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PHOTOGRAPHIC MEASUREMENTS OF ELECTRICAL DISCHARGES.(U)
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PHOTOGRAPHIC MEASUREMENTS OF ELECTRICAL DISCHARGES

Randall B. Sluder, Irving L. Kofsky

PhotoMetrics, Inc.
442 Marrett Rd., Lexington, MA 02173

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across an insulating gap separating two sections of the cylindrical body, and the plasma sheath surrounding it.



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FOREWORD

This report describes the design, fabrication, installation on a sounding rocket, and flight into the ionosphere of a split-view automatic camera for observing electric discharges induced by changes in the vehicle's electrical potential. Hollex, Inc. (Melrose, MA) designed the intervalometer electronics, and J. Costa the instrument housing. C. Miller (PhotoMetrics Instruments, Inc.) provided valuable assistance in optical design. The cooperation of other members of the rocket group, in particular W. Huber of Tri-Con, Inc. (Cambridge, MA), W. Lynch of AFGL/LCR, and the payload integration engineers of Wentworth Institute (Boston, MA), is gratefully acknowledged. The authors express their thanks to H.A. Cohen of AFGL/LKB for his continued encouragement and support.

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SECTION I

OVERVIEW OF THE MEASUREMENTS

INTRODUCTION

The objective of the program reported here was to measure by photographic photometry the surface brightness distribution of electrical discharges in the ionosphere-plasma surrounding a sounding rocket charged to positive and negative potentials. From the optical radiation emitted in these discharges information about current densities and potential distributions in the region near the vehicle can be derived. The photographic measurements are one component of an experiment by Air Force Cambridge Research Laboratories (LKB Branch) on spacecraft charging and its effects. Beams of kilovolts electrons and positive ions are fired from onboard accelerators; and potentials relative to the plasma, accelerator performance, and rocket housekeeping parameters are measured using probes of several types.

The rocket, Aerobee-F A31.603, was launched successfully to 250 km altitude from White Sands Missile Range, NM, on 21 Jan 1978. The camera system designed and fabricated for the optical measurements of discharge operated satisfactorily.

DOCUMENTATION

Complete design and engineering particulars of the camera system, along with operating and diagnostic procedures, are presented in the Equipment Information Report submitted in November 1977 to facilitate the system's integration into the rocket (Ref 1). A critical review of the considerations leading to the specific design, and of performance in ground tests of the realized instrument, was submitted in the Design Evaluation Report (Ref 2). Sections in these detailed reports will be referenced in the brief narrative description of the system which follows.

OPTICAL DESIGN

The means by which the photometric camera views the luminous volumes is illustrated in Fig 1. The ion and electron guns are mounted in the rocket's nose 90 inches from the camera's optic axis, to fire along the rocket's long axis (Fig 1b of Ref 2). Electrical discharges are expected across 0.15 inch gaps set flush in dielectrics in a two-inch circumferential insulator between two conducting sections of the rocket $8\frac{1}{2}$ inches aft (Fig 2), and (associated with return currents) in the plasma sheath surrounding the essentially-cylindrical body. The electrodes (dark areas in Fig's 2 and 3) are tungsten, and three inserted dielectric strips are teflon, nylon, and glass-epoxy.

To image these two regions with a single fixed camera, the field of view is split by a pair of plane mirrors outboard from the rocket as shown in Fig 1, which is erected in flight before the guns and camera are activated (when the rocket reaches 120 km). Fig 4 shows the mirror assembly with boom in its extended position, and Fig's 2 and 3 the complete imaging system in place on the rocket. The camera axis points to the line of intersection of the two mirrors, so that the $8.6^\circ \times 13.8^\circ$ field of its 50 mm focal length lens (on 16 mm double-perforated film) is split into two $8.6^\circ \times 6.9^\circ$ fields.

A major consideration in the design of the optical system was achieving usefully-high depth of field at the high lens aperture ratio needed for imaging at the low expected radiance levels of the discharges (pp 3-7 of Ref 2). The maximum outboard distance for a simple linearly-extended boom, which is set by the rocket's diameter, is 6 inches from the rocket skin. (The engineering cost of a more complex, articulated erection system with sufficient reliability was determined to be beyond the program's resources.) This constraint makes the range to the insulator about

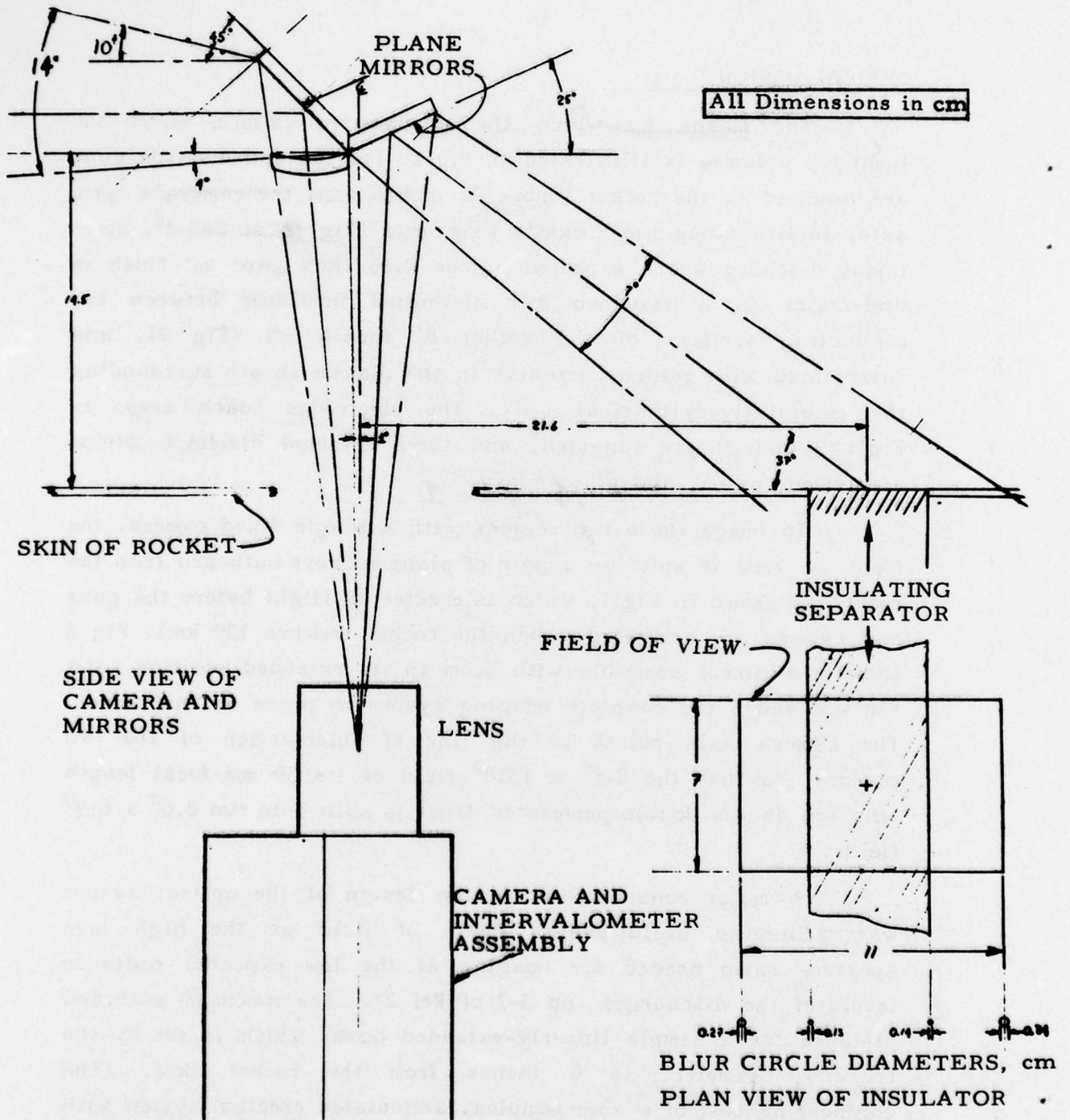


Figure 1. Diagram, to scale, of optical components and camera position relative to the separator ring. The inset at lower right shows the field-of-view on the rocket skin and the blur circles near the insulator. The edge of the field at the insulator is $3\frac{1}{2}$ mm below the centerline.

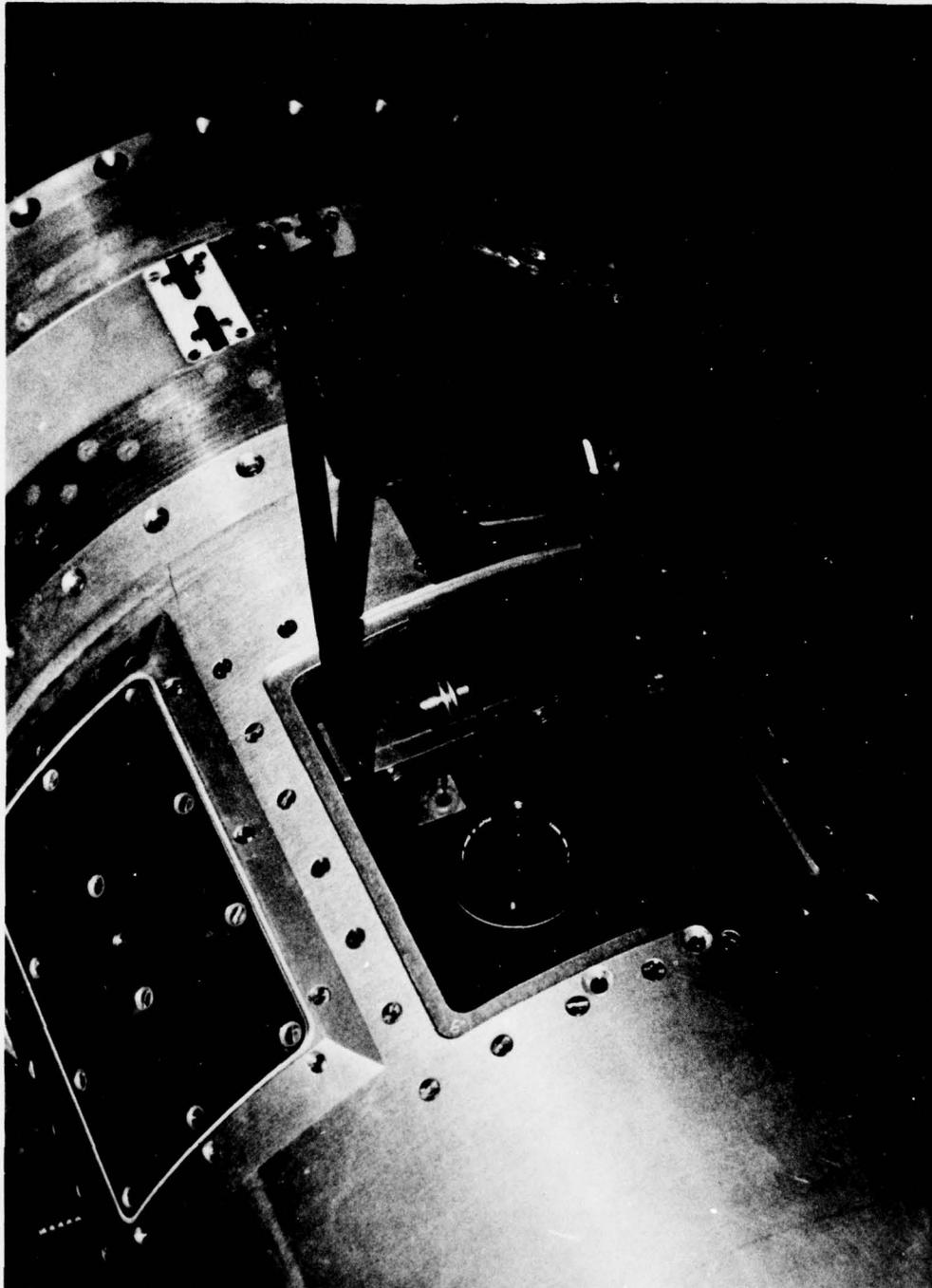


Figure 2. Camera lens viewing the split mirror and relay lens assembly in erected position. The insulating separator is in the background.

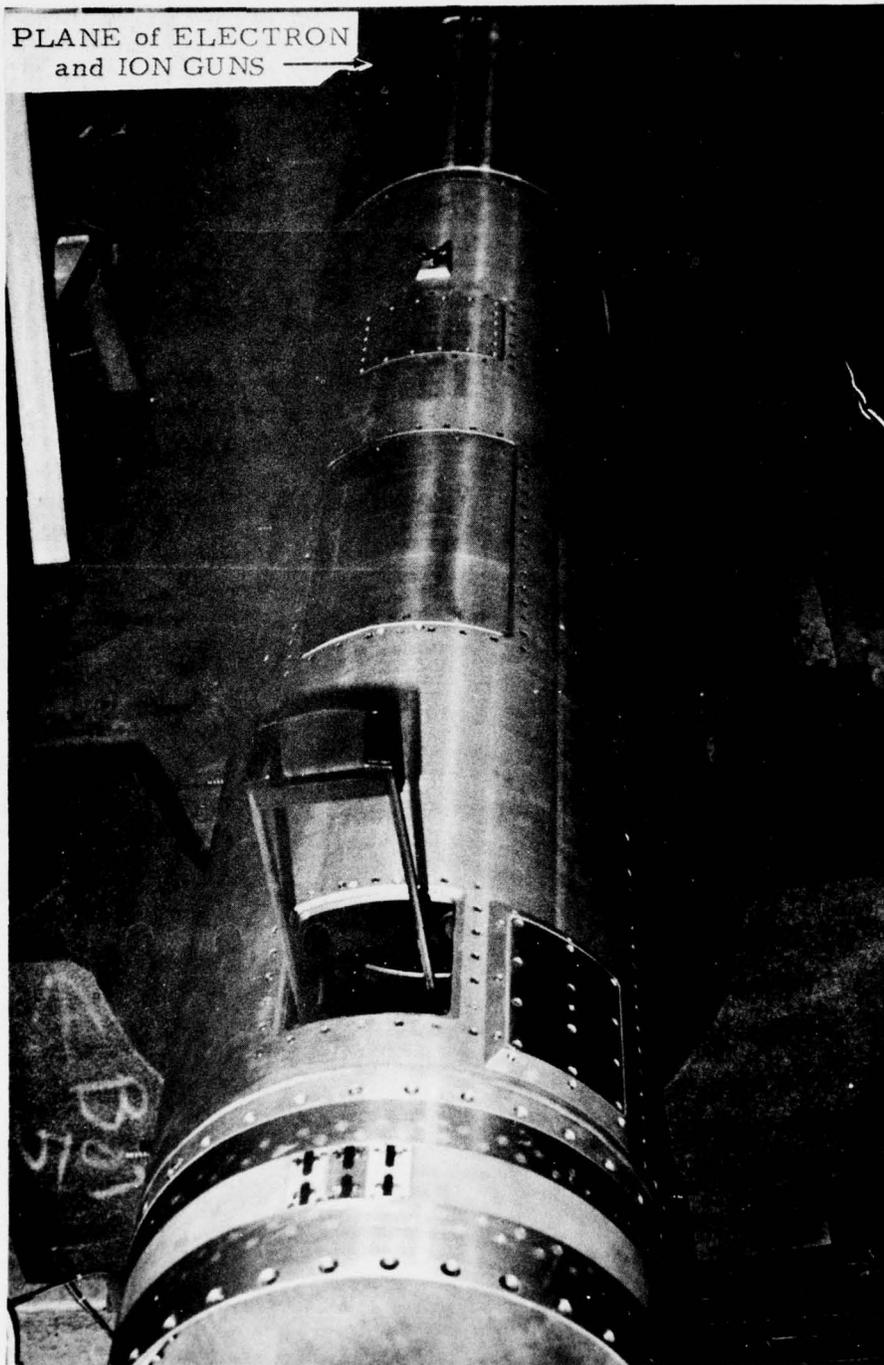


Figure 3. Position of the camera with respect to the rocket body and the insulating separator with its three dielectric strips and electrode pairs (foreground).



Figure 4. View of the camera with its split-field mirror in extended, operating position.

50 cm. Since the angular resolution of the high-speed film needed for imaging weak sources is about 1/700 radians (70 μ m "resolution" for a low contrast target, projected through a lens of 50 mm focal length), the blur circle diameter at the insulator with a low-aperture lens would be 0.07 cm. Selecting an aperture ratio of f/1.4 increases the blur due to the lens at the insulator's edge on the centerline to about twice this value, as shown at the lower right of Fig 1. The total image smear at these points becomes $\sqrt{0.14^2 + 0.07^2} = 0.15$ cm, and is ≤ 0.20 cm at the corners of the insulator. Thus discharges across the gap would be imaged with spatial resolution not less than 2 mm (the photographic half-image has about 40 resolution elements across its field).

To achieve a sufficiently wide coverage of the plasma sheath - 55 cm in the plane defined by the camera and rocket axes at the plane of the electron and ion guns -, the angular field in the forward-pointing sector is increased to 16 $^\circ$ x 14 $^\circ$ by a -33 cm focal length diverging relay lens. Effective demagnification in this half of the image is $\sim 2x$. This lens replaces a spherical convex mirror that was originally intended to increase the field, which was found to produce images with unacceptably-high primary astigmatism when viewed at the necessary 45 $^\circ$ from its axis. Focus in this half of the film field is placed near the rocket's nose, and the image blur over the plasma within 1/2 meter of the plane perpendicular to the rocket is calculated to be $\leq 1/2$ cm. Results of tests of actual image quality are in Section II.

The boom for the mirror assembly, which is driven outward by a constant-force motor, was designed by Wentworth Institute staff under AFGL direction.

CAMERA, INTERVALOMETER, AND FRAME IDENTIFIER

It was judged that the known rocket-reliability and saving in weight of 16 mm-format cine cameras designed principally for

military applications overweighed the limitation of number of lines resolvable across the 7.6 x 12 mm image field (7.6 x 2 mm of frame, at one edge, was used for identification). The unit specified is the 1VN manufactured by Photo-Sonics, Inc., Burbank, CA. This camera, diagrammed with its film magazine and intervalometer-display box in Fig 5 and shown in the photograph in Fig 4, has further desirable features: relative ease of integration with the rocket, low electrical power consumption, pin-registration to ensure reproducibility of geometry, automatic iris control if desired, and - principally - ability to perform to military standards of vibration, shock, and temperature.

We modified the camera for open-shutter operation under control of an intervalometer, which is in turn controlled by the programmer for the rocket's electron and ion accelerators (Ref 1). A 65-ft film magazine (2600 frames, giving capability of 4 exposures/sec in a 10 min rocket data period, for example) was used. Double-perforated Eastman Kodak Specification 430 film was spooled onto Kodak No. 6 magazine cores (to achieve Eastman Kodak Specification 560, otherwise available only by purchasing lots of 150 rolls of a single emulsion). Eastman Kodak 2475 film, the most sensitive commercially available in 16 mm width, was used. Minimum detectable fluence at the film plane at visible wavelengths is 3×10^{-3} ergs/cm², which with the f/1.4 lens (refer to p 10 of Ref 2) requires a scene radiance of 7×10^{-3} ergs/cm²-ster in a 1-sec-duration exposure.

A Canon lens with 50 mm focal length provides the field of view ($8.6^\circ \times \frac{1}{2} 13.8^\circ$) appropriate for imaging a segment of insulators and their tungsten electrodes. It in turn determines the focal length of the aforementioned negative lens needed to widen the field to encompass the expected discharges in the plasma sheath surrounding the rocket body. The electrical discharge across the insulating gap in near-vacuum (refer to Ref 3 for a discussion and

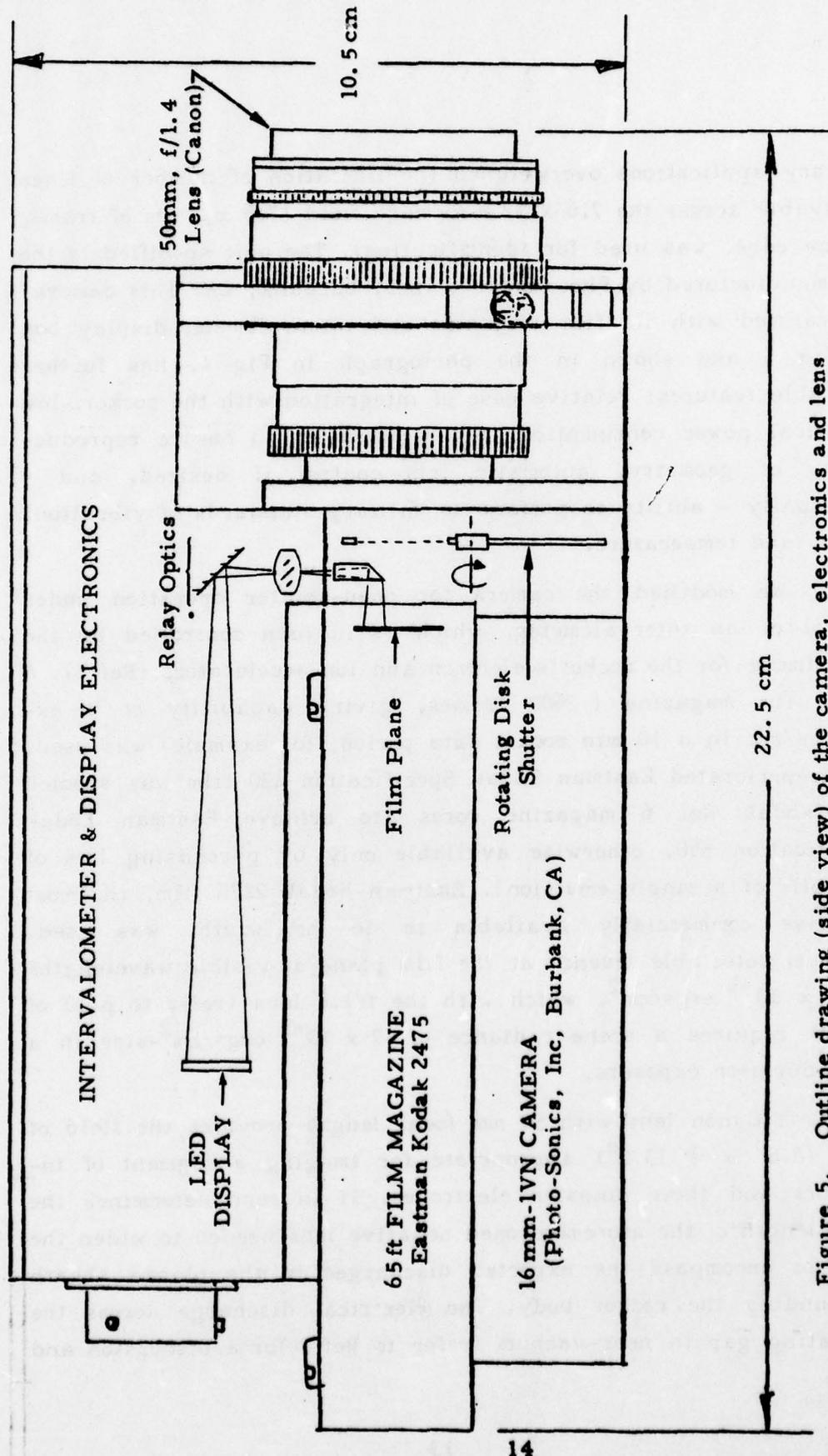


Figure 5. Outline drawing (side view) of the camera, electronics and lens assembly. The unit is attached to the rocket frame by mounting holes in the camera body shown in Fig 2 of Ref 2. Total weight of the assembly with film is 2.7 kg. See also Fig's 1, 2, and 3 of Ref 1.

further references on the theory of such breakdowns) represents a plane emitting source; discharges associated with the vehicle's potential with respect to the ionospheric plasma, on the other hand, would be expected to be volume sources, whose photographic images are two-dimensional projections of the 3-D emission.

The rocket's electron and ion accelerators operate cyclically in twelve voltage-current-gun selection modes. A six decimal digit LED display on the film records which mode is in use and how many complete cycles have taken place, in the simple code described on p 8 of Ref 1. This frame identification (pp 9-11 of Ref 1) is imaged between sprocket holes.

An intervalometer (pp 13-27 of Ref 1) controls the display and the film advance, and places a pulse checking on its performance on one of the rocket's housekeeping telemetry channels. The onboard programmer for the accelerators - the master sequencing device for the rocket experiment - inputs into this intervalometer the mode and cycle information in binary coded format on 12 parallel data lines. The intervalometer in turn translates these data into the digital format displayed on the film; creates a 28 VDC, 15 ± 5 msec pulse that energizes the camera's run relay to advance the film at each mode change; and outputs the pulse acknowledging that it has acted on the input signal.

As noted, the shutter remains open during the full period in which an accelerator is operated in one of the twelve (total) modes. The time required for the film to advance, during which the shutter is closed, is 30 millisecc. Typical exposure times are 1/2 sec, so that about 6% of the mode length is missed by the camera.

An overview of the camera is presented in Table 1.

Table 1. Camera System Parameters

Lens	50 mm, f/1.4, Broadband-coated with -330 mm relay lens over $\frac{1}{2}$ field
Film	EK 2475, Developed to $\gamma = 1.3$, 16 mm double-perforated on EK No. 6 spool
Camera Body	1VN, Photo-Sonics, Inc. (Burbank, CA), pin-registered, 65 ft magazine
Shutter	Rotating sector disk, normally open
Mode Cycle Code	6 decimal digit imaged between sprocket holes. Refer to Ref 1
Intervalometer	Under control of rocket master programmer. Refer to Ref 1 for operation

SECTION II
FIELD PROGRAM

INTRODUCTION

The field program was conducted at White Sands Missile Range, New Mexico, between 3 January and 17 January 1978. The camera, its electronics package, mirror mount and erecting mechanism were assembled onto rocket A31.603 during this payload build-up period. We performed tests of the camera and optical system to evaluate the imaging performance of the split field-of-view, and of its intervalometer control to check the pulsed operation of the camera and frame identifier display in conjunction with the onboard programmer. Although similar tests were performed during fabrication in the laboratory, this series provided performance evaluations with the rocket in its precise flight configuration.

The image of the mode/cycle code was recorded on EK2475 film while the onboard programmer cycled through the twelve gun modes, to determine that the displayed cycle number and mode were correlated with the programmer output, and that the image was correctly exposed. The rocket's mechanical timers were operated to ascertain that the door ejection mechanism, which allows the mirrors to extend, was triggered on time, and that as planned, the camera was started at 95 sec after launch.

For optical tests of the forward-looking field, we fabricated a simple target, consisting of a grid for field-of-view measurements, and sets of bars to evaluate spatial resolution. This target was held adjacent to the skin in a plane perpendicular to the rocket's axis, and photographed through the lens-and-mirror field splitter, extended as it is in flight (Fig 3). Test images at camera centerline-to-target distances of 3 ft to 7½ ft (near the plane of the electron and ion guns) are reproduced in Figure 6.

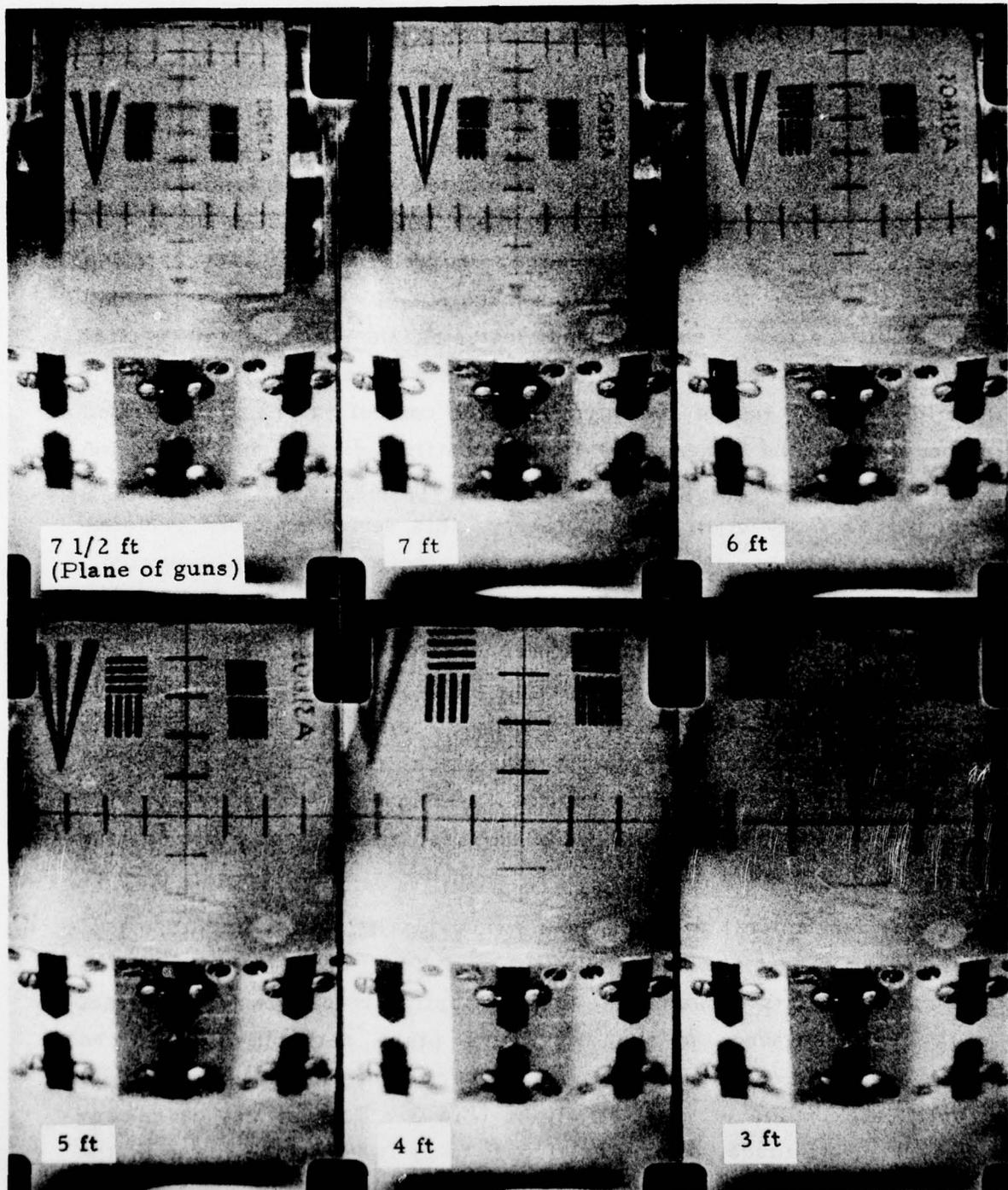


Figure 6. Field-of-view and resolution checks for the forward pointing half-field, at distances of 3 to $7\frac{1}{2}$ ft from the camera centerline along the rocket's axis. The frame identifying code is displayed between the lower sprocket holes.

By measurement of the image of the target's 2 in grid spacing, we determined the field-of-view to be 16° horizontally and 14° vertically. The lower apex of the small triangle near the frame's center is resting on the rocket skin. The hazy appearance of the image in this region is due to overlap of the two fields-of-view, which results from the proximity of the field-splitting mirror to the f/1.4 primary lens with its shallow depth-of-focus. This overlap could be reduced by decreasing the aperture ratio at the penalty of raising the minimum detectable scene brightness.

The two pairs of bar targets (to the left and right of the frame center) have spatial frequencies of 4 and 8 lines/in, which, at $7\frac{1}{2}$ ft distance, correspond to 13 and 26 lines/mm in the image plane of the camera. There is some defocusing in the corners of the field, and a moderate amount of barrel (negative) distortion - note that the horizontal grid lines are bowed outward - both of which are due to the addition of the field widening lens near the mirror (Fig 1).

GROUND-BASED MEASUREMENTS

It was planned to use the telescopes of the Lincoln Laboratory-operated Ground-based Electro-Optical Deep Space Surveillance (GEODSS) site (Ref 4) to follow the rocket during its flight. The function of this observation was to provide a measure of the integrated brightness of spatially unresolved electrical discharges within the volume of the plasma sheath surrounding the rocket body. We co-ordinated the use of the telescopes with launch operations, and arranged communications to provide updated trajectory information during flight for real time pointing corrections. However, since clear weather conditions at the GEODSS site

was not a primary launch criterion, overcast sky on 21 Jan prevented these ground-based measurements from being performed.

GEODSS is located within WSMR at Stallion site, 160 km due North of the launch complex. The rocket flight azimuth was very nearly 0° , thus presenting favorable geometry for tracking since apparent azimuth look-angle changes are small during flight and tracking motions are primarily in elevation. The main instrument is a 31 in, f/5 Cassegrain telescope with 1° fov, and the tracking telescope is a 14 in f/1.7 Schmidt with 7° fov. Both instruments are on a single mount, guided either manually by an operator or under computer control. Two low light level vidicon cameras located in the focal planes provide dark-sky limiting equivalent stellar magnitudes of 16.5 for the 31 in, and 14 for the 14 in unit. Television monitors on the control console provide a real time display of the images, which are also recorded on magnetic tape. A procedure was established in which the telescopes were pointed at the expected rocket elevation and azimuth of gun turn-on near 130 km, and if the rocket were not acquired visually on the video monitors, they would be stepped ahead of the nominal trajectory in a series of programmed stages.

SECTION III

PRELIMINARY DATA REVIEW

INTRODUCTION

The photographic camera system exposed a total of 1109 data frames during combined ascent and descent portions of the rocket's flight. The first frame at 02.0200 was fogged as expected by exposure to ambient light, as the shutter remained open until 95 sec after rocket launch. The second frame, 03.0200, and all succeeding frames are free of fog and suitable for later detailed analysis.

We present here the film processing procedures, a preliminary review of the principal features of the images recorded, and tentative suggestions for the origins of these images.

FILM PROCESSING

Before developing the actual flight film, we processed test rolls of 2475 emission on which calibration steps had been placed to ascertain that the contrast was near 1.3 (a value chosen as a compromise between dynamic range and the detectivity of small density changes), and that development was uniform over the entire length of film. A sufficient quantity of the same emulsion batch of 2475 film had been procured to allow all preprocessing tests to be carried out on film identical to that used for the flight. We chose to have the film developed by an outside laboratory in a continuous processing machine, rather than manually on conventional spiral reel equipment in our own laboratory. Continuous processing ensures the necessary uniformity of development, and in addition, does not limit the length which can be handled at one time, as does the reel size in manual processing. The 35 ft length of the combined data, calibration and leader sections of the film was developed as a single piece by Cine Service Laboratories, Inc., Watertown, MA.

The calibration exposures which we placed on the film consisted of the usual series of 21 steps, exposed through a step tablet with density difference 0.15 per step. The characteristic curve of diffuse density vs the relative log of exposure (D-log E) is shown in Figure 7. The gamma, or mean slope, is 1.26 in the straightline portion of the curve between relative log E values of 0.75 and 2.1. We used a 1/2 sec exposure duration to simulate the nominal mode length of the electron and ion accelerators in flight operation.

PHOTOGRAPHIC RESULTS

View Toward Insulator

At launch, the 12 day old moon was near 27° elevation, and $\sim 140^{\circ}$ azimuth west of the rocket's planned due north trajectory. As the rocket rotated in flight the moon intermittently illuminated the insulating ring and nearby skin. The moon's presence was in part beneficial, however, in that it provided images of the diffusely reflecting dielectric substrates in which the electrodes are imbedded, and thus confirmed that the mirror-and-lens assembly were extended properly. (Compare Fig's 6 and 8.) Images also were recorded of the semi-specular lunar glint from the skin, and from the heads of the metallic screws in the insulator (Figure 8). The rocket's spin is apparent in successive frames as a progressive motion of the lunar glint image across the field-of-view. Rounded heads on 12 of the 24 screws which attach the electrodes to the rocket, produced one or more points of glint in 4/5 of the data frames.

Preliminary visual inspection of the film thus far gives no evidence of glow or discrete spark discharges, or in particular, of electric discharge across the set of three electrodes imbedded in the insulator section.

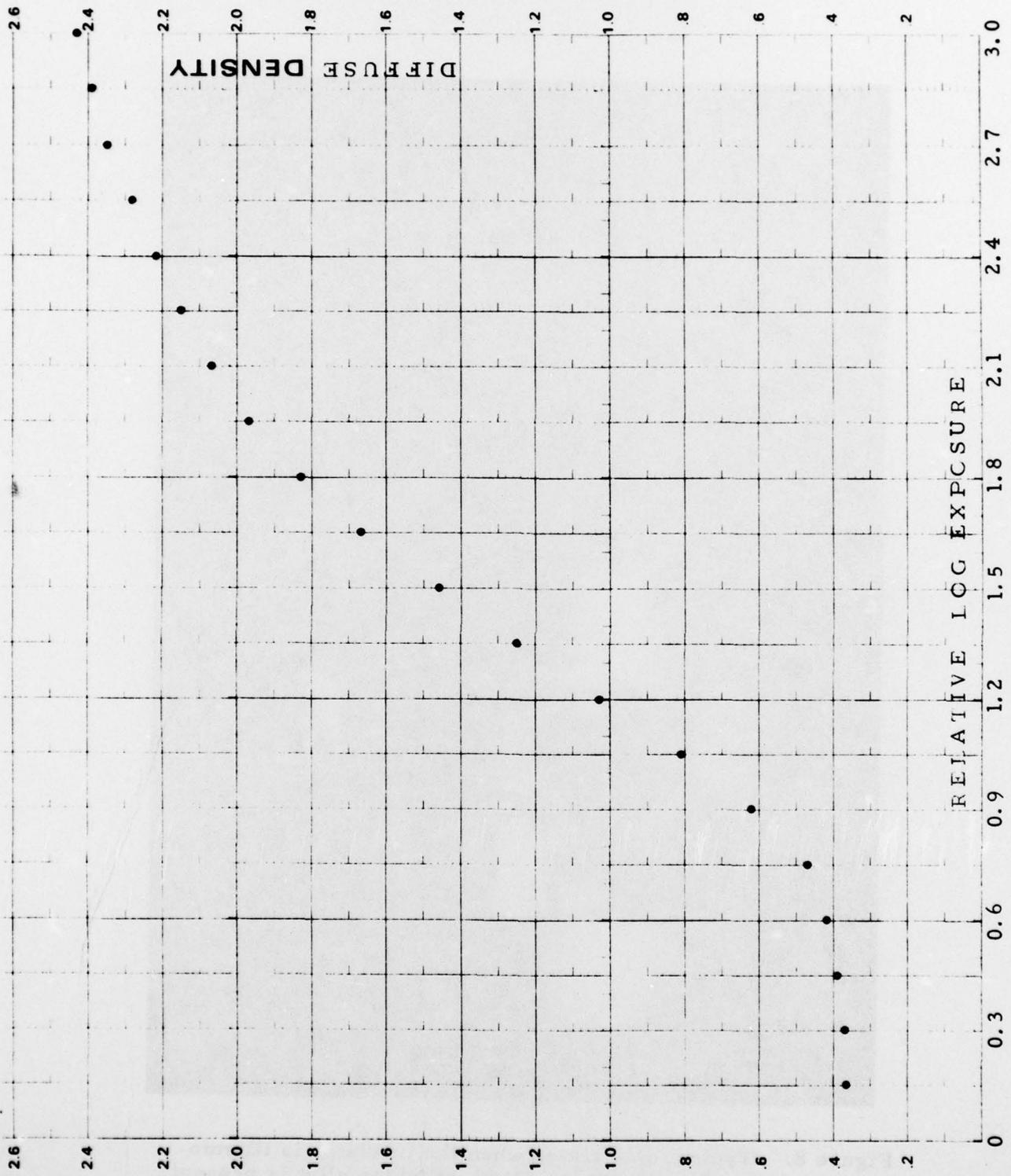


Figure 7. H&D curve of EK2475 used in flight of A31.603. Tungsten illumination was used at an exposure time of 1/2 sec.

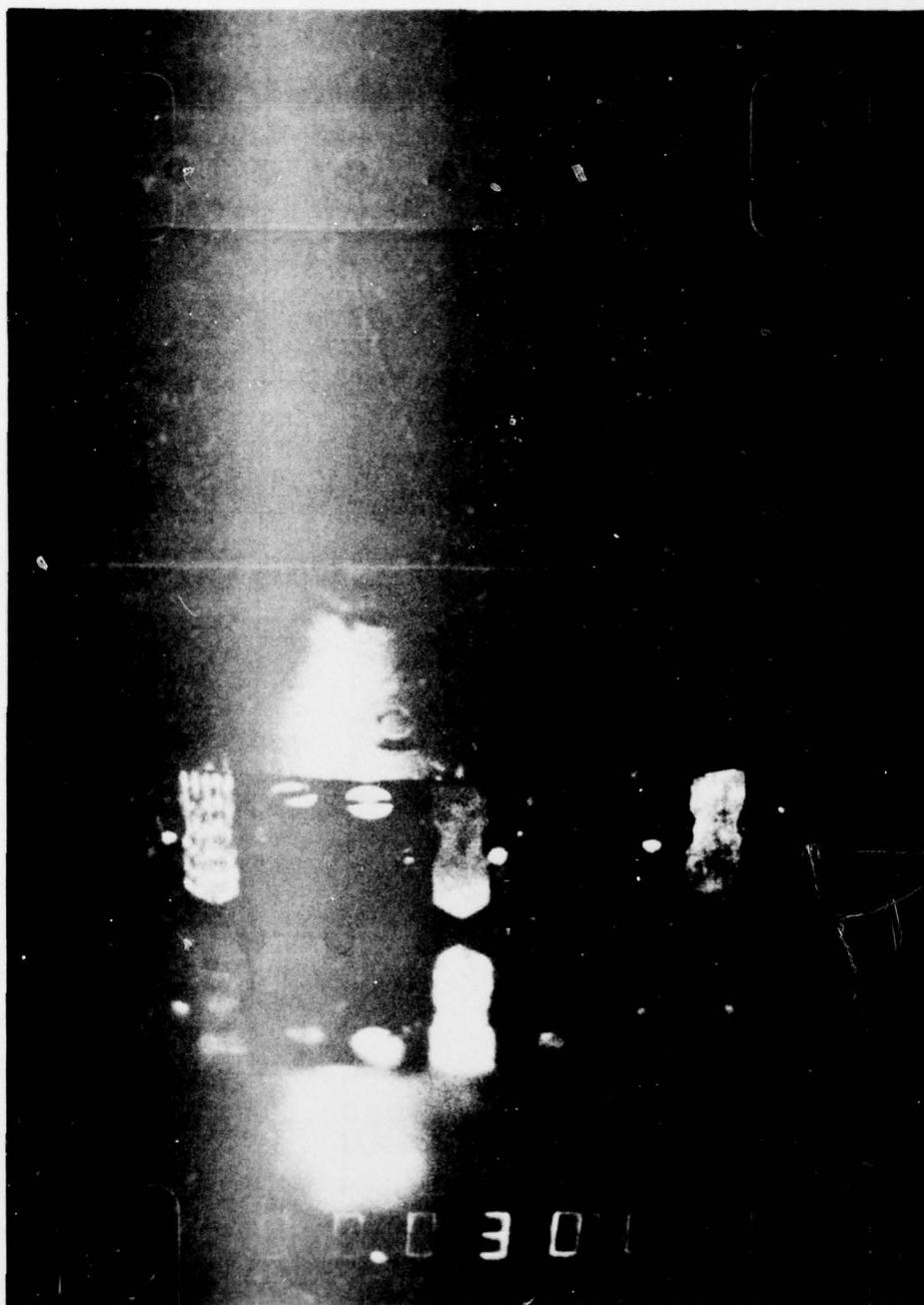


Figure 8. Typical data frame when the insulator is illuminated by the moon. Semi-specular glint is present on the electrodes, screw heads and nearby skin. The two vertical lines at left are cracks in the film emulsion.

Field-of-view Along Rocket Axis

Regions with density-above-chemical-fog were recorded in this half-field, and appear as two types of images. First, there are diffuse regions with little fine structure, sometimes appearing over all the half-field, with maximum density to the left of the upper right sprocket hole (as viewed with the mode/cycle code at bottom). This effect can be seen clearly in Fig 9, and is present faintly in Fig 8. The shape of these regions is nearly uniform from frame to frame and their occurrence frequently is correlated with semi-specular glints in the other half-field. We tentatively attribute this image to scattering of out-of-field lunar illumination by not-completely blackened internal parts of the 1VN camera's film chamber. Second, well defined, near circular images occur infrequently, and generally do not correlate with either overall increases in density of this half-field or with the specular glints in the other. One such image has the shape of the field-widening lens - circular with two missing chords. We suggest off-axis lunar illumination is again the source of these images, and that possibly they are due to internal reflection within the primary f/1.4 lens.

Other Features

Microscopically narrow fractures of the film emulsion, which appear as extremely fine lines running between pairs of sprocket holes or from edge-to-edge of the film, occur throughout the section of film exposed during flight. Two of these can be seen at the left of Fig 8. Since they are not present in portions of the film not advanced in flight, we suggest that the emulsion may have become brittle by drying in the near vacuum, and then cracked by the mechanical stress imposed during film transport.

Another recurring feature has a comet-like appearance - that is, it consists of a well-defined nucleus and a diffuse tail -

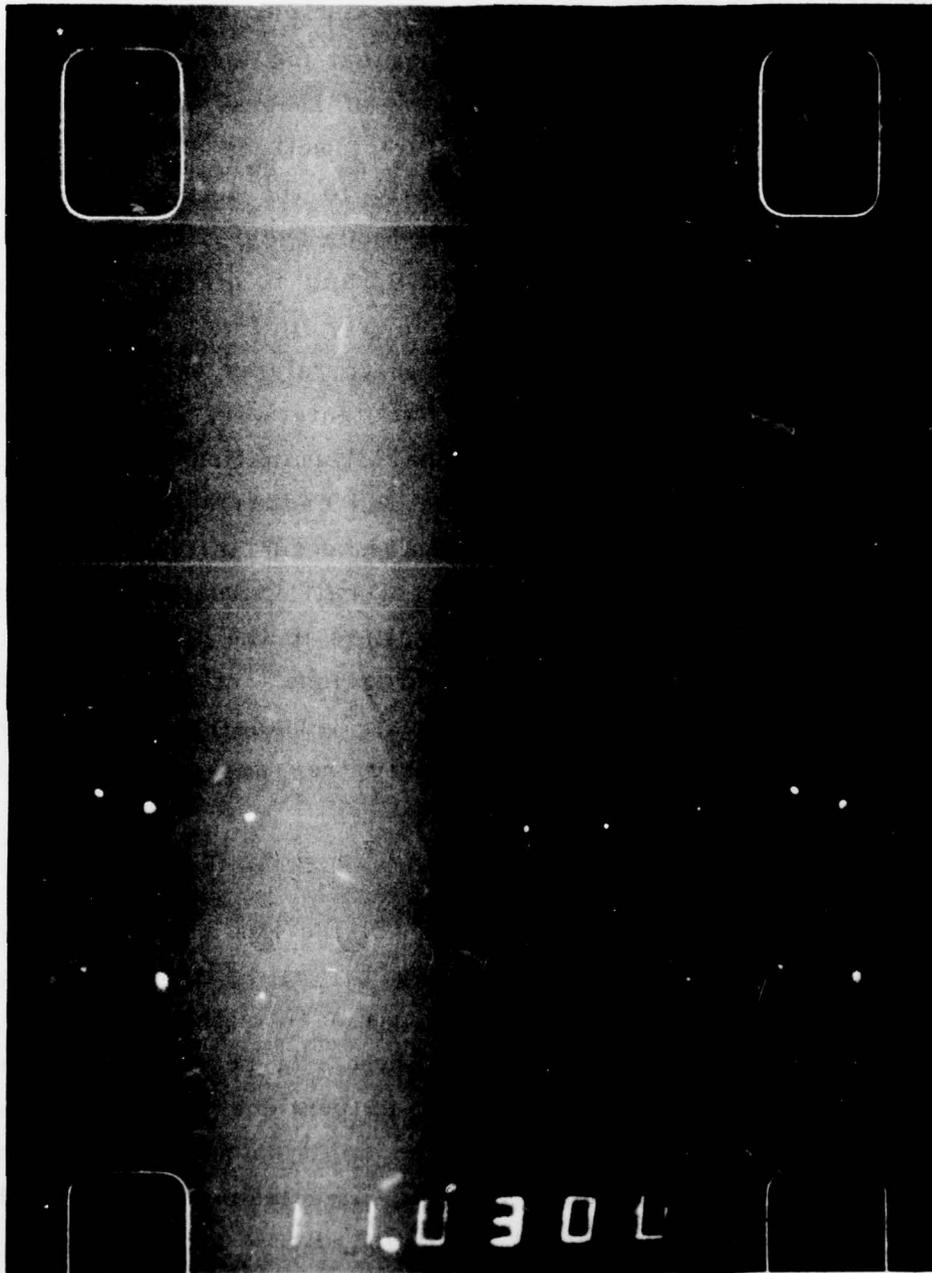


Figure 9. Typical data frame showing diffuse region in upper-half-frame, and glint from electrode attachment screws (below).

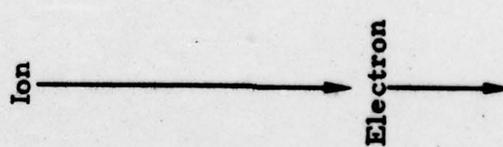
with dimensions on the order of 1 mm x 1/5 mm. However, these features are found outside as well as within the imaging areas, and in sections of the film not exposed or advanced in flight. Thus, these comet-shaped objects probably are unrelated to the experiment. Possible sources are chemical artefacts produced during development, and static discharges which occurred during film handling.

Frame Identifier Code

The digital code, which identifies each frame by mode number and cycle, was correctly displayed and sharply imaged onto each frame (Fig's 8 and 9). During certain periods of the flight noise induced erratic signals from the onboard programmer, and at such times one or more digits (usually the least significant cycle number digit) of the code are missing. However, it is possible to identify each frame unambiguously by correlating the displayed code with the other telemetry channels which indicate programmer output and accelerator operating conditions. Planned electron and ion gun parameters and their corresponding mode numbers are shown in Table 2.

Table 2. Summary of Accelerator Parameters

<u>Mode</u>	<u>Accelerator</u>	<u>Current, ma</u>	<u>Voltage, kV</u>	<u>Neutralizer</u>	<u>Neutralizer bias, V</u>
00	Ion	1	1	off	-10
01		1	1	off	-10
02		2	2	off	-10
03		2	2	on	-10
04		2	2	on	-10
05		2	2	on	-1 kV
10		2	1	off	-10
11		0	0	off	-10
12		1	1½	off	-10
13		13	1½	off	-10
14		35	3	off	-10
15		0	0	off	-10



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