registered set of imagery is the spatial resolution of the lowest resolution band of imagery. Also, for a set of imagery of identical spatial resolution R, the multiband spatial resolution R_M, resulting when one or more images is misregistered by a distance d, in micrometers, is approximated by

$$R_M \cong R/(1 + 10^{-3}Rd). \qquad (1)$$

ABSTRACT: *The requirements and tolerances for multiband cameras are related to their general geometric and spectroradiometric properties. The SO65 camera used on Apollo 9, an optical multiplexing camera, the S190 camera for Skylab, and the return-beam-vidicon camera for the Earth Resources Technology Satellite are compared. The use of an intensifier-vidicon storage tube system, a dispersing element and vidicon, an image dissector, and solid state arrays in four novel multiband cameras are described.*

The exact form of this expression will change with the shape of the spread function of the system; however, for practical purposes the approximation is sufficient. In fact, the accuracy of measurement of registration error is commensurate with the approximation. We will return to the use of this definition of multiband spatial resolution later.

Ideally, a multiband camera should be an accurately calibrated spectroradiometric recording instrument with low geometrical distortion and high spatial resolution. Although these characteristics are not mutually incompatible, they do constitute a challenge to the lens and camera designer and to the filter, film, and electro-optical sensor manufacturer.

We can divide the requirements for multiband cameras into those describing the

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geometry and the spectroradiometery of the system as follows.

Geometric:

- High spatial resolution in each band.
- Registration to a fraction of a resolution element between each band across the format.
- Low distortion, less than 5 μm for mapping purposes.

Spectroradiometric:

- Uniform spectral irradiance across format.
- Sharply defined spectral sensitivity in each band.
- Shutter repeatability.

We will proceed to discuss some of these requirements.

RESOLUTION

In spite of the special problems created by the need to have precisely registerable images from different spectral bands, it is possible for a set of highly corrected, matched *f*/2.8 lenses covering 25° fields to be designed, each covering a different 100-nm wavelength range in the visible and photographic infrared. For the present electro-optical sensors, such as vidicons and solid-state arrays with resolving powers less than 100 cycles/mm, a well corrected *f*/2.8 optical system is more than adequate. Film comes closer to exploiting the potential of high-performance designs; for example, Eastman Kodak's High Definition Film 3414 can yield a resolution on the order of 400 cycles/mm with an *f*/2.8 diffraction-limited lens for a high-contrast target. However, it is important to note that none of the high-resolving-power films available are sensitive in the photographic infrared, i.e., 700 to 900 nm. For example, an *f*/2.8 diffraction-limited lens yields only 70 cycles/mm high-contrast resolution, using Eastman Kodak Infrared Aerographic Film 2424. We hope the film manufacturers will respond to the challenge by producing an infrared sensitive film of resolving power comparable to that of 3414.

REGISTRATION

The causes of misregistration in multiband cameras have been considered in detail elsewhere (Slater, 1970) and will be listed here only briefly.

- Differences in image heights from one multiband image to another owing to aberrations or assembly errors in the image-forming optics. For example: differential asymmetrical distortion, chromatic variation in focal length, chromatic distortion, and lateral chromatic aberration.
- Boresighting error owing to the lack of parallelism of the axes of the various optical channels. This gives rise to a difference in "keystoning" between the various images.
- Midpoints of the shutter exposures not synchronized, giving rise to an induced boresighting error depending on the attitude rates of the camera carrier.
- Lack of flatness of the film across the frame.
- Differential film distortion caused by tension, temperature, or humidity differences between films in the cameras or processing equipment.

The multiband spatial resolutions, as given by Equation 1 for various amounts of misregistration, are listed in Table 1. The table applies to the pair of photographs in a multiband combination that are most out of register. The addition of photographs in better register than these will not affect the multiband resolution as we have defined it. We have assumed in Table 1 that both photographs of the pair have the same resolution.

We will now show how Table 1 can be used in conjunction with appropriate graphs to determine the relationship between misregistration tolerance, the focal length difference, and the boresighting error. If each optical channel has the same distortion characteristics, then the misregistration Δx due to a focal length difference Δf is given by

TABLE 1. MULTIBAND SPATIAL RESOLUTION AS A FUNCTION OF MISREGISTRATION

Resolution, Cycles/mm		*Maximum Misregistration, in Terms of—*		
On Each Film	*Of Misregistered Film Combination*	*Resolution Elements*	*Micrometers*	*Curve Number when Applicable*
10	5	1	100	1
10	7	0.5	50	2
10	8	0.25	25	3
20	10	1	50	2
20	13	0.5	25	3
20	16	0.25	12.5	4
40	20	1	25	3
40	27	0.5	12.5	4
40	32	0.25	6.3	5
60	30	1	16.7	—
60	40	0.5	8.9	—
60	48	0.25	4.1	—
80	40	1	12.5	4
80	53	0.5	6.3	5
80	64	0.25	3.1	6
100	50	1	10	—
100	67	0.5	5	—
100	80	0.25	2.5	—
120	60	1	8.3	—
120	80	0.5	4.2	—
120	96	0.25	2.1	—
140	70	1	7.1	—
140	93	0.5	3.6	—
140	112	0.25	1.8	7

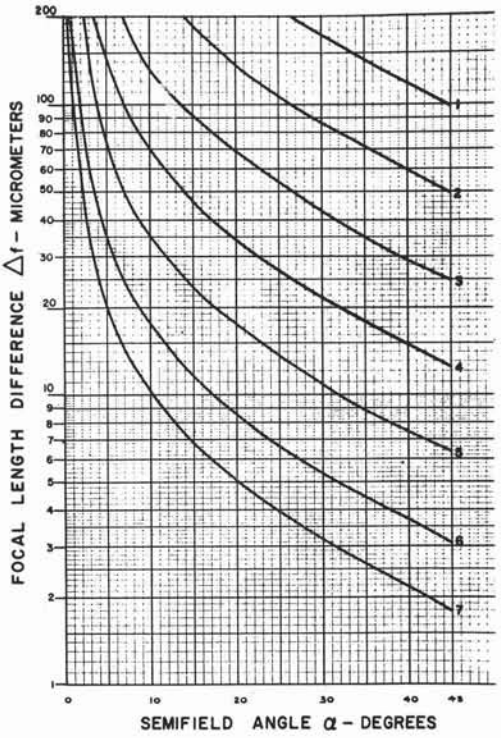

Fig. 1. Focal length difference *vs* semifield angle.

$\Delta x = \Delta f \tan \alpha$, where α is the semifield angle. Curves of Δf vs α for several values of Δx are shown in Figure 1.

As an example, let us consider two lenses of semifield angle 45°, which yield a radial resolution 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 1 we see that the maximum misregistration is 0.5 resolution elements, or 12.5 μm, and that the corresponding curve on Figure 1 is number 4. From this curve the tolerance on focal length match is found to be 12.5 μm at 45°. This is a tight tolerance; however, it should be remembered that the depth of focus tolerance will be on the order of ± 50 μm. Therefore, assembly errors amounting to 112.5 μm difference in focal length between two lenses can be tolerated if precision refocusing is allowed.

Misregistration, Δx, due to a boresighting error, θ, is given by $\Delta x = f\theta \tan^2 \alpha$, where f is the focal length of two identical lenses and α is the semifield angle. This relationship is plotted for several values of Δx in Figure 2 for $f = 150$ mm. Let us use the requirements in the above example again. We see from Curve 4 of Figure 2 that for $\Delta x = 12.5$ μm, the tolerable boresighting error is 0.083 mrad or 17 arc sec. From Figure 2 we can also predict that, if this tolerance is held, there will be less than 9 percent decrease in multiband resolution if the radial resolution should increase to 80 cycles/mm at a semifield angle of 26°.

UNIFORMITY OF IMAGE PLANE IRRADIANCE

Uniformity in image plane spectral irradiance is desirable in multiband photography to ensure high tonal fidelity across each frame. The increased atmospheric path associated with angles off axis will modify the image plane irradiance. This varies according to conditions, and it is preferable to use a system of good uniformity which, for wide angle lenses, necessitates the use of an antivignetting filter.

In several instances the exposure times in the various channels of a multiband camera array have been adjusted by changing the f-number rather than the shutter time. This is an incorrect procedure because the uniformity in image plane irradiance is strongly affected by the f-number for most lenses. The average

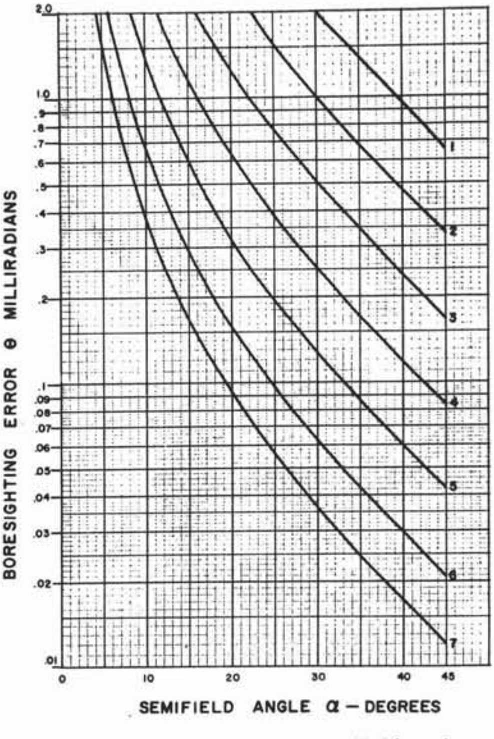

FIG. 2. Boresighting error *vs* semifield angle.

$f/2.8$ photographic lens, for example, exhibits vignetting at the low f-numbers, and it is not until the lens is stopped down to about $f/8$ that the image plane irradiance assumes a falloff of approximately $\cos^4 \alpha$. In many multiband applications it may be worthwhile to suffer some image motion by operating at a modest f-number on all lens rather than to avoid image motion by using the lower f-numbers on some of the lenses.

SHUTTER REPEATABILITY

One of the worst problems encountered in quantitative multiband work is shutter repeatability. Focal plane and leaf shutters, by their action, not only can affect uniformity of image plane irradiance but can give different exposures as a function of temperature and pressure. Worse still, these changes are usually not the same from shutter to shutter and, therefore, taking the ratio of the data from the various channels does not correct the error. The best solution is to use a continuously rotating disk-type shutter that is intrinsically more repeatable than the others and in addition is highly efficient.

With reference to processing, we can say that in a precision processing laboratory variations across the width or along a length of several meters of film should not exceed 0.02 density units, corresponding to 5 percent in exposure level. The tolerances on image plane uniformity of irradiance and shutter repeatability should be set with this value as a guide.

We have dealt only briefly with the requirements and tolerances of multiband cameras. More details can be found in Slater (1970), and we will turn now to some of the special systems that have been used or proposed for multiband work.

MULTIBAND CAMERA SYSTEMS

THE CAMERA FOR THE SO65 EXPERIMENT

The multiband camera used in the SO65 experiment was flown on the Apollo 9 flight of March 1969. It consisted of an array of four Hasselblad cameras (see Figure 3), attached during flight to the hatch window of the Command Module for Earth photography. Experiment SO65 took the first multiband pictures of Earth from space in the NASA program. The equipment was simple, and the components were not specially selected to give matched multiband data. Nevertheless, the results did show promise for the future of multiband photography from space; much credit belongs to Allen Grandfield and others at NASA/MSC who took advantage of the opportunity afforded by Apollo 9.

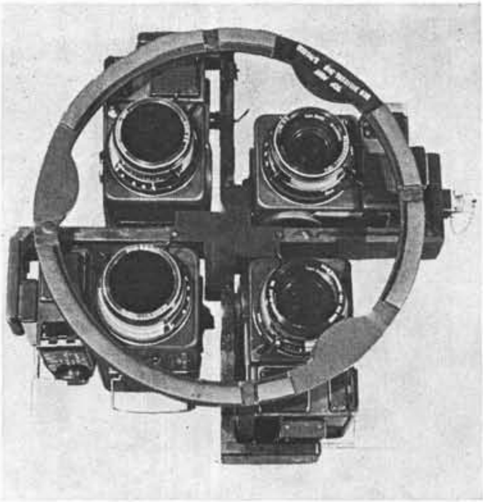

Fig. 3. The four-Hasselblad-camera array used in the SO65 experiment on Apollo 9.

The camera's historical significance and the fact that it represents a typical multiband camera assembled from off-the-shelf components make it worthwhile to list some of the camera data and performance figures (Tables 2, 3, and 4). In Table 4, note that the red (*DD* camera) and black-and-white IR (*CC* camera) are laboratory measurements of high-contrast standard Air Force targets. The ground resolution figures are derived from these assuming an average altitude of 200 km (108 n. mi.). The low-contrast resolution estimated from these is summarized in Table 5.

The uniformity of image plane irradiance as a function of field angle and f-number is shown in Figure 4 (see Cuneo, 1970). Further data on the SO65 multiband camera can be found in Keenan, Schowengerdt, and Slater (1970).

OPTICAL MULTIPLEXING

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 subcarriers 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. (See Mueller, 1969, for a detailed theoretical treatment of the method.) Here we describe

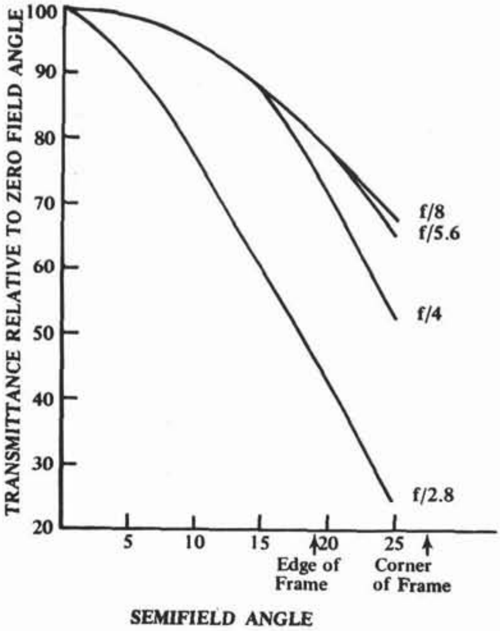

FIG. 4. Lens transmittance as a function of field angle for an 80-mm Zeiss planar lens at the indicated *f*-number. Note that the curve for *f*/8 follows the $\cos^4$ relationship.

TABLE 3. REGISTRATION ERRORS (CENTER TO CORNER OF FORMAT)

Type of Error	*Typical Magnitude of Error*	*Resulting Image Height Error μm*
Chromatic variation in focal length	500 μm	250
Chromatic variation in distortion	12 μm	12
Filter wedge	3 arc min	20
Film flatness	100 μm	50
Boresighting	1°	300

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. 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 Figure 5, where the original scene *A* is photographed on black-and-white film and is shown at *B* as modulated by the tricolor grating. The method used to obtain the color reconstruction of the scene is shown in the lower half of Figure 5. 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

TABLE 2. REFERENCE DATA FOR SO65 CAMERAS

Camera Designation	*AA*	*BB*	*CC*	*DD*
Wratten filter no.	15	58	89B	25A
"Color"	yellow	green	deep red	red
Film type	SO180	3400	SO246	3400
(Eastman Kodak)	ir color	Panatomic-X	ir B&W	Panatomic-X
Focal length (mm)*	80	80	80	80
f-number*	8	4	16	4
Shutter speed (sec)*	1/250	1/125	1/250	1/250
Focus setting (ft)	50	∞	30	∞
Camera serial no.	1026	1030	1041	1043
Lens serial no.	4488988	4489010	4591824	4593432

* Nominal.

TABLE 4. RESOLUTION AT TARGET CONTRAST>100:1

Camera	*Focus Setting*	*Radial or Tangential*	*Semifield Angle* 0°	7.5°	15°	22.5°	*AWAR lp/mm*	*Ground Resolution m (ft)*
DD (red)	∞	R	67	75	41	40	51	50 (160)
		T	67	69	53	38		
CC(B&W ir)	33 ft	R	37	36	28	30	31	80 (270)
		T	37	35	31	26		

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. Similarly, the barn and sky will be reconstituted in red and blue.

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 true in the original scene. To reduce the saturation and at the same time 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.

TABLE 5. ESTIMATED LOW-CONTRAST RESOLUTION

Target Contrast	*Camera*	*Focus Setting*	*AWAR (lp/mm)*	*Ground Resolution m(ft)*
1.6:1	DD	∞	36	70 (230)
	CC	33 ft	20	125 (400)

We 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 (1971).

- 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 cycle/mm gratings yields a final resolving power of 28 cycles/mm. Higher frequency carriers will yield correspondingly higher frequency imagery. The best obtained so far is 53 cycle/mm AWAR using an 80 cycle/mm tricolor grating on 70 mm film.
- 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.
- The image reconstruction system, or viewer, is inefficient, as only the first order spectra are used. The image is not bright enough to permit viewing on a large projection screen. Sufficient brightness is available when the scene is viewed through an eyepiece.
- Tricolor gratings are now being stripped directly onto the emulsion. The advantage is that moving film FMC can now be used if necessary. The color gratings are dissolved off the film during processing. A modification to procedure has recently been described (Kurtz, Eisen, and Higgins, 1971) in which the carrier gratings are present in three color-sensitized layers of the film as preexposed latent images.

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 it for space and some airborne applications. Because it is a single-frame system, registration is no problem. TV analogs to optical multiplexing on film have been developed by Stanford Research Institute and RCA (Briel, 1969). In the TV application a single camera tube is used and, although

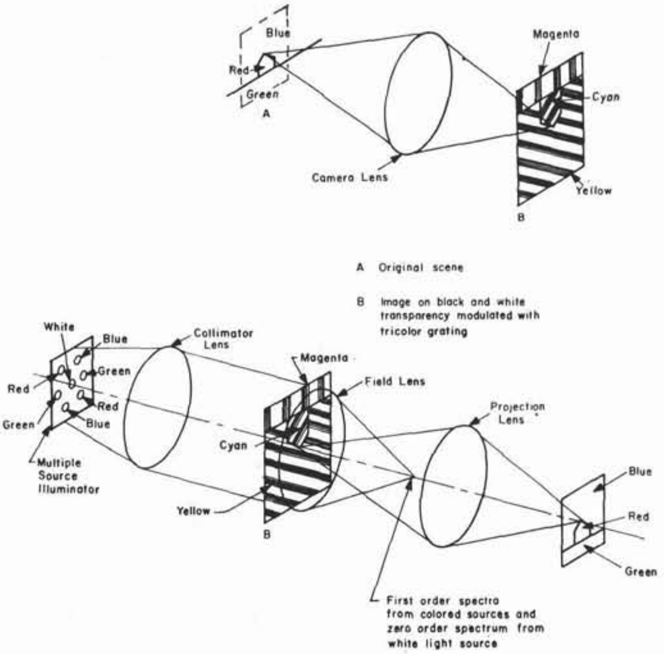

FIG. 5. Optical multiplexing as applied to multiband photography.

only low carrier frequencies (~10 cycles/mm) are available, further work at SRI is being conducted on systems of higher resolving power.

S190 SKYLAB MULTIBAND CAMERA

The Skylab multiband camera system, referred to as experiment S190, will be part of an Earth Resources experiment package scheduled for launch on Skylab in early 1973. An artist's concept of the camera is shown in Figure 6. The orbital inclination will be 50°. Some of the design specifications for the system are given in Table 6.

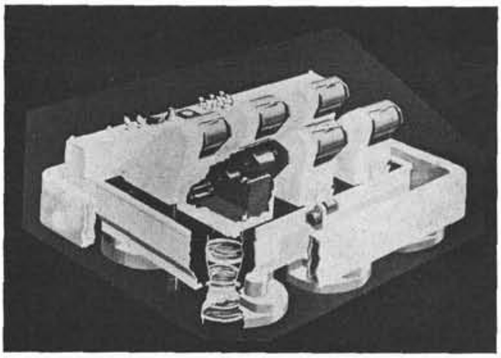

FIG. 6. Artist's concept of the Itek six-camera array to be used in the S190 experiment on Skylab.

The ground resolution values are the writer's estimates and are not part of the NASA specifications to which Itek is designing and constructing the S190 multiband camera. Some of the resolution data are based on the use of new films 3414 and SO-242, and it is probable that Kodak will have available films of improved resolving power to replace 2424 and 3443 by the time Skylab is launched. The lower resolution estimates for the IR bands are due largely to the poor resolving powers of 2424 and 3443 and not to the image-forming characteristics of the lenses.

The following should be noted in conjunction with the resolution data in Table 6:

- The data are based on the modulation transfer functions of the lens designs weighted over the filter passbands for a field angle of 0.7 full field, which approximates an area-weighted MTF over the entire format.
- A 10 percent decrease in modulation from the design data has been estimated to allow for fabrication and alignment errors and dynamic operation of the camera.
- A scene contrast ratio of 1.6:1 has been assumed for each band. As examples, this corresponds roughly to average plant *vs* dry loam in the band 500 to 600 nm and average plant *vs* shadow in the band 600 to 700 nm as seen from Earth orbit.
- The resolution values are for conventional three-bar targets as described in Military Standard 150A.

The S190 multiband camera for Skylab represents an important advance in multiband camera design and manufacture. The specifications for the camera in terms of shutter accuracy and repeatability, uniformity of image plane irradiance, and filter bandpass shape ensure a system that will provide highly reproducible relative spectroradiometric data over four nonoverlapping spectral bands. Moreover, this system will show substantial improvements over earlier multiband cameras in registration accuracy, angular resolution, and photogrammetric accuracy. In regard to the latter, before each exposure the film in the six film planes will be pressed against glass platens that constitute the last element of each lens. On the platens will be a reseau grid consisting of an array of nine crosshair marks that will enable the location of the principal point of a photograph to be determined to within 5 μm. The reseau will also serve to calibrate any distortion of the film that may occur after exposure. The design data show that the lenses are essentially distortionless, for the value of 0.01 percent quoted in Table 6 is an allowance for errors introduced during fabrication and alignment. Thus, the S190 multiband camera system will be of the highest photogrammetric quality, facilitating the production of maps from the multiband photography obtained.

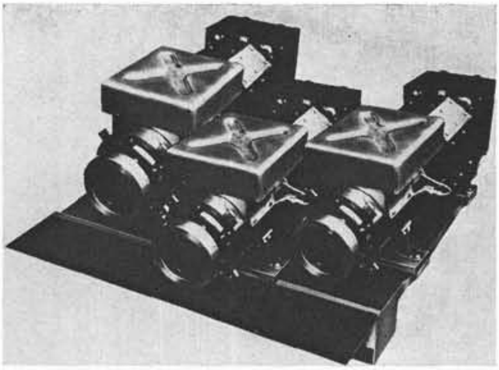

FIG. 7. The three-return-beam vidicon camera to be used on the Earth Resources Technology Satellite.

TABLE 6. DESIGN SPECIFICATIONS FOR S190 MULTIBAND CAMERA FOR SKYLAB

Area imaged	150×150 km from 435 km altitude
f-number (minimum)	2.8
Focal length	150 mm
Film width	70 mm
Base thickness	60 μm or 100 μm
Image distortion	0.01%
Registration	All bands registered to <12 μm
Image plane irradiance	Uniformity better than ±8% including any vignetting effects
Boresighting	Optical axes all fall within a cone of 1 arc min full angle
Repetition rate	1 frame per 2 sec
Stop openings	Waterhouse stops at ½ stop increments from *f*/2.8 to *f*/16 accurate to ±1.5%
Forward motion compensation	Error 5%
Shutter speeds	2.5, 5, and 10 ms accurate to 5% with ±2.5% repeatability. Six shutters synchronized to 4 ms.

*Wavelength Bands (nm)**	*Film Number*	*Ground Resolution in m/line pair***
500–600	3414	20
600–700	3414	20
700–800	2424	110
800–900	2424	110
500–880	3443	95
400–700	SO-242	30

* Six other filters will be provided for selecting different wavelength bands in addition to those specified here.

** Writer's estimates; not part of NASA specifications.

RETURN-BEAM VIDICON CAMERA

Plans call for a three-return-beam vidicon (RBV) multiband camera to be flown unmanned on an Earth Resources Technology Satellite in 1972 in a sun-synchronous nearly polar orbit. Figure 7 is a photo of the camera. Table 7 lists the design specifications for the camera system, and Table 8 indicates the resolution of the system for various scene contrasts, most of which can be found in NASA (1970).

The three boresighted cameras, aimed at nadir, will be exposed simultaneously and read out serially. The video signals from the cameras will be recorded on magnetic tape at ground stations where processed tapes and hard-copy reproductions will be produced with annotations to identify the time and location of the photography. Selected sets of images will be processed to correct for geometrical errors and allow for improved multiband registration.

The RBV development work and the design and construction of the ERTS multiband

TABLE 7. DESIGN SPECIFICATIONS FOR MULTISPECTRAL TV CAMERA SYSTEM (RBV)

Spectral Bands	*475–575 nm*	*580–680 nm*	*690–830 nm*
f-number (minimum for lens)	2.8	2.8	2.8
Focal length	126 mm	126 mm	126 mm
Image distortion (max)	1%	1%	1%
Size and centering change (absolute max)	2%	2%	2%
Picture overlap along track	10%	10%	10%
Field of view (diagonal)	16.2°	16.2°	16.2°
Gray scale ($\sqrt{2}$ steps)	10	10	8
Signal-to-noise ratio	33 dB	33 dB	35 dB

Area imaged: 185×185 km at 920 km alt (100×100 n. mi. at 496 n. mi. alt)

camera are being carried out by RCA. ERTS constitutes an important step in multiband photography, as for the first time we will obtain near-global coverage with repeat coverage over the same region in this country every 18 days.

INTENSIFIER-VIDICON STORAGE TUBE CAMERA

For rapid sequence photography, a frame camera should be judged on the product

$$(\text{resolving power})^2 \times \text{frame area} \times \text{cycle time}.$$

The first two terms are higher for the RBV than for other vidicons. This is more than offset by the slow cycle time owing to photoconductor lag. Thus, one RBV with, say, a rapidly rotating filter wheel, cannot be used because of the long image lag of the photoconductor used in the RBV. In the ERTS system three RBV's are required, which introduce errors in boresighting, matched distortion properties, and uniformity of sensitivity across the photoconductive surfaces.

An alternative to the RBV approach is to use a short lag time, conventional vidicon, and collect and record more information by stepping a mirror in front of the camera to give ground coverage as shown in Figure 8. In this approach a rotating filter wheel and a single camera tube can be used, thus avoiding the problems of boresighting, distortion variations, and uniformity of sensitivities. The block diagram of such a system designed by Baker and Slater (1971) is shown in Figure 9.

Two additional features of the system are worth noting. First, the vidicon is preceded by a fiber optics coupled image intensifier which not only increases the sensitivity and thus reduces the sampling time of the system, but also acts as the shutter to the system. The advantage of an electrical over a mechanical shutter for long unattended space flight systems should be stressed. The second interesting feature is the way the rapidly sequenced images are stored for slower playback onto tape. Three storage tubes are used for this purpose. The advantage of the storage tube is that it is self-correcting for distortion because the read-out of the tube is deflected by the same electron optics as the read-in.

The intensifier-vidicon storage-tube camera has been tested in the laboratory under simulated Earth orbital conditions, and its performance has been up to expectations. It seems that this approach could equal the resolution performance of the RBV system over the same field of view (a longer focal length would be used than with the RBV) but without the losses in the multiband spatial resolution inherent in the three-RBV system.

IMAGE SPECTROPHOTOMETER

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 Figure 10. 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

TABLE 8. DESIGN SPECIFICATIONS FOR MULTISPECTRAL TV CAMERA SYSTEM RESOLVING POWER FOR TYPICAL SCENE OBJECTS AND LIGHTING

Band Targets:	*Average Ground Resolution, m/line pair* (m/TV line)*		
	475–575 nm	*580–680 nm*	*690–830 nm*
High contrast (laboratory)	130 (45)	130 (45)	140 (50)
Desert sand vs shadow	140 (50)	140 (50)	170 (60)
Average plant vs wet loam	∞ (∞)	185 (65)	240 (85)
Average plant vs dry loam	155 (55)	140 (50)	240 (85)
Average plant vs water	240 (85)	230 (80)	170 (60)
Average plant vs shadow	170 (60)	185 (65)	170 (60)

* Assuming a Kell factor of $1/\sqrt{2}$ for the return beam vidicon (RBV).

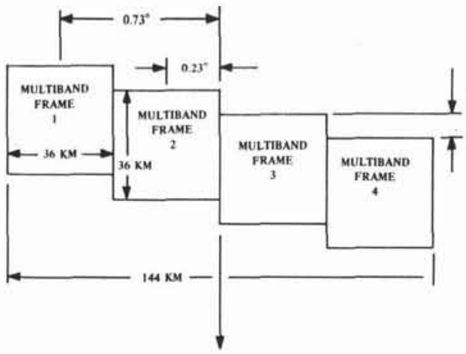

FIG. 8. Ground coverage.

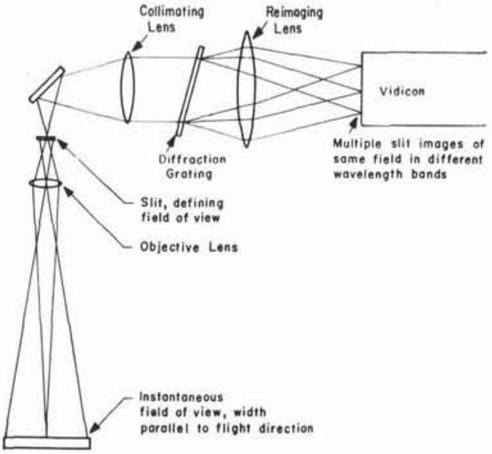

FIG. 10. "Wide-range image spectrophotometer" (WISP) as described by TRW Systems Group.

the fact that it contains no 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.

IMAGE DISSECTOR CAMERA

The principle of the image dissector camera is similar to that of the strip camera insofar as it produces a continuous record of the ground scene by virtue of the forward motion of the camera carrier. In the multiband image dissector camera, filter strips are laid over an array of fixed scan slits aligned perpendicular to the forward motion and in the plane of the aerial image, as shown in Figure 11. Each scan slit is followed by an electron multiplier, thus providing three simultaneous output signals of different portions of the image formed by the camera optics. The advantage over a three-image-dissector system is that the same focus-deflection coil is used for all the slits. Thus the scans have identical lengths and linearities, and their separation, determined by the separation of the slits, is constant.

Because an image dissector comprises a photomultiplier preceded by scanning electron optics, it has the basic advantages of a photomultiplier of high sensitivity and wide linear dynamic range. It is unlike vidicons, for example, in that image motion and image lag are not problems. The sensitivity range is from 300 to 950 nm, and it is as suitable for precision radiometry as an ordinary photomultiplier. Because the geometry of the

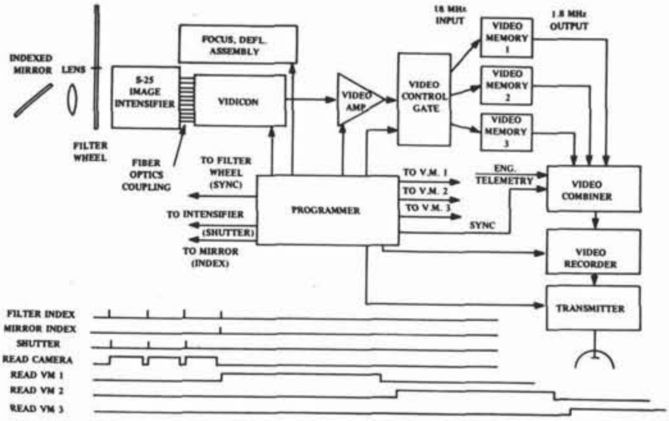

FIG. 9. Electro-optical multiband imaging system.

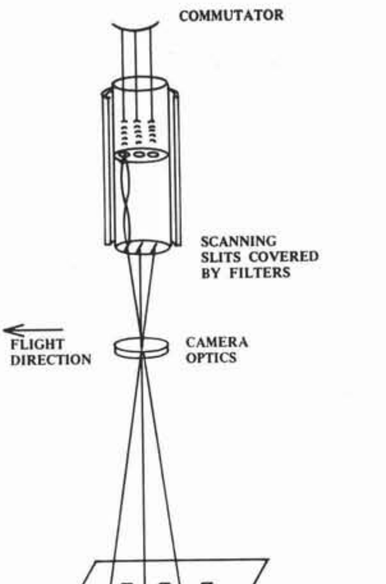

FIG. 11. Image-dissector camera.

system is fixed and nonlinearities are the same for each band, the system is well suited for multiband work. A disadvantage is that it has a wavelength cutoff at 950 nm, and there seems to be little hope of extending the sensitivity of photocathodes appreciably beyond this point. A second disadvantage is that, unlike the photoconductor of a vidicon, the photocathode is nonintegrating; therefore, extremely fast fore optics have to be used to get an adequate S/N.

To give an example of performance, assume the camera is at an altitude of 12 km (40,000 ft) flying with a ground speed of 740 km/hr (400 knots). Using a 100-mm focal length T/1.2 lens, the camera images a strip of terrain 5.3 km (17,500 ft) wide. If a slit 150 μm wide is used, the instantaneous field of view beneath the aircraft will be 2 m. The camera would operate at a scan rate of 110 scans/sec, and a video bandwidth of about 190 kHz would be required for each channel. If spectral passbands in the visible and near-ir of about 100 nm width are used, then the ground resolution would be approximately 2 to 3 m/line depending on ground contrast. In optical terms the resolution would be approximately 6 to 9 m/cycle.

ITT, Fort Wayne, has developed a multiband image dissector and tested it under simulated flight conditions in the laboratory with considerable success.

SOLID-STATE ARRAYS

The use of solid-state arrays in place of film may prove to be a major milestone in the development of aerial and space cameras. The resolving power of present arrays (such as are now under development at Fairchild Space and Defense Systems) is stated to be on the order of 20 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 photodiodes have a more useful wavelength range for most multiband purposes than vidicons, which cut off in the infrared at about 850 nm. They also have high reliability and extended useful life since neither cathodes nor mechanical scanners are involved. In comparison with vidicons, silicon photodiodes have a higher *low light sensitivity* (better S/N) due to the high quantum efficiency of silicon plus the storage mode of operation employing many sensors. Because the photodiodes are fixed, a solid-state-array camera has greater mensuration accuracy than a vidicon camera, and registration errors can be minimized. In spite of its continuous strip operation, it can be used for mapping purposes even though there may

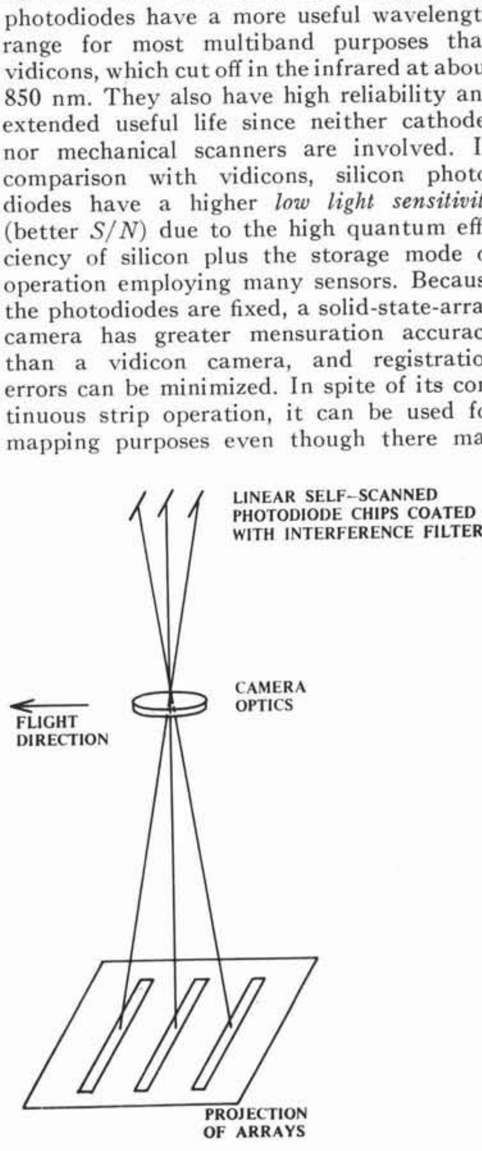

FIG. 12. Solid-state array camera.

be significant attitude rates. Short arrays fore and aft of the main array can be used to determine the required correction.

A diode array can consist of several monolithic silicon chips butted together. Typically a chip contains 256 microphotodiodes located linearly with a spacing between centers of 25 μm, as well as a monolithic MOS shift register for sequentially addressing the photodiodes. The sequential addressing enables bussing of the diode outputs into two video output lines, one for the even-numbered and one for the odd-numbered diodes. The photodiodes and shift register are contained in the same chip, resulting in only six external connections for each chip of 256 photodiodes. Fairchild has successfully developed an arrangement whereby adjacent chips are staggered in a bilinear array. For space applications their output could be linearized at signal-receiving ground stations, and the effect of the discontinuity caused by butting two chips together could thus be eliminated.

A camera using a solid state array (see Figure 12) operates in a manner analogous to that of a conventional strip camera; that is, the image is scanned across the array by virtue of the forward motion of the camera carrier. At present, photodiodes are about 25 μm apart as mentioned earlier; however, there are developments in progress that indicate that this may soon be reduced to 20 or 15 μm for production quantities. Although this separation limits the packing density, there is no theoretical limit to the number of chips that can be used in a bilinear array. Thus, arrays containing the equivalent of 50,000 to 100,000 TV lines are a possibility for the future.

CONCLUSIONS

Many of the above electro-optical multiband cameras are in a developmental stage, and it is therefore inappropriate to attempt a detailed comparison. We can, however, emphasize the fact that the solid state array is essentially unidimensional and can be of any length. Vidicons and image dissectors, however, are limited to an active diameter of about 10 cm by the size of the photosensitive area that can be produced. Should a significant advance in technology permit much larger photoconductors and photocathodes to be manufactured, then the corresponding increase in the volume of the device, the additional size of the deflection coils, and the greater power requirements will become major considerations. Recent developments of charge-coupled devices (Boyle and Smith, 1971) with their low power requirements and their high sensitivity, packing density, and yield, may well result in a revolution in the future of aerial and space photography techniques.

The conventional frame film camera is likely to maintain its pre-eminent position for precision mapping work, and whenever available volume requires a system of the highest information packing density the choice is among frame, panoramic, and strip *film* cameras. For the next few years electro-optical cameras are not likely to challenge film cameras for *routine* aerial photography applications.

An important feature of multiband continuous-strip photography, whether recorded by film, solid-state array, image dissector, or multiline (as distinct from frame) recording vidicon, is that the instantaneous field of view is unidimensional rather than two-dimensional as it is in frame photography. Thus, for a given angle on one side of nadir, the sun-target-camera angle is nearly constant along the length of the imagery, provided the flight line is straight and changes in altitude are small. The main variation that may occur is due to a change in solar altitude, but unless the flight line is very long, as it can be from orbit, the variation is usually small. The substantial advantage is obvious in the analysis of multiband photography in minimizing variations in the sun-target-camera angle.

For global multiband photography from Earth orbit, there is a strong argument favoring the use of both film and electro-optical cameras. Although the film camera has many advantages, it suffers the drawback of delay in data return. This can be overcome, at the cost of system simplicity, by the use of inflight processing, scanning, and telemetry to ground stations. Alternatively, exposed film can be returned to Earth at intervals in pods that are detached from the spacecraft. In the former case a limitation is imposed by the bandwidth of the telemetry, and in both instances the amount of film that can be carried is a limiting factor. In any event, the prudent use of film seems to be indicated. The use of an electro-optical camera to obtain a continuous record of both good and marginal quality imagery in real time can be of immediate value for interpretation purposes, and it can be monitored by ground-based scientists to determine when to turn the film camera on and off. The higher quality film data could then be analyzed at a later time, and the available film could be conserved for critical work. We conclude that for space applications—and these may include the multiband photography of other planets—film and electro-optical cameras are complementary rather than duplicative or competitive.

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