NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Man-Machine Interactive Imaging and Data Processing Using High-Speed Digital Mass Storage

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PREFACE

The work described in this report was performed by the Advanced Technical Studies Office of the Jet Propulsion Laboratory. This report was presented as a paper at the Human Factors Society's 18th Annual Meeting in Huntsville, Alabama, on October 15-17, 1974.

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ABSTRACT

The role of vision in teleoperation has been recognized as an important element in the man-machine control loop. In most applications of remote manipulation, direct vision cannot be used. To overcome this handicap, the human operator's control capabilities are augmented by a "tele"-vision system. This medium provides a practical and useful link between workspace and the control station from which the operator performs his tasks.

The function of the video system is to reproduce the original scenes in pictorial form. Systematic errors in terms of photometry, resolution, geometry and perhaps color can be removed by decalibration procedures. Human performance deteriorates when the images are degraded as a result of instrumental and transmission limitations. Recovering images from various degradation effects is commonly referred to as restoration. Image enhancement is used to bring out selected qualities in a picture to increase the perception of the observer.

At the Image Processing Laboratory (IPL) of JPL, we employ a general purpose digital computer (IBM 360/44) utilizing an extensive special purpose software system (VICAR) to perform an almost unlimited repertoire of processing operations. This approach has proven to be most flexible, versatile and suitable for experimental work.

Guided by the experience of the IPL and the recent advances in LSI technology, we are reporting on special hardwired algorithms which have speeded up the processing by several orders of magnitude. Although quantum limited imaging was made possible by noise removal and contrast enhancement as part of a development in electron microscopy, these methods and experiences are transferrable to other teleoperator applications. The processing and enhancement of images are controlled by the operator/scientist matching his perceptual needs to optimally adjust the instrument. Central to the near real time image processing is a high speed digital solid state mass memory operating at input/output speeds compatible with standard TV rates. Thus, the operator, as the most important link in the loop, is provided with a real time interactive display which enables him to perceive the remote workspace as required to execute remote manipulation tasks.

MAN-MACHINE INTERACTIVE IMAGING AND DATA-PROCESSING USING HIGH-SPEED DIGITAL MASS STORAGE

INTRODUCTION

With the processing complexity of space mission objectives and spacecraft system requirements, the need for interactive and adaptive remote manipulator systems has become unavoidable (Ref. 1). Potential control applications are anticipated for extending orbital missions, exploration of planets, docking and repair of orbiting spacecraft, or long-term deep space missions. These controls will include the ability to perform work in near real time. Fast control reaction will be required for example: in docking, cargo handling, in-space assembly and deployment, operation and maintenance of individual spacecraft and vehicle subsystems. The problems and costs to perform such functions nearly in situ are formidable. A more effective solution to these problems is to situate man in a well established and comfortable working environment and provide the facilities to remotely perceive and affect the space environment. In order to make this possible, machines and interfaces must be made available to amplify man's sensory, cognitive and effector capabilities. Depending on the task requirements, these capabilities can only be provided by various levels of autonomous action characteristics. It is safe to speculate that systems of variable autonomy will emerge which provide a flexible division of man and machine responsibilities. This approach effectively will protect man from the hostile environment while optimizing the use of his unique abilities for perception, cognition, goal setting, strategy planning, and performance supervision in getting "work done".

In any such system, one of the most important links between man, machine and the environment is through the visual sensory subsystem. The ideal visual subsystem provides, for most tasks, a vital element in establishing a sense of presence for the human operator. It conveys information for observing the environment and for planning of actions as well as feedback information for monitoring and evaluating the results of previous actions. At the present level of technology, visual subsystems are limited in terms of achieving these goals (Ref. 2).

THE "TELE"-VISION SYSTEM

Present technology provides augmentation of human vision by means of television systems.

This medium can be used as a practical and useful link between work space and the control station (Fig. 1) from which the operator performs his task.

Assuming that we wish to transmit the image from workspace and display it to the operator as a television picture, ideally we expect to see a picture which is a replica of the point projection of the 3D scene onto a two dimensional image plane. This replication means that the scene contrast and brightness levels are maintained on pictorial display. There should be no geometric degradation in terms of line or picture element structure or noise and loss of fine detail.

Available television imaging systems realistically do not reproduce the scene faithfully. Unfortunately in searching the literature (Ref. 3) one finds that subjective evaluation of television pictures has been rather limited in extent and that no concerted effort has been made first to examine seriously the human factors and then to design a pictorial data processing system taking them into account. Most subjective testing was done after systems have been built. M. Baldwin (Ref. 4) seems to be one of the first to do any subjective testing, where he investigated the effect of image sharpness as function of focus adjustment, noting subjective reaction to change in image sharpness.

Coltman and Anderson (Ref. 5) have investigated noise limitations to resolving power in electronic imaging displays by using electronically generated bar patterns displayed together with a noisy background. F. A. Rosell and R. H. Wilson (Ref. 4) continued this work by considering the effects of a finite aperture of real TV type sensors.

IMAGE DISTORTION IN TV SYSTEMS

The point image projection transmitted by a television system is likely to produce images at the display which may be distorted to amplitude, shape or phase, or all three. These distortions are introduced by the objective lens, optical and electrical defocussing, electron scanning beams at the sensor and display, bandwidth limitations, etc. The overall effect appears as a reduction of image sharpness or a progressive attenuation of the higher spatial frequencies. This degradation is analogous to a one dimensional low pass electrical filter which is often referred to as the system modulation transfer function or the spatial frequency transformer. In imaging two dimensions are involved. They are either independent or possess radial symmetry; this means that the sets of information can be treated separately or become one dimensional in character respectively. The effective apertures of the individual system components have been found to be additive whereby the response to one input stimulus is identical to the sum of the responses produced individually. This is characteristic for linear systems. It is therefore possible to decompose complex input signals by the use of Fourier analysis to sine wave functions. In the mathematical description, the system modulation transfer function F(S) in the spatial frequency domain is expressed by the Fourier transform (Ref. 9) from real space g(k, y) to frequency space $F(\omega_x, \omega_y)$. It is defined as

$$F(S) = F(\omega_x, \omega_y) = \mathscr{F}[g(x, y)]$$

$$= \mathscr{F}_x[g(x)] * \mathscr{F}_y[g(y)]$$

$$\int\int_{-\infty}^{\infty} f(x, y) \exp[-j(\omega_x x + \omega_y y)]\, d_x\, d_y$$

where $\mathscr{F}$ denotes the taking of the Fourier transform and g(x, y) is an imaging having brightness g at the spatial position (x, y) and $F(\omega_x, \omega_y)$ is a vector of amplitude F with frequency components ω_x and ω_y.

IMAGE RESTORATION

Considering the typical spatial frequency response of a TV System (Fig. 2), spatial filtering can be used to correct or equalize the overall system response. These methods have been used extensively for digital image processing (Ref. 7 and 8). Ideally restoration and degradation are inverse functions, which, from the mathematical point of view, may be expressed as

$$F(i) = F(S) * F(0)$$

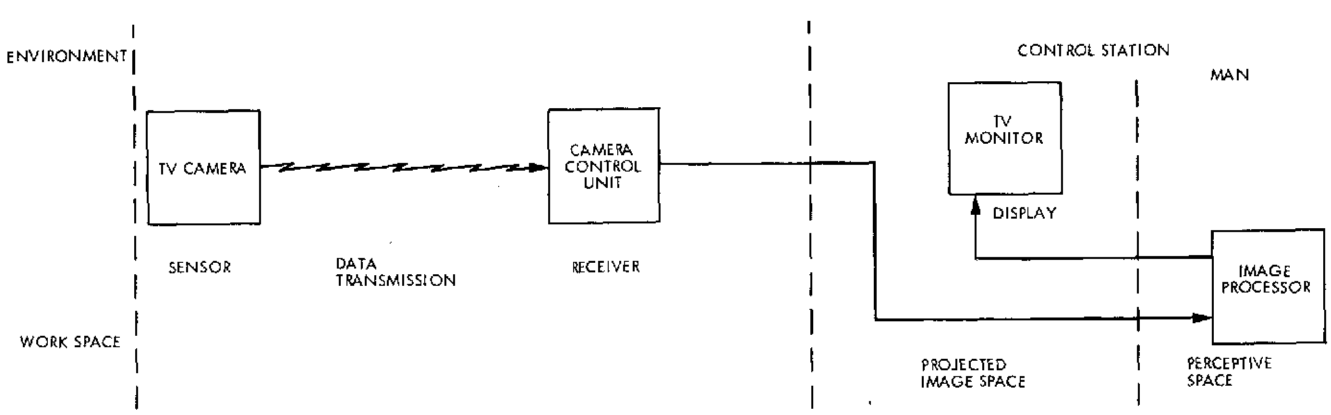


Figure 1. "TELE"VISION system

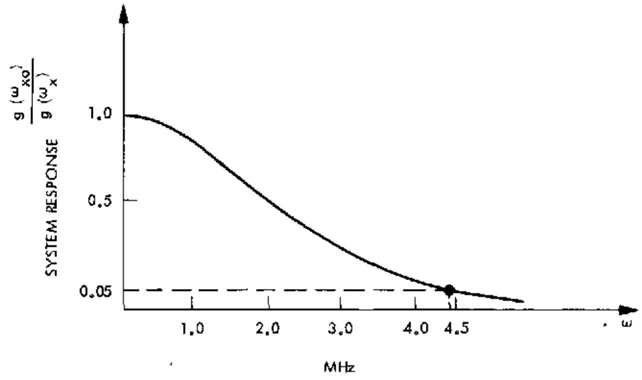


Figure 2. Typical system frequency response

and

$$F(0) = \frac{F(i)}{F(S)}$$

where F(i) is the Fourier transform of input image function, F(S) is the transform of the system modulation transfer function, and F(0) is the output or displaced picture transform. The conditions for correct image restoration are met when F(i) = F(0) or the transform of the output is identical to that of the input and

$$F(0) = \frac{F(i)}{F(S)} = F(i) * \frac{1}{F(S)}$$

Image restoration may be accomplished by operating in the frequency domain, multiplying of the Fourier transforms of the picture (F(i)) with the corrective filter (Fig. 3), the inverse of the modulation transfer function (1/F(S)) and then by reinversion of the resulting compensated spectrum back to real (image) space. This method has been extensively used by digital processing system (Fig. 4). The practical limitation to system aperture equalization is essentially set by the random noise contained within the system band pass.

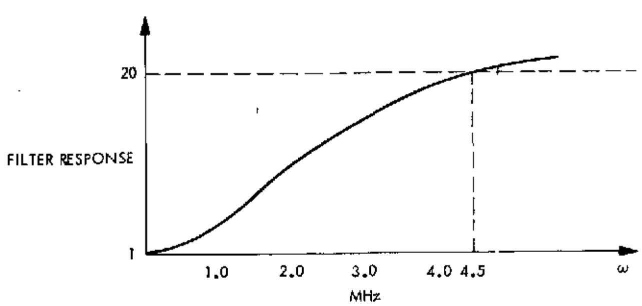


Figure 3. Corrective filter spatial frequency characteristic for equalization of system shown in Figure 2

NOISE LIMITATIONS

The dependence of image detectivity and recognition on the random noise level has been treated extensively by Coltman (Ref. 5), Johnson (Ref. 10), Rose (Ref. 11) and Rosell (Ref. 6). If image restoration is to be used, the effects on the signal to noise ratio in the displayed picture must be considered.

White noise usually originates from the statistical fluctuations in the signal, and background photoelectrons, and the noise generated by the video preamplifier of the TV camera. The power spectrum of white noise is of uniform amplitude and frequency distribution. Therefore, in a system which has a given aperture response, the signal-to-noise ratio decreases from the maximum value at very low spatial frequencies to one at the limiting resolution (Fig. 5). Utilizing a low pass filter for image restoration (Fig. 6) does not improve the signal to noise ratio although the modulation transfer characteristic has been equalized. Therefore, equalization of the system modulation transfer characteristic enhances images only when the signal-to-noise ratio of the imaging system is high. JPL has recognized this problem and decided to improve the signal-to-noise ratio of images first and then proceed with further processing.

DIGITAL IMAGE INTEGRATOR

CIT/Hale Observatories have made available, on loan, a digital image recorder which has been built around a high speed digital memory system. JPL has used the system to demonstrate high speed noise reduction as means of image enhancement.

The digital image recorder (DIR) has been described in detail by Sachs, H. G. (Ref. 12) and Dennison, E. W. (Ref. 13). The DIR accepts standard video signals from a television camera. A high speed analog to digital converter is used to quantize the image brightness levels at a 4.8 MHz sampling rate. In this configuration the image is interrogated as an array of 256 x 256 picture elements (pixels) and each elemental photoelectron charge is transferred into a 65,536 word memory. Each word consists of 16 binary bits, or has a dynamic range of 65,536. The memory consists of dynamic MOS shift registers, which are accessed sequentially in synchronism with the read out of the sensor. The DIR control system was arranged to operate as "multiple frame grabber".

The "frame grabber" concept centers around the ability of the DIR to operate as a digital image buffer. The memory array size dictates how many picture elements can be stored and the pixel clock indicates the data rate at which the information is accessed. Since the memory addressing scheme is arranged in the manner of raster scanned TV systems, it is easy to utilize television terminology which identifies pictures as frames. Due to the access speed and digitization rates the name "frame grabber" was only natural. By control of the array address timing, it is possible to input one frame of data into memory. The dynamic shift registers, of which the memory is comprised,

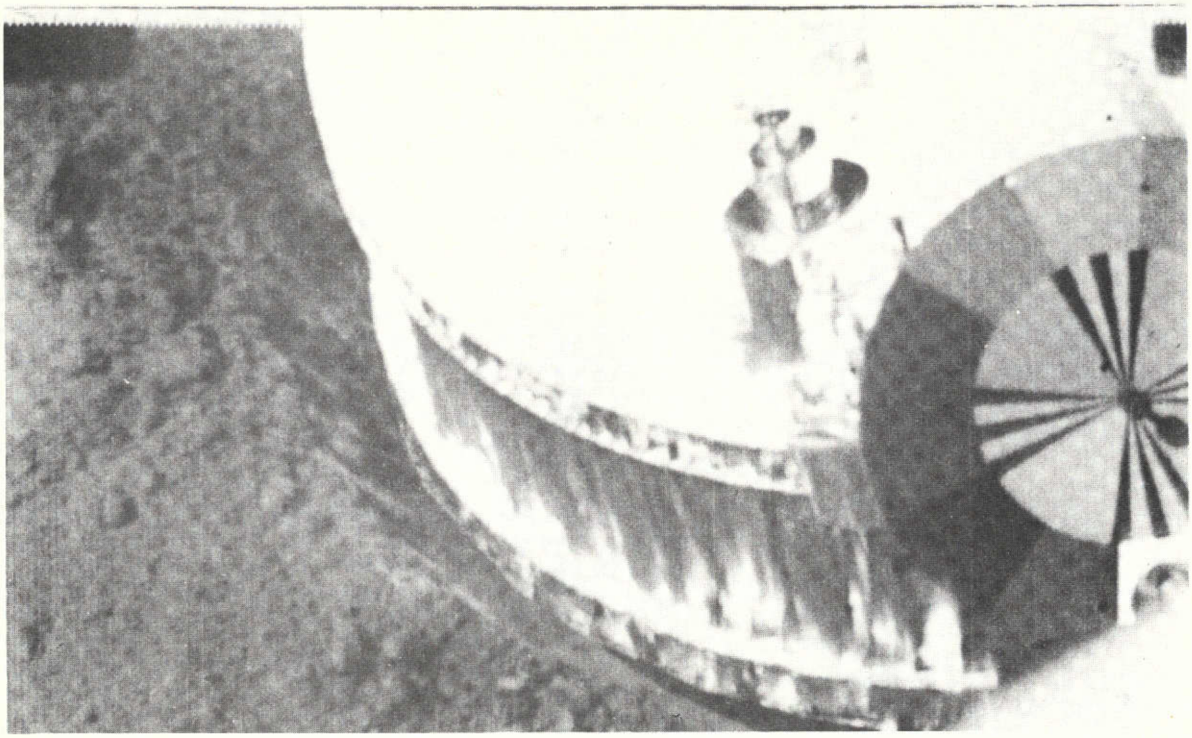


Figure 4a. Surveyor spacecraft footpad on lunar surface before restoration

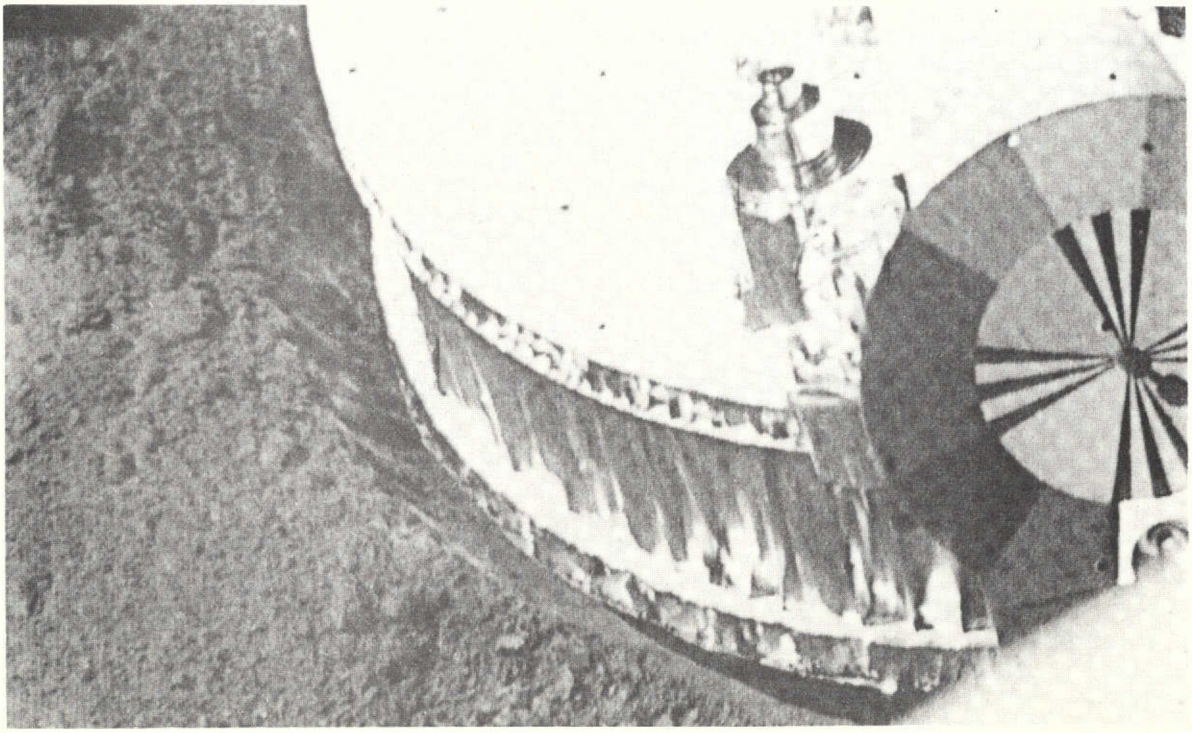


Figure 4b. After image restoration (note improvement in resolution shown by wedges)

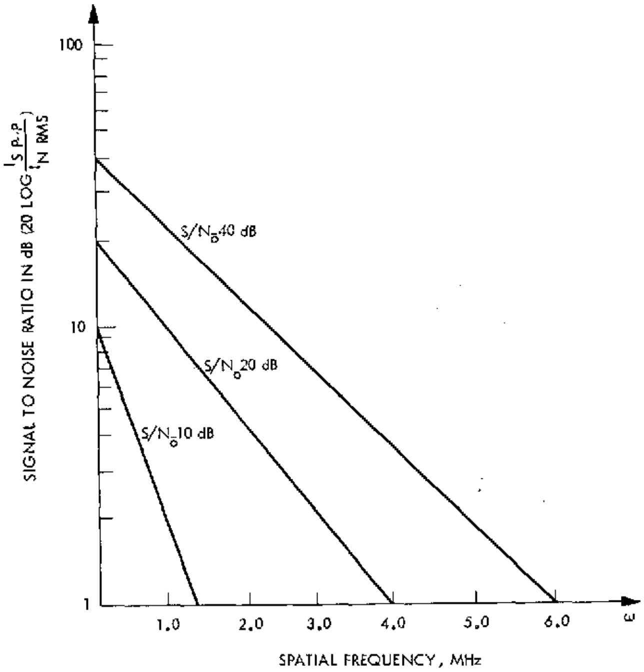


Figure 5. Signal to noise ratio as a function of spatial frequency

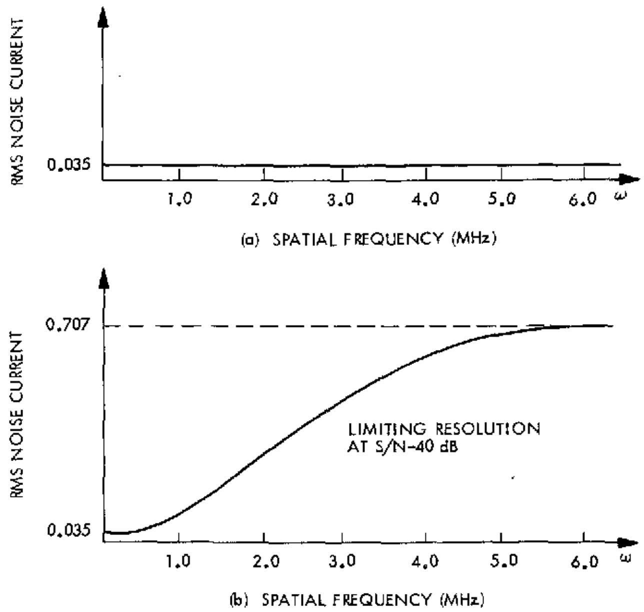


Figure 6. Noise current as a function of frequency (S/N-40DB)
(a) Non-equalized system
(b) Fully equalized system

provide a nondestructive readout of the frame stored. This process operates at a frame rate of 60 per second which guarantees a flicker free display on standard TV monitors.

By continuous application of the video signal to the input of the DIR, the system will operate as a multiple additive frame grabber or integrator. The frame integration time, or the number of frames accumulated, is controlled by an acquisition timer. How quickly the memory is filled (saturates) depends on the signal levels received from the camera system.

To illustrate:

Maximum bit count	65,536 counts
Highlight in image	64 counts (64 bits)
Maximum integration time	17 seconds
Maximum number of frames per integration	1024

The interesting and significant aspect of frame integration is the improvement in signal-to-noise which can be materialized. In the above example, the signal to noise ratio could be improved by a factor of (number of frames integrated)$^{1/2}$ which would be 32. The picture illustrated by Fig. 7a shows a single quantum noise limited electron micrograph frame. The same image integrated for 2 seconds, or 120 frames, is seen in Fig. 7b and shows a signal to noise improvement from 1:1 to approximately 10.5:1 while the theoretical improvement factor should have been 11. The Fourier transforms corresponding to Fig. 7 are shown pictorially by Fig. 8 and graphically by Fig. 9.

CONCLUSION

Television systems can be used to augment man's capabilities in the control loop of remote manipulation systems. This can be accomplished despite instrumental and transmission system limitation normally causing signal deterioration. Experimentation to evaluate various image enhancement techniques can be performed by computer based Image Processing Laboratories such as JPL's IPL System IBM 360/44. This approach has been considered most flexible, because it permits the use of an almost unlimited repertoire of operations. Unfortunately, in systems where operations depend on the responses of man in a control loop, even with the fastest machines conceivable, the general digital computer approach is too slow. For repetitive enhancement and restoration, hardware approaches offer very positive solutions. We have demonstrated that high speed frame integration can be used to improve the signal to noise ratio in near real time imaging. The hardware design was made possible by the advances in LSI Technology, which have sped up processing by orders of magnitude. Signal to noise improvements within a few seconds improve the otherwise noise limited resolution and provide an excellent base for image restoration and contrast enhancement. Most significantly, the operator as the most important link in the control loop, can be provided with a near real time display, which he controls interactively, thus enabling him to perceive the remote work space as required for the timely execution of remote manipulation tasks.

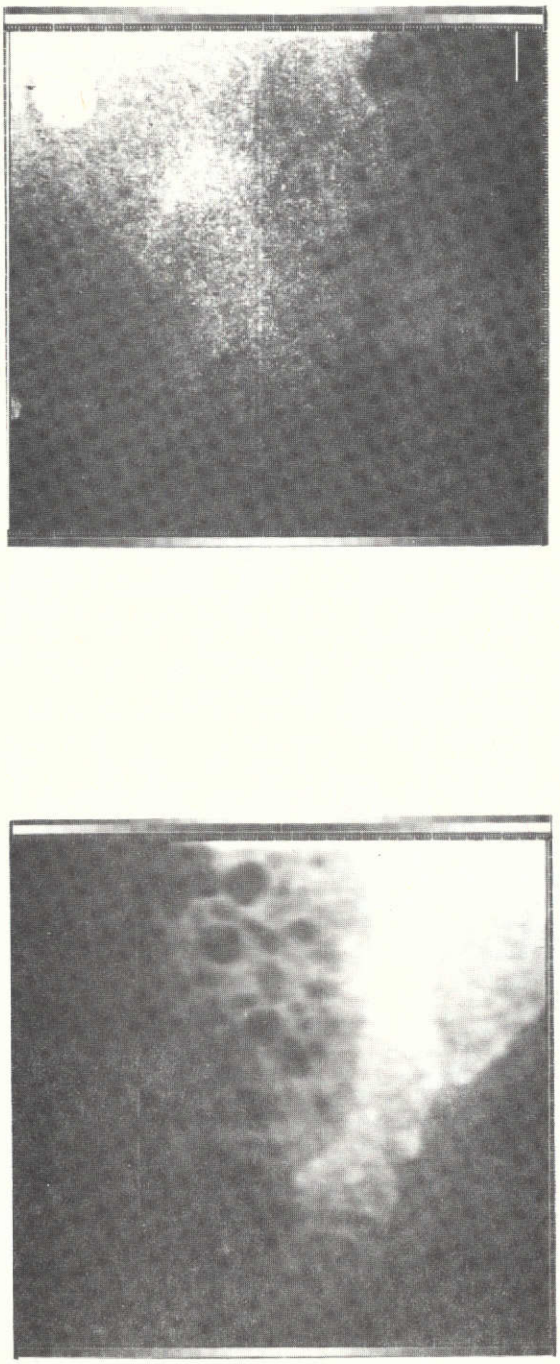
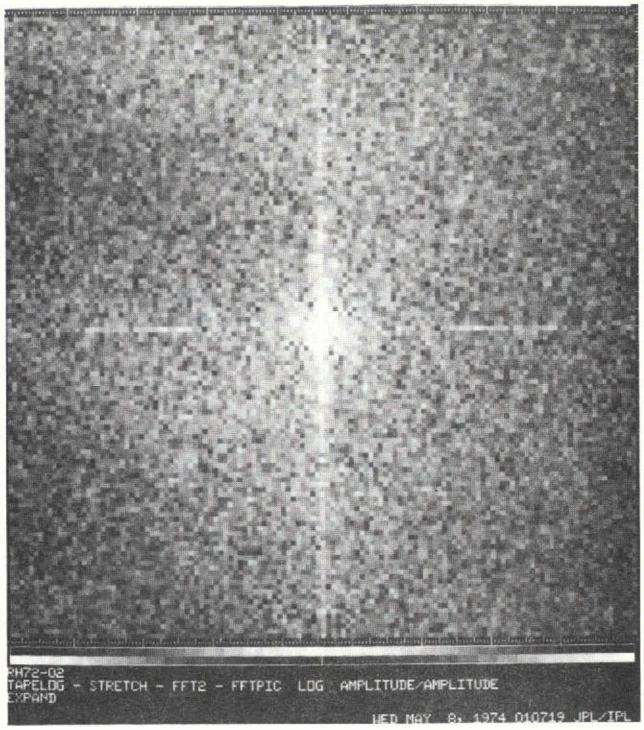


Figure 7. Images at output of DIR

(a) Single frame - S/N - 1

(b) Integrated frames - S/N - 11.5



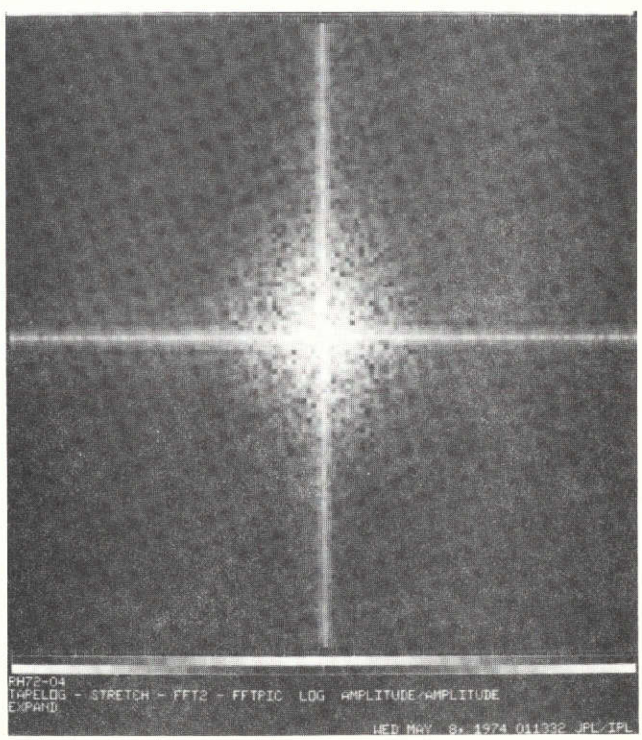


Figure 8. Fourier transforms of images

(a) Single frame, corresponding to Figure 7.a

(b) Integrated frames, corresponding to Figure 7.b

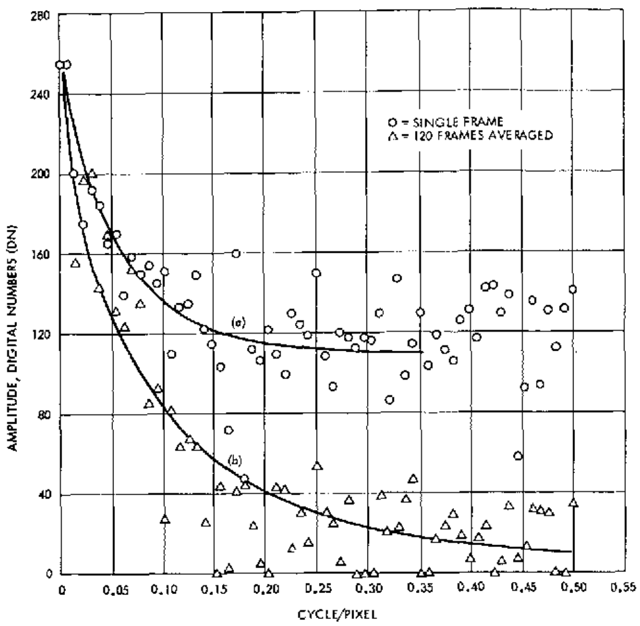


Figure 9. Graphical representation of Fourier transforms corresponding to Figures 7 and 8

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