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ELECTRONICS RESEARCH LABORATORY

TECHNICAL MEMORANDUM

ERL-0112-TM

APPLICATION OF INTERFRAME FILTERING TO LINE SCANNED INFRARED IMAGING SYSTEMS

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SUMMARY

The use of frame storage in an imaging system to implement interframe filtering is analysed and its effects on image signal to noise ratio determined. Simulation of interframe processing on imagery obtained using an AGA Thermovision is described.

The application of interframe filtering to real time imaging systems is examined.

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1. INTRODUCTION

A raster scanned image is obtained when a defined field of view is scanned by a sensor to produce a two dimensional representation of the distribution of some parameter within the field of view (i.e. light intensity). Real time imaging systems update the information (usually at a constant rate) to produce a representation of the field of view, which is perceived by the observer as a continuous display of the distribution of information within the field of view. Imaging systems can be considered as sampled data systems with the data acquisition being performed in three coordinates - these being the two spatial and one temporal coordinate with sampling being performed in at least one coordinate. In terms of the signal processing which may be performed on the data acquired by an imaging system there is no preferred coordinate on which the processing may be based, other than the physical limitations of implementation of the processing. The decrease in cost of semiconductor memory systems has removed some of the obstacles to processing in other than one spatial coordinate which previously existed and allows the implementation of signal processing schemes which would have otherwise not been achievable.

Image enhancement through the use of linear processing almost invariably involves some filtering. The most obvious form of this process is the decrease in R.M.S. noise signal through the use of a band limiting filter, although other means of image enhancement can be implemented using linear filters e.g. edge enhancement may be achieved by mixing the output of a high pass filter with the original video signal. If means for storage of data is not available this processing can only be performed continuously in the time domain hence along whichever scan axis is continuously addressed e.g. for the AGA Thermovision or television imagery the horizontal (X) axis. If sufficient storage is available to store data a digital filtering process may be applied along the sampled data axes (the vertical or Y axis and the interframe time axis). However any form of low pass filtering which is applied to the spatial (X and Y) axes reduces the resolution of the imaging system. This is easily seen in the direction of continuous scan since the transfer function of the filter is multiplied by the sensor Modulation Transfer Function to obtain the overall system transfer function and therefore any low pass filtering must degrade the overall system response. Therefore in any system in which the performance is limited by noise any attempt to improve the signal to noise ratio by linear processing filtering of the detector output must involve a reduction in system bandwidth if the process is applied to the spatial axes.

When the frequency spectrum of a line scanned image composed of a single spatial frequency input (which can be a function of both spatial axes) is examined it is observed that the spectrum (figure 1) is composed of frequency components occurring at intervals equal to the frame scanning interval and these components form clusters separated at intervals equal to the line scanning frequency. Examination of the frequency spectrum of a complex image reveals that the structure contributed by the line scanning process is still evident with the sidebands still contributed by the frame frequency harmonics. The video spectrum is therefore occupied sparsely by discrete components separated by the frame frequency and having maximum amplitudes at the line frequency. As with Fourier analysis of one dimensional signals it is possible to construct all possible images from the spectrum of all possible sinusoidal spatial frequency components and the shape of the spectrum of a general video signal is similar to that just described for a single spatial frequency image.

In order to transmit the complete video picture and preserve all detail in the image, the transmission system used must have a bandwidth sufficient to pass the highest frequency components. For such a passband with flat response from D.C. to the maximum frequency required the wideband noise from the detector occupies all regions of the frequency spectrum including those not occupied by video signals. If instead of a flat passband the processing electronics and transmission system had a 'comb' filter response centred on multiples of the frame repetition frequency the equivalent noise bandwidth of the system would be reduced and the signal to noise ratio of the image improved. This paper reviews the theory behind the implementation of a 'comb' filter using frame storage and discusses its application to infrared imaging systems.

2. THE VIDEO SPECTRUM AND SIGNAL PROCESSING

Raster scanning of an image distribution in effect is a one dimensional sampling of a two dimensional function. The scanning of each line by the sensor transforms the spatial intensity distribution of each line sample into the time domain e.g. a spatial intensity distribution of 1000 cycles/rad scanned by a sensor which is moving at 1 rad/s produces an output signal of 1000 cycles/s. If the distribution is scanned repetitively, the video signal obtained is therefore a periodic function whose repetition rate is the line scanning rate. Such a periodic function may be represented as a Fourier series, the fundamental frequency of which is the repetition rate of the periodic function and whose higher frequency components are determined by the structure of the periodic signal. The generation of an image by scanning the raster then introduces a periodic structure at the frame repetition rate. Each line of the frame is then sampled at the frame repetition rate and is separated in time from adjacent lines. The video signal then consists of a repetitive function (for stationary imaging) whose period is the frame period and whose structure is determined by the line scanning process within the frame. The spectrum of this signal then consists of a series of discrete frequency components whose frequencies are multiples of the frame frequency.

The signal from the scanning sensor however does not exhibit this discrete frequency characteristic. The wideband electronic noise from the sensor and the following amplifiers occupies the whole available frequency spectrum. Further, any time variation of the image is observed as a spreading of the discrete components of the original image spectrum. For a stationary image this time varying signal can only arise from background noise. The video signal then has a structure in the frequency domain similar to that illustrated in figure 1 but with the discrete components broadened into bands by any motion in the image and the addition of the wideband noise component from the detector and the electronics.

In order to improve the signal to noise ratio of an image a 'comb' filter with the pass frequencies of the comb equal to multiples of the frame frequency can be implemented. If the number of components in the comb was sufficient to cover all frequencies of interest in the video signal, no loss of resolution would result. The implementation of such a filter in a serial data (i.e. single channel) processing environment presents great difficulties since the number of discrete bands in the comb filter is very high (for an AGA Thermovision Model 661 5000 elements are required for the comb, for a television signal 600 000). The synthesis of such a filter for serial data using either analogue or digital technology is not practical, however the implementation of a comb filter in a processing environment which incorporates a large number of parallel processing operations is possible.

In order to implement an approach using a high degree of parallel processing, data storage must be provided and since such storage can only be achieved using discrete sampling techniques we will consider the image field to be sampled in the scan direction as well as the raster direction. The image then consists of a two dimensional array of data values which are updated at the frame rate, and if each data point (pixel) is processed separately, parallel processing is achieved in the time domain and this is used to implement the required comb filter.

Since each pixel is updated at the frame rate, the processing could be implemented using a single frame of storage on a sequential basis - i.e. the data could be handled in a byte serial mode but the frame storage effectively converts this to a parallel mode, due to the time sampling for frame update.

A single pixel within a frame is sampled at the frame rate. For a normal sampled data system the effective passband would be taken to be half the sampling frequency and the input signal would be filtered to remove all frequency components above the effective passband and this prevents 'aliasing' of the data (i.e. translation of the input frequency rate to a lower frequency on reconstruction of the data). This is not possible for an imaging system and the pixel data contains all input frequencies which may arise from the field of view or the detector and this is sampled at the frame rate. The data displayed consists of a sequence of data values $\{x(n)\}$ and the display system may be considered to have a transfer function of unity for all input frequencies with uniform phase in the sense that an input signal sin (ωt) produces the same sequence values $\{x(n)\}$ as a signal sin $(\omega + \omega_s)t$ where ω_s is the sampling frequency. A discrete time filtering operation may be implemented on this sequence to improve the signal to noise ratio and this is usually achieved as a digital filter.

3. FILTER IMPLEMENTATION

We will consider the processing of a single pixel of data represented by the sequence $\{x(n)\}$ where the sample values are updated at the frame rate. The systems to be considered fall into the class of linear shift invariant systems and may have an impulse (or unit sample) response of finite or infinite duration (figure 2) and can be classified as non recursive (finite impulse response, F.I.R.) or recursive (infinite impulse response, I.I.R.) systems.

The subclass of linear systems that these systems correspond to can be described by linear constant coefficient equations of the form

$$a\, y(n) = \sum_{r=o}^{M} b_r\, x(n-r) \qquad \text{for F.I.R. systems and}$$

$$\sum_{k=o}^{N} a_k\, y(n-k) = \sum_{r=o}^{M} b_r\, x(n-r) \qquad \text{for I.I.R. systems}$$

which can be written

$$a_o\, y(n) = \sum_{r=o}^{M} b_r\, x(n-r) - \sum_{k=1}^{N} a_k\, y(n-k)$$

where $y(n)$ is the sequence of data values obtained as the output of the filter for input values $x(n)$.

To implement a nonrecursive (F.I.R.) filter requires $M + 1$ bytes of storage per pixel since for each output value $y(n)$ the processor must add $M + 1$ input values including the last (i.e. $x(n)$). Having added these values the output $y(n)$ must be stored (if data readout is not coincident with data input - the most general case) as well as the input values $x(n)$ to $x(n - M + 1)$ in order to calculate $y(n + 1)$ when $x(n + 1)$ is used as the next input. If $y(n)$ is not to be stored M bytes of storage per pixel are required. The recursive filter requires M + N bytes of storage per pixel in the most general case (data readout not coincident with data input).

The analysis of linear systems may be done using the Z transform and the Fourier Transform of the system function may be derived from the Z transforms. For a linear system of the form

$$\sum_{k=o}^{N} a_k\, y(n - k) = \sum_{r=o}^{M} b_r\, x(n - r)$$

(a non recursive system for N = 0)

the system function is

$$H(z) = \sum_{r=o}^{M} b_r\, z^{-r} \Big/ \sum_{k=o}^{N} a_k\, z^{-k}$$

which is a ratio of polynomials in z(ref.1).

The Fourier transform of the system is obtained from the system function by evaluating the system function on the unit circle $|z| = 1$ in the z plane for the required values of input frequency i.e.

$$F(\omega) = \sum_{r=o}^{M} b_r\, e^{-j\omega r} \Big/ \sum_{k=o}^{N} a_k\, e^{-j\omega r}.$$

In the implementation of simple filtering schemes for signal to noise ratio improvement of pixel values we will not follow the traditional filter approach of transforming an analogue filter design into a digital filter design because we do not have an analogue filter specification to aim at as a design criterion. We will instead examine the frequency response of a few easily implemented filters. We will examine the behaviour of three non recursive and two recursive filters.

Non recursive filters

(i) Filter difference equation $y(n) = 0.5\, x(n) + 0.5x(n - 1)$ having system function $H(z) = (0.5z + 0.5)z^{-1}$.
This filter provides an output value which is the average of the current pixel and the previous pixel. The system function has a zero at $z = -1$ and a pole at $z = 0$ producing the frequency response illustrated in figure 3 for a 16Hz sampling rate.

(ii) Filter difference equation $y(n) = 0.25(x(n) + x(n - 1) + x(n - 2) + x(n - 3))$ having system function $H(z) = (z^3 + z^2 + z + 1)/4z^3$ and providing an output value which is the average of the current pixel and the the three previous pixels. The frequency response is illustrated in figure 3 for a 16 Hz sampling rate.

(iii) Filter difference equation $y(n) = 0.125 \sum_{k=o}^{7} x(n - k)$

having system function $H(z) = \sum_{k=o}^{7} z^k/8z^7$

which averages the current pixel and the seven preceding pixels. The frequency response is illustrated in figure 3.

Recursive filters

(iv) Filter difference equation $y(n) = 0.5\ (y(n - 1) + x(n))$
having system function $H(z) = \frac{Z}{2(z-0.5)}$.
This filter produces an output which is the infinite series

$y(n) = \sum_{k=o}^{\infty} x(n - k)/2^{k + 1}$ and has the frequency response shown in

figure 4.

(v) Filter difference equation $y(n) = (0.8\ y(n - 1) + x(n))/1.8$ having system function $H(z) = \frac{z}{1.8z - 0.8}$
This filter produces an output which is the infinite series

$y(n) = 0.55 \sum_{k=o}^{\infty} 0.44^k\ x(n - k)$ and has the frequency response shown in

figure 4.

By implementing these filters on each pixel in parallel the comb filter discussed previously can be simulated, with the filter frequency response determining the shape of the 'teeth' of the comb function.

4. FILTER PERFORMANCE

Two aspects of the performance of these filters are important, these being the improvement in signal to noise ratio afforded by the filters and their effect on scene motion or motion of targets within the image. The change in signal to noise ratio can be predicted theoretically and the theoretical results have been verified by simulating four of the filters described on an in house Data Acquisition System(ref.3). The effect of the filters on images with motion has not been simulated but can be predicted and will be discussed later.

The simplest analysis of filter performance with respect to signal to noise ratio is obtained by considering the variance of a sequence of discrete random variables. The variance is defined as

$$\sigma^2 = E\ (x - \eta)^2$$

when E $\{\emptyset\}$ is the expectation value of the quantity $\emptyset$, x is the random variable and η is the mean value of x or $\eta = E\ \{x\}$. If x is a discrete random variable then

$$\sigma^2 = \sum_n (x_n - \eta)^2 .\ P\ \{x = x_n\}$$

where P $\{x = x_n\}$ is the probability that the variable x can have the value x_n and for a sufficiently large population the variance is given by

$$\sigma^2 = \frac{1}{N} \sum_{i=1}^{N} (x_i - \eta)^2$$

for a variable distributed over all possible outcomes with equal probability.

If we consider a sequence of random variables which can be described by the expansion $S(t_k) = S_1(t_k) + n(t_k)$ where $S_1(t_k)$ is the value of the signal at each point and $n(t_k)$ is the additive noise at that point in the sequence, if the additive noise $n(t_k)$ has a mean value of zero the signal to noise ratio is defined as

$$(S/N) = \frac{S1(t_k)}{\sigma\ \mathrm{RMS}}$$

where σ_{RMS} is the root mean square value of the noise signal and since for a zero mean variable x;

$$\sigma^2\ \mathrm{RMS} = \frac{\sum_{i=1}^{N} x_i^2}{N}.$$

the root mean square value of the noise signal is the variance of the noise signal. By taking a number of samples of a process we can produce an estimate of the signal $S_1(t_k)$ by averaging the samples and obtain

$$S^1(t_k) = \frac{1}{M} \sum_{i=1}^{M} S(t_k)$$

and if the signal is constant this is obviously

$$S^1(t_k) = S_1(t_k) + \frac{1}{M} \sum_{i=1}^{M} n(t_k).$$

The variance of $S^1(t_k)$ which is obtained from the sum of a sequence of random variables is

$$\mathrm{Var}(S^1(t_k)) = \frac{1}{\sqrt{N}}\mathrm{Var}(S(t_k))$$

and if

$$S(t_k) = S_1(t_k) + n(t_k)$$

where $S_1(t_k)$ is a constant

$$\mathrm{Var}(S^1(t_k)) = \frac{1}{\sqrt{N}}\mathrm{Var}(n(t_k))$$

and the signal to noise ratio of $S^1m(t_k)$ is then

$$S/N = \frac{S^1(t_k)\sqrt{N}}{\sigma\ \mathrm{RMS}}$$

where σ_{RMS} is the root mean square value of the additive noise $n(t_k)$ and if $n(t_k)$ has zero mean $S^1(t_k) = S(t_k)$ for constant input therefore the signal to noise ratio is improved by $\sqrt{N}$ where N is the number of samples used. Thus the implementation of a filter which produces an output signal which is the average of N samples of the input signal improves the signal to noise ratio by $\sqrt{N}$.

The recursive filter output signal is not such a simple function of a sequence of input signals - in effect it produces a continuous sum of the input signals with varying weighting coefficients. The output signal can be expressed as

$$S^1(t_k) = p\sum_{k=1}^{\infty} S(t_k)/r^k$$

where the multiplicative factor p is used to normalise the range of the variables and

$$E\{S^1(t_k)\} = p\sum_{k=o}^{\infty} E\{S(t_k)\}/r^k$$

$$= E\{S(t_k)\}$$

The variance is

$$E\{(S^1(t_k) - E\{S^1(t_k)\})^2\} = p^2\left(1 + \frac{1}{r^2 - 1}\right)\sigma^2$$

$$= \frac{\sigma 2}{3} \text{ for filter (iv)}$$

$$\text{and } \frac{\sigma 2}{2.6} \text{ for filter (v)}$$

The signal to noise ratio is thus a complex function of the weighting coefficients and decreases with the increasing weight given to the most recent samples. No attempt has been made to include here the effect of finite precision arithmetic.

This may be seen when we examine the frequency response of the comb teeth. Using the 3db bandwidth as a measure of the effective filter bandwidth we can see from figure 3 that for a non recursive filter the 3db bandwidth decreases approximately linearly with the number of samples used (i.e. the number of elements in the filter) and the noise voltage therefore varies approximately as the square root of the filter bandwidth in agreement with the previous argument.
The behaviour of the recursive filter is more difficult to describe but for the simplest filters the filter bandwidth is in part a function of the weighting coefficient of the last sample, i.e. increasing this with respect to the other coefficients increases the filter bandwidth and thus the observed noise.

To examine the behaviour of these filters with infrared imagery they were implemented on the Data Acquisition Facility using infrared imagery obtained using an AGA Thermovision. Filters i to iv were implemented and the results are shown in table 1 for filters i to iii. Table 1 also illustrates the effect of Filter iv implemented over successive frames and illustrates the asymptotic behaviour (infinite impulse response) of this form of filter. The imagery used to implement the filters was of a distant target at sea against a sky background. The results of applying a non recursive filter to this imagery is shown in figure 5.

The noise reduction predicted by the theoretical analysis is not achieved in these samples since the AGA Thermovision is non linear in its DC response across the full frame extent which introduces a slight error in the estimate of variance. It can be seen however that thefirst order recursive filter approaches the performance of the fourth order non recursive filter and by suitably adjusting the weighting coefficients could be made to exceed the performance of this filter. figure 5 illustrates the results which can be obtained with these filters on low resolution imagery (AGA Thermovision). Each quadrant represents the original image after it has been processed by 2, 4 and 8 element non recursive filters. The effect of the filtering process (especially on the long duration noise burst at the top of the original frame) is easily seen. In real time the subjective effect is greater since existing noise is no longer seen as fixed pattern noise as seen in figure 5.

The recursive filter has been implemented with television systems(ref.2) and has been found to work acceptably with a filter difference equation of the form

$$y(n) = (x(n) + (M - 1)y(n - 1))/M$$

where M was restricted to four possible values, however this system was implemented with a 'non-redundancy detector' in which the signal averaging filter was by-passed if the frame to frame difference signal exceeded a predetermined threshold. This technique was used to eliminate problems which may occur with image motion since the effect of the filter is to attenuate high frequency motion.

This aspect of the filter performance is of particular concern for military infrared systems which are expected to be used against targets which may be moving at high speeds. For example, for a 1 mrad sample spacing with a target at 10 km an 8 element non recursive filter output will lag scene motion by 4 sample periods to 50 percent response for a step change in signal input. A recursive filter of the form of filter iv will respond to the same level in 1 sample period, and therefore would be preferable for fast moving targets, i.e. in this example a crossing velocity at 10 km at a frame rate of 30 frames/s of 30 m/s - (an angular velocity of 3 mrad/s).

5. APPLICATIONS

The use of frame to frame averaging to improve the signal to noise ratio performance of infrared imaging systems has other benefits for the military users of infrared systems. The first of these arises from the previous discussion on image motion response in that the detection of interframe differences which exceed a predetermined threshold in effect provides an elementary form of motion detection which may be used to augment the performance of the human observer. This process is an elementary pixel by pixel correlation between frames of imagery and could be expanded to provide an area correlation detection facility.

Of further interest is the possibility of using frame storage to enhance the performance of remote sensors which use low framing rates to achieve low information bandwidths by improving the signal to noise ratio and providing a conversion of framing rate to higher speeds compatible with readily available display equipment. The use of frame storage to implement interframe filtering provides a data base upon which further signal processing, e.g. target tracking or detection may be based.

For military systems the use of techniques such as interframe filtering and image restoration may allow the development of battlefield surveillance systems based on low cost expendable (perhaps uncooled) remote sensors which can be used in conjunction with frame storage based processing systems located at a command post. With the decreasing cost of semiconductor memories and processing components, such systems (perhaps based on multiple low cost remote sensors) could be implemented for tasks such as perimeter surveillance and may provide cost advantages over more conventional infrared surveillance systems based on cooled high cost detectors.

6. CONCLUSION

The use of recursive and non recursive filtering on a frame to frame basis by applying the filter algorithm pixel by pixel on stored data, has been verified as a technique for improvement of image signal to noise ratio of infrared imagery. Improvements comparable to those obtained with television systems(ref.2) can be achieved giving worthwhile improvements in performance. The implementation of frame to frame filtering using digital storage of the imagery may be extended to allow more sophisticated processing of the imagery using the data base provided by the frame storage.

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3	Poropat, G.V.	"A Microprocessor Based Image Storage and Analysis Facility for Infrared Signature Measurement and Image Processing". ERL-0050-TM, November 1978

TABLE 1. VARIANCE OF VIDEO DATA WITH FILTERING

Non Recursive Filtering (Filters i to iii)	
Sample Period 0.1 Second	
Original Data	Variance of Data 19.46
Filter i	11.35
Filter ii	6.087
Filter iii	3.89

Recursive Filtering (Filter iv)	
Sample Period 0.1 Second	
Number of Frames Processed	Variance of Data
1 (Original Frame)	19.46
2	11.35
4	7.866
8	7.34

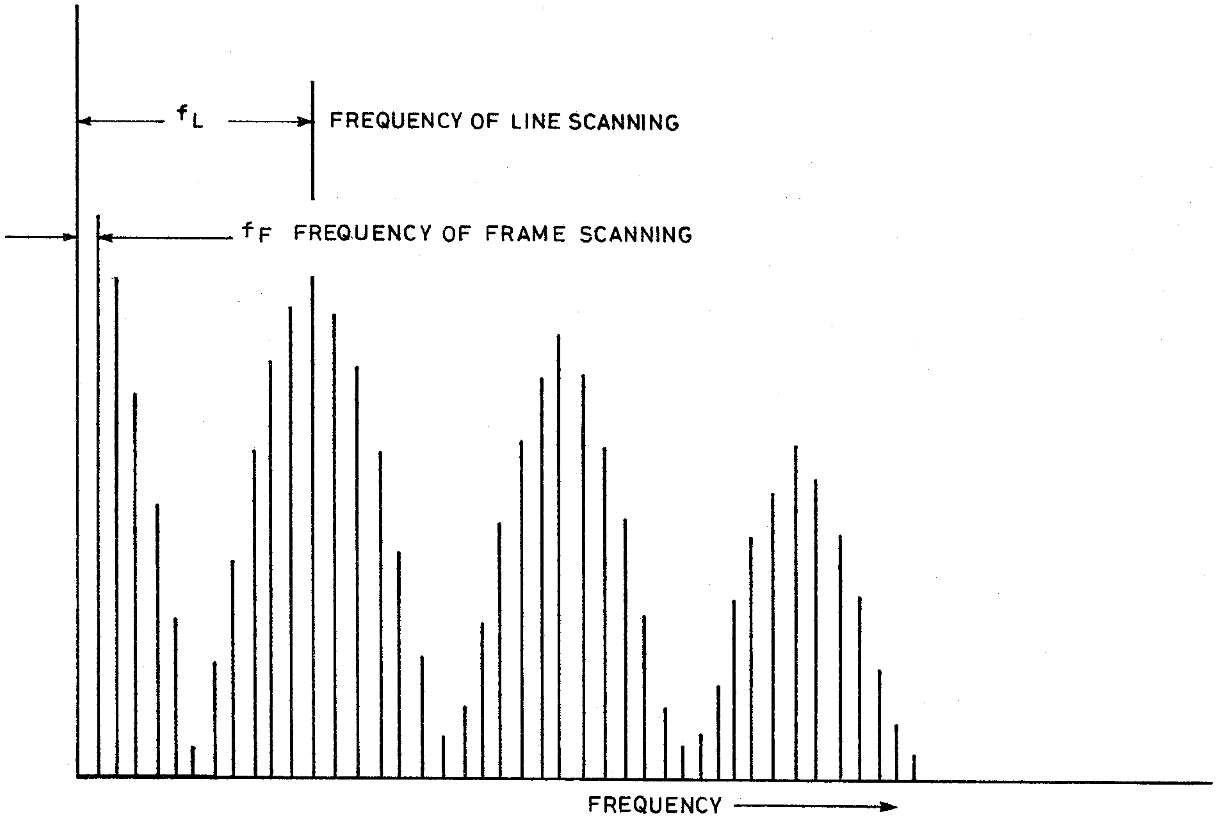
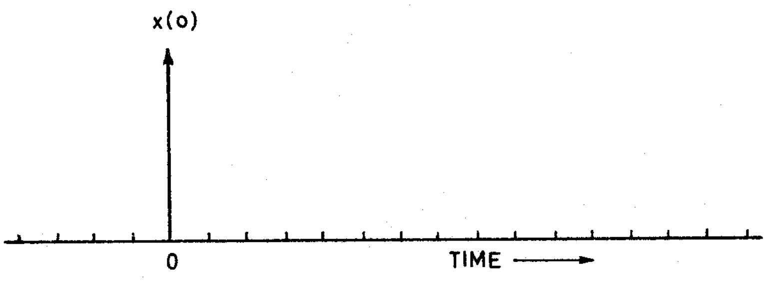
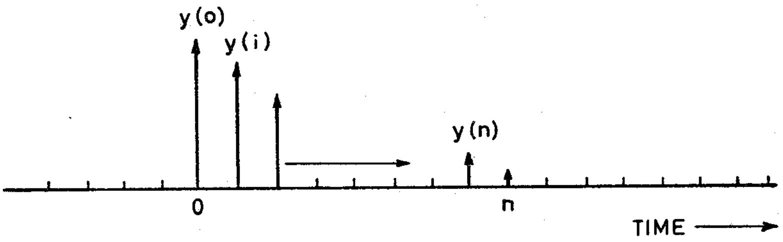


Figure 1. Video signal spectrum of an image with a single spatial frequency



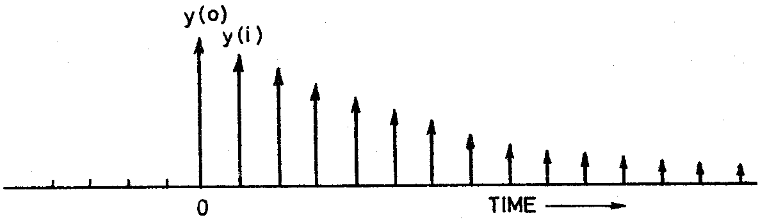
Impulse Input to Filter at t=o



Output of n element non recursive filter

$y(n)=o$ for $t > t_n$

Finite Impulse Response Filter

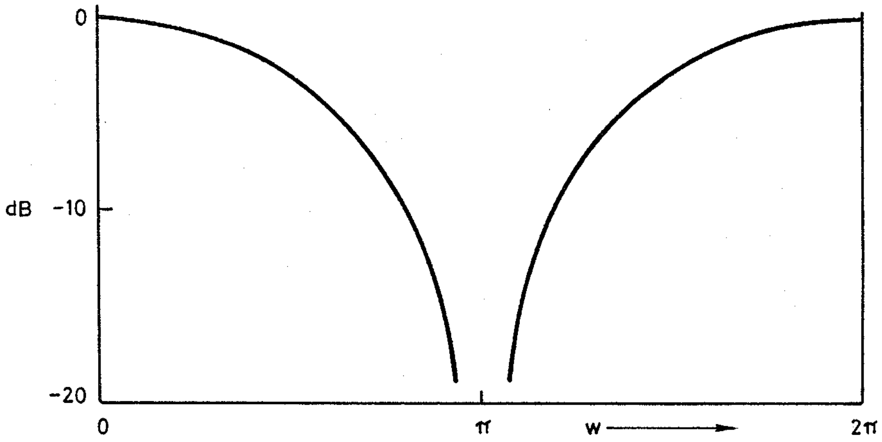


Output of recursive filter

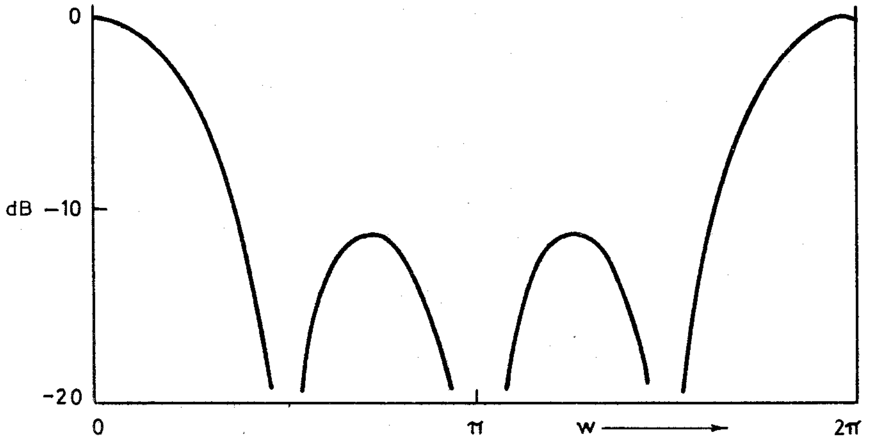
$y(n) \to o$ for $t_n \to \infty$

Infinite Impulse Response Filter

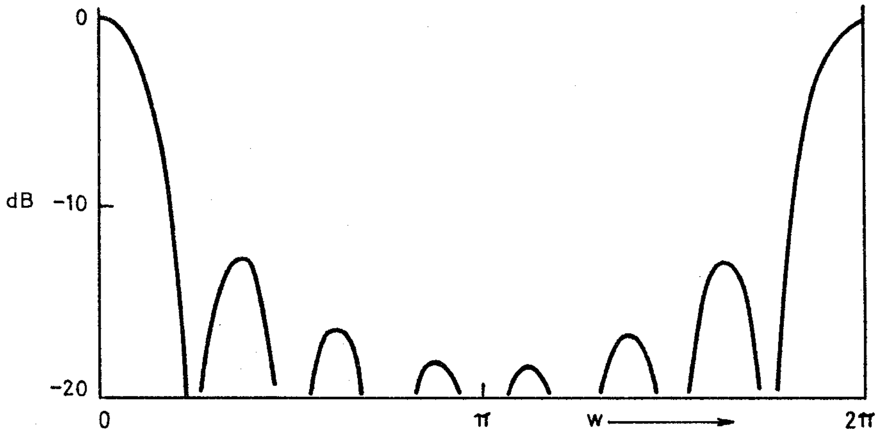
Figure 2. Impulse response of digital filters



Filter i $y(n) = 0.5(x(n) + x(n-1))$

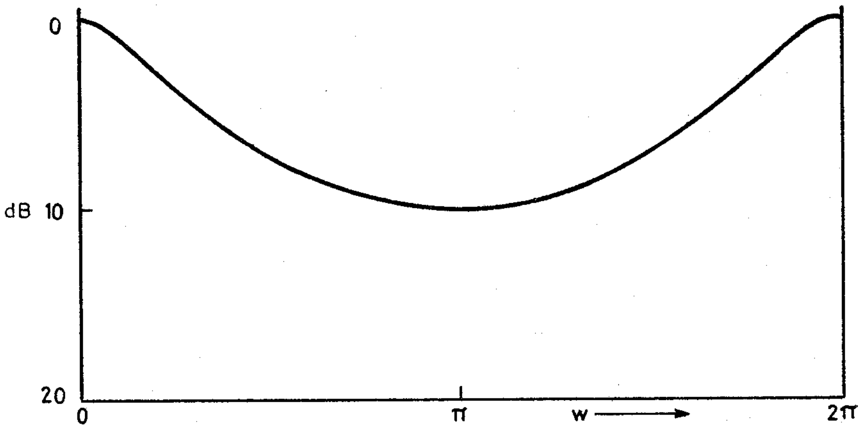


Filter ii $y(n) = 0.25(x(n) + x(n-1) + x(n-2) + x(n-3))$

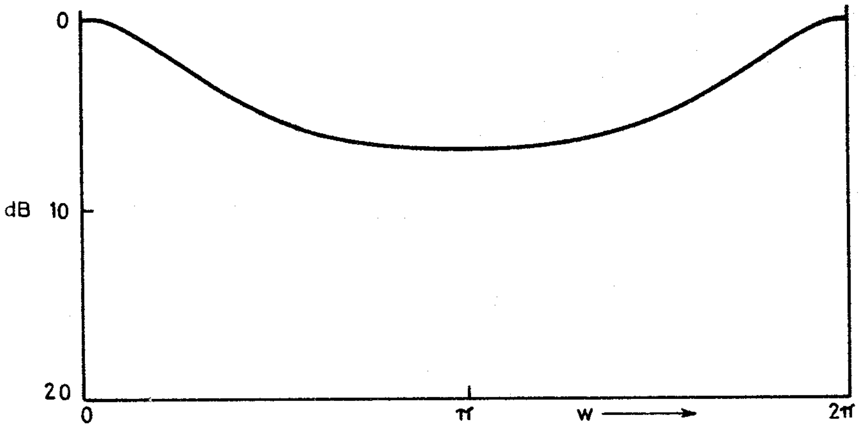


Filter iv $y(n) = 0.125 \sum_{k=o}^{7} x(n-k)$

Figure 3. Normalised frequency response of non recursive filters implemented

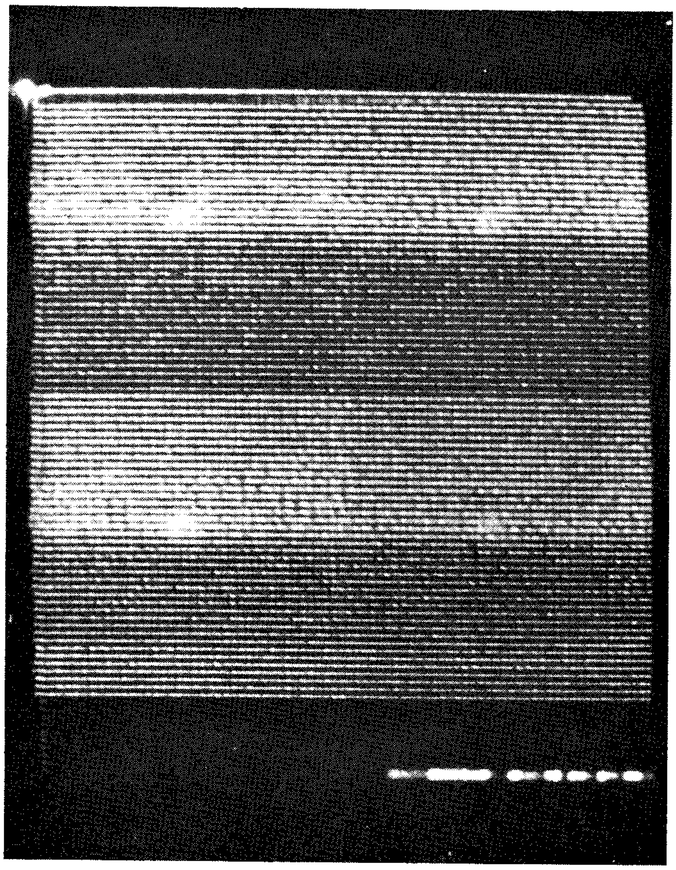


Filter iv $y(n) = 0.5(y(n-1) + x(n))$



Filter v $y(n) = (0.8y(n-1) + x(n))/1.8$

Figure 4. Normalised frequency response of recursive filters implemented



ORIGINAL DATA	OUTPUT OF FILTER i
OUTPUT OF FILTER ii	OUTPUT OF FILTER iii

Figure 5. Effect of implementation of non recursive filters on infrared imagery with a point source

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