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DATA ANALYSIS OF FILM FROM AFGL ROCKET A31.603.(U)
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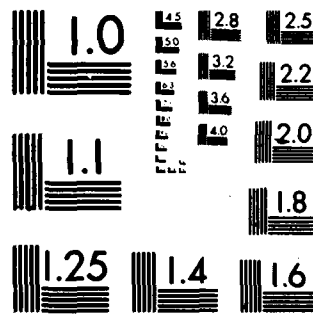
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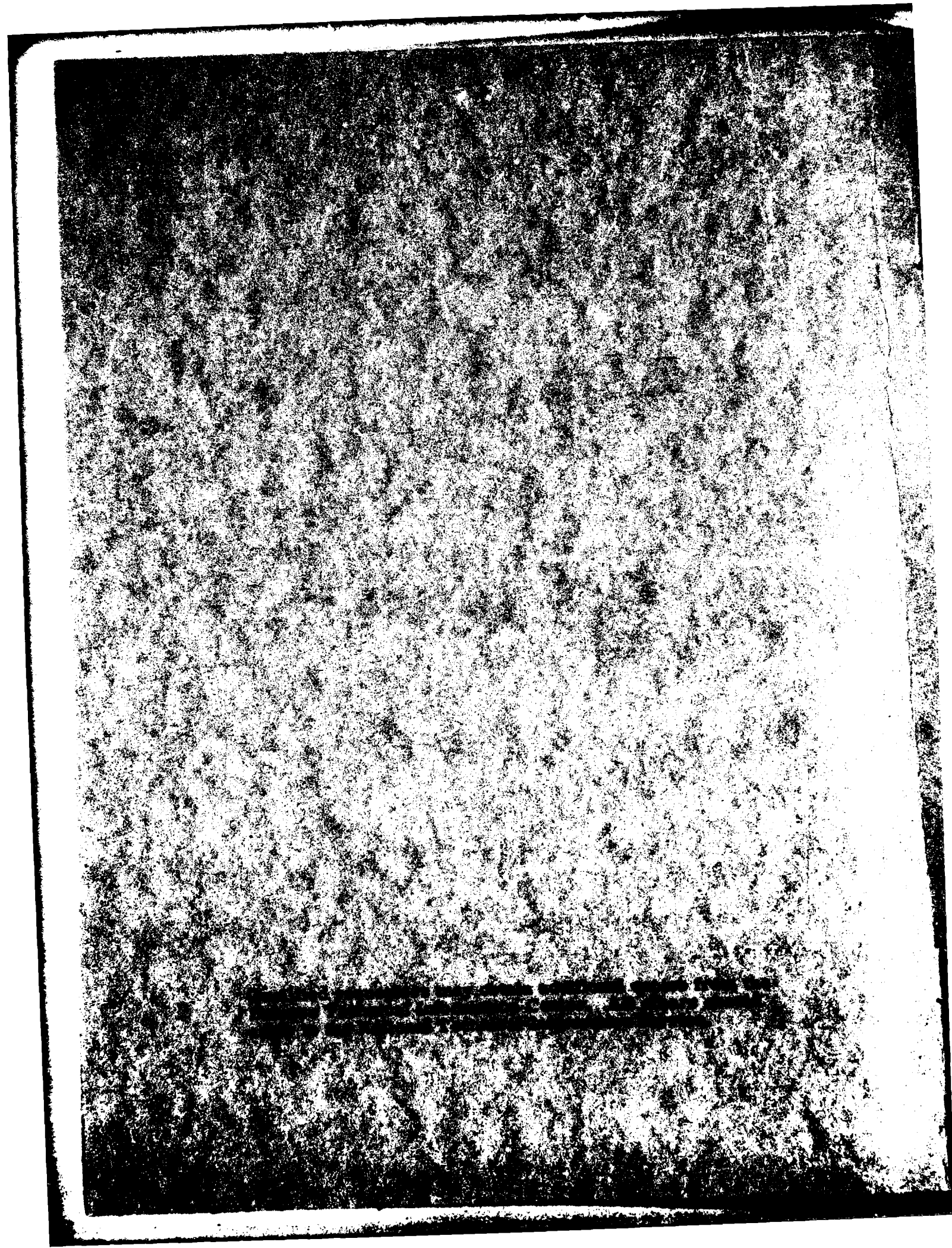
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20. Abstract (continued)

plasma surrounding the vehicle and the vehicle surface. Upper limits determined for the radiance and volume emission rate of glows excited near the rocket were compared with theoretical predictions.

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SECTION I

OVERVIEW OF THE DATA ANALYSIS

This report describes analysis of the film data from a split field automatic 16 mm camera system flown on AFGL rocket A31.603 from white Sands Missile Range NM on 21 Jan 1978. The objective of the camera was to measure by photographic photometry the surface brightness distribution of luminous electrical discharges in the plasma surrounding the rocket charged with respect to the ambient ionospheric plasma, and also to record arcing between parts of the rocket payload at different potentials. The work was part of an experiment by the Air Force Geophysics Laboratories (LKB Branch) on spacecraft charging at F-region altitudes. The rocket experiment and camera system are described in Ref 1.

Positive and negative charging with respect to the surrounding plasma was achieved by emitting programmed beams of ~ 2 keV Xe^+ ions and electrons from the rocket (refer to Table 2 of Ref 1 for beam currents and accelerating voltages). The camera functioned somewhat differently from planned, supposedly due to electronic interference by high voltage pulses from the ion accelerator. Its time sequencing was not immediately obvious from the preliminary examination of the film. Hence some further effort was needed to coordinate the film data with the telemetered data on beam currents and rocket potential.

The preliminary examination of the film (Section III of Ref 1) showed no readily-detectable evidence of any luminosity in either segment of the camera's field of view beyond scattered moonlight in the forward direction and reflections of moonlight from the payload surface. It was necessary to determine the actual timing of the camera before attempting to relate in more detail the film density distribution to vehicle potential or accelerator operation. We therefore have carefully re-examined the film and the data on camera

pulsing (also part of the telemetry record), and identified each frame unambiguously. Developed densities on selected frames were then measured by scanning microdensitometry to search for evidence of beam plasma discharge in the payload sheath and particle excited fluorescence on the payload skin. Upper limits are set for intensities of radiation excited by these mechanisms, and supporting calculations were made of theoretically expected volume emission rates in the sheath for various amounts and scenarios of xenon ions, ambient ions and/or electrons traveling through the sheath to the payload surface.

In addition timing of lunar reflections from the payload skin has been used to infer the vehicle aspect during flight. This was required to reduce ambiguities in aspect information provided by the onboard magnetometers.

SECTION II

FILM ANALYSIS

PREVIOUS DOCUMENTATION

A preliminary review of the photographic data is presented in Ref 1. Complete design and engineering particulars of the camera system, including operating and diagnostic procedures, are given in the Equipment Information Report submitted in Nov 1977 (Ref 2). Some description of the camera control procedure and method for labeling the frames is included in Ref 3. 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 4).

FILM FRAME IDENTIFICATION

Synchronization between the camera and the ion and electron accelerators was determined by comparing the film, frame by frame, with printed lists of telemetry records of the accelerator operation. Coded numbers representing the mode of operation of the ion and electron accelerator and the program cycle had been placed on the film during the flight. (These numbers were intended to provide a unique identification for every frame but, as neither the camera or the accelerators themselves functioned exactly as planned, this was not the case.) The MODE numbers were compared with a listing of experimental parameters (not included in this report) in which the accelerator mode had been derived from analog chart of the on-board programmer voltage staircase (telemetry mainframe word 15).

The CYCLE number encoded on the film was incorrectly described in Ref 2, page 16. Its behavior tended to follow the description in Ref 3 (p 57 ff), but was so erratic that it could not be reliably used as an aid to frame identification. However every frame on the film could be readily identified by matching the coded MODE

numbers with the accelerator modes (as shown on the list), bringing the program sequence on the two records into synchronism. The possibility of a systematic error in coding of numbers on the film, which could have led to displacement of the film record with respect to other records, was removed by the occurrence of an occasional very short exposure when the electrodes in the camera's field of view were illuminated by the moon. The resulting low image density identified the short film exposure, which in each case agreed with the listing. The film frame list is given in Appendix A with results of film density measurements described later.

CAMERA MALFUNCTION

The camera operated as programmed for the first 93 sec after camera turn-on at 94 sec after launch, except for a few periods when it ran in cine mode after pulsing. After the data frame at 186.962 sec there were usually two frames for each MODE number on the film, and in addition often several digits of the CYCLE number were blank, usually in the first frame of each pair. Each frame, or pair of frames, could nonetheless be identified, but as there was no way to determine the exposure duration of each frame when they appeared in pairs this section of the film was generally not considered when searching for optical emissions.

The telemetry record showed that the camera battery voltage dropped to near zero volts for about $\frac{1}{4}$ sec at time 32587.967Z or flight time 186.967 sec, i. e. at the time of the change in character of the film record. Post-flight inspection showed some badly burnt components in the camera's speed-limiting optical tachometer. It is now believed that a short in this circuit caused the severe momentary drop in battery voltage.

Examination of the camera indicated that the damaged tachometer allowed the film advance and shutter mechanism to run so fast that it

could not stop after advancing just one frame as required.
Actual cause of the component failure has not yet been determined.

PAYLOAD ATTITUDE

Semi-specular reflections of the moon from the payload skin in the vicinity of the electrodes mounted on the insulating ring were used to obtain information about payload orientation during flight. The rocket was believed to be tumbling end-over-end and was also understood to roll very slowly about its longitudinal axis. Four separate sequences of lunar reflections were photographed on the payload skin at various times during the flight. The overall timing between sequences was irregular but within each sequence the reflection point (highest scene brightness) was seen to move in a regular fashion around the payload, indicating a slow spin about the axis. This can be seen in Figure 1. At the time of the flight the lunar disc was 92% illuminated and was at elevation 37° , azimuth 272.3° .

At four times during the flight, i.e. once during each of the sequences mentioned above, a reflection was recorded approximately centered on the electrodes as in the frame numbered 01.0000 in Figure 1. The line from the central electrode pair to the mirror by which the camera viewed the skin was at 37° to the rocket surface, and therefore at those times the rearward vehicle axis would have been pointing 37° away from the moon if the rocket surface were indeed producing true specular reflection. The vehicle axis would then have been somewhere on a cone of half-angle 37° about the direction vector to the moon and the vehicle's forward axis, at the four times shown in Table 1, on a cone of 37° semi-angle having a direction elevation -34° , azimuth 92.3° .

Examination of the rocket surface in the vicinity of the insulating separator containing the electrodes showed fine circumferential

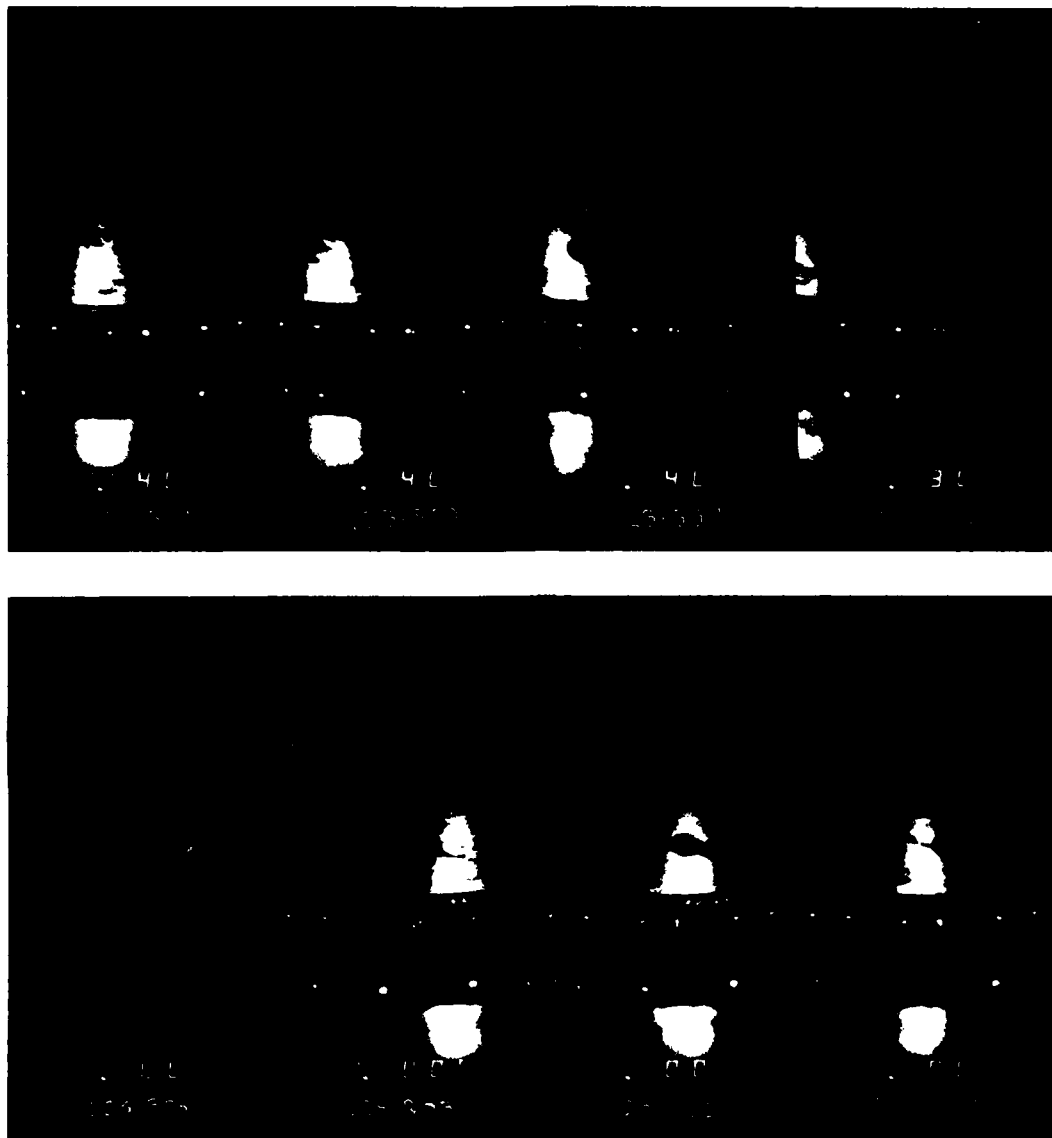


Figure 1. Sequence of consecutive film frames showing lunar reflections on the rocket surface, to determine payload rotation rate from angular rate of progression of reflections. The frame marked 01.0000 is the first entry in Table 1 and was used to infer payload aspect information at time of that exposure. Time from launch, in seconds of start of corresponding experiment program mode has been added below the MODE. CYCLE coding at the bottom of each frame.

machining marks. Reflection of a point, or nearly point, source of light from such a surface is not a well defined spot as would be seen on a smooth surface but a line of reflections, one from each groove, running over a considerable length of the cylinder. As the observed reflections were limited in this case by the camera field of view rather than the geometry of the reflections it is not possible here to locate the moon, with respect to the rocket, any better than to say that, at the times in Table 1, it was in the plane quadrant defined by the rocket's rearward axis and radius vector through the mirror mount.

Such reflections were recorded during accelerator modes starting at times 124.839, 159.300, 265.936 sec, and between the modes starting at 405.837 and 406.329 sec. These modes were of duration $t = 463, 468, 390$ and 490 millisec respectively. The corresponding shutter opening was later than the mode change by the 40 millisec taken for film advance so that the mid-point (in Table 1) of these exposures would be $40 + \frac{t - 40}{2}$ millisec later than the nominal starting times listed above.

Table 1. Mean times for film exposures showing lunar reflections at central electrode pairs on rocket surface, with film frame identification and magnetic pitch angle of the rocket's longitudinal axis

<u>Adjacent Footage Numbers</u>	<u>Code</u>	<u>Rocket Time, sec</u>	<u>Universal Time, 21 Jan 78</u>	<u>Magnetic Pitch Angle</u>
51346-45	01.0000	125.091	32526.091	65.6°
51341-40	01.0100	159.554	32560.554	36.8°
51323-22	02.0300	266.151	32667.151	36.7°
51301-00	$\left\{ \begin{array}{l} 11.0400 \\ 12.0400 \end{array} \right\}$	406.348	32807.348	21.2°

Payload rotation rate was determined from the sequence of film frames in Figure 1, showing reflections of the moon on the vehicle skin. Estimates were made of the distance x of successive reflections around the payload surface from the central electrode pair. The geometry of the imagery is shown in Figure 2. The viewing mirror M is a distance h above the surface of the rocket which has radius r , and reflections were recorded at position S on the surface. The angle β is the rocket rotation angle, calculated from the following -:

$$\Theta = x/r \text{ radians}$$

$$\overline{MS} = [r^2 + (r + h)^2 - 2r(r + h) \cos \Theta]^{\frac{1}{2}}$$

$$\alpha = \sin^{-1} [r/\overline{MS} \sin \Theta] \text{ radians}$$

$$\beta = (\Theta + \alpha) \text{ radians.}$$

The mid point for each exposure was taken to be $t_s + 0.04 + \frac{t - 0.04}{2}$ sec, where t_s is the starting time of the appropriate program mode and t is the duration of that mode. This expression accounts for the delay between mode change and shutter opening and also for the loss of ~40 millisec observing time during film advance.

A linear least squares fit to a plot of β vs time gave a slope, or rotation rate, of $0.091 \pm 0.006 \text{ radians sec}^{-1}$. This is $0.014 \pm 0.001 \text{ revolutions sec}^{-1}$ or about 1 revolution every 71 seconds with a precision of the order of 7%.

Rotation rate derived from the y-magnetometer data was $1/23 \text{ sec}^{-1}$. The disagreement between this figure and the one derived from the optical data may be due in part to the other components of the vehicle motion, e.g. tumbling. Figure 2 is a projection of the ray paths onto a plane normal to the rocket axis and thus does not fully describe the 3-D geometry of the reflections. If the magnetometer-derived rotation rate is assumed to be correct and the reflection geometry considered in a full three-dimensional representation further information relating to vehicle aspect might be obtainable.

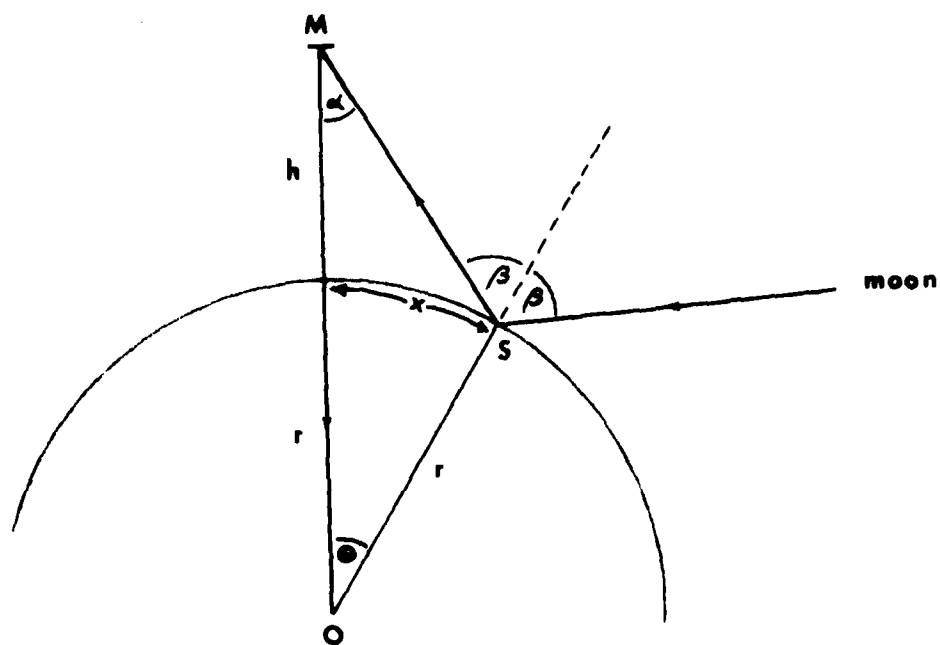


Figure 2. Geometry used to calculate apparent payload rotation rate from lunar reflections on surface.

FILM SENSITIVITY CALIBRATION

Processing of the Eastman Kodak 2475 has been described in the preliminary report on the camera experiment (Ref 1). A $\frac{1}{2}$ sec sensitometer exposure duration was used to match the nominal shutter-open time and so eliminate reciprocity failure effects. The low intensity end of the H&D curve given in Figure 7 of Ref 1 is repeated here in Figure 3 with absolute values of log exposure. The gamma, or mean slope, is 1.26 in the straightline portion of the curve between absolute log E values of -1.72 and -0.21. Film exposure (erg cm^{-2}) in each calibration step is the product of the known sensitometer irradiance ($8.0 \text{ erg cm}^{-2} \text{ sec}^{-1}$), transmission of the appropriate step of the Kodak tablet, and the exposure time ($\frac{1}{2}$ sec).

Although the film was developed in a continuous processing machine (by a commercial developer), fog density was found to vary both along and across the roll. In particular the density was 0.01 to 0.02 greater between the perforations than in the center of the film, an effect believed to be due to turbulence in the developer generated by the perforations when passing through the developing solution. Along the film, variations of 0.01 density unit were sometimes found across distances as small as six inches. For these reasons a density change of 0.02 was considered to be the minimum that could meaningfully be related to luminescence in the plasma around the rocket or to fluorescence on the vehicle skin.

The calibration indicates that we should see a density ~ 0.02 above fog for the exposure of calibration step 18, i.e. for $E \approx 10^{-2.04} \approx 9 \times 10^{-3} \text{ erg cm}^{-2}$, or an irradiance I of $1.8 \times 10^{-2} \text{ erg cm}^{-2} \text{ sec}^{-1}$ during a $\frac{1}{2}$ sec exposure. The exposure E (in erg cm^{-2}) is related to scene brightness B ($\text{erg cm}^{-2} \text{ s}^{-1} \text{ ster}^{-1}$) by

$$E = It = \frac{\pi}{4} \frac{BTt}{f^2} \frac{1}{(1+m)^2}$$

or

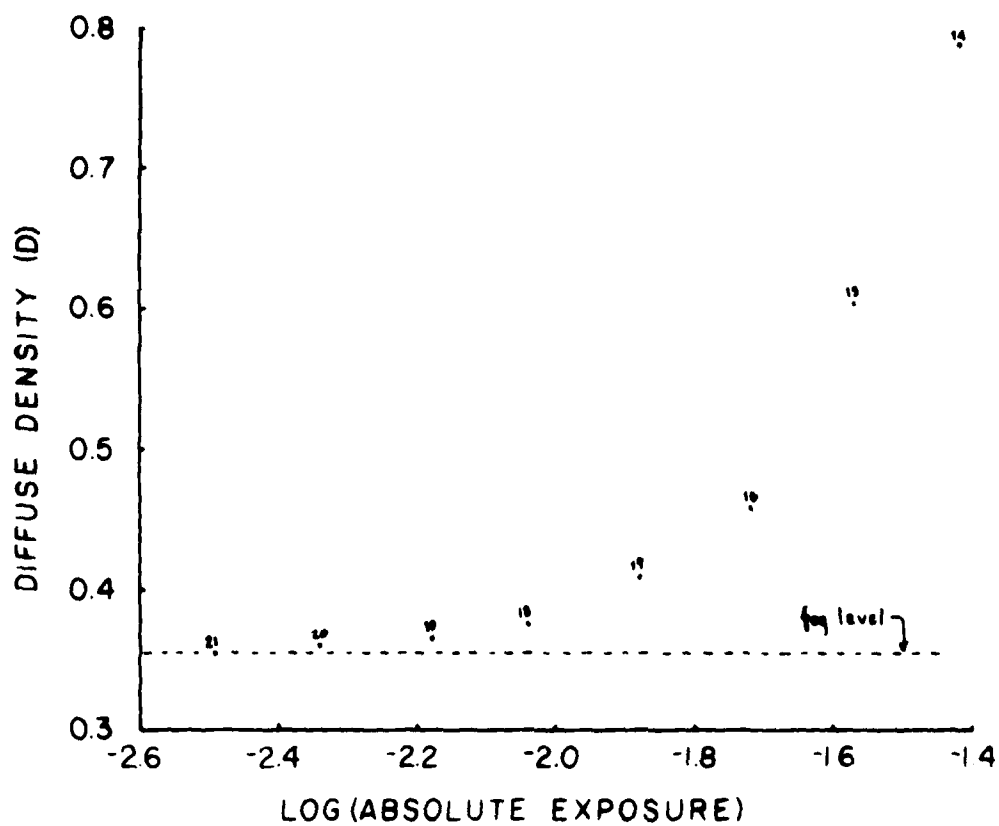


Figure 3. Log exposure part of the D-Log E curve of the film exposed on board AFGL rocket A31-603. Exposure units are erg cm^{-2} .

$$B = \frac{4If^2(1+m)^2}{\pi T}$$

where T = optics transmission, f = lens f-number and m = magnification. In this case $f = 1.4$, $T \approx 0.9$, $m \sim 1/100$ for the forward field of view and $1/16$ for the image of the electrodes on the rocket skin.

Thus, a half second exposure in the forward-directed part of the field of view should give a detectable density for a brightness

$$B \geq 1.8 \times 10^{-2} \cdot 4 \cdot (1.4)^2 \cdot (1 + \frac{1}{100})^2 / (\pi \cdot 0.9), \text{ or}$$

$$\underline{B \geq 5.2 \times 10^{-2} \text{ erg cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1}}.$$

This is equivalent to

$$\frac{4\pi}{10^{-6}} \times 5.2 \times 10^{-2} \times \frac{\lambda}{hc} \text{ rayleighs} \approx \underline{160 \text{ kR}}.$$

Detection of fluorescence on the vehicle skin in the vicinity of the insulating ring would require a scene brightness

$$B \geq 1.8 \times 10^{-2} \cdot 4 \cdot (1.4)^2 \cdot (1 + \frac{1}{16})^2 / (\pi \cdot 0.9), \text{ or}$$

$$\underline{B \geq 5.7 \times 10^{-2} \text{ erg cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1}}.$$

FILM DENSITY MEASUREMENTS

The original objectives of the photographic experiment were to record arcing, if any, between electrodes embedded in the insulator ring on the rocket, and to determine the volume emission rate of luminescence excited in the payload sheath by returning ions or electrons during the flight. In this study we have also considered the possibility of fluorescence excited by charged particles striking the payload surface. The printed lists of telemetered data supplied

by AFGL included measurements from two thermal emission probes giving vehicle potential with respect to the ambient plasma. This information was used to select film frame sequences at times of vehicle potential and accelerator conditions at which discharges would be most probable, in particular times of rapidly changing potential.

Film sequences thus selected were then examined with a MacBeth densitometer to determine what exposure might have resulted from a beam-plasma discharge in the sheath or from fluorescence on the skin. As chemical fog in unexposed areas was found to vary both along and across the film, measurements of fog density were made on the leader and trailer and in those frames exposed when the camera ran in cine mode. There were sufficient such sequences for fog measurements to be made physically close to each region of interest. As the density of most $\frac{1}{2}$ sec exposures was very close to that measured on unexposed film, the density in the 1/24-sec cine exposures was considered an accurate representation of chemical fog density.

Density measurements were made at the edge of the forward field of view (between the sprocket holes) in the center of the forward field, and on the image of the insulator band. In those frames when this band was not visible, i.e. when it was not illuminated by the moon, density readings were taken at approximately the same point in the frame. Fog density measurements were made in an identical manner. The three density values for each frame measured are included in the data list given in Appendix A and a summary of experimental parameters (time, accelerator mode, net emitted current and vehicle potential) is presented in Table 2 with comments on the film density readings. In Table 2, a positive current indicates ion emission and a negative current indicates electron emission, achieved by biasing the beam neutralizer filament.

Six film frame sequences were examined but no change of film density could be found to give any correlation with changes in accelerator operation on payload potential. In some sequences

Table 2. Summary of film density measurements for selected particle beam currents and vehicle potential changes

Time	Mode	Beam Current, μA	Vehicle Potential, Volts	Comments
101.454	10	0	-17	Throughout this sequence there was no detectable density above fog
101.954	11	0	-17	
102.456	12	0	-19	
102.958	1	192	-633	
103.329	2	192	-634	
103.788	3	375	-1033	
104.048	8	0	-47	
113.933	11	-2134	245	Scattered moonlight steadily increasing, but no detectable changes at times of potential changes
114.435	12	-2189	276	
114.936	1	-652	147	
115.276	6	-861	197	
115.772	7	15	-544	
116.274	8	0	-74	
116.772	9	0	-80	
117.276	10	0	-79	
129.302	5	18	-428	Measured density within 0.01 of fog level, variations ≤ 0.005 , not correlated with potential changes
129.772	6	-9951	65	
130.273	7	12	-446	
130.776	8	0	-60	
131.277	9	0	-60	
130.074	5	18	-394	Film densities within ≤ 0.005 of fog level
135.576	6	~ -9932	83	
136.078	7	11	-334	
136.578	8	0	-31	
138.585	12	0	-27	Scattered moonlight in forward field. See Fig 4(a)-(c) and text for modes 2, 6, 8. Scattered moonlight gradually decreased, disappeared by mode 5.
139.085	1	11	-257	
139.587	2	10	-251	
140.089	3	15	-277	
140.460	4	16	-269	
140.924	5	16	-250	
141.467	6	-9900	90	
141.968	7	10	-210	
142.470	8	0	-18	
168.455	2	-10296	60	Electron emission from neutralizer (~ 10 ma to 0) No detectable density above fog
168.957	3	-10297	62	
169.459	4	-10292	61	
169.959	5	-1541	30	
170.461	6	-2365	18	
170.962	7	0	2	
171.464	8	0	1	

evidence of diffuse illumination was found in the forward-looking field, represented by a density only about 0.01 above the local fog level. One example of this is shown in Figure 4(a), an iso-density plot of the frame taken at time 139.587 (emitted ion current $10\mu\text{A}$, rocket potential - 250 volts). Spot density readings in the region of higher density in the sequence of frames about this time showed no detectable change in the image characteristics at the time of ion accelerator burn-on one second earlier. Rocket potential, from thermal emission probe data, changed from -27 volts to -257 volts at turn on (MODE 12 to MODE 1 transition). The isodensity plot is from the frame for MODE 2.

This small density enhancement is characteristic of frames recorded about the times that the moon illuminated the rocket skin in the rearward field of view. It occurred for a longer period than the actual specular reflections from which payload spin rate was determined. The extra exposure due to scattered moonlight should in fact increase the sensitivity of the film because it raises the overall exposure to a more steeply sloped part of the Density-log E curve. However, the slope of the D-log E curve for a density of 0.01 above fog is still only about 0.07, calculated from the values for wedge steps 18 and 19 on the film. Using this as an approximation to the slope of the curve where D is 0.01 above fog, as at step 19, the exposure E required for a further increase of 0.01 in density is a further $2.5 \times 10^{-3} \text{ erg cm}^{-2}$, corresponding to approximately 45 kR.

To raise the film density to 0.01 above fog initially requires about the same exposure as for calibration step 19, i.e. $\sim 6.6 \times 10^{-3} \text{ erg cm}^{-2}$ which, in a $\frac{1}{2}$ sec exposure, requires a scene brightness of the order of 120 kR. As the slope is very small in this region of the D-log E curve, and is continually changing, the errors in this estimate may be as high as a factor of two.

As no detectable density changes were found coincident with changes in accelerator operation on payload potential, we may conclude that charged particle impact excited fluorescence around the

rocket contributed less than about 45 kR to the optical radiation viewed by the camera.

Figures 4(b) and (c) are isodensity plots of frames recorded during modes 6 and 8 respectively of this sequence. The scattered moonlight component in the forward field had disappeared by this time and the entire forward field is at fog density in both these frames. In Figure 4(b) there is actually a slight decrease of ~ 0.1 in density at the position of the insulator band in the lower part of the frame.

In Figure 4 captions:

i = beam current

V = potential of the rocket with respect to the
ionospheric plasma.

MODE refers to the mode of operation of the accelerator system as explained in Table 4 of Ref 3.

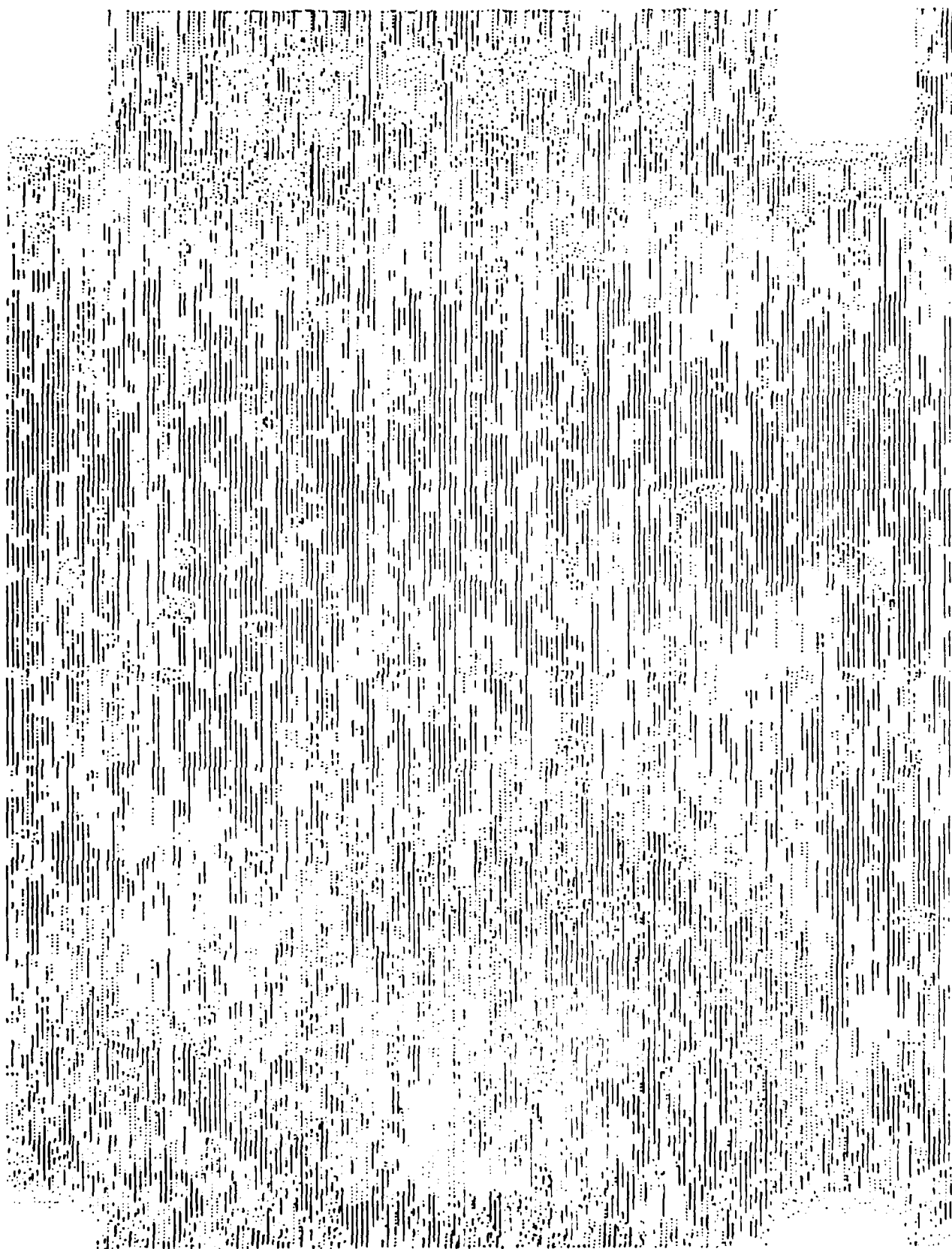


Figure 4(a). Scanning microdensitometer plot of frame exposed at flight time 139.587 sec from launch MODE 2, $i = 10\mu\text{A}$, $V = -251$ volts; contour interval $\Delta D \sim 0.004$ between symbols.

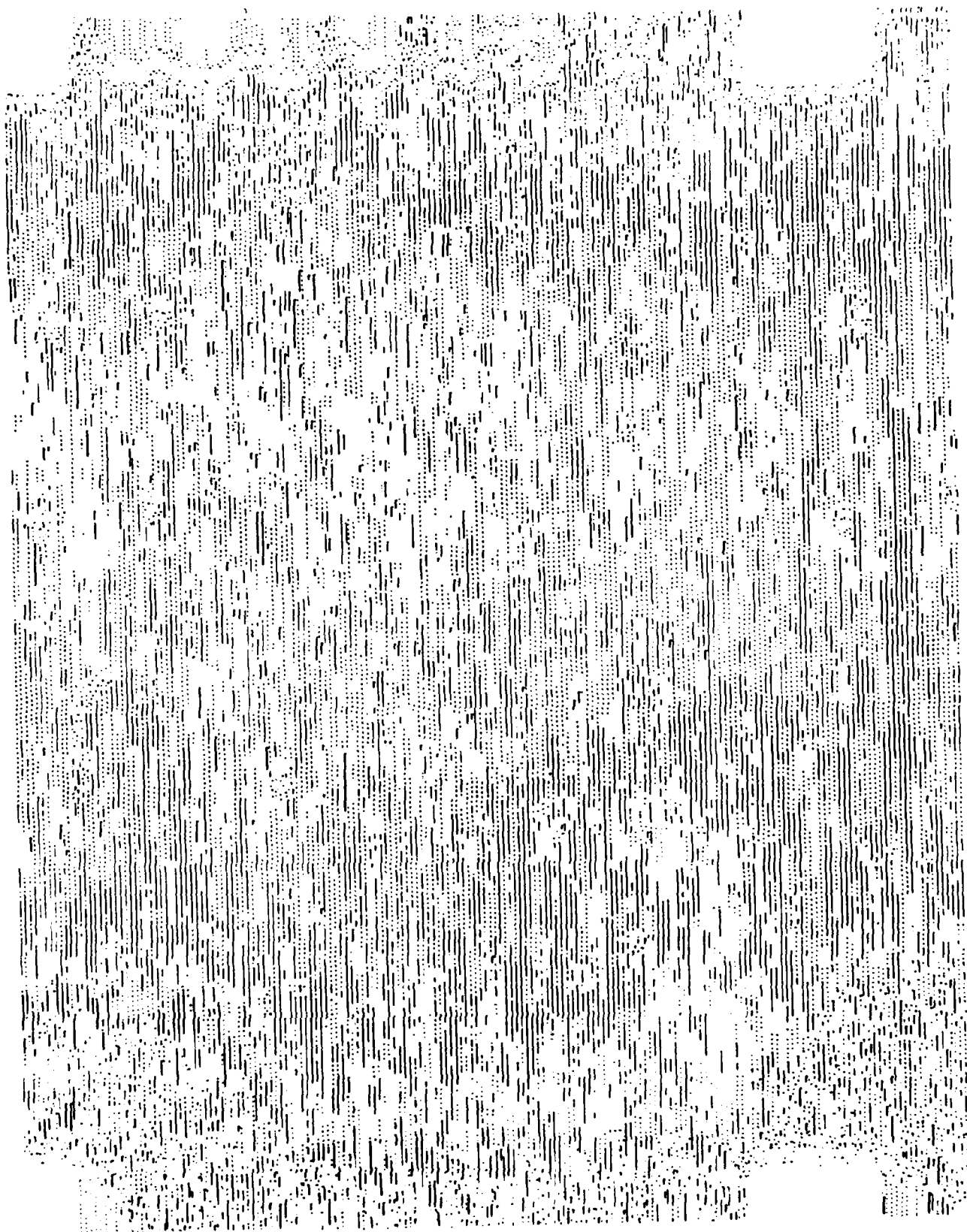


Figure 4(b) Scanning microdensitometer plot of frame from 141.467 sec from launch. MODE 6, $i = -9.9$ mA, $V = +90$ volts; contour interval $\Delta D \sim 0.004$ between symbols.

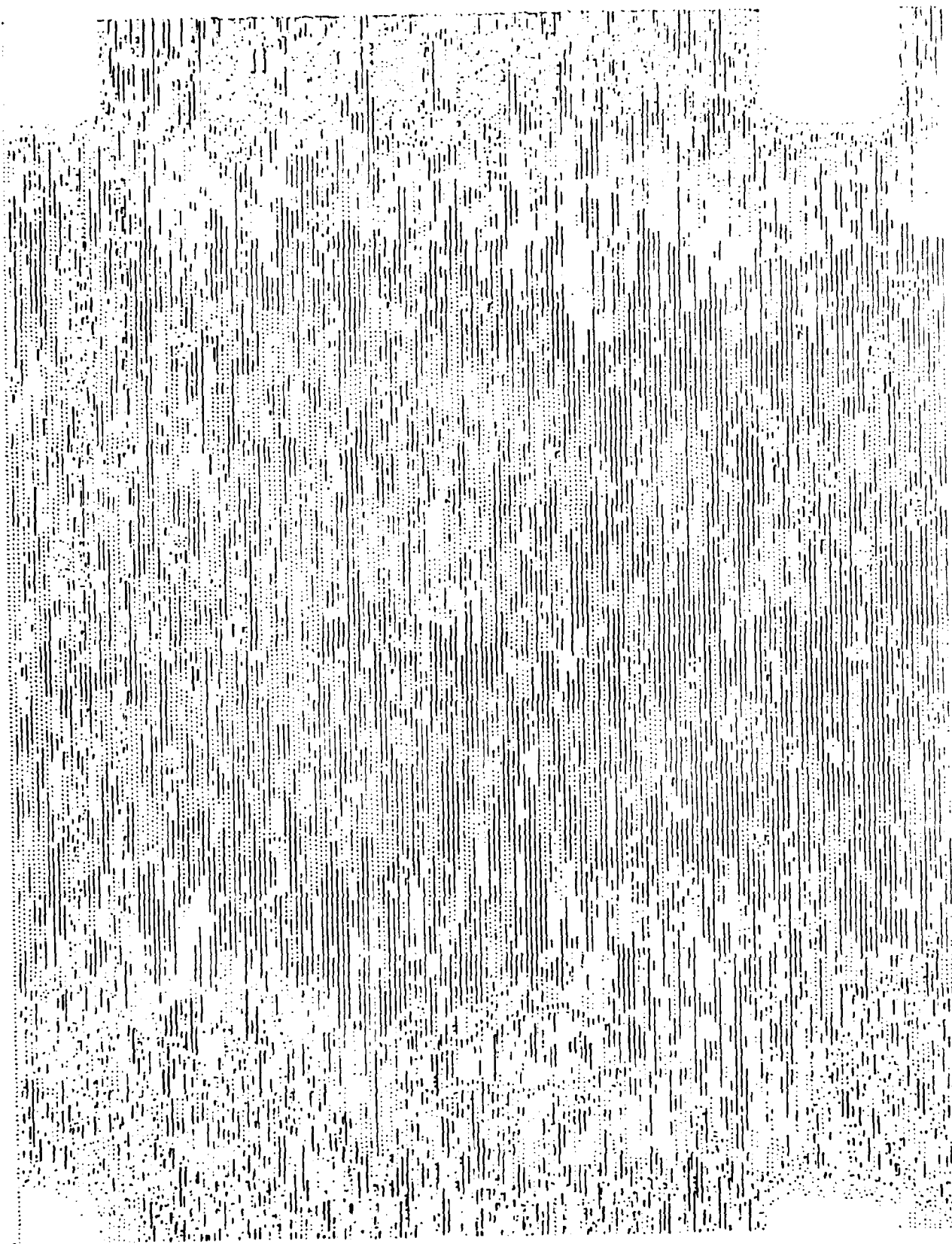


Figure 4(c) Scanning microdensitometer plot of frame from 142.470 from launch. MODE 8, $i = 0$, $V = -18$ volts; contour interval $\Delta D \sim 0.004$ between symbols.

SECTION III

THEORETICAL CONSIDERATIONS, INTERPRETATION

SHEATH DIMENSIONS

To estimate the dimensions of the plasma-depleted sheath surrounding the rocket, we use the concentric-spherical approximation of Ref 5. The ratio of the distance to the external "electrode" r_o to the characteristic dimension of the rocket r (19 cm) is then given by the parametric equation

$$i = 4\pi 2.3 \times 10^{-6} \frac{V^{3/2}}{\alpha(r_o/r)^2} \quad \text{for electrons}$$

$$= 4\pi \frac{5.45 \times 10^{-8}}{\sqrt{M}} \frac{V^{3/2}}{\alpha(r_o/r)^2} \quad \text{for ions of molecular weight } M.$$

The procedure is to determine α^2 from the emitted current i resulting in charge-up voltage V measured by the onboard instruments, from which the ratio r_o/r is found in Table II of Ref 5.

For a return current of $10\mu\text{A}$ of ions of atomic weight 16 and a charge-up voltage 250 volts $\alpha(r/r_o)^2 = 67.7$, for which $r_o/r \approx 17$ and hence $r_o \approx 323$ cm. This value will apply above about 200 km where $^{16}\text{O}^+$ is the dominant ion in the ionosphere. For molecular weight 30 α^2 is 49.4; an interpolation in Table II of Ref 5 gives $r_o/r = 14$ and hence $r \approx 266$ cm. This value will apply below about 200 km where NO^+ is the dominant ion.

For a return current of 10 mA of electrons at a charge-up voltage of 100 volts, this approach gives a sheath radius of about 60 cm, which is less than the length of the rocket. This case was therefore recalculated using the cylindrical approximation of Ref 6:

$$i' = 14.68 \times 10^{-6} V^{3/2} / r\beta^2,$$

where i' is in amperes/cm and β a geometric parameter analogous to the function α above. Thus $i' = 10^{-5}/300$ (the rocket length l is 300 cm), and $r/\beta^2 = 440$. As $r = 19$ cm, $\beta^2 = 23.2$; interpolation in Table III of Ref 6 gives $r_o/r = 7.7$, so that $r_o = 146$ cm, which gives a sheath thickness of 127 cm.

The sheath dimensions, as calculated here, are independent of the ionosphere plasma density or temperature except for the choice of ion mass number which depends on the identity of the dominant ion.

RADIATION DENSITIES

We considered next the excitation of air by 10 mA of 100 eV electrons returning through the cylindrical sheath of surface area $A = 2\pi Rl$. At the typical rocket altitude of 150 km ambient N_2 density $n(N_2)$ is $2 \times 10^{12} \text{ cm}^{-3}$. The electron impact cross section σ for the First Negative system of N_2^+ is about 10^{-17} cm^2 near 100 eV. The viewing mirror is 15 cm from the rocket surface and looks parallel to the rocket axis, so that $R = 15 + 19 = 34$ cm and $l = 300$ cm. The volume emission rate in the line of sight will be $(i/eA) \sigma n(N_2) \approx 2.8 \times 10^7$ photons $\text{cm}^{-3} \text{ sec}^{-1}$ (e is the electronic charge). The length of the line of sight within this emitting region is ~ 200 cm, so the column emission rate is 6×10^9 photons $(\text{cm}^2 \text{ column})^{-1}$ or 6 kilorayleighs.

This brightness is far lower than the detection threshold of this experiment. Further contributions may be expected from other emission features (principally, the First and Second Positive systems of N_2), but as these will probably result in an increase of less than a factor of two the main conclusion is not changed. Further, the ends of the cylindrical sheath have been neglected in the calculation; the sheath will in fact extend beyond the ends of the vehicle and as a result be slightly thinner than calculated here but again the expected emission rates will change only slightly.

At higher rocket altitudes the concentrations of N_2 and O will be lower and so the expected emission rates will be still lower.

For positive ions returning to a negatively charged rocket, the surface radiances will be still lower: cross sections for excitation of visible radiation by ion impact at the energies of only a few hundred electron volts are small, and in addition the ion current density is some orders of magnitude less than that of the electrons.

If an electronic discharge occurs, most of the returning energy will be dissipated in the sheath. For a discharge with input power equivalent to 10 mA at 100 V, in which the total visible fluorescence efficiency is ϵ , the volume emission rate in a cylindrical sheath of radius r_o about a vehicle of (inner) radius r and length l will be

$$\frac{Vi}{\pi l (r_o^2 - r^2)} \epsilon \text{ watts cm}^{-3} \text{ sec}^{-1}.$$

With the above conditions $r_o = 146$ cm, $r = 19$ cm, and $l = 300$ cm, and adopting $\epsilon = 0.02$, this become 10^{-9} watts $\text{cm}^{-3} \text{ sec}^{-1}$ or $\sim 2.5 \times 10^9$ photons $\text{cm}^{-3} \text{ sec}^{-1}$. Taking again the above camera line-of-sight distance of 220 cm, the radiance is 5.6×10^{11} photons $(\text{cm}^2 \text{ column})^{-1} \text{ sec}^{-1}$ or 560 kilorayleighs, which would have produced a density about 0.32 above fog in the rocket experiment.

Again neglect of the effects of the ends of the sheath is not expected to change the overall conclusion, which is that an electric discharge excited during electron emission in this experiment should have produced a film density greater than any actually recorded. It should be noted that small changes in the current output have only a small effect on the surface brightness of the discharge (the decrease in total energy input is compensated by a decrease in the radius of the sheath; the volume emission rate therefore stays about the same, and as the path length is unchanged the surface brightness is also unchanged).

A discharge during emission of $10\mu\text{A}$ of ions for an effective charge-up potential of 250 volts may be expected to produce a total emission of $10 \times 10^6 \times 250 \times 0.02 \times \frac{\lambda}{hc} \approx 1.3 \times 10^{14}$ photons sec^{-1} (again adopting the plausible $\epsilon = 0.02$). If this radiation is produced

in a volume of the order of the sheath size determined above the average volume emission rate will be $\sim 10^6$ photons $\text{cm}^{-3} \text{sec}^{-1}$. The length of the path seen by the camera through this spherical discharge region will be about 4 meters so that the apparent brightness will be of the order of $10^6 \times 4 \times 10^2 \approx 4 \times 10^8$ photons $(\text{cm}^2 \text{column})^{-1} \text{sec}^{-1}$ or $\sim \frac{1}{2}$ kR. This radiance would not be detected by the camera system.

RADIATION EXCITED AT THE ROCKET SURFACE

We estimate next the surface radiance of the rocket's skin that results from fluorescence excited by counterflowing energetic electrons or ions. This radiance can be expressed as

$$f \frac{1}{\pi} Vi/A,$$

where i is the return current flow through the sheath at potential difference V , A is the skin surface area over which this current is distributed (the current density i/A is assumed uniform), f is the effective fluorescence efficiency of the skin material in the visible (and near-UV and -IR wavelengths at which commonly used photo-detectors are sensitive), and the factor $1/\pi$ as usual converts the total output flux to the flux per steradian in the direction normal to the surface. The factor iV/A will be recognized as the power deposited per unit area of skin by the impinging particles; we have neglected the small loss (see previous subsection) from their excitation of atoms and molecules within the sheath, and assumed no beam plasma discharge is taking place.

Following the argument in the previous subsection, we take as standard conditions $i = 10$ ma, $V = 100$ volts, and $A = 2\pi \times 19 \text{ cm} \times 300 \text{ cm} = 3.6 \times 10^4 \text{ cm}^2$ (end plates neglected). The power density iV/A is then $1 \text{ watt}/3.6 \times 10^4 \text{ cm}^2 \approx 28 \mu\text{w}/\text{cm}^2$, and the surface radiance is $28 \times 10^{-6} f/\pi \text{ watts}/(\text{cm}^2 \text{sterad})$ or $280 f/\pi \text{ erg}/(\text{cm}^2 \text{sec})$. As Fig 3 shows, the threshold exposure of our (fast) photographic film is about $10^{-2} \text{ erg}/\text{cm}^2$, so that for detection in a 1-sec exposure with an $f/1.4$ lens

$$\frac{\pi}{4} \cdot \frac{280 f}{1.98 \pi} > 10^{-2}, \quad f > 3 \times 10^{-4}.$$

In practice the fluorescent yield of clean metals is many orders of magnitude less than 10^{-4} , so that the "cathodoluminescence" at metal surfaces would be far below photographic threshold. In addition, none of the partially-conducting plastic materials on the surface, or the oxide film or aluminum, would be expected to have efficiencies as high as 10^{-4} . Thus no electron bombardment-induced surface fluorescence would be expected in onboard photography images of A31.603. As yield under bombardment by ~ 250 eV ions are even lower, no ion-induced surface fluorescence would be detectable either (efficiencies of $\sim 25\%$ would be required for the $10\mu\text{A}$ beam to be above threshold).

On the other hand, conventionally-used phosphor materials - such as ZnS and alkali halides - have efficiencies for visible and near-UV emission between 10^{-1} and 10^{-2} under irradiation by sub-kilovolt electrons (Ref 7). Hence phosphor coatings - and perhaps even luminescent paint - applied to the rocket surface would "map" the spatial distribution of return electron-beam power at the levels of power-per-unit-area of these calculations.

Additionally, the transverse currents in pn junction semiconductors induced by the returning electrons (Ref 8) can be used to map out the energy distribution. The basic instrument is a simple diode biased at a few volts, with a current amplifier. As each 100 eV electron creates ~ 10 hole-electron pairs, the collected current in a 1 cm^2 -area diode would be

$$\frac{10^{-2} \text{ amps}}{36000 \text{ cm}^2} \cdot 10 \approx 3 \text{ microamps}.$$

(It is worth noting that both the electron beam-induced currents and luminescence concepts are in routine use in electron microscopy for mapping surface distributions.)

SUMMARY AND RECOMMENDATIONS

The main results of this study may be summarized as follows:

1. Each frame on the film has been unambiguously identified with respect to time and operation of the particle accelerators.
2. Determination of rocket aspect from lunar reflections off the skin was only partially successful due to the nature of the skin surface. The reflections permitted location of the moon, relative to the rocket, to within the plane quadrant defined by the vehicle's rearward axis and the radius vector through the mirror mount.
3. Lunar reflections from the rocket surface were used to determine an apparent rotation rate about the longitudinal axis of $\frac{1}{71} \text{ sec}^{-1}$, which differed from that derived from magnetometer data ($\frac{1}{23} \text{ sec}^{-1}$) but which might be useable in further clarifying the aspect information from the magnetometers.
4. Detection threshold for air fluorescence has been determined to be $\sim 160 \text{ kR}$ for film density 0.02 above fog.
5. Microdensitometric examination of the film revealed no density changes which could not be attributed to scattered moonlight and none which could be related to changes in vehicle potential or accelerator operation. Densities in areas not exposed to moonlight were generally within 0.01 of fog levels.
6. Calculations of expected fluorescence in the ambient plasma due to particle ejection and vehicle charging indicate that no visible radiation would have been detected during ion or electron ejection in the absence of a discharge. Radiation should have been detected in the presence of discharges when the electron accelerator was on and vehicle potential was of the order of 100 volts.
7. Surface-excitation efficiencies needed for detection of charged particle impact fluorescence on the rocket skin have been calculated as $\geq 3 \times 10^{-4}$ for the electron emission conditions. As metals and other rocket surface materials have much lower fluorescence efficiencies, no detectable surface radiation is expected. On the other hand, fluorescent material placed on the rocket surfaces should readily "map" the return current distribution.

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APPENDIX A

16 mm Film Listing from AFGL Rocket A31.603

All data frames on the film from the 16 mm camera flown on rocket A31.603 are listed here. The list identifies MODE and CYCLE codes from film, decoded mode numbers, film footage numbers (numbered every $\frac{1}{2}$ foot), flight time after launch in seconds, exposure times, and densitometer readings.

Film Footage Numbering

Footage is indicated on the film by a 5 digit number every 6 inches. In the list, the number is listed with the frame at the position of the two least-significant digits; the other three digits are at the edge of an adjacent frame. In most cases only the two least significant digits are listed. The numbers are in descending order, i. e., the film was run backwards through the camera.

Timing

Times given here and on the reduced telemetry record are times from launch in seconds. Some telemetry seconds have time of day in seconds (Z). Launch time was 0900 Z + 1 sec = 32401 Z; subtracting this number from the time of day gives time of flight from launch. The exposure time of each frame is listed in milliseconds.

[illegible]

Footage Number	Mode Code	Mode	Cycle Code	Cycle	Time	Exposure Time	Densities		fog densities
							Edge	FWD	Shin
47	07	7	010a	3	5 frames		.340	.320	.325
	07	7	010a		4 frames				
	12	9	0000		112.013	429			
	11	8	0100		112.442	491			
	12	9	0100	3	112.933	500			
	13	10	0100		113.433	500			
	14	11	0100		113.933	502	.355	.340	.330
	15	12	0100		114.435	501	.355	.340	.330
	00	1	0200		114.936	340	.350	.340	.330
	05	6	0200		115.276	496	.355	.345	.330
	10	7	0200		115.772	502	.350	.355	.330
	11	8	0200		116.274	498	.350	.355	.330
	12	9	0200		116.772	504	.360	.360	.335
	13	10	0200		117.276	502	.360	.360	.330
	14	11	0200		117.778	501			
	15	12	0200		118.279	502			
	00	1	0300	4	118.781	502			
48	01	2	0300		119.283	503			
	02	3	0300		119.786	076			
	05	6	0300		119.862	467			
	10	7	0300		120.329	500			
	11	8	0300		120.829	502			
	12	9	0300		121.331	502			
	13	10	0300		121.833	502			
	14	11	0300		122.335	500			
	15	12	0300		122.835	502			
	00	1	0400		123.337	502			
	01	2	0400		123.839	502			
	02	3	0400		124.341	498			
	01	2	0000	1	124.839	463			
	06	7	0000		125.302	501			
	07	8	0000		125.803	503			
	12	9	0000		126.306	114			
	14	12	0000		126.420	211			
44	02	3	0100	2	126.631	468			
	03	4	0100		127.099	501			
	12	9	0100		127.600	3-9			
	16	12	010a		127.969				
	17	13	010a		0 frames				
	17	13	010a		128.354	637			
	02	3	0200		128.991	246			
	03	4	0200		129.237	065			
	04	5	0200		129.302	470			
	05	6	0200		129.772	501			
	10	7	0200		130.273	503			
	11	8	0200		130.776	501			
	12	9	0200		131.277	500			
	13	10	0200		131.777	502			
	14	11	0200		132.279	501			
45	02	3	0100	3	128.354	637			
	03	4	0100		128.991	246			
	12	9	0100		129.237	065			
	16	12	010a		129.302	470			
	17	13	010a		129.772	501			
	02	3	0200		130.273	503			
	03	4	0200		130.776	501			
	04	5	0200		131.277	500			
	05	6	0200		131.777	502			
	10	7	0200		132.279	501			
	11	8	0200		132.791	501			
	12	9	0200		133.293	501			
	13	10	0200		133.795	501			
	14	11	0200		134.297	501			
	15	12	0200		134.799	501			

Footage Number	Mode Code	Mode	Cycle Code	Cycle	Time	Exposure Time		Densities		Skin	B10 +394 - 83 +334 + 31
								Edge	FWD		
43	15	12	0200	6	132.780	502					
	00	1	0500		133.282	502					
	01	2	0500		133.784	500					
	02	3	0500		134.284	331					
	03	4	0500		134.615	459					
	04	5	0500		135.074	502	.370	.360	.340		
	05	6	0500		135.576	502	.370	.360	.330		
	10	7	0500		136.078	500	.360	.360	.340		
	11	8	0500		136.578	502	.365	.365	.340		
	12	9	0500		137.080	502					
	13	10	0500		137.582	502					
42	14	11	0600	7	138.084	502	.340	.340	.330		
	15	12	0600		138.585	501	.340	.340	.330		
	00	1	0600		139.085	500	.355	.340	.330		
	01	2	0600		139.587	502					
	02	3	0600		140.089	371					
	03	4	0600		140.460	464	.360	.335	.330		
	04	5	0600		140.924	543	.360	.335	.330		
	05	6	0600		141.467	501	.360	.335	.330		
	10	7	0600		141.968	502	.360	.340	.335		
	11	8	0600		142.470	502	.360	.340	.335		
	12	9	0600		142.972	500	.360	.340	.330		
	13	10	0600		143.472	502	.360	.335	.330		
41	14	11	0600	8	143.974	501					
	15	12	0600		144.475	502					
	00	1	0700		144.977	502					
	01	2	0700		145.479	500					
	02	3	0700		145.979	265					
	03	4	0700		146.244	613					
	04	5	0700		146.857	500					
	05	6	0700		147.357	175					
	13	10	0700		147.532	495	.360	.340	.340		
	14	11	0700		148.027	264					
	15	12	0700		148.293	260					
	00	1	1000		148.553	277					
40	01	2	1000	9	149.030	500					
	02	3	1000		149.530	419					
	03	4	1000		149.949	316					
	04	5	1000		150.365	377					
	05	6	1000		150.742	492					
	16	7	0000		151.234						
	17	8	0000		151.684	599	.380	.365	.340		
	02	3	0100		152.283	422	.380	.350	.340		
	03	4	0100		152.705	069	.370	.350	.340		
	04	5	0100		152.774	406	.380	.355	.350		
	11	8	0100		153.180	237	.370	.350	.350		
	00	7	0000		153.417	500	.385	.370	.360		
39	01	2	0000	1	153.917	502	.390	.370	.360		
	02	3	0000		154.419	502	.390	.370	.360		
	03	4	0000		154.921	500					
	04	5	0000		155.423	500					
	05	6	0000		155.925	500					
	06	7	0000		156.427	500					
	07	8	0000		156.929	500					
	08	9	0000		157.431	500					
	09	10	0000		157.933	500					
	10	11	0000		158.435	500					
	11	12	0000		158.937	500					
	12	13	0000		159.439	500					

Footage Number	Mode Code	Mode	Cycle Code	Cycle	Time	Exposure Time	Edge	Densities FWD	Skin
40	05	6	0000	1	155.421	503			B8 up at 155.951
	10	7	0000		155.924	503			
	11	8	0000		156.427	500			
	12	9	0000		156.927	501			
	13	10	0000		157.428	502			
	14	11	0000		157.930	500			
	15	12	0000		158.430	502			
	00	1	0100	2	158.932	502			
	01	2	0100		159.300	468	.380	.360	.360
	02	3	0100		159.768	330	.375	.350	.350
	04	5	0100		160.098	500			moon
	05	6	0100		160.598	502	.380	.355	.355
	10	7	0100		161.100	502			
	11	8	0100		161.602	501			
	12	9	0100		162.103	501			
39	13	10	0100		162.605	502			
	14	11	0100		163.107	500			
	15	12	0100		163.607	502			
	00	1	0200	3	164.109	502			
	01	2			164.611	501			
	02	3			165.112	262			
	03	4			165.374	491			
	04	5			165.865	500			
	05	6			166.365	342			
	10	7			166.707	299			
	02	3	0300	4	167.006				B8 down at 167.375
	03	4	0300		5 frames				
	04	5	0300						
	05	6	0300	3 frames			.380	.355	.355
	05	6	0300	7 frames					fog
38	05	6	0000	1					
	11	8	0000	5					
	10	7	0400	5			.380	.350	.340
	00	1	0400						fog
	01	2	0400						
	01	2	0400				.365	.345	.345
	02	3	0400				.360	.340	.340
	03	4	0400				.360	.340	.340
	04	5	0400				.360	.340	.340
	05	6	0400				.360	.340	.340
	10	7	0400				.360	.340	.340
	11	8	0400				.360	.340	.340
	12	9	0400				.360	.340	.340
	13	10	0400						
	14	11	0400						
10	15	12	0400	5					B8 up at 170.212
	00	1	0500	6					
	01	2							
	02	3							
	04	5	0500				.370	.340	.340
	05	6	0500				.36-.38	.340	.340
	10	7	0500				.360	.340	.340

Footage Number	Mode Code	Mode	Cycle Code	Cycle	Time	Exposure Time	Densities	
							Edge	Skin
37	11	8	0500		176.393	503		
	12	9	0500		176.896	501		
	13	10	0500		177.397	502		
	14	11	0500		177.899	498		
	15	12	0500	6	178.397	502		
	00	1	0600	7	178.899	501		
	01	2	0600		179.401	501		
	02	3	0600		179.902	268		
	09	4?	0600		180.170	045		
	04	5	0600		180.215	481		
	05	6	0600		180.696	501		
	10	7	0600		181.197	502		
	11	8	0600		181.699	502		
	12	9	0600		182.199	501		
36	13	10	0600		182.701	501		
	14	11	0600		183.202	500		
	15	12	0600	7	183.702	502		
	00	1	0700	8	184.204	502		
	01	2	0700		184.706	502		
	02	3	0700		185.208	374		
	03	4	0700		185.582	378		
	04	5	0700		185.960	500		
	05	6	0700		186.460	500		
	10	7	0700		186.962	502		
	11	8	06---		187.359			
	12	9	---					
	13	10	0---					
			0---					

Camera battery monitor (B4 in telemetry listing) showed a drop to ~0 volts at ~186.960. Remainder of film incomprehensible.

* indicates blurred character, not readable.