TRADEOFFS BETWEEN ALIASING AND MTF

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ABSTRACT

Imagery produced by a CCD (Charge Coupled Device) with varied degrees of prefiltering is presented as an empirical basis for trading off MTF against aliasing. Differences between frequency domain and space domain analyses of aliasing error are discussed. It is concluded that the aliasing error caused by contiguous imaging elements is not severe enough to merit further prefiltering.

INTRODUCTION

CCD (Charge Coupled Device) technology offers great flexibility in the design of two-dimensional imagers. Each different design must be evaluated on the basis of such factors as complexity, fabrication yield, speed of operation, responsivity, spatial resolution, etc. Barbe and White[1] have examined the major differences between the two basic CCD imager designs - frontside illuminated interline transfer and backside illuminated frame transfer, emphasizing such factors as responsivity and MTF (Modulation Transfer Function) within the spatial frequency passband defined by the pixel (picture element) spacing. It has been suggested, however, that since CCD's sample the image plane and are, therefore, subject to aliasing, that the spatial frequency response beyond the sampling limit is a major design consideration. It is argued that since response beyond that limit serves only to introduce spurious signals into the allowable passband, this response should be eliminated by filtering the scene before sampling. In practice, however, this cannot be done perfectly. Some response to frequencies within the passband must be sacrificed if spurious response is to be avoided. Thus, in the design and use of sampling imagers there is a tradeoff to be made between the adversity of aliasing and the inevitable loss in image sharpness incurred in reducing aliasing. Although several authors[2, 3, 4] have offered arbitrary guidelines for making this tradeoff, there is no firm theoretical basis for trading off desirable response to reduce spurious response. It is, therefore, necessary to resort to an empirical approach, utilizing representative scenes reproduced with an imaging system for which true and spurious response is known. Such an approach has been applied by Root[5] using an image dissector camera to simulate a sampling imager. Prefiltering was accomplished by the well-defined circular aperture of the dissector. The degree of prefiltering was controlled by adjusting the aperture diameter relative to the fixed sampling distance. Each image sample point was reproduced at the display as a square, uniform picture element, contiguous with the adjacent samples. Two scenes were used in the simulation - a lunar landscape and a cloud formation. Each scene was reproduced with each of three prefiltering conditions. It is the authors' impression of

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the published imagery that the quality of the reproduced imagery decreased as the degree of prefiltering increased. This observation runs counter to the notion that "it pays to prefilter the signal before sampling"[3] and has a direct bearing on the design of CCD's, where the active picture element size can be controlled relative to the sampling spacing over the range used in the Root experiment. However, the two scenes used in the experiment are hardly an adequate sample from which to draw firm conclusions. Indeed it is questionable whether any two, or for that matter, any two hundred scenes could serve to establish general design rules. However, an extension of the empirical base established by Root would serve to broaden the CCD designer and user's intuition into the elusive aliasing "problem" so that he can set realistic limits on how much weight can be given to either side of the aliasing argument. To that end we have utilized a 100 x 100 element CCD imager as a vehicle to produce a wide range of imagery under controlled conditions of spatial frequency response.

THE IMAGING SYSTEM

A Fairchild CCD-201 area imager was used to make the pictures reproduced herein. This device has 100 columns, spaced at 1.6 mils, and 100 rows at 1.2 mils. The array utilizes the interline transfer structure[1], with more than 50% of the image area obscured by the aluminum gates on the vertical scanning registers, as shown in figure 1. In the vertical direction, sensing elements are contiguous rather than overlapped as in the interlaced vertical frame transfer structures[1]. The non-contiguity in the horizontal direction makes this structure particularly vulnerable to aliasing, as is evidenced by the imagery shown in figure 2. Each of the nine views shown are of a different set of vertical bars extending over the entire sensing area. The frequency of the bars is expressed in multiples of the sampling frequency, f_N. Since the horizontal cell spacing is 1.6 mils, f_N is 12.3 cycles per millimeter. Thus, only the top row of figure 2 represents true imagery. The remaining six views are Moire' patterns produced by the interaction of the CCD structure and the bars of the test chart. It is evident from figure 2 that the Fairchild structure is an excellent vehicle for producing spurious signals, and is therefore well suited for our purposes.

The imagery in figure 2, and all subsequent CCD imagery reproduced herein was photographed from a CRT display. The sensor is clocked at 2 MHz, interlacing two 50 x 100 fields in each frame, 120 frames per second. The video was smoothed by a bandpass filter, rolling off at 80 dB per decade at 1 MHz. The scan lines of the display were wobbled vertically in order to smooth the line structure. This technique was not completely successful due to a slight pairing of lines in the interlaced fields.

The scene was transfered to the CCD image plane using a 50 mm lens at a magnification of 25:1, so that the element spacing at the object plane was about 0.75 millimeter vertical and 1.0 millimeter horizontal. The lens was stopped down to f/5.6 to increase MTF. The scenes were black and white and color photographs illuminated with 3200°K photoflood lamps. Blue filters were used to eliminate the degradation of MTF caused by the red response.[6]

MTF MEASUREMENT

MTF was measured using square wave test patterns. The patterns were traversed across the CCD camera's field of view using an x-y recorder. The signal produced by an element near the center of the array was sampled at each frame and held for one frame period as the test pattern was slowly traversed across the element. The resultant low frequency (0.1 Hz) waveform was plotted on a second x-y recorder slaved to the first. Waveforms were plotted at each of 15 spatial frequencies ranging from 1.2 to 48 cycles per millimeter. The sine wave response was calculated from the measured square wave response using a truncated series transformation.[7] In this manner the horizontal and vertical MTF of the sensor lens combination plotted in figure 3 was derived.

PREFILTERING

In order to reduce the strength of spurious signals, it is necessary to filter the input scene before sampling. In a CCD this can be accomplished at the image plane by varying the size of the sensing element relative to the element spacing. Carrier diffusion also degrades MTF.[6] Further prefiltering can be accomplished using an optical low-pass filter at the input to the lens,[8] or by simply defocussing the lens. Since in this experiment the object distance was fixed, it was convenient to utilize the latter effect. MTF was measured at several focus positions of the lens. The measurements showed a surprising effect. At each focus position the additional MTF degradation produced by defocussing the lens had the form:

$$\frac{\sin(\pi f/f_c)}{(\pi f/f_c)} ,$$

where f is the spatial frequency, and f_c is a parameter dependent on focus. Thus it was possible to closely simulate various conditions of cell size/cell spacing by merely rotating the lens focus ring to preselected positions.

Three different focus conditions were used. Condition "A" is that of best focus, where the MTF is as shown in figure 3. Note that the null of the horizontal response is slightly beyond 4 f_N. In condition "B" the MTF is degraded so that the first null of the horizontal response occurs slightly beyond 2 f_N (figure 4). This condition is an approximation to the case of contiguous elements, also treated by Root. Condition "C" approximates the case of overlapped elements, where the first null of the MTF occurs at about 1 f_N (figure 5).

TEST IMAGERY

Figure 6 shows imagery produced by the Fairchild CCD-201 sensor for each of the three prefiltering conditions. Each view is composed from six photographs of the 100 x 100 element display. Condition "A" of course, represents the worst case for aliasing errors, while condition "C" has the least aliasing error. As in Root's study, "the effects of aliasing errors would appear to be subtle rather than dramatic," while the effects of defocussing are clear: view A appears sharper than view C. There is one noticeable consequence of non-contiguous horizontal elements noticeable in view A. A large antenna near the center of the ship seems to be detached from the superstructure, since the lower segment has fallen between elements. This is not the case for view B since the defocussing has the effect of making the sensing sites contiguous.

Figure 7 shows an aerial view of Arlington, Virginia, as imaged with the CCD. The scene includes the Pentagon and a large parking area. As before, condition "A" is sharpest, although the serrated appearance of the linear structure of the Pentagon in views A and B may be somewhat objectionable, especially if the scene is moving.

In figure 8 the CCD is used to image an aerial photograph of an off-shore platform. Figure 9 is a moonscape similar to that used by Root. In both scenes, prefiltering has an obvious deliterious effect. As in figure 7, small details such as the legs of the platform, and small craters are lost in Condition "C."

Other scenes, too numerous to reproduce herein, were imaged as above. In all the result was the same: Condition "A" produced sharp imagery with no obvious aliasing problem other than an occasional dropout of small details. Condition "B" produced slightly less sharp with no drop-out of small details. Condition "C" produced images that were generally inferior than those of A and B.

This result, consistent with our observations made from Root's imagery raises the question: "When does it pay to prefilter?" To answer this we set up a very unusual scene, consisting of a set of vertical bars at 1.6 f_N as a background, with various aperiodic forms superimposed. Figure 10 contains the CCD images of this scene. The scene contains a pair of vertical bars, one white and one black, which are positioned so that they are aligned with the light and dark bars of the Moire' produced by the interaction of the imager and the periodic background. In view C these bars stand out quite clearly, since pre-filtering has greatly reduced the spurious response. However, in view A the bars are quite difficult to see since the spurious signal has a high contrast. Note, however, that if the bars are not aligned with the Moire' pattern, as with the large black bar at the left, they stand out quite well as an interruption of the Moire' pattern. In fact, several large gray objects in both scenes are visible in views A and B but not in view C where they blend in with the uniform gray produced by prefiltering. Thus, in this very artificial situation, aliasing in the form of Moire' can be detrimental or beneficial, depending on the exact conditions of size, orientation, and intensity.

DISCUSSION OF RESULTS

It seems evident from the imagery presented that the "aliasing problem" is not as severe as has been supposed. Indeed the prefiltering required to significantly reduce the response beyond the sampling limit appears to do more harm than good in most instances. This result may seem surprising considering the large degree of spurious response in the sensor as indicated in figures 2 and 3. Intuitively it would seem that all of the scene energy contained in the two-dimensional frequency domain beyond the sampling limit would be reproduced as a spurious signal, or noise occupying the same frequency space as the signal, thereby tending to obscure it. The problem with this analysis is that the viewer is influenced primarily by the spatial content of the reproduction rather than the frequency content. Although a Moiré pattern might occupy the same frequency domain as the true signal, it does not occupy the same space in the image plane as is the case with additive noise. This is illustrated graphically in figure 10, where the Moiré pattern extends up to, but not through, the objects of interest.

A similar argument can be used in the case of aperiodic objects. Suppose the scene contains many sharp edges and lines. The frequency spectrum of these scene elements may extend far beyond the sampling limit, and will, therefore, fold into the useful passband. In the image plane these elements will be reproduced as sharp but broken edges and lines. However, this distortion does not extend beyond those elements subtending the original edges and lines, and therefore, does not affect the appearance of scene elements elsewhere in the scene. While prefiltering may render the edges and lines as continuous, it also spreads part of the energy of these scene elements to adjacent areas, thereby blurring the image and reducing the edge contrast. Thus, it appears that frequency domain analysis is not adequate for judging the effect of aliasing at the image plane.

The principal shortcoming of this empirical study of aliasing is that it is done with static imagery. When there is relative motion between the scene and sensor, aliasing manifests itself in a different way. Serrations in the image of a solid line move up or down along the line as the position of the line changes with respect to the sensor elements. In the case where there are gaps between sensors, lines may jump in and out of the image as in figure 7. Moiré patterns will move through the area occupied by the original periodic pattern with speed and direction different than the actual motion. This effect is not unfamiliar to all who watch the evening news commentator move in front of the camera in his plaid suit. It is clear that such effects can be distracting, especially for entertainment viewing. However, in many industrial and military applications, the goal is to present a trained viewer with as much information as possible. His experience should enable him to focus on important areas in the scene and to recognize aliasing effects for what they are. Indeed, the very presence of Moiré, moving or static, may be a vital piece of information, such as when a chain link fence is detected far beyond the resolution limit. In such instances spurious signals are better than no signals.

If the sensor is to be used to detect subresolution sized objects, such as point images of stellar objects, it is a definite disadvantage to have unresponsive intensities at the image plane. In these instances it would be preferable if the sensors were contiguous, or if the scene were prefiltered to that degree. The former solution would be preferable for those applications where sensitivity is a prime consideration. Although further prefiltering will eliminate the abrupt jumps of the point image as it moves from element to element, it is questionable whether defocussing to Condition "C" is merited. If in a given application it becomes clear that such effects are a real problem additional prefiltering external to the sensor is easily implemented.[8]

In summary, the effects of aliasing are not as severe as might be predicted from frequency domain analysis. An excellent compromise between aliasing and image sharpness is obtained when sensing elements are contiguous. Further prefiltering should be considered only if it has been experimentally demonstrated that aliasing will be a real problem.

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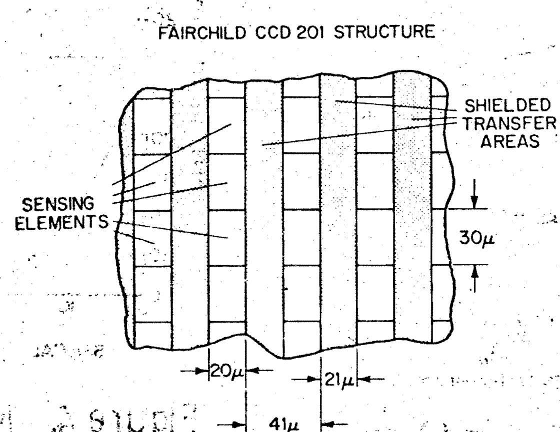


Figure 1. Structure of CCD Imager

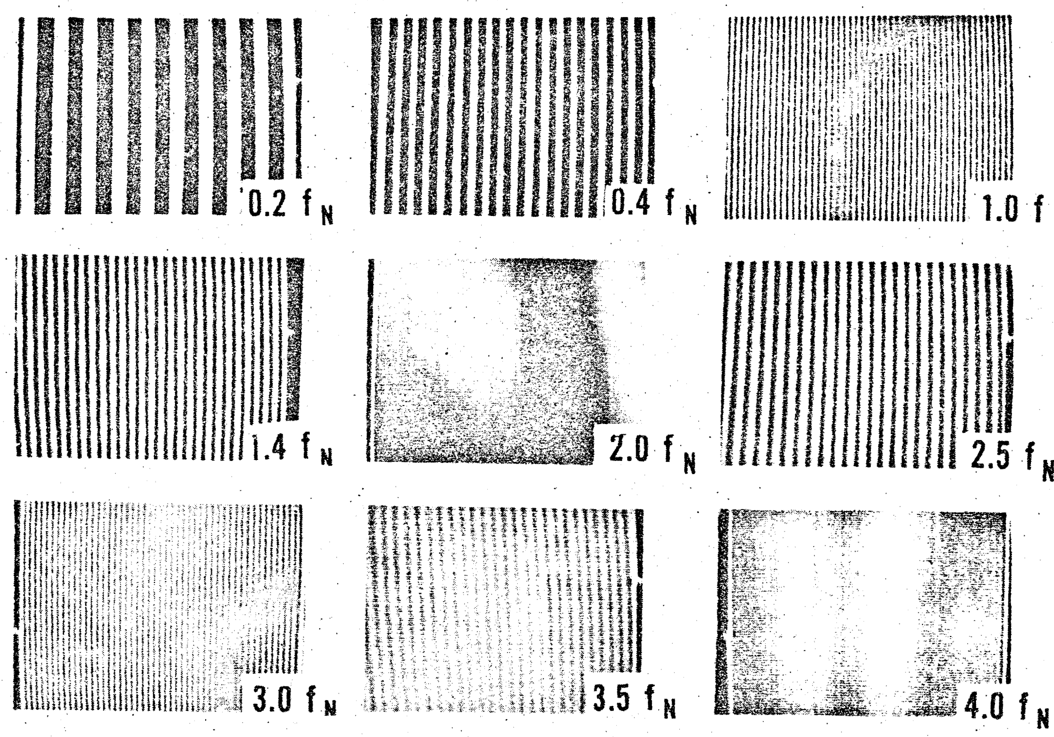


Figure 2. CCD Imagery:
Vertical Bars

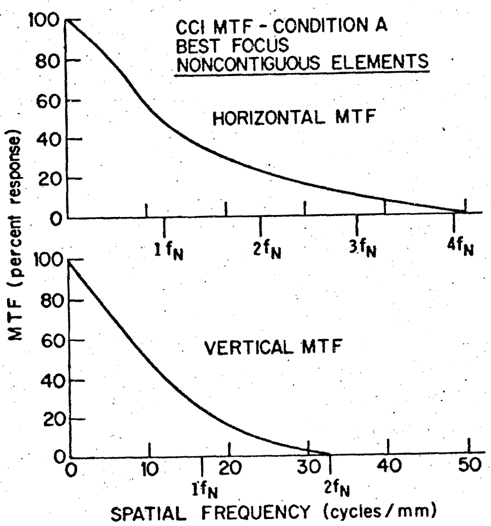


Figure 3. MTF: Condition A

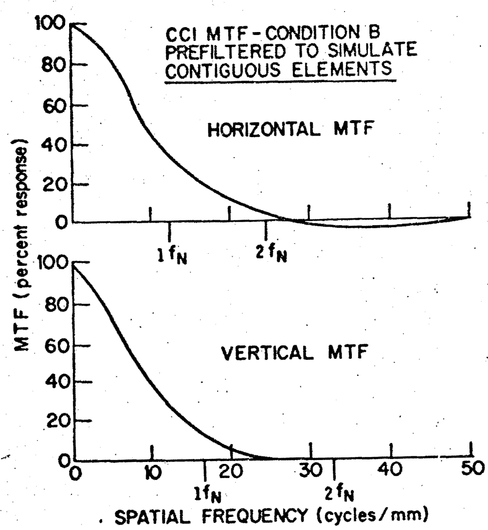


Figure 4. MTF: Condition B

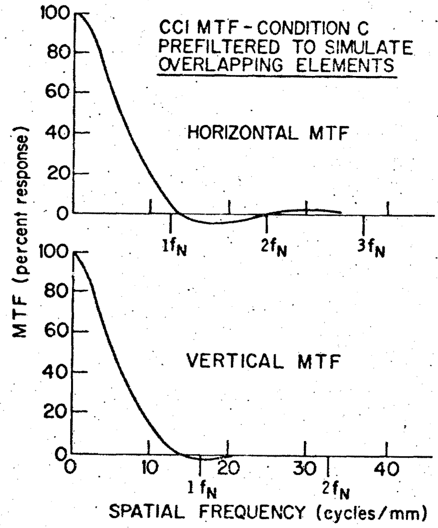


Figure 5. MTF: Condition C

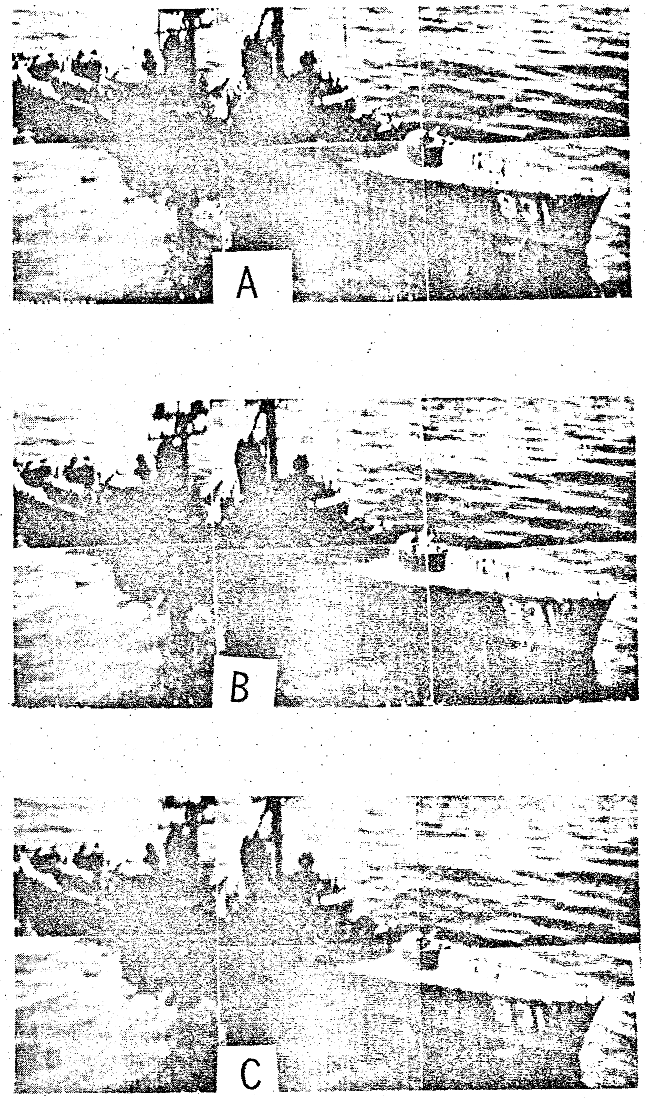
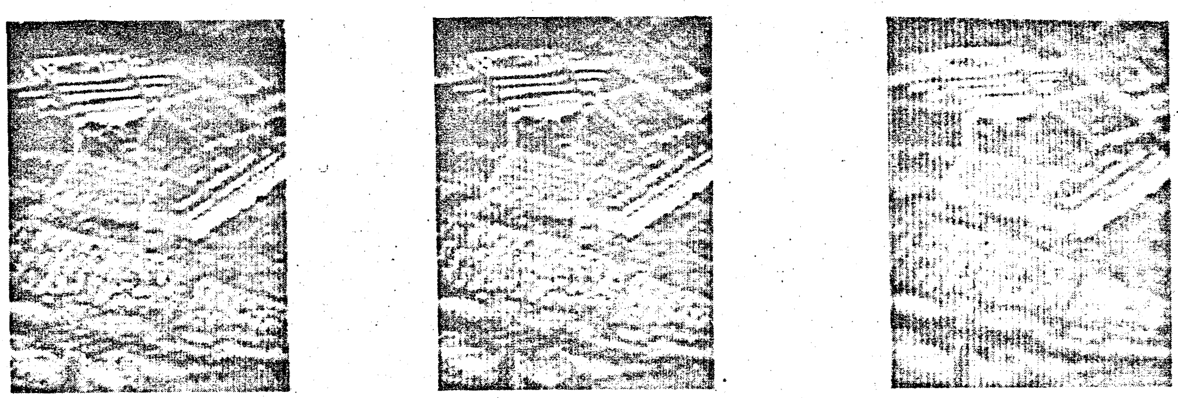
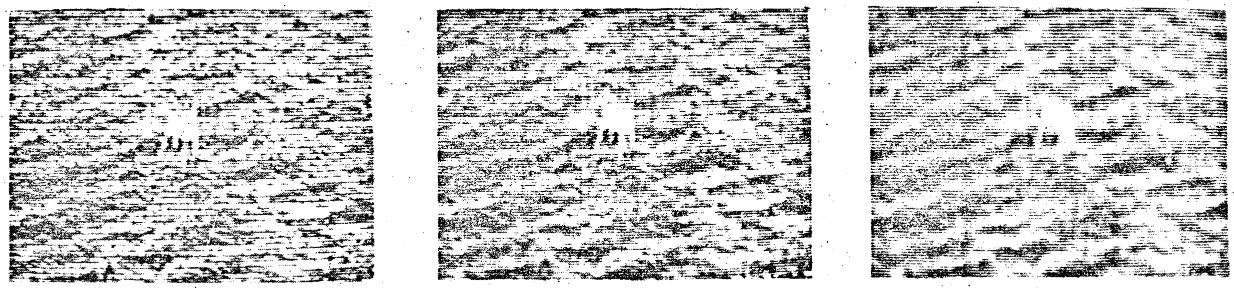


Figure 6. Composite CCD Imagery: Warship

Figure 7. CCD Imagery: The Pentagon

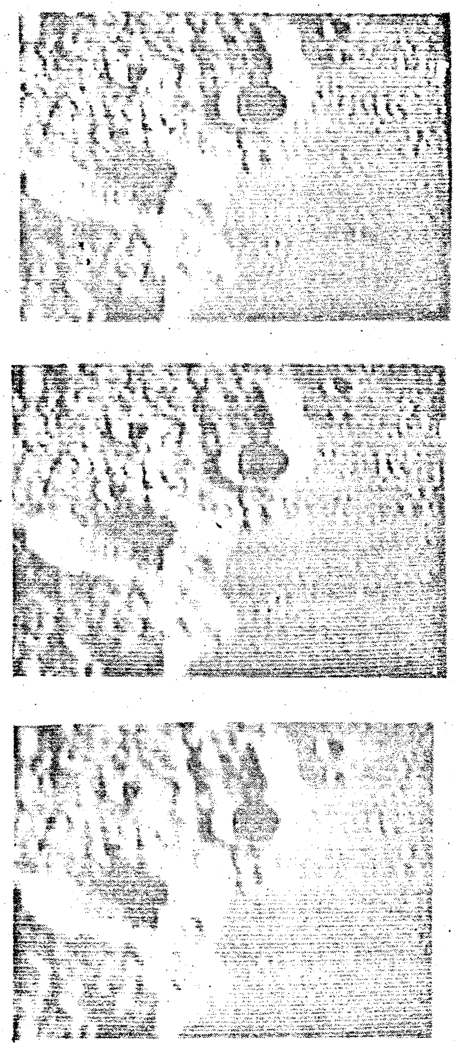


A B C



A B C

Figure 8. CCD Imagery: Off-Shore Platform



A

B

C

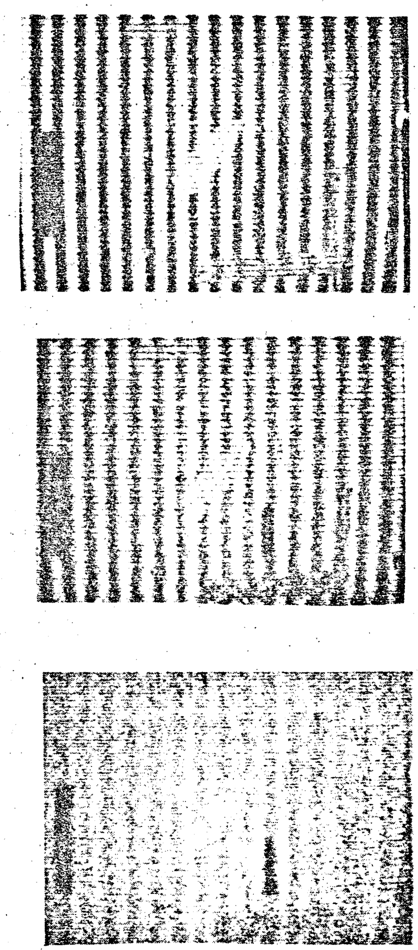


Figure 10. CCD Imagery: Periodic Background

Figure 9. CCD Imagery: Lunar Landscape