R. WELCH
University of Georgia
Athens, Georgia 30601

Quality and Applications of Aerospace Imagery

Sufficient planimetric detail for 1:24,000-scale maps can be compiled from photographs at 1:400,000 scale, or even smaller.

(*Abstract on page 380*)

INTRODUCTION

MODERN PHOTOGRAMMETRIC cameras manufactured by Wild and Zeiss have been installed in aircraft such as the Lear Jet and NASA RB-57 to obtain photographs at altitudes of 11–18 km for photomapping, aerotriangulation, and experimental studies in the earth sciences which may permit a more objective assessment of the potential of the forthcoming Earth Resources Technology Satellite (ERTS-A) and SKYLAB missions. In addition to this work, photogrammetric camera systems (f = 15–30 cm) are being considered for use in aircraft (such as the U-2) at altitudes of 21 km or greater and in spacecraft at orbital altitudes of 180–300 km (Subcommittee Report, 1969).

High-altitude aerial photographs may permit the compilation of topographic and photomaps at scales as large as 1:24,000, and space photos may be suitable for maps in the range 1:1,000,000 to 1:250,000 or larger and for the establishment of supplemental control for topographic maps at scales of 1:24,000 to 1:50,000. Because of their higher resolution capabilities, reconnaissance cameras of longer focal lengths such as panoramic (Itek Optical Bar, $f = 61$ cm) and narrow-angle frame systems (Actron ETC*, $f = 46$ cm) may be employed in spacecraft with metric cameras in an attempt to provide photographs with the detail required for compilation of maps at 1:24,000 scale. Several possible aerospace systems are listed in Table 1.

The feasibility of performing these tasks is determined by geometry, spectral relationships and image quality. Geometry has been considered by Schmid (1964), Case (1967), Colvocoresses (1970), Karren (1970), Petrie (1970) and McEwen (1971) for the various types of camera systems and the multispectral approach has been much discussed (*Manual of Color Aerial Photography*, 1968). Considerations of image quality as related to environmental studies and photogrammetric applications, however, have been limited (Welch, 1971a).

To examine the potential imaging characteristics of the various systems and their relationship to photointerpretation, photogrammetry, or environmental studies, it is essential to determine a reference standard for comparisons. For photogrammetrists and earth scientists, an excellent reference standard is the mapping camera of 23 cm square format, with a focal length of 15 or 30 cm. The familiar concepts of resolving power, detectability, and measurability of small detail are suggested as appropriate measures of image quality in the applications being considered.

AEROSPACE PHOTOGRAPHY

In this discussion two general types of photographic platforms will be assumed: a jet aircraft operating at a nominal altitude of 21 km and a speed of 925 km/h, and a spacecraft at 230 km travelling 27,000 km/h (Widger, 1966). Assumed environmental parameters will include a solar altitude of 45 degrees or higher and clear atmospheric conditions (light to normal haze). Based on these parameters, estimated exposure data for representative photogrammetric camera systems, such as the Wild RC8 (or RC10) or Zeiss RMK A 30/23, are given in Table 2. A third metric camera, $f = 30$ cm, $f/4$, with shutter speeds to 1/3,000 sec, is also listed although it does not correspond exactly to any currently marketed camera. These cameras

* Actron (formerly Hycon) has modified the KA74 camera for use in SKYLAB. This camera has been designated as the Earth Terrain Camera, ETC.

ABSTRACT: *Experiments with laboratory and aerial photographs in combination with theoretical considerations have compared the imaging characteristics of photogrammetric camera systems with those of reconnaissance, multispectral, and return-beam-vidicon systems considered for aerospace use. From these experiments it is estimated that photogrammetric cameras in combination with high-quality reconnaissance films will provide high-altitude aerial photography with image qualities comparable to those obtained with reconnaissance and multispectral systems. It also seems possible to use currently available photogrammetric camera systems in place of reconnaissance systems to obtain space photographs of good quality at about 1:380,000 scale. These photographs would be suitable for the compilation of planimetric maps to 1:24,000 scale if adequate viewing magnification is available in the plotting instrument. Furthermore, such photographs could also be used to establish supplemental control, to produce photomaps and to make reasonably detailed studies of earth resources. The economic benefits of using smaller-scale imagery for mapping tasks include the replacement of several older plotting machines by one precision mechanical-projection or analytical instrument of greater versatility and accuracy. Detailed earth resources studies are feasible with improved high-altitude aerial photographs, particularly if better color-infrared films can be manufactured. The small-scale space imagery to be produced by the ERTS-A system will be useful for very generalized regional studies of earth resources. SKYLAB experiments are planned to provide multispectral and high-resolution photographs useful for both resource studies and photomapping; however, the inclusion of a metric camera in SKYLAB would greatly enhance its value to the cartographer.*

are not equipped with image-motion compensation, although the Fairchild KC-6A photogrammetric camera built to military specifications does have this compensation. Other camera systems listed in Table 1 have larger apertures and permit image motion compensation. Consequently, they can generally use any of the films mentioned.

Before the selected measures of image quality can be considered, the effects of the lens, filter, shutter, image motion, film, and atmosphere on aerospace photography must be discussed. Most of these factors can be individually characterized by modulation transfer functions and approximately related to limiting resolving power; however, their effect on detectability and measurability cannot be simply described on a theoretical

TABLE 1. POTENTIAL EARTH SATELLITE CAMERA SYSTEMS

Mission	*Altitude (km)*	*System*	*Scale*	*Film or Tube Size (mm)*
ERTS A	910	RBV, 12.5 cm, CRT	1:7,300,000	25
SKYLAB	435	Itek, 15 cm, f/2.8 3414 or 3400, SO-242, 3443, 2424	1:2,900,000	70
		Hctron ETC, 46 cm, f/4, 3400, 3414, SO-242	1:945,000	125
Recommended	230 (est.)	Itek Panoramic, 61 cm, f/3.5, 3400 or 3414	1:380,000	125
		Metric, 30 cm, f/4 (or f/5.6), 3400	1:750,000	230

TABLE 2. ESTIMATED EXPOSURE DATA (Kodak Aerial Exposure Computer)[1]

Camera	*Aperture*	*Film*	*Shutter*[2]	*Image Motion (space)*	*Image Motion (air)*
Wild RC 8 (RC 10)	f/8	2402/2424	1/700 sec	8 μm	4 μm
	f/5.6	3443	1/700	8	4
	f/5.6	3400	1/500	10	4
	f/5.6	SO-242 (no filter)	1/150	33	11
	f/5.6	3414	1/60[3]	84	28
Zeiss RMK A 30/23	f/8	2402/2424	1/1000	10	4
	f/5.6	3443	1/800	12	4
	f/5.6	3400	1/700	14	4
	f/5.6	SO-242 (no filter)	1/150	67	22
	f/5.6	3414	1/100	100	32
Metric (f=30 cm)	f/8	2402/2424	1/2000	5	4
	f/4	3443	1/1600	7	4
	f/4	3400	1/1400	8	4
	f/4	SO-242 (no filter)	1/300	33	11
	f/4	3414	1/200	51	17

[1] Solar altitude of 45 degrees or higher, normal haze. Orbital altitude (space) taken as 230 km with approximate speed of 27,000 km/h. Flying height (air) taken as 21 km with approximate speed of 925 km/h.

[2] Factors for filters such as the Wratten 12, 15 or 25 and *antivignetting* (Wild) taken into account.

[3] Shutter inoperable at this speed.

basis. Instead, an approach which combines both theoretical calculations and empirical measurements has proved to be most useful in assessing image quality (Welch, 1969b), and this is the approach taken here.

LENS, FILTER, SHUTTER, IMAGE MOTION

Figure 1 displays the modulation transfer functions (MTF) for several camera lenses, including the Wild Universal Aviogon (*f*/5.6 and *f*/8) and Zeiss Topar A (*f*/5.6) with minus-blue filters having a cutoff at 500 nm, an Itek Petzval (*f*/3.5) lens with Wratten 23A filter (Short and Turpin, 1969), and a diffraction-limited *f*/2.8 lens similar to that planned for the multispectral (MS) facility on SKYLAB. The MTF for the return-beam-vidicon (RBV) camera *system* to be used in ERTS-A is also shown (Weinstein, Miller, and Barletta, 1971). With the exception of the ERTS RBV system, all the MTF's have been degraded for about 4 μm of uncompensated image motion ($(\sin x)/x$ function). This correction includes the effects of vibrations, shutter action, and possible small errors of focus. A similar value has been mentioned by Kinney (1971) and although it will vary between camera systems, deviations of 3 to 4 μm from the assumed 4 μm value will not substantially affect the image quality of the photogrammetric systems and will be only a marginal factor with the other camera systems. Of course the lens MTF's will vary according to the filter, angular distance off-axis, and target orientation. Only the axial position and optimum filter combinations are shown. For translational image motions greater than 4 μm a further $(\sin x)/x$ function must be applied (see Scott, 1959).

FILMS*

Film characteristics such as speed, resolving power, and granularity are given in Eastman Kodak Publication M-57 (1970), and film MTF's are available from various Kodak publications (M-29, M-45, M-58, M-69, M-73). Although these characteristics

* The films primarily discussed include Eastman Kodak 3414, SO-242, 3400, 2402, 3443 and 2424. 3414 type films include 3404 and SO-243. 3443 (color-infrared) has imaging properties similar to those of SO-180, SO-117 and 8443. SO-242 (high-resolution color) replaces SO-121.

are extremely useful for selecting a film for a particular task, they do not indicate the photographic quality that can be expected as a result of the interaction of these characteristics with those of the lens system, the environmental parameters, and the human observer.

This problem has been partially overcome through the use of Threshold Modulation (TM) curves or 3-bar detectability curves which encompass the effects of target contrast, film granularity, MTF, gamma, resolving power, and the human observer to provide a graphical plot of contrast (modulation) against resolving power (Brock, Harvey, Kohler, and Myskowski, 1966; Scott, 1966, Lauroesch et al., 1970). Unfortunately, TM curves for aerial films have not been published by the manufacturers and consequently are not generally available for system studies. However, experience with photogrammetric cameras and small-format cameras having lens characteristics similar to those of the very-narrow-angle cameras (Itek, Actron) indicates that modified TM curves applicable to operational exposures can be obtained by

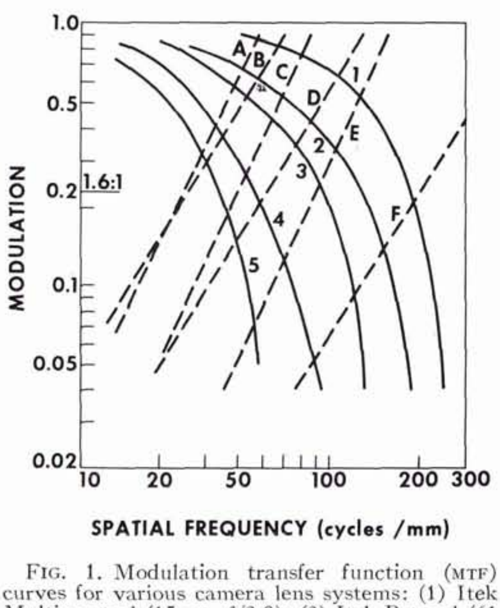

FIG. 1. Modulation transfer function (MTF) curves for various camera lens systems: (1) Itek Multispectral (15 cm, $f/2.8$); (2) Itek Petzval (61 cm, $f/3.5$, Wratten 23A filter); (3) Wild Universal Aviogon (15 cm, $f/8$) and Zeiss Topar A (30 cm, $f/5.6$) and minus-blue filters; (4) Wild Universal Aviogon (15 cm, $f/5.6$, 500 nm filter); (5) RBV/CRT system. Modified Threshold Modulation (TM) curves for films: (A) 3443, (B) 2424, (C) 2402, (D) 3400, (E) SO-242, (F) 3414. Except for the RBV system, the intersection points of the MTF and TM curves define the high-contrast system resolution.

taking approximately 80 percent of the manufacturer's listed film resolving power values at high contrast (1,000:1; 1.0 M) and low contrast (1.6:1, 0.23 M), plotting these values on log-log paper, and connecting the points with a straight line (Welch 1972). Modified TM curves of this type are shown intersecting the lens MTF's in Figure 1.

ATMOSPHERIC EFFECTS

Atmospheric turbulence and haze are often cited as factors limiting image quality. Data from Hufnagel (1965) and Hulett (1967) indicate, however, that turbulence in normal clear weather will not limit the resolution of photographs obtained with cameras of the focal lengths being discussed. Atmospheric haze and less-than-perfect transmission reduce the contrast of the ground scene and must be considered. Data from Boileau (1964) Brock, et al. (1966), and more recent studies by the author indicate that effective atmospheric luminances of 600 to 1,000 foot-lamberts can be expected at altitudes above 10 km in clear weather. An average transmission factor of 0.7 for vertically oriented minus-blue photographs can also be assumed. From tables indicating solar horizontal plane illuminance as a function of solar altitude, a value of 7,000 foot-candles is obtained for solar altitudes of 45 degrees. Measurements by Krinov (1947), Carman and Carruthers (1951), Brock (1952), and Welch (1969a) indicate that a background reflectance of 10 percent is a representative value. Using these values, the contrast in the aerial scene at the camera lens (Figure 2) can be estimated using the formula

$$Ca = \frac{I \cdot R_1 \cdot Ta + Ba}{I \cdot R_2 \cdot Ta + Ba} \text{ (Brock, et al, 1966)}$$

where Ca is aerial image contrast at the camera lens; I, the illuminance in foot-candles; R, the reflectance in percent; Ta, the atmospheric transmission; and Ba is the atmospheric luminance.

From Figure 2 it is evident the contrasts of the aerial scene in the visible spectrum are normally less than 1.6:1, a standard ratio for a low-contrast resolution target. If required, contrasts for the infrared portion of the spectrum can be computed in radiometric units. However, experimental measurements with high-altitude aerial photographs indicate that a maximum contrast of about 5:1 for the effective sensitivity range of panchromatic film (500–700 nm) is increased to

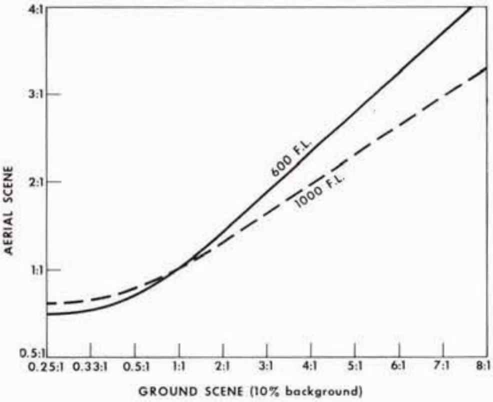

FIG. 2. Relationships between ground and aerial scene contrasts for atmospheric luminances of 600 and 1,000 foot-lamberts. Aerial image contrast is normally less than 1.6:1.

about 7:1 for the effective sensitivity range of color infrared (500–900 nm). Consequently, a 1.6:1 contrast ratio is still a reasonable value. The density differences in high-altitude aerial photographs on 2402 film developed to a gamma of 1.3 and SO-180 (a color-infrared film similar to 3443) developed to a gamma of 2.4 are shown for urban and natural terrain scenes in Figure 3. The higher gamma film accentuates the images of small low-contrast details, thus insuring that they are imaged above the visual threshold of the observer (0.02 to 0.04 M).

Resolving Power

In Figure 1, the intersection of the appropriate system MTF and modified TM curve determines the system resolving power for a high-contrast target. By translating the MTF

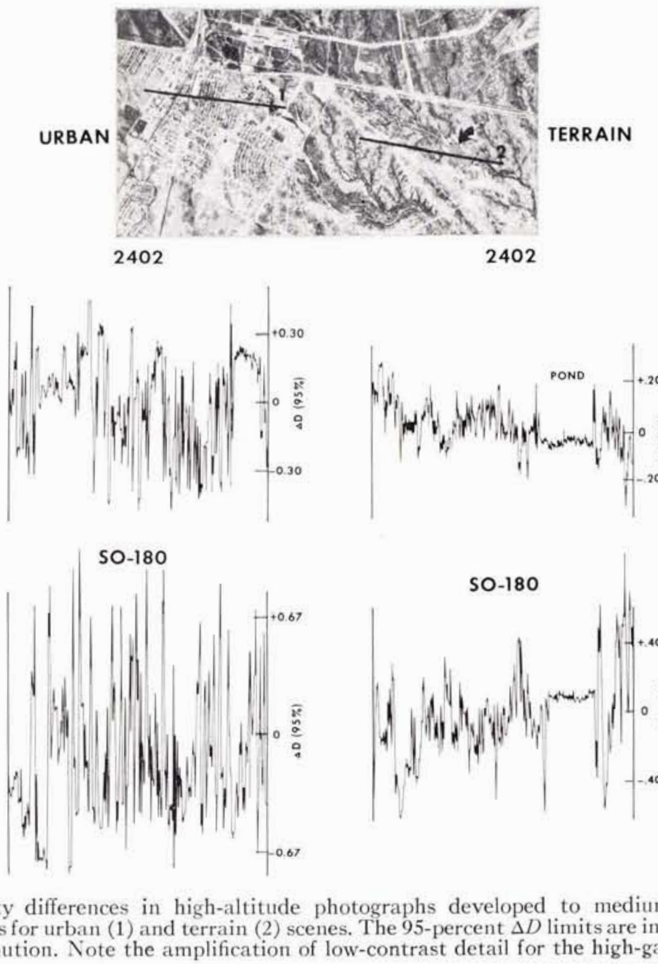

FIG. 3. Density differences in high-altitude photographs developed to medium (2402) and high (SO-180) gammas for urban (1) and terrain (2) scenes. The 95-percent ΔD limits are indicated for a normal frequency distribution. Note the amplification of low-contrast detail for the high-gamma color infrared photo (SO-180).

vertically downward through a series of target contrasts, a number of intersection points defining the system resolving power for corresponding target contrasts are obtained. These points upon being replotted on log-log paper with respect to contrast produce resolution functions indicating the relationship between target contrast and resolving power (Welch, 1972). In most instances these functions approximate a straight line (Figure 4). Predicted on-axis low-contrast (1.6:1 aerial image) resolutions derived from appropriate combinations of system transfer functions and film TM curves and rounded off to the nearest 5 l/mm are shown in Figure 5 for targets oriented both parallel and perpendicular to the flight path. The values for the Wild and Zeiss systems have been confirmed by visual measurements on aerial photographs obtained on several films, and it is assumed that the method is also valid for other camera systems.

The off-axis reduction in resolution depends on the film, relative aperture, lens aberrations and angular distance from the optical axis. Resolution levels for the Wild and Zeiss cameras remain high to about 15° off-axis. For example, under static conditions with high-resolution films such as 3414, photogrammetric cameras are capable of low-contrast resolutions of 80–100 l/mm on axis, whereas with films such as 2405 or 2402 a maximum resolution of about 40 l/mm is indicated. However, the maximum resolution under either laboratory or operational conditions may be about 25 l/mm at 30° off the axis for a wide-angle camera system regardless of the film employed. For a narrow-angle camera such as the Zeiss RMK A 30/23, the average maximum resolution obtained at 15° off-axis with a film similar to 3414 is about 60 l/mm. For the narrower field angle of the reconnaissance cameras, resolution variations due to lens aberrations are insignificant. However, high-resolution systems are very susceptible to degradations due to improper correction of image motion and errors in exposure and processing. Consequently, resolving power is more predictable with photogrammetric cameras. From Table 2 and Figure 5, it is evident that slow-speed, high-resolution reconnaissance films such as SO-242 and 3414 can be used in current photogrammetric cameras in high-altitude aircraft, but that image motion in space photography would cause unacceptable degradation. Higher resolution values could be obtained with 3400 film. As the infrared films, such as 2424 and 3443, have inherently low resolving power, correspondingly low-system resolution values can be expected regardless of the camera or operational mode (Figure 6). Figure 7 indicates ground resolution values as a function of scale for systems with resolving powers of 20, 35, 60 and 110 l/mm. Most of the systems discussed can be approximated by one of these values.

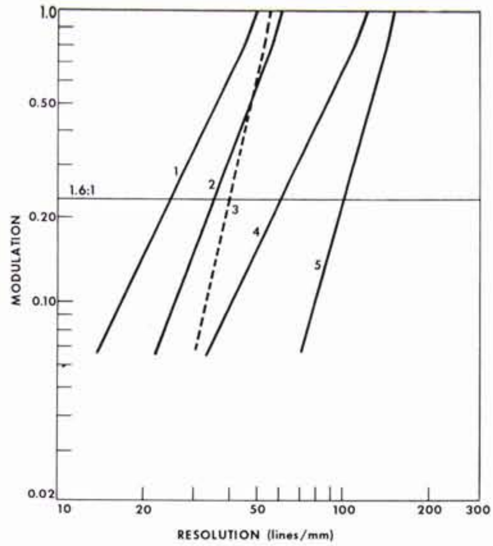

FIG. 4. Estimated resolution functions for selected camera systems: (1) Itek Multispectral, 3443 film, (2) Zeiss RMKA 30/23, 3400 film; (3) ERTS RBV (laboratory); (4) Itek Multispectral, 3400 film; (5) Reconnaissance (Itek panoramic and Hycon), 3414 film.

DETECTABILITY

The interpretability of a photograph is determined by an observer's ability both to detect and to identify small detail as recorded. Unfortunately it is extremely difficult to quantify the ability to identify an imaged object because of the many subjective factors involved. In comparison, the detectability of an imaged object at a known location can be evaluated simply (that is, the observer does or does not detect it), and statistics are readily accumulated. Consequently, detectability is a fairly unambiguous measure of image quality.

In considering detectability two classes of image detail are discussed: (1) symmetrical; and (2) linear. The detectability of symmetrical images such as squares and circles has been explored by MacDonald (1958) and Carman and Charman (1964) but relatively little information is related to modern photogrammetric camera systems (Welch,

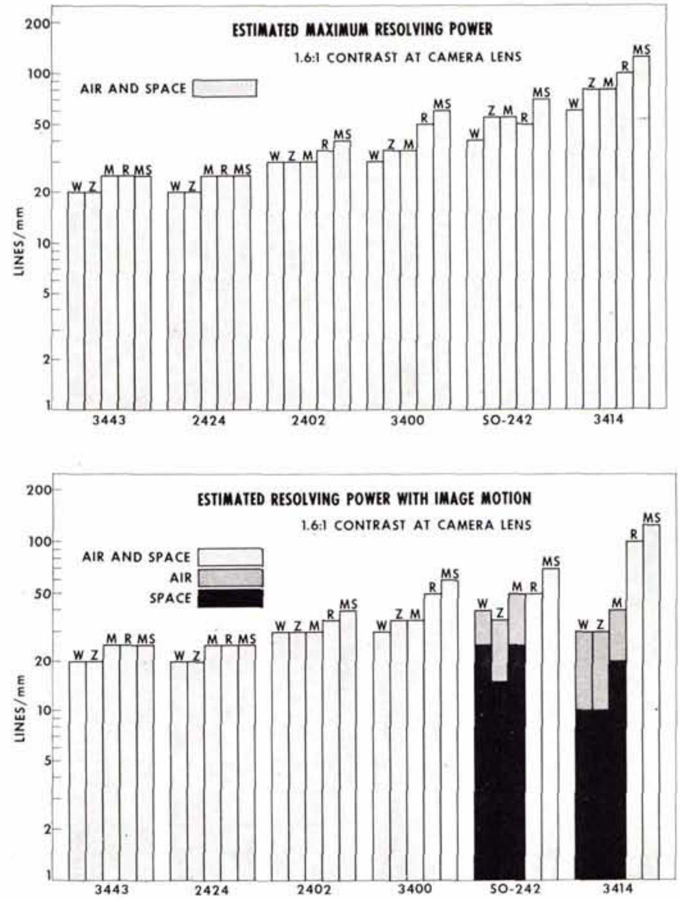

FIG. 5. Estimated resolving power (to nearest 5 l/mm) of various systems for targets of 1.6:1 contrast at the camera lens oriented parallel and perpendicular (image motion) to the flight line. Key: (*W*) Wild, (Z) Zeiss, $f=30$ cm; (*M*) Metric, $f=30$ cm, $f/4$; (*R*) Reconnaissance (Itek panoramic, $f=61$ cm, and Actron, $f=46$ cm); (MS) Itek Multispectral, $f=15$ cm.

1969b). Consequently, for this study, squares of decreasing size with a contrast of 1.6:1 at the camera lens were photographed under laboratory and controlled operational conditions with the Wild and Zeiss cameras. From visual evaluations of these photographs it is possible to estimate detectability thresholds (Table 3 and Figure 8). Although these values are generalized and may vary with different exposure and processing, they represent reasonable magnitudes for the cited cameras. Figure 9 indicates detectability as a function of scale.

From these experiments it is evident that, with the exception of a film such as 3414, the film rather than the lens determines the detectability of small objects imaged near the optical axis. Consequently, similar values can be expected for the reconnaissance and multispectral systems. For image locations 15° or more off-axis, the detectability threshold for the low-contrast squares was reduced to about 30 μm regardless of the type of film because of the effects of lens aberrations. The detectability of high-contrast squares, on the other hand, is considerably less affected by format position and the influence of lens aberrations; that is, the image is diffused but remains detectable. This is a reverse situation from resolution in which the *separation* between imaged lines of high contrast can be severely attenuated by small aberrations.

The detection of linear images (roads, railways, or pipelines) is sometimes cited as a measure of system performance. However, it is well known that the eye can integrate a series of image points which are individually

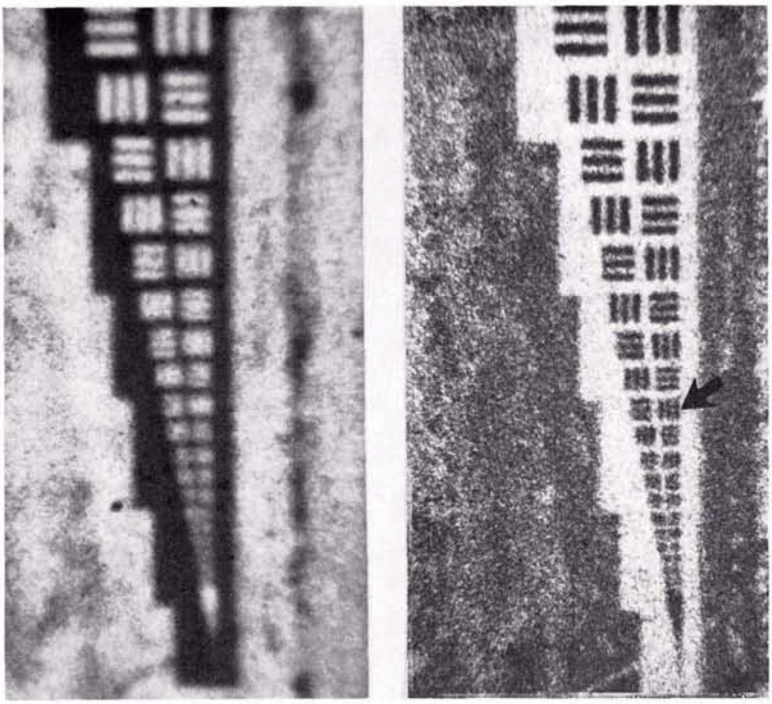

FIG. 6. Photomicrographs (40×) of medium-contrast resolution targets imaged on color infrared (SO-180) and panchromatic (2402) films at a scale of 1:24,000 with the Wild RC8. Arrow on 2402 photograph (right) indicates 40 l/mm resolution.

below the threshold of detection (because of granularity or some other factor) to detect a linear feature. Charman (1965) has discussed the relationship between resolving power and the detectability of linear detail. He concludes that the minimum detectable image line width is always less than that of the resolved distance and that, because of the interrelated actions of variables such as MTF, granularity, gamma, adjacency effects, target contrast, and the observer, a change in the resolving power by a factor of N does not change the minimum detectable linear width by $1/N$. Because of these factors, the detectability of linear objects is difficult to quantify. Brock (1967), however, has suggested that a single-bar response function derived from edge traces or system MTF's and the frequency spectra of bars of different widths uses objectively measured system parameters to provide a relationship between image bar width and contrast (exclusive of gamma) which has subjective meaning for the photogrammetrist. There are two problems with this

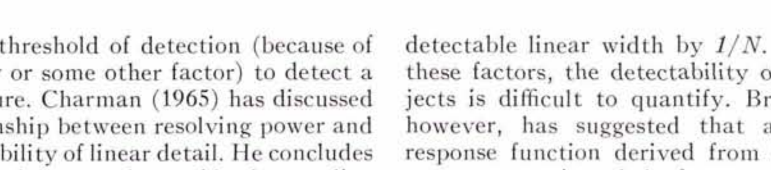

FIG. 7. Ground resolution as a function of photoscale for 20, 35, 60, and 110 l/mm.

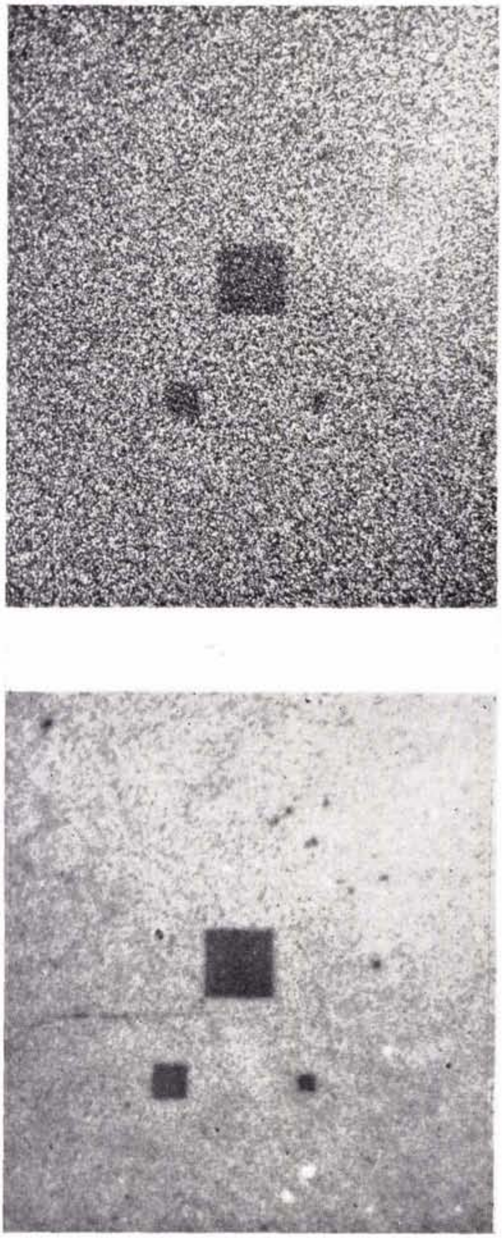

FIG. 8. Photomicrographs (60×) of low-contrast square targets imaged in the laboratory by the Wild RC8 camera system on 2402 (*top*) and 3414 type (*bottom*) films. The largest square represents a linear dimension of about 125μm and the third-largest square 30μm.

type of function: the difficulty in determining a practical threshold level, above which the linear image will be detected; and the effects of gamma, which amplify the contrast level in the developed image.

Because of interest in the ability to detect linear detail, single-bar response functions were developed from edge traces on high-altitude aerial photographs obtained under nearly identical conditions on different films with the Wild RC 8 camera. Similar functions were derived from laboratory photographs taken on a high-resolution reconnaissance film similar to 3414 with the Wild RC 8 camera system with Universal Aviogon lens and with the Itek Petzval *lens* (panoramic camera lens). These normalized functions are shown in Figure 10. The functions obtained for the Wild RC 8 aerial photographs, except those on films similar to 3443 and 3414, correspond at a response below 0.1, indicating that linear objects of about equal width will be detected although the edges of large images may seem to differ in sharpness.

TABLE 3. DETECTABILITY THRESHOLDS

Film	*Detectability Threshold (1.6:1)*
3414, SO-242	10 μm
3400, 2402	20
3443, 2424	30

The similarity of the single-bar response functions for the laboratory photographs taken with the Itek lens and Wild camera system on 3414 type films are of particular interest. For example, as with resolution, the photogrammetric-system produces results comparable with those of a reconnaissance system for images produced near the center of the photograph. However, due to the inability to correct for aberrations over wide angles and the limitations imposed by apertures of $f/5.6$ to $f/8$, the panoramic camera produces superior imagery throughout the photograph. If a photogrammetric camera with a lens of reasonably narrow angle (e.g., 56°, $f=30$ cm) is used with an aperture of $f/4$ or $f/3.5$ and high-resolution reconnaissance film, it would be difficult for an interpreter to distinguish with which camera the photographs were obtained.

Figure 11 illustrates detectable-bar-width functions based on a modulation detection threshold of 0.02 units and derived from the functions in Figure 10. It is estimated that low-contrast linear images of about 1, 2, and 4 μm width could be detected on the 3414/SO-242, 2402/3400 and 3443/2424 systems respectively. Visual evaluations of linear features imaged on high-altitude aerial photographs indicate that these values are reasonable for optimum exposure. However, single-

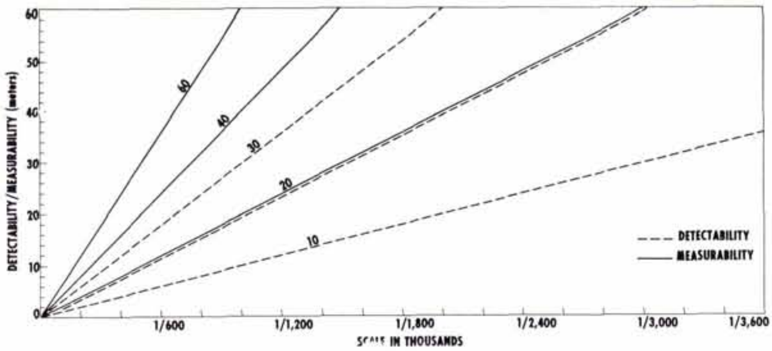

FIG. 9. Detectability/measurability thresholds for 10, 20, 30, 40, and 60 μm.

bar functions are most useful indicators if combined with other measures of image quality.

MEASURABILITY

The ability to measure small imaged objects reliably is of interest to scientists needing areal or linear dimensions and the contrast and size of images are particularly significant. To determine the effect of contrast on measurement error, original (negative or positive) high-altitude aerial photographs containing the images of resolution targets of various contrasts were selected. Monocomparator measurements (at a viewing magnification of 35–40×) were made along the edges of bar targets oriented parallel to the flight line and large enough to overcome the effects of the system spread functions (typically 1–2 l/mm). Straight lines were then fitted to each series of pointings by the method of least squares and the mean distance between the lines was computed to obtain the imaged width of the bars (Figure 12). The absolute measurement error is then the difference between the image and ground width (reduced by the correct scale factor). Precision of measurement is indicated by the standard errors after the least-squares fit. Figure 13 illustrates the relationships between measurement errors and density differences of images on aerial photographs taken

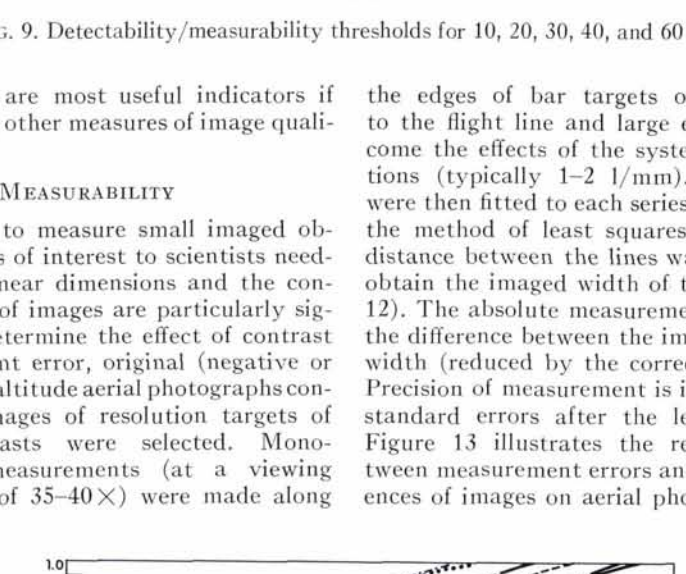

FIG. 10. Normalized single-bar response functions for laboratory photographs: (1) Itek Petzval, $f/3.5$, 3414 type film; (2) Wild RC8/Universal Aviogon system, $f/8$, 3414 type film. For aerial photographs with RC8/Universal Aviogon on (3) 2402 film at $f/8$; (4) 3400 film at $f/5.6$; (5) high-resolution color film (SO-121) at $f/5.6$; and (6) color infrared film (SO-180) at $f/5.6$.

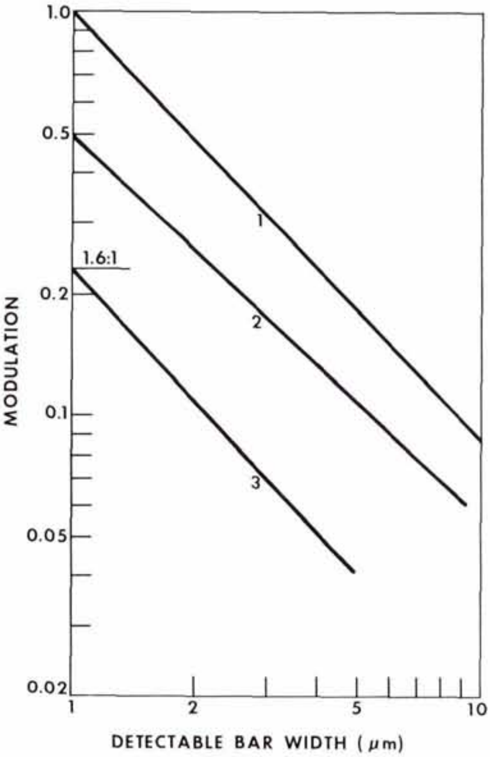

FIG. 11. Estimated detectable-bar-width functions for systems employing the following films: (1) infrared, 3443/2424; (2) panchromatic, 2402/3400; (3) high-resolution panchromatic and color, 3414/SO-242.

with the Wild and Zeiss cameras.

Target contrast, lens, film, exposure, gamma, and the comparator operator all contribute to the illustrated results. For example, with respect to contrast-exposure-gamma relationships, as the density extremes of an imaged bar approach the toe and shoulder of the *D*-log-*E* curve, image spread increases, and measurement errors rapidly reach a maximum; these factors account for errors that increase to the left in Figure 13. The errors that increase to the right are due largely to the operator's uncertainty in setting the index mark. For light or dark edges of less than 0.2 density difference, these errors increase rapidly. Most significantly, linear dimension errors of 3–7 μm can be expected for midrange density differences on panchromatic and high-resolution color films and approximately 15 μm on color-infrared. The precision of the pointings averages about 1.5 μm for midrange density differences, increasing to 3–4 μm for a ΔD of 0.1. As might be expected, precision is slightly poorer for the color-infrared films. Figure 13 implies the necessity for correct gamma and strict exposure control. On the basis of these data combined with laboratory data, the linear measurement errors to be expected with photographs properly exposed in photogrammetric or reconnaissance cameras equipped with well-corrected lenses are listed in Table 4.

The relationship of image size to measurability (Figure 14) was determined from measurements of the images of high-contrast bar

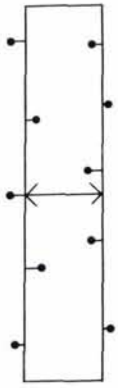

FIG. 12. Measurements of imaged bar.

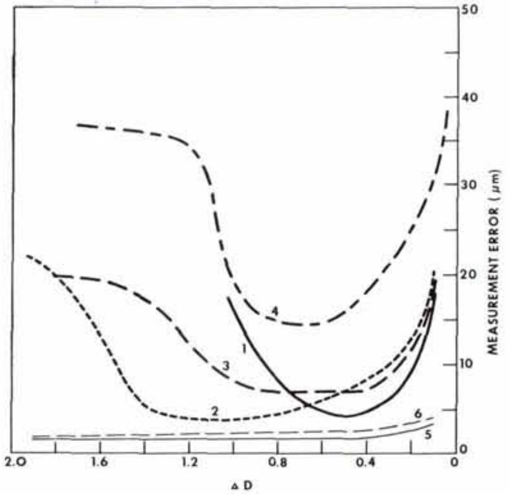

FIG. 13. Measurement error *vs* density differences (ΔD) for large bars of different contrasts on aerial photographs taken with Wild and Zeiss cameras: (1) panchromatic (2402), gamma 1.3: (2) panchromatic (3400), gamma 2.7; (3) high-resolution color (SO-121), gamma 2.4; (4) color-infrared (SO-180), gamma 2.4. The precision of pointing to target images is indicated for (5) panchromatic and color and (6) color-infrared. The shape of individual curves will change with different combinations of target contrast, exposure, and development.

TABLE 4. ESTIMATED LINEAR MEASUREMENT ERRORS

Film	*Measurement Error*
3414/SO-242/3400	3 μm
2402	5
3443/2424	15

targets of decreasing size. Here again, the errors of measurement are affected by contrast, exposure, gamma, and image density differences as well as target size. As might be expected with high-contrast targets, a medium-gamma film such as 2402 ($\gamma = 1.3$) produces the smallest errors. The decrease in error as the bar spacing is reduced occurs as the high and low densities come together on the linear portion of the *D*-log-*E* curve. For low-contrast targets the measurement error remains nearly constant or may even become greater as bar spacing decreases. The resolution limit to which the operator could measure on the panchromatic and color films was about 32 l/mm, despite observed resolutions of 40 and 60 l/mm.

For an additional determination of measurability, pointings were made to the edges of images of the graded-square targets mentioned under detectability. The point measurements were plotted at an enlarged scale using the IBM 360/65 computer and visual judgments made to determine the threshold image size required for reasonable linear measurements and correct shape of the imaged object (Figure 15). Generally, this threshold ranged from 1.5 to 2 times the size of the minimum detectable image. Estimates of measurability thresholds for the imaged squares are listed in Table 5. These values are shown plotted as a function of scale in Figure 9.

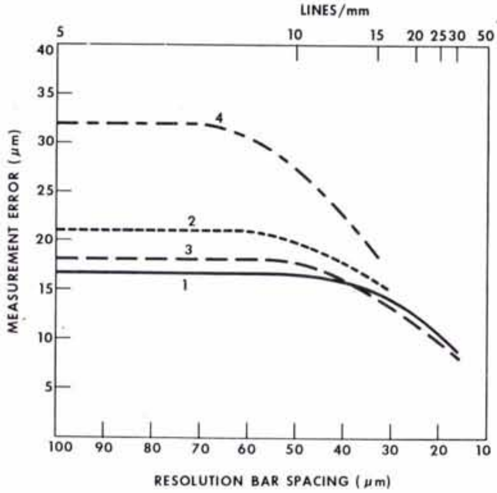

FIG. 14. Measurement error vs bar spacing for high-contrast targets. Data are same as given for Figure 13.

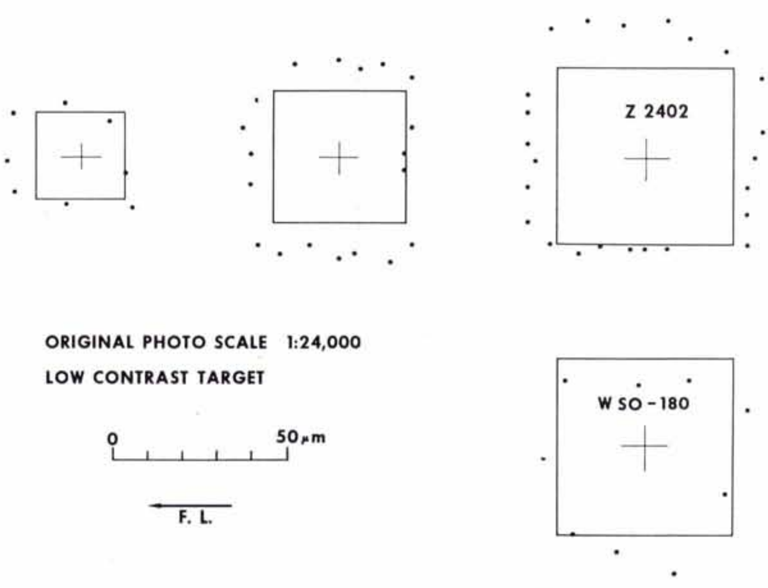

FIG. 15. Dots indicate comparator pointings to the edges of square targets imaged on panchromatic and color infrared films.

TABLE 5. MEASURABILITY THRESHOLDS OF IMAGED SQUARES

Film	*Measurability Threshold*
3414/SO-242	20 μm
3400/2402	40
3443/2424	60

It is interesting to note that the empirically determined measurability thresholds closely approximate the objectively determined bar widths required for maximum response (Figure 10). This indicates that image size must approximate the width of the system spread function to define object shape. Trinder (1971) discussed a similar relationship based on laboratory experiments for the determination of optimum target size.

IMAGE QUALITY RELATED TO PHOTOGRAMMETRIC MAPPING

Topographic maps at scales of 1:24,000 to 1:50,000 generally have been compiled from aerial photographs with scales larger than 1:50,000, although occasionally photoscales as small as 1:100,000 have been used (Pichlik, 1968). The reasons for relatively large photoscales include such limitations as aircraft ceiling, stereoplotter capabilities, and alleged inferior interpretability of small-scale photographs. However, the recent availability of suitable jet aircraft has nearly doubled the flight heights possible for civilian applications (to about 21 km). Modern stereoplotters have also been improved (Schermerhorn, 1968) and new analog instruments, such as the Wild A10, Kern PG3, Zeiss Planimat and Jena Stereotrigomat, are equipped for earth curvature corrections, coordinate readout to about 5 μm, and plotting enlargements to 45×. Schellens (1971) has reported that spot-heighting accuracies of about 0.1°/₀₀ (0.01 percent) of the flight height can be expected with photographs taken by current 15 cm or 30 cm focal-length cameras. Comparable values are reportedly obtained with analytical plotters (Chapelle, Whiteside, and Bybee, 1968). Consequently, contour intervals of 0.33°/₀₀ of the flight height probably will meet National Map Accuracy Standards (Figure 16). As these vertical accuracies are about double those claimed for older plotters and available flight heights have also been doubled, it seems that current standards for topographic mapping can be met with photographs at scales two or more times smaller than those now in common use, provided that the interpretation of planimetric detail is adequate. Therefore, it is of particular interest to examine the performance of current photogrammetric camera systems with respect to imaging planimetric detail at scales smaller than those now used for compilation. Table 6 indicates measures of image quality for a Wild RC8 camera and 2402 film.

TABLE 6. CURRENT IMAGE QUALITY (1.6:1 Contrast at Camera Lens)

	1:50,000 Scale	*1:100,000 Scale*
Resolution	30 l/mm	30 l/mm
Ground resolution	1.7 m	3.4 m
Detectability of symmetrical object	1.0 m	2.0 m
Measurability	2.0 m	4.0 m

In order to evaluate the usability of smaller

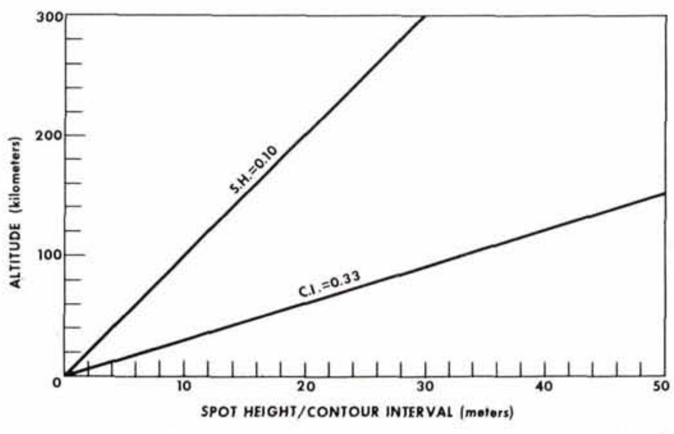

FIG. 16. Spot heights and contour intervals related to accuracies of 0.0001 and 0.00033 of flight altitude respectively.

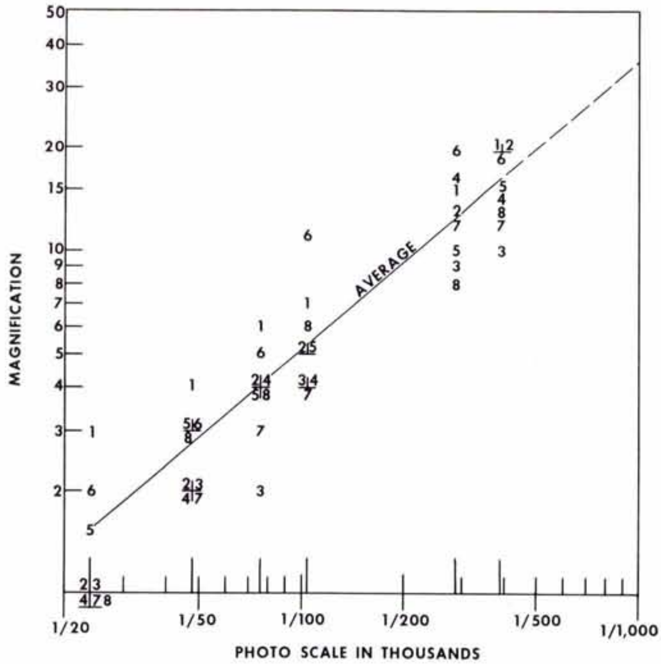

FIG. 17. Magnification needed (as a function of photoscale) for compilation of planimetric detail for 1:24,000 scale topographic maps. Based on observations of 8 experienced compilers.

scale photographs in compiling planimetric detail for 1:24,000-scale maps, a series of photographs of the same urban area obtained under similar conditions with RC8/2402 and Hasselblad/3400 camera-film combinations (30–40 l/mm low-contrast resolution) at scales of 1:48,000, 1:76,000, 1:104,000, 1:290,000, and 1:390,000 were placed on a light-table for binocular viewing at 1× to 60× magnification. Eight observers with practical experience in compiling 1:24,000-scale maps viewed the photographs in sequence, beginning with the smallest scale and adjusted magnification as needed for compiling small planimetric detail. Each observer rated each photo as usable or not usable for compiling planimetric detail to current 1:24,000 map scale standards for completeness and accuracy. Information about the purpose of the experiment and the photographs being viewed was intentionally withheld.

The observers indicated unanimously that the required planimetric detail could be plotted from any of the photographs with the selected magnifications. Furthermore, if these magnifications were plotted against the respective photoscales on log-log paper, a nearly straight-line relationship was indicated (Figure 17). Moreover, the photoscale factor divided by optimum magnification yielded an average factor of 20,000. Hence the formula

$$M = \frac{\text{photoscale factor}}{20{,}000}$$

provides a reasonable estimate of the magnification needed. As most stereoplotting instruments offer magnifications no higher than 8× or 10×, photo-scales should be limited to 1:200,000 and larger (Figure 18).

Although these deductions are subject to verfication in actual production, they leave little doubt that current limits on photoscales for compilation are conservative. It should also be obvious that the image quality of photographs taken with currently available camera systems will permit the compilation of topographic maps at scales of 1:24,000 to 1:50,000 from photographs at scales as small as 1:400,000 provided that image quality and magnification are adequate. It is also interesting to note that the often-quoted relationship

$$M = \frac{\text{photo resolution}}{\text{visual resolving power (about 5 l/mm)}},$$

where M is the desirable magnification, is not necessarily valid for photoscales larger than 1:100,000. The magnification selected by an observer was generally based on his ability to

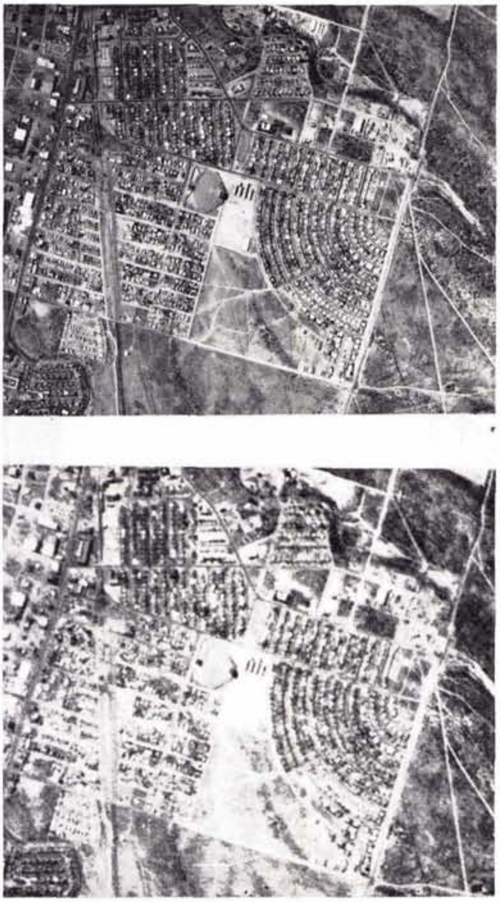

FIG. 18. Aerial photographs at approximately 1:24,000 scale; *top* photo contact printed from negative having low-contrast resolution of 30 l/mm; *bottom* photo enlarged in two steps from 1:290,000-scale negative having resolution of 40 l/mm.

delineate houses and other minimum-size details with a fair degree of ease and reliability. Obviously, as scale decreases, image quality and magnification become increasingly important. From viewing resolution targets imaged at different contrasts and scales, it was found that one unit of magnification for each line per millimeter of photographic resolution (up to 60 l/mm) was the maximum required by an observer (also reference Selwyn, 1948).

On the basis of this evidence, it seems that fairly large-scale planimetric mapping from space photographs is feasible. For example, at a nominal altitude of 230 km, cameras of 15 cm and 30 cm focal lengths will produce scales of 1:750,000 and 1:1,500,000. Although the possibilities of drawing contours (as opposed to point measurements and analytical methods) at a reasonable interval seems to be remote regardless of the base/height ratio (Welch, 1970) unless accuracy standards are relaxed, direct compilation of planimetry and production of photomaps at scales of 1:100,000 and smaller seem practical. At present there is a lack of agreement concerning the value of small-scale photomaps, and standards of interpretability based on experience with direct compilation of maps at small scales are not generally available. In the absence of more complete data Figure 19 provides an insight into possible photo-to-map scale relationships; it is apparent that with ratios of 2 or higher, 1:250,000-scale maps can be produced from photographs at scales smaller than 1:1,000,000.

It is appropriate to consider here the Actron ETC and Itek panoramic reconnaissance cameras. The advantages of these

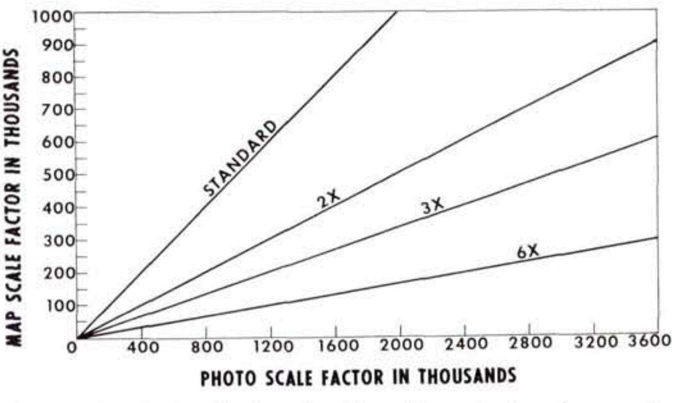

FIG. 19. Map/photo scale relationships based on linear interpolation of assumed requirement of photos$\geq$1:50,000 for compilation of 1:24,000-scale maps (standard).

cameras are primarily their higher resolution and longer focal lengths. However, if a metric camera of equivalent focal length were to be used with the same films and image-motion compensation, nearly comparable image quality could be obtained. For example, 3414 film used in a 30-cm photogrammetric camera would yield resolutions of approximately 80 l/mm for targets oriented parallel to the orbital path, but image motion would cut this resolution to about 10 l/mm for targets oriented perpendicular to the path (Figure 5). In comparison, the resolution for a panoramic camera is estimated at 100 l/mm in both directions, although the resolution does decrease with increasing scan angle. Therefore, it is suggested that for both mapping and interpretation applications, a metric camera with focal length of 46 cm or 61 cm and image motion compensation would prove superior to reconnaissance systems with their limited coverage, poor geometry, and multiple distortions. As a matter of interest, Zeiss currently manufactures not only a Topar lens ($f/4.5$, $f=46$ cm) suitable for a 23×46-cm format but also a metric camera of 61 cm focal length, the RMK A 60/23 with Telikon lens ($f/6.3$) and 23×23 cm format. This latter camera could be used in an orbiting spacecraft with films such as 3401 or 2402 to produce photographs at 1:380,000 scale having low-contrast resolutions of 30–35 l/mm throughout the format. These photographs would cover an area of 86×86 km (54×54 miles) and could be used in currently available instruments to produce photomaps at 1:50,000 scale and planimetric maps to 1:24,000 scale. For these reasons, the use of reconnaissance cameras does not seem to be justified for photogrammetric tasks.

Image Quality Related to Resource Studies

Aerial photographs have long been used by earth scientists for detailed studies in a variety of applications, and color and color-infrared photographs have proved to be of particular value (Welch, 1966). Table 7 Lists a number of scientific disciplines and the range of preferred photographic scales mentioned in the literature over the last 20 years. Generally photoscales of 1:50,000 or larger have been preferred.

Because of the possibilities for improving image quality, high-altitude aerial photographs of scales from 1:70,000 to 1:200,000 may prove to be satisfactory for both detailed and generalized studies in many of these disciplines. In fact, photographs in this scale range may come to be preferred because of their synoptic view, which emphasizes the relative positional relationships so important to interpretive studies in the earth sciences. It is not reasonable, however, to extend this hypothesis and assume that similar studies can be accomplished from space imagery ranging in scale from 1:3,000,000 to 1:7,000,000. Certainly the useful information extracted from the Hasselblad photographs taken on the Gemini and Apollo missions has been very generalized (Wobber, 1971).

Table 7. Disciplines and Preferred Photo Scales

Forestry	1:1,000 to 1:25,000
Geology	1:10,000 to 1:60,000
Soils	1:20,000 to 1:25,000
Hydrology and Hydrography	1:5,000 to 1:50,000
Geomorphology	1:10,000 to 1:50,000
Geography	1:10,000 to 1:100,000
Ecology, Biogeography	1:4,000 to 1:12,000
Archeology	1:5,000 to 1:25,000

The space imagery to be obtained with the ERTS-A return beam vidicon (RBV) and multispectral scanner (MSS) on an 18-day repetitive cycle (Doyle, 1970a), will be useful for generalized studies of such problems as the configuration of the earth's surface and the distribution of water, vegetation, and population as described by the NAS-NRC Committee on Space Programs for Earth Observations (Subcommittee Report, 1969). However, the extent to which even these limited goals can be achieved is debatable because the specified minimum ground resolution of 30 to 60 m does not appear to be possible with the ERTS-A system. According to current data (Weinstein, Miller, and Barletta, 1971), ERTS-A will have an estimated resolving power of 40 to 45 l/mm (photographic) on the cathode-ray tube (CRT) (1:7,300,000 scale) for a low-contrast scene. This corresponds to a ground resolution of about 180 m, a value which will almost certainly be degraded in the subsequent processing steps (Schramm, 1971). Resolution at the user's picture scale of 1:1,000,000 can be estimated at 3 to 5 l/mm or a ground resolution no better than 200 to 330 m. More data are needed on this system, but the values cited seem realistic based on available studies.

The multispectral camera assembly planned for SKYLAB (Itek, 1971) will probably meet the specified ground resolutions for some of the camera/film combinations and

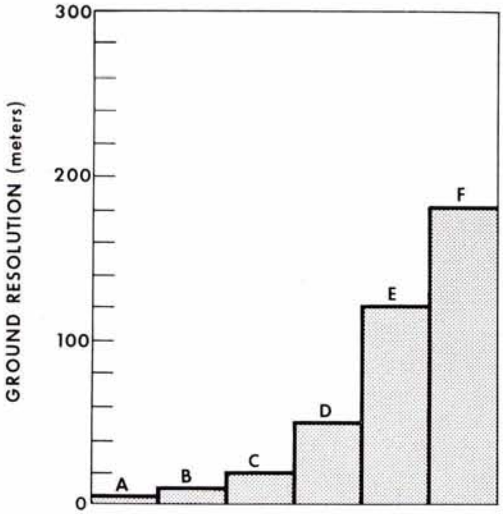

FIG. 20. Estimated ground resolution for (*A*) Itek panoramic camera at 230 km with 3414 film; (*B*) Actron ETC camera at 435 km with 3414 film; (*C*) metric camera at 230 km with 3400 film; (*D*) Itek Multispectral assembly at 435 km with 3400 film; (*E*) Itek Multispectral assembly at 435 km with 3443 film; (*F*) ERTS-A RBV/CRT at 910 km.

should provide a better indication of the possibilities of using small-scale multispectral imagery for studies of earth resources (Doyle, 1970b). However, the SKYLAB camera system that seems to offer the best opportunity to evaluate space imagery for photomapping and resource studies is the Actron ETC This camera system can produce photographs with resolutions of 100 l/mm at a scale of 1:945,000, which is equivalent to a ground resolution of 10 m. Although somewhat poorer ground resolution could be expected from a metric camera ($f=30$ cm), its inclusion in the SKYLAB experiments would greatly enhance the value of the program. Figure 20 indicates the estimated ground resolutions for various systems.

In addition to resolution, data on detectability and measurability characteristics are particularly important in such applications as land-use classification and subsequent area determinations. For example, using color-infrared photographs (with detectability and measurability thresholds of 30 and 60 μm) at about 1:3,000,000 scale, a field would have to be approximately 90 m square to be detected and 180 m square before its shape could be reasonably defined. Considering a probable linear measurement error of approximately 15 μm, an error of 50 percent or greater in area determination could be expected. To obtain area measurements that are better than 95 percent correct, the land-use units would have to be on the order of 1 mm square on the image or about 3 km square on the ground. For ERTS-A imagery which will probably have similar detectability and measurability thresholds, land-use units on the order of 7 km square would be required before comparable accuracies could be expected. Figure 21 indicates the approximate percent error in area determinations based on measurability data.

CONCLUSION

Measurements on laboratory and aerial photographs in combination with theoretical evaluations of the factors influencing image quality have enabled comparisons of the performance capabilities of photogrammetric camera systems with other reconnaissance and multispectral camera systems considered for aerospace use. Table 8 summarizes resolution, detectability, and measurability values used as a basis for these comparisons. The

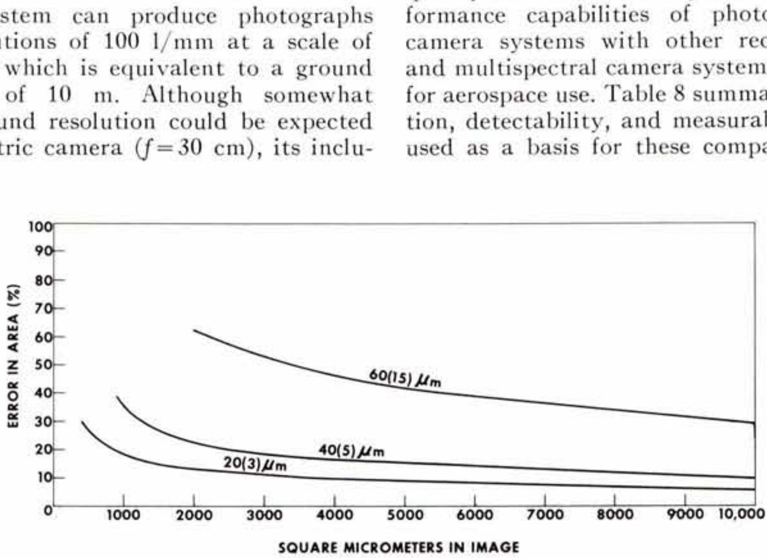

FIG. 21. Percentage error in measured areas of square images as a function of image area in square micrometers for measurability thresholds of 20, 40, and 60 μm, and linear error measurements of 3, 5, and 15 μm.

values are of the correct order of magnitude but will vary depending on cameras, lenses, films, exposure parameters, environmental conditions, instrumentation, and observers.

Experiments involving a series of aerial photographs at different scales indicate that sufficient planimetric detail for 1:24,000-scale maps can be compiled from photographs at 1:400,000 scale, or even smaller, provided they are of good quality and viewing magnification equivalent to the photoscale factor divided by 20,000 can be selected. Consequently, greater advantage should be taken of high-altitude jet aircraft (and less crowded airlanes) for obtaining mapping photographs. Photoscales to about 1:200,000 are currently possible, and the latest plotters in the hands of experienced operators can provide spot heights accurate to about 0.1°/₀₀ of the flight height (for $f = 15$ cm or 30 cm), indicating that contours compiled at intervals of 5–10 m (or 20 feet) would meet the National Map Accuracy Standards. Because of the greater area coverage per model and the increased accuracy and versatility of precision mechanical projection or analytical instruments, fewer instruments would be required for mapping a given area. The advantages of producing photomaps for large areas from single photographs are also well known.

The photographic quality obtained with photogrammetric cameras can be approximately doubled through the use of high-performance reconnaissance emulsions developed to gamma values between 1.8 and 2.2. These emulsions could be coated on a 4-mil polyester base to provide greater dimensional stability; however, it is likely that with careful handling the 2.5-mil polyester base will prove sufficiently stable for most mapping tasks (Figure 22). The use of 4-mil to 7-mil base film transparencies for photogrammetric tasks has been previously demonstrated (Welch, 1968), and most modern instruments will accept the original film negatives or positives to take advantage of maximum image quality.

TABLE 8. IMAGE QUALITY DATA FOR PHOTOGRAMMETRIC, RECONNAISSANCE AND MULTISPECTRAL SYSTEMS
(1.6:1 Target Contrast at the Camera Lens)

Film	*Resolution (l/mm)*	*Detectability (μm)*	*Measurability (μm)*
3443/2424	20–25	30	60
2402	30–40	20	40
3400	30–60	20	40
SO-242	40–70	10	20
3414	60–130	10	20

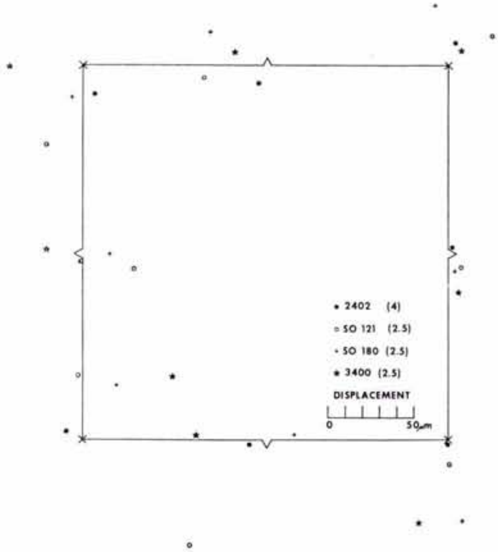

FIG. 22. Film distortion after linear transformation based on corner fiducials for single examples of photographs on 4-mil and 2.5-mil polyester base. Careful handling could have reduced displacements on thin-base films.

Because of the availability of excellent instruments, films, and metric cameras, and the demonstrated possibilities of improving image quality, it is considered feasible (but not necessarily economical) to produce planimetric maps at scales as large as 1:24,000 from photographs taken in space vehicles at orbital altitudes of about 230 km. However, the potential of available photogrammetric camera equipment and materials for space use seems to have been overlooked in favor of reconnaissance systems capable of higher resolution. The lens quality of narrow-angle photogrammetric cameras does not significantly differ from that of the lenses in high-performance reconnaissance systems over the regions in which other than the slowest-speed, high-resolution films are used. The differences in image quality of 1:380,000-scale photographs produced by a current metric camera on a film such as 2402 developed to a gamma of about 1.8 and that produced by a panoramic camera on 3414 film are insignificant if the advantages of the metric camera are considered.

If improved metric cameras with relative apertures of about $f/4$ or $f/3.5$ were manufactured, shutter speeds increased, and high-performance film speeds doubled, then planimetric and photomapping tasks from space photographs could be readily accomplished. Standard 23×23 cm formats are desirable because the resulting photographs could be used in comparators, enlargers, rectifiers, and plotting instruments of standard design, which are available to many scientists. A judicious choice of high-resolution color films and improved color-infrared films would also permit the photographs to be used both for detailed and generalized studies of earth resources.

Detailed studies of earth resources based on repetitive coverage and multispectral imagery at smaller scales are possible if image quality can be improved. Although the degree to which photoscales can be eventually reduced awaits the evaluation of small-scale imagery by the earth scientists concerned, it is not reasonable to assume that extremely small scales (1:3,000,000 to 1:7,000,000) will prove to be satisfactory for tasks now requiring scales of 1:50,000 or larger. ERTS-A, for example, incorporates a good RBV camera system but, because of its design characteristics, can only be expected to produce a ground resolution of approximately 180 m at a CRT image scale of 1:7,300,000. This ground dimension is about three times larger than that defined for the generalized tasks of determining the distribution of water, vegetation, and population. These kinds of information are already available for the United States, over which most of the ERTS imagery will be obtained (Doyle, 1970a). If considered with the restricted possibilities of deriving reliable area measurements, the rather slow changes that take place in population distribution and nature, and the tremendous volume of imagery to be reduced, the proposed advantages of the system, particularly with respect to multispectral and sequential coverage, seem to be limited.

The SKYLAB experiments should provide a better opportunity to assess the value of using small-scale multispectral imagery for earth resources studies. Although the Actron camera to be carried on SKYLAB may provide photographs adequate for photomapping experiments, the inclusion of a metric camera in the SKYLAB experiments would greatly enhance its value to the cartographer.

In conclusion, the relative merits of film *vs* RBV-type systems for civilian use will probably be determined on the basis of such factors as frequency, relative area coverage, lifetime, and purpose. For example, if closely spaced, periodic, world-wide coverage is required for both resource studies and small-scale mapping, an improved RBV-type of satellite system may prove to be the most practical solution. If single coverage of the United States and contiguous areas is required for the establishment of supplemental control, planimetric mapping, and resource studies, with coverage thereafter at relatively long intervals, then a spacecraft with metric cameras and a film-return system seems to be the logical choice. High-altitude aerial photographs taken with metric cameras and proper films are well suited for mapping tasks and detailed studies of earth resources.

Acknowledgments

The research on which this paper has been based was conducted under a National Research Council-National Academy of Sciences Post-doctoral Research Associateship granted in cooperation with the U. S. Geological Survey. The views expressed in the paper are the author's and are not intended to reflect the official policies or attitudes of any of these agencies. The assistance of Messrs. Baensch, Jackson, Sorem, and Specht of Eastman Kodak Company and numerous individuals within the U. S. Geological Survey is acknowledged and appreciated. Without the invaluable cooperation and assistance of James Halliday this project could not have originated or been completed.

References

American Society of Photogrammetry, 1968, *Manual of Color Aerial Photography.* 105 N. Virginia Ave., Falls Church, Va. 22046.

Boileau, A. R., 1964, "Atmospheric Properties." *Applied Optics*, v. 3, no. 5, p. 570–582.

Brock, G. C., 1952, *Physical Aspects of Aerial Photography.* London, Longmans, Green and Company, p. 267.

———, 1967, "Reflections on Thirty Years of Image Evaluation." *Photographic Science and Engineering*, v. 11, no. 5, p. 356–362.

Brock, G. C., et al., 1966, *Photographic Considerations for Aerospace.* Itek Corporation, Lexington, Mass., p. 118.

Carman, P. D., and Carruthers, R. A. F., 1951, "Brightness of Fine Detail in Air Photography." *Journal of the Optical Society of America*, v. 41, no. 5, p. 305–310.

Carman, P. D., and Charman, W. N., 1964, "Detection, Recognition and Resolution in Photographic Systems." *Journal of the Optical Society of America*, v. 54, no. 9, p. 1129–1130.

Case, J. B., 1967, "The Analytical Reduction of Panoramic and Strip Photography." *Photogrammetria*, v. 22, no. 4, p. 127–141.

Chapelle, W. E., Whiteside, A. E., and Bybee, J. E., 1968, "Automation in Photogrammetric Compilation." *International Archives of Photogrammetry*, 17, Lausanne Congress.

Charman, W. N., 1965, "Resolving Power and the

Detection of Linear Detail." *Canadian Surveyor*, v. 19, no. 2, p. 190–205.

Colvocoresses, A. P., 1970, "ERTS-A Satellite Imagery." *Photogrammetric Engineering*, v. 36, no. 6, p. 555–560.

Doyle, F. J., 1970a, "Mapping Techniques and World Mapping Problems." Paper presented to Canadian Institute of Surveying, Halifax, Nova Scotia, April 16th.

———, 1970b, "Photographic Systems for Apollo." *Photogrammetric Engineering*, v. 36, no. 10, p. 1039–1044.

Eastman Kodak, 1970, Characteristics of Kodak Aerial Films: *Publication* M-57. Also refer to publications M-29, M-45, M-58, M-69, M-73.

Halliday, J., 1969, "Applications of Color Aerial Photographs in Topographic Mapping," *New Horizons in Color Aerial Photography*, ASP-SPSE *Seminar Proceedings*, p. 131–144.

Hufnagel, R. E., 1965, "Random Wavefront Effects." *Photographic Science and Engineering*, v. 9, no. 4, p. 244–247.

Hulett, H. R., 1967, "Limitations in Photographic Resolution of Planet Surfaces." *Journal of the Optical Society of America*, v. 57, no. 11, p. 1335–1338.

Itek, 1971, "Multispectral Photographic Facility." *Technical Bulletin*.

Karren, R. J., 1970, "Theoretical Study of Map Compilation from NASA Satellite Photographs." *Proceedings* of the 36th Annual Meeting of ASP, March p. 23–58.

Kinney, W. C., 1971, "Apollo Optical Bar Camera Photographic System Analysis and Lunar Object Detection Study." Paper presented at the 37th Annual Meeting of ASP, March 7–12.

Krinov, E. L., 1947, "Spectral Reflectance Properties of Natural Formations." *National Research Council of Canada, Technical Translation no. 439*, Ottawa, Canada.

Lauroesch, T. J., et al., 1970, "Threshold Modulation Curves for Photographic Films." *Applied Optics*, v. 9, no. 4, p. 875–887.

Macdonald, D. E., 1958, "Resolution as a Measure of Interpretability." *Photogrammetric Engineering*, v. 24, no. 1, p. 58–62.

McEwen, R. B., 1971, "Geometric Calibration of the RBV System for ERTS." *Proceedings of the 7th International Symposium on Remote Sensing*, p. 791–807.

Petrie, G., 1970, "Some Considerations Regarding Mapping from Earth Satellites." *Photogrammetric Record*, v. 6, no. 36, p. 590–624.

Pichlik, V., 1968, "Parameters and Accuracy Criteria of Plans and Maps Compilation." *International Archives of Photogrammetry*, Vol. 17, Lausanne Congress.

Schellens, D. F., 1971, "Experiences with the Zeiss Planimat." *Proceedings* of the 37th Annual Meeting of ASP, p. 8–25.

Schermerhorn, W., 1968, "News of Classical Analogue Restitution Instruments." *International Archives of Photogrammetry*, Vol. 17, Lausanne Congress.

Schmid, H., 1964, "Satellite Photogrammetry." *Jubilee Volume Dedicated to Willem Schermerhorn on his Seventieth Anniversary*, Delft, I.T.C., p. 219–240.

Schramm, S. J., 1971, "RBV System Resolution Model." *General Electric Report*.

Scott, F., 1966, "Three-Bar Target Modulation Detectability." *Photographic Science and Engineering*, v. 10, no. 1, p. 49–52.

Scott, R. M., 1959, "Contrast Rendition as a Design Tool." *Photographic Science and Engineering*, v. 3, no. 5, p. 201–209.

Selwyn, E. W. H., 1948, "The Photographic and Visual Resolving Power of Lenses." *The Photographic Journal*, v. 88B, p. 6–12 and p. 46–57.

Short, P. B., and Turpin, R. T., 1969, "Photographic Capability and Photogrammetric Potential of the Panoramic Camera for Scientific Instrument Module." *Itek Report 69-9440-1*.

Subcommittee on Space Science and Applications, 1969, "Earth Resources Satellite System." *Report for the Subcommittee on NASA Oversight of the Committee on Science and Astronautics*, U. S. House of Representatives, Ninetieth Congress, Second Session, Serial W., U. S. Government Printing Office, Washington, D. C.

Trinder, J. C., 1971, "Pointing Accuracies to Blurred Signals." *Photogrammetric Engineering*, v. 37, no. 2, p. 192–202.

Weinstein, D., Miller, B. P., Barletta, J., 1971, "Simulations of ERTS RBV Imagery." *Proceedings of the 7th International Symposium on Remote Sensing of Environment*, p. 1177–1188.

Welch, R., 1966, "A Comparison of Aerial Films in the Study of the Breidamerkur Glacier Area, Iceland." *Photogrammetric Record*, v. 5, no. 28, p. 289–306.

———, 1968, "Film Transparencies vs Paper Prints." *Photogrammetric Engineering*, v. 34, no. 5, p. 496–501.

———, 1969a, "Reflectance Characteristics of a Glacial Landscape and their Relation to Aerial Photography." *New Horizons in Color Aerial Photography*, ASP-SPSE Seminar *Proceedings*, p. 17–35.

———, 1969b, "Analysis of Image Definition." *Photogrammetric Engineering*, v. 35, no. 12, p. 1228–1238.

———, 1970, "Height Difference Measurement Errors." *Photogrammetric Engineering*, v. 36, no. 6, p. 576–577.

———, 1971a, "Earth Satellite Camera Systems." Resolution Estimates and Mapping Applications: *Photogrammetric Record*, v. 7, no. 38, p. 237–246.

———, 1972, "The Prediction of Resolving Power of Air and Space Photographic Systems." *Image Technology*, in press.

Widger, W. K., 1966, "Orbits, Altitudes, Viewing Geometry, Coverage, and Resolution Pertinent to Satellite Observations of the Earth and its Atmosphere." *Proceedings of the 4th Symposium on Remote Sensing of Environment*, p. 489–537.

Wobber, F. J., 1971, "Orbital Photos Applied to the Environment." *Photogrammetric Engineering*, v. 37, no. 8, p. 852–864.