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COHERENT OPTICAL DATA PROCESSING AND REMOTELY SENSED IMAGERY

by

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There are no color illustrations in this report.

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This is a report on and evaluation of a specialized data processing system which is relatively recent in development and potentially very useful in the analysis of very large two dimensional arrays such as photographs or other images. The procedure generates a measure of the information content and distribution in the original image termed the power spectrum or spectral density. This measure has already been demonstrated as uniquely powerful in information theory.[1] Two-dimensional applications have been limited, however, because of the need until recently to use digital estimates.

The digital computation of power spectra for large two-dimensional arrays is prohibitively expensive in computer time. Even a very large system would take many hours or days (and several thousand dollars) to compute an estimate of the spectrum of a single digitized photograph.

For this reason, considerable attention has been directed to coherent optical processing, a procedure which generates power spectra in seconds at a unit cost of a few dollars. This report summarizes the principal of such processors, describes the system in the Department of Geography of the University of Toronto, and presents illustrations and discussion of spectra of representative remotely sensed images. It is assumed that the reader has at least some knowledge of the notion of the two dimensional power spectrum and its possible application. The mathematical sections in Part II assume a familiarity with complex notation, but are not formally presented.

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[1] R. B. Blackman and J. W. Tukey, <u>The Measurement of Power Spectra,</u> Dover Publications, New York, 1959.

Coherent optical data processing is a relatively recent development for at least two reasons.[2] First is the necessity for a source of coherent light with reasonable power. Although high pressure mercury vapour lamps could be used for the purpose before 1960, the key stimulus has been the development and commercial production of the helium-neon gas laser in this decade.[3] The second reason is that the possible utility of power spectra of large data arrays has only recently been recognized.

At present, most large American universities have a processor in their engineering or geophysics departments for research purposes, and oil companies use such systems for processing of seismograms on a production basis. The demand is now such that several firms manufacture systems and one is sufficiently large to advertise in SCIENCE.

Part II. The Coherent Optical Processor

Fourier Transforms in Optics

The basis of coherent optical data processing is that Fourier transform relationships exist between the front and back areas of lenses. The principle will be developed in this section in somewhat abbreviated

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[2]It is relatively recent in regular and sustained application. In fact, successful spatial filtering experiments were first reported in 1906. (A. B. Porter, "Diffraction Theory of Microscopic Vision," Phil. Mag., 11: 154, 1906. Cited by E. L. O'Neill, "Selected Topics in Optics and Communications Theory," Technical Note No. 133, Boston University Physical Research Laboratories, 1957).

[3]For a review of the development of gas lasers before early 1966, see A. L. Benson, "Gas Lasers," Applied Optics, 5:1500-14, 1966.

fashion by considering an ideal optical system first to set out the mathematics,[4] then with a diffraction grating in a plane to illustrate the operation on a more intuitive basis.[5] Throughout, it will be considered that the source of illumination is coherent.

A monochromatic wave may be described by its amplitude and phase as a function of Cartesian coordinates. For example

$$E_1 = \iint A(x,y) \cos\left[\omega t + \phi(x,y)\right] dx\,dy$$

where A is an amplitude factor, ϕ a phase factor and ω the radian frequency of the wave. It is conventional in the description of optical systems to represent the wave in complex rather than trigonometric form. Thus

$$E_1 = \iint A(x,y) \exp\left[jk(x,y)\right] dx\,dy$$

where k is the frequency defined by $\frac{2\pi}{\lambda}$ where λ is wavelength of the light. The Fourier property of optical systems that we wish to demonstrate here is that this wave at a plane with Cartesian coordinates u, v, beyond

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[4]A useful reference for optical processing which is mathematically based is L. J. Cutrona, B. N. Leith, C. J. Palermo, and L. J. Porcello, "Optical Data Processing Filtering Systems," IRE Transactions on Information Theory, June, 1960, pp. 386-400.

[5]The author has found the diffraction grating example ideal for simple quick explanations, having had the operation first explained to him in this way in 1967. Others have apparently earlier also found this example useful -- see M. B. Dobrin, A. L. Ingalls, and J. A. Long, "Velocity and Frequency Filtering of Seismic Data Using Laser Light," Geophysics, 30:1144-78, 1965.

a lens is described by an expression of the form

$$E_2 = \iint A(u,v) \exp\left[-jk\,(u,v)\right] du\,dv$$

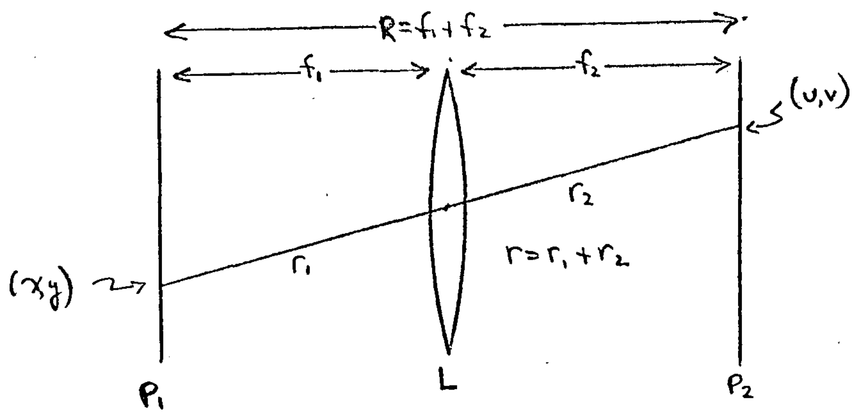

Figure 1

Consider Figure 1. If a collimated monochromatic beam E_1 with coordinates x, y is incident at P_1, then is imaged by lens L on P_2, the calculation of E_2 requires determining the distance between points on P_1 and P_2, since this distance will delay in phase E_1. This distance is given by

$$r^2 = R^2 + (x-u)^2 + (y-v)^2$$

or

$$r = R\left[1 + \frac{1}{2}\left(\frac{x-u}{R}\right)^2 + \frac{1}{2}\left(\frac{y-v}{R}\right)^2 + \cdots\right],$$

$$r = R\left(1 - \frac{xu}{R^2} - \frac{yv}{R^2} + \cdots\right)$$

$$r = \frac{1}{R} - \frac{xu}{R} - \frac{yv}{R} + \cdots$$

This distance r is used in the integral which defines the distribution at P_2.

$$E_2 = \iint I_1(x,y) \exp(-jk)\, dx\, dy,$$

thus

$$E_2 = \iint I_1(x,y) \exp\left[-\frac{jk}{R}(xu+yv)\right] dx\, dy.$$

This reasoning can then be used to determine that

$$E_1 = \iint I_2(u,v) \exp\left[\frac{jk}{R}(xu+yv)\right] du\, dv$$

is the integral at P_1 of the image of E_2.

Considering now the example of a diffraction grating of very fine closely spaced slits, when a coherent light wave is incident in the plane at 90°, each slit is the source of a fresh disturbance and thus a new train of waves (Figure 2).

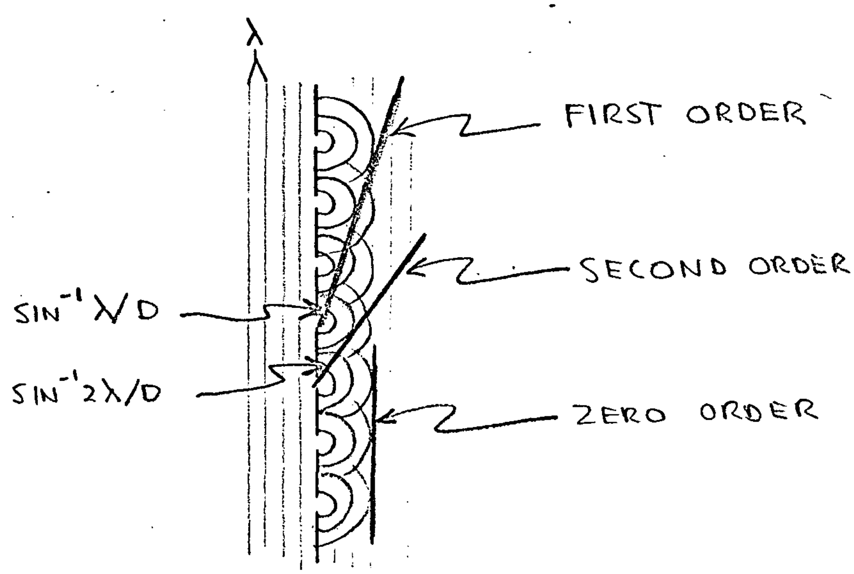

Figure 2

The new disturbances will reinforce each other and form wavefronts in phase for angles where

$$\sin\alpha = n\lambda/D$$

where α is the angle from the normal to the plane and n corresponds to the "orders" of the diffraction, a series 0, 1, 2, 3, 4.... The zero order wave will thus continue in the direction of the incident wave, first order waves will leave at an angle which is $\sin^{-1}\lambda/D$ above and below the normal to the place, and so forth.

When these wavefronts are passed through a spherical lens, they will come to a focus on or around the optical axis of the system, the exact location depending upon the angle of incidence to the lens, and thus the order of the diffraction at the grating. Figure 3 illustrates this for zero, first, and second orders.

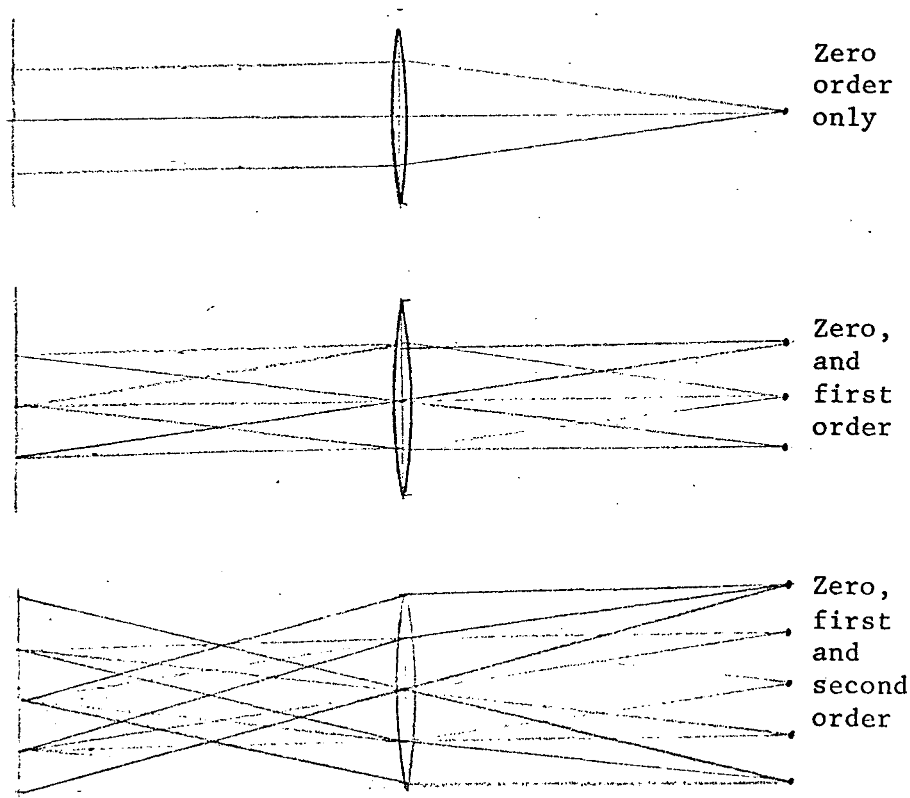

Figure 3

The zero order fronts focus as a dot on the optical axis; this is usually referred to as the dc component. The first and second order waves focus as dots above and below the optical axis at a distance DZ which is close to

$$f_1 \cdot \tan\left(\sin^{-1} \frac{n\lambda}{D}\right),$$

that is, the grating lens distance times the tan of the angle of deviation above or below the normal. For the very small angles involved

$$\sin^{-1} \frac{n\lambda}{D} \approx \frac{n\lambda}{D}$$

and

$$\tan \frac{n\lambda}{D} \approx \frac{n\lambda}{D}$$

therefore

$$Z \approx \frac{f_1 \, n\lambda}{D},$$

that is, the separation of successive higher order dots is inversely proportional to the distance between the grating lines or directly proportional to their spatial frequency. The image thus represents the power spectrum of the line pattern. Disregarding the dc component (which represents the mean normally subtracted in digital computation), there are two strong dots, mirror images of each other, above and below the optical axis corresponding to the principal spatial frequency or wavelength of the grating. There are a further series of dots beyond these two resulting from higher order diffraction of the grating, and corresponding to the harmonics of the basic spatial frequencies. Examining Figure 4, one can see that in the optical system, these higher order dots will have

Figure 4

Example of Optical Processor Output

The four spectra at the right of the page are all of a vertical line pattern, part of which is shown in the upper left corner. The frequencies of the original input image increases, or the wavelength decreases, from the top of the page to the bottom. The frequencies are 16, 25, 37.5, and 50 lines per inch. The first and second spectra are enlarged 2.1 times, the third 3.0, and the last 2.5.

The spectra are also useful to illustrate system precision, in that there is apparent additional information around the dc component, and in one case, frequency 25, there is a fairly strong diagonal effect. These all arise from the nature of the original input diagram - a piece of cardboard with lines ruled with a felt pen. Parts of the original diagram were not so carefully ruled, and thus apparently introduced additional information. The diagonal effect may be due to a fingerprint on the input film.

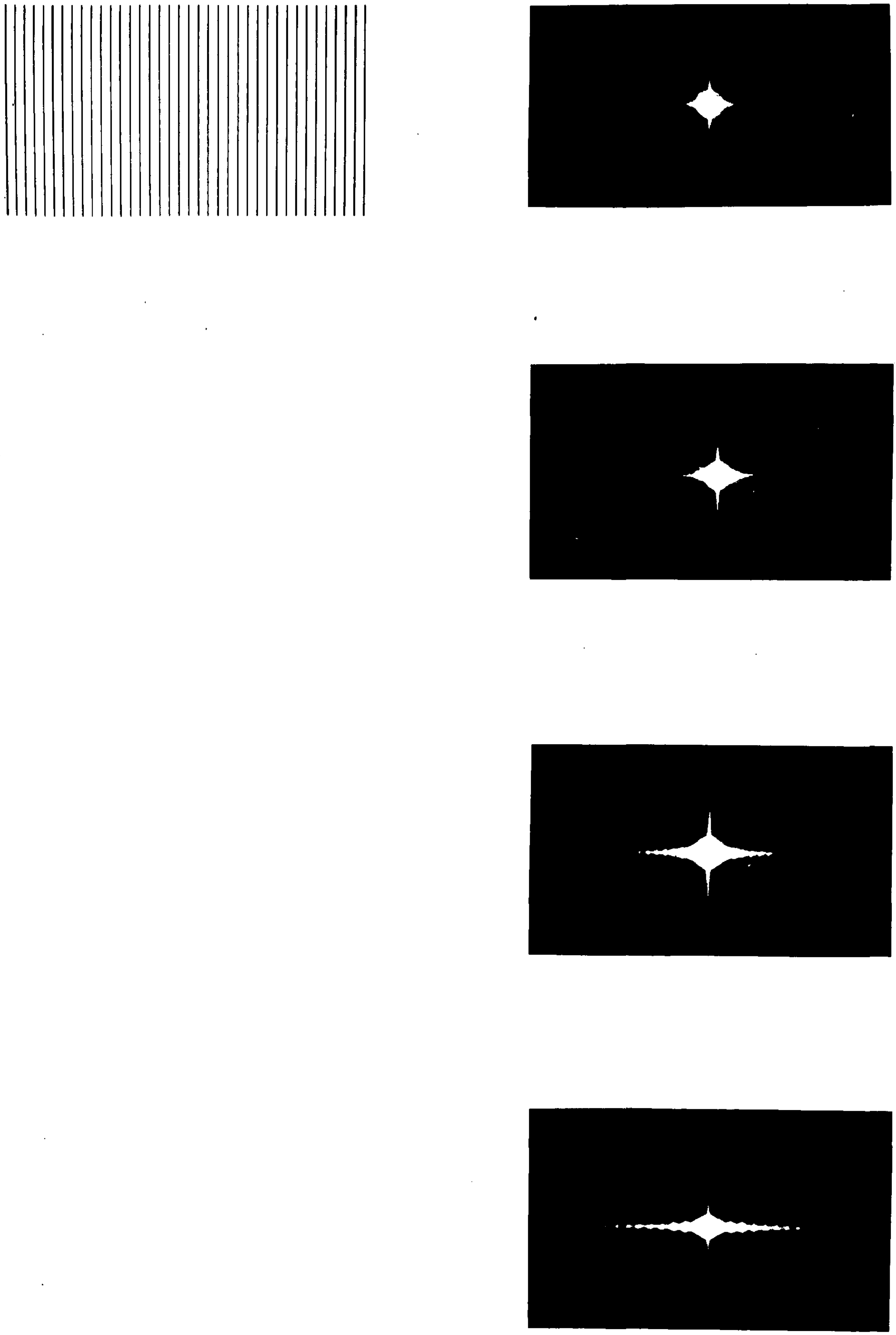

Fig. 4

less intensity because there is less contribution from each slit as the order increases. This result corresponds to what one would expect of the power spectrum of a series of parallel lines.

This example may be presented mathematically[6] by representing the luminance of the diffraction grating (in one dimension for simplicity,) by

$$f(\gamma) = 1 + \frac{4}{\pi}\left(\sin\frac{2\pi\gamma}{p} + \frac{1}{3}\sin 3\frac{2\pi\gamma}{p} + \cdots\right)$$

where p is the grating spacing as indicated in Figure 5. (For further simplicity, the contrast of the object will be ignored).

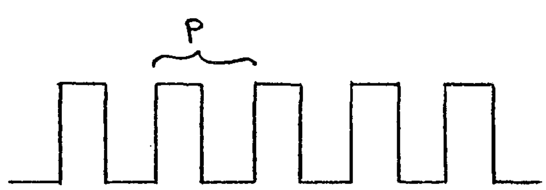

Figure 5

[6]This presentation is set out more completely in M. Francon, Modern Applications of Physical Optics, Wiley, New York, 1963, pp. 65-70.

The expression in trigonometric form may be converted to complex form using the Euler formulas[7]

$$f(x) = 1 - \frac{2j}{\pi}\left[\left(\exp\left\{j\,\frac{2\pi x}{p}\right\} - \exp\left\{-j\,\frac{2\pi x}{p}\right\}\right) + \frac{1}{3}\left(\exp\left\{j\,3\,\frac{2\pi x}{p}\right\} - \exp\left\{-j\,3\,\frac{2\pi x}{p}\right\}\right) + \cdots\right]$$

The Fourier transform is then

$$t(v) = 1 - \frac{2j}{\pi}\left[\left(\exp\left\{j\,\frac{2\pi x}{p}\right\}\exp\left\{j\,2\pi v x\right\} - \exp\left\{-j\,\frac{2\pi x}{p}\right\}\exp\left\{j\,2\pi v x\right\}\right) + \cdots\right]$$

which can be simplified to

$$t(v) = 1 - \frac{2j}{\pi}\left[\exp\left\{j\,2\pi\left(\frac{1}{p}+v\right)x\right\} - \exp\left\{-j\,2\pi\left(\frac{1}{p}-v\right)x\right\} + \cdots\right]$$

This expression is plotted in Figure 6, with the amplitudes as ordinates and frequencies as abscissas. The similarity with Figures 3 and 4 is apparent.

A process similar to this diffraction example takes place in optical data processing to generate power spectra. Instead of a grating, a transparency is inserted whose varying density acts as a variable diffraction grating. This is described in the following section.

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[7]These allow trigonometric expressions to complex form. Thus the fundamental sinusoid of the first expression

$$\frac{4}{\pi}\sin\frac{2\pi x}{p}$$

becomes

$$-\frac{2j}{\pi}\left(\exp\left[j\,\frac{2\pi x}{p}\right] - \exp\left[-j\,\frac{2\pi x}{p}\right]\right)$$

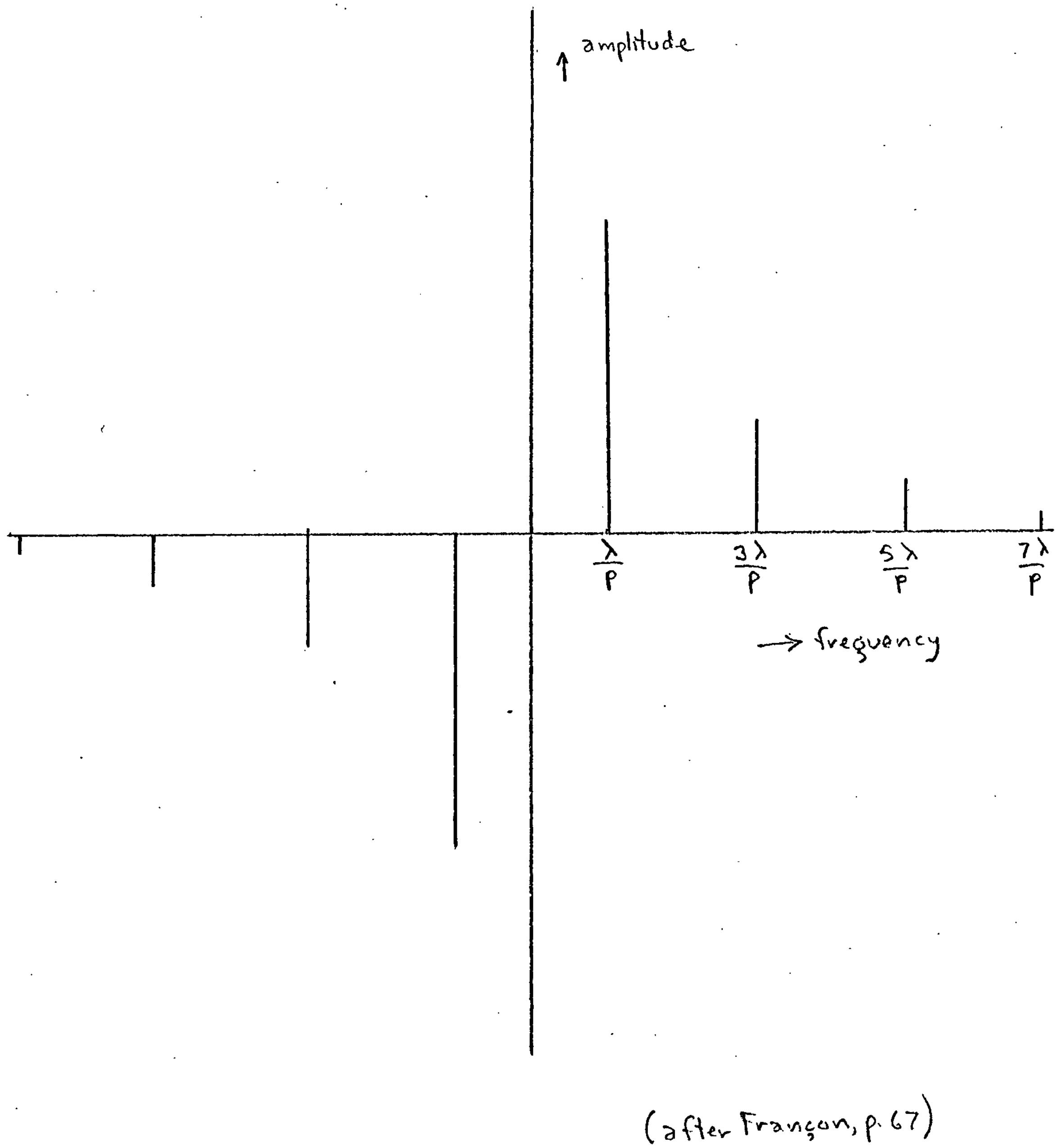
amplitude
$\frac{\lambda}{p}$
$\frac{3\lambda}{p}$
$\frac{5\lambda}{p}$
$\frac{7\lambda}{p}$
frequency
(after Françon, p. 67)

Figure 6.

The Basic Processor Configuration

The essential components of an optical processing system are a point source of coherent light, lenses, and planes for signal or input images and for recording. These are illustrated in a basic configuration in Figure 7. The system operates in the following way:

1. A laser source is focussed on a pinhole to provide a point source. (The pinhole is required because it is this light which is in fact imaged at later stages. The smaller this source, the higher the system resolution).

2. The light from this pinhole is collimated by lens L_c to form a parallel beam.

3. This beam is then incident on an input transparency at P_1, giving an emergent wave E_1.

4. The Fourier lens L_1 images the Fourier transform of E_1 at P_2. This is a power spectrum of the modulated beam because the energy of the light wave is proportional to the square of the wave.

5. A further lens such as L_2 image the power spectrum into its Fourier transform, which is the reconstituted signal.

Some Alternative Configurations

It is possible to rearrange the optical elements of the processing system for particular applications. For example, it is often useful to magnify a reconstituted image. Other modifications may be made to either reduce the total number of lenses required or to improve certain

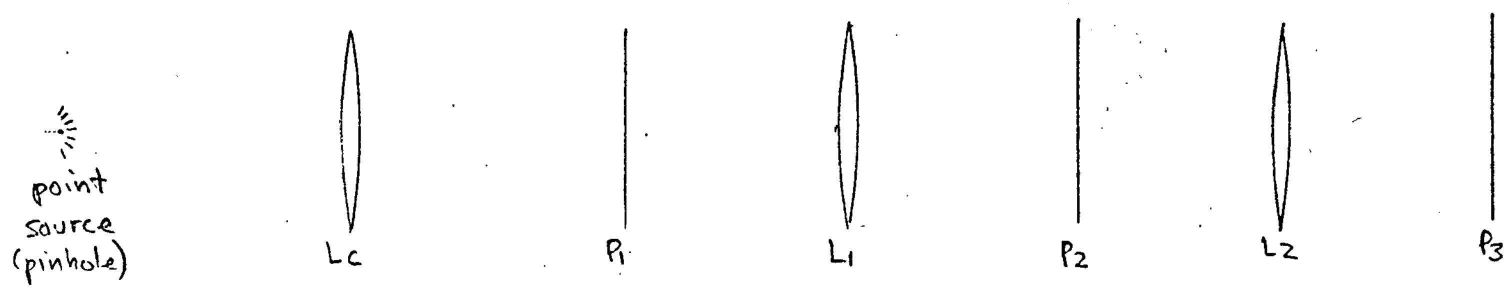

Figure 7.

performance characteristics. Both these applications are illustrated by three possible systems[8] shown in Figure 8. The performance characteristics of each system are summarized in Table I.

TABLE I.

Comparison of Three Processing Configurations

(Based on lenses with focal length of 200mm, a coherent source at 5000°A, lens apertures of 25mm)

	One Lens System	Two Lens System	Three Lens System
Maximum frequency response	125 1/mm	125 1/mm	250 1/mm
Maximum signal length for a signal limited at 50 1/mm	7.5 mm or 30% of lens aperture	15 mm or 60% of lens aperture	20 mm or 80% of lens aperture
Total system length	800 mm	1000 mm	600 mm

Recording

A number of alternative systems exist which are suitable for recording signals at various stages in optical processing, among them xerography, cathode ray tubes, ultrasonic cells, and thermoplastic materials. Photographic film is most commonly used because of its low cost, ready availability, and high storage capacity (i.e., resolution). The principal limitation is that a delay is involved for processing.

Several film characteristics are of relevance in optical data processing applications. The importance of speed and resolution is apparent and will not be discussed here other than to note that low speed,

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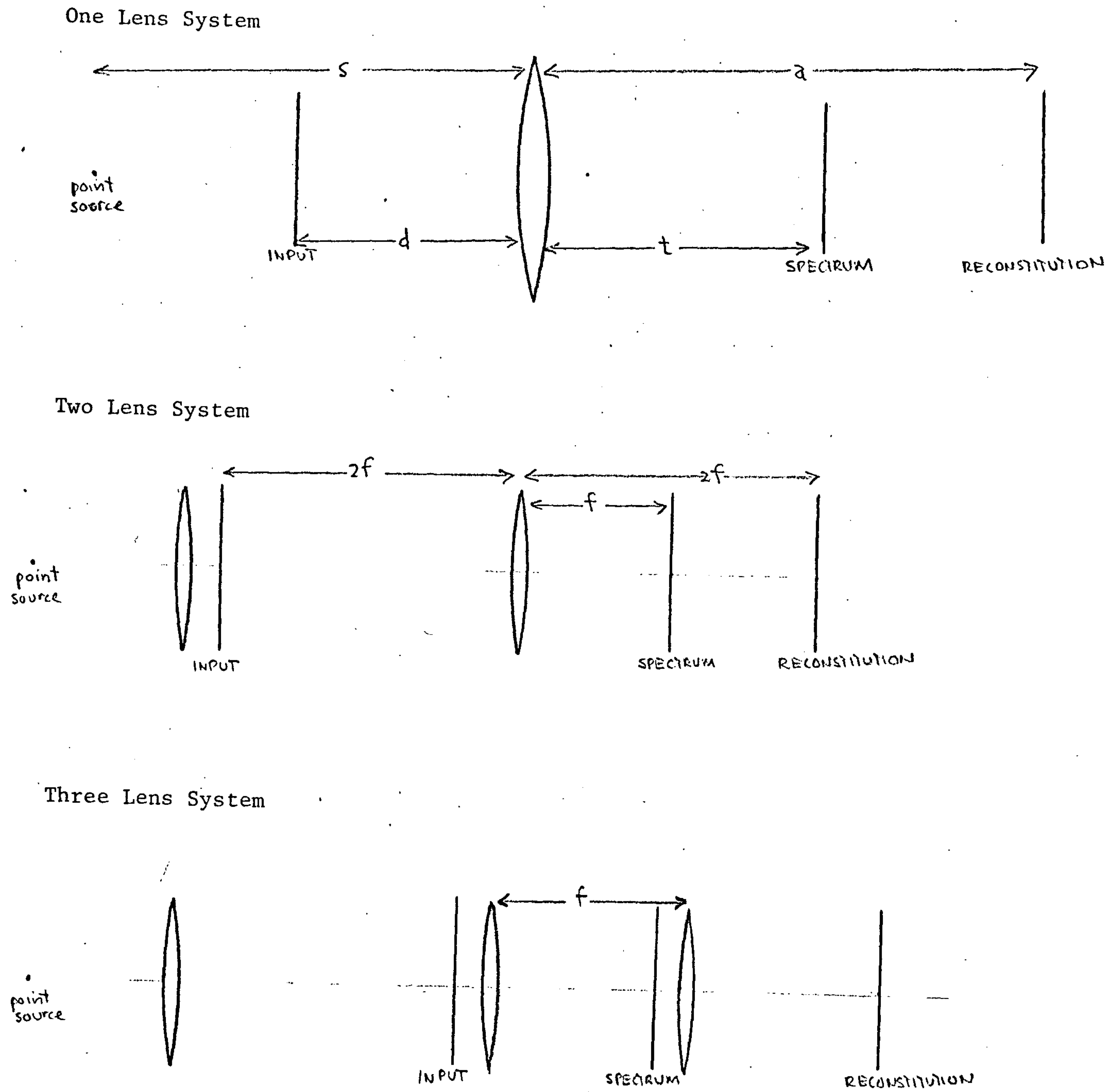
[8] These are adapted from unpublished material by J. Palermo shown to the author by D. L. Kelly, Gulf Research Labs, Pittsburgh.



NOTES:

① f = focal length of lenses

② t & a dependent on s, d and f.

Figure 8.

high resolution films are usually most suitable. Variations in film and emulsion thickness and grain noise are important variables for some critical applications, but for the processing of remotely sensed imagery are usually insignificant in their effect or easily controlled. The most important variable, then, is the response of the film to light.

The ideal photographic film for this application would exhibit a linear relationship between exposure and the film density, where exposure is defined as

$$E = It$$

where I is the signal or spatial distribution of light intensity incident on the film, and density is given by

$$D = \log \frac{1}{T}$$

where T is the film transmission.

The usual expression of the relationship between exposure and density is the Hurter-Driffield curve or the characteristic curve of a film.

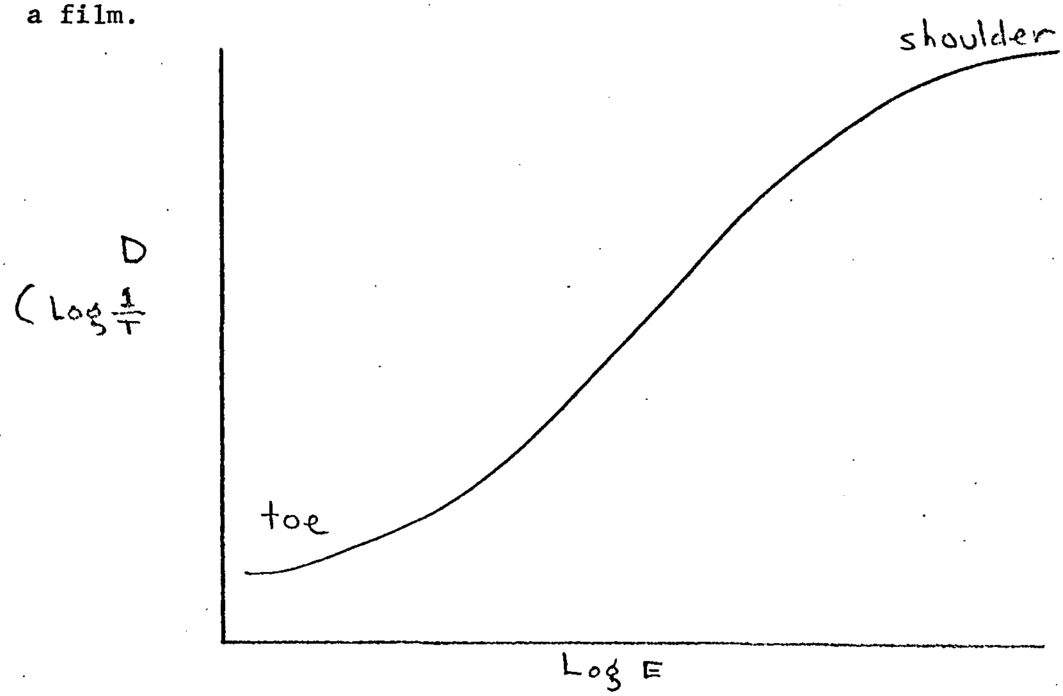


Figure 9

Figure 9 shows a typical characteristic curve and illustrates the fact that film materials are linear in their response only over a portion of the exposure range. The higher the inherent contrast of a film, the greater the range in densities which can be recorded and the longer this linear portion of the Hurter-Driffield curve. Thus Kodak high contrast copy is more suitable for optical processing than Panatomic -X (Figure 10).

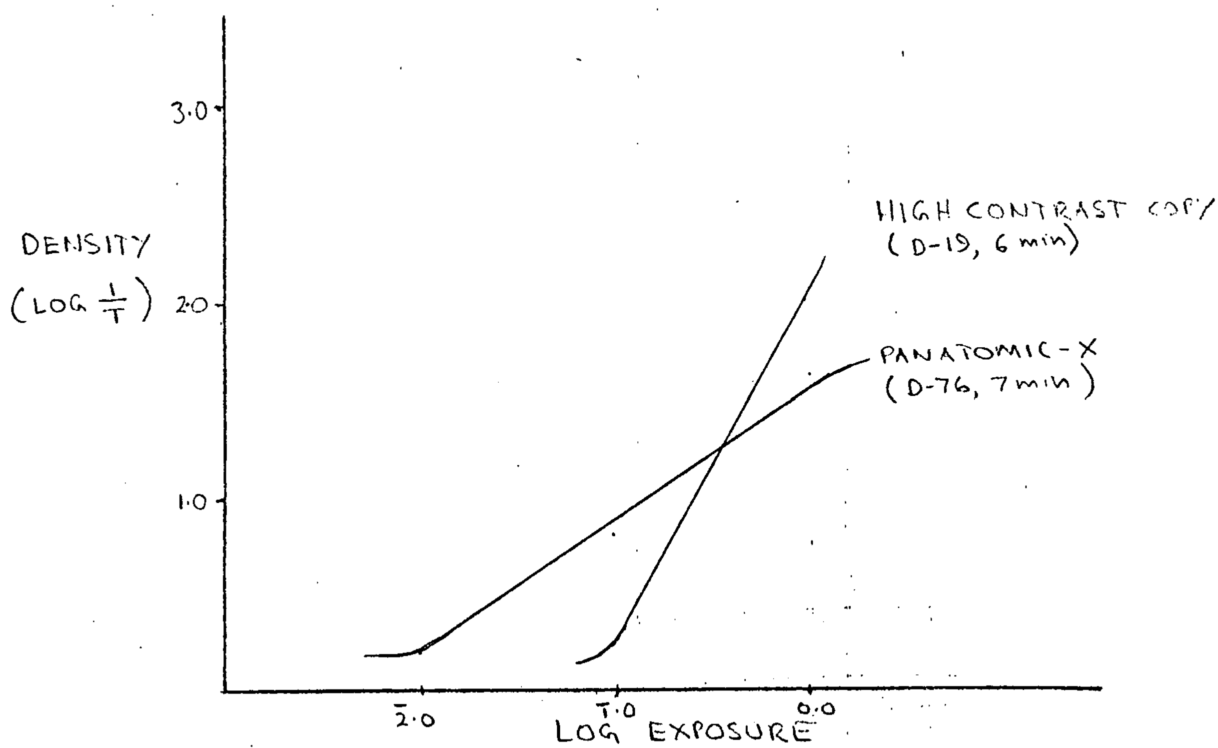


Figure 10.

The Input or Signal Film

Since films tend to be non-linear over at least a portion of their response range, the distribution of densities in the input frame is unlikely to be a valid representation of the original object (map or air photo) which was photographed. For many applications, this deviation may not be of interest. Such would be the case if the original were a line drawing or an air photo with unknown contrast characteristics (i.e., unknown gamma). It is normally at least useful, however, to have some knowledge of transmission and exposure characteristics for particular film emulsions, and this information is essential for applications which involve subsequent digital processing.

The Hurter-Driffield curve could be used to describe the film characteristics for input applications. A more useful measure than density is amplitude transmittance, defined as

$$T_a = (I/I_o)^{\frac{1}{2}}$$

where I_o is the light intensity incident on the film and I is the light intensity transmitted by the film. The advantage of using amplitude transmittance rather than density is that

$$\int_{P_1} T_a^2 \, dx\,dy = \int_{P_2} I_o \, dx\,dy$$

where P_1 is the input plane and P_2 the output plane, ignoring transmission losses in the system. Thus any measure of power in the spectrum can be directly related to a measure of transmittance in the input plane.

The procedure for calibrating a film's amplitude transmittance involves the following steps:

1. Photograph a standard set of gray levels with the film to be treated.
2. Insert these negatives in the input plane and record or measure with a photocell the intensity of the dc component at the spectral plane.
3. Record or directly measure the intensity at the spectral plane with the film removed.
4. Calculate the amplitude transmittance of the film by taking the square root of the ratio of intensity with the film to intensity without the film.
5. Plot values of amplitude transmittance over exposure (in this case, the photocell reading).

Spatial Filtering

On of the unique features of the optical processor is that it is possible to carry out simple spatial filtering. This is done by introducing opaque material at the spectral plane and reconstituting the filtered image at a later plane. The material may be black paper, tape, or actual photographic images. (The latter is used in the Toronto system.)

This operation is designed to filter amplitude. Phase filtering requires varying the thickness of a transparency to correspond to varying retardations. Amplitude filtering is related to the optical density of the filter.[9]

The simplest types of amplitude filters are completely opaque, thus completely rejecting information at certain wavebands. Four basic types are shown in Figure 11. The labels on the filters refer to the frequencies which are passed or rejected.

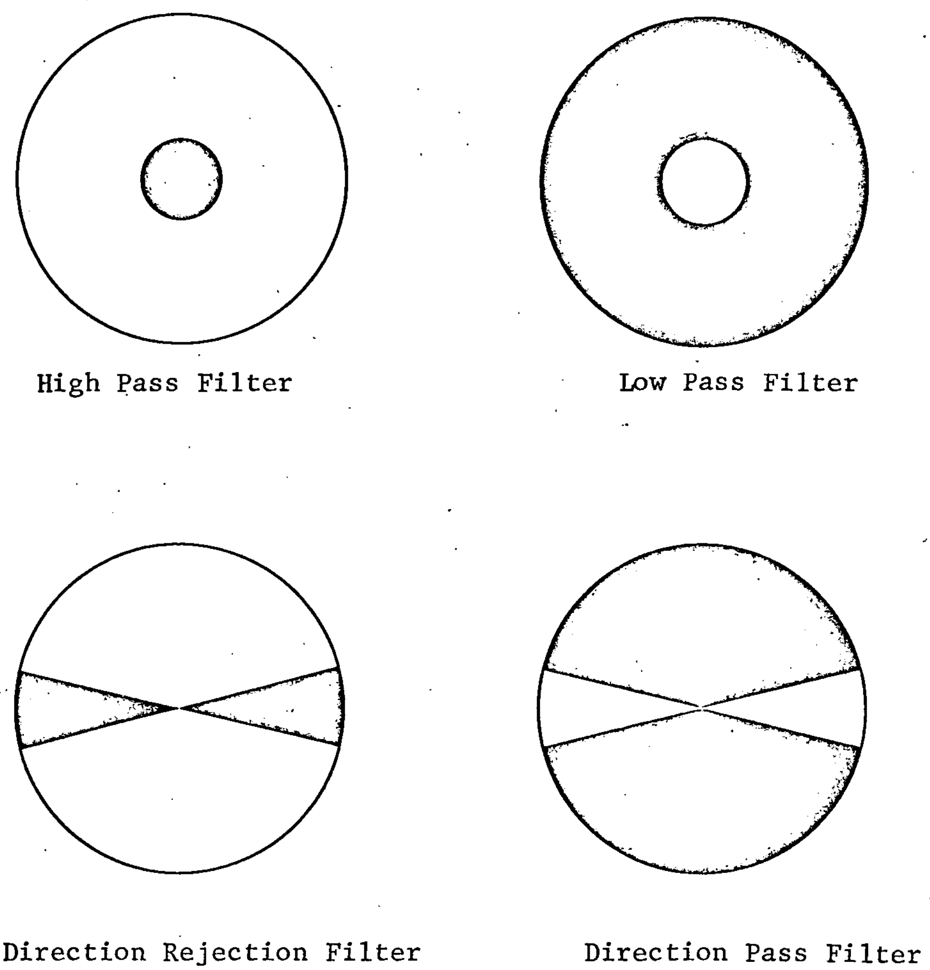


Figure 11

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[9] It is possible experimentally to filter both amplitude and phase. This operation is termed matched filtering. For an exmple, see Adam Kogma and David Lee Kelly, "Spatial Filtering for Detection of Signals Submerged in Noise," Applied Optics, 4: 387-392, 1965.

System Precision

It has been assumed to this point that optical components and images are sufficiently free of possible error that the output of the system at any stage is exact. In fact, there are many possible sources of error. Images reconstituted after passing through the system are considerably inferior to the original.

No detailed discussion of the system limitation will be presented here. It is sufficient to note that errors commonly arise from the following sources:

1. imperfections in the pinhole or the lenses,

2. dust on the optical components,

3. poor alignment of the components.

The errors arising from these conditions can be critical for many applications of coherent processing. For processing remotely sensed imagery, it has been found in this research that these problems are easily controlled by careful selection of components, regular cleaning of lenses and checking of alignment.

The Toronto System

The system assembled and used in the Department of Geography, University of Toronto, is illustrated in Figure 12. The basic elements are

1. an aluminum alloy platform, ½ inch by 16 feet by 4 feet,

2. an optical bench (Spindler and Hoyer) approximately 15 feet in length,

3. a Spectraphysics laser, model 122,

4. three 6 inch coated lenses, with focal length 24 inches,

5. miscellaneous special fittings and accessories.

Figure 12

A - laser (only front end visible)

B - microscope objective (barely visible)

C - pinhole assembly

D - collimating lens (barely visible)

E - input assembly

F - Fourier lens

G - spatial filtering assembly

H - reconstituting lens

I - recording camera (lens is removed)

(The recording camera has been moved towards the reconstituting lens so that it would fit in picture frame. If the system were operated in this way, the reconstituted image would be out of focus).

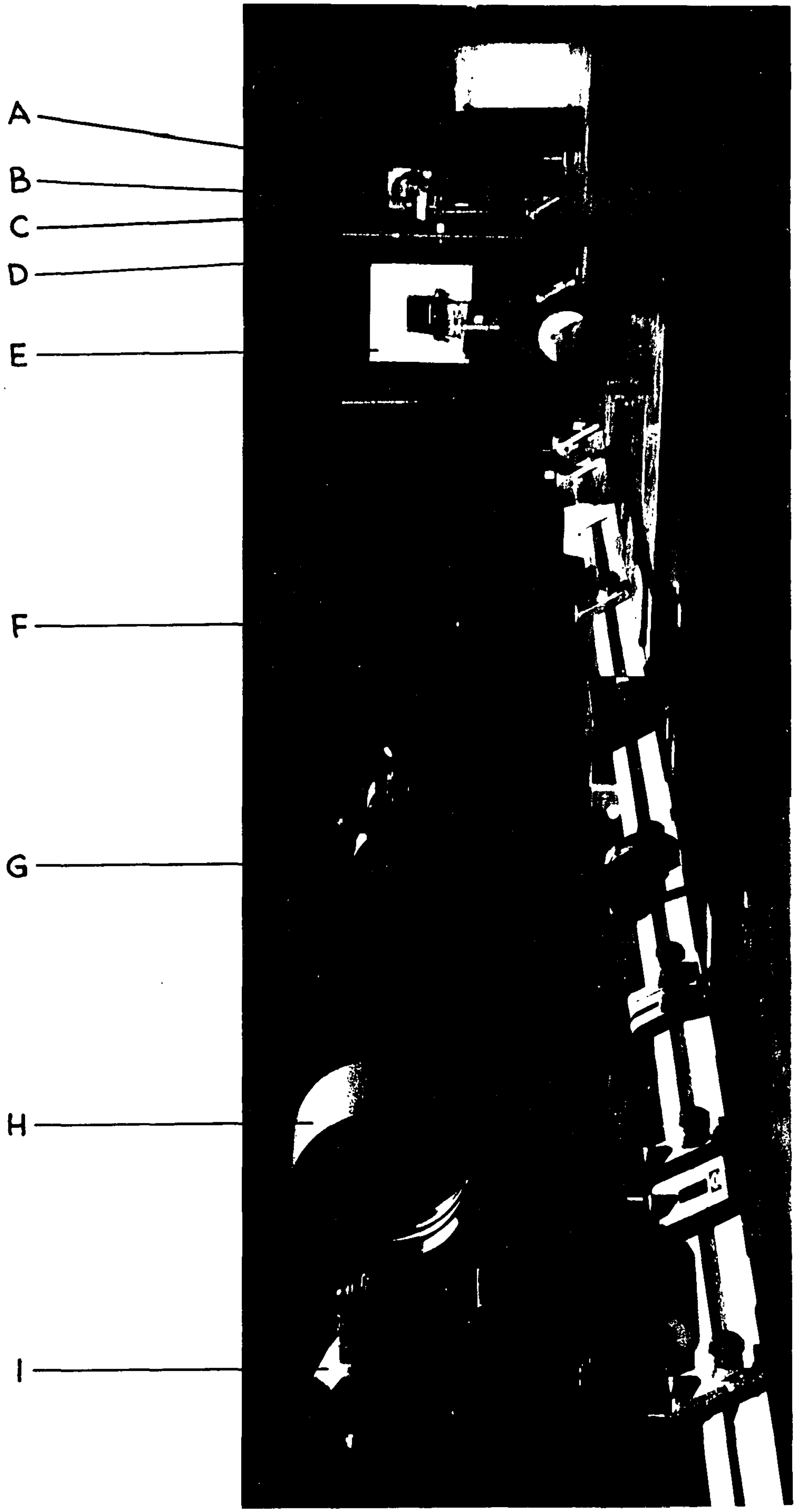

Fig. 12

Part II. Processing of Remotely Sensed Imagery

Two main types of applications of coherent optical processing appear useful for remotely sensed imagery. One of these may be termed substantive, and involves using the processor to produce power spectra to test hypotheses about spatial variation or to further analyses of particular spatial patterns. Examples of this application are two studies being carried out under the direction of L. Curry at the University of Toronto -- temporal variation in spatial frequencies of apparent temperature from thermal infrared imagery, and terrain analyses from shadow information on imagery of several types.

The second type of application will be discussed here. This is the application of the procedure as an image processing system to assist in the identification and classification of geographical patterns. The author's research has focussed on three approaches: (1) spatial signatures of particular textures; (2) power spectra as discriminants of information content of imagery obtained by different sensing systems; (3) image enhancement by spatial filtering. Some results of this research is presented in this section, largely in the form of sample images and their spectra.

Spatial Signatures

It is apparent from the discussion in Section I that certain spatial patterns give rise to distinctive power spectra. Most spatial processes on the surface of the earth do not give this result. The typical spectrum is a field of light with no particular peaks other than an X and Y axis corresponding to the aperture in the input plane. This type of spectrum does in fact contain a great deal of information which can be extracted by measuring intensity at various points in the field and subsequently carrying out various operations on a digital computer. This system of analysis is probably the most significant possible application of the processor, but is still some time from practical completion.

However, the spectrum is still a valuable interpretive tool because some natural processes give rise to highly regular spatial patterns and correspondingly distinctive power spectra. Examination by an interpreter or a coarse scanning system will easily note these spectral characteristics and thus make possible inferences about spatial patterns on the ground.[10]

The spectral peaks which correspond to regular ground patterns can be classified into two types: (1) arrays of distinct points, and (2) considerably higher power in certain directions, but as a smear rather than a series of points. It should be apparent that the first type of pattern should arise from equally spaced lines or points on the ground, such as ploughed fields and crops, particularly orchards. Examples of these cases are presented in Figures 13, 14, and 15. The captions on these figures provide more discussion.

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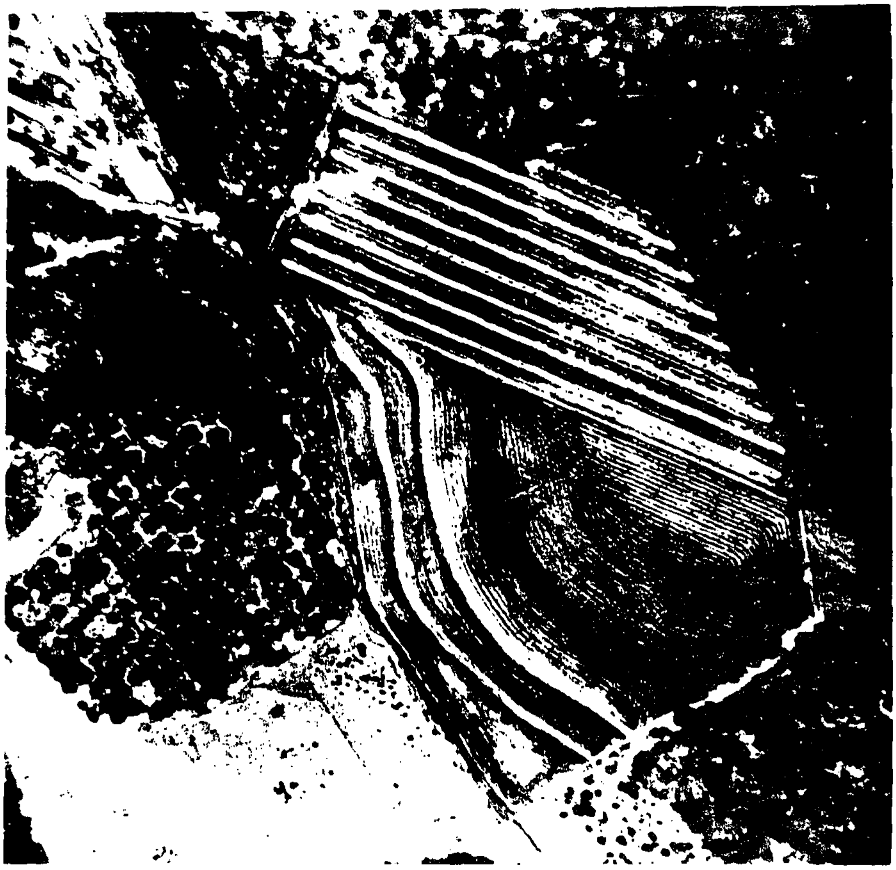
[10]This type of application is not unique to this research. See J. T. Tippett, et. al., Optical and Electro-Optical Information Processing, MIT Press, Cambridge.

Figure 13

Two regular spatial patterns are apparent on the image - the orchard and the furrows in the ploughed field. The spectrum shows the second of these very clearly as a series of distinct points corresponding to the basic spatial frequency of the furrows plus harmonics. The orchard is only barely visible in the spectrum as four points around the dc component. It is less apparent than the furrow pattern because: (1) the frequency is lower, and thus closer to the dc and the spectra of random spatial elements which tend to obscure it; (2) the power of this frequency is lower, that is, the contrast between trees and the surrounding area is not as high as in the case of the ploughed field.

The photograph is band nine (740-880mu) of a multiband image set from the Asheville, North Carolina test site. This and other photographs in this report were copied from positive transparency film onto Panatomic-X. The spectra in all cases have been recorded on Kodak high contrast copy film. The prints are also on relatively high contrast paper (usually F-3; some spectra are on F-4).



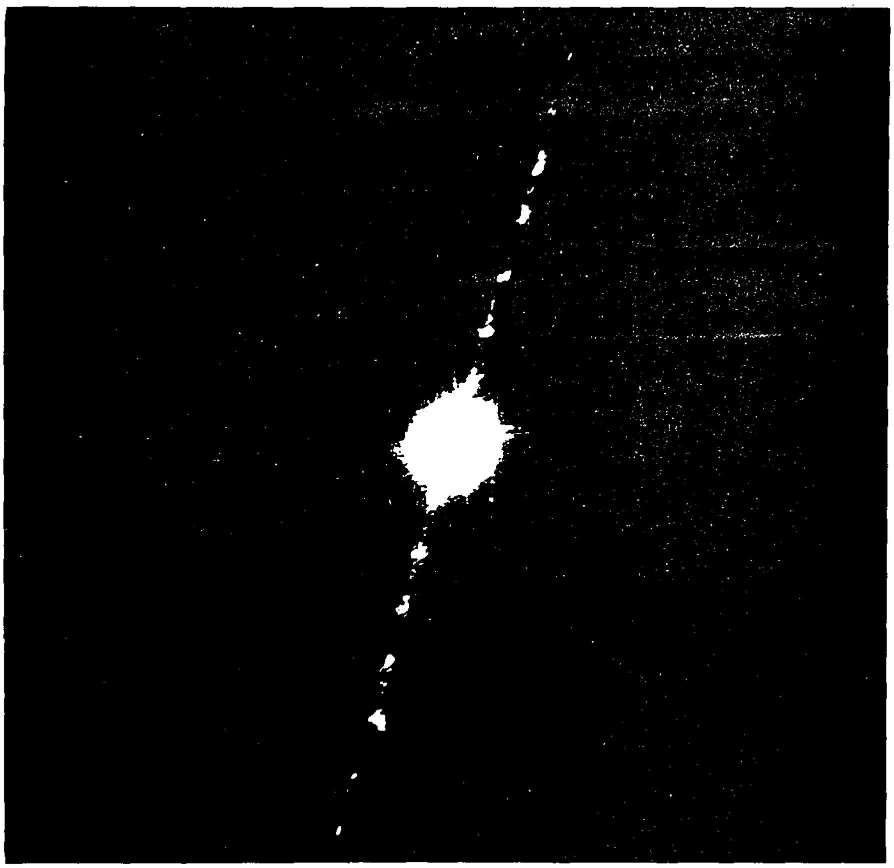


Fig. 13

Figure 14

This is a photograph of part of a sewage treatment facility and orchards (probably apricots) near Miltipas, at the extreme southern end of San Francisco Bay. The spectrum shows a distinct pattern which corresponds to the rectangular arrangement of the orchards. Study of the photograph will show that the orchards are not all aligned in the same way. This is also apparent in the spectrum, particularly at the frequencies somewhat further out from the dc component.

The photograph is band 9 of a multiband set. Bands 3, 6, and 4 are used in illustrations which follow.

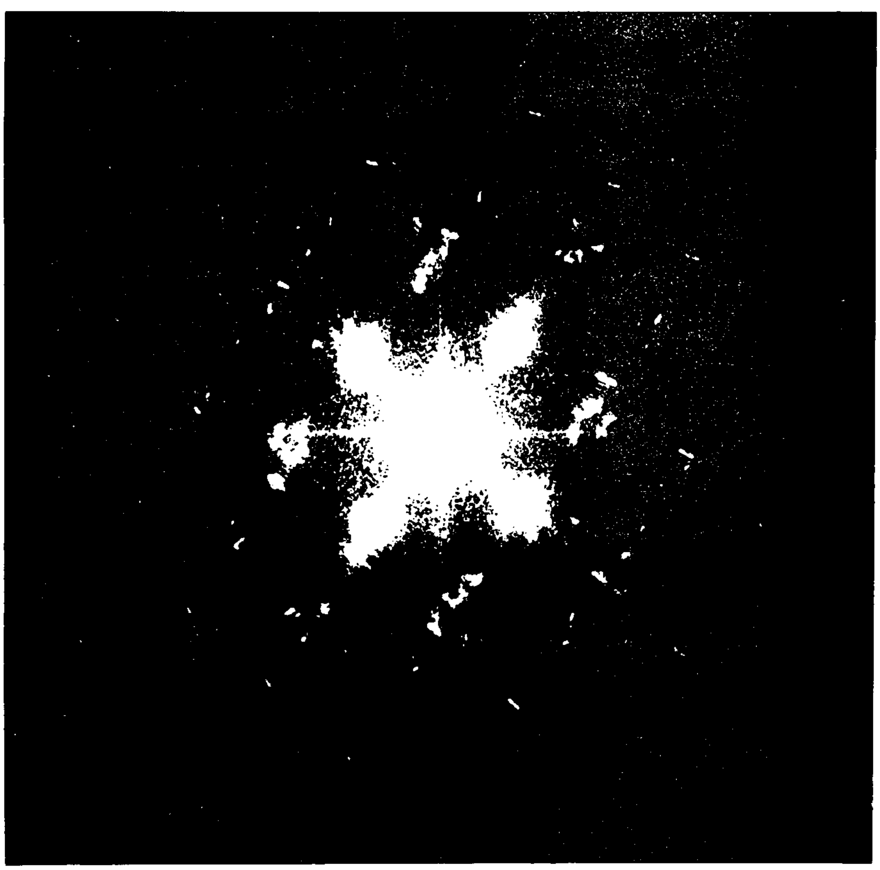
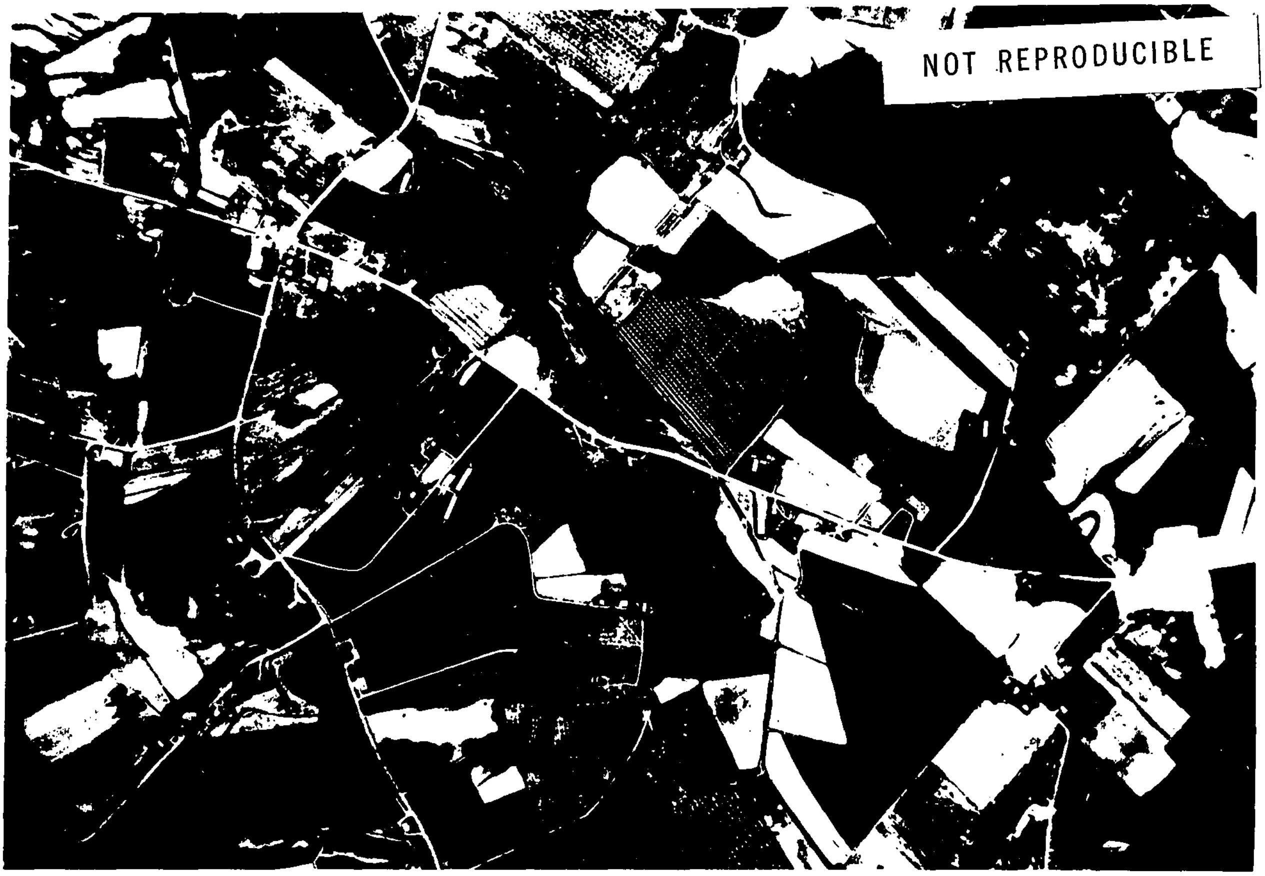


Fig. 14

Figure 15

In the spectrum of this image of an agricultural area near Asheville, N.C., there are apparent five different orientations of high frequency information. Examination of the image shows that each of these corresponds to the orientation of orchard areas.

The image was originally recorded on Ektachrome, and was subsequently copied on Panatomic-X for processing.



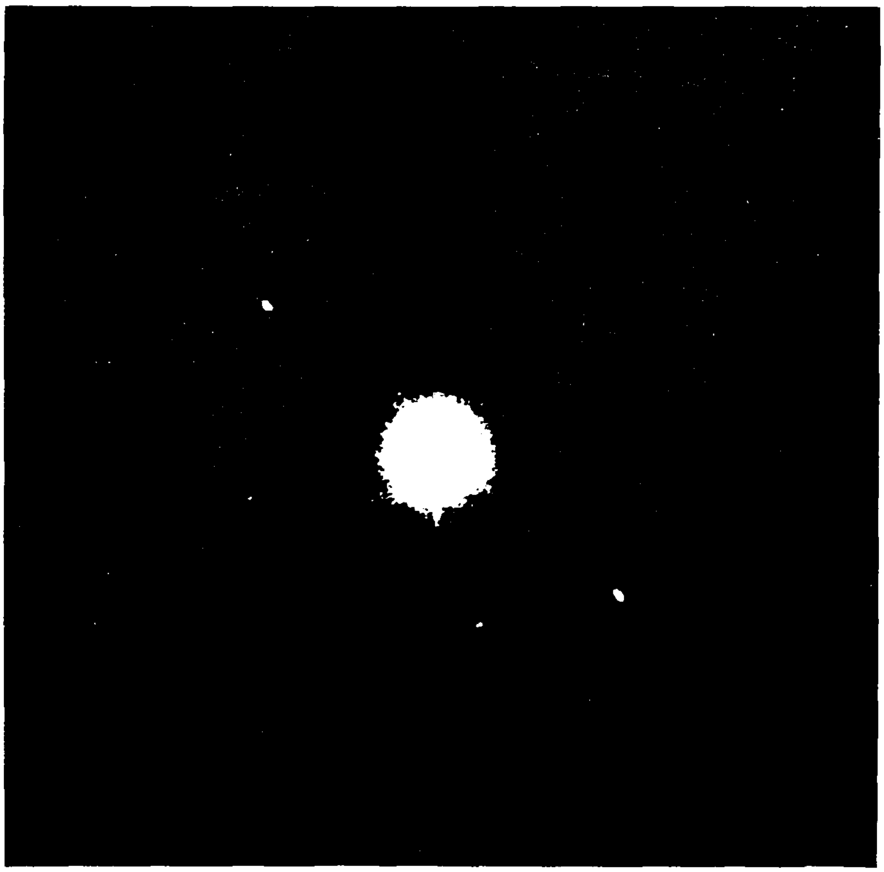


Fig. 15

If the spatial pattern is regular in the sense of more contrast differences occurring in certain directions, but without equal spacing the spectrum has the second form described above. Examples of these are presented in Figures 16 and 17.

The author would argue that the photo interpreter would find spectral output associated with an image a valuable aid. There has been no real opportunity to test this idea, but he has found that people faced with a spectrum and an image are forced to examine images more carefully to determine the relationship between the spatial and the frequency domains (i. e., image and spectrum). The author and his assistants in this research have found that one develops considerable competence at this comparison, but rarely can predict a spectrum accurately from an image. Thus the spectrum serves as a check on ideas about spatial regularity in an image and as such should be valuable in the interpretation process.

Of further possible value is the fact that spatial regularity on an image appears so distinctly in the spectral output. This means that the necessary resolution of a scanning device and storage in a computer in an automated interpretation system is considerably reduced. Consider Figure 14. In order to categorize the patterns of orchards in the spatial (image) domain one would require examining in the order of one million locations (1000 by 1000), but in the frequency domain 10,000 (100 x 100) or less would be adequate.

These distinct spectra reflect spatial difference in an image, and the more the difference (i.e., the more the contrast), the stronger the intensity in the spectrum corresponding to that frequency and direction. To make full use of spatial signatures, then, one must be aware of the

Figure 16

In this photograph of a residential area in Asheville, the houses and streets are arranged in an approximately rectangular distribution, so that the spectrum shows that more power (more contrast difference) occurs along two axes. If the houses were more regularly arranged, the spectrum would show distinct dots corresponding to their spatial frequency. The photograph was originally taken on Ektachrome, and has been copied on Panatomic-X for optical processing.

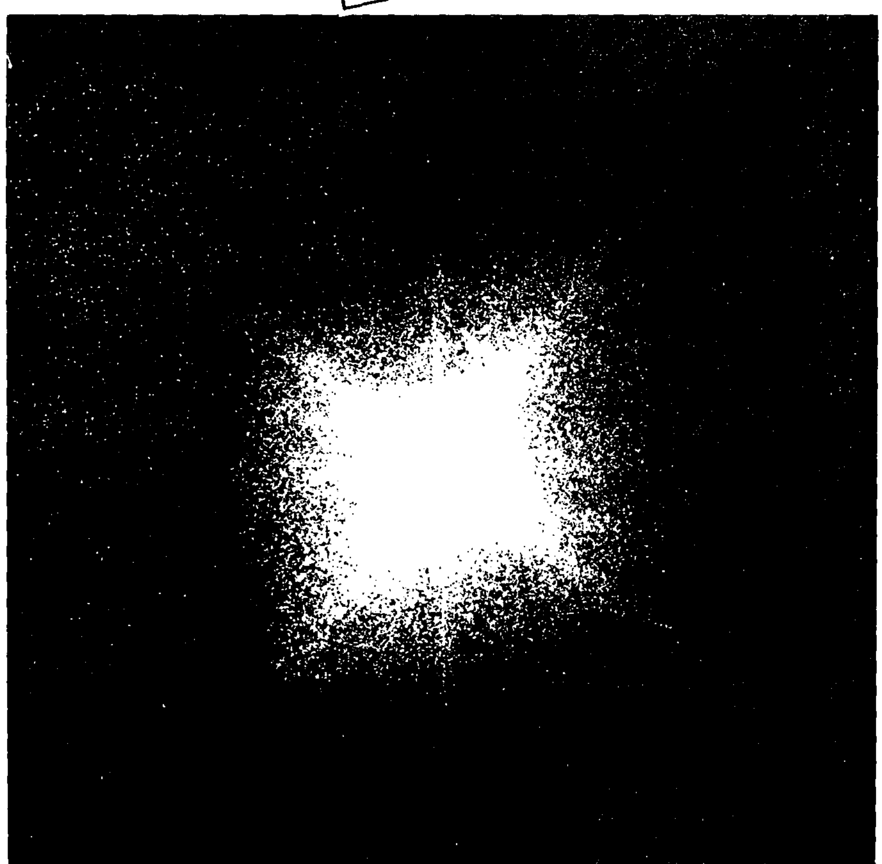


Fig. 16

Figure 17

The spectrum of this forested area in the North Carolina test site shows not a distinct smear in certain directions but the opposite, a lack of power in one direction, along the longitudinal areas of similar density in the image. If these differences in vegetation are due to topographic influences, this spectrum may in fact bear a relationship to the spectrum of surface elevations. (The original photograph is on Ektachrome.)

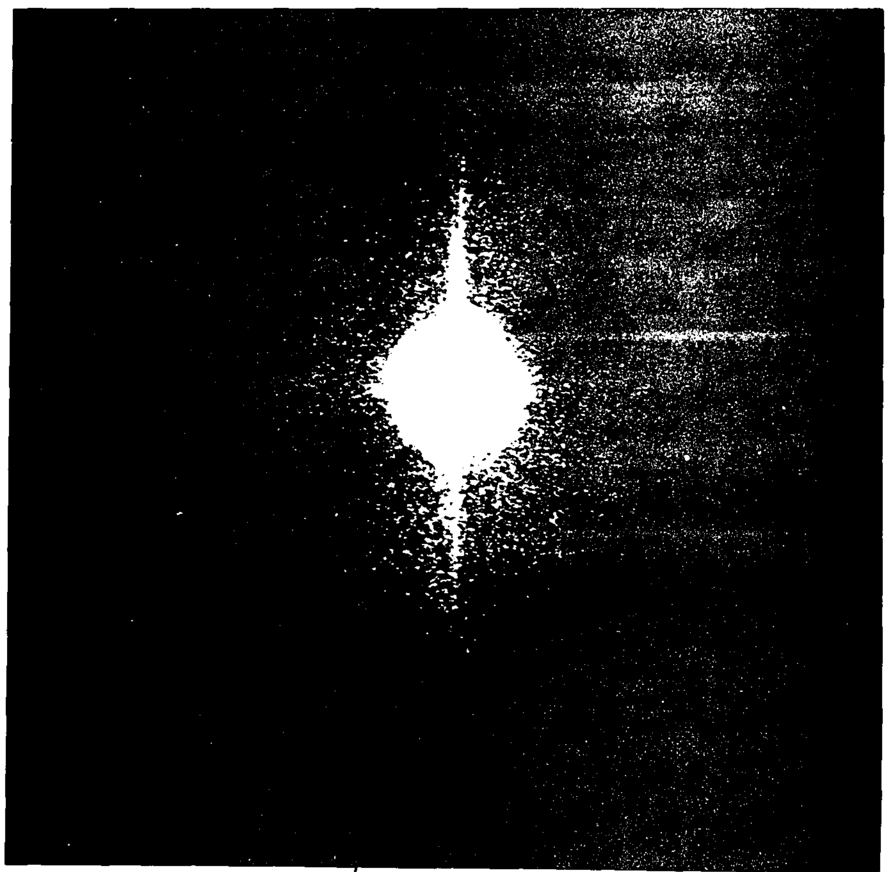


Fig. 17

gray level corresponding to a particular type of feature in a particular sensing system. Some research has been directed to determine these differences for things such as tree species.[11] The characteristic gray level by sensing waveband is termed the "spectral signature," where the term spectrum refers to the sensing waveband. Given a set of spectral signatures, a choice of sensing systems, an optical processor, and a scanning and computing system, it should be possible to produce not only an estimate of the type of objects on the ground (from the spectral signatures), but also their relative frequency on the area they cover (from the spectrum). Further, some objects may be expected to exhibit characteristic spatial ordering patterns, so it might be possible to characterize a phenomenon not only by a spectral signature but also a spatial signature. This would considerably increase the reliability of an estimate from an automated processing system. Some further comments on these possibilities are presented at the end of the discussion on the application of the optical processor and in the appendix.

Imagery Comparison

Since the return to a sensing system from a surface or object on the ground varies with the waveband of the sensor and the characteristics of the surface, it may be expected that spatial differences in the image

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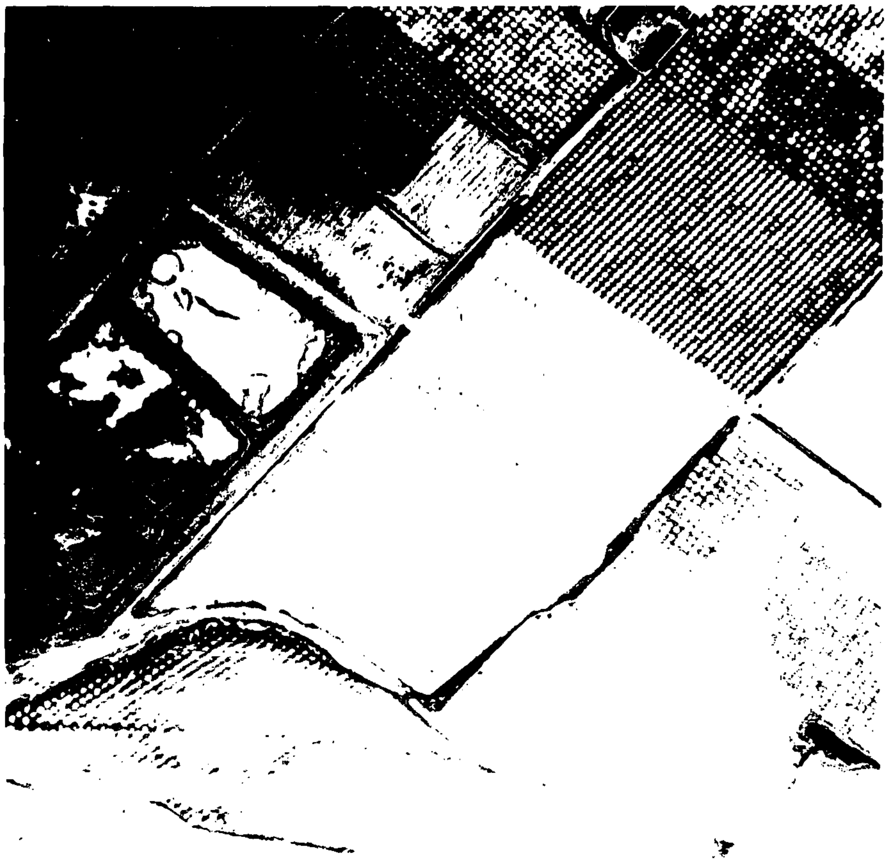
[11]For example, David M. Gates, "Characteristics of Soil and Vegetated Surfaces to Reflected and Emitted Radiation," Proceedings of the Third Symposium on Remote Sensing of Environment, 1964, pp. 573-600, and R. R. Legault and F. C. Poleyn, "Investigation of Multi-Spectral Image Interpretation, Ibid., pp. 813-821.

and the output from the processor will also vary considerably. This expectation can be tested by such methods as densitometer scans of the contrasts of images. The coherent optical processor appears to be a considerably less expensive and perhaps even more efficient system for discriminating information content of imagery obtained by different sensing systems.

This idea has been tested by processing multiband imagery, specifically images obtained at nine different wavebands in the visible spectrum. It has been found that in some cases the difference between sensing wavebands is only in total power in the spectrum output, that is, contrast in the image. This illustrated by Figures 18 and 19 compared to Figure 14. In some cases, however, spatial differences which appear at some wavebands are completely absent at others. This is illustrated in quite striking fashion by comparing Figure 20 to Figure 13. It is obvious that if some types of surfaces are quite different in return at certain wavebands and are spatially ordered, the power spectrum will show this very clearly.

Figure 18

This image of the Miltipas area is band three of a multiband set, corresponding to somewhere in the green-orange portion of the visible spectrum. Band nine, in Figure 14, is in the near infra-red. The principal difference between the two is in the intensity of power at various points. It is likely that a longer exposure for this spectrum in the processor would result in apparently identical spectra.



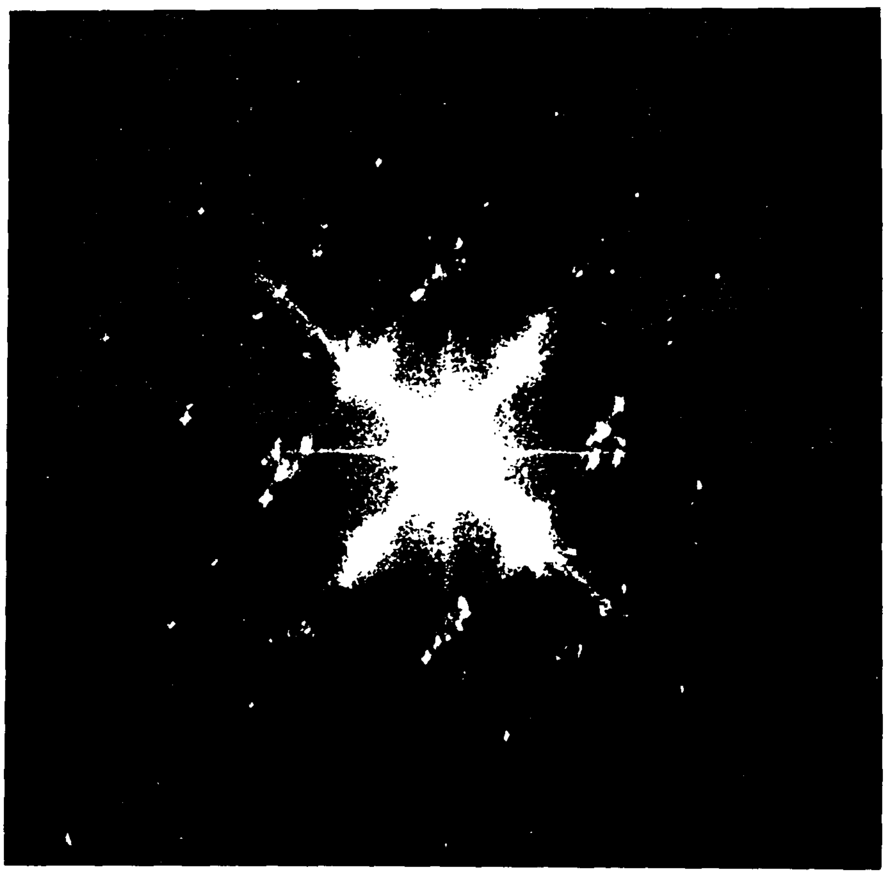


Fig. 18

Figure 19

The spectrum of band six of the Miltipas multiband set is also similar in shape to band nine (Figure 14), differing only in an apparently lower power level over the entire picture.

Figures 14, 18, and 19, show that multiband photography is not always discriminating of differences in ground patterns. Changing sensing wavebands appears only to change contrast levels, and thus total power in the spectrum.

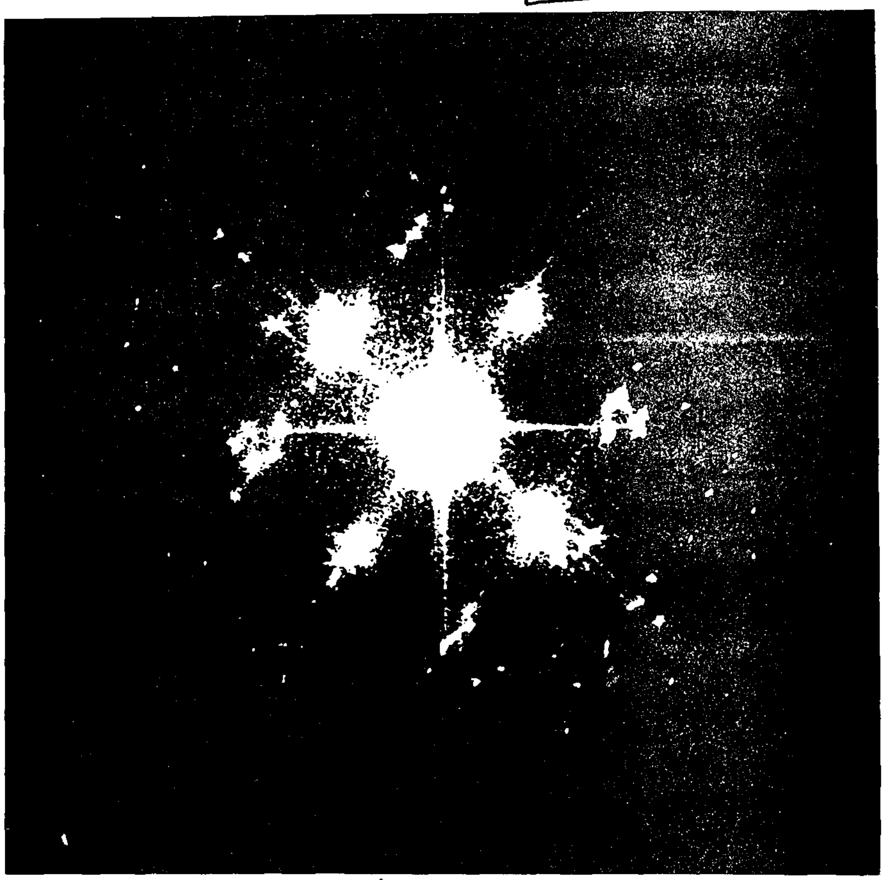
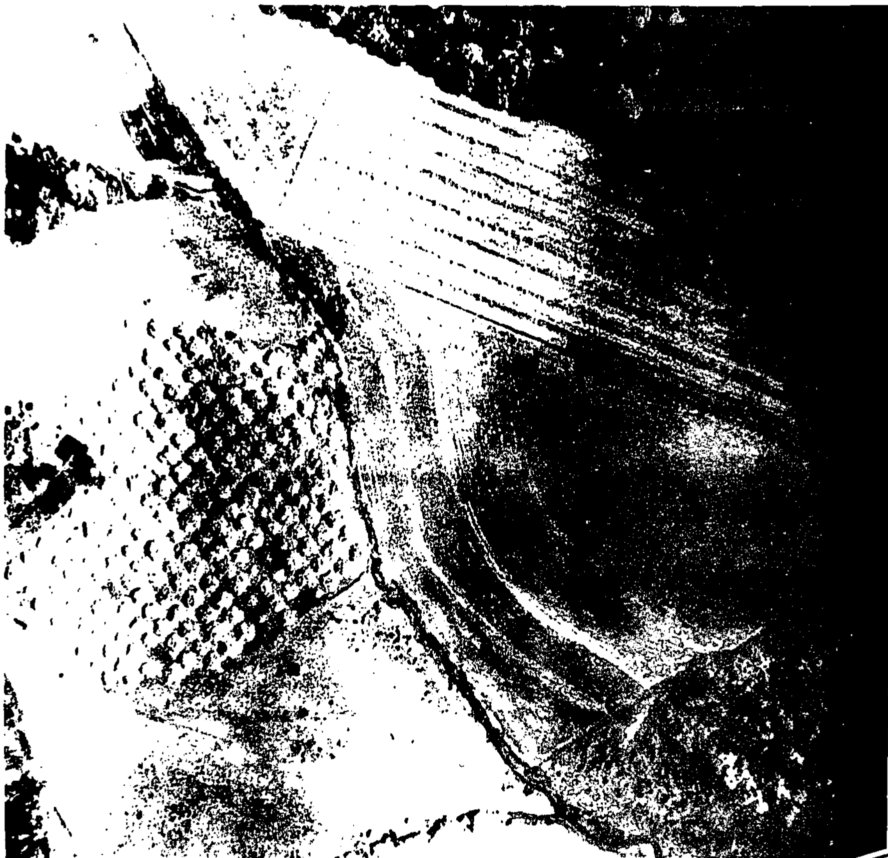


Fig. 19

Figure 20

This image is band nine of a multiband set, and can be compared with band six in Figure 13. The shapes of the spectra are quite different due to the relative unimportance of the diagonal series of dots in this figure. Comparing the two images shows that this waveband does not record the contrast differences in the cultivated area so apparent in band six. This illustrates that under some circumstances comparison of different wavebands in a multiband set can show significant differences. To be able to make full use of this information, it is necessary to have knowledge of characteristic spectral returns of various surfaces (spectral signatures).



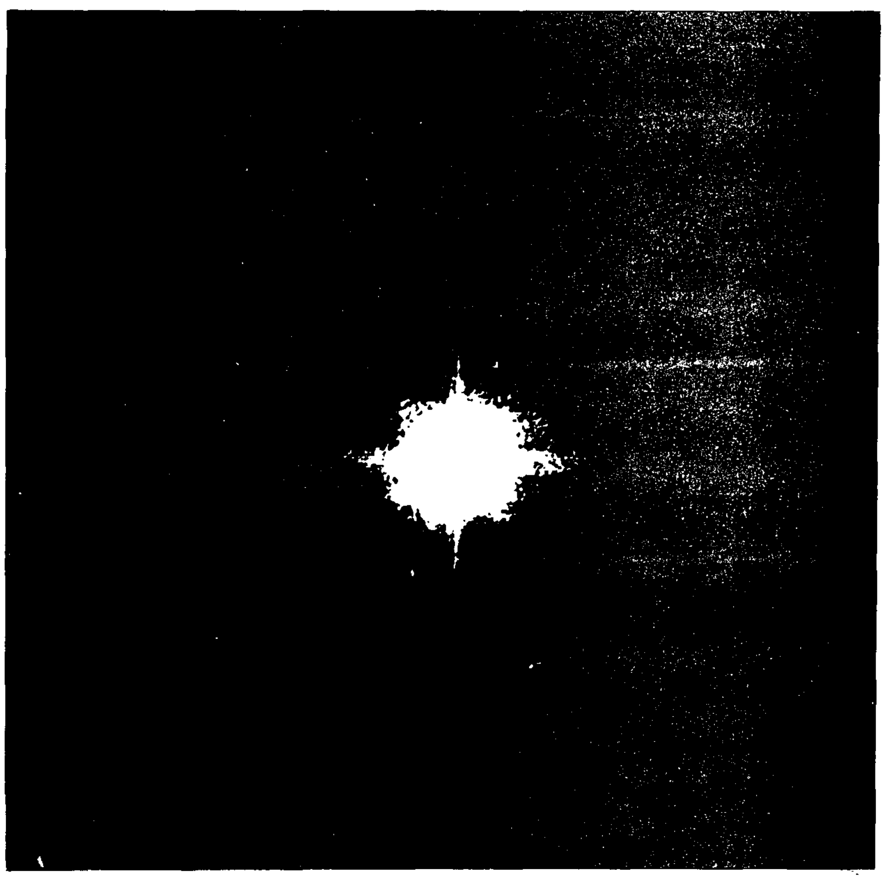


Fig. 20

Image Enhancement

Spatial or frequency filtering as described in Part I is applied in processing remotely sensed imagery by inserting opaque objects in the spectral plane and reconstituting the filtered images. It is not a simple operation, since it requires that the filter be carefully prepared and, perhaps more important, it be properly positioned in the spectral plane. The main problems encountered with filtering in the Toronto system are (1) unintentional phase filtering due to variations in filter thickness, and (2) unintentional filtering at very low frequencies. In the output presented in this report, the second problem is apparent in zones which are distinctly lighter or darker.

The most apparent application of filtering of remotely sensed imagery is in the removal of certain frequencies to enhance differences in a reconstituted image. The effect of this operation is illustrated in Figures 21, 22, and 23.

However, since there are an infinite number of filters which may be used, this operation may not be particularly valuable unless one has some idea of the frequencies and directions which should be removed or passed. This decision depends on a careful examination of the power spectrum.

Filtering would be more valuable in interpretation if it were possible to examine its influence in real time. This would mean having available a procedure for immediately introducing opaque material at any desired coordinates in the spectral plane and viewing the result of the operation in a display system. Such a modification would, of course, be quite expensive, probably more than the entire cost of the remainder of the system.

Filtering with variable density filters has not yet been attempted in this research. Its possible value may be considerable in that one may introduce as a filter the spectrum of a process and then view the image information which was not a result of the particular process. The success of such applications depends on theoretical knowledge of spatial processes in frequency terms. Professor L. Curry is involved in research in these problems at Toronto.

Finally, mention should be made of matched filtering. If knowledge of processes is sufficiently advanced, it may be possible and useful to construct matched filters to remove both amplitude and phase components.[12]

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[12] Kozma and Kelly, op. cit.

Figure 21

This and the following figure are filtered images of band four of the Miltipas multiband set. The upper frame is the result of a high pass filter, that is, only high frequencies (or short wavelengths) were allowed to pass the spectral plane to reconstitute the filtered image.

The lower frame is the result of low pass filtering. The frequency cutoff point was sufficient to subdue or eliminate only part of the orchard pattern. Low frequency information such as contrast differences between fields is, of course, quite apparent.

Fig. 21

Figure 22

The upper frame in this figure is also a low pass filter of the Miltipas image, but here the frequency cut off point was sufficiently low to practically eliminate the individual trees in the orchards. The result is a picture of the general spatial trend in the area. It should be noted that it is impossible to obtain a sharp reconstituted image after low pass filtering since it is the high frequency information which defines the sharpness.

The lower frame is an attempt at directional filtering. Information at all frequencies along an axis from the lower left to the upper right corners has been blocked. Because of intercorrelation among one dimensional spectra at various azimuths, the passed information is still sufficient to reconstitute the shape of objects at all frequencies.

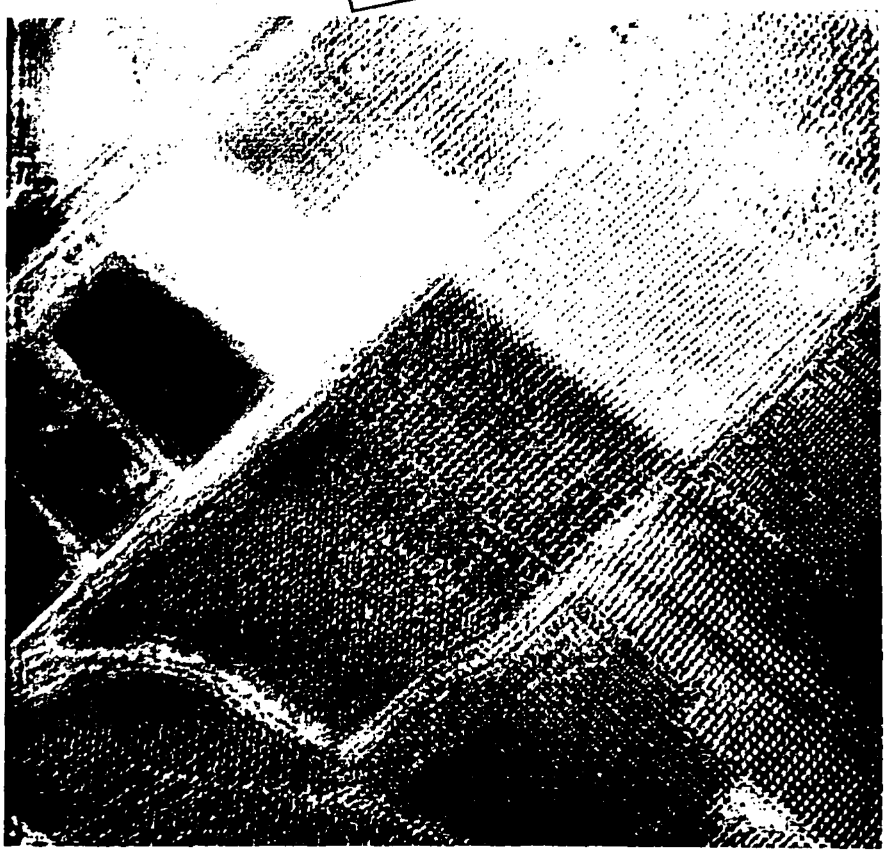
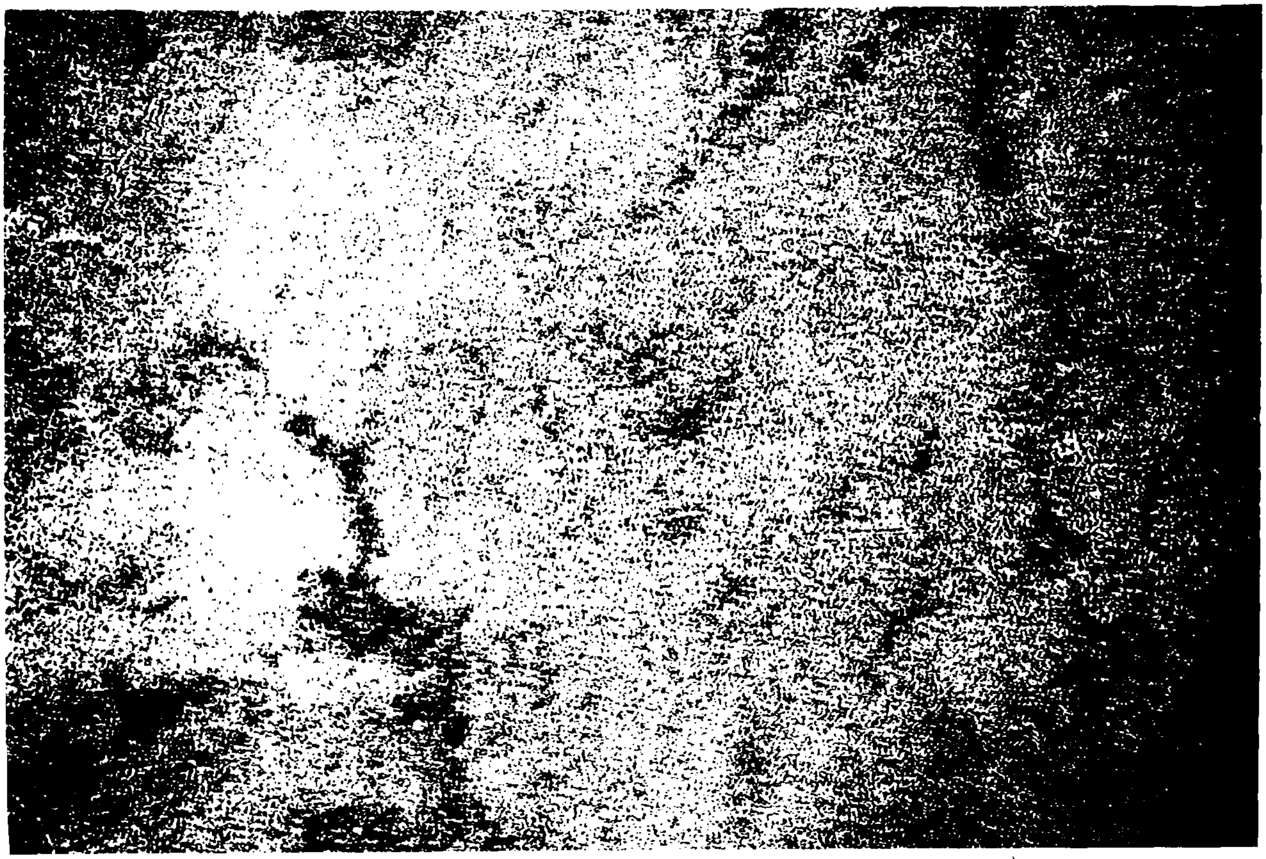


Fig. 22

Figure 23

This figure shows two filtered images of the photograph presented in Figure 17. The upper frame is the result of a high pass filter, and the lower a result of the low pass filter. The low pass filtering is particularly interesting because it appears to show the pattern of topography of the area.



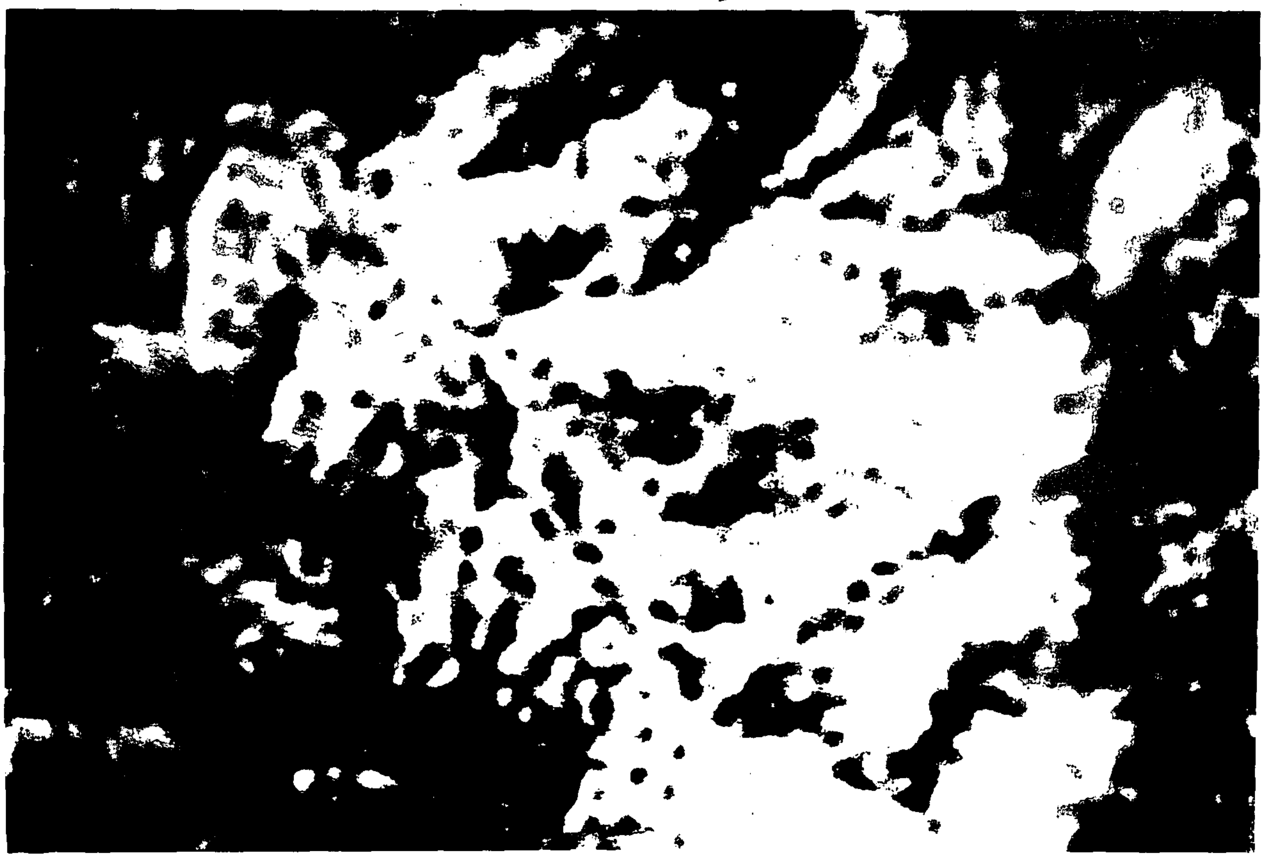


Fig. 23

Automated Systems

Some discussion has been presented earlier concerning the possible application of coherent optical processing in an automated image processing system. The most important points concerning this application are that (1) storage requirements are decreased by at least one order of magnitude (perhaps more), (2) the processor output provides an additional easily determined parameter for the classification of the image content, (3) the image itself is retained as storage.

The basic hardware requirements of such a system would thus be

(1) a coherent optical processor under computer control for input of images, and interfacing with a computer through a vidicon at the spectral plane, a vidicon at the reconstituted image plane, a filter assembly system at the spectral plane, and camera assemblies at various points for recording.

(2) a digital computer with digital/analogue interfacing for control of the processor, medium size core (32K), sufficient tape or disk storage to dump relevant spectra or positions of image, but with no particular requirements for very fast computation (cycle times of 5 microseconds or more would be adequate).

(3) a display system for the operator/interpreter, probably consisting of both a direct projection from the processor plus a cathode ray display from the computer.

Since the operation of such a system would often hinge on decisions of the operator / interpreter, the system would ideally interface with a shared time system, using in the order of 25 to 75 per cent of available time on the system.

The particular advantage of such a hardware configuration is that it is relatively inexpensive compared with systems based on complete image scanning. In particular, computer requirements can be met at intermediate or large research installation or can be purchased from commercial shared-time systems. A system based on complete image scanning would require an extraordinarily large and fast computer to operate in real time. The cost of a suitable optical processor would range upwards from $25,000 depending upon the degree of computer control and the desired speed of operation. Adequate display systems can be leased together with the computer time.

The success of such an automated interpretation system would probably hinge less on the hardware than on the state of knowledge of spatial patterns and the spectral signatures of objects and surfaces with different sensing systems. On the other hand, results which take days with the Toronto system would take seconds or minutes on even a semi-automated system. The author would suggest that such a system is worthy of careful consideration in order to be able to adequately cope with the vast amounts of imagery available now and the increased amounts we can expect in the future.

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Appendix

A Note on a Possible Automated Image Interpretation System[1]

It has become apparent in the research on optically produced power spectra of remotely sensed imagery that there is considerable possible benefit to be gained by using these techniques as part of an automated photo interpretation system. These notes are intended to summarize and supplement comments in the text and to suggest a possible configuration.

The Power Spectrum of a Photographic Image.

The fundamental principle of the possible system is that Fourier transform relationships exist between the front and back areas of lenses. As a result a collimated coherent beam passed through a transparency and then through a lens images the two dimensional power spectrum at some point. A further lens will re-image the spectrum back into a reconstituted image, less any frequency components which may be blocked at the spectral plane. These operations, which occur instantaneously in an optical system, require image digitizing and many hours of computer time when estimated with a digital computer. However the advantages of the optical procedure are not only its speed and low cost, but also that the conversion of an image from the spatial to the frequency domain (1) greatly emphasizes spatial ordering, (2) reduces subsequent digital storage requirements by at least one order of magnitude, (3) facilitates the use of spatial signatures for image

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[1] Originally prepared as a separate report.

interpretation (which can be compared with spectral signature information if images are available at different sensing wavebands), and (4) possibly is of considerable theoretical value since it appears easier to express spatial processes in frequency than spatial terms.

Thus an interpretation system which has an optical processor as its key operational component may be far superior to a system using direct scanning of images in efficiency, speed, and cost.

The General Procedure.

In a completely automated system, it is visualized that an image would be processed in the following steps:

(1) An operator or executive computer program would select an image from a library and load it in the optical processor.

(2) The spectrum from this image would be received by a vidicon which would interface with a digital computer. If desired, this spectrum could be displayed for the operator.

(3) In the computer, a processing program would compute general parameters of the spectrum and probability estimates of the corresponding texture pattern. If images at different wavebands were available, it would also use information about the spectral reflectance of various surfaces in the identification estimates. The success of this step depends, of course, on accumulated knowledge about image/spectrum relationships so that a key element would be a library of this information which could be regularly updated.

(4) If desired, frequency components and directions could be filtered at the spectral plane and a reconstituted image produced. This could be valuable for image enhancement or as part of the interpretation process. It would be most desirable that the specification of the filter be numerical so that it could be placed under computer control.

If the procedure were sufficiently automated, the operator could simply specify the images to be processed, then the computer would initiate steps cne to three the required number of times, providing a list of probability estimates of the information content of each image. The author sees no particular advantage to a standardized filtering procedure under monitor control, since one usually decides on the type of filter after a study of the spectrum. However, computer assistance here would still be of considerable value.

A more detailed flow chart of a possible system is attached as Figure 1.

Hardware Requirements.

Most parts of the suggested configuration are available "off-the-shelf," and their assembly into a system would pose no particularly unusual problems except perhaps at the interfacing points and in digital/analogue conversion. The most expensive component is, of course, the digital computer. One possible approach would be to use a small unit such as a PDP with extended storage capabilities. This would involve a capital expenditure of $25,000 to $50,000. The author would suggest a much cheaper and more flexible alternative is time sharing on a large system such as a 360/65. This would simplify programming and provide much larger storage if ever required, as well as shifting maintenance and service problems to a different organization.

The optical processor could be acquired from one of a number of firms, or assembled from standard components. The author suggests that the latter is more desirable so that interfacing problems can be reduced.

The interfacing components required are basically one or more vidicons, various mechanical positioning sub-systems, and a digital/analogue conversion system. The most appropriate procedure would probably be the design of a control unit with a small memory, D/A and A/D capability, connected to the main computer. This unit could also contain a teletype input/output unit (rentable) which could act as console for the operator.

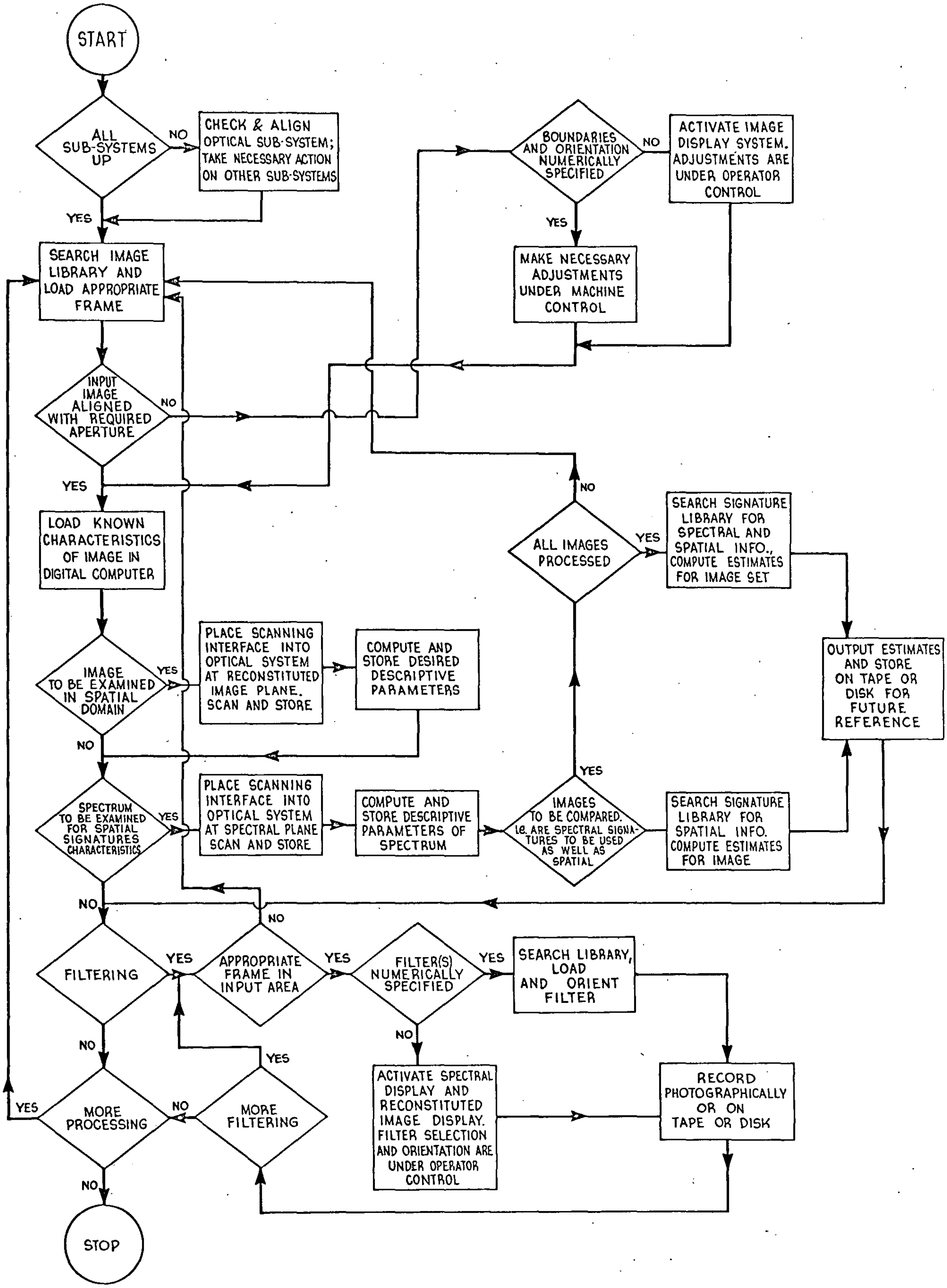

FIGURE 1 SIMPLIFIED FLOW CHART OF A POSSIBLE AUTOMATED PHOTOINTERPRETATION SYSTEM

The control unit would evaluate typed codes and either direct them to the main computer or initiate independent action for simple operations (such as direct optical displays).

The principal hardware expense is the design of the control unit, particularly its logic capabilities, and the interfacing controls of the optical processing system.

Overall, the author can only suggest a magnitude of cost which is in the order of $100,000 initial capital, and an annual operating cost depending on the amount of computer time used.

The alternative to the proposed system is one which operates directly on a digitized image. Such a system would require only the digitizing system plus a main digital computer; both of these could probably be rented. However, the throughput and efficiency of such a system will be less because it operates in the spatial rather than the frequency domain. It is impossible to specify the exact difference in cost, but the author would suggest it would be in the order of one-tenth as expensive to operate with an optically based system.

Programming.

Perhaps the most important part of a possible automated interpretation system is a set of coded procedures in a digital computer to actually examine characteristics of an image. Basically this involves evaluating

$$I_i = f\ (P_{x,y})$$

where I is the probability that an image can be classified as containing i, and P_{xy} is the power spectrum. If spectral signatures are also involved, the function becomes $I_i = f\ (P_{j,x,y},\ P_{j+1,x,y,}\ldots P_{n,x,y},\ S_i)$

where j....n are different sensing wavebands and S_i is the spectral signature of i.

At present little is know of the form of this function. L. Curry is investigating a related problem from a theoretical standpoint as part of this project, but otherwise there appears to have been little more than speculation about it.

This problem can be somewhat overcome in the programming of the automated interpretation system by incorporating a "learning" mode. Thus images can be introduced where the content is specified. This information is added to the existing library and the constants of the identifying function recomputed, probably by least squares. A further desirable feature is that the user be able to suggest forms of the identifying function which can be tested with stored data.

It is apparent that the operator/interpreter is of considerable importance in the suggested system, particularly when dealing with the interpreting program. It is almost necessary, therefore, that the programming be in a conversational language.

<u>Conclusion.</u>

It appears that an automated image interpretation system consisting of a combination of optical and digital computer elements is not only feasible but has considerable advantages over direct image scanning systems. With such a system, it becomes possible to process the very large quantities of remotely sensed imagery which are now being accumulated.