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9G45-68

APPLICATIONS of OPTICAL PROCESSING for IMPROVING ERTS DATA

TECHNICAL REPORT NO. 16
VOLUME I

OCTOBER 1970
CONTRACT NO. NAS 5-10343

JACK J. O. PALGEN

prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

ALLIED RESEARCH ASSOCIATES, INC.
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FOREWORD

This report was prepared by the Geophysics and Aerospace Division of Allied Research Associates, Inc., Contract No. NAS 5-10343. The objective of the study was to Investigate the potential application of optically diagnosed noise information toward the development of filtering subroutines for improvement of digital sensing data tape quality. The report is Volume I of three volumes presenting studies of ERTS data management, processing and dissemination procedures.

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1. INTRODUCTION

One of the principal activities of the Earth Resources Technology Satellite (ERTS) Data Center will be Quality Assurance (QA). The QA efforts must be directed at:

1. Internal processes that are part of the data-handling efforts in the data center.
2. External processes that are associated with the spacecraft, peripheral electronic components, communication links and ground recording systems.

In this study we have addressed the problems associated with external processes, their diagnosis and potential cures.

Preliminary studies (Merritt, et al. 1969) had shown that noise diagnosis in near-real time could readily be accomplished using modern optical data-processing techniques. These optical techniques can also be used for image improvement, but it is recognized that many users of the ERTS data will not be working with images alone but will, rather, be using digital tapes. Since the users of digital tapes will be utilizing more density (gray) levels than can the human interpreter, the problem of noise control becomes increasingly more important. Hence, in this study we have examined the following hypothesis:

> "Optically diagnosed noise parameters can be used to develop filter routines useful for the improvement of the digital sensory data tapes."

In the examination, we have looked at past work in the allied discipline of communication theory and the noise filtering of the Mariner imagery. Recent experiments to improve Nimbus imagery for use in the evaluation of earth surface phenomena were also studied. The Nimbus work provides a close analogy to the problems anticipated for the ERTS A and B systems, not only in the use to which the data are to be put, but also in the general mode of tape storage, line scan display, etc.

2. BACKGROUND

Space imagery appears at first glance to be much the same as ordinary TV imagery and, as such, amenable to filtering techniques developed for TV image improvement. However, the difficulty with this analogy is that the TV work, based heavily on the theory of Shannon (1945) and Wiener (1953), was directed toward improvement of the image to the point where the human mind can complete the sampled image. For earth resources data, we are concerned with the information in the image matrix and cannot generally depend on the mind's ability to make up for the missing information*. It is this difference between TV and space imagery that may provide a basis for understanding why many space imagery users have difficulty in translating their subjective interpretation of an object or pattern to definitions amenable to automated pattern recognition techniques.

Noise in space imagery must be diagnosed and filtered to optimize information extraction. For ERTS data this is especially important since the background of many users does not provide them with the associative interpretation keys needed for information extraction.

The imagery from Nimbus provides a unique basis for evaluation of the potential ERTS noise problems. Personal contact with various earth science investigators working with the Nimbus imagery from the High Resolution Infrared Radiometer (HRIR) (daylight and night) has indicated that:

1. The Nimbus imagery (photographic and digital prints) contains a considerable amount of periodic and aperiodic noise.

2. The investigators have developed empirical procedures whereby the data modifications related to noise effects can be identified and adjusted or disregarded, depending on the requirements of the investigation.

An example from one ongoing investigation by Dr. N. MacLeod of NASA/GSFC Laboratory for Meterology and Earth Sciences demonstrates how periodic noise in the Nimbus NMRT manifested itself on an isoreflectance map over south central United States (Mississippi Delta). Figure 1 presents a copy of Dr. MacLeod's map as displayed using a CalComp Plotter contouring routine. The circular contours

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*Review studies on the theory and physiological basis for recognition have been prepared by Chevallier (1956) and Hempenius, et al. (1967).

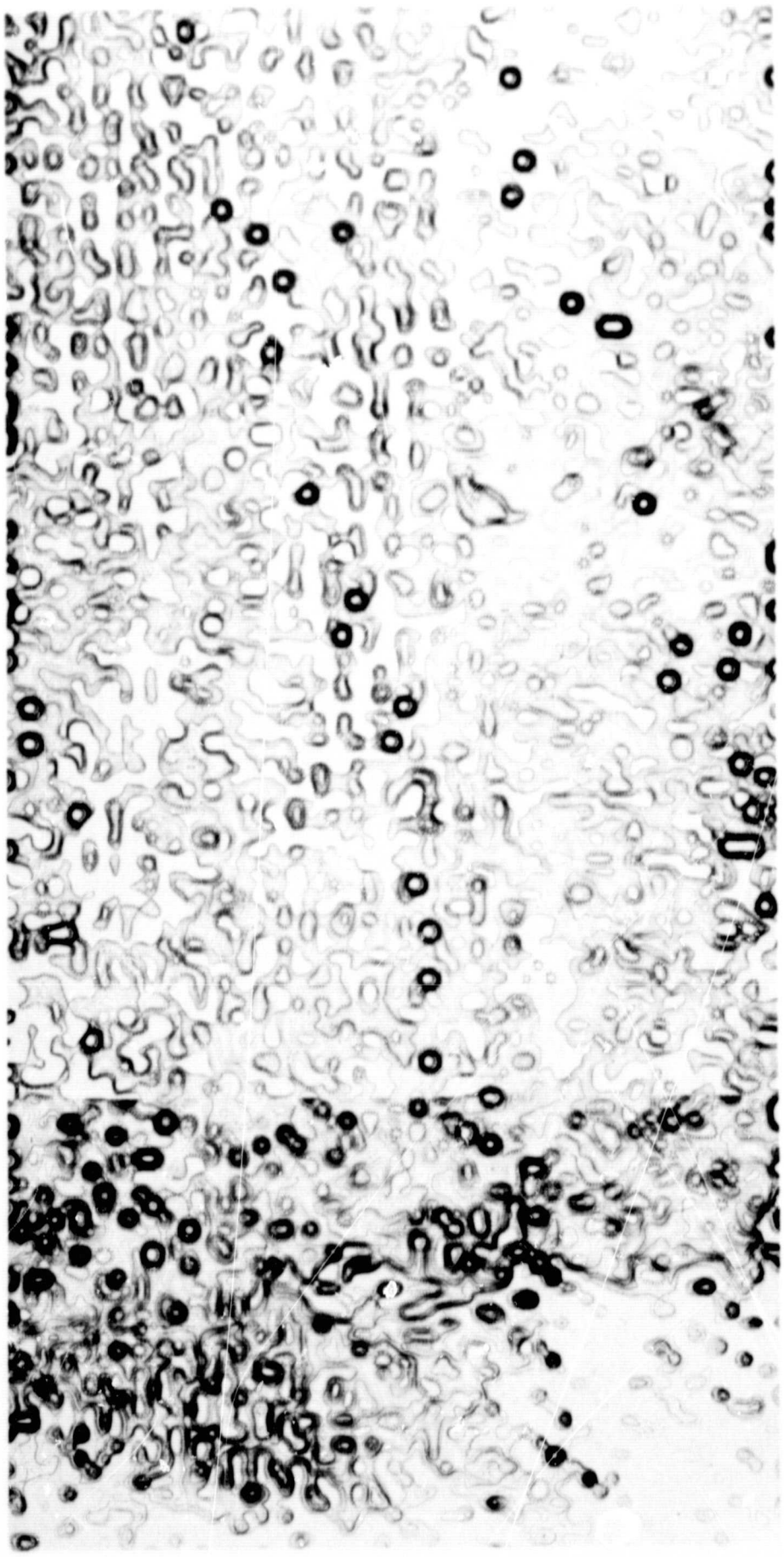

Figure 1 Pictorial Noise Patterns in Isodensity Tracings of Reflectance Data (35 Levels). Nimbus III HRIR, Average July 5 - 9, 1969.

which appear somewhat like holes or "bull's eyes" arrayed at regular intervals approximately parallel to the satellite path over the ground (approximately along the vertical center line) are points where the periodic noise associated with the High Data Rate Storage System - A (HDRSS-A) had enhanced the otherwise fairly flat contrast reflectance pattern. This noise pattern is enhanced by: (1) the particular display technique utilized*; (2) the use of 35 levels, i.e., far more than is possible in the photographic analog image reproduction; and (3) the fact that the mind does not attempt to "smooth" a scene such as this, which is basically not within our common visual experiences. The noise pattern was recognized by the investigator because he had an extensive background of what to expect in this area and these periodic "bull's eyes" were well outside of the anticipated response.

Obviously, the use of such statistical models of expected reflectance behavior contributed greatly to the investigator's interpretation of "noise". On the other hand, the mere visual appearance of a periodic reflectance pattern does not always mean that noise is present. In the case of future ERTS imagery, the pictorial noise should be diagnosed to a level that the investigators can be sure that variations away from the anticipated patterns are related to real physical phenomena, and not noise.

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*Average of digital values from NMRT tapes over five consecutive days. Similar techniques are currently in use at ESSA for eliminating or enhancing cloud and haze influences.

3. DIAGNOSIS OF PICTORIAL NOISE

In order to develop appropriate procedures to filter the noise in space-acquired imagery, the characteristics of the noise must first be diagnosed. The diagnosis of pictorial noise can be achieved digitally or optically. Special emphasis is given in this section to the characteristics of the optical diagnosis technique since it is felt that this technique is more appropriate to the real-time (or near-real time) constraints of the ERTS Data Utilization Center.

3.1 Digital Noise Diagnosis

Digital techniques in the diagnosis of both the trend and the trend-free components of noise are well developed. These include:

1. Direct-Trend Analysis, which can be performed by obtaining the non-stochastic, harmonic series (periodic or cyclic in nature) from a harmonic process which contains a random variable.
2. Fourier Analysis, which is a means of obtaining the resolution (amplitudes) of the harmonic functions, in the case where they involve trigonometric terms.
3. Power Spectrum Analysis, which is useful in matching the variance (frequencies) represented in the cycles describing the trends.

For 1-dimensional or time-related data sets, the above methods are expected to be useful for analyses of harmonics in space pictorial data on a line-by-line basis. They can be used to separate primary trend components (information) and secondary oscillatory residual terms (pictorial noise) from basic data subjected to a combination of cyclic or oscillatory contamination processes.

3.2 Optical Noise Diagnosis

A photographic negative (or positive) in an optical data processor modifies the amplitude or phase of incident coherent light (laser), producing a diffraction pattern (optical Fourier transform). The diffraction patterns reflect any sinusoidal pattern in the image. Measurements of the diffraction patterns can provide a quantitative measurement of the noise in the image.

The patterns used for measurements are representations of zero-order and first-order wave fronts. Zero-order wave fronts are those which maintain their

initial direction after passing the input image. First-order wave fronts are those which change their direction after interaction with the input image. The distance between the zero-order group and the first-order points is proportional to the spatial frequency of the noise in the input image. (See Figures 2 and 3.)

Expressed in terms of Fourier transform, the zero-order component corresponds to the fundamental frequency of the Fourier series which can be used to represent the whole viewed image area. The wavelength of this fundamental frequency is equal to the distance between the repeated spatial elements. The first-order component corresponds to the wavelengths of the fundamental frequencies of the pictorial noise: distances between the groups of repetitive noise elements in the image are translated into pairs of points in the Fourier domain.

Another important aspect of this analysis is that the first-order image point is imaged on a line orthogonal to the direction of the periodic elements of the input image. This property is useful to define the angular orientation of the periodic component, provided a common reference direction is available in both the input and the transform.

3.3 Optical Diagnosis of Nimbus HRIR Noise as an ERTS Test

In order to obtain a test of the ability of optical processing to define noise in space imagery, a series of Nimbus III HRIR images were processed. These images were chosen from a sample period, 3 August 1969 to 26 November 1969. The selection included pairs of images recorded on the HDRSS-A and HDRSS-B systems (the HDRSS-A tape recorder had been identified as a noise source in other studies). Inspection of the optical transforms* shows combinations of transitory, fluctuating complex noise components, identifiable as orthogonal and nonorthogonal energy peaks. The summarized results of the experiment indicate:

1. The transforms for the HDRSS-B images retain a constant pattern, outside of the zero-zone, for the entire test period.
2. The transforms from the HDRSS-A images begin to show variations from the HDRSS-B transform on 20 August. The pattern appears to indicate a reduction in noise on 6 October and an increase toward the end of the test period (Figure 4).

*The transforms were prepared with the cooperation of Dr. A. Shulman, Optical Data Processing Laboratory of the Advanced Development Division, NASA/GSFC. Pictorial examples of the tests are available but are not reproduced in this report.

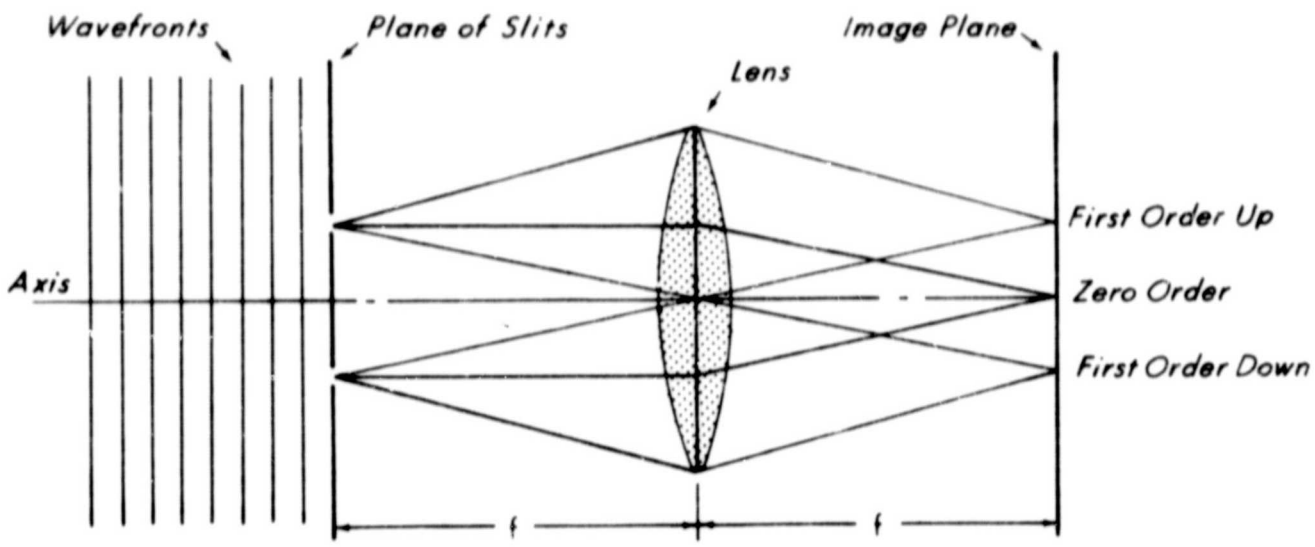

Figure 2 Diffraction Pattern Focused in Focal Plane (Shulman, 1966 and 1970)

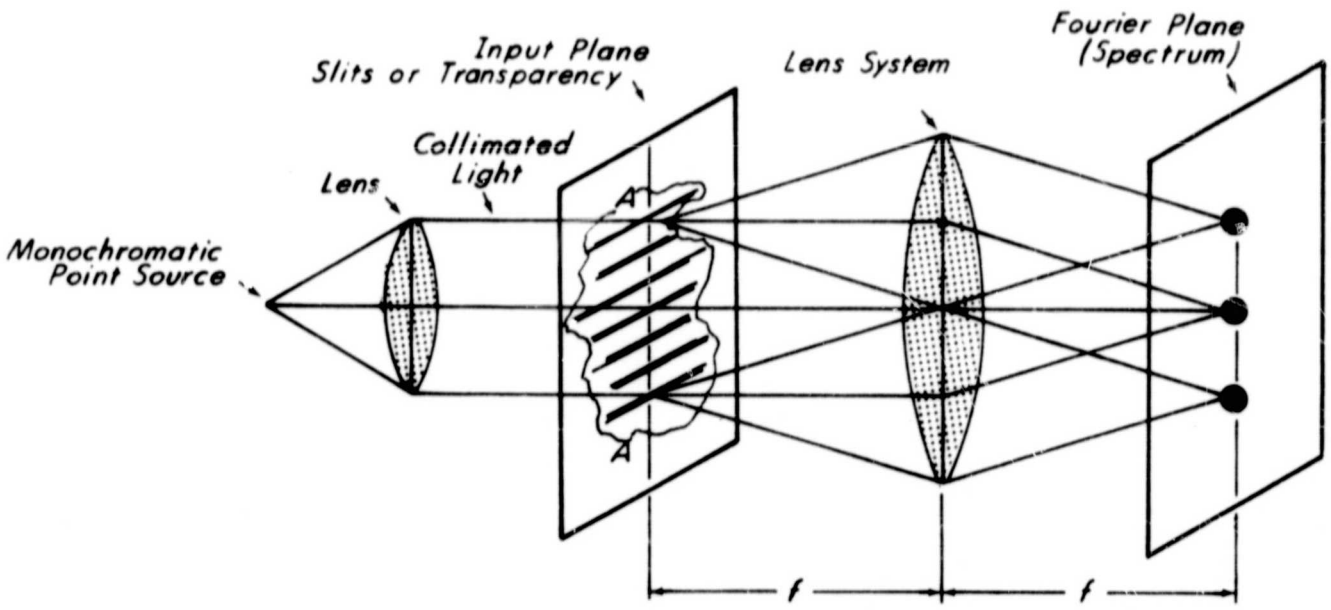

Figure 3 Optical Spectrum Analyzer (Shulman, 1966)

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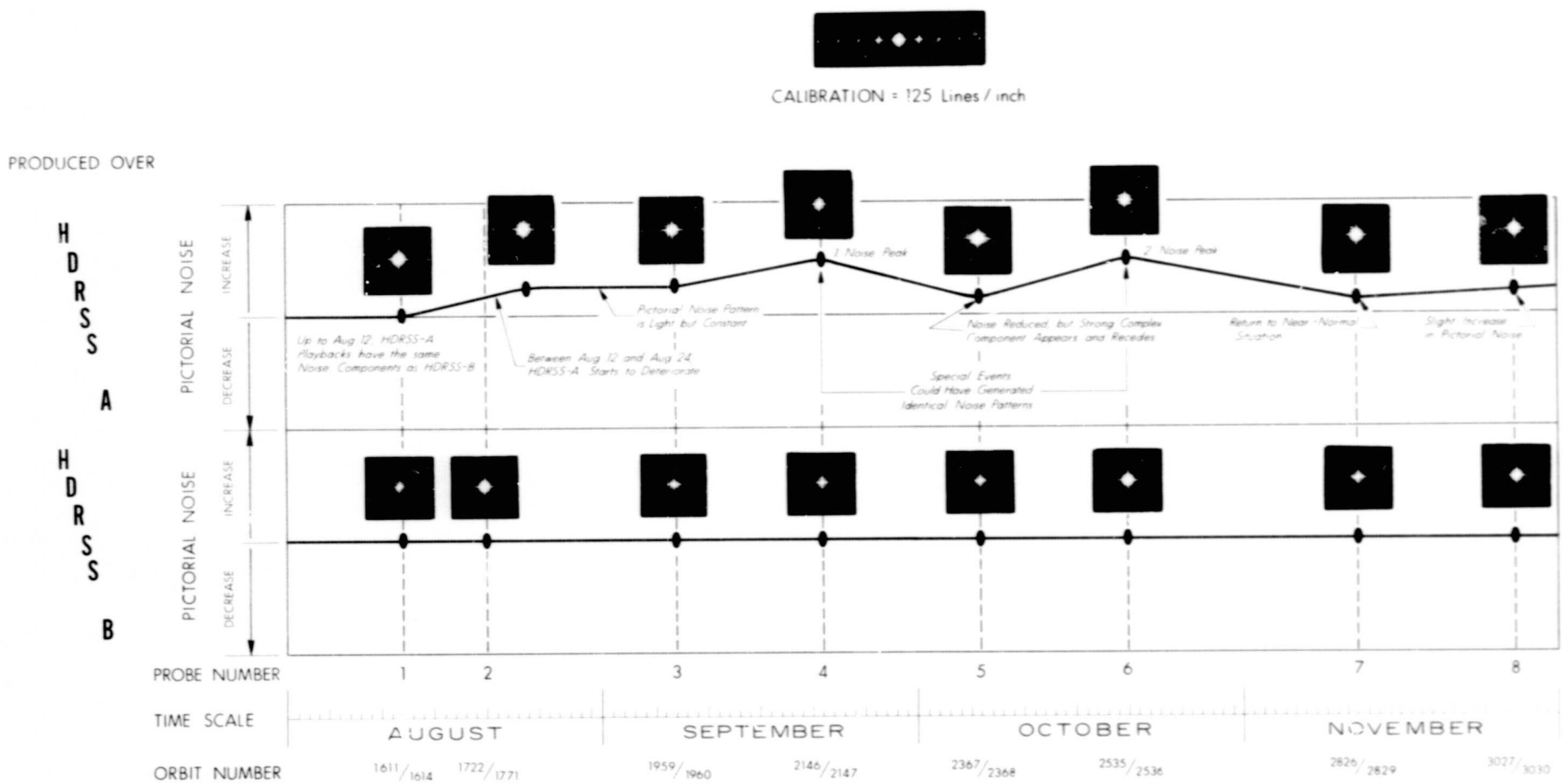

Figure 4 Time - Sequence Study of Pictorial Noise Pattern Transforms

These tests indicate that optical processing can be used to identify complex and periodic pictorial noise patterns that vary over time.

Techniques for quantitative measurement of noise are required and will be described in the following sections.

3.4 Optical Pictorial Noise Measurement

Equivalence between the theoretical properties related to pictorial noise measurement and their conjugate coherent optics systems has been realized in many R and D laboratories since the advent of the laser (Stroke, 1968). However, operational use of noise-measuring techniques requires a higher level of repetitivity, linearity and stringent quality assurance in the outputs. Thus it is necessary to carefully select the potential collector media, and provide stringent control of each phase of the imagery processing sequence.

3.4.1 Selection of an Optimum Photosensitive Collector

Current practice in preparing optical Fourier transforms is to display the transforms on photographic film. There are, however, various other and better methods which may find eventual utilization in an operational system. These include:

1. Photochromic Flats produced by Corning and other manufacturers; this glass responds to light energy by changing density. A transform could be imaged directly, temporarily stored and then read off with a camera or line scanner. An IR source would then erase the image and make the flat available for re-use.

2. Various Dry Silver materials could be used too; these are essentially photographic but provide ease of processing at very high resolutions; i.e., 200 to 300 lines/mm and low cost.

3. Cathode-Chromic CRT's are presently under development which could permit interactive activities with the transform and its associated imagery.

Resources did not permit any experimentation with any of these display systems and, hence, no discussion of their relative merits is presented here.

3.4.2 Film Selection and Processing Control Procedures

The current procedures for photographic display of the Fourier transform leave much to be desired. The films that have been used are often nonlinear, may have a poor grain structure and processing is at current commercial level. Tests* were performed (see Appendix B) to compare the linearity and definition of different types of films. Of the films tested, the EGG Extended Range (XR) film produced the most satisfactory results.

3.4.3 Optical Component Considerations

Selection of good optical components and reduction of dust particles is essential to effective optical processing. The Optical Processing Laboratory of the Advanced Development Branch, NASA/GSFC under Dr. A. Shulman is very much aware of this problem and is working on various approaches to provide the best transforms obtainable (see e. g., Grebowsky, 1970 and Grebowsky, et al, 1970). Several experiments have been conducted together with Dr. Shulman toward the development of the best approach. These tests are now being extended to various NASA-suggested approaches.

*Very stringent photographic processing control was exercised at the NADUC Photographic Laboratory for these tests.

4. IMAGE FILTERING CONSIDERATIONS

Space-acquired imagery can be filtered to suppress unwanted pictorial noise phenomena. This is achieved by means of a filter, defined as a device which operates (e.g., "blocks" as in the optical domain) on a given part of the data set to modify it in some predictable manner. Filters are properly classified as either digital (algorithmic) or analog. In the analog domain, there are optical, electronic and fluidic filters among others. In the following sections, we shall consider only digital (electronic) and optical (analog) filters and their applications to the filtering of space-acquired imagery.

It should be pointed out that smoothing is a special case of filtering directed toward attenuation of high-frequency events in a data set. Ideally, smoothing should not influence low-frequency events. However, since attenuation is roughly proportional to frequency, the limiting frequency of the smoothing process is difficult to define. If the amplitude, frequency and phase of the pictorial signal are changing, as is commonly the case in space-acquired imagery, smoothing can lead to either a considerable information loss, or to unwanted aliasing phenomena (spurious signal-like pictorial features) and significant user frustration in his attempts to interpret the spurious phenomena. Thus, ideal filtering operations should be understood as operations which modify the data set in a predictable manner without appreciable reduction in information content. The choice of filter to accomplish the "cleaning" depends on the source of noise and the characteristics of the scene. It also may heavily depend on the way in which further use will be made of the imagery. If the data are to be used only by human interpreters, then optical filtering alone may be suitable. If the data are to be used in automated spatial signature processing, then digital filtering is required. The digital approach can also serve both purposes; i.e., preparing a clean tape to provide a new image output or a clean tape for further digital processing.

4.1 Optical Filtering

4.1.1 Procedure

Once the noise frequency and directional components have been defined, as described in Section 3, it is possible to use appropriate optical filters. Shulman (1966) has defined the process. Basically, a single lens is added to the optical processor (Figure 5). The purpose of the first lens is to image the spectrum of the negative on the image plane. This produces in the back focal plane (spectrum plane)

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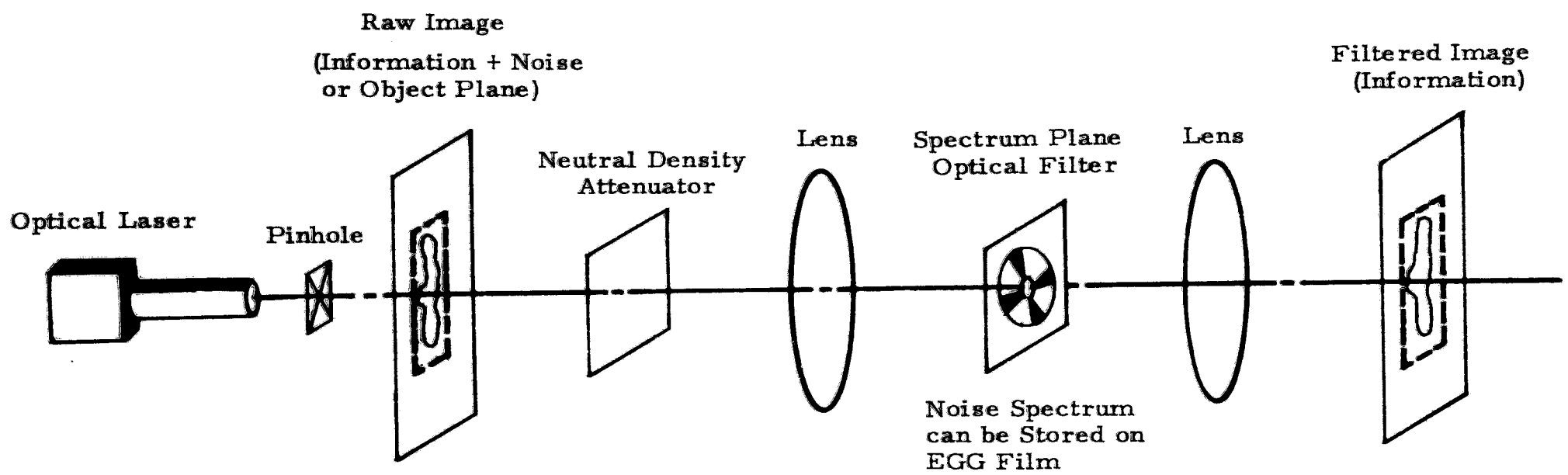


Figure 5 Experimental Optical Processor (used at Applied Optics Division, Goddard Space Flight Center)

the spectrum of the transmission function generated in the front focal plane (object plane). The second lens produces a transform of the transform of the filtered image, which is the inverse transform.

If the energy from a pair of dots which corresponds to any repetitive (sinusoidal) transmission function has been blocked in the transform, the energy reaching the image plane will be deficient in the blocked frequency. Optical filters merely block energy in specified frequencies and angular orientations. Figure 6 illustrates various filter configurations.

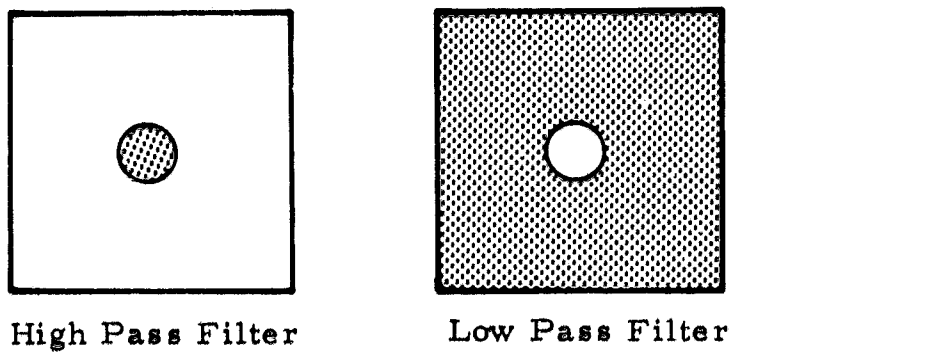
1. High-pass filters are generated by blocking the area around the zero-order zone, eliminating related low frequencies.
2. Low-pass filters are generated by putting a standard pinhole in the transform plane, passing all the energy on low frequencies, but blocking high-frequency energy.
3. Bandpass filters, constructed from low-pass filters, pass only energy in a given frequency interval.
4. Directional filters are generated by blocking energy corresponding to the orientation which is perpendicular to the related noise components of the original imagery.

4.1.2 Experiments in Filtering

A test of optical filtering of Nimbus imagery is currently underway. Earlier tests were accomplished, but the results suffered from the optical component problems mentioned in Section 3. The preliminary results from new tests indicate marked improvement over previous results. It is anticipated that the current tests will be completed in the near future and these should provide a valid basis for any further thinking on the use of optical "cleaning" in the ERTS Data Center.

4.1.3 Some System Characteristics

Optical filtering systems behave and operate quite differently from the more familiar electronic filtering systems. Some of these differences are summarized below.



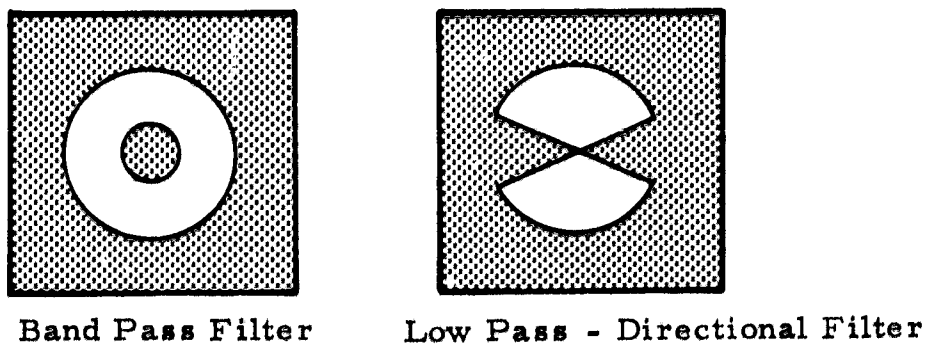


Figure 6 Optical Filters (Shulman, 1966)

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1. The response of an optical filtering system varies from zone to zone in the image plane: in the electronic sense, this corresponds to operating with a signal storage, a processing "black box" and a receiver system which are constrained to vary their response in real time. Such an electronic system is theoretically feasible, but is very difficult to achieve.

2. Optical filtering systems do not maintain mathematical symmetry between time and frequency domains. Unlike electronic systems, the optical systems do not depend on past inputs and, furthermore, the physical implementation in the case of filtering operations with optical components) of the integrals does not necessarily have one of their limits equal to zero.

3. Optical frequency cutoffs can be much sharper than is even possible with electronic systems.

Basic similarities in the two types of systems do exist; e. g., the point source image of a perfect lens looks, in amplitude, like the response to a unit impulse of an electronic network. However, indiscriminate consideration of one system equalling the other should be avoided.

4.2 Digital Filter Design Considerations

In the selection of an algorithm as a digital filter, Wiener (1953) and Elias (1953) have proposed that the following property of the algorithm be considered:

1. Its Neighborhood Modification Property (NMP), i. e., its ability to "map" a closed collection of adjoining pictorial data into an acceptable output.

2. Its maximum transmitted signal-to-noise ratio (S/N), i. e., its property to retain the input data pictorial pattern without attempting to reproduce any particular shape.

The optimal filter should be designed to make maximum use of the fact that in pictorial data, the data points appear in a 2-dimensional row/column matrix and the dependent variables (density values) are discrete, steplike, values forming a now continuous set. It should also be noted that cross-correlation, in pictorial matrices, exists both orthogonally and in a Laplacian mode, independent of any cardinal direction pairs. Current space imagery sets contain unique radial properties around any image point which, to this time, has not been used in pictorial noise processing This characteristic of "quasi-topological neighborhood relationships" is shared with optical processing. Their equivalence in time-sequenced imagery sets has not been used either.

In theory, then, the general configuration of any digital spatial filter should permit use of two classes of input:

1. Positional information of the data; i. e., of the densities inside a discrete Laplacian neighborhood centered on the cell to be filtered.
2. Statistical correlations between similar-sized Laplacian cells with previously analyzed neighborhoods.

Thus, there is a dual concern in the design of digital filters: to minimize the Laplacian cell size, and at the same time to optimize the Laplacian operators.

In the design of digital filters, the following additional factors should also be considered:

1. The finite size of the filter limits the steepness of the filtering function itself; i. e., its efficiency in the medium frequency range.
2. The selected sampling grid and its local size affect the filter response.
3. The orthogonal shape of the sampling grid as well as the usually symmetrical (square) shape of the neighborhood area should be expected to introduce specific directional effects leading to eventual biases or pictorial aliasing.
4. The effects of the above factors tend to interrelate and to become reinforced, when more than two cardinal orientations are used.
5. The discrete character of the pictorial neighborhood area tends to introduce unwanted truncations, and to bias the filtering algorithms in favor of specific conjugate directions (Simon, 1970).

4.3 Experiments in Electronic Digital Filtering

Both 1-dimensional and 2-dimensional digital filtering techniques have been applied to space-acquired imagery. An evaluation of the results is presented below.

4.3.1 1-Dimensional Filtering

1-Dimensional filtering has been applied to Nimbus HRIR imagery. This test* appears, superficially, to have greatly improved the pictorial quality. The process as verbally described by RCA personnel is basically as follows (all processing is accomplished electronically):

*Performed by RCA Astroelectronics for NASA/GSFC.

1. A 1-dimensional Fourier analysis is performed for every line of the picture matrix as generated by data recorded on a channel of the HDRSS tape recorder, using data sets drawn from another channel in the tape recorder.

2. On the basis of the Fourier analysis, a matching notch filter is defined and applied to the 1-dimensional image record. The output is then cleaned of noise with the Fourier-diagnosed frequency. A time-delay is introduced so that the line-by-line filtering can proceed in near-real time.

In order to evaluate the aliasing effects of the filter on the picture information, Allied Research Associates, Inc., (ARA) personnel secured the three images: the original HDRSS-A noisy image, an original HDRSS-B clean image used as reference and acquired at the same time, and the filtered HDRSS-A image (Figure 7). Notice that the herringbone pattern is quite well removed, thus testifying to the visual adequacy of the filtering system. However, the dynamic range appears to be reduced and there appears to be a resolution loss as might be expected from any "smoothing" operation. Of course, local contrast effects are decreased.

Evaluation of the information content, however, by a competent Nimbus image interpreter detected an unexpected number of pictorial aliasing effects. Some 40 different "false" features appeared or disappeared from the image. Tables 1 and 2 list the features*. Many of the features could lead an interpreter to a completely different interpretation of the information on terrestrial objects.

Theoretical aspects of aliasing phenomena on 1-dimensional data sets are described in the literature**. In the Nimbus example, the pictorial aliasing appears to arise from sharp contrast features. These features provide a marked contribution to the frequencies being removed by the adaptive filter; i.e., when the filter moves through such an area of data, its harmonics contribute to the display of "false" density values. Modifications could be devised to improve this aspect of the filter but would not totally correct it, since it does not take into account the 2-dimensional "neighborhood" properties mentioned under Section 4.2.

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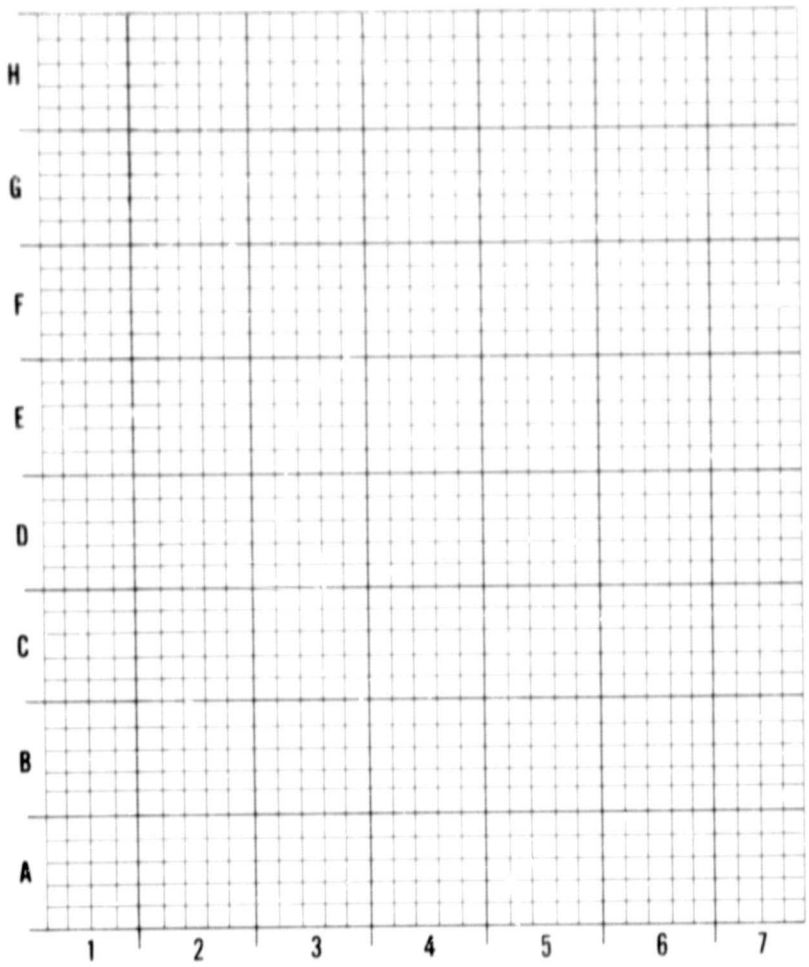
*It is interesting to note that, although the image interpreter was not aware of the mathematical formulation of the aliasing process and of its expected symmetry, he discovered a nearly equal number of added (22 examples) and/or missing (20 examples) features in the "filtered" image.

**No review on 2-dimensional aliasing seems to exist in the open literature (Palgen, 1970).



Grid

Referenced

Raw

Filtered

Figure 7 Aliasing Effects Due to 1-Dimensional Filtering

TABLE 1

COMPARATIVE VISUAL ANALYSIS OF
LINEARLY FILTERED NIMBUS III HRIR IMAGERY

Features added, i. e., present in cleaned image, but not in reference image.

Location	Comment
3B 9	HZ block spot
2C 9	Vertical lineament change to structure
5H 10	Bay in coastline
4H 10	Bay added in coast - could be break in cloud
2G4	Dark spot added - igneous?
3G 8	Linear dark line - river?
4G 13	Dark circle - oasis? rocks?
1F	Several dark circles somewhat regular and linear
2F 7 and 8	Two bright spots - sand seas?
2F	Several dark circles
4F 7	Dark circular feature
5F 19	"Real" dark area larger on A than B
6F	Several additional dark circles and lines
1E	"Real" dark area appears larger on A than B
6E 12	"Real" dark area appears larger on A than B
2D 4 and 9	Separate dark circles on B appear joined on A
3D	Several dark circles added in light area
4D	Dark areas appear blurred and joined to A
6D 19	"Real" dark circular area larger on A than B
4C 4	Small, dark circular feature added
3A 8	Small, dark circular feature added in A
6A 7 and 8	Three small, dark circles in row on A

TABLE 2

COMPARATIVE VISUAL ANALYSIS OF
LINEARLY FILTERED NIMBUS III HRIR IMAGERY

Features lost, i. e., present in reference image, but not in cleaned image.

Location	Comment
2D right	Vertical lineaments
1H	Some thin cloud information lost
2H	Some thin cloud information lost
5H	Some loss of cloud detail
6H	Some loss of cloud detail
7H	Some loss of cloud detail
1G	Loss of gray scale definition
5G	Coastline more uneven
7G	Some loss of cloud detail
2E 7	Dark linear feature "lost", fewer shades of gray
4E	N edge of crescent feature less distinct on A
5E	To "real" dark linear features less distinct on A
1D 20	Dark/light boundary less distinct on A
5D 2 and 6	Dark linear feature blurred on A
1C 17	Dark linear feature becomes lost in background noise
2C	Dark/light boundaries less distinct on A
5C	Dark features of different shapes in A
6B 17	Linear very indistinct
7B 20 and 25	Circular feature more linear on A than B
4A 17	Dark, linear feature indistinct on A

In summary, this work in filtering is excellent for developing cleaned images for PIO users and for users, e.g., meteorologists or hydrologists, looking for large features (small scale). Users seeking small features (large scale), e.g., geologists or ecologists, may find the imagery deceptive. The use of such 1-dimensional routines to clean the Nimbus digital tapes (NMRT) would have similar limitations, but they would be more troublesome since the human eye would no longer provide a smoothing function. Users of ERTS data will often fall into the small feature interpreter category; hence, 1-dimensional digital filtering routines may not be extremely useful because of the previously discussed aliasing effects.

4.3.2 2-Dimensional Filtering

An operationa 2-dimensional filtering of pictorial noise was successfully accomplished in the Mars-Mariner TV imagery by the Jet Propulsion Laboratory of University of California. This work made full use of the mathematical theory of filtering briefly described earlier in this section.

Successive refinements of the method described by Nathan (1966) and Rindfleisch (1968) were used to "clean" 200 pictorial frames. The procedure utilizes a subroutine to eliminate scan line noise, and an algorithm based on the Fourier transform approach to eliminate other noise effects. The first operation requires three minutes per picture, the second has varying application times depending on the window size and on the complexity of the Fast Fourier transform used. Hard wired circuitry has been used effectively in recent runs.

However, sequential computer times of two to three hours per picture with third-generation equipment has been common; this seems outside of the ERTS Data Center capabilities. Comparison of information retrieval ratio with different filtering operators, vs correlated processing times need to be performed, first with simulated inputs and second with real imagery interpreted prior to and after filtering.

4.3.3 Summary of Electronic Filtering

The results of 1- and 2-dimensional experiments in image filtering suggest that pictorial filtering capabilities for the ERTS system should lie somewhere between: perhaps closer to the 2-dimensional in filtering, but closer to the 1-dimensional in time efficiency. Advancing technology in hard-wired Fast Fourier transform systems may make the complete digital 2-dimensional approach practical in the time between now and the launch of ERTS.

5. SUGGESTIONS FOR OPERATIONAL ERTS DATA FILTERING

This study has examined the contributions of, and problems associated with, the use of optical and digital approaches to ERTS imagery filtering. The potential for the use of a combination of both appears to be quite high. The advancement of the technology for digital image array handling may, however, make the fully digital approach more feasible in the future. The following sections will examine both optical and digital approaches and suggest potential operational techniques.

5.1 Optical

The prime advantage of the optical processor is the shorter time required for various types of 2-dimensional image processing. The principal disadvantage may be in the use to which the data will subsequently be put. The initial phase of ERTS operation might consider the following optical possibilities:

1. Using the optical processor to define (diagnose) the noise frequency components, digital filtering algorithms would then be defined on the basis of the optical noise diagnosis.

2. Using a system which combines the optical processor* with a cathode-chromic CRT such that an interactive control could be maintained over the image. The image could be displayed in a filtered format using 2-dimensional optical or digital techniques, and then read onto a digital tape by a built-in optical scanner.

In (1), there is no problem of implementation, although techniques still need to be developed for the use of the optical Fourier transform noise diagnosis in effective 1- or 2-dimensional digital filtering subroutines. In (2), while there are inherent difficulties, implementation is basically attainable. In fact, Dr. Shulman has already achieved appreciable success in overcoming some aspects of the optical problems.

Another advantage to an optical approach is that the optical setups can be readily translated into digital software and/or hardware. In terms of visual interpretation and inferences, the optical systems offer, in many ways, a preferable approach.

Film transparencies will be available for Quality Assurance review approximately 1-1/2 hours after the film enters the MPPL from the TIDP. Optical Fourier transforms should be prepared on each image entering the Quality Assurance and

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*This approach was basically suggested by Dr. A. Shulman.

Standards section. The transforms can be displayed in any suitable manner; however, the tests conducted in this study suggest that the EGG XR film may be the most appropriate. The transforms could then be matched either visually or via an optical correlator to a bank of previously defined noise transforms. The simplest approach would be to compare an image transform to two known noise transforms to obtain limiting values for the probable noise. The noise transform bank should be complete with noise patterns, analyzed noise components and recommended filtering routines.

In cases which match the existing transforms, the filtering routines will be defined. In cases where no match occurs, a detailed review of the noise data will be required. A no-match will also indicate a change in the sensor system noise.

This approach is presented as an alternative to the direct measurement of the transforms as outlined in Merritt, et al (1969). The accuracy requirements of direct measurement techniques are probably outside of the capabilities of the ERTS Data Center.

5.2 Digital

Development of digital filtering techniques for ERTS imagery should receive priority because all received data will be in electronically processible formats. The complexity of 2-dimensional filtering programs may, however, delay operational implementation of 2-dimensional filtering until special processors are available.

The 1-dimensional, line-by-line filtering which was attempted for Nimbus HRIR data, may offer some improvement if the annoying aliasing effects can be reduced through appropriate subroutines or hard-wired equivalent.

An approach to reducing aliasing would be to devise means to "turn off" the filter in the vicinity of sharp contrast regions by sampling the neighborhood. When a filtered value in the neighborhood is greater than a specified threshold, it should be replaced by the original value. The logic of this approach is more subtle than that of the standard electronic filtering, because of the need for interaction with the real data domain. Implementation of a hard-wired sensor to accomplish these changes is attainable, dependent only on the availability of reliable buffers.

Analog buffers seem to be ruled out here due to the very strict requirements on internal time-keeping they would impose on the system if an acceptable throughput rate is to be expected. Instead, rapid-access digital buffers could be used to store and to tag the raw data as they come out of a broadband analog-to-digital converter. These are available as off-the-shelf items with a capacity of over 4000 words; i. e., sufficient for ERTS line format. No more than five such operational

buffers are needed in the filtering algorithms (such as weighted polynomials of the 3rd order). Two additional buffers would be needed to correlate 1-dimensional activities. Extra memory requirements for extending 1-dimensional filtering to 2-dimensional filtering would not exceed 30 K words, even including allowance for the extra software. This requirement is met in the CPU core with most available computers.

Hard-wired digital Fourier transforms and hard-wired recursive (or self-adaptive) 1-dimensional filters are currently being developed. Progress started with the so-called Fast Fourier Transform (FFT) algorithms (Cooley and Tuckey, 1965; and Sande and Tuckey, 1966) in a software form. Hard-wired versions of the same logic are now available in plug-in units compatible with standard EDP processors. These hard-wired FFT circuits are operating over linear neighborhoods of over 2000 elements in less than 50 microseconds. Their cost is about $40K each to industry. Combined with a buffer memory of 128 x 128 positions, they could generate 2-dimensional transforms of square pictorial subarrays sufficient for the monitoring of pictorial noise components. If two additional buffer memories of the same capacity are added and operated in an inverse FFT n they would enable the production of filtered data sets using any of the 1-dimensional digital filtering packages available (Otnes, 1969; Broome, 1970).

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APPENDIX A

NUMERICAL NOISE ANALYSIS TECHNIQUES

A. 1 Autoregression

Subtraction of the trend from the original data tends to isolate a residual term, or noise component. The stochastic difference equations

$$X_p = aX_{p-1} - bX_{p-2} - cX_{p-3} - \ldots + E_p,$$

where

- p is the position of the X-term in the series: a, b, c, ... are isolating constant coefficients relating each X-term with the preceding term;
- E_p is the independent random variable with zero mean.

The residuals form a <u>linear Markov chain</u> of the first order, by regression of X_p on X_{p1}, when

$$X_p = aX_{p-1} + E_p.$$

One-dimensional autoregression is useful for analyzing terms which are not periodic in nature. The same technique extended to 2-dimensional sets can be applied to analysis of oscillatory phenomena related to pictorial noise. It may also be utilized to identify secondary oscillations in any harmonic phenomena isolated by the following method. See Agterburg (1964) for further discussion.

A. 2 Nonstochastic Harmonic Analysis

One-dimensional nonstochastic harmonic series express periodic noise cycles in terms of trigonometric functions; e. g., in the form of sine wave combinations. If a series is characterized by a definitive period, w, such that

$$X_p = X_{p+w} = X_{p+2w} = \ldots$$

where

X terms are the terms of the series representing individual observations, and p denotes the position in the series, the series is said to be cyclic. Addition of a random component (or white noise) results in a stochastic harmonic process.

This analytical approach is useful for detecting systematic or "colored noise" cycles in periodic phenomena. It may be applied, of course, to the analysis of cyclic pictorial noise components, in time-alternated sections of any type of pictorial imagery. See Schwartzacker (1964) for further discussion.

A. 3 Moving Averages

A moving average is the arithmetic mean achieved by the addition of a specified number of points which precedes and succeeds a given point in a 1-dimensional series. An example of a 5-point moving average is shown in Table A-1.

TABLE A-1

EXAMPLE OF A 5-POINT MOVING AVERAGE COMPUTATION

Point (X)	Observed Value (u)	Moving Total	Moving Average
1	15	-	-
2	5	-	-
3	30	85	17
4	10	90	18
5	25	-	-
6	20	-	-

A 5 x 5 moving average operates similarly on a 2-dimensional pictorial matrix.

Smoothing is the process of transforming the observations, which are characterized by irregular finite differences, into a regular succession of finite differences; this process results in a loss of some observations at the beginning and end of the smoothed succession. In the mathematical expression

$$X_{p+1} = u_{1+i} + u_{2+i} + \ldots + u_{k+i} + E_{p+i} \text{ (for i and k = 1, 2, ...)},$$

p is the position of X in the series,

E is a random variable

and u terms are the factors which determine X.

When extended to a 2-dimensional pictorial space each (X, Y) value shares some u values with its preceding value; in this sense, autocorrelation of 1- or 2-dimensional serials is effective. Changes in (X, Y) are determined by the correlation between members of the series. The pictorial arrays treated that way are to be described as a stochastic (random) process of moving averages.

Generally, the moving average technique is applied to correlation analysis. It tends to mask and shift both high and low signals, which may be important, since the new random components tend to obscure the original periodic elements.

It is useful, however, for detecting trends and cycles; and can be predictive, as with tides, sunspot cycles, and evolutionary cycles. However, smoothing may artificially generate oscillations in the residual aliasing. For further discussion and applications to resource analysis, see Fox and Brown (1965), Miller and Kahn (1962), Schwartzacker (1964) and Vistelius (1961).

A. 4 Fourier Analysis (One- or Two-Dimensional)

One-dimensional Fourier analysis is a means of reducing a cyclic series into its component parts, then describing the complete cycle by a combination of sine or cosine waves. The number of cycles determines the order of the series. Single Fourier Series is used for cyclic data represented by curves or 1-dimensional functions; 2-dimensional Fourier series for analyzing tridimensional surfaces or 2-dimensional arrays. Single infinite Fourier series are used to approximate a known function of the form

$Z = f(x)$, in which Z is a variate observed in terms of a number of intervals, x.

Graphically, this function plots as a continuous curve which can be represented by discrete, orthogonal intervals to which an approximating curve can be fitted by least squares methods according to the trapezoidal rule. According to this rule, the area of the trapezoid formed under the curve for each equal x segment is determined. As an example of single Fourier series, the value of Z is given by

$$Z = a_o/2 + L^{\infty}_{n=1} [a_n \cos (n \pi x/L) + b_n \sin (n \pi x/L)],$$

where

a_o, a_n, b_n for $n = 1, 2, \ldots,$

are the coefficients or numerical descriptors of the data, and L is one-half the sampling length. (Figure A-1.)

The coefficients are determined from

$$a_n = (2/k) \sum_{i=0}^{k-1} Z_i \cos (n \pi x_i/L);$$

$$b_n = (2/k) \sum_{i=0}^{k-1} Z_i \sin (n \pi x_i/L),$$

where

k is the number of sampling intervals.

Due to the independent nature of the orthogonal trigonometric polynomials, they are algebraically additive in two perpendicular directions, in which the scales can be independently varied; therefore, complex surfaces can be formed with a few terms.

For a Z function with a fundamental period of 2L in the X direction and 2H in the Y direction, a 2-dimensional Fourier series having m and n terms in the two perpendicular directions is given by:

$$Z = \sum_{m=0}^{M} \sum_{n=0}^{N} \lambda m, n \, [a_{m,n} \cos (\pi mx/L) \cos (\pi ny/H)$$

$$+ b_{m,n} \sin (\pi mx/L) \cos (\pi ny/H) + c_{m,n} \cos (\pi mx/L) \sin (\pi ny/H)$$

$$+ d_{m,n} \sin (\pi mx/L) \sin (ny/H)],$$

where

$$\lambda_{m,n} = 1/4 \text{ for } m = n = 0;$$

$$\lambda_{m,n} = 1/2 \text{ for } m = 0,\ n > 0 \text{ or } m > 0,\ n = 0;$$

and

$$\lambda_{m,n} = 1 \text{ for } m > 0, n > 0.$$

When mapped, single and 2-dimensional Fourier coefficients calculated from pictorial sensor data should clearly show local variation of the measured properties; so, 2-dimensional Fourier series may be effectively applied to the analysis of superposed pictorial phenomena in which a periodicity is manifest, such as analysis of harmonics in density maps, reflectance printouts or topographic surfaces, and for classification purposes. For further discussion and applications to resource analysis, see Anderson and Koopmans (1963), and Harbaugh and Preston (1968).

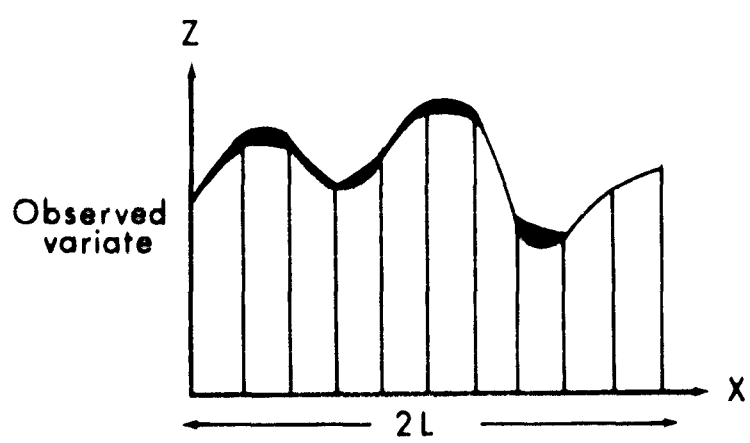

Figure A-1 Example of Approximating a Curve by Means of the Trapezoidal Rule.

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APPENDIX A

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APPENDIX B

TESTS OF FILM FOR RECOVERY OPTICAL FOURIER TRANSFORMS

Our initial optical noise diagnosis tests in this study were made with Polaroid Type 55 P/N film. This film is, of course, very useful because of its instant processing properties. However, the linearity is not suitable for precision analysis of the transforms, as demonstrated on tests performed with the Joyce-Loebl microdensitometer. We, therefore, prepared experimental transforms on two fairly specialized film types, i. e.,

1. Kodak SO-243: A special fine-grain aero film
2. EGG Extended Range (XR): A special 3-layered film, designed for imaging scenes with extreme dynamic ranges.

Both of these films have D-log E curves that are nearly linear over a wide range of exposure. Processing control of the films was accomplished in the NADUC Photographic Laboratory by including a preexposed standard gray-scale with each roll of film. Each roll is then processed according to the control test strip. Figures B-1 and B-2 present examples of test transforms of a line Ronchi grating for several shutter speeds. Note the excellent definition of the zero-zone in the EGG XR test (Figure B-2). The SO-243 test in Figure B-1 is satisfactory but is not comparable to the XR*.

Further tests of the XR displays of optical Fourier transforms are underway. The reason for the test is to find an exposure combination that can make optimum use of the exposure latitude in each layer of the XR film. This is essential for detailed analysis of the transform.

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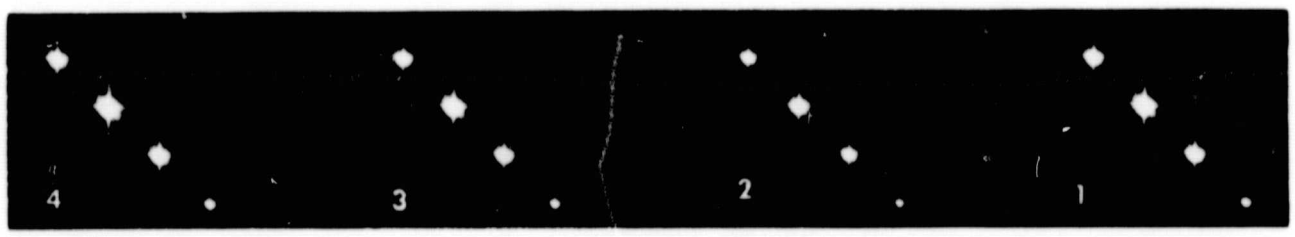
*A large measure of the success in these tests is due to the excellent control over photographic processing provided by Mr. Walter Ahlin of the NADUC Photographic Laboratory, and his technical staff.

Kodak SO 243



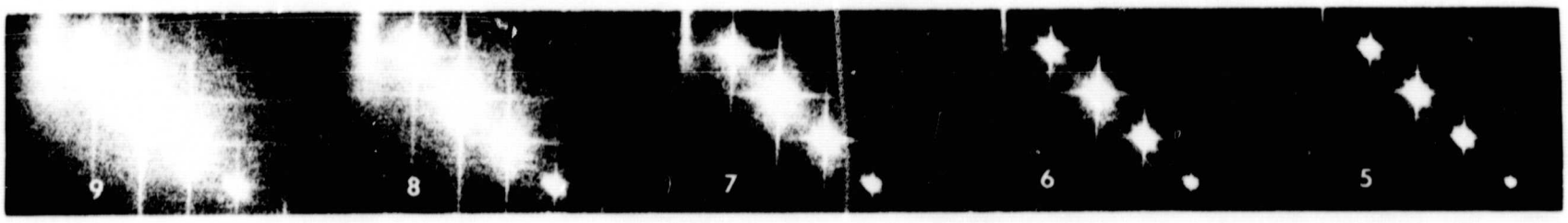
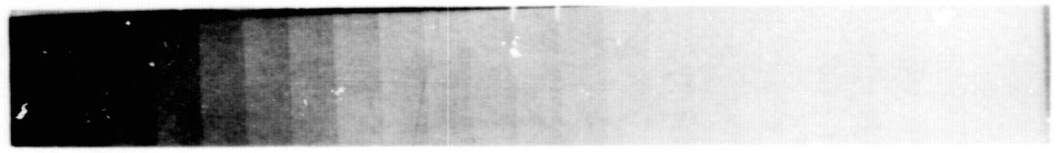


Figure B-1 Initial Test with Kodak SO 243 Fine-Grain Aero Film. Shutter Speeds for 1/2500 to 1/30 Sec.



EGG XR

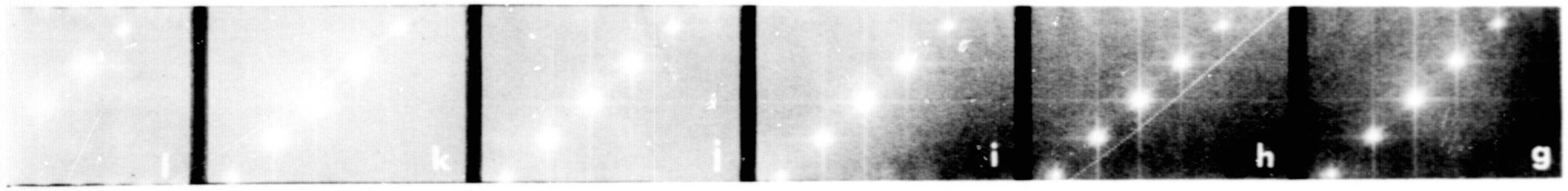


Figure B-2 Initial Test with EGG Extended Range (XR) Film and Bi-Color Filter. Shutter Speeds for 1/2500 to 1/30 Sec.