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COMMITTEE ON THE PEACEFUL USES OF OUTER SPACE

CHARACTERISTICS AND CAPABILITIES OF SENSORS FOR EARTH RESOURCES SURVEYS

Study prepared by the Committee on Space Research (COSPAR) of the International Council of Scientific Unions

(Comparison of the resolution of photographic cameras and instantaneous field of view of linescan instruments)

Note by the Secretariat

Addendum

In the report on the work of its fifteenth session (A/AC.105/216, para. 30) the Scientific and Technical Sub-Committee noted the Secretariat report on the characteristics and capabilities of sensors for earth resources surveys (A/AC.105/204). It indicated that it was unable to agree upon specific recommendations on the need for classification of data or the manner in which such a classification may be made. The Sub-Committee, however, noted the suggestion that the work in this field, initiated by COSPAR, could be continued theoretically and experimentally to gather relevant information to relate different classes of data with various applications as well as further elaboration on the relationship of system characteristics, spatial resolution and instantaneous field of view, and agreed that the Secretariat should be requested to submit a supplemental study thereon to the Sub-Committee for consideration at its next session.

Accordingly, the Secretariat requested COSPAR to prepare a study which would deal in particular with:

(1) The instantaneous field of view and the photographic resolution; and

(2) The demonstrated performance of remote sensing systems.

An expert panel was established by COSPAR for this purpose under the chairmanship of Mr. E. A. Godby. Other members of the panel included P. Bhavsar, W. D. Carter, J. N. de Villiers, J. Otterman, W. M. Strome and N. K. Vinnichenko.

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INTRODUCTION

1. In this report the subject of photographic resolution versus field of view has been dealt with in a rigorous manner, using published modulation transfer function (MTF) data for specific sensor systems.

2. During the analysis, certain assumptions have been made regarding the contrast ratio and the target configuration to be taken as "standard". The reader is cautioned against using the results for different target configurations, contrast ratios or instruments without taking into account the possible difference which could affect the conclusions.

3. The subject of demonstrated performance of remote sensing systems has also been amplified over the discussion in the first report by referring to reports resulting from the LANDSAT follow-on studies and from a report by the Indian Space Research Organization. These reports summarize the experience of a large number of investigators from many disciplines and represent present knowledge regarding the usefulness of existing sensor systems for particular applications and the advantages to be gained from using sensors with improved capabilities, including improved spatial resolution.

I. DEFINITIONS

4. For the purposes of this study, certain basic terms are defined as follows (keeping in mind that some of them are defined in more detail in chap. III below).

A. Spatial resolution of an imaging system

5. This is the minimum spatial separation between two objects at which the objects appear distinct and separate on an image obtained from the system; resolution depends on the shape, size, arrangement and contrast ratio of the objects. Spatial resolution if measured with the aid of a test bar target (see below) is the distance between the centre of one bar and the centre of the adjacent bar of the same colour in the smallest test bar target that can just be distinguished on the image.

B. Instantaneous field of view of a scanner (mechanical or push-broom)

6. This is the size of the spot on the ground which just fills the area of the detector of a scanner at the instant of observation. The shape of the instantaneous field of view is dependent on the configuration of the detector; it may not necessarily be square or circular. The instantaneous field of view (IFOV) for the LANDSAT MSS, as defined above, is a square of side 70 m. It should be noted that the scan lines are in fact 79 m apart, and the digital samples along a scan line are quantized every 57 m. The nominal IFOV is usually quoted as the

79 m scan line spacing because of the pixel size in the along track direction which is used to construct an image.

C. Contrast ratio

7. It is the ratio of the brightness of an object in a scene to that of the background. This ratio may depend on the spectral band in which it is measured.

D. Test target

8. This is a specially constructed geometrical arrangement of shapes of a given size and contrast ratio used for determining the spatial resolution of an imaging system. One target that is often used is an arrangement of alternatively light and dark bars of equal width. Examples of 2, 3 and 4 bar targets are shown in figure 1.

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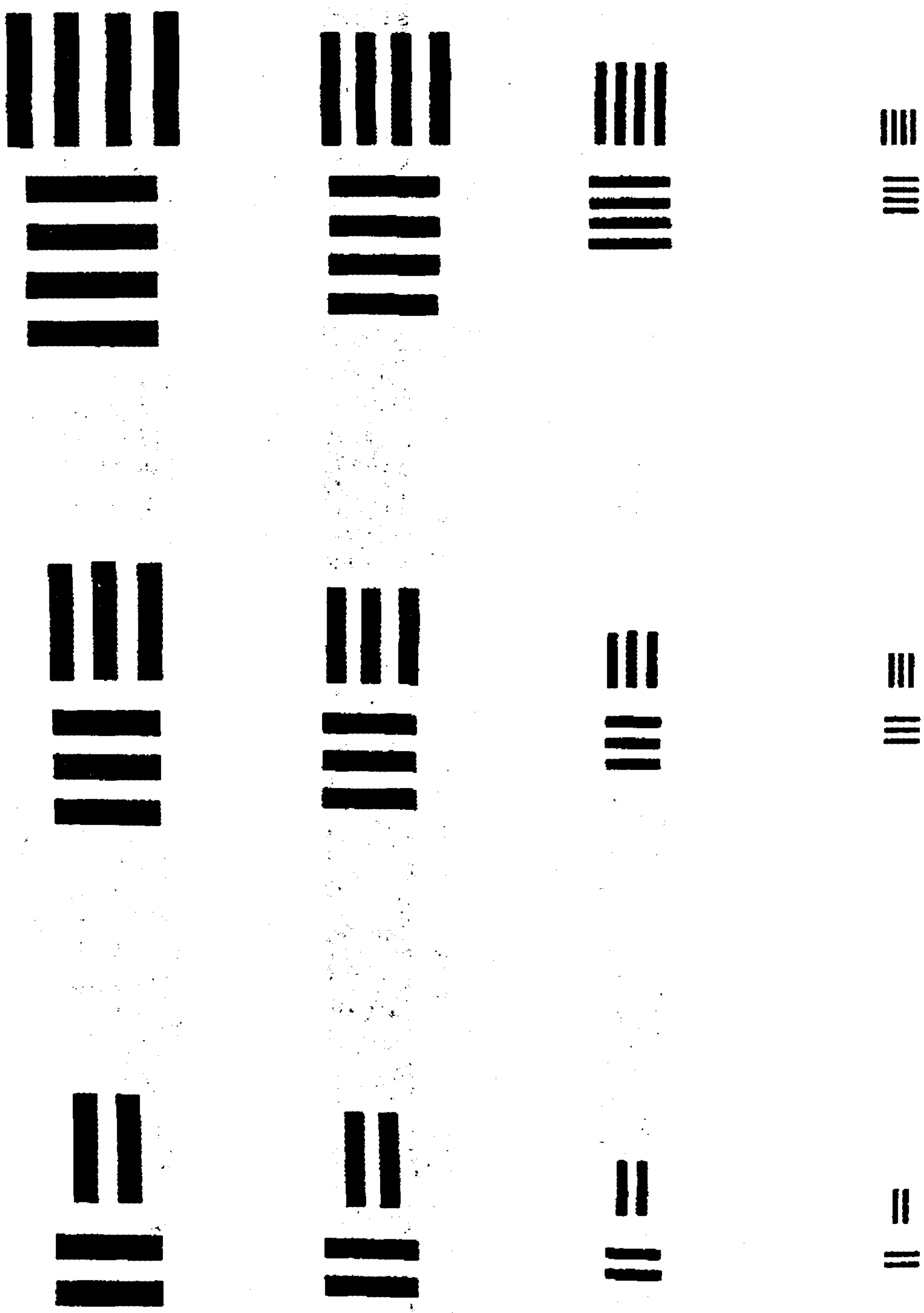

Figure 1

Examples of 2, 3 and 4 bar resolution targets

II. REPORT SUMMARY

9. For the purposes of this study it is assumed that the targets of interest correspond to 2 bar targets of contrast ratio 2:1. For such targets, the analysis which follows predicts that the equivalent photographic resolution of the LANDSAT MSS scanner is equal to the product of its instantaneous field of view and a factor 2 to 2.5. It should be understood that in practice, the value of this factor may differ from the above, as it depends on the real contrast ratic and geometrical arrangement of the objects in the scene and the general brightness of the scene as compared with the full scale sensitivity of the scanner.

10. In examining available studies which dealt with the usefulness of present sensor systems and the advantages to be gained in using systems with improved capabilities, the panel came to the conclusion that higher spatial resolution, greater spectral resolution, improved signal-to-noise ratio, and better radiometric resolution will make an instrument more useful for gathering remote sensing information for use in virtually all applications. However, it is very difficult to quantify these improvements. It appears extremely difficult to accurately separate the expected improvements due to changes in each of the parameters. Moreover, it is not possible to define rigid boundaries of the type of application which will result from arbitrary limits on the various sensor parameters. Rather, there seems to be a gradual improvement in each application as each of the sensor parameters is gradually improved.

III. AN ANALYSIS OF THE RELATIONSHIP BETWEEN THE INSTANTANEOUS FIELD OF VIEW AND THE PHOTOGRAPHIC RESOLUTION

A. The problem

11. Imaging systems are often quoted as having a certain resolution. The nature of the test which measures the resolution is often not given, nor is it possible to translate the resolution to a different situation or target.

12. Often the resolution quoted is for a test situation which yields an impressive result, even though real life situations may seldom have targets of the type used for the test.

13. How does one know whether or not a camera with a given resolution, or a scanner with a given IFOV will discern a given target? And which instrument will be "better"?

14. To help answer these questions, it is necessary to carry out tests on an imaging system to define and measure its performance under known conditions, and to be able to translate these results to another imagined situation.

15. The two most useful performance parameters or descriptors for imaging systems are the MTF and the system response to a specific geometrical target of known contrast.

B. A camera system

1. What is resolution?

16. The resolution of a camera is usually measured by observing the smallest target of a given type that can just be resolved on the film by an observer. Typical targets are 2, 3 and 4 bar patterns of contrast ratios 1.6:1, 2.0:1 and ∞:1. The resolution is usually defined as the centre to centre spacing of like coloured bars in the target that can just be resolved. This definition will also be adopted here, augmented by information on the number of bars and the contrast ratio. It turns out, not unnaturally, that higher contrast ratio bar targets yield superior values of resolution; hence the choice of some manufacturers to quote the resolution figure for high contrast targets. In practice, the low contrast target resolution is much more appropriate to real life.

2. What is the modulation transfer function?

17. It is instructive to look at the performance of a camera system from the MTF point of view. If a sine wave pattern of many cycles is photographed by a camera system, and the image of the pattern on the film is quantified by measuring the modulation (the difference between the intensity of bright peaks and dark valleys), then this modulation remains substantially constant at low spatial frequencies, but decreases as the frequency rises. In fact, a point is reached at which the granularity (or noise) of the film makes it impossible to discern the patterns in the image. The curve obtained by plotting these modulations against the spatial frequency, if normalized with respect to the modulation at very low spatial frequencies, is called the modulation transfer function of the system (or MTF for short). (Usually the spatial frequencies against which the MTF curve is plotted are those appropriate to the image plane; it is easy to convert them to those of the object plane, for any given situation, using the value of the image scale factor.) One can, and often does measure the MTF of the individual components of a camera film system, and the over-all MTF is obtained simply by multiplying together the individual contributions at each value of spatial frequency.

3. The MTF of a camera film system

18. The over-all MTF of a camera film system is the product of the MTFs of the system's three component parts:

(a) The lens (with filter, if appropriate);

(b) The film;

(c) The duplicating film if the original film is not considered to be the output medium.

Figure 2 and table 2 show the MTF of the lens of the S-190B earth terrain camera on Skylab, together with the MTFs of the various original and duplicating films employed. It can be seen that the MTFs of the black and white films are superior to that of the lens, while those of the colour films are inferior to that of the lens. (These data are taken from Welch, 1976.)

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19. The MTF of a camera film system can conveniently be measured in the following two ways:

(a) By photographing a series of extended sinusoidal patterns of different spatial frequencies;

(b) By edge analysis.

20. The former method is obvious. The latter is a technique perhaps more familiar to those versed in the use of Fourier Transforms as applied to linear systems. Basically, it can be shown that if a sudden step from one intensity level to another is used as the input spatial function to an imaging system, the MTF of the system can be derived by Fourier transforming the spatial derivative of the system response. In practice, an image may contain several examples of such steps (coastlines, field boundaries, etc.). Figure 3 shows the over-all MTF curve predicted from laboratory measurements for the Skylab S-190A multiband camera film system for one particular set of original and duplicating films (Welch, 1974). Also in figure 3 is shown the MTF curve as measured by edge analysis of actual Skylab imagery (Welch, 1974) for the same film set. The agreement is good, and shows that few other effects were degrading the system in its operating environment compared to the ideal laboratory situation. In particular, image motion during exposure, which would normally blur the image in the direction of motion, has been fairly effectively removed by the rocking mount that is actuated during exposure to "follow the scene".

21. The MTF of the camera system is not constant over the whole field, usually being best on axis. This is largely due to the superior performance of a lens on axis, although the film additionally spreads the image when the rays hitting it come at an oblique angle, as is the case off axis.

4. Sine wave versus square wave MTF

22. Since it is more convenient to carry out MTF tests by photographing square wave targets to varying spatial frequency, it is of interest to see if the square and sine wave MTFs are related. In fact they are, and this is shown in figure 4 (from Charman, 1964) for the lens of a diffraction limited camera. In fact the square wave MTF is not only "higher", but is comprised of two distinct parts. The region from the zero of the MTF, shown at a normalized spatial frequency of unity, extended back to one third of this frequency is almost exactly a factor $4/\pi$ greater than the sine wave MTF. Why? A square wave can be synthesized from a Fourier series of sinusoids consisting of a fundamental of the same frequency as the square wave, plus odd (and only odd) harmonics. The amplitude of the fundamental is $4/\pi$ times the amplitude of the square wave. In the region mentioned, only the fundamental of the square wave produces an image; the third and higher harmonics are at frequencies where the sine wave MTF is essentially zero. For spatial frequencies below one third of the "zero MTF frequency", the harmonics come back one by one, as one moves to lower spatial frequencies, until eventually the modulation of the image is the same as that of the target. The figure also illustrates the effect of reducing the extent of the square wave pattern to 3 and

finally 2 bars. These latter MTFs (defined as the average modulation between the bars, but not outside them) is hardly different at all from the square wave MTF. (This figure shows quite clearly how the response of an imaging system can vary with the type of target used.)

23. In fact, if the real MTF is a curve that falls smoothly to zero, and effectively remains at zero as the spatial frequency rises further, and if we are given one of the MTF curves, either for the sine wave or the bar test pattern, then we can estimate the other from the $\frac{4}{\pi}$ relationship discussed above.

5. Resolution versus MTF

24. What relationship is there between resolution and MTF? The ability to discern, say, a bar target in an image does not hold as far out as the point at which the MTF falls to zero. It occurs at that lower spatial frequency at which the modulation in the image (the signal) can just be distinguished from the granularity of the film (the noise). One might say that the signal-to-noise ratio has a value of unity. Two things, in the main, determine this. The first is the contrast of the target itself; the second is the granularity of the film.

25. One can introduce the concept of threshold modulation function (the curve of amount of modulation impinging on the film at each spatial frequency required to produce a discernible image) (Charman and Olin, 1965: Lauraesch et al, 1970), and compound this with the MTF of the rest of the system scaled down vertically to account for the lack of contrast in the real target of interest. One arrives at a resolution figure at the point of intersection of the two curves that is identical to that arrived at from carrying out the more straightforward resolution test. The advantage of the threshold modulation function is that it expresses the noise level of the film in the form of a modulation needed at each value of spatial frequency to achieve a signal to noise ratio of unity, and from which one can predict the resolution for different target contrasts. What is of note is that the shape of the threshold modulation function curve is one which is essentially constant at low spatial frequencies, but increases progressively at higher frequencies. This latter rise can be accounted for by the fact that in looking at finer and finer bar patterns, the background area to each bar also becomes narrower and narrower; there is less spatial averaging (or noise reduction) of the granularity, hence a higher modulation is needed for the pattern still to be discernible.

26. Similar effects to those of the threshold modulation function can be obtained by marking the points on the MTF curves for different film combinations in a camera film system which correspond to the resolution (expressed as its inverse in line pairs per millimetre). In figure 5, the laboratory MTFs of the S-190B earth terrain camera lens with three different film combinations are shown, marked with the points as measured in the laboratory at which the resolution limits for a finite bar target occur for two different target contrasts (taken from Welch, 1976). The real modulation on the film would of course have been $4/\pi$ greater since square wave MTF curves should have been used. However, this difference is due to a fixed factor which can be omitted to be completely systematic. First, it can be seen, as may be expected, that lower contrast targets can only be discerned higher up on the MTF curves. Secondly, if one allows for the fact that the

granularity of the 3443 film is twice that of 3414, it can be seen that for a given contrast the modulation level at which the image is just discernible increases with spatial frequency as one moves to "better" MTF curves. Thirdly, it can be seen that granular films need higher image modulation levels for the target to be discernible.

27. Of particular significance is the fact that if the film is not excessively granular, then the limiting resolution points for the different lens-film combinations occur at modulation values on the sine wave MTF curves of as low as 5-11 per cent for the more typical low contrast bar targets. (The corresponding modulation values for the more unrealistic case of high contrast bar targets are slightly smaller.) This observation will be of use in determining the corresponding point on a line scanner MTF curve at which the low contrast bar target resolution is reached.

C. A line-scan system

1. What is a scanner?

28. A line scanner forms an image in a manner similar to a television camera. A point detector at the focal point of a telescope is "swept" across the ground by the motion of a scanning mirror, analogous to the horizontal scan of a television system. The size of the detector when imaged on the ground is the IFOV of the system. The motion of the platform, on which the system is mounted, in a direction orthogonal to the mirror scan corresponds to the frame or vertical scan of a television system. In addition, high quality line scanners have their output digitized for ease of data transmission and manipulation.

2. The MTF of a scanner

29. Just as the MTF of a camera film system was considered in 3.2.3, so also can the MTF of a scanner be developed. Again, the over-all MTF can be obtained by multiplying together the individual contributions. It is necessary to consider the MTF in the two orthogonal directions of:

(a) Along a scan line;

(b) At right angles to a scan line;

as the very nature of the scanning process leads to anisotropic effects in the image data. For the purposes of illustration, it will be convenient to consider the multispectral scanner (MSS) in LANDSAT-1, 2 and 3.

30. The MTF of the MSS along a scan line has contributions due to:

(a) The optical system (corresponding to the lens of a camera);

(b) The spatial averaging effect of the detector dimension across track;

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(c) The electrical low-pass filter to remove high frequency noise from the detector output which lies outside the signal band, and to reduce an effect known as aliasing in sampled systems;

(d) The averaging effect in reconstituting an image due to sampling the data at discrete points;

(e) The averaging effect of the finite width of the spot in the film recorder used to convert the data into an image.

31. The MTF at right angles to the scan line has contributions due to:

(a) The optical system;

(b) The spatial averaging effect of the detector dimension along track;

(c) The averaging effect in reconstituting an image due to the sampling action of distinct scan lines in the along track direction.

32. The over-all MTFs are shown in figure 6. It is of course no accident that they are almost identical. (The laboratory performance before flight was in accordance with these curves, as the specifications for the MSS required that the MTF be not less than 0.3 at a spatial frequency of 7.3×10^{-3} cycles per metre (at orbit altitude) both along and across track.)

3. The resolution point of the MTF curve

33. In the camera film system, one of the factors that limits resolution is the noise or granularity of the film. With the scanner system this is exchanged for other forms of limiting noise. The film on which the scanner image is finally formed need not degrade the scanner resolution at all. One is free on the one hand to enlarge the image electronically to avoid being limited by the resolution effects of the film, and on the other hand to amplify the data radiometrically to avoid being limited by the granularity of the film. However, one is still limited by one or the other of two effects. The first effect is due to the quantization interval of the digitizing processes; for example, signals with a modulation even at low spatial frequencies of about one quantization level will not be distinguishable as having modulation. The second effect is due to the noise inherent in the data themselves, which, depending on the channel being considered the health of its detector(s) and the gain mode employed, may be less or more than the quantization level. In general, the scanner noise turns out to be less than the quantization effect. Some more subtle effects may also occur, e.g. the inherent mismatch between the six detectors of a band which careful computer processing can minimize but never completely remove. (This effect is responsible for the inherent six-line banding effect in LANDSAT imagery.)

34. A high contrast bar target which at low spatial frequencies would cause the bright bars to be close to a full scale signal of 64 quantization levels and the dark bars to be close to a zero signal, might be expected to be discernible at a modulation corresponding to three quantization levels.

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35. The corresponding spatial frequency is approximately 10^{-2} cycles/metre, and its inverse (the resolution) is 100 metres. A lower contrast target (contrast ratio 2:1, which is more typical) might need to produce a modulation nearer to 0.3, corresponding to a spatial frequency of 7.3×10^{-3} cycles/metre, or a resolution of about 140 metres. These two sets of figures should be compared with the IFOV of the detectors of 70 metres. Thus the two resolutions suggested are 1.4 times and twice the IFOV.

36. There is, however, an effect which tends to argue that the resolution figures are optimistic. A LANDSAT MSS image consists of rectangular array of blocks of dimensions 57 m x 79 m. (The distance between samples is 57 m and the line to line spacing is 79 m.) The resulting mosaic constitutes a form of spatial noise when attempting to discern a given form of target. A subjective judgement based on the authors experience is that the resolution figures should, therefore, be relaxed from 1.4 times and twice the IFOV, to 1.6 and 2.4 times the IFOV. It should be noted that the predicted resolutions assume that the brightnesses of the different parts of the target encompass a significant portion of the scanner's radiometric dynamic range. If the general brightnesses were low, the resolution figures would have to be relaxed yet further. These results are summarized in table 1.

Table 1

LANDSAT 1, 2, 3 predicted resolution performance for a standard 2 bar test target

	Instantaneous field of view (IFOV)	Basic resolution R	$\frac{R}{IFOV}$	Resolution adjusted for spatial sampling R'	$\frac{R'}{IFOV}$	Resolution for low brightness condition
Low contrast (2:1) standard 2 bar target	70m	140m	2	170m	2.4	Degraded further
High contrast (∞:1) standard 2 bar target	70m	100m	1.4	110m	1.6	Degraded further

D. The response of cameras and scanners to real scenes

37. The response of cameras and scanners to real scenes can only be predicted from a knowledge of the relevant system parameters for relatively simplistic "targets".

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38. For purposes of illustration, let us postulate a real life target to be divided highway in which the width of the median is the same as the width of the pavements. Further, assume that the pavements have a uniform reflectance of one value, and that the median and surrounding ground have a uniform reflectance of a second value (e.g. dark pavements and highly reflecting vegetation in a near infra-red portion of the spectrum). What we have postulated is a classical two bar square wave resolution target. We might also postulate, as a similar target, two docks jutting out into water where the width of each dock equals the space in between. The question we wish to ask is:

> "For a given low or high contrast version of these targets of a given size, what camera film system resolution, or scanner IFOV is needed to discern that there are two roadways or docks?"

39. The answer can now be predicted fairly easily. For the camera film system, the resolution has to be at least as good as the distance between the centre lines of the roadways or docks, the resolution figure being that for the appropriate target contrast. For the scanner case (assuming the LANDSAT MSS), the IFOV should be about 1/1.6 of the centre line spacings of the roadways or docks for the high contrast case, and about 1/2.4 of the spacing for the low contrast case, assuming the target brightness is a significant fraction of the scanner radiometric full scale sensitivity.

40. Put another way, with the LANDSAT MSS, one would expect to discern as distinct bars those 2 bar patterns with centre to centre spacings of about 1.6 times the IFOV for the high contrast case and about 2.4 times the IFOV for the low contrast case, provided the target brightness is a significant fraction of the scanner radiometric full scale sensitivity.

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Figure 2

MTFs for the S-190B ETC lens and the Eastman Kodak films employed to record and duplicate ETC photographs (from Welch, 1976. Film characteristics are given in table 2 below.)

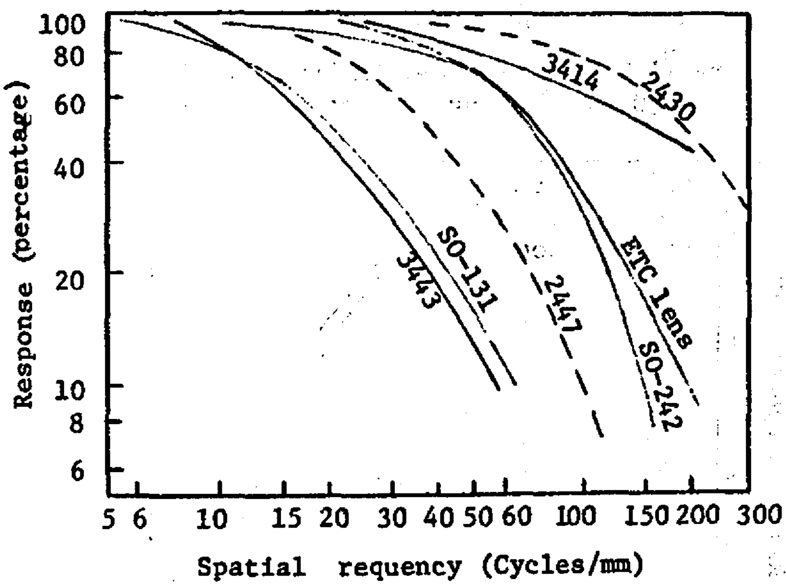


Table 2

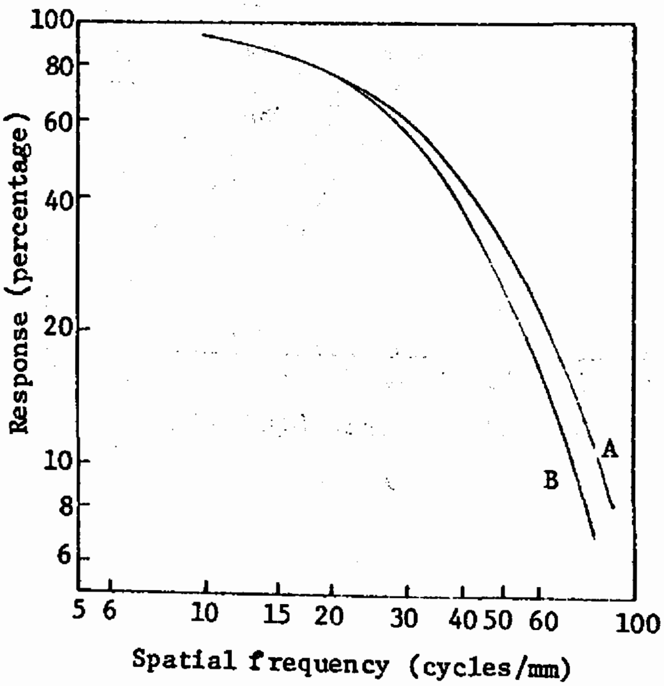
Image structural properties of Eastman Kodak films (1973-1975) (from Welch, 1976)

EK Film	Resolving ower (ℓpr/mm) CR 1000:1	CR 1.6:1	Granularity	Comments
3414	630	250	8	Panchromatic
SO-242	200	100	11	Colour
SO-131	160	50	9	Colour IR
3443	63	32	17	Colour IR
2430	320	125	7	Duplicating film for 3414
2447	100	50	9	Duplicating film for SO-242 and SO-131

CR = Contrast radio

Figure 3

Over-all MTF for the S-190A lens/SO-22 film/2430 duplicating film combination



A = Predicted MTF

B = Measured MTF

Figure 4

MTF curves for a diffraction limited lens with the various resolution targets indicated (from Charman, 1964)

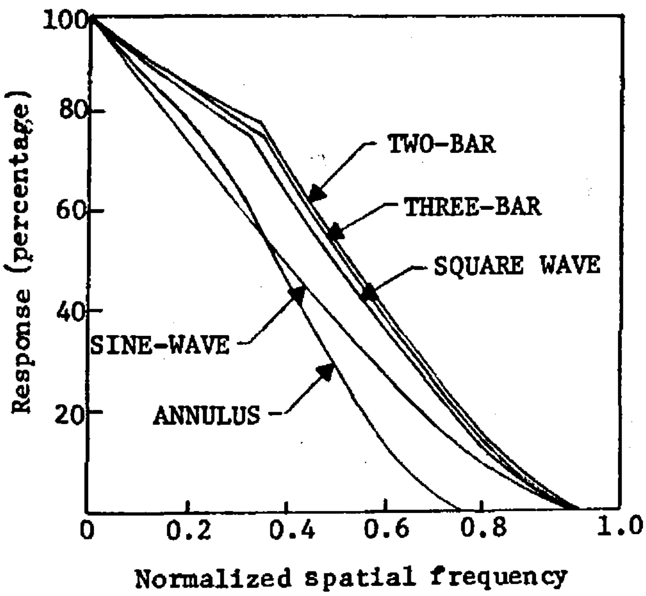
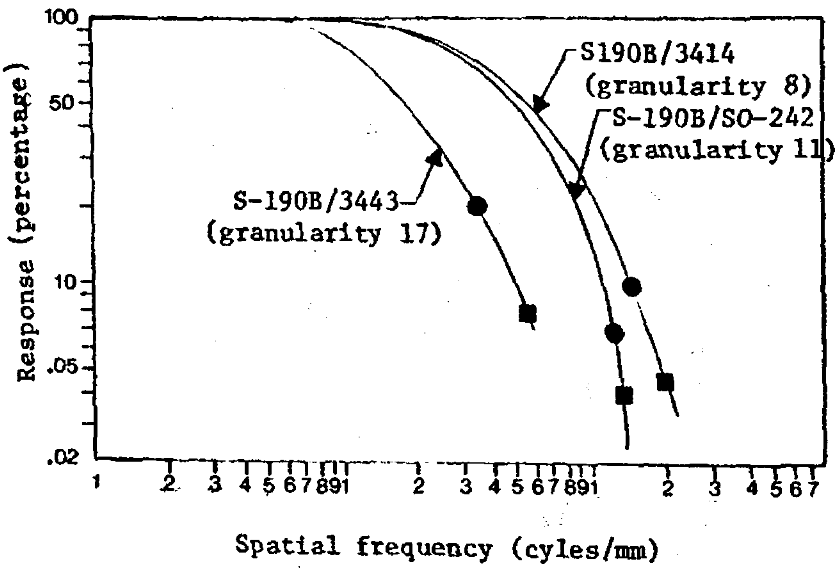


Figure 5

MTFs of S-190B with 3414, SO-242 and 3443 films, together with bar target resolutions (from Welch, 1976)



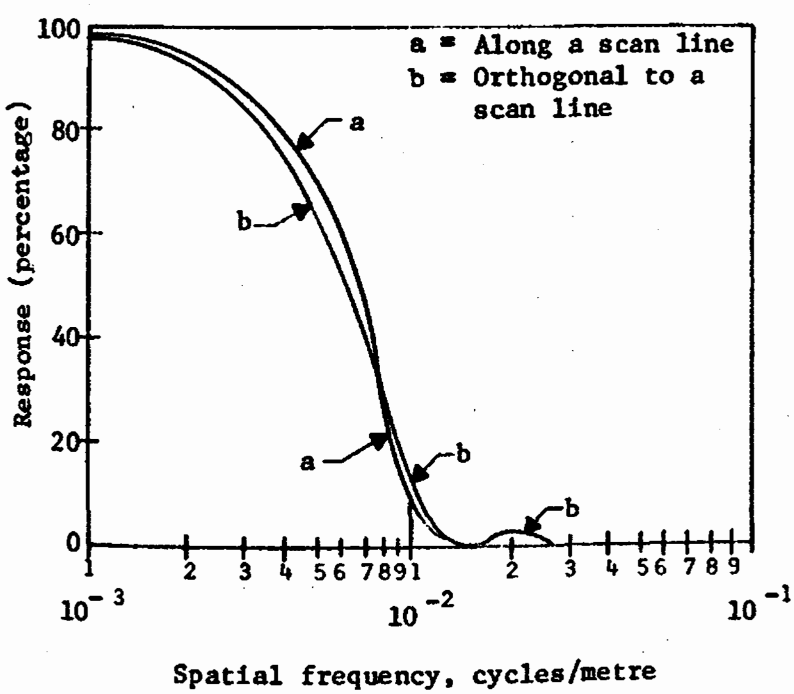
■ Area weighted resolution
1000:1 contrast bar target

● Area weighted resolution
2:1 contrast bar target

Figure 6

MTF of LANDSAT MSS

(Private communication)



IV. EXPERIMENTAL RESOLUTION TESTS

41. To test the conclusions arrived at in the above section, the panel members made tests of resolution using imagery of varying nominal resolutions taken over one area.

42. The imagery used was (a) NASA high altitude 65,000' aircraft photo No. 0104 (2 February 1962) taken with a 12-inch lens. Nominal photographic resolution is 15 m, (b) LANDSAT MSS image E-30117-15075 band 5 (red 0.6-0.7 μm of the Washington D.C.-Baltimore Md. area (30 June 1978) (IFOV 70 m) and (c) LANDSAT III return beam Vidicon subscene (E-30117-15075-A) covering one quarter of the area of the above LANDSAT scene.

43. The aircraft data was used to select and measure the dimensions of features corresponding as closely as possible to a two bar test target. Divided highways and parallel taxi strips and runways at Dulles airport provided targets varying in width from 60 m to 216 m. The results are as follows:

Table 3

Experimental resolution tests

Target	Separation*	Performance	
		Return beam Vidicon	Multi spectral scanner
Parallel roadways running into Dulles airport	60 m	just resolvable	not resolvable
Two parallel taxiways	96 m	easily resolvable	not resolvable
Divided highway	120 m	easily resolvable	just resolvable
Runway with parallel taxiway Dulles airport	216 m	easily resolvable	easily resolvable

* Measured from the air photograph.

44. These tests, although limited in scope, do support the results shown in table 1, i.e. that the MSS can resolve 2 bar pattern with spacing in the range of 110 m to 170 m depending on the target contrast ratio.

V. EXPECTED PERFORMANCE OF IMPROVED REMOTE SENSING SYSTEMS

45. A number of studies have been conducted to evaluate the expected improvement which might be achieved in many applications as a result of the use of the LANDSAT-D thematic mapper (TM) compared to that of the LANDSAT-1, 2 and 3 multispectral scanner system (MSS). These studies can provide some insight as to the differences of utility of various systems with different sensing capabilities.

46. The TM is planned to have improvements in spatial resolution, spectral resolution, signal-to-noise ratio and radiometric resolution over the MSS. The TM will have more spectral channels. The parameters of the two instruments are compared in table 4. (JPL, 1976.)

Table 4

Comparison of LANDSAT 1, 2 and 3 MSS with LANDSAT-D thematic mapper

Parameter	MSS	TM
IFOV	70 m (nominal 79 m)	30 m 120 m thermal
Radiometric resolution	64 levels	256 levels
Average full scale S/N (near visible)	>50	>100
Spectral bands	0.50-0.60 μm 0.60-0.70 μm 0.70-0.80 μm 0.80-1.10 μm 10.0-12.0 μm[a]	0.45-0.52 μm 0.52-0.60 μm 0.63-0.69 μm 0.76-0.90 μm 1.55-1.75 μm 2.08-2.35 μm 10.4-12.4 μm

[a] LANDSAT-3 only for a very short period of time nominal IFOV 240 m.

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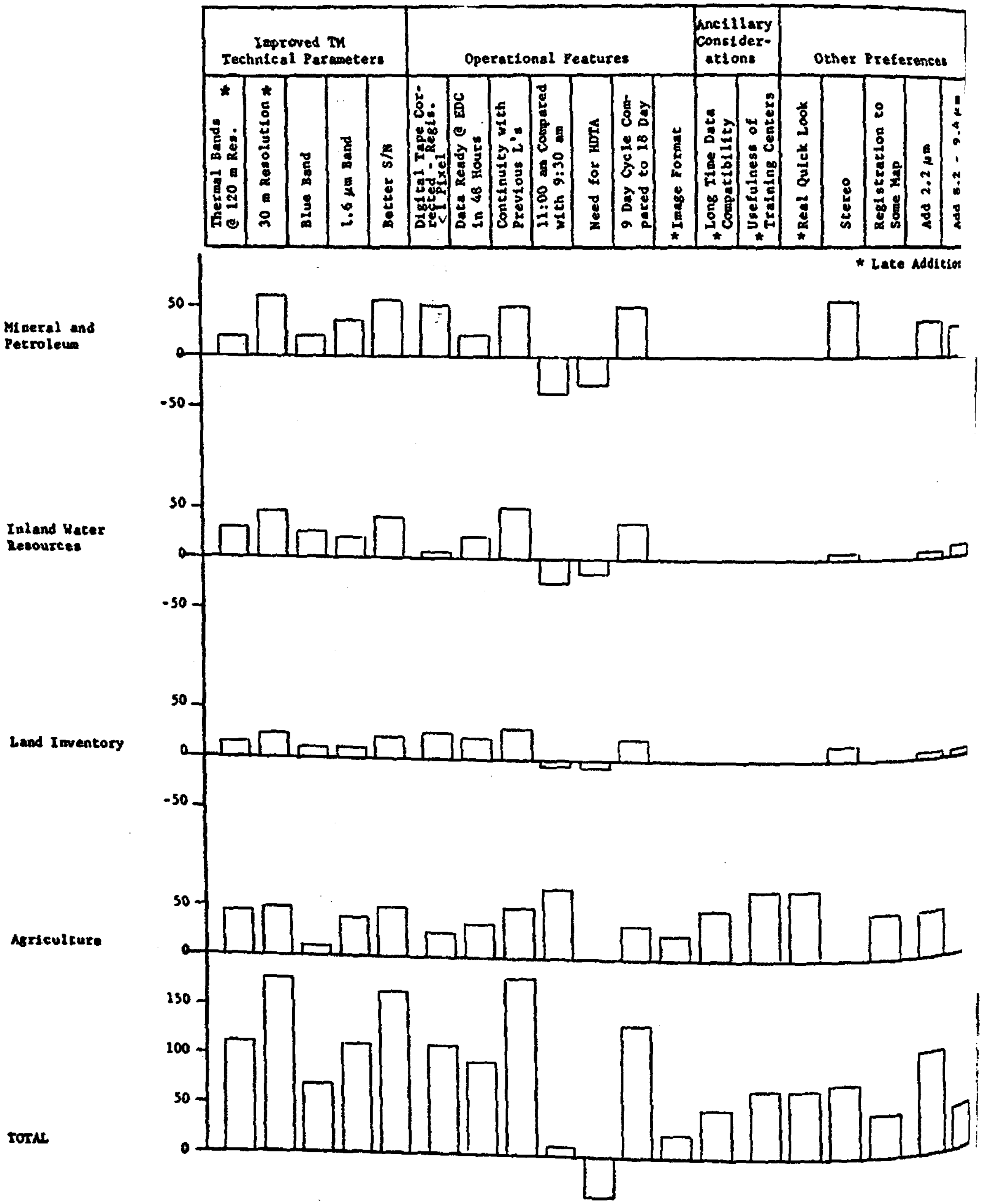

FIGURE 7. PARAMETER ASSESSMENT HISTOGRAM

* "Resolution" as it is used here should read "Instantaneous Field of View"

47. In 1976, the Jet Propulsion Laboratory undertook a study to evaluate the features of the LANDSAT Follow-on Program of the United States from the point of view of "... users attempting profitable use". (Jet Propulsion Laboratory (JPL), 1976). The term "profitable use" was chosen to avoid the problem of trying to distinguish among operational users on the one hand, and those whose raison d'être was the development of technology. Four broad categories of users were considered, on the basis of application discipline. These were: mineral and petroleum exploration; inland water resources; land inventory; and agriculture.

48. In the United States, the total LANDSAT Follow-on Program will result in a large number of changes, not only in the sensor as outlined in table 1, but in the operational procedures involved in transmitting the data to ground reception stations, ground processing and dissemination to the users. The representative users were surveys to ascertain their views on the likely effect of the numerous proposed changes in the system. For each of 80 subapplications, the users rated the expected effects on a scale of -3 (makes data useless) through 0 (inconsequential) to +3 (essential). For each of the four main application areas, the results were summed to provide the data presented in figure 7. As can be seen in this figure, the most important paramaters are improved spatial resolution (to 30 m IFOV) and continuity of data with improved signal-to-noise ratio in third place in relative importance. Other parameter changes which were ranked relatively highly with regard to improving the system's ability to support the various applications considered include: geometric correction of digital data; addition of the 1.6 μm band; provision of the 11 μm band; provision of the 2.2 μm band; and rapid availability of the data.

49. A proposal to provide data on high density digital tapes (HDT) was generally considered to be detrimental to the programme. For many applications, later equator corssing time (11.00 a.m. instead of the current 9.30 a.m.) was considered detrimental, although this was balanced by agricultural users who felt coverage later in the day would be an asset.

50. A study carried out by NASA (Tucker, 1978) compared the choices of spectral bands in LANDSAT-1, 2 and 3, LANDSAT-D, SPOT (CNES, 1978) and Colvocoresses' proposed operational satellite system (Colvocoresses, 1977) for monitoring vegetation. Thirty-five test plots were sampled in situ by spectroradiometric measurement over the 0.38-1.00 μm region every 0.005 μm. After the measurements were made, the plots were clipped of all standing vegetation, which was then subjected to laboratory analysis for total wet biomass, total dry biomass, dry green biomass, dry brown biomass, leaf water content and chlorophyll content. By integration of spectrophotometer readings over each of the bands of the various sensors considered, total spectral irradiance and spectral reflectances were estimated in these bands. Regression analyses provided an indication of the correlation which might be achieved between the observations which could be made with the various satellite systems and the biological parameters of interest. The conclusion reached was that the finer spectral resolution coupled with the proper positioning of the bands in both the TM and SPOT should result in significant improvements over LANDSAT-1, 2 and 3 for remote sensing of vegetation targets.

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51. In Canada, a workshop was held in the spring of 1978, (CCRS, 1978) to consider the probable impact of the improved paramaters of LANDSAT-D over the earlier series. The attendees of this workshop included representative and highly knowledgeable users from the various remote sensing user disciplines. While the workshop did not address the various parameters in the same structured way, or to the detailed level reported in the JPL study, the conclusions reached were generally qualitatively the same. With very few exceptions, all applications are expected to benefit from the higher spatial and spectral resolutions planned for LANDSAT-D and SPOT. Few totally new applications were foreseen, however. It is most likely that some of the marginally useful applications of LANDSAT-1, 2 and 3 data will become more practical with LANDSAT-D. The new 1.6 μm and 2.2 μm bands may be particularly useful in improving the ability to distinguish cloud from snow.

VI. EXPERIENCE IN INDIA WITH SYSTEMS OF DIFFERENT CAPABILITIES

52. In India several workers have studied LANDSAT imageries for their applicability in different fields of remote sensing applications. Studies are also being conducted for defining and designing a domestic remote sensing satellite system for the early 1980s. As a first step, India's experimental satellite, satellite for earth observations (SEO), is getting ready for an early 1979 launch. This satellite will look at the earth through two television cameras, in spectral bands 0.54 to 0.66 um and 0.75 to 0.85 um, with a ground resolution of about 1 km. To understand the possible capabilities of SEO imageries, simulation studies have been conducted by generating simulated SEO imageries out of LANDSAT scenes. Comparative studies of the usefulness and imaging quality of aircraft camera photos, aircraft MSS, LANDSAT, simulated SEO and NOAA imageries have also been conducted, and a detailed report has been prepared by Bhavsar (1978). The findings can be summarized as follows.

A. Detectability of topographical details in LANDSAT imagery

53. In LANDSAT imagery, when appropriately enlarged for comparison with a 1:250,000 scale topographical map, streams appearing on the map were visible; large townships showed up only vaguely; major roads and railway lines showed up only at a few places and most of the time could not be detected unless a map was used as a guide; water bodies were clearly seen but a dam or a reservoir was identifiable only by inference; forest areas showed up clearly in bands 5 and 6 and villages and habitated areas consisting of settlement of small huts were not identifiable.

B. A study of the effect of scale and resolution changes on visual interpretation of imageries

54. The results of a study conducted through the examination of aircraft photographs, LANDSAT imageries, and a few RBV imageries of LANDSAT-3 of the same region, using the standard visual interpretation techniques, are summarized in tables 5 and 6.

C. Computer-assisted LANDSAT imagery studies

55. Computer-aided studies, utilizing the standard digital image interpretation techniques, of the LANDSAT imagery, have been made. Colour composites made using MSS4/5, MSS5 and (MSS 6 + 7) have shown that this process enhanced the detectability of vegetative cover, and especially the drainage patterns having vegetative covers stood out. This example points to the value of combinations of spectral bands in recognizing features of interest more clearly. Comparison of false colour composites with topographic maps at 1:100,000 scale showed that significant changes in landscape could be detected when spectral information was used even though the spatial resolution was low. A comparison of LANDSAT imageries taken at different epochs on a 1:1000,000 scale, have shown that without any special aids a change or displacement of 200 to 500 m could be easily detected.

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Table 5

Results of comparison between LANDSAT MSS and aircraft imageries

SR No.	Object	Tone	LANDSAT MSS	Aircraft imagery
	Non-linear objects			
1	Reservoir (area 15,750 sq.m.)	Grayish-black	A minute pin point (very difficult to identify	Clearly seen
2	Reservoir (area 81,000 sq.m)	Black	A black dot (identifiable)	Clearly seen
3	Reservoir (area 123,750 sq.m.)	Black	A black body (distinct)	Clearly seen
4	Cultivated fields	Gray to grayish-black	Rarely seen	Clearly seen
5	Village (area approx. 15,000 sq.m.)	Grayish-white	Not seen	Clearly seen
6	Small town (area approx. 100,000 sq.m.)	Light white	A white tiny patch (less identifiable)	Clearly seen
7	Trees	Grayish-black	Not seen	Clearly seen
8	Dam	Bright white	Not seen (could be identified from the discontinuity of river waters)	Clearly seen
	Linear objects			
9	Canal (30 m. width)	Black	A hairline linear	Clearly seen
10	Railway line	Grayish-black	A hairline linear	Clearly seen
11	Road	Grayish-white to gray	Rarely seen	Clearly seen
12	Cart track	Whitish gray	Not seen	Clearly seen

Table 6

Comparison of RBV images with MSS images

SR. No.	Object	LANDSAT-1, 2, 3 MSS (80m IFOV)	LANDSAT-3 RBV (40m IFOV)
1	Drainage: fine textured	Not clearly seen	Clearly seen
2	Oxbows (cut off loops)	Fairly seen	More clearly seen
3	Drainage in estuary region	Not clearly seen	Clearly seen
4	Braided channels	Minor braided channels not seen clearly	Clearly seen
5	Relief features of flood plain (levees, low ridges and depressions)	Rarely seen	Seen fairly well
6	Flat surface on the top of the hill	More or less uniform - looks like one unit	Non-uniform - more than one unit
7	Cultivated area	Can be seen	Clearly seen
8	Geological structure	Seen	More clearly seen
9	Railway line	Not clearly seen	Clearly seen

D. Study of simulated lower resolution imageries

56. Simulated low resolution imageries have been generated out of 80 m (nominal IFOV) LANDSAT digital data through computer processing. Studies of such lower resolution simulated imageries corresponding to 160 m and 800 m spatial resolutions, after transcribing into photo products at 1:1,000,000 scale, when used to analyse large uniform forest areas were found to contain most of the information which the original image did have. This was true for colour composites, but the single band black and white images were found to lose interpretable quality. From this study it has been concluded that for the application multiband data with low resolution - like 800 m - give information comparable to high resolution data in a single band. The 800 m resolution data in multiband, containing large forest, when digitally analysed, showed that as many as six cover types were identifiable compared to seven cover types obtained using the original 80 m LANDSAT data.

E. Results of the ISRO-MSS flown on an aircraft

57. ISRO-MSS imagery which is collected in five spectral bands has a IFOV of 15 m and is usually rendered into photographs of scale 1:150,000 or 1:75,000 which are used as reference images. These multispectral data were enlarged to 1:25,000. It was observed that this image of 1/25,000 scale in a single band did not contain sufficient capabilities to allow interpretation of agriculture types of covers. However, when a colour composite using three bands was made, discrimination between the cover types improved. In general it could be summarized that the experience of the Indian workers in the use of satellite and aerial survey data for extraction of resource information pertaining to land-use and agriculture indicates that the spectral information is vitally important in correctly mapping these resources. It has also been observed that, when using aerial imagery, very high spatial resolution was ineffective if suitable spectral signature information was not available. It is also their experience that enlarged LANDSAT pictures to scales 1:250,000 and 1:100,000 do provide information leading to change detection when the pictures are made into colour composites by mixing of spectral bands.

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