Reprinted from

Symposium on
Machine Processing of
Remotely Sensed Data

June 3 - 5, 1975

The Laboratory for Applications of
Remote Sensing

Purdue University
West Lafayette
Indiana

IEEE Catalog No.
75CH1009-0 -C

RESOLUTION ENHANCEMENT OF ERTS IMAGERY*

C.D. McGillem, T.E. Riemer and
G. Mobasseri

Purdue University, Lafayette, Indiana; Texaco,
Bellaire, Texas; Purdue University, Lafayette, Indiana

I. ABSTRACT

A method is described for combined interpolation and enhancement of ERTS multispectral scanner data sets. Previous research has shown that good enhancement is most easily achieved when there are a large number of data points contained within the radius of gyration of the system point spread function. This requirement can be met using ERTS data by interpolating the data before enhancement. By varying the interpolation scale factor the data set can be empirically matched to a precalculated optimum restoration filter. Once the proper match of data and filter has been found the enhancement can be carried out directly or the enhancement and interpolation operations can be combined into a single filter thereby greatly reducing the processing time. Experimental results of applying this technique are shown along with more conventional methods of image interpolation and enlargement.

II. INTRODUCTION

The subject of image enhancement, using numerous techniques to upgrade the quality of the image, has been under intensive investigation for a number of years. Enhancement is required because of the fact that no physical picture generating system can faithfully and exactly reproduce the original scene. In any such process inevitable degradations occur, the extent of which depends on the quality of the reproducing system and on natural phenomena associated with the process. The output of an imaging system can often be processed further to offset some of the undesirable characteristics inherent in the system. The nature of enhancement to be employed is strongly dependent on the particular problem parameters and the type of degradation being considered.

This research relates to an enhancement process applicable to the Earth Resources Technology Satellite's (ERTS) multispectral scanner (MSS) data.

III. DEGRADATION SOURCE

The ERTS scanner is an electro-optical device which scans transverse to the motion of the satellite and receives the radiant electromagnetic energy from the scene below. With this scanner is associated a two-dimensional impulse response or point-spread function (PSF), a cross-section of which is shown in Fig. (1). A spatially small or, ideally, an impulse input would result in such an output. The system performance would be satisfactory if only slow changes in the scanned field were present, but in general this is not the case.

If the input signal along one scan line was as shown in Fig. 2a, one would expect a blurring process to take place degrading the quality of the image considerably and resulting in poor resolution as shown in Fig. 2b. This blurring process would occur in two dimensions.

IV. PROPOSED SOLUTION

Based on what has been said so far, one might expect to alleviate this problem by developing an optimum restoration filter that could operate on the measured data. Methods have been developed for designing a processor that minimizes the width of the composite system point-spread function subject to constraints that prevent undesirable side effects from occurring that seriously affect image quality. The specific approach is to minimize the radius of gyration of the composite system subject to the following constraints:

*This research was supported by the National Aeronautics and Space Administration under Grant Number N64-15-005-112 and Contract NAS9-14016.

1. Specified magnitude of radius of gyration of restoration filter.

2. Specified magnitude of noise power out of composite system.

3. Side lobes of composite system shall be minimized.

Riemer and McGillem, [Riemer and McGillem 1973; 1974] have treated this problem in detail and have derived optimum processors for Gaussian shaped point-spread functions under various combinations and degrees of the above constraints. These results will be used directly in developing an optimum processor for ERTS data.

V. ESTIMATION OF BLURRING APERTURE

There does not appear to be available an accurate estimate of the overall system point-spread function of the ERTS multispectral scanner system.

One could estimate the point-spread function from the data; however, due to the large quantization noise present in the data, this method does not appear promising. Ultimately, a Gaussian model was chosen because of its plausibility, its mathematical convenience and its suitability for approximating other aperture shapes. Such an assumption implies a separable blurring process which substantially reduces processing complexity, cost and time.

The problem of matching the blurring aperture or equivalently the data to a precalculated restoration function arises due to the fact that available ERTS data has so few samples per blurring width that a restoration function designed specifically for this situation does not operate effectively. It has been found empirically that the enhancement of discrete data sets is most easily accomplished when there are more than a few samples per blurring width. The effective scanner aperture has a standard deviation with an equivalent ground distance of about 80 meters. The data is collected so that a rectangular array of points is generated with an effective ground distance between adjacent vertical points in the array of 79 meters and an effective ground distance between adjacent horizontal points in the array of 56 meters. Thus it is unlikely that there are more than 3-5 sample points within a circle having a radius of three standard deviations centered at the centroid of the aperture. One way to obtain more samples is to interpolate additional values between the original data points. If this is done, an important question that must be answered is how large a magnification factor should be used. The answer to this question is affected by the specific restoration function selected and the fact that there is a scale difference existing in the ERTS data between the horizontal and vertical directions. This scale factor difference arises from the fact that the effective ground distance between adjacent samples along vertical and horizontal axes differs by about 30%. When the samples are displayed as if their vertical and horizontal spacing was equal, the resulting image is compressed vertically. This distortion can be corrected by using a different magnification factor along the horizontal and vertical axes. By magnifying the vertical axis 79:56 with respect to the horizontal axis, this distortion should be corrected. So far, only the ratio of magnification factors has been considered.

The restoration filter corresponding to a blurring aperture with a radius of gyration containing 5 sampling intervals is the largest that has been computed. In this blurring function there are approximately 45 samples within the 1% amplitude levels of the blurring function along each axis. Therefore to match the data set to the restoration filter, a magnification factor of approximately $45 \div 3 = 15$ is required along the horizontal axis. Previously, it was determined that the ratio of vertical to horizontal magnification factor should be $79 \div 56 \simeq 1.41$. After some search it was found that $17 \div 12 \simeq 1.42$ is the smallest rational number providing the required scale factor correction and also matching the ERTS data to the corresponding restoration function. The ratio of 16:12 also gives good results except that the scale factor difference is not as fully corrected.

VI. COMPOSITE SYSTEM NOISE

The optimum restoration filter is dependent on the magnitude and spectral shape of the system noise. The composite system noise is defined as the total noise process including both the noise introduced by the ERTS data collection system and that introduced by the restoration process. The primary source of noise from the data collection system is the A/D processor. The data is quantized into six bits producing a signal dynamic range from 0 to 63. The total noise power, $\overline{n^2}$, introduced by uniform quantization is given by [Blackman and Tukey, 1959].

$$\overline{n^2} = \frac{\Delta v}{12}$$

where Δv represents the quantization increment which here is equal to 1. Thus the quantization noise is

$$\overline{n^2} = \frac{1}{12}$$

This noise process may be shown to have an essentially flat spectrum extending to many times the sampling frequency. A conservative estimate of the power spectrum of this noise can be obtained by assuming that it lies entirely within the band occupied by the signal. The resulting one-sided noise spectral density is given by

$$\Phi_{nn}(f) \leq \frac{2}{12\, fs} = \frac{1}{6\, fs} \qquad f_s \geq 0$$

where f_s is the sampling frequency of the A/D process. It will be assumed that $f_s = 128$ which is the number of samples used to define the restoration filter along each axis, then

$$\Phi_{nn}(f) \leq \frac{1}{6(128)} = 1.3 \times 10^{-3}$$

Because the ERTS data set does not occupy the full 64 level dynamic range. The signal-to-noise ratio is further deteriorated. It is found that a typical data set may have a dynamic range of $\pm$ 15 units resulting in an input SNR of 34 dB. In view of the flat noise spectrum and the fact that the restoration filter enhances the high frequency components, special precautions are necessary to avoid serious degradation of the signal-to-noise ratio during enhancement. Another source of noise, is the round-off error in the Fast Fourier Transform program. When using this algorithm to compute the spectrum of a Gaussian blurring aperture, it was found that magnitude of the resulting spectrum never became less than approximately 10^{-5} when normalized to the DC term. Consequently, the round-off error noise process may be assumed to have a flat spectral density of approximately 10^{-5} below the DC level of the data being corrected. Thus the round-off error noise spectral density is assumed to have a magnitude of about 10^{-4}.

VII. RESOLUTION ENHANCEMENT OF ERTS DATA

For purposes of filter parameter adjustment, an area near Washington, D.C. was chosen as a test site with the Pentagon building serving as a reference feature. The area is shown in the center of Fig. 3 which is the original ERTS data set and in Fig. 4 which is an enlargement of the Pentagon area obtained by a 17 x 12 interpolation and 2 x 2 digital enlargement of the center portion of Fig. 3. A decision must be made as to the specific restoration function to use and this in turn depends on the noise present in the original data set. The approach used was to assume a certain noise spectrum, compute the corresponding restoration function and then apply it to the data to determine which assumption led to the best result. The filter performance was judged from the general appearance of the enhanced image and from the appearance and spectrum of an individual scan line passing through the Pentagon. The scan line through the Pentagon and its frequency spectrum are shown in Fig. 5a and 5b. A variety of different spectral shapes and magnitudes were tried and it was found that the results were quite sensitive to both the magnitude and shape of the assumed noise spectrum. The best performance was obtained using a filter based on a flat noise spectrum of magnitude 10^{-3}. The enhanced image using this filter is shown in Fig. 6 and the scan line through the Pentagon and its frequency spectrum are shown in Fig. 7a and 7b respectively. Note the increased detail and structure in the scan line and the modification of the spectrum in the low frequency region. Comparison of Fig. 6 with Fig. 4 shows a sharpening effect, an increase in contrast in the image, a coalescing of distributed intensities into individual features and a delineation of features near the Pentagon from the Pentagon itself.

The sensitivity of the enhancement to the assumed noise spectrum may be seen from Fig. 8 and 9 which correspond to enhancement with a filter designed for a flat spectrum with an amplitude of 10^{-4}. The excessive noise is evident in both the image and the spectrum of the line. Using a filter designed for too large an assumed magnitude for the noise spectrum leads to a substantial reduction in enhancement.

VIII. COMBINED ENHANCEMENT AND INTERPOLATION

The approach that has been described so far involves two separate operations: interpolation of the data; and convolution with the proper restoration function. One can model such an operation as an open-loop sampled-data system as shown in Fig. 10 where h_1 is the interpolator and h_2 is the restoration filter. Due to the relatively large magnitude of K, the sampling rate expansion factor required to match the data stream to the restoration filter, the final image is enlarged to an inconveniently large magnitude and some type of undersampling is required to make the results useful. Enahncement by this procedure is quite lengthy, time consuming and sometimes beyond a reasonable machine processing computation time.

A more effective procedure makes use of the fact that if all interpolated and corrected sample values between two data points are not required, they need not be calculated to begin with, thereby reducing the computation time. To accomplish this objective, the interpolation and restoration functions are convolved first and then sampled at the desired rate. This process reduces the interpolation factor required to match the data stream to the combined function from 17 to a more useful number, say 3 or 4. The above procedure can be modeled as shown in Fig. 11.

The initial sampling of data (3T) is inherent in the original data set. The already discrete data is then sampled at an increased rate which, from a practical point of view, corresponds to augmenting the data with zeros between the samples. The resulting function is then convolved with the sampled restoration and interpolation function g(t). The output will be a resolution enhanced image whose magnification factor is controlled by the sampling rate of the convolved interpolation and restoration function. In practice magnification factors of 3 and 4 are used along the x and y axes, respectively. A polynomial interpolation scheme is employed and is performed by passing a third order polynomial through four points and determining the coefficients by the Lagrange method. Other forms of interpolation such as trigonometric or sinc function could be used equally well [McGillem,1975]; however, the polynomial routine appears to give satisfactory results. The interpolation operation can be considered as a convolution of the following form

$$f(u) = \sum_{k=-\infty}^{\infty} f(k)\, h_1(u-k)$$

where h_1 is the interpolating pulse as shown in Fig. 12, f(k) is the original data set augmented with zeros at the points where interpolated values are to be computed and f(u) is the interpolated data set. The interpolator actually used is shown in Fig. 13 with a magnification factor of 12. Figure 14 shows the restoration function that has been used in the course of this development. It is interesting to look at these functions in the frequency domain. Figure 15 is the spectrum of the interpolation function. It is seen that there is rather strong amplification of low frequency components as well as modest amplification of high frequency components.

Figure 16 shows the spectrum of the convolved interpolation and restoration function. Note that in this figure high frequency components have been increased compared to Fig. 15. Figure 17 is the combined interpolation and correction function in the time domain.

IX. EXPERIMENTAL RESULTS

In this section application of the enhancement technique to experimental data is considered and the results compared to more conventional methods of signal processing. The most frequently used methods of processing for examination of image detail are photographic enlargement in which each pixel is magnified and digital enlargement in which each pixel is repeated a number of times during image generation. A more refined approach makes use of some type of interpolation in which new points intermediate between the original data values are computed from the measured data.

For test purposes the upper left corner of Fig. 18, which is an ERTS image of the Battle Mountain area of Nevada, will be used. A 4 x 4 photographic enlargement of this area is shown in Fig. 19 and a 4 x 4 digital enlargement is shown in Fig. 20. An enlargement using cubic polynomial interpolation is shown in Fig. 21. The enhanced image is shown in Fig. 22. In this enhancement an enlargement of 4 x 4 is employed to facilitate comparison with the other methods even though this leaves the scale factor error in the image.

Figure 19, which is the pure enlargement, gives the least satisfactory performance in that the image appears diffuse and blurred. The digitally enlarged image of Fig. 20 has a discontinuous appearance with abrupt changes in grey level. On close inspection it does not look "real". The interpolated image shown in Fig. 21 is a significant improvement over the enlargements and provides an improved image for recognizing details in the picture. Note that the linear features in the image are somewhat fuzzy. The enhanced image of Fig. 22 shows a further improvement in image resolution. The linear features have been narrowed and various closely spaced features are resolved into separate elements.

The same general scene is shown in Fig. 23 where a 3 x 4 interpolation and enhancement has been carried out. In this image most of the scale factor difference between the x and y axes has been removed giving a geometrically corrected image.

As a further example of enhanced imagery, Fig. 24 and 25 show a 3 x 4 interpolation and enhancement of the Washington, D.C. area in two different channels of ERTS data. It is seen that much detail can be observed in the enhanced images and that many familiar features such as the Pentagon, the monument reflecting pool and the Washington National Airport are clearly delineated.

REFERENCES

1. Riemer, T.E. and C.D. McGillem, "Constrained Optimization of Image Restoration Filters," Applied Optics, Vol. 12, No. 9, Sept. 1973, pp. 2027-29.

2. Riemer, T.E. and C.D. McGillem, "Optimum Constrained Image Restoration Filters," LARS Information Note 091974, Laboratory for Application of Remote Sensing, Purdue University, W. Lafayette, Indiana.

3. Blackman, R.B. and J.N. Tukey, "The Measurement of Power Spectres," Doner, New York, 1959.

4. McGillem, C.D., "Interpolation of ERTS-1 Multispectral Scanner Data," LARS Information Note 022175, Laboratory for Applications of Remote Sensing, Purdue University, W. Lafayette, Indiana.

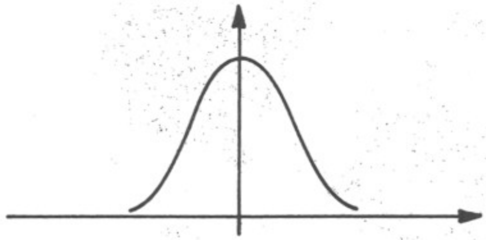

Figure 1. A Cross Section of MSS Scanner PSF

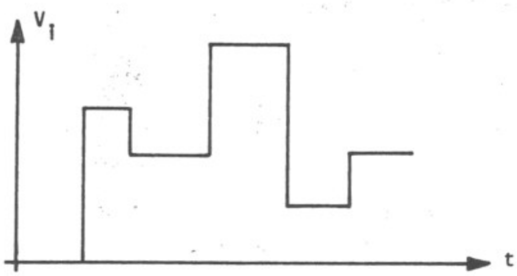

Figure 2a. A Fictious Scan Line

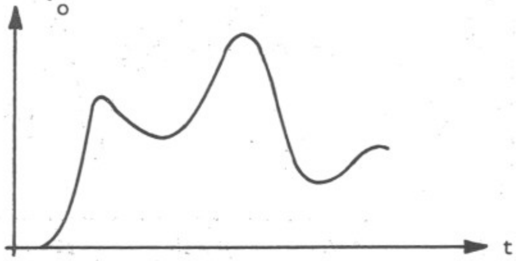

Figure 2b. Scanner Output with Figure 2a As Input Signal

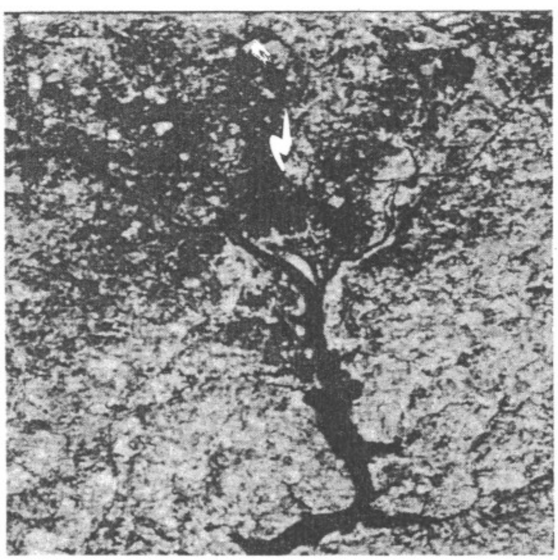

Figure 3. Original ERTS Data Set in Washington, D.C. Area

Figure 4. 17x12 Interpolation and 2x2 Digital Enlargement of Pentagon Area

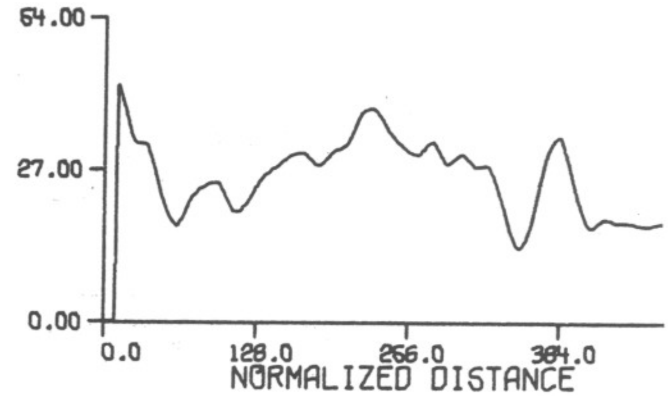

Figure 5a. A Scan Line Passing through Pentagon

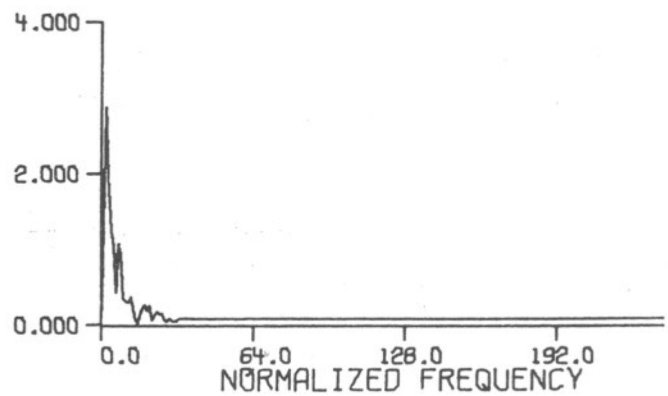

Figure 5b. Frequency Spectrum of Figure 5a

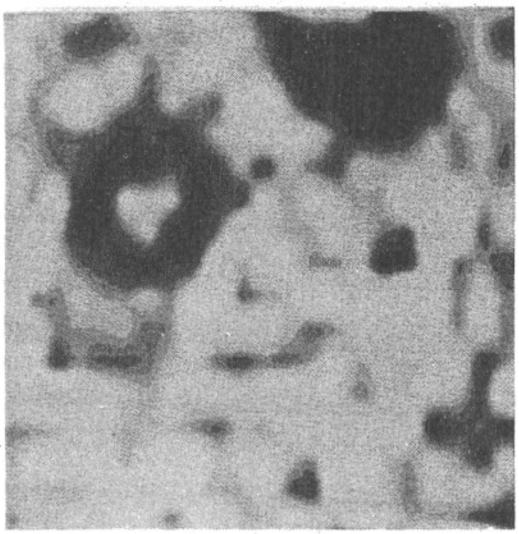

Figure 6. Enhanced Image of Pentagon Area

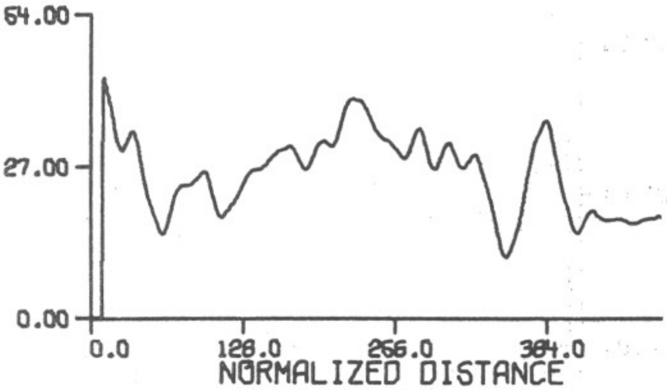

Figure 7a. A Scan Line Through the Pentagon in Enhanced Image

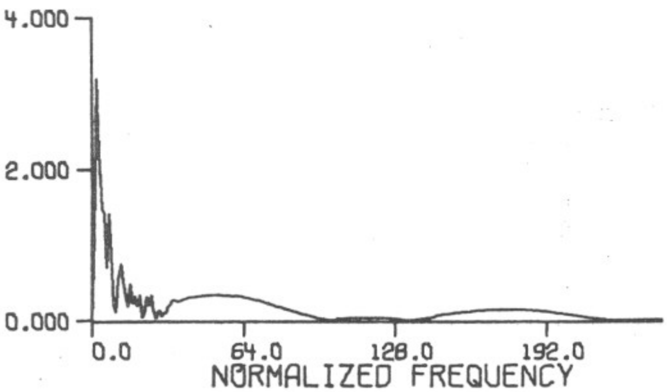

Figure 7b. Frequency Spectrum of Figure 7a

Figure 8. Enhancement of the Pentagon Area Using $\Phi_{nn}(f) = 10^{-4}$

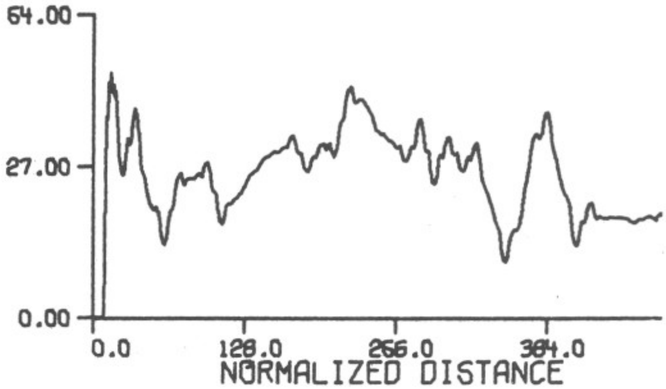

Figure 9a. Scan Line through Pentagon in Figure 8.

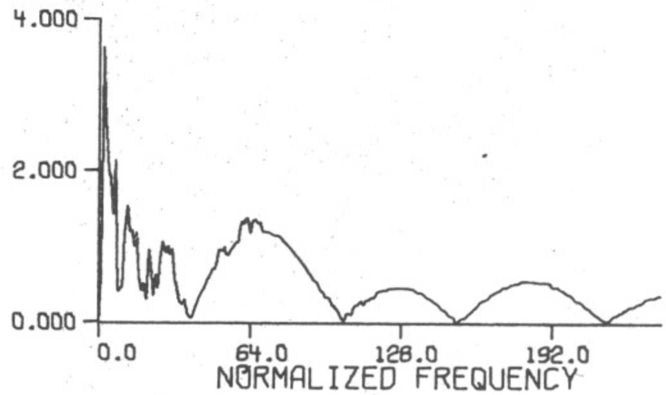

Figure 9b. Frequency Spectrum of Figure 9a

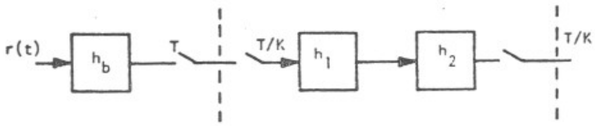

Figure 10. Model of the Enhancement Process

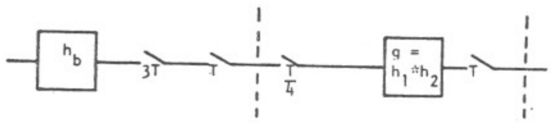

Figure 11. Model of Combined Interpolation/ Enhancement

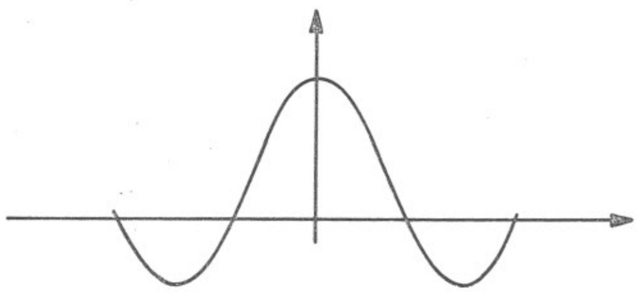

Figure 12. Form of the Interpolating Pulse

INTERPOLATING FUNCTION

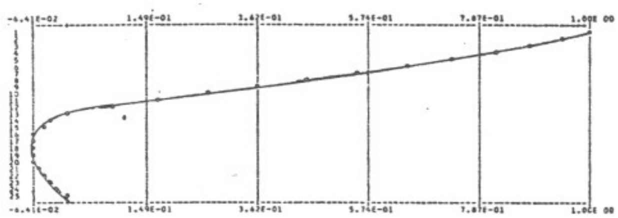

Figure 13. Interpolation Function used in the Enhancement Process (X dim)

RESTORATION FUNCTION

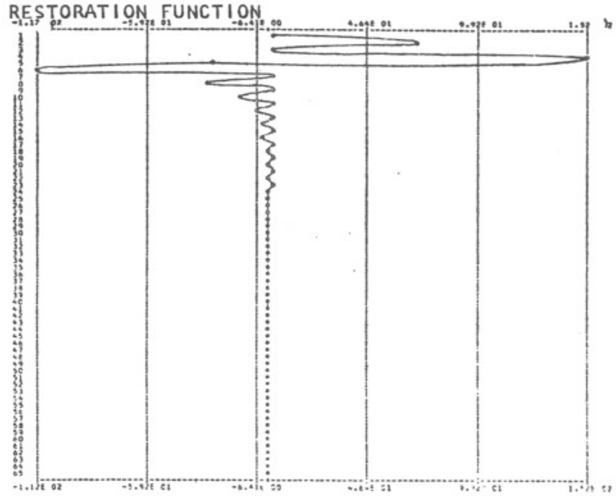

Figure 14. Restoration Function

MAGNITUDE OF INTERPOLATION SPECTRUM

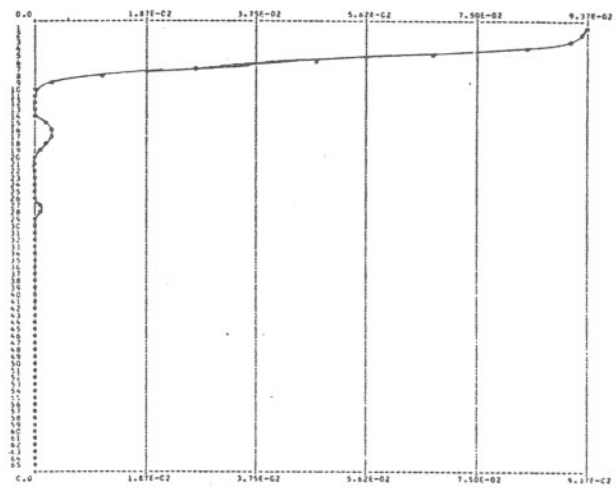

Figure 15. Spectrum of the Interpolation Function

MAGNITUDE OF COMPOSITE CORRECTION SPECTRUM

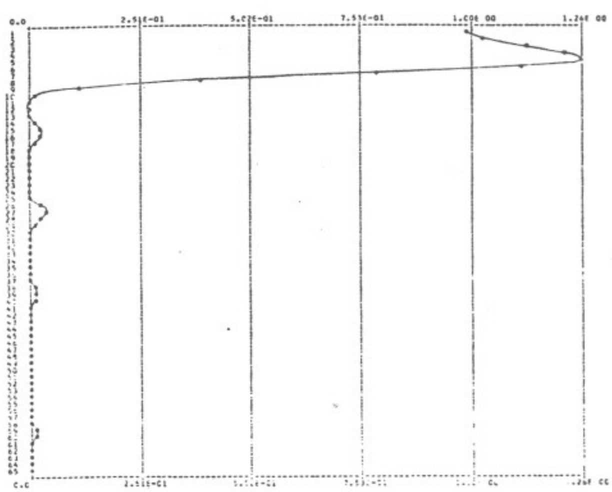

Figure 16. Spectrum of the Convolved Interpolation and Restoration Function

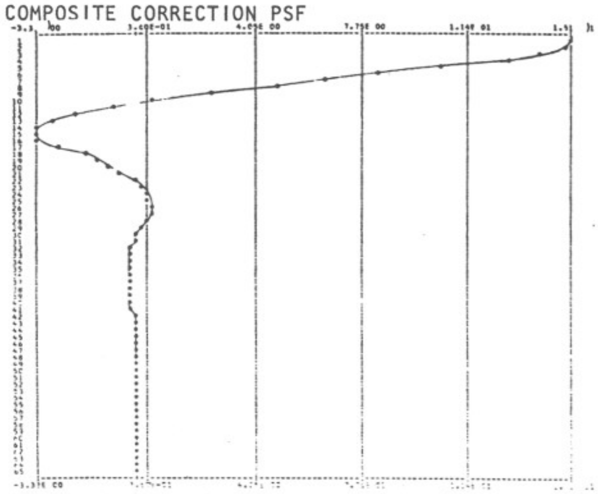

Figure 17. Combined Interpolation/Enhancement Filter Function

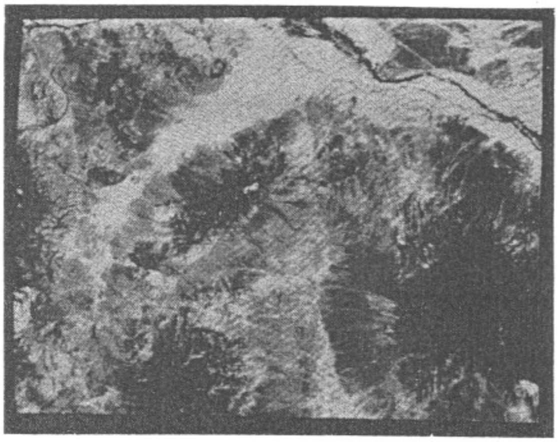

Figure 18. Test Area in Nevada (Band 5) (Upper left hand corner)

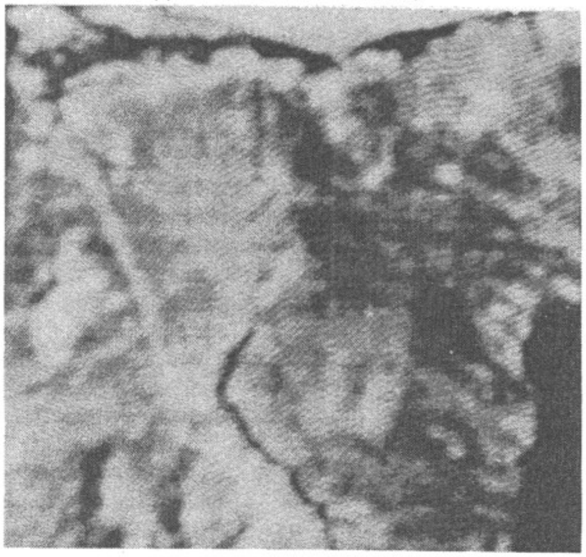

Figure 19. 4x4 Photographic Enlargement of Test Area

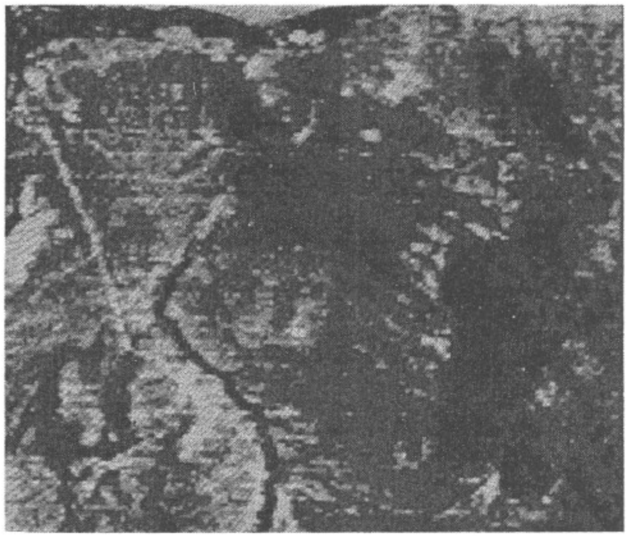

Figure 20. 4x4 Digital Enlargement of Test Area

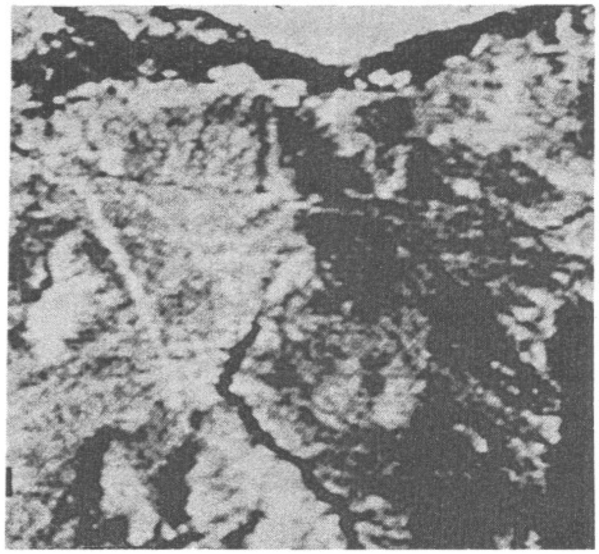

Figure 21. 4x4 Interpolation of Test Area

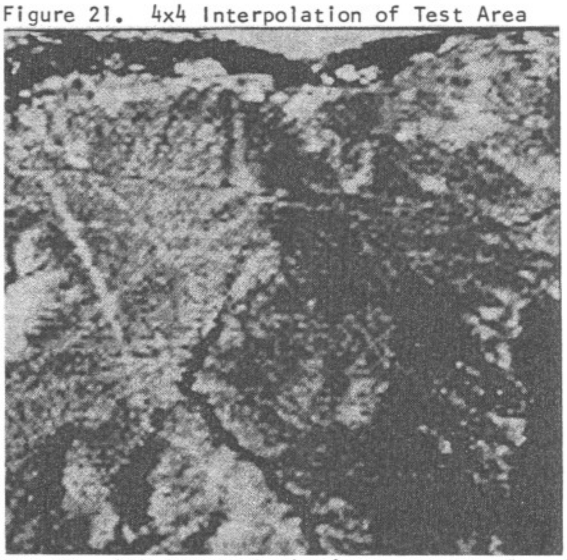

Figure 22. 4x4 Interpolation/Enhancement of Test Area

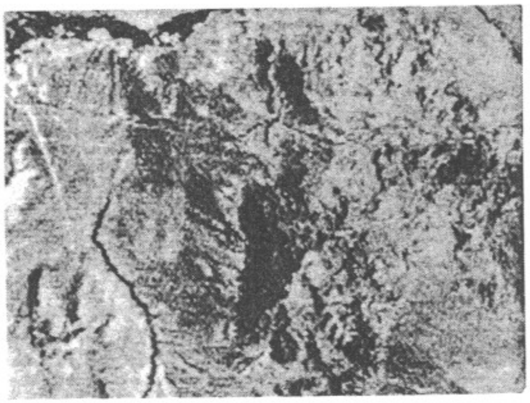

Figure 23. 3x4 Interpolation/Enhancement of 150 Lines and 256 Samples of Test Area

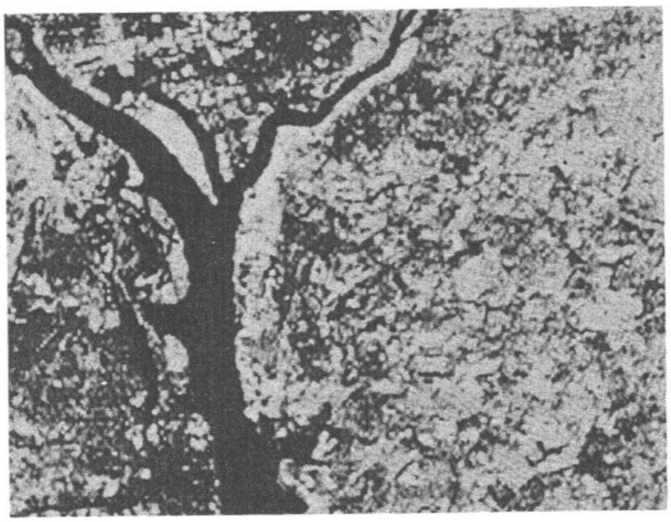

Figure 24. 3x4 Interpolation/Enhancement of Washington, D.C. Area (Band 6)

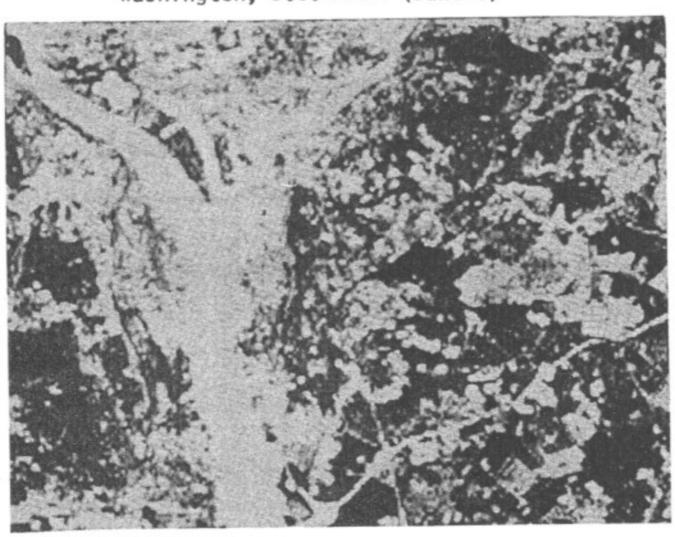

Figure 25. 3x4 Interpolation/Enhancement of Washington, D.C. Area (Band 5)