# The Characterization of Facsimile Camera Systems for Lunar and Planetary Surface Exploration

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For imagery of lunar and planetary surfaces from stationary or stopped remotely controlled vehicles, facsimile camera systems offer unique advantages: better geometric fidelity than television systems, more picture elements per frame, ability to take single frame panoramic pictures, a very high contrast ratio within a picture, a choice of one or more narrow-band spectral responses over a wide possible range, image transmission over a low bit-rate communications channel without storage, very low power, small size, low weight, and ruggedizability to meet space flight requirements. Systems of this kind are under development for the 1975 Viking Martian lander, and have been used by the Soviets on Lunas and Lunokhod. JPL has recently completed laboratory and field evaluation of an existing facsimile camera system. The results of this test program are presented. The applicability of facsimile cameras to lunar and planetary rovers is demonstrated.

## Introduction

In pursuit of NASA interests in electronic imaging for lunar and planetary automated rover applications (Reference 1), the Marshall Space Flight Center (MSFC) initiated a facsimile camera evaluation program in the winter of 1970. The program involved MSFC, the U.S. Geological Survey, and JPL, and consisted of laboratory and field evaluation of the one existing sample of the Philco Ford-designed and built Minifax television camera and its film reproducer. The camera is shown in Figure 1, and the specifications of the camera and reproducer are given in Tables 1 and 2, respectively. A sample Minifax panorama is shown in Figure 2.

[1] Work performed during prior assignment to the Space Sciences Division.

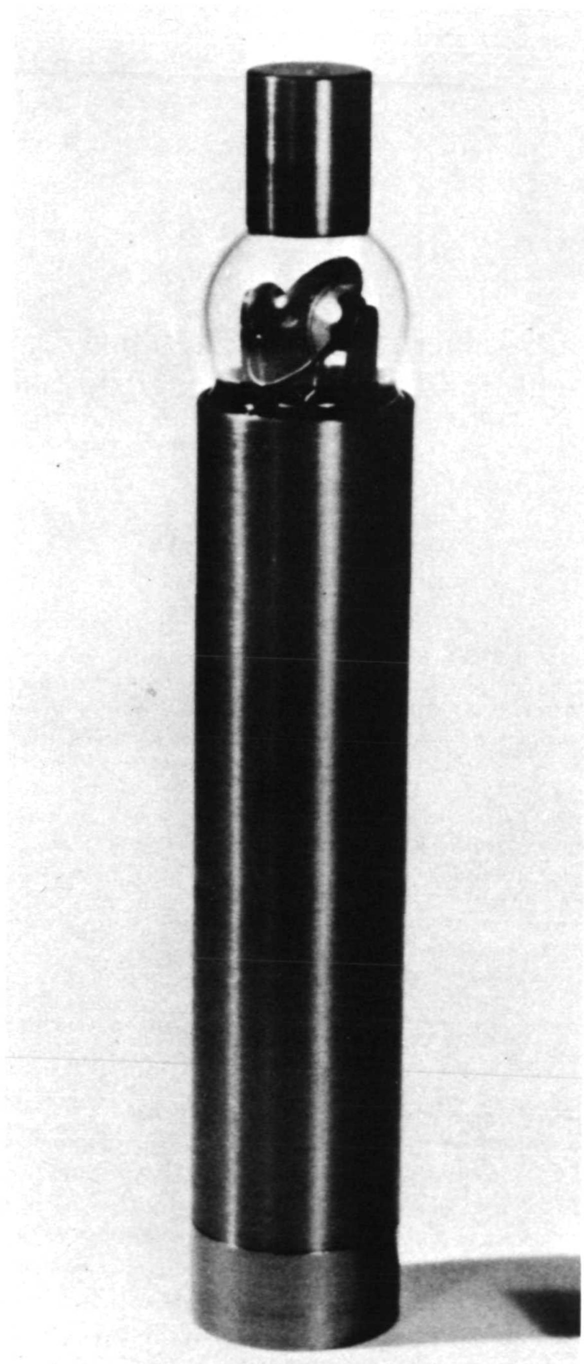

Figure 1. Minifax camera

**Table 1. Minifax camera specifications after Philco Ford**

| | |
|---|---|
| Image field of view | $+1.05, -0.525 \times 2\pi$ rad |
| Scan format | 900 horizontal lines |
| Image point spacing | 1.74 mrad |
| Scan rate | 30 lines/s |
| Data rate | 108,000 image points/s |
| Frame time | 30 s |
| Spectral response | Silicon, 0.4–1.0 $\mu$m |
| Noise equivalent brightness | 86 cd/m$^2$ at 54 kHz |
| Dynamic range | 86–34,300 cd/m$^2$ |
| Data synchronization | Line and frame sync |
| Scan sync reference | 6 kHz |
| Operating power | 1.5 W at 14 Vdc |
| Video output | 0–10 V |
| Size | 2.5 cm diam $\times$ 15 cm long |
| Weight | 260 g |
| Environment | 1000-g delivery shock |
| | −23 to +72°C exposure, 1 yr |

**Table 2. Minifax recorder specifications after Philco Ford**

| | |
|---|---|
| Image size | 11.4 $\times$ 45 cm |
| Record medium | Photographic film |
| Line spacing | 0.0127 cm |
| Line-to-line correlation | 0.0025 cm (0.35 mrad) |
| Recording dynamic range | 200/1 |
| Operating power | 150 W at 110 V, 60 Hz |
| Size | 23 $\times$ 36 $\times$ 36 cm |
| Weight | 23 kg |
| Operating features | Gain and bias controls |
| | Daylight loading |
| | Real-time recording portable |

Figure 2. Minifax field site panorama (Sun covered by shading disc)

The test program was intended to fill gaps in knowledge about functioning, flightworthy, mechanical scanning telephotometers. The first facsimile-equipped U.S. spacecraft flight will be the 1973 launching of the Radio Astronomy Explorer B whose cameras are to observe antenna deployment and dynamics. The first U.S. lander facsimile camera will be on the 1975 Viking to Mars which will carry two such devices, providing both stereo and color panoramic imaging. The present Minifax camera is descended from one developed for the Ranger Project in 1960–1964 but never flown to the Moon. The principle of building up and transmitting an image point-by-point has been demonstrated in space, for example, by the spin-scan cameras on the Applications Technology Satellites.

In spite of the present lack of U.S. flight experience, facsimile cameras are not strangers in space. The USSR has a long history of use covering lunar landers and the recent Lunokhod automated rover (Reference 1). Lunokhod carried four facsimile cameras, two on each side of the vehicle. One of each pair was mounted to take vertical panoramas, and one to take horizontal panoramas. A Lunokhod telephotometer panorama is shown in Figure 3. The time to take the picture was indicated to be 1800 s. Analysis of the print shows a vertical scan line orientation with a scan line spacing of approximately 1.3 mrad, and a field of view of approximately 4.7 rad horizontal by 0.61 rad vertical.

The justification for facsimile cameras instead of, or supplementing, vidicon types stems from certain basic problems to be solved by imaging on a remotely controlled lunar or planetary mobile vehicle. These problems are to see where the vehicle is located, to determine its relationship to the surrounding region, and to identify features of potential scientific interest for further exploration. The solution lies in obtaining an appropriate full-circle panorama from the rover. In the case of a stationary lander, this can be done by assembling many frames from a raster scan television camera together into a single, full-circle, panoramic mosaic, as was done for Surveyor. In the case of a roving vehicle, this is too time consuming and tedious to be performed at each site of interest, along an entire traverse, and suffers from other shortcomings. Of possible alternatives to vidicon camera mosaics, the most direct, optimum choice for the job is the photo facsimile television camera.

## Facsimile Camera Functional Description

Basically, facsimile cameras consist of a telephotometer (a point detector with a lens) which is mechanically scanned across the image. A variety of implementations is possible, but the simplest, and most efficient, for most rover panorama purposes is a helical scanning camera, such as the Minifax with a scan that starts in the upper lefthand corner of the frame and ends in the lower righthand corner.

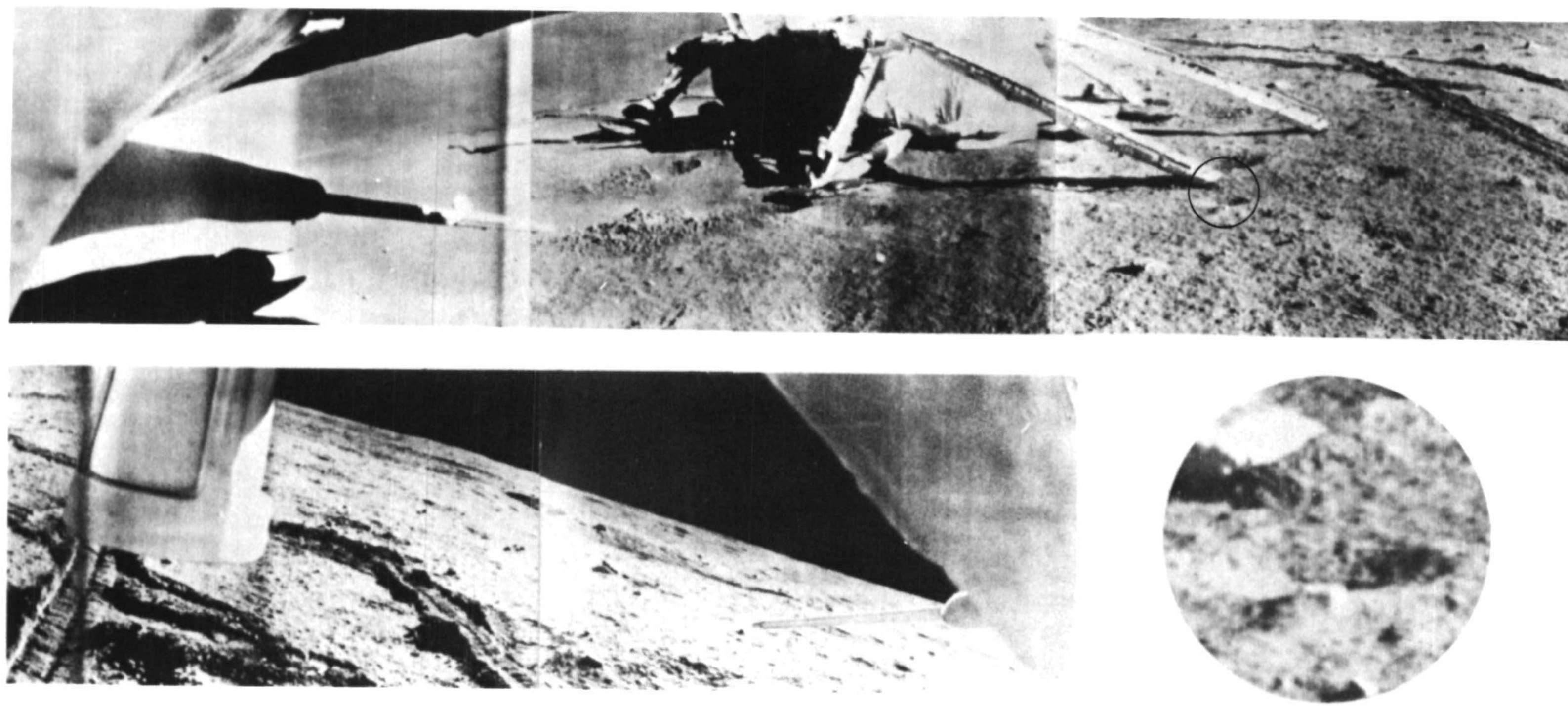

Figure 3. Lunar panorama from Lunokhod telephotometer showing landing platform and tracks of Lunokhod, Jan. 19, 1971
(courtesy of Dr. K. P. Florensky)

The advantages of a facsimile camera for this application are as follows:

(1) *High geometric accuracy.* This is a requirement for terrain navigation. Since the camera operates as a precision optical divider head, it may be designed to be calibrated to about one scanning line width of relative geometric accuracy over the entire frame. This is in contrast to the much larger geometric nonlinearities of electronically scanned cameras.

(2) *Panoramic capability.* There is no inherent restriction on the horizontal field of view. Therefore, full-circle coverage is possible without variations in response or shading. This large field of view, with its attendant large number of picture elements per frame, would be impossible in a single frame with a vidicon camera.

(3) *Large dynamic intensity range.* The point sensor of the camera can be operated linearly over an intensity range in excess of three decades starting with the preamplifier noise level and extending to the saturation point of the electronics. A range of this magnitude is generally impossible to achieve using other imaging techniques.

(4) *Direct solar imaging.* Direct solar imaging is possible without damage to the detector. Typical solar thermal loading of the detector is only 2 mW. This removes restrictions on solar pointing encountered with vidicon cameras. Rapid recovery from solar saturation to normal video levels within a few picture elements can also be incorporated in the design. Imaging the Sun would destroy many types of vidicon cameras, as happened during Apollo 12.

(5) *Wide spectral coverage.* The commonly used silicon phototransistor detector is usable over the entire visible spectrum, and beyond into the near infrared. With a trade-off between the total spectral coverage and sensitivity, narrow-band spectral filters may be introduced as required.

(6) *Low data rate matched to telemetry requirements.* There is no limitation on the minimum data rate of the camera. It may be operated at any rate below a maximum dictated by the threshold sensitivity. This then permits matching the generally low telemetry rates available from a rover without sensor or electronic storage, as required for other cameras.

(7) *Small size, low weight and power.* A facsimile camera simultaneously combines small physical volume, low weight, and low power consumption. Generally, at least an order of magnitude improvement in all of these parameters is realized compared to vidicon types.

(8) *Easily ruggedized.* The construction of the camera permits meeting shock loads to over 1000 g, thus meeting space flight launch and landing requirements with a large margin to spare.

## JPL Test Program

The JPL test program was conducted in the two phases of laboratory tests and field tests, with emphasis on the laboratory effort. The work was done as part of the JPL Advanced Lunar Studies Program.

The purpose of the laboratory tests was to quantitatively characterize the performance of the camera in areas where this had not previously been done, and to isolate the limiting aspects of performance as they are pertinent to a lunar rover. The field pictures were taken to be used for scientific site evaluation, using previously obtained film panoramas of the sites as a reference. Additional horizontal and vertical stereo pairs were taken to judge the value of facsimile stereo and the relative merits of the two techniques.

The approach to the laboratory tests was to divide the measurements into the two groups of photometric and resolution related parameters. Additionally, an indirect test of azimuthal geometric accuracy was run, which isolated static and dynamic errors. Other parameters, such as solar flare and saturation recovery, were estimated from the field pictures.

## Measurements and Summary of Results

An outline of the laboratory tests performed on the camera is given below.

(1) Photometric tests.

- (a) Photometric transfer response.
- (b) Preamplifier noise spectrum analysis at three light levels.
- (c) Relative spectral response.

(2) Horizontal resolution tests.

- (a) Modulation transfer function at a reference light level and at four lower levels.
- (b) Modulation transfer function (MTF) derived from constituent components of video frequency response, jitter MTF, and optical MTF.

A summary of the test results is given in Table 3. The projected requirements for a lunar rover camera are given in Table 4 (Reference 2).

## Stereo Results

Vertical and horizontal stereo pairs were taken near JPL, at a site in the Arroyo Seco, for the purpose of determining the value of stereo in aiding terrain assessment. Two horizontal camera spacings of 2.2 and 5.5 m were

**Table 3. Measured values of minifax parameters[a]**

| Parameter | Value |
|---|---|
| Light transfer independent linearity | ±6% from 34 to 12,300 $cd/m^2$ |
| Spectral response | 370 to 970 nm (est) at 5% response |
| Peak spectral response | 675 nm |
| Threshold sensitivity | 58 $cd/m^2$ at 7.8 mrad per line pair resolution at 10% modulation |
| Preamplifier random noise equivalent brightness | 21 $cd/m^2$ at unity S/N ratio |
| Horizontal resolution | 1.9 mrad per line pair at 5% response at 1300 $cd/m^2$ |
| System horizontal resolution | 12 mrad per line pair at 5% response at 1300 $cd/m^2$ |
| Repeatable geometric error | 3.3 mrad peak to peak (approx) |
| Random geometrical error | 0.23 mrad (rms approx) |
| Solar flare | 600 $cd/m^2$ (est) |
| Solar saturation recover | 150 picture elements (est) |

[a] All specifications on camera only, except "system horizontal resolution."

**Table 4. Lunar rover facsimile panorama requirements**

| Parameter | Value |
|---|---|
| Field of view | +0.26 rad, −0.52 rad vertical × $2\pi$ rad horizontal |
| Scan line resolution | 0.87 mrad |
| Slant range | 3 m to ∞ |
| Frame scan time | 60 s |
| Active scan lines | 900 |
| Video bandwidth | 55 kHz |
| Threshold sensitivity | 3.4 $cd/m^2$ |
| Intensity dynamic range | 2500:1 |
| Geometric accuracy | 1.74 mrad |
| Spectral coverage | Visual, monochromatic |
| Power | <8 W |
| Size | <170 $cm^3$ |
| Weight | <900 g |

used. Vertical spacings were 30 cm, 70 cm, and 1 m. The vertical stereo showed the expected benefit of radially uniform separation in the ground plane; however, interpretation of the 1-m pair by R. Choate (Reference 3) revealed the following unexpected dividend:

"Many terrain features of interest are large in two dimensions within the ground plane, but are small in the vertical dimension. Thus, when viewed from near ground plane elevations, such features appear as long linear elements. A common terrestrial example would be a terrace, which when viewed from near the ground is almost invisible, i.e., it appears as a horizontal thin line. Lunar examples are craters of all sizes and ejecta rims surrounding many of them. When viewed from near the ground, the only evidence indicating the presence of these two features would be the rim of ejecta which would look like a long low linear ridge.

"Therefore, from the reasoning above, it would be expected that vertical stereo pairs would enhance the presence of planar features by presenting views from different elevation angles to each eye. This was borne out by the pronounced appearance of terrace-like features in the vertical base Arroyo Seco pairs. This effect was lost in monocular pictures, and in horizontal stereo pairs. Also, the uniform, full-circle stereo of the vertical pair aided substantially in the identifications of rocks, holes, mounds, and other three-dimensional objects."

The conclusion, then, from the field stereo work is that facsimile stereo is a worthwhile adjunct to monocular facsimile imaging terrain assessment and that the preferred stereo mode is vertical.

## Performance Results

The results of the test program are given here in the form of performance graphs encompassing specific photometric and resolution characteristics of the Minifax system.

The first graph is that of the light transfer curve for the camera (Figure 4). The curve was taken with the scanner stopped. The camera was pointing at a Mariner flight TV, flat field, xenon light cannon. The intensity range of the light cannon was extended downwards from its 160-cd/m$^2$ lower limit with a log 1.1 neutral density filter taped over the imaged spot. The camera's electrical output was filtered with a 1-s time constant, low-pass filter and monitored with a digital volt meter.

The resulting intensity curve exhibits good linearity (unity gamma) over its central portion from 70–7000 cd/m$^2$. The beginning of saturation is seen above 7000 cd/m$^2$, and nonlinearities due to the silicon phototransistor detector dominate the low end of the response. The latter effect is a correctable design defect.

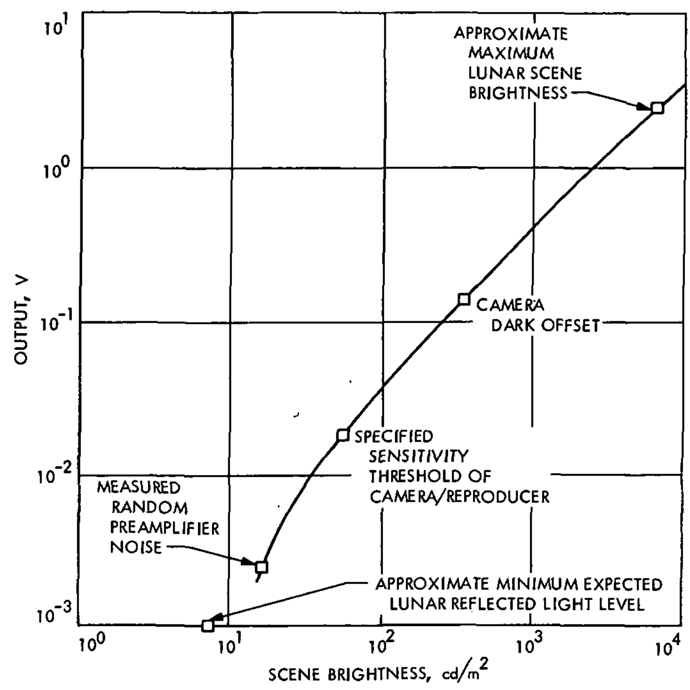


**Figure 4. Camera light transfer**

A spectrum analysis of the camera's preamplifier and detector noise is shown in Figure 5. The curves were taken with the scanner stopped, using a seven-cycle bandwidth analyzer. The curves are for zero, ½-scale, and full-scale light levels. Aspects of note are the lack of $1/f$ noise in the 100- to 1000-Hz range, the relatively flat nature of the noise, and the expected increase of noise as a function of light level.

The noise shown in Figure 5 is of interest in representing the limits of camera performance. Actual operating noise (with the scanner running) is much higher due to the pickup of interfering signals in the camera tested. Reduction of actual noise to approach the detector and preamplifier levels would be a requirement in a flight camera design. Low intensity photoelectron noise is not a limitation for the levels of interest which are above 3.4 $cd/m^2$.

Figure 6 covers the relative spectral response of the camera. The photopic response of the eye and the response of a Surveyor-type vidicon are shown for reference. The wide spectral response of the camera makes it possible to use narrow-band spectral filters to produce visual color, or to do near-IR studies, with a corresponding loss in sensitivity.

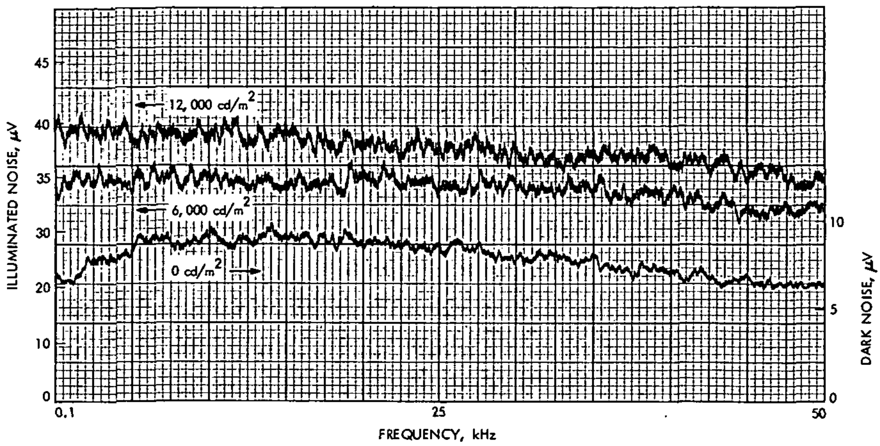


**Figure 5. Camera noise spectrum at three light levels**

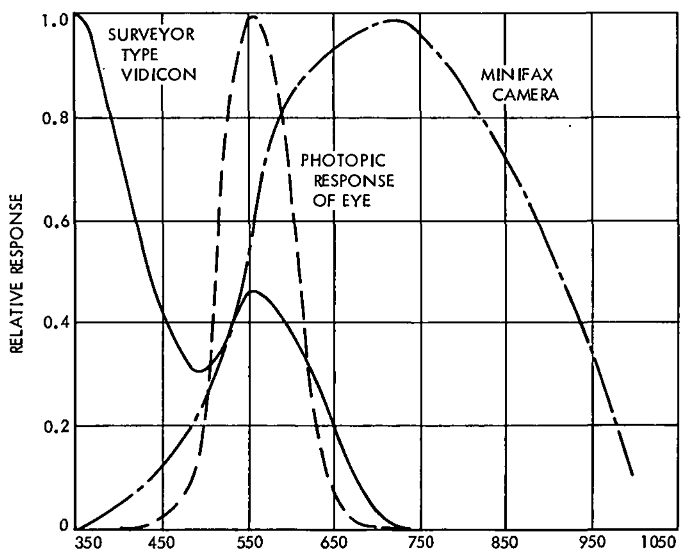


**Figure 6. Camera relative spectral response**

The next set of curves (Figure 7) covers camera and camera/reproducer resolution. They were made with the use of opaque high contrast U.S. Air Force and National Bureau of Standards bar charts. Resolution is presented in the form of modulation transfer function (MTF) curves which portray relative output (% modulation) as a function of spatial frequency, in units of cycles per radian. Here, a cycle is either one input optical square wave, or one input optical sine wave. Since the test charts are bar charts, creating input optical square waves, sine wave equivalent input curves were calculated from the square wave data. Sine wave curves are essential where individual parameters are convolved together, as is done in Figure 7d.

Figure 7a shows the measured camera-only resolution at a light level of 1300 $cd/m^2$. The measurements were made using single lines of video scanning a selected bar group of a test chart. The video was recorded on photographic film from an oscilloscope presentation. Illumination light levels were obtained from the camera itself operating as a non-scanning telephotometer.

The response of the camera at the current line rate of 285 cycles/rad (equivalent to 1.75 mrad scanning line spacing) is seen to be 39%. The limiting resolution at 5% response is 475 cycles/rad, indicating the good potential for improving resolution to the desired value specified in Table 4 of 570 cycles/rad.

The effect of reduced light levels on resolution is illustrated in Figure 7b. Measurements were made at levels down to 58 $cd/m^2$.

Figure 7c demonstrates the loss in system resolution caused by the degradation of the film reproducer. In fact, this degradation is sufficient to mask any changes in camera focus resulting from changes in the target-to-camera distance at 2.6, 3.9, and 4.8 m. Line-to-line sync jitter appeared to be the principal factor in reproducer resolution losses.

The camera/reproducer measurements were made from the reproducer film, not from paper print copies. The film images were enlarged by a factor of ~5 on high resolution, unity gamma film, and then relative response measurements were made with a recording microdensitometer. Modulation was calculated from the microdensitometer values, including approximate corrections for the enlarging lens and the scanning slit MTFs.

The final curves are those of Figure 7d for the components of camera resolution, with the overall camera response obtained by convoluting the components together. The top curve of the set is the MTF equivalency of the video channel frequency response. This measurement was made by exciting the stopped camera with a sine wave modulated light source generated by a light emitting diode.

The second curve is that for the MTF loss caused by jitter in the motion of the mirror scanning mechanism. An approximate rms value of jitter was derived from the line-to-line phase error of the scanning motor control signal over a single frame composed of 900 scanning lines. The jitter was assumed to be random, and was then translated into an effective MTF curve based on the techniques of M. D. Rosenaue, Jr.

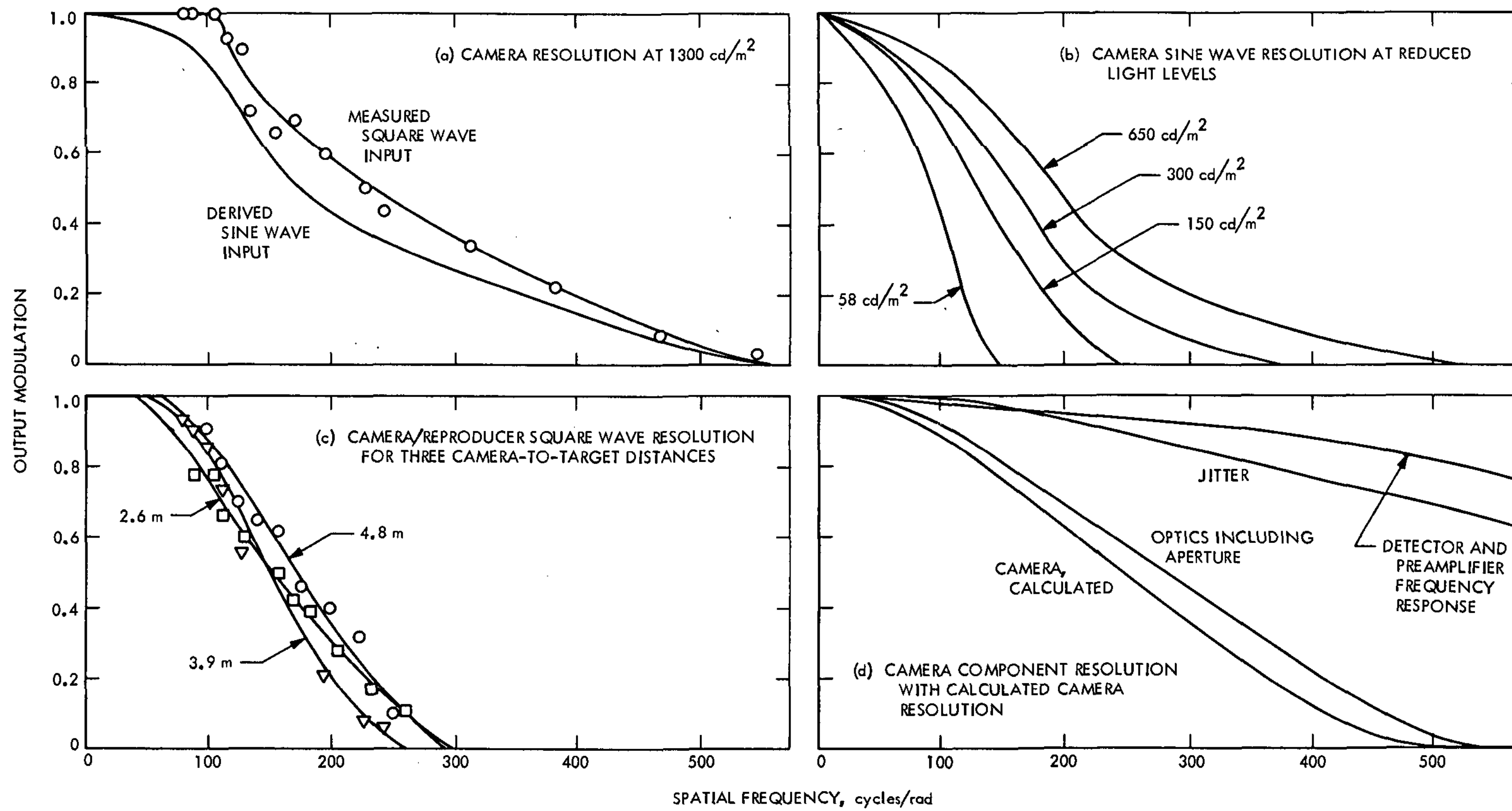


Figure 7. Minifax modulation transfer functions

The third curve is that of the camera's optical MTF, which was measured by driving the test targets at a constant slow rate past the beam of the non-scanning camera.

The components of camera MTF of frequency response, jitter, and optics were then multiplied together to obtain the camera resolution curve of Figure 7d. The results indicate a response about 40% better in the midspatial frequencies than the measured response of Figure 7a. The greater derived response is likely to be due to measurement errors (particularly jitter), and to the non-inclusion of potentially significant terms such as electrical motor sync signal noise. However, the derived curve does demonstrate that the principal determinant of resolution is the optics, and that the camera resolution could be significantly improved with an improvement in beam size and shape.

## Conclusions and Recommendations

The results of the JPL Minifax test program can be summarized as follows:

(1) Helical scanning facsimile cameras can meet lunar rover panoramic imaging requirements for scientific and navigation purposes.

(2) The present Minifax camera design can be modified to do the above job.

(3) Facsimile camera vertical base stereo is a valuable aid in terrain assessment from a rover.

The evaluation of the Minifax camera system revealed that the following feasible modifications would be required in the camera design in order to fully meet present lunar rover requirements:

(1) Reduce line spacing by 2:1.

(2) Improve optical focus to 0.88 mrad.

(3) Reduce azimuth sweep rate by 4:1.

(4) Improve coherent noise ratio by 20:1.

(5) Improve random noise ratio by 3:1.

(6) Improve solar saturation recovery to less than 20 picture elements.

(7) Improve low level light transfer linearity to within 6% to 3.4 cd/m$^2$.

(8) Change vertical field of view to 0.26 rad, -0.52 rad, relative to the horizon.

## References

1. Brereton, R. G., Burke, J. D., Coryell, R. B., and Jaffe, L. D., "Lunar Traverse Missions," in *JPL Quarterly Technical Review*, Vol. 1, No. 1, pp. 125–137. Jet Propulsion Laboratory, Pasadena, Calif., Apr. 1971.

2. Jaffe, L. D., Choate, R., Coryell, R. B., Eisenman, A., Hornbrook, G. K., and Strelitz, R. A., *Payload Requirements for Remotely Controlled Long Range Lunar Traverse Vehicles*, Document 760-62, Aug. 1971 (JPL internal document).

3. Choate, R., *The Value of Stereo Using the Minifax Camera*, July 1971 (JPL internal document).