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REPORT OF THE IMAGE QUALITY WORKING GROUP (WG 1/1), 1976-80

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Abstract

The Image Quality Working Group (WG 1/1) has performed investigations in three areas: 1) tests of photogrammetric lenses and camera systems; 2) performance characteristics of optical and electro-optical sensor systems; and 3) measures of image quality. These studies indicate that OTF/MTF techniques are considered reliable for evaluating lenses and sensor system performance, and are useful in assessing the measurability and interpretability of image data. Future efforts should be directed toward assessments of earth satellite sensor performance required for the compilation of map products and the interpretation of thematic data; evaluation of the interrelationships between parameters such as IFOV, sampling frequency, quantization and signal-to-noise ratios; integration of measures of spatial and radiometric resolution; and definition of processing techniques for improving the fidelity of analog and digital image data.

REPORT OF THE IMAGE QUALITY WORKING GROUP
(WG 1/1), 1976-80

by

R. Welch, P. N. Slater
H. Tiziani, and J. C. Trinder

At the Helsinki Congress in 1976 the following resolutions were developed to encourage investigations of image quality during the four year period 1976-80.

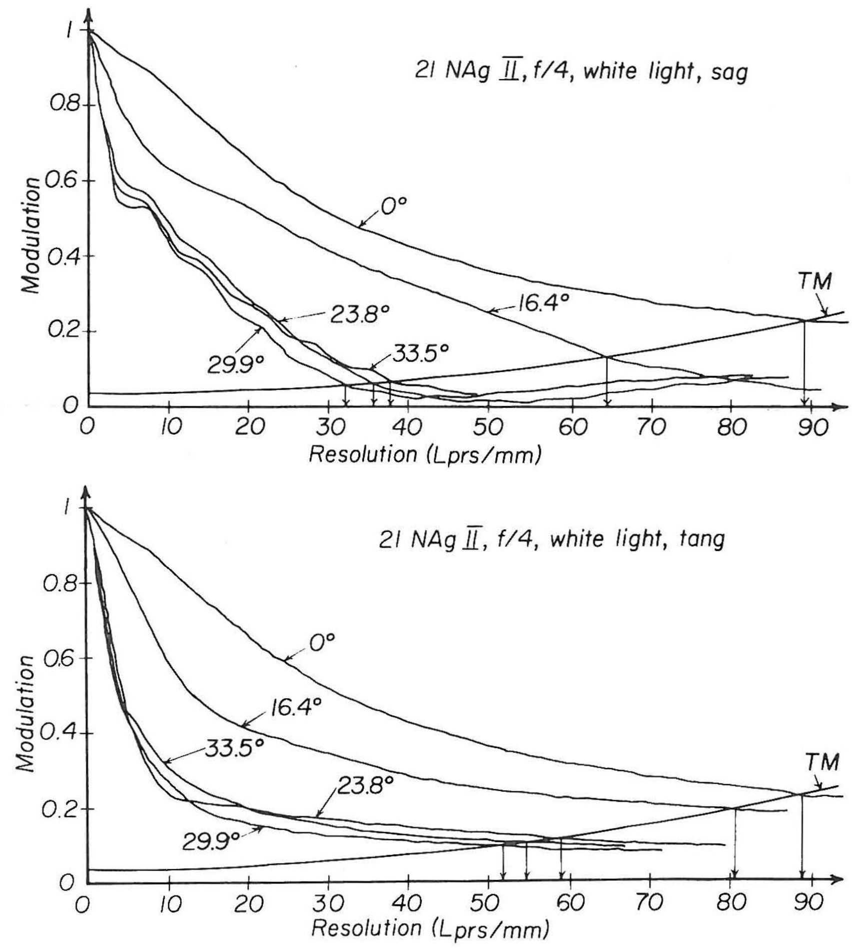
1. Commission I recommends the expansion of the present OTF/MTF Working Group to include more general studies of the quality of images and acquired data. Methods of measuring sensor system performance and image quality should be studied and related to the interpretability and measurability of image detail. Optical and modulation transfer function (OTF/MTF) standards and analysis procedures should be included within the activities of this group.

2. The activities concerned with image quality and image geometry should be coordinated to look further at relationships between image quality and photogrammetric accuracy, for example, at the question of assigning realistic weights to measured image coordinates.

As a consequence of these resolutions and of the data presented in Helsinki, the Image Quality Working Group (WG 1/1) was established in early 1977 (Norton, Brock and Welch, 1977; Welch, 1977). Members of the Image Quality Working Group were selected to investigate:
1) OTF/MTF evaluation procedures and their applications in testing photogrammetric lenses and camera systems (Dr. Hans Tiziani, University of Stuttgart, FRG); 2) optical and electro-optical sensor system characteristics and performance (Dr. R. Welch, University of Georgia and Dr. P. N. Slater, University of Arizona, USA): and 3) measures of image quality and their relation to the measurability and interpretability of image detail (Dr. J. C. Trinder, University of New South Wales, Australia). The activities of the group in each of these subject areas are summarized in the following paragraphs.

OTF/MTF

Techniques to measure the OTF/MTF of photogrammetric camera lenses are now well-established in countries such as Great Britain, Germany (Bode, Untergutsch and Bibmann, 1978), Switzerland, and Japan (Geographical Survey Institute, 1979), and it is generally agreed that good correlation can be obtained between measurements conducted at different laboratories. Consequently, in addition to classical area-weighted average resolution (AWAR) tests, MTF's offer an objective means of determining "quality numbers" suitable for ranking and comparing optical systems. One approach suggested as a substitute for the conventional procedures is to determine an AWAR value from the intersections of measured lens MTF's at different field positions with the threshold modulation (TM) curve of the test film (Figure 1). Good agreement between observed resolution value and those predicted by intersection techniques has been experienced in laboratory tests (Figure 2).



g. 1 MTF curves for a Wild photogrammetric camera lens at five field angle positions. Predicted resolution values are obtained from the intersection of a film TM irve with the MTF's.

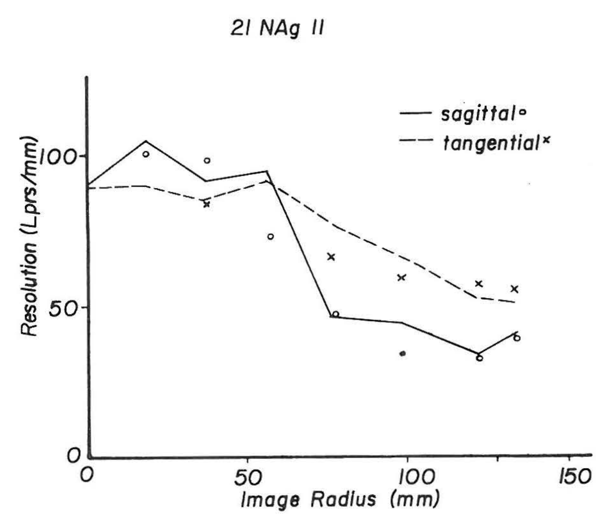


Fig. 2 Comparison of resolution values for 21 NAg obtained by classical observation methods (lines) and intersection (o,x) techniques.

A possible alternative approach involves the determination of an area-weighted average modulation (AWAM) value determined by integrating over the area bounded by: 1) the average of the tangential and sagittal MTF's for given field positions (i.e. the average lens MTF at each of several specified format positions); 2) a TM curve for the eye; and 3) a limiting spatial frequency based on the intersection of the eye TM curve with the lower MTF (sagittal or tangential) curve at a given field position. Quality values based on this approach rank systems similarly to resolution values and are more sensitive to system perturbations. For the user, the MTF at the point midway between zero and the limiting spatial frequency was found to correlate with visual impressions of image quality (Tiziani, 1978).

The phase component, included in the specification of OTF, remains troublesome and is often omitted in tests of photogrammetric lenses. Practical procedures for utilizing phase measurements to assess lens distortion remain to be determined.

The selection of lenses for photogrammetric applications or the specification of image quality should consider the following:

1. area below the MTF curve to a limiting spatial frequency (e.g. to 20 or 30 lpr/mm);
2. variation between the tangential and sagittal MTF's at the same field angle;
3. variation in image quality over the entire field as predicted by the intersection of the lens MTF and film TM curves.

Under given laboratory or operational conditions, the MTF's for selected spatial frequencies, say 10, 20 and 30 lpr/mm, at different fieldpoints may, in themselves, prove to be an adequate measure of quality.

An important advantage of MTF's to the photogrammetrist interested in evaluating system performance, is the possibility for cascading the MTF's of the individual components such as the lens, film, environment (atmosphere, vibration, image motion) to obtain a single MTF representative of the image forming system (Welch, 1976). This procedure insures the selection of system components best suited to a particular task. In summary, MTF's are very appropriate for assessing lens performance as well as the performance of the entire system.

OPTICAL AND ELECTRO-OPTICAL SENSOR SYSTEMS

Investigations of earth resources and cartographic applications with small-scale satellite images have resulted in numerous discussions on the advantages and limitations of two groups of sensor systems: 1) high-resolution film cameras;and 2) electro-optical sensor systems such as return beam vidicon (RBV's), mechanical scanners, and solid-state line array sensor systems. Each of these groups of sensor systems is briefly discussed, and reference made to means of assessing image quality.

High-Resolution Film Cameras

Film cameras which have received considerable attention include the Itek Large Format Camera (LFC) and the Zeiss RMK A 30/23 Metric Camera which will be utilized on the Space Shuttle/Spacelab experiments (Doyle, 1979). Both cameras have 30 cm focal length lenses and are capable of low contrast image resolutions of approximately 50 to 80 lpr/mm, depending on the film employed. The LFC, for example, will produce an AWAR of approximately 80 lpr/mm (2:1 contrast) with EK 3414 film, which from the nominal attitude of 300 km (scale = 1:1,000,000) equates to a ground resolution of approximately 12 m. Image motion compensation permits the relatively long exposures required when using slow, high-resolution reconnaissance films. The Metric Camera probably will be employed with more conventional mapping films such as EK 2404 or 2443 which allow faster shutter speeds to compensate for image motion. Image resolution of 40 to 20 lpr/mm can be expected with these films for 1:6:1 or 2:1 target contrasts. These values equate to ground resolutions of 25 to 50 m.

Results of aircraft tests with the Metric Camera will be discussed in the WG 1/1 session by Schroeder, Ducher, Pinson, Togliatti and Sievers (1980). A principal objective of the Shuttle/Spacelab experiments is to demonstrate the feasibility of compiling maps at scales of 1:50,000 and smaller from space photographs obtained with cartographic cameras.

High quality mapping cameras such as the Wild RC 10, Zeiss RMK A 15/23 and Itek Meritek cameras are being employed in high-altitude aircraft such as the Lear Jet, Lockheed U-2 and the Canberra RB-57 (Gregory, 1975; Gut and Hohle, 1977; NASA, 1978). When used with a typical mapping film such as EK 2402 these cameras will deliver image resolutions of about 30 to 40 lpr/mm for low contrast targets. These image resolutions will permit the compilation of topographic maps in the 1:25,000 to 1:50,000 scale range from photographs of about 1:400,000 scale or larger.

Electro-Optical Sensor Systems

Electro-optical sensors which are well known include the MSS and RBVs of Landsats -1, -2 and -3 (Taranik, 1978; USGS, 1979; Slater, 1979). Other sensors receiving attention are the Thematic Mapper of Landsat-D and the line array cameras planned for SPOT, Stereosat and Mapsat (Williams and Salomonson, 1979; Chevrel, Courtois and Weill, 1980; JPL, 1979; Colvocoresses, 1979). These sensor systems represent image tube, mechanical scanner and solid-state line array technology. Most satellite sensor systems envisioned for the 1980's will make use of solid-state line arrays (Koshiishi, et al., 1978; Hirai, 1978; Table 1).

Parameters which determine the quality of image data recorded with these sensor systems include the dimensions of the instantaneous field-of-view (IFOV) or pixel, sampling frequency, quantization and signal-to-noise ratio. The first three parameters, plus the swath width and number of spectral bands determine the data rates which must be accommodated (Figure 3).

The IFOV is the angular subtense defined by the limiting detector aperture of a diffraction and aberration-free sensor system. Commonly, the IFOV is expressed as the dimension(s) of the "footprint" of the detector on the ground at a given instant. A picture element (pixel), on the other hand, is the data sample in the output product to which a radiance value is assigned. Its dimensions are not necessarily related to the sensor system parameters. Normally, the IFOV is taken as the resolution element of the system. Because the MTF for a square or rectangular aperture can be represented by a sin x/x function, it is

Table 1

	SENSOR SYSTEM	IFOV	SWATH	REPEAT	BANDS	DATA	PRODUCTS	PURPOSE
SHUTTLE/ SPACELAB (1981)	LFC MC	5-10m*	225km	?	WB	FILM	PHOTOS*	CART.
LANDSAT-D (1982)	TM MSS	30m 76m	185km	~17 dys	7 4	100mb/s TDRSS & DIRECT	IMAGES CCT's	EARTH SCI.
STEREOSAT (1984)	3 camera* fixed, along track	15m	61km	48 dys	1	32mb/s TDRSS	IMAGES* CCT's DTM	GEO. SCI. CART.
SPOT (1984)	HRV(2)* pointable, cross-track	20m 10m	60km	26 dys*	4	50mb/s DIRECT TAPE	IMAGES* CCT's DTM	EARTH SCI. CART.
MAPSAT (mid-1980's)	3 camera* fixed, along track	10-30m	185km	18 dys	3-4	15-30mb/s TDRSS & DIRECT	IMAGES* CCT's DTM	AUTO. MAP.
	LINE* ARRAYS	EST.* EQUIV.		POINT-* TABLE			STEREO*	

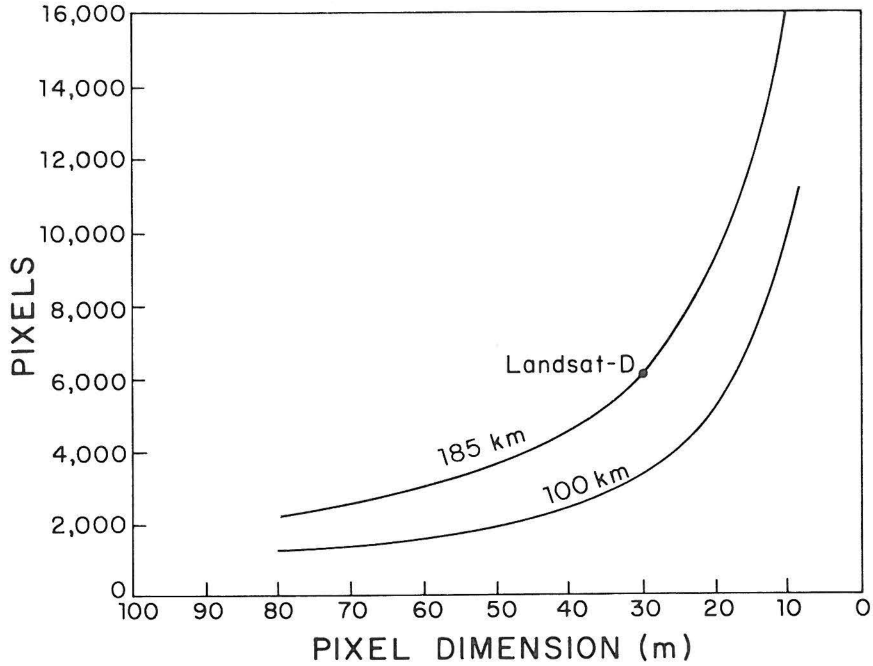


Fig. 3 Number of pixels/scan line as a function of pixel dimension for 185 km and 100 km swath widths.

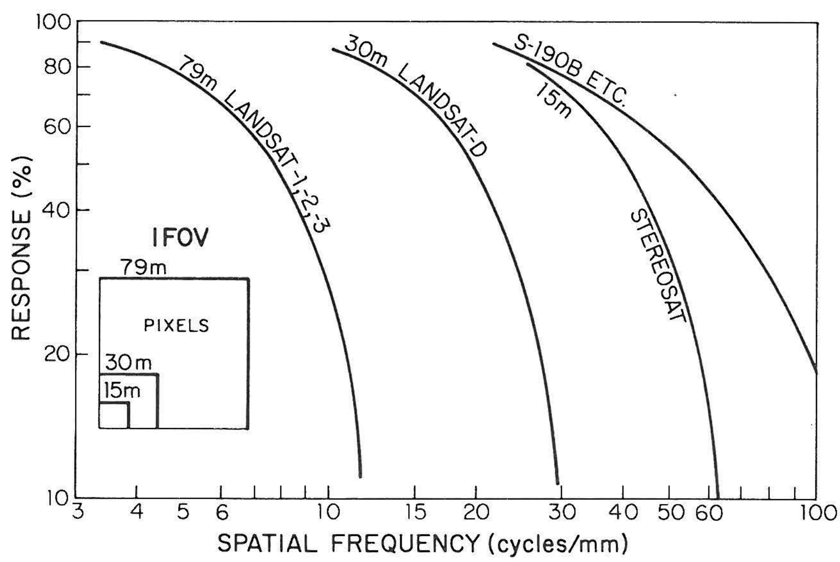


Fig. 4 MTF's permit a comparison of the performance of optical (ETC) and electro-optical sensor systems.

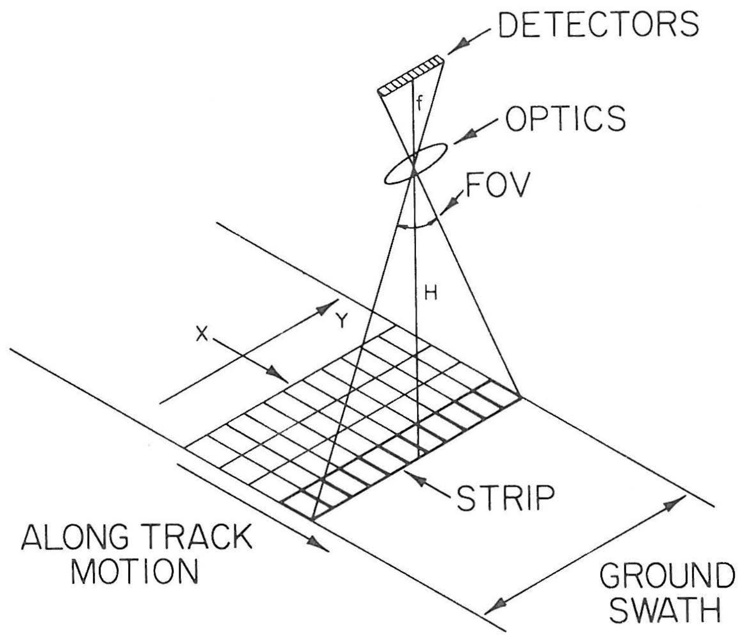
relatively easy to obtain first approximations of electro-optical sensor system performance and to compare these MTF's with those calculated for optical systems (Figure 4). It will be noted, however, that more than one electro-optical sensor resolution element is required to resolve a bar target of equivalent spacing. A United Nations study (1978), for example, based on examinations of Landsat MSS (76 m IFOV) and RBV imagery has indicated that the equivalent photographic ground resolution of the MSS for high contrast targets is about 1.6 times the IFOV. For low contrast targets it is appropriate to use 2.4 times the IFOV. These conversion factors are simple to employ and suggest a reasonable method for comparing electro-optical and optical sensor performance, provided one is willing to accept the inadequacies of both IFOV and photographic resolution as measures of performance. Based on the predicted ground resolutions of 12-50 m for the LFC and Metric Camera, the IFOV's required for a scanner designed to provide image data of approximately equivalent low contrast resolutions range from 5 to 21 m.

The sampling frequency represents the ground or image distance between radiometric samples. For image tubes and scanners such as the RBV and MSS which generate a continuous signal, their signal will normally be sampled at a rate equivalent to 1-2 X the scan line width or IFOV. Thus, for the MSS with a 76 m IFOV, sampling occurs every 57 m in the cross-track direction or 1.4 X the IFOV (Slater, 1979). In the in-track direction sampling occurs at a nominal distance of 79 m, giving substance to the pixel dimension of 57 x 79 m. The RBV format of 25.4 x 25.4 mm for Landsat-3, on the other hand, contains 4,125 scan lines and 4500 cross-track samples are recorded per scan line.

Information theory dictates that in systems such as these, optimum data quality requires 2 samples per IFOV. Lesser sampling intervals may degrade image quality slightly, but this degradation may be preferred when weighed against the higher data rates required for closer sampling intervals.

With line array cameras, there is one detector element per sample in the cross track direction and the minimum detector size in the image plane is limited to about 15 μm. All detectors are exposed simultaneously and the charges generated are clocked out sequentially, much like a bucket brigade (Figure 5). A readout time of about 2-3 milliseconds per line is required to offset the high forward velocity of the satellite (e.g. 6.5 kms-1) and to allow the independent recording of successive lines. This is the "pushbroom" mode of operation (Dowman, 1979).

The number of gray levels (quantization) in an image are represented in terms of "bits," and the data from sensors utilized or planned for earth resources applications are normally encoded to 6 (64), 7 (128), or 8 (256) bits. Studies by Ferneyhough (1975) of IBM have indicated that encoding to 5 or 6 bits is required to obtain maximum information from image data by visual interpretation. However, there appears to be a negligible improvement in image interpretability when more than 6 bits are employed (Figure 6). Investigators working with digital data, on the other hand, have expressed a need for 8 bit encoding (as planned for the Thematic Mapper) which is equivalent to a radiometric resolution of better than 0.5 percent over the radiance interval. The value of 8 bit data for computer assisted thematic classifications remains to be



, 5 Schematic diagram of a line array camera system. Along track coverage is generated by the forward motion of the satellite.

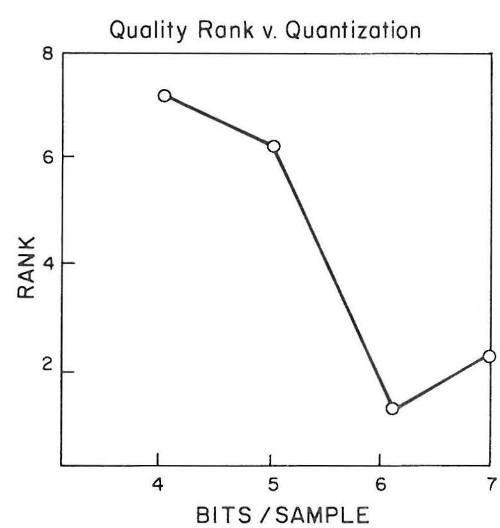


Fig. 6 Rank of image quality as a functi , of bits/sample (Ferneyhough, 1975).

demonstrated, and some investigators have pointed out that temporal variations in object radiance exceed 0.5 percent and that it is difficult to achieve ground instrument accuracies of this magnitude (Slater, 1977). Consequently, there may be some redundancy in the data.

Signal-to-noise ratios in excess of 4 are generally required for the reliable detection of objects. For equivalent IFOV's, the line array sensor systems planned for the 1980s exhibit better signal-to-noise characteristics than do mechanical scanners such as the MSS and Thematic Mapper (Figure 7, Thompson, 1979). Further information on signal-to-noise ratios, as related to visual interpretation, is presented in the section, Measurability and Detectability of Photographic Details.

The recognition that an IFOV of given spatial dimensions plus its radiometric fidelity may determine the quality of image data, has led some investigators to believe that new measures of resolution are required. One such measure proposed by Colvocoresses (1979) is the effective radiometric resolution element (ERRE). The problems associated with defining an ERRE are considerable and some of the complexities associated with the ERRE concept are addressed by Strome (1980).

MEASURABILITY AND DETECTABILITY OF PHOTOGRAPHIC DETAIL

Studies of the measurability and interpretability of image detail for photogrammetric applications were previously reviewed by Welch (1975) and Trinder (1978). The following aspects were discussed:

1. Theoretical precision of measurement to circular photogrammetric targets, and the appropriate weights to be applied to coordinate measurements in aerial triangulation;
2. Accuracy of image edge location;
3. Detectability and recognition of detail.

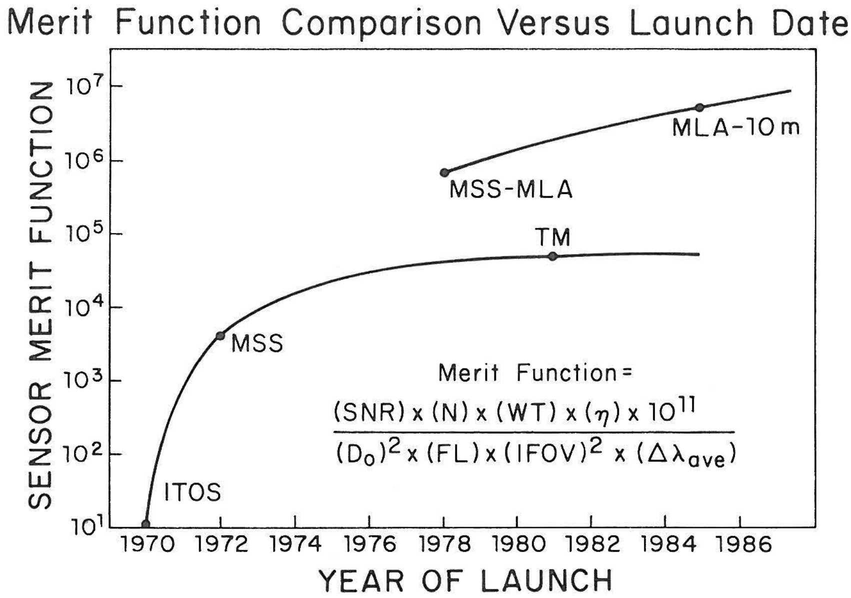
Trinder's 1980 report reveals that considerable work remains to isolate the effects of factors associated with these visual tasks. These factors may be grouped as follows:

<u>GROUP 1</u> Physical Factors of Image Formation. These include the camera lens, film, image movement and film granularity. The observation conditions must also be considered, including quality of the observation optics, optical magnification, field-of-view and illumination.

<u>GROUP 2</u> Psychophysical Factors. These factors are associated with observer performance under the different physical conditions, i.e. quality and size of target, image content etc.

<u>GROUP 3</u> Psychological Factors. Variables such as length of observation period, perhaps leading to fatigue and emotional aspects which may affect performance. This last group of factors is difficult to study and is not the subject of this discussion.

A major objective is to relate the factors of Group 1 to those of Group 2. Typical parameters employed for this purpose include the Frequency Limit (FL), size of the spread function, and resolving power (determined from standard resolution charts). Each of these parameters



.ig. 7 Merit function developed by Thompson (1979, indicates superiority of linear array (MLA) sensors for the 1980's.

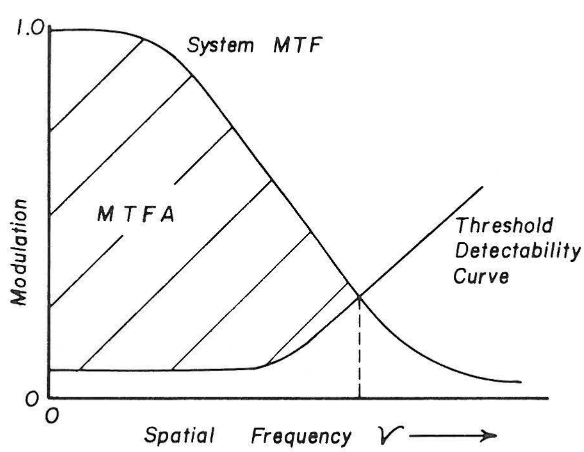


Fig. 8 The MTFA concept.

suffers from limitations, however, more acceptable parameters have yet to be found. It is important that the Working Group arrive at a reasonably simple means of assessing the measurability and detectability of recorded detail based on the characteristics of the imaging system. Some approaches to this problem are summarized in the following paragraphs.

MTFA Concept

One proposed parameter or summary measure of image quality discussed by Charman and Olin (1965) and by Biberman (1973) is the Modulation Transfer Function Area (MTFA), the area between the MTF curve and the threshold detectability (or modulation) curve of the total system including the eye, as shown in Figure 8. High correlations were found by experimenters between the MTFA and the ability of observers to interpret details. Granularity was not a significant factor, but it is not clear what optical magnifications were used for the experiments. These findings, however, are important as they demonstrate that a measure of image quality involving all relevant spatial frequencies may be applicable to such studies. The method has also proved successful in studies of target recognition on raster scan images.

The MTFA has the advantage that all relevant spatial frequencies are considered in the computation, and therefore in the image assessment model. Recent studies postulate that the visual system discriminates intensities independently within specific spatial frequency channels over a certain limited band width (Graham 1977). Consequently, a consideration of the reaction of an observer to all spatial frequencies inherent in the image is important.

Methods Based on Signal-to-Noise Ratio

Many visual display media are subject to small random fluctuations in intensity which are due to physical characteristics of the image formation process; for photography it is referred to as granularity of the emulsion. The viewed image may be considered in a similar way to that in which communications engineers treat noisy communications channels, based on the ratio of the strength of the signal over the noise component, i.e. the signal-to-noise ratio.

...is approach has been pursued by many researchers in the field of visual detection. For example, Barnard (1972) in his study of recognition of a number of discrete targets--Landolt-C, numerals and Stokes-type targets--found agreement between experimentally determined probabilities of target recognition and predicted possibilities based on signal-to-noise ratios. Neville and Saunders (1974) and Hempenius (1964) have effectively used the ratio of contrast of the object and RMS granularity without reference to the frequency domain.

Hufnagel (1965) has studied several formulations which have proved to be linearly related to subjective ranking of image quality. Each contains some or all of the elements of the MTF of the photography, the noise power, and the MTF of the eye.

Parameter 1

$$\frac{\int T(\nu)d\nu}{1 + \beta \int N(\nu)\ T(\nu)^2 d\nu}$$

Parameter 2

$$\frac{\int T(\nu)^2\ T^2_{eye}\ (\nu/m)d\nu}{1 + \alpha \int N(\nu)\ T^2_{eye}\ (\nu/m)d\nu}$$

where $T(\nu)$ refers to the MTF of the photograph
$N(\nu)$ is the noise power spectrum
$T_{eye}\ (\nu/m)$ is the transfer function of the eye for a viewing magnification m
α and β empirically determined constants.

Hufnagel stated that in the absence of grain, modulations of 0.04 to 0.1 were significant. As grain increased, higher modulations were important, while in the presence of extreme grain visual performance becomes independent of MTF, being dependent only on grain, image contrast and certain secondary factors. These statements may be interpreted in the following way.

As grain increases the signal-to-noise ratio of the image decreases leading to impaired visual performance. This is presumably a function of both the quality of the image (determined by the MTF of the imaging system) and the granularity of the photographic material. Thus, at high spatial frequencies, low modulations are obscurred by granularity. At the limit of perception visual performance is inhibited because the signal-to-noise ratio drops below a threshold.

A parameter incorporating the MTFA together with a detectability curve which is subject to variation in position, depending on the signal-to-noise ratio, would appear to be an appropriate approach in the formulation of Hufnagel's statement. The basis of this method is shown in Figure 8, where the threshold detectability curve may be moved horizontally and vertically as a function of granularity and object modulation respectively. A method for determining the magnitude of these translations, however, has yet to be determined.

Significance of Optical Magnification

Few studies on visual performance by photogrammetrists have considered the optical magnification of the observation instrument as a variable. Hempenius (1964) incorporated it in his method of image assessment, which was the basis for the determination of pointing precisions in the presence of granularity. Further studies by Trinder (1978) revealed that pointing precisions in some cases were worse for optical magnifications of 20x than for 10x depending on the quality of the image.

Neville and Saunders (1974) and Charman (1977) indicated that the optimum viewing magnification should be equivalent to 0.5x the maximum resolving power (expressed in lpr/mm). In studies of the optimum magnifications for conducting height measurements from satellite images, Welch and Lo (1977) established the equation:

$$\text{Opt. Mag.} = 0.7R+7$$

where, R = low contrast image resolution in lpr/mm.

As magnification increases, the effect of granularity also increases (equivalent to scanning film with small aperture) and therefore the signal-to-noise ratio decreases, with a consequent effect on visual performance.

However, under high magnifications, an observer's ability to discriminate fine details in the absence of grain improves. Consequently, there exists an optimum magnification for viewing determined by these two conflicting factors of granularity on the one hand and improved detectability on the other. Clearly, if the optimum magnification is exceeded visual performance will deteriorate and granularity will impair the observer's ability to discriminate detail on the photographic image.

CONCLUSION

The activities of WG 1/1 indicate that OTF/MTF analysis techniques are considered reliable for evaluating lenses and sensor system performance. They also provide a basis for assessing image quality and the measurability and interpretability of image detail.

For the period 198-84, it appears that the activities of WG 1/1 should be extended to consider the following subjects of interest:

1. Measures of performance for the sensor systems planned for earth satellite missions;
2. Interrelationships between IFOV, sampling intervals, quantization and signal-to-noise ratios, and their influence on the interpretability and measurability of image detail in both analog and digital formats;
3. Satellite sensor performance levels required to insure recording of adequate detail for the compilation of maps in the 1:25,000 to 1:100,000 scale range, and for thematic studies of earth resources;
4. Assessment of the interrelationships between spatial and radiometric resolution, and the possibilities for defining measures of resolution which encompass both attributes;
5. Possibilities for improving image resolution through data compression, digital enhancement and processing techniques (e.g. Schowengerdt, 1980).

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