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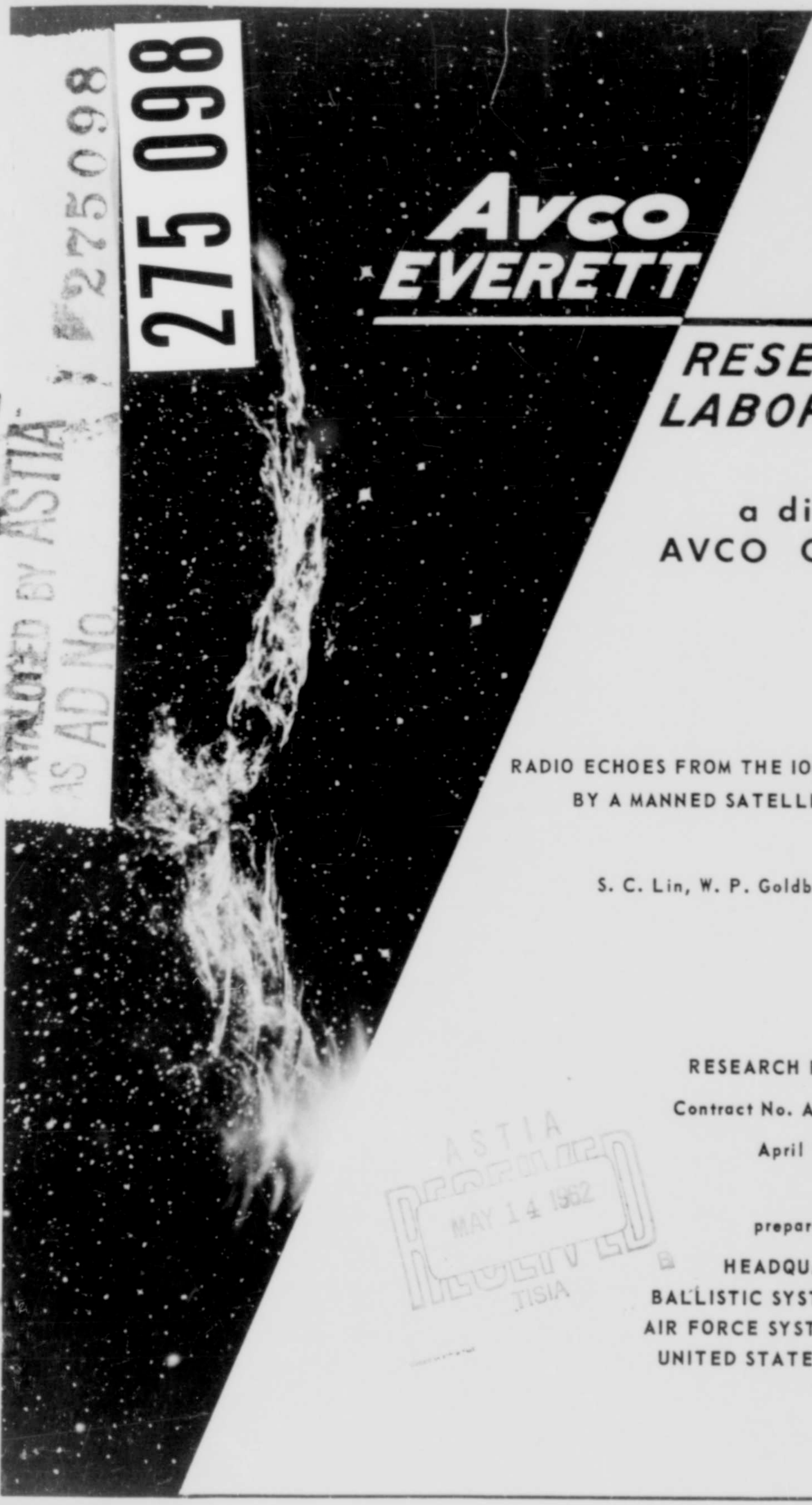

AVCO EVERETT RESEARCH LABORATORY

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SUMMARY

Observation has been made of the ionized trails produced during re-entry by the MA-6 Mercury capsule carrying Lt. Col. John Glenn in his first orbital flight on February 20, 1962. The observation was made from San Salvador Island (Bahama Island Group), approximately 370 miles uprange from the impact point. The apparatus employed was an omni-directional pulsed radar (of 30.25 Mc/sec carrier frequency) similar to those employed by radio astronomers in the study of meteor echoes.

When the Mercury capsule was passing over the vicinity of the observation station at about 14 hr. 33 min., E. S. T., five clearly separated ionized trails were observed. The most prominent trail, which may be identified with the wake of the main capsule, was visible to the radar for a total duration of about 20 seconds, and displayed an equivalent isotropic scattering cross-section of about 10^6 square meters at its peak. The other four trails, which were probably due to fragments of the disintegrating retro-rocket package reported by Col. Glenn, showed only short duration glints (of the order of one second) characteristic of

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the smooth, rapidly decaying trails of small meteors.

While some of the fine structure of the long-duration, scintillating echo from the main capsule trail is not yet understood, the overall characteristics of the trail can be accounted for by a combination of high-light from a strongly reflecting front segment of the ionized wake,* which appeared electromagnetically smooth to the 10-meter wavelength employed; and diffuse scattering from a fully developed turbulent rear segment of the wake, which appeared rough to the wavelength. This readily suggests a simple explanation for the formation of "head-echoes" by large meteors, which have been previously reported (but not explained) in the literature. The fact that the main capsule trail appeared turbulent indicates a Reynolds number of less than 10^5 (based on the velocity and diameter of the MA-6 capsule, and on the ambient air density) for transition from laminar to turbulent flow in the wake.

I. Introduction

The radio-echo techniques for the study of ionized trails produced by meteors in the upper atmosphere were well developed since the early work of Skellett, Schafer, Goodall, and others some thirty years ago.[1,2] The use of these techniques have not only greatly facilitated the study of many astronomical problems of meteors, but also yielded much valuable information concerning the dynamics[3,4] and other physical properties[5] of the upper atmosphere. As a means for upper atmosphere and hypersonics research, observation of meteor trails is, unfortunately, handicapped by the fact that the physical properties of the object

* In the present paper we shall use the words "trail" and "wake" interchangeably.

producing the ionized trail are generally not known, and that the experiment is, in a sense, not reproducible. However, as a result of recent advances in rocket technology, these inherent drawbacks can now be remedied by replacing the meteors with man-made hypervelocity objects of predetermined properties. This has been demonstrated by the recent series of ionized trail experiments conducted by the M.I.T. Lincoln Laboratory at Wallops Island, Virginia.[6]

In the present paper, we shall present the results of a more recent experiment of similar nature conducted in connection with the first U.S. manned orbital flight of February 20, 1962. As we shall see from the general results, the radio echo from the ionized trail generated by the re-entering satellite was surprisingly strong and long-lasting (i.e., insensitive to aspect angle), even at a relatively high altitude of about 230,000 ft and at a distance of about 400 miles from the landing point. This strong echoing characteristic of the ionized trail with respect to radio waves of suitably chosen frequencies may prove to be a very valuable aid for locating re-entering satellites and spacecraft in the future.

II. Description of the Experiment

The MA-6 Mercury flight of February 20, 1962, was planned for three orbits around the Earth,[7] to be followed by re-entry over the Bahama Islands and landing in the Atlantic Ocean northwest of Puerto Rico, as shown in Fig. 1. The Island of San Salvador was chosen as the observation point for this experiment principally because it lay close to the trajectory plane at a point sufficiently far uprange from the peak deceleration point, so that observation could be made over a considerable period of time during which the velocity and altitude of the Mercury capsule remained approximately constant. For transportation and other practical reasons, the experimental apparatus was set up near the airport somewhere in the Northwestern corner of the Island. The actual trajectory plane turned out to pass almost exactly through the center of the Island, so that the normal distance between our observation station and the trajectory plane was only about two nautical miles, as shown in Fig. 2.

The post-flight trajectory data[8] for the MA-6 capsule, as deduced by NASA from velocity vector measurement over Corpus Christi, Texas, are shown in Fig. 3. According to these data, the capsule was to have passed over our observation station at San Salvador Island (see Fig. 2) at 14 hr. 33 min. and 01 sec. Eastern Standard Time, at an altitude of approximately 220,000 ft, and at a velocity of approximately 23,000 ft/sec. At this point, the dip angle γ of the trajectory with respect to the horizontal plane should be only about 1.5°; but the heat transfer rate at the stagnation point of the capsule should have reached about 85 percent of the peak value.

The principal apparatus employed in this experiment was an omnidirectional pulsed radar, essentially similar to that used by McKinley[9] and Millman[10] for meteor observations. The actual carrier frequency employed during the experiment was 30.25 Mc/sec. The peak radiated power from the transmitter was continuously variable between 10^5 and 10^6 watts, but during this experiment it was set at a constant value of

2×10^5 watts (after due allowance was made for the impedance mismatch at the antenna). The pulse width at half-peak power was approximately one μ-sec.* The pulse repetition rate had a nominal value of 100 pulses/sec, but the actual rate during the experiment was closer to 94 pulses per second. The half-wave dipole transmitting-receiving antenna was oriented horizontal and parallel to the trajectory plane (see Fig. 2), so that the electric field vector was longitudinally polarized with respect to the axis of the ionized trail. The receiving amplifier was a linear voltage amplifier, with a band-width of approximately one Mc. The output from the amplifier of the pulsed radar was simultaneously fed into three separate cathode ray display tubes in the receiver-display unit. The first tube was intensity-modulated by the received signal and was used to produce the 100 nautical mile full range, intensity-modulated range-time record. The second cathode ray tube was used to record the received pulse amplitude (in the form of vertical deflection) within the fine range gate, which occupied about 10 percent of the full range and could be placed anywhere within the 100 mile range by the operator through a control knob during the experiment. The third cathode ray tube, which displayed the received pulse amplitude as a vertical deflection over the full range, was used as a visual monitor by the operator. The receiver sensitivity was controlled by a stepwise adjustable attenuator located at the input end of the receiving amplifier. All recordings were made by

* This was a nominal value. The effective pulse width as determined from observation of small isolated targets, such as airplanes, in the receiver display (which also takes into account the effect of broadening by the receiver due to its finite bandwidth) was found to be closer to 1.5 μ-second.

motor-driven, 6-inch wide film-strip cameras, the speed of which could be independently adjusted by the operator.

On the day of the orbital flight, approximately 30 minutes before the scheduled arrival time of the MA-6 Mercury capsule, the transmitter was tuned to the desired frequency and power, and the standing wave ratio between the transmitter and the antenna was measured. A pulse of known amplitude was fed into the receiving amplifier, and the fine range display recording camera was run for a few seconds to record the absolute receiver sensitivity. The receiver attenuator setting was recorded. The receiver was then checked for noise figure and was found to have the normal value of 9 db above kT_oB with the antenna disconnected; and 15 db above kT_oB with the antenna connected (T_o being room temperature, and B the receiver bandwidth). Approximately five minutes before the scheduled arrival time of the capsule, the clock used for timing and film time mark generation was reset to correct local time (Eastern Standard Time) as broadcasted by the Bureau of Standards radio station WWV. This was a hand operation and therefore could not be expected to be more accurate than $\pm$ .5 seconds.

Throughout the period beginning about one hour before the scheduled arrival time, phone calls were received at irregular but frequent intervals from Mercury Control through the local communication station at San Salvador Island relaying "corrected" estimates of "horizon time." The last of these arrived not more than five minutes in advance. From this last telephone message, it was calculated that the recording cameras should be turned on at 14 hr. 33 min. 15 sec. local time, to provide 40 seconds of film recording before "overhead" and 60 seconds beyond "overhead."

The test procedure was set up as follows: The operator was to watch the monitoring scope, turn on the recording cameras at the proper moment, and manipulate the receiver input attenuator and range gate control. At about 14 hr. 32 min. 58 sec. the operator observed a signal at a range somewhat over 50 miles. Noting that this signal began to grow very rapidly in amplitude and decrease rapidly in range, the cameras were immediately started. The time, as noted by the operator's assistant, was 14:33:00. There was, possibly, a one to two second delay between the first appearance of the signal and the start of the cameras. The time of the camera start, that is 14:33:00, E. S. T. should be accurate to about .5 seconds, since it was an actual observation. The time of first appearance of the signal, 14:32:58 was estimated by the operator from memory after completion of the test and could, therefore, be several seconds off. Apparently, the Mercury capsule had arrived at the vicinity of the observation station somewhat earlier than had been expected.

III. Observational Results

The intensity-modulated range-time record thus obtained from the full range display is shown in Fig. 4(a) through (e). The corresponding pulse amplitude record from the fine range display is shown in Fig. 5(a) through (j), and some selected magnified segments of this record are shown in Figs. 6(a) through (d). The time scale in all cases refers to the time after the recording cameras were turned on, which had been fixed at 14 hr. 33 min. 00 sec., Eastern Standard Time. As noted by the operator viewing the monitoring scope, the returned signal was visibly unusual at its first appearance, being somewhat wider than the normal echo from a point target. The signal then began to grow very rapidly in amplitude and decrease in range. At times it grew wider, displayed a double peak and appeared to vary in amplitude rapidly in a somewhat irregular manner. Throughout this period, the operator attempted to keep the signal within the fine range gate and to adjust the input attenuator to prevent the signal from saturating. However, on account of the rapid changes in echo intensity, some temporary saturation of the receiver amplifier was found inevitable. When the signal reached a range of approximately 38 miles, about 13 seconds after the cameras were turned on, it appeared to be composed of two distinct parts: a narrow pulse of very high amplitude, and a considerably wider pulse of lower amplitude. The narrow pulse remained stationary at a range of about 38 miles, fully saturated in amplitude, while the wider pulse receded in range, decreased in amplitude and appeared to grow still wider. As the range gate could no longer encompass both signals, the operator tried to track the wider signal until it disappeared, then jumped back to the narrow signal. The wider signal was lost in the noise at a range of about 55 miles, while the narrow signal persisted for a few seconds at a fixed range of 35 miles and then it too disappeared.

While the time variation of these various signals seems difficult for one to follow from the original long film strip records, a condensed time scale picture of the intensity-modulated range-time record can perhaps be helpful in the interpretation of these results. This is illustrated by Fig. 7, which was obtained by projecting the original film strip through a narrow slit onto a printing paper strip, and then moving the film at about 10 times the speed of the paper strip during the exposure process. In this picture, the parabola-like range-time variation of the main echo* similar to the "head echoes" observed for large meteors,[9,10] and the short duration glints of the weaker echoes similar to those observed for faint meteors, become quite apparent. As was well-known in meteor studies, the parabolic shape of the radio echo indicates the existence of a non-aspect sensitive scattering region in uniform rectilinear motion past the observation point. This is illustrated in Fig. 8 which shows the vertical projection of a point A in uniform rectilinear motion at velocity V with resepct to a fixed ground observer O. If $R_{min.}$ is the perpendicular distance between the observer and the trajectory of A; x is the distance of A past the foot of the perpendicular along the trajectory; and θ is the angle between the instantaneous radius vector $\vec{R}$ and the perpendicular $\vec{R}_{min.}$, we have

$$\tan\theta = \frac{x}{R_{min.}} = \frac{V(t-t_o)}{R_{min.}} \tag{1}$$

$$\frac{R}{R_{min.}} = \sec\theta = \sqrt{1+\tan^2\theta} = \sqrt{1+\frac{V^2(t-t_o)^2}{R^2_{min.}}} \tag{2}$$

* Note that the apparent asymmetry of the main echo with respect to the minimum range point was largely due to the changes in the receiver sensitivity by the operator.

Thus, for small absolute values of the aspect angle θ, Eq. (2) becomes approximately,

$$\frac{R}{R_{min.}} \cong 1 + \frac{V^2}{2R^2_{min.}}(t - t_o)^2 \tag{3}$$

which is a parabola in the range-time plane.

A more detailed plot of the range-time history for the various scattering regions produced by the Mercury re-entry is given in Fig. 9. This is obtained from a close correlation between the coarse-range record shown in Fig. 4 and the fine-range record shown in Fig. 5, which allows range determination to the nearest tenth of a nautical mile.* The plotted points correspond to the brightest spot on the returned signal (i.e., the point of maximum amplitude in each pulse), and the vertical bars correspond to the decernable range spread of the pulse. Note that only representative points have been plotted, as there were approximately 2000 pulses altogether in the 20 sec time interval. In this plot, there appear to be five clearly separable echoes. We shall accordingly identify them as echoes A, B, C, D, and E, as marked on Fig. 9. In addition, there were two fairly well separated branches of echo A, which we shall denote A_1 and A_2. From the apparent strength and persistence of Echo A, one may conclude that it was most likely due to the ionized trail produced by the MA-6 capsule itself. The weaker echoes, which

* Note that there was some jitter in the fine range gate from time to time, which has been duly taken into account in the range determination.

showed only short duration glints characteristic of faint meteor echoes, may be interpreted as caused by smaller ionized trails produced by fragments of the disintegrating retro-rocket package reported by Col. Glenn.[11] Since these echoes appeared at later times and came from closer ranges (i.e , lower altitudes), the objects producing the ionized trails which gave these echoes must have separated from the main capsule for a considerable period of time before they arrived at the observation station; and they must have higher drag area/weight ratio than the capsule itself. The two branch echoes A_1 and A_2, on the other hand, were probably caused by ionized trails produced by fragments separating from the main capsule only moments before the capsule arrived at the observation station.

By best-fitting the solid points of echo A to Eq. (2), one may deduce an apparent velocity for the strongest echoing region in the main capsule trail. This is illustrated by the solid curve shown in Fig. 9, which indicates a velocity of 22,600 ft/sec. As one can see from the post-flight trajectory data shown in Fig. 3, this apparent velocity is only about two percent lower than the NASA value of 23,000 ft/sec for the capsule itself. The minimum range of 228,000 ft for echo A, which corresponds to an altitude of about 227,000 ft, is about three percent higher than the NASA value of 220,000 ft.

By noting that the main ionized trail was also visible to the radar at some distance ahead of the brightest spot of the trail, as evident from the well-defined range spread of the echo from time to time (see for example Figs. 5(c) and 6(a)), one may conclude that the brightest spot of the trail must be located at some distance behind the capsule itself. The dotted curve in Fig. 9, which is approximately the outer envelope of the decernable range spread of echo A, indicates that the capsule must have led the brightest spot of the trail by at least 0.6 sec, or approximately 14,000 ft. The fact that the apparent velocity for the trail agreed well with the velocity of the capsule suggests that this lead distance, aside from some short period fluctuation, did not change with time in any significant manner during the observation.

As indicated by the symbol t_{M_0} in Fig. 9, the "overhead" time for the MA-6 capsule past our observation station at San Salvador Island can now be fixed at 14 hr. 33 min. 07 sec., E. S. T., which is about six seconds later than that indicated by the NASA post-flight data, but about 48 seconds earlier than what the up-range stations estimated just before re-entry.

From the calibrated pulse amplitude record shown in Fig. 5, together with the known transmitted power, which was continuously monitored through a calibrated power meter during the experiment, one may deduce the "equivalent isotropic scattering cross-section," which we shall presently define, for the various ionized trails as functions of time.

For observation of isolated point-targets* using radar systems with identical transmitting and receiving antennas, it has been customary to define an isotropic scattering cross-section σ, such that the received power P_r is related to the transmitted power P_t through the

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* That is, targets with physical dimensions that are small compared with the range resolution of the radar and also with the length of the first Fresnel zone $\sqrt{2\lambda R}$ about the target.

equation[12]

$$\frac{P_r}{P_t} = \frac{\lambda^2 G^2 \sigma}{64 \pi^3 R^4} \tag{4}$$

where λ is the wavelength; R is the range; and G is the "antenna gain" over an isotropic pattern, which is generally a function of antenna geometry and orientation with respect to the target. The implied time relationship between P_r and P_t was that there is a constant time delay 2R/C between the two, corresponding to the two-way propagation time over the range R, so that a transmitted pulse of certain shape (see Fig. 10)

$$P_t(\tau) = P_{t_o} \cdot \phi(\tau) \tag{5}$$

would result in a received pulse of identical shape.* Thus, if there were a large number of <u>independent</u> point targets distributed over a range interval between R'_1 and R'_2, which is large compared with the range spread of the transmitted pulse, and $\Omega(R')dR'$ is the sum of the back-scattering cross-sections of the point targets that lie within the differential range interval between R' and R' + dR', the received power at any time t = 2R/C after the emission of the transmitted pulse would be given by,

---

* Assuming that the rate of change of R is small compared with the velocity of propagation C; and that there is no distortion of the pulse shape by the receiver.

$$P_r(R) = \frac{P_{t_o}\lambda^2 G^2}{64\pi^3}\int_{R_1'}^{R_2'} \phi\left(\frac{2R}{c} - \frac{2R'}{c}\right)\frac{\Omega(R')}{R'^4}\, dR' \qquad (6)$$

If the transmitted pulse were sufficiently sharp and the distribution of point targets were sufficiently smooth so that $\Omega(R')/R'^4$ does not vary appreciably over the range spread of the transmitted pulse, then the above equation may be approximated by,

$$P_r(R) \cong \frac{P_{t_o}\lambda^2 G^2}{64\pi^3} \cdot \frac{\Omega(R)}{R^4} \cdot \Delta R \qquad (7)$$

where

$$\Delta R \equiv \frac{c}{2}\int_{-\infty}^{\infty} \phi(\tau)\, d\tau \qquad (8)$$

is the characteristic thickness of the range cell.

For an extended scattering region, such as the ionized trail under consideration, one may therefore define an equivalent isotropic scattering cross-section $\sigma_E(R)$ according to the instantaneous returned signal intensity, such that the received power corresponding to a particular range R is given by,

$$P_r(R) = \frac{P_{t_0} \lambda^2 G^2}{64 \pi^3 R^4} \cdot \sigma_E(R) \qquad (9)$$

It may be noted that even though the above definition of $\sigma_E(R)$ has been purely phenomenological and arbitrary, it has the obvious advantage that for the case where the extended scattering region can be approximated by a collection of independent point-scatterers, the equivalent isotropic scattering cross-section becomes,

$$\sigma_E(R) = \Omega(R) \cdot \Delta R \qquad (10)$$

The "equivalent isotropic scattering cross-section" as defined by Eq. (9) for the brightest spots on the various ionized trails is plotted in Fig. 11 as functions of time. In obtaining these numerical results we have taken G = 2 = constant, as the gain for the half-wave dipole antenna for want of a more precise antenna pattern determination.* This introduced some uncertainty in the absolute magnitude of the deduced

* It may be noted that for an idealized Hertzian dipole, $G = \frac{3}{2} \cos^2 \theta$ where θ is the angle between the line of sight and the plane which passes through the middle of the dipole and perpendicular to the axis of the dipole (see Refs. 1 and 12). The actual dipole antenna employed in this experiment had a small ground plane which was made of chicken-wire, 4 ft wide by 16 ft long, and was placed about 4 ft underneath the dipole. Therefore, a numerical value G = 2 was used to allow for the somewhat higher gain of the antenna at small value of θ.

cross-section, but this uncertainty is not likely to be greater than a factor of 2 or 3 since the physical dimensions for all the antenna elements involved were smaller than the wavelength. It may also be mentioned that the results for trails A, A_2, and E were obtained directly from the calibrated pulse amplitude record;* but the results for trails A_1, B, C, and D, which fell outside the fine range gate, were estimated from the intensity-modulated range-time record and were therefore less accurate. Again, only representative points among the 2000 pulses are plotted, but the scintillating (or fading) histories are quite faithfully reproduced. It is seen that, as for the case of meteors, the equivalent cross-sections for the ionized trails are generally many orders of magnitude greater than the geometrical cross-sections of the solid objects themselves. In fact, the peak value of about 10^6 square meters, or 1 square kilometer, reached by trail A near the point of normal incidence (i.e., minimum range point) at $t = 7.5$ sec is about 3×10^5 times greater than the geometrical projected area of the MA-6 capsule.

IV. Theoretical Interpretation

As has already been mentioned earlier, the glinting echoes from trails B, C, D and E are similar to those of small meteors[1,2] and are therefore relatively easy to understand. The time variation of the echo,

* During the periods when the output stage of the receiver amplifier was saturated, the peak received power was estimated from the width of the saturated pulse, assuming that the natural shape of the pulse (i.e., pulse shape at the receiver input) did not vary appreciably throughout the period of saturation.

and the duration of the glint, can all be interpreted in terms of the diffraction pattern for a moving line source of ionized gas (the transverse dimension of which is much smaller than the wavelength) past the point of normal incidence.[1,2] The peak echoing intensity can also be accounted for by existing theories. For example, according to the theory of Lovell and Clegg,[13] the equivalent isotropic scattering cross-section at the point of normal incidence for an underdense meteor trail (i.e., $N_e < N_e^*$) that is long compared with the length of the first Fresnel zone $\sqrt{2\lambda R}$ is given by,

$$\sigma_E = \frac{2}{\pi}\left(\frac{N_e}{N_e^*}\right)^2 \lambda R \qquad (11)$$

where N_e is the number of free electrons per unit length of the trail (assumed to be a constant), and

$$N_e^* \equiv \frac{m_e c^2}{\pi e^2} \cong 10^{12} \text{ electrons/cm} \qquad (12)$$

is the critical electron line-density. For a long overdense trail (i.e., $N_e > N_e^*$), Kaiser and Closs,[14] and Greenhow,[15] have shown that the corresponding cross-section is given by,

$$\sigma_E \cong \frac{2}{\pi}\sqrt{\frac{N_e}{N_e^*}}\ \lambda R \qquad (13)$$

Thus, for trails B, C, D, and E, $R \cong 35$ N. Mi. $\cong 6.5 \times 10^4$ meters, so that for $\lambda = 10$ meters, we have $\lambda R \cong 6.5 \times 10^5 \text{ m}^2$. Therefore, in order to account for the peak echoing intensity of these trails, as shown in Fig. 11, it would only be necessary to assign a mean electron line-density that is slightly super-critical for trail B; and line-densities that are somewhat sub-critical for trails C, D, and E.

The maximum cross-section of about $1.6 \times 10^6 \text{ m}^2$ for the main trail A can likewise be accounted for by the high-light from the strongly reflecting front segment of the ionized wake at normal incidence. In view of the fact that the 10-meter wavelength employed was large compared with the diameter of the MA-6 Mercury capsule, which was about two meters,[7] it is to be expected that the front segment of the ionized wake would appear electromagnetically smooth to the incident wave, irrespective of whether the flow behind the capsule was laminar or turbulent. As we have mentioned earlier in Section III, the Mercury capsule appeared to have led the brightest spot of the trail by at least about 14,000 ft, or 4,300 meters, so that the length of the strongly reflecting front segment of the wake must have been of the same magnitude. Since this was sufficiently long compared with the length of the first Fresnel zone $\sqrt{2\lambda R_{min.}} \cong 1{,}200$ meters, one may use Eq. (12) to estimate the electron line-density required to give the observed maximum echoing strength. In doing this, one obtains $N_e \cong 2 \times 10^{13}$ electrons/cm, which is not inconsistent with what one would expect from a realistic consideration of the ionization history in the hypersonic flow field.[16,17*]

The time dependence of the main trail A is somewhat more complicated, but the gross feature of this long-lasting echo (i.e., ignoring the short-period scintillation, or fading, for the moment) can still be accounted for by a simple model of a turbulent, diffuse-scattering wake. From laboratory experiments, Hidalgo, Taylor and Keck[18] have found that the luminous wake behind spherical pellets at hypersonic speeds in air becomes turbulent in appearance whenever the pellet Reynolds number

$$R_e \equiv \frac{\rho_\infty V D}{\mu_\infty} \tag{14}$$

exceeds a value of about 6×10^4. Here ρ_∞ and μ_∞ denote respectively the undisturbed air density and viscosity; V the pellet velocity; and D the pellet diameter. Since the flight Reynolds number for the MA-6 Mercury capsule during the period of observation (i.e., D = 6 ft and V = 23,000 ft/sec at 220,000 ft altitude) was about 10^5, it is reasonable to expect a turbulent wake behind the capsule. Thus, if the fluctuating electron density in the turbulent wake remains sufficiently high at a distance behind the capsule where the wake boundary becomes "rough" with

* Note that in a situation where the electron concentration (i.e., number of electrons per unit volume) in the flow field is mainly controlled by the electron-ion recombination rate, the electron line-density would be insensitive to turbulent diffusion and mixing, so that inviscid stream-tube calculations, such as those illustrated in Ref. 17, would suffice for rough estimate of the local electron line-density. According to these calculations, the total electron line-density in the wake at distances greater than 50 diameters behind the MA-6 Mercury capsule should be of the order of 10^{14} electrons/cm.

respect to the incident wavelength, diffuse scattering would develop.

In Fig. 12, the equivalent isotropic scattering cross-section for the brightest spot of trail A is plotted as a function of the aspect angle θ for comparison with the maximum cross-section that can be expected from a diffuse-scattering wake. The aspect angle θ plotted here is based on the range-time relationship of the mean curve for trail A (i.e., solid curve shown in Fig. 9), since the lateral displacements of the branch trails A_1, A_2 from the capsule trajectory during the time of observation were not known. The maximum diffuse scattering cross-section for a segment of wake intercepted by a concentric spherical cell of thickness ΔR is simply the geometrical projected area of the same segment of wake in the plane normal to the line of sight. That is,

$$(\sigma_{D.S.})_{max.} = b_w \cdot \Delta S \tag{15}$$

where b_w is the geometrical width of the wake, and

$$\begin{aligned} \Delta S &= 2R \cdot \tan \frac{\Delta\theta}{2} \\ &\cong \Delta R \cdot \cot\theta \qquad \left(\theta >> \sqrt{\frac{\Delta R}{R_{min.}}}\right) \end{aligned} \tag{16}$$

is the normal projection of the wake segment intercepted by the range cell (see Fig. 7). As indicated on Fig. 12, the diffuse-scattering curve $(\sigma_{D.S.})_{max}$ plotted for comparison with observation was based on a range cell thickness of 230 meters (corresponding to an effective pulse width of 1.5 μ-sec), and on a wake width of 30 meters. It may be noted that 30 meters is the geometrical width to be expected of a turbulent wake at a distance of 2,000 diameters behind a sphere of 1.5 meters at hypersonic speeds.[16,19] It is, therefore, also approximately the width to be expected of a turbulent wake at a distance of about 14,000 ft behind the MA-6 Mercury capsule, which had an overall diameter of 6 ft, but was a somewhat blunter object than a sphere of the same diameter.[7]

It is seen that the observed echoing intensity from the brightest part of the trail was indeed very close to the maximum possible value for diffuse scattering, except in the regions where the branch echoes A_1 and A_2 predominated. While the excess of the observed echo from the main trail A over the diffuse-scattering curve at small angles can readily be accounted for by high-light from the front part of the trail, as we have already demonstrated earlier in this section;* the excess of the echoes from branch trails A_1 and A_2 over the diffuse-scattering curve at large aspect angles can only be attributed to some explosive nature of the disintegrating fragments which caused these branch trails.

In order to see if it is at all reasonable for the observed scattering intensity from the main trail A at large aspect angles (i.e., $|\theta| \gg \sqrt{\lambda/R_{min.}}$) to have approached the maximum possible value under the given experimental conditions, one may proceed to estimate the minimum electron density fluctuation in the turbulent wake in order to give the observed scattering intensity as follows:

* Some scintillation of the high-light is to be expected as the leading edge of the reflecting segment passed successively through the first few Fresnel diffraction zones. However, scintillation of the echo at large aspect angles cannot be accounted for in this manner.

In a treatment of radio wave scattering from irregularities in the ionosphere, Booker[20] has shown that the power scattered per unit solid angle, per unit incident power density, from a unit volume of an inhomogeneous dielectric medium is given by,

$$S = \overline{\left|\frac{\delta\epsilon}{\epsilon}\right|^2} \frac{\pi^2 \sin^2\chi}{\lambda^4} \cdot F(\underline{k}_s - \underline{k}_i) \tag{17}$$

where $\overline{|\delta\epsilon/\epsilon|^2}$ is the mean square fractional deviation of the dielectric constant of the inhomogeneous medium; χ is the angle between the direction of scattering and the electric field vector of the incident wave; $\underline{k}_s$ and $\underline{k}_i$ are propagation vectors of magnitude $2\pi/\lambda$ along the direction of the scattered and the incident wave respectively; and

$$F(\underline{k}_s - \underline{k}_i) \equiv \int_U \psi(\underline{r}) e^{j(\underline{k}_s - \underline{k}_i)\cdot\underline{r}} \, dU \tag{18}$$

is the Fourier transform of the normalized autocorrelation function $\psi(\underline{r})$ of $\delta\epsilon/\epsilon$, which is in turn defined by ($\underline{r}$ being the radius vector within the volume of integration U; and $\delta\epsilon^*/\epsilon$ being the complex conjugate of $\delta\epsilon/\epsilon$),

$$\psi(\underline{r}) \equiv \frac{\int_U \frac{\delta\epsilon^*}{\epsilon}(\underline{r}')\frac{\delta\epsilon}{\epsilon}(\underline{r}+\underline{r}')\,dU'}{\overline{\left|\frac{\delta\epsilon}{\epsilon}\right|^2}\,U} \tag{19}$$

The scattering coefficient S as derived by Booker was based on the first Born approximation and the neglect of multiple scattering,[21] so that Eq. (17) is applicable only to scattering regions that are not too dense, such as that corresponding to the dilute ionized wake at large distances behind a hypersonic object(which we shall refer to as the "far wake"). It may be noted that at the altitude under consideration (i.e., h = 220,000 ft), the ambient air density was approximately 10^{-4} times the standard sea level density, so that the momentum transfer collision frequency, ν_c , between free electrons and air molecules[22] in the far wake should have been about 5×10^7 collisions/electron-sec. Since this is sufficiently small compared with the angular frequency of the incident wave $\omega = 2\pi f \cong 2 \times 10^8$ $\sec^{-1}$, the ionized wake may be treated as a lossless medium with local dielectric constant

$$\frac{\epsilon}{\epsilon_o} \cong 1 - \frac{n_e}{n_e^*} \tag{20}$$

where n_e is the local electron density; and $n_e^* = \frac{\pi m_e}{e^2} f^2$ $\cong$ 1.2×10^7 electrons/cm^3 is the critical electron density corresponding to plasma resonance at the incident wave frequency f. Thus, for a sub-critical wake (i.e., mean electron density $\overline{n_e} < n_e^*$), Eq. (17) becomes,

$$S \cong \frac{\overline{(\delta n_e)^2}}{(n_e^* - \overline{n}_e)^2} \cdot \frac{\pi^2 \sin^2 \chi}{\lambda^4} \cdot F(\underset{\rightarrow}{k_s} - \underset{\rightarrow}{k_i}) \qquad (21)$$

The Fourier transform $F(\underset{\rightarrow}{k_s} - \underset{\rightarrow}{k_i})$ for some typical autocorrelation functions of δn_e has been carried out by Booker and presented in Table 2 of Ref. 20. From these, one can calculate the scattering coefficient and hence the equivalent isotropic scattering cross-section per unit volume of the dilute ionized wake if the autocorrelation function for the fluctuating electron density were known. For example, if the autocorrelation function were an isotropic Gaussian function, such that

$$\psi(\underset{\rightarrow}{r}) = e^{-r^2/\ell^2} \qquad (22)$$

Table 2 of Ref. 20 gave,

$$S = \frac{1}{16\sqrt{\pi}} \frac{\overline{(\delta n_e)^2}}{(n_e^* - \overline{n}_e)^2} \frac{\ell^3}{\lambda\!\!\!^{-4}} \cdot \sin^2 \chi \cdot e^{-\left(\frac{\ell}{\lambda\!\!\!^{-}} \sin \frac{\beta}{2}\right)^2} \qquad (23)$$

where $\lambda\!\!\!^{-} \equiv \lambda/2\pi$, and β is the angle between the wave vectors $\underset{\rightarrow}{k_s}$ and $\underset{\rightarrow}{k_i}$. Thus, for back-scattering, $\chi = \frac{\beta}{2} = \frac{\pi}{2}$

so that Eq. (23) becomes

$$S = \frac{1}{16\sqrt{\pi}} \frac{\overline{(\delta n_e)^2}}{(n_e^* - \bar{n}_e)^2} \frac{\ell^3}{\lambda^4} \cdot e^{-\ell^2/\lambda^2} \tag{24}$$

Note that the back-scattering cross-section as defined by Eq. (4) for a unit volume of the ionized wake is now given by 4π times the above quantity, the equivalent cross-section as defined by Eq. (9) due to diffuse scattering for the entire segment of wake bounded within the range cell of thickness ΔR is therefore given by (treating each scattering volume element as independent, and neglecting any spatial variation of S within the segment),

$$\sigma_{D.S.} = \frac{\pi b_w^2}{4} \cdot \frac{2R\tan(\Delta\theta/2)}{\cos\theta} \cdot 4\pi S \tag{25}$$

$$= \frac{\pi^{3/2} b_w^2 R \tan(\Delta\theta/2)}{8\cos\theta} \cdot \frac{\overline{(\delta n_e)^2}}{(n_e^* - \bar{n}_e)^2} \frac{\ell^3}{\lambda^4} e^{-\frac{\ell^2}{\lambda^2}}$$

If one now divides Eq. (25) by Eq. (15), one obtains (for $\cos\theta \cong 0.9$, and $b_w/\lambda \cong 6\pi$).

Table I. Relative diffuse scattering intensity from turbulent wake as a function of root-mean-square electron density fluctuation and autocorrelation length, assuming isotropic Gaussian autocorrelation function.

$\frac{\sigma_{D.S.}}{(\sigma_{D.S.})_{max.}}$		$\frac{\ell}{\lambda}$ = 0.1	0.2	0.5	1	2	5
$\frac{\sqrt{\overline{(\delta n_e)^2}}}{n_e^* - \overline{n}_e}$	0.05	1.8×10^{-5}	1.4×10^{-4}	1.8×10^{-3}	6.7×10^{-3}	2.7×10^{-3}	3.2×10^{-11}
	0.10	7.2×10^{-5}	5.6×10^{-4}	7.1×10^{-3}	2.7×10^{-2}	1.1×10^{-2}	1.3×10^{-10}
	0.25	4.5×10^{-4}	3.5×10^{-3}	4.4×10^{-2}	0.168	6.7×10^{-2}	7.9×10^{-10}
	0.6	2.6×10^{-3}	2.0×10^{-2}	0.256	0.966	0.386	4.6×10^{-9}

$$\frac{\sigma_{D.S.}}{(\sigma_{D.S.})_{max.}} = \frac{\pi^{3/2}}{16\cos\theta} \cdot \frac{b_w}{\lambda\!\!\!^-} \cdot \frac{\overline{(\delta n_e)^2}}{(n_e^* - \overline{n}_e)^2} \left(\frac{\ell}{\lambda\!\!\!^-}\right)^3 e^{-\frac{\ell^2}{\lambda\!\!\!^-{}^2}} \qquad (26)$$

$$\cong 7.3 \frac{\overline{(\delta n_e)^2}}{(n_e^* - n_e)^2} \left(\frac{\ell}{\lambda\!\!\!^-}\right)^3 e^{-\frac{\ell^2}{\lambda\!\!\!^-{}^2}}$$

The relative diffuse scattering intensity $\sigma_{D.S.}/(\sigma_{D.S.})_{max.}$ for some typical values of $\sqrt{\overline{(\delta n_e)^2}}/(n_e^* - \overline{n}_e)$ and $\ell/\lambda\!\!\!^-$ as given by the above formula is shown in Table I. From this table, it is clear that in order for the relative diffuse scattering intensity to approach unity, there must exist in the turbulent wake a large population of irregularities, or "eddies," of characteristic dimension lying in the range $0.8 \lesssim \ell \lesssim 3$ meters; and that the root-mean-square electron density fluctuation associated with these "eddies" must have been not too small in comparison with n_e^* or with ($n_e^* - \overline{n}_e$). Similar conclusions can be drawn when one considers other possible forms of the autocorrelation function for δn_e, and takes into account the effects of multiple scattering and wave amplitude attenuation in the perhaps not-too-subcritical ionized wake.*

V. Discussion

In the preceding section, we have shown that all major features of the radio echoes from the various ionized trails generated by the MA-6 Mercury capsule and its fragments can be satisfactorily explained. However, there remain some questions concerning the detailed features of the main echo, which we shall now briefly discuss.

(i) The Leading Edge Echo: It may be noted that quantitative interpretation of the diffuse scattering intensity from the turbulent wake was based on the assumption that the decernable leading edge of the main echo, which appeared to have led the brightest spot of the trail by about 0.6 sec, may be used to determine the approximate distance between the MA-6 capsule and the most intense scattering region. In view of the fact that the back scattering cross-section of the solid capsule itself should be at most of the order of 10 m^2, and that the minimum detectable cross-section for the radar at 40 mile range was of the order of $10^2 m^2$, a question naturally arose as to the validity of such an assumption. While the answer to this question is by no means

* As we have mentioned earlier in another footnote, according to the finite reaction rate hypersonic flow field calculations (Ref. 17), the total electron line-density in the wake at distances greater than 50 diameters behind the MA-6 Mercury capsule should be of the order of 10^{14} electrons/cm and should decrease very slowly with time. Therefore, the mean electron density $\overline{n_e}$ over most of the volume of the 30-meter diameter wake could approach the critical electron density $n_e^* \cong 10^7$ electrons/cm^3, even if one allows for the fact that there would be a high electron concentration in the inner core of the wake due to the finite turbulent diffusion time.

certain, consideration of the photoionization effect from the shock wave tends to substantiate strongly the plausibility of such an assumption. That is, at high altitudes where the photon mean free path is long, the far ultraviolet radiation originated from the high temperature reaction zone behind the shock wave[24] around the blunt-nose capsule may photo-ionize the cold ambient air at sufficiently great distance ahead of the shock to produce a large diameter "ionization halo" of sufficiently high electron density to be strongly reflecting with respect to low frequency electromagnetic waves.* The approximate size of such an "ionization halo" may be estimated as follows:

Let Γ_i be the number of ionizing photons emitted from a point source per unit solid angle per unit time; λ_i be the mean free path of the ionizing photons in the ambient atmosphere; so that the instantaneous rate of photoionization per unit volume at a distance r from the point source is given by,

$$\frac{dn_e}{dt} = \frac{\Gamma_i}{\lambda_i r^2} e^{-\frac{r}{\lambda_i}} \tag{27}$$

If the point source is moving at a constant velocity $\underrightarrow{V}$, then the cumulative electron density for a volume element at a fixed perpendicular distance $y = r \cos \varphi$ from the velocity vector $\underrightarrow{V}$ would be given by (neglecting recombination, attachment, and diffusion),

* The possibility of such "ionization halo" formation by re-entry objects was first pointed out by Dr. A. R. Kantrowitz at the Avco-Everett Research Laboratory in 1958.

$$n_e = \frac{\Gamma_i}{y \lambda_i V} \int_{-\frac{\pi}{2}}^{\varphi} e^{-\frac{y}{\lambda_i \cos\varphi'}} d\varphi' \qquad (28)$$

For $y/\lambda_i >> 1$, the above integral may be replaced by an asymptotic series (saddle-point expansion),

$$n_e \sim \frac{\Gamma_i}{y^2 V} \sqrt{\frac{\pi y}{2\lambda_i}} e^{-\frac{y}{\lambda_i}} \Big\{ 1 + \frac{\varphi}{|\varphi|} \mathrm{erf}\left(\sqrt{\frac{y}{2\lambda_i}}\varphi\right)$$

$$- \frac{15\sqrt{\pi}}{48} \frac{\lambda_i}{y} \Big[1 + \frac{\varphi}{|\varphi|} \mathrm{erf}\left(\sqrt{\frac{y}{2\lambda_i}}\varphi\right)$$

$$+ \left(\sqrt{\frac{2y}{\pi \lambda_i}} \varphi + \frac{1}{3} \sqrt{\frac{2y^3}{\pi \lambda_i^3}} \varphi^3 \right) e^{-\frac{y}{2\lambda_i}\varphi^2} \Big]$$

$$+ \cdots\cdots\cdots\cdots \Big\} \qquad (29)$$

so that at the minimum distance of approach (i.e., $\varphi = 0$),

$$n_e \sim \frac{\Gamma_i}{y^2 V} \sqrt{\frac{\pi y}{2\lambda_i}} e^{-\frac{y}{\lambda_i}} \left(1 - \frac{15\sqrt{\pi}}{48} \frac{\lambda_i}{y} + \cdots\cdots \right) \qquad (30)$$

The ultraviolet radiation intensity in the spectral range $8 < h\nu <$ 14 e.v. from a normal shock wave propagating at a velocity of 6.8×10^5 cm/sec (or 22,300 ft/sec) in air at an initial pressure of 20 μHg has been measured by Camm, et al.[25] The total intensity per unit shock surface per unit solid angle was found to be approximately 3×10^{-2} watts/cm^2-steradian. Extrapolating this to the air density of 1.2×10^{-4} N.T.P. (corresponding to 220,000 ft altitude) according to the density dependence suggested by Hammerling,* and considering an equivalent normal shock area of about 4 m^2, one obtains 5×10^3 watts for the total radiation in this spectral range from the entire bow shock wave around the MA-6 capsule. Assuming that only one-third of this total radiation was in the spectral range $12 < h\nu < 14$ e.v. (see Ref. 24), then the total photon flux available for photoionization of O_2 ahead of the shock should be,

$$\Gamma_i \sim 10^{21} \text{ photons/steradian-sec.} \tag{31}$$

According to Po Lee and Weissler,[26] the photoionization cross-section σ_i for O_2 in the energy range $12 < h\nu < 14$ e.v. is of the order of 2×10^{-18} cm^2, so that at the altitude of interest,

$$\lambda_i \equiv (\sigma_i n_{O_2})^{-1} \cong 5 \text{ meters} \tag{32}$$

* Note that the total radiation intensity from the high temperature reaction zone behind a normal shock wave should be density-independent, except for the "collision limiting" effect discussed in Refs. 24 and 25. Since the precise air density at which this effect sets in is actually not known, the suggested density correction, which amounts to a factor of about 4 in this case, must be regarded as tentative.

If one now substitutes (31) and (32) into (30), one obtains $n_e \sim 10^7$ electrons/cm^3 at y = 20 meters and φ = 0. Similarly, by substituting (31) and (32) into Eq. (28) or (29), one may obtain the coordinates with respect to the moving point source for a surface corresponding to any given electron density. This is illustrated in Table II where the approximate polar coordinates for the surface corresponding to $n_e = 10^7$ electrons/cm^3 are shown.*

Table II. Polar coordinates for a surface of constant electron density $n_e = 10^7/cm^3$ around the MA-6 capsule at 220,000 ft due to photoionization of O_2. ($\varphi = -\pi/2$ refers to the forward direction.)

φ	$-\frac{\pi}{2}$	$-\frac{\pi}{3}$	$-\frac{\pi}{6}$	0
r, meter	17.3	17.6	18.5	20

It is seen that the mean radius of curvature of this surface in the forward direction is approximately 18 meters, so that one may expect a back scattering cross-section of the order of 10^3 m^2 from such a surface over a considerable range of aspect angles at the radio frequency under consideration. It may be noted that this is just what was needed

* It may be noted that the point source approximation is applicable only to the half-space forward of the MA-6 capsule (i.e., $-(\pi/2) \leq \varphi \leq 0$). In the rear half-space, the ambient air will be in the shadow of the capsule and hence would not see much of the ultraviolet radiation from the normal shock surface. Therefore, one may expect the electron density to begin to decrease (by recombination and attachment) as soon as the volume element passes the φ = 0 point.

in order to account for the observed leading edge echo.*

(ii) Fading Frequency: From the intensity-modulated record shown in Fig. 4, as well as from the pulse amplitude records shown in Figs. 5 and 6, it is seen that there was definite periodic fading of the main echo. By following the distinct successive strengthening and weakening of the main echo, the fading (or scintillating) history of the echo is approximately reproduced in Fig. 11. It is seen that deep fading appeared to occur quite regularly at a frequency of between 2 and 5 cycles/sec over the whole period of observation. While some of the fading near the point of normal incidence (see Fig. 12) may or may not be attributable to Fresnel diffraction, as we have mentioned earlier, the fading at angles far away from the specular aspect definitely was not related to the diffraction pattern as the length of the successive Fresnel zones rapidly approaches $\lambda/4$ for $|\theta| \gg \sqrt{\lambda/R_{min.}} \sim 0.7^\circ$.

The cause of fading by the radiation pattern of the transmitting-receiving antenna or by ground interference was unlikely, if at all possible, since the antenna was basically a dipole.

The cause of fading by the oscillatory motion of the MA-6 capsule can also be ruled out since the range cell thickness ΔR was small compared with the longitudinal dimension of any undulation of the ionized wake that might have been caused by the oscillatory motion of the capsule.

* The dissociative recombination coefficient for molecular ions generally shows an inverse temperature dependence, so that the O_2^+ ions produced by photoionization in the cold ambient air may be expected to have a shorter life time than the ions in the warmer wake. In other words, the presence of the "ionization halo" may have very little effect on the echoing characteristics of the far wake.

The only remaining plausible explanation is, therefore, that the observed fading of the echo was due to the random motion of the scattering centers in the turbulent wake. In fact, the apparent amplitude distribution of the fading echo is not unlike that of the Rayleigh type fading observed by Booker in ionospheric scattering.[20] If one accepts such an explanation, then the random velocity of the scattering centers as may be deduced from the Doppler spread (i.e., fading frequency) should lie in a range somewhere between 20 and 50 meters/sec. It may be noted that this magnitude of random velocity is not at all unreasonable for the electron density irregularities in the turbulent wake under consideration.

While the above interpretation of the existing experimental result is still preliminary and tentative, the present physical model of the ionized wake already appears to be sufficiently self-consistent to allow some speculative application to meteoric problems. In particular, it is felt that many quantitative as well as qualitative aspects of the "meteoric head echo" reported by McKinley,[8] Millman[9] and others can be treated in a similar manner. Thus, the appearance of "double head echo" may be attributed to the existence of a sufficiently large "ionization halo" in the front, and a strongly scattering turbulent wake in the back, as we have observed during the MA-6 re-entry. If the "transition Reynolds number" as defined by Eq. (14) at meteoric velocities were known, then the onset altitude of the spreading head echo may be used for meteor size determination.

Aside from their possible connection with meteoric phenomena, the general results from the present experiment clearly demonstrated that the ionized trail generated by a large hypersonic object, such as a re-entering manned satellite, would produce strong radio echoes over great distances and over a wide range of aspect angles even during the early phase of re-entry. This strong echoing characteristic of the wake could, perhaps, be utilized as a navigational aid for re-entering satellites and spacecraft in the future.

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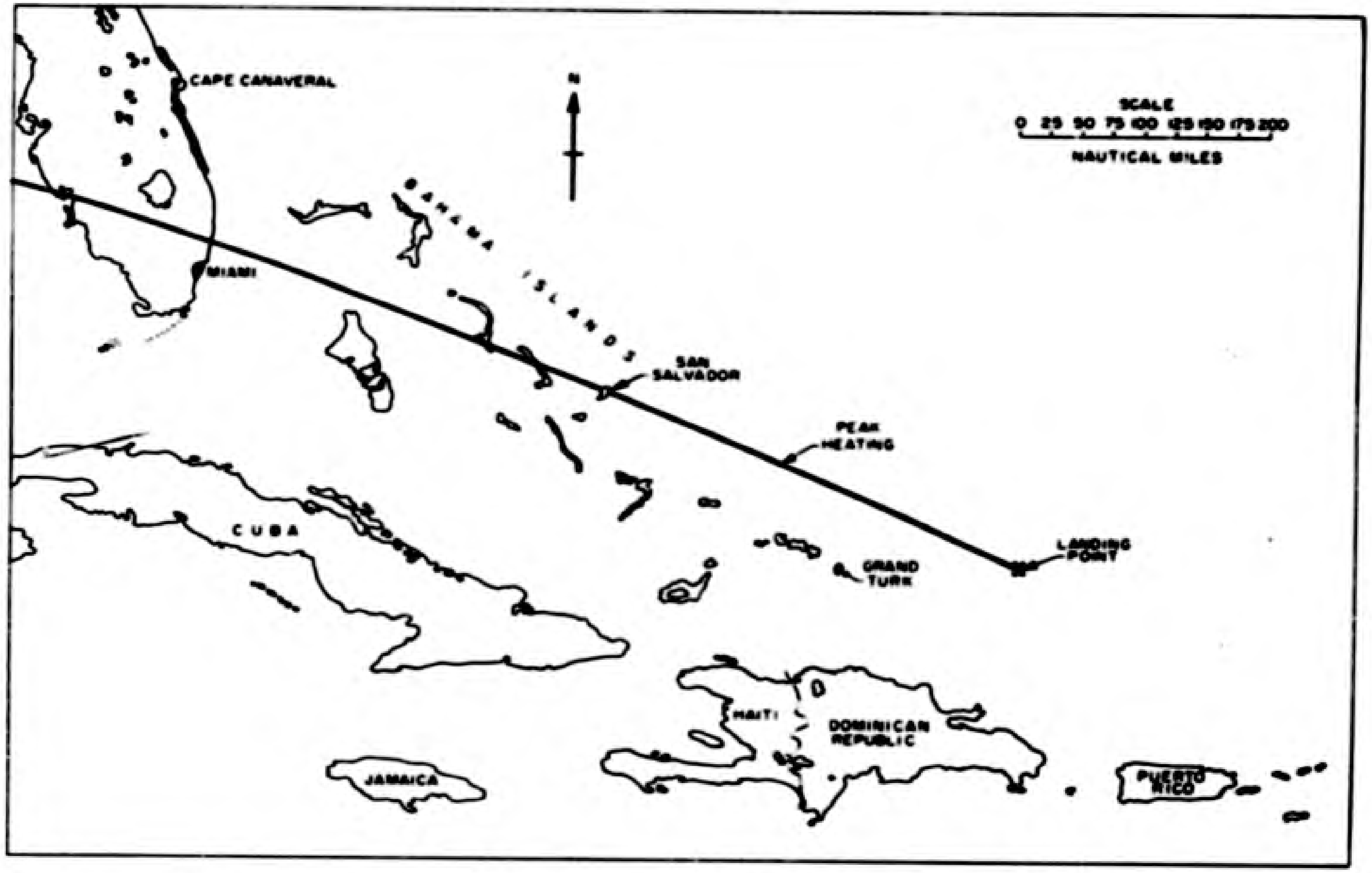

Fig. 1 Projection of the re-entry trajectory over the Atlantic Ocean for the MA-6 Mercury orbital flight of February 20, 1962. The pulsed radar employed in this experiment was located on San Salvador Island, approximately 370 nautical miles up-range from the landing point.

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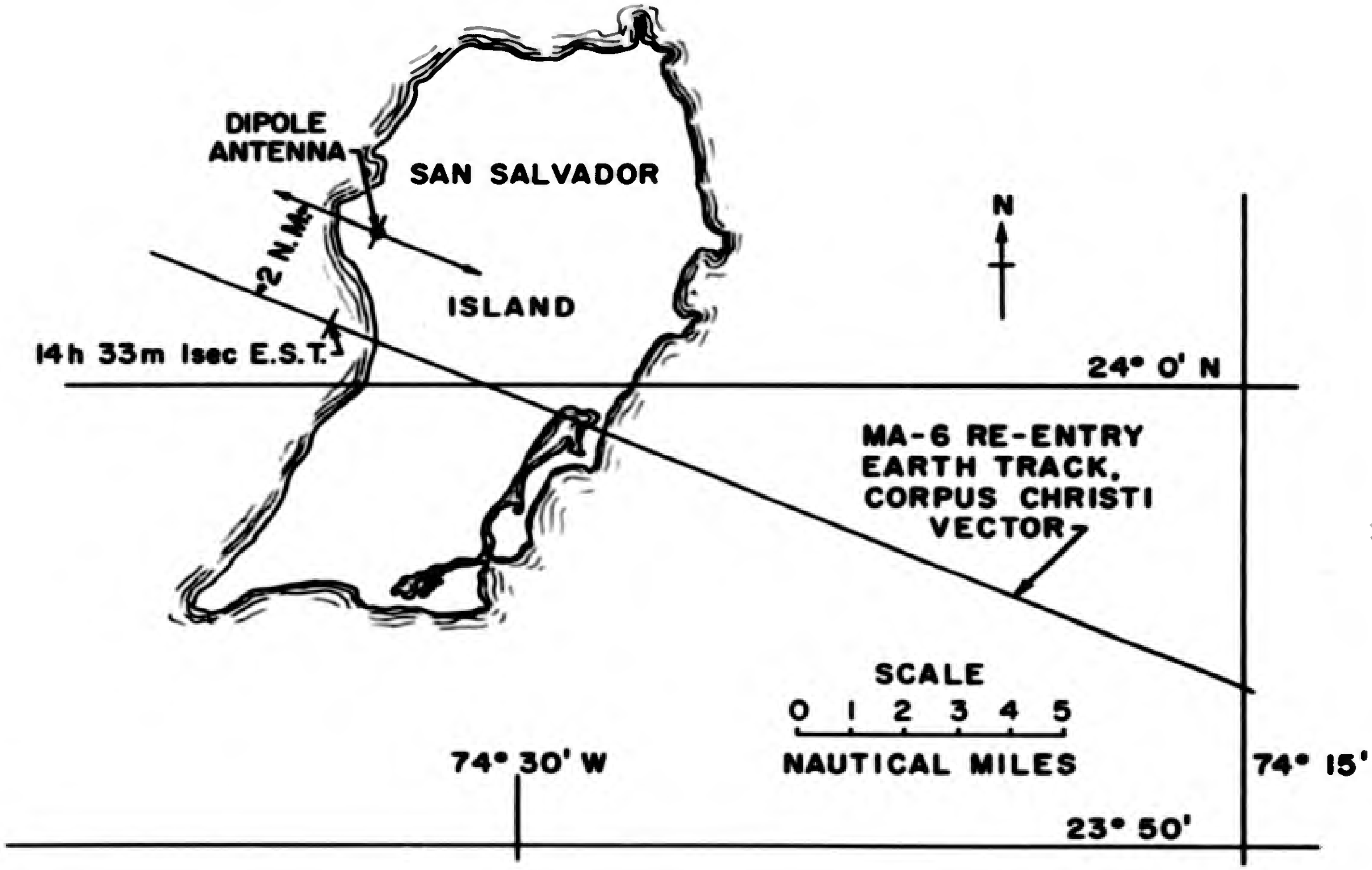

Fig. 2 Close-up map of San Salvador Island showing location and orientation of the dipole antenna for the pulsed radar with respect to the trajectory plane of the MA-6 Mercury capsule as determined by NASA after the flight (based on velocity vector measurement at Corpus Christi, Texas).

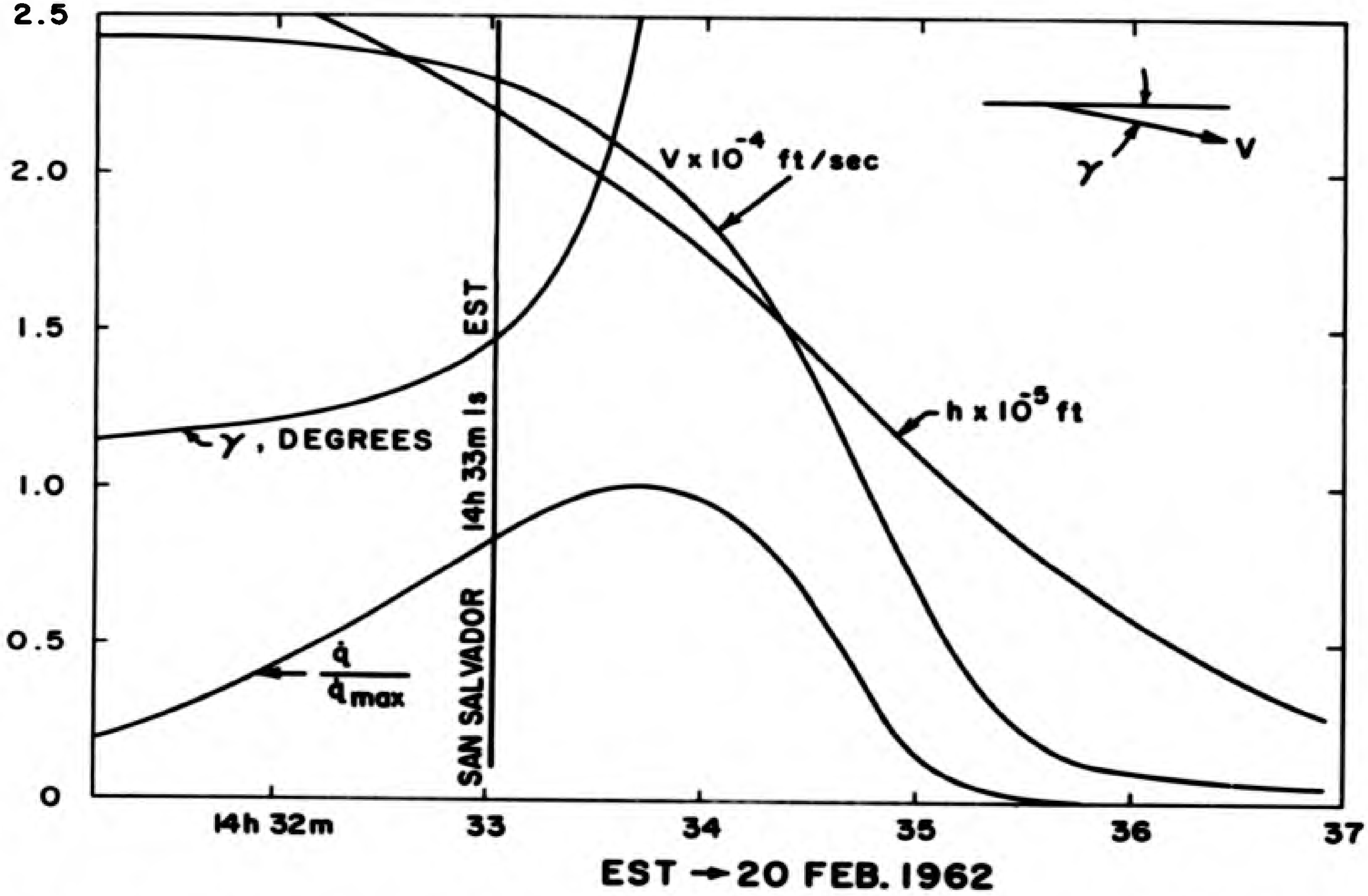

Fig. 3 Post-flight trajectory data for MA-6 Mercury re-entry as provided by NASA (based on velocity vector determination at Corpus Christi, Texas). According to these data, the MA-6 capsule was to have passed over San Salvador Island (see Fig. 2) at 14 hr, 33 min, 01 sec, Eastern Standard Time at an altitude of approximately 220,000 ft and at a velocity of approximately 23,000 ft/sec, about 40 sec before peak heating ($\dot{q} = \dot{q}_{max}$).

8094

Fig. 4 (a) through (e)

Intensity-modulated range-time record of the radar echoes from the ionized trails produced by the MA-6 Mercury re-entry on February 20, 1962, as observed from San Salvador Island by an omni-directional pulsed radar. The radiated frequency of the radar was 30.25 megacycles/sec and the pulse repetition rate was about 94 pulses/sec. The time scale in seconds refers to the time after the moving-film-strip recording cameras were turned on, which took place at 14 hr, 33 min, 00 sec, Eastern Standard Time. The large white dots evenly distributed near the top of the film strip were time markers produced by a neon bulb which was actuated by a clock calibrated against the standard time from the Bureau of Standards radio station WWV. The band of fine dots tracking the main signal near the middle of the film strip indicates the exact instantaneous location of the fine range gate which carried the pulse amplitude record shown in Figs. 5 (a) through 6 (d). The random dots distributed over the entire film strip were due to noise of various sources, and the sudden changes in population of these noise dots at various times were due to sudden changes in the receiver input attenuator setting, which is marked accordingly at the top of the film strip.

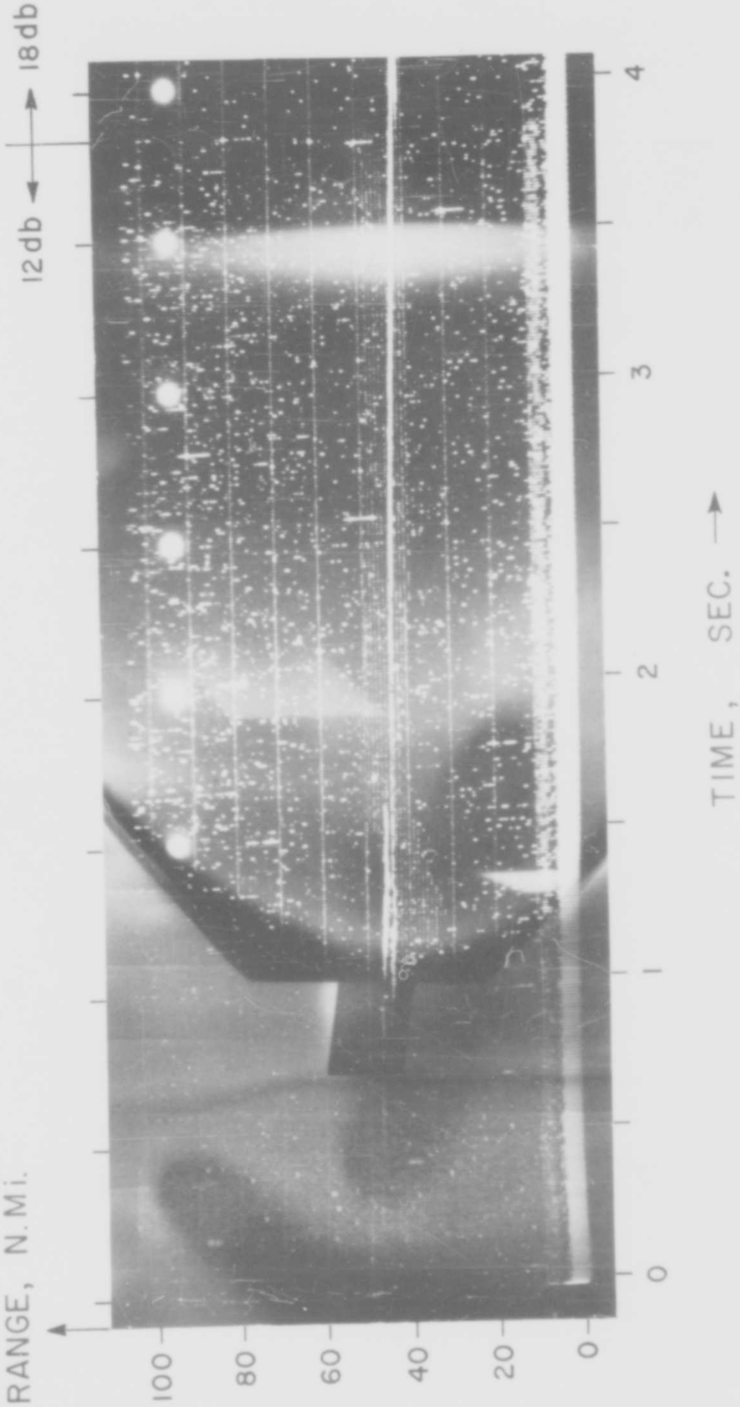

Fig. 4 (a)

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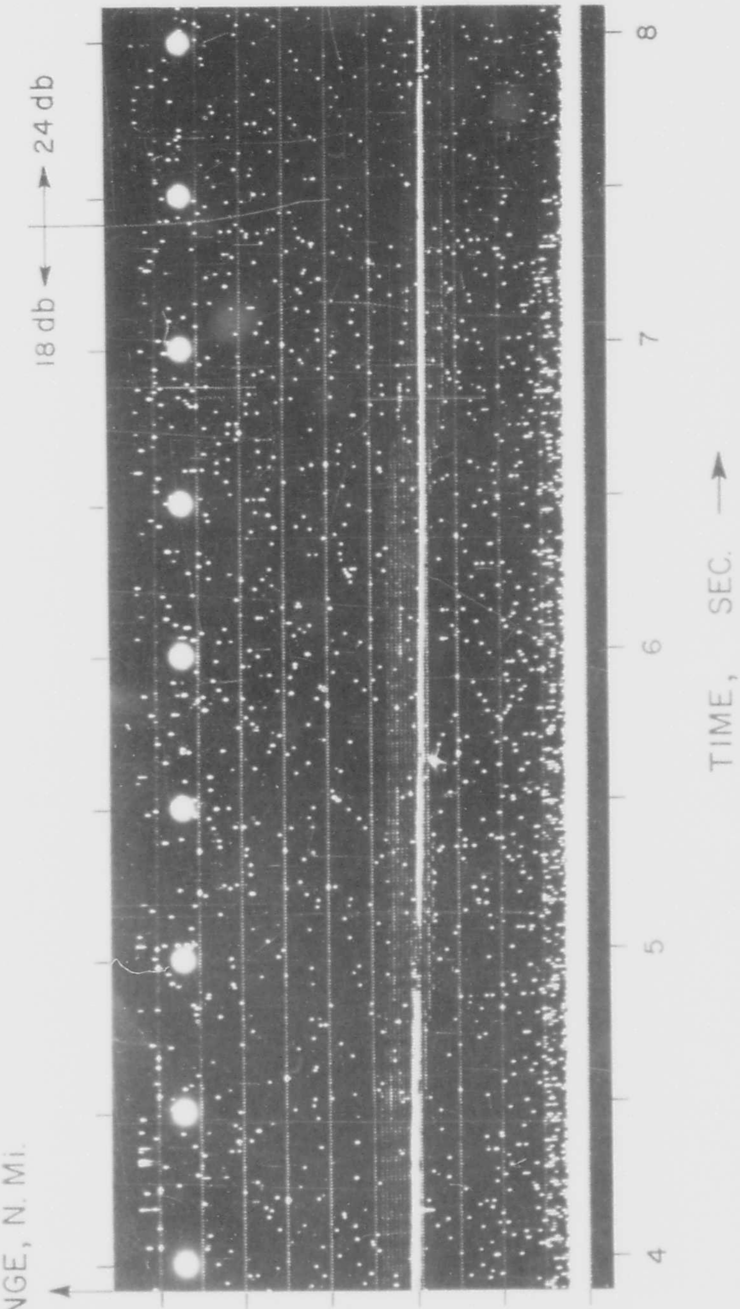

Fig. 4 (b)

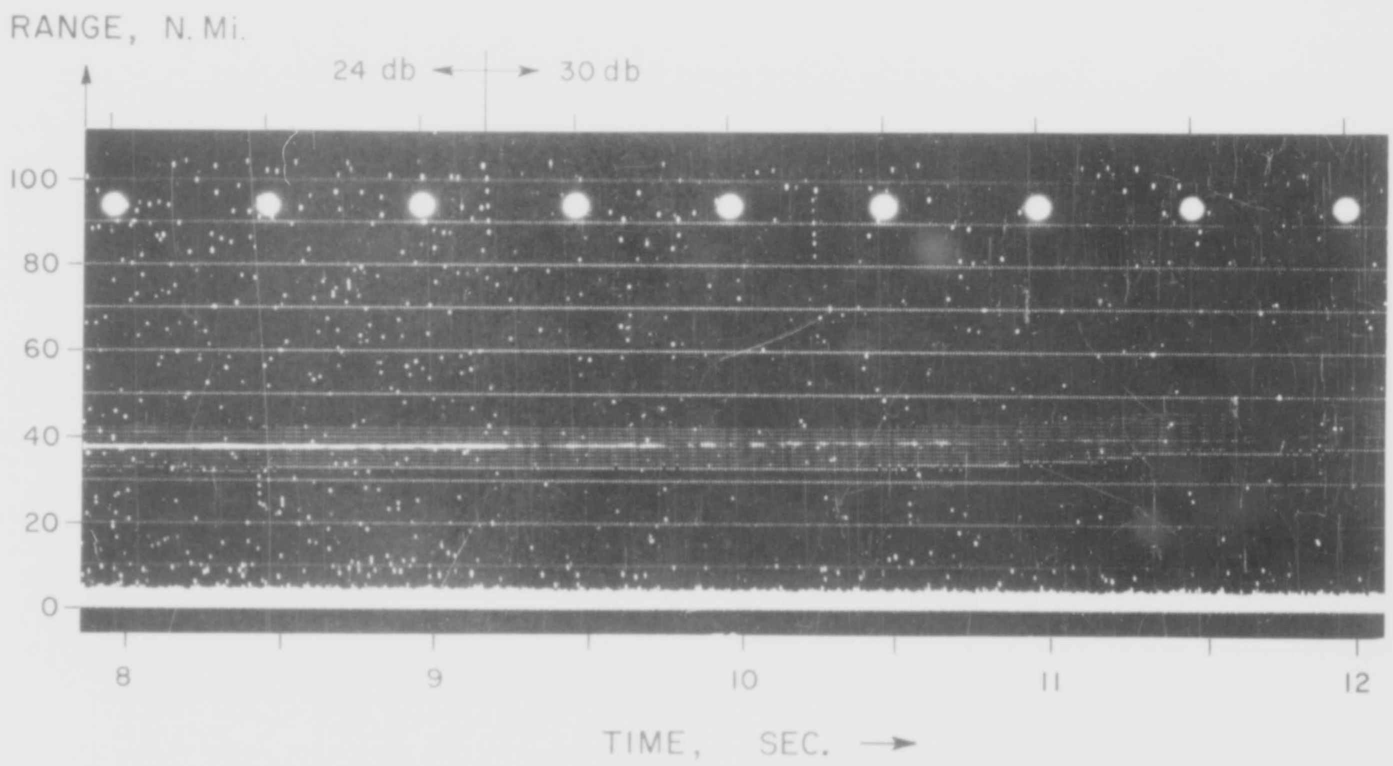

Fig. 4 (c)

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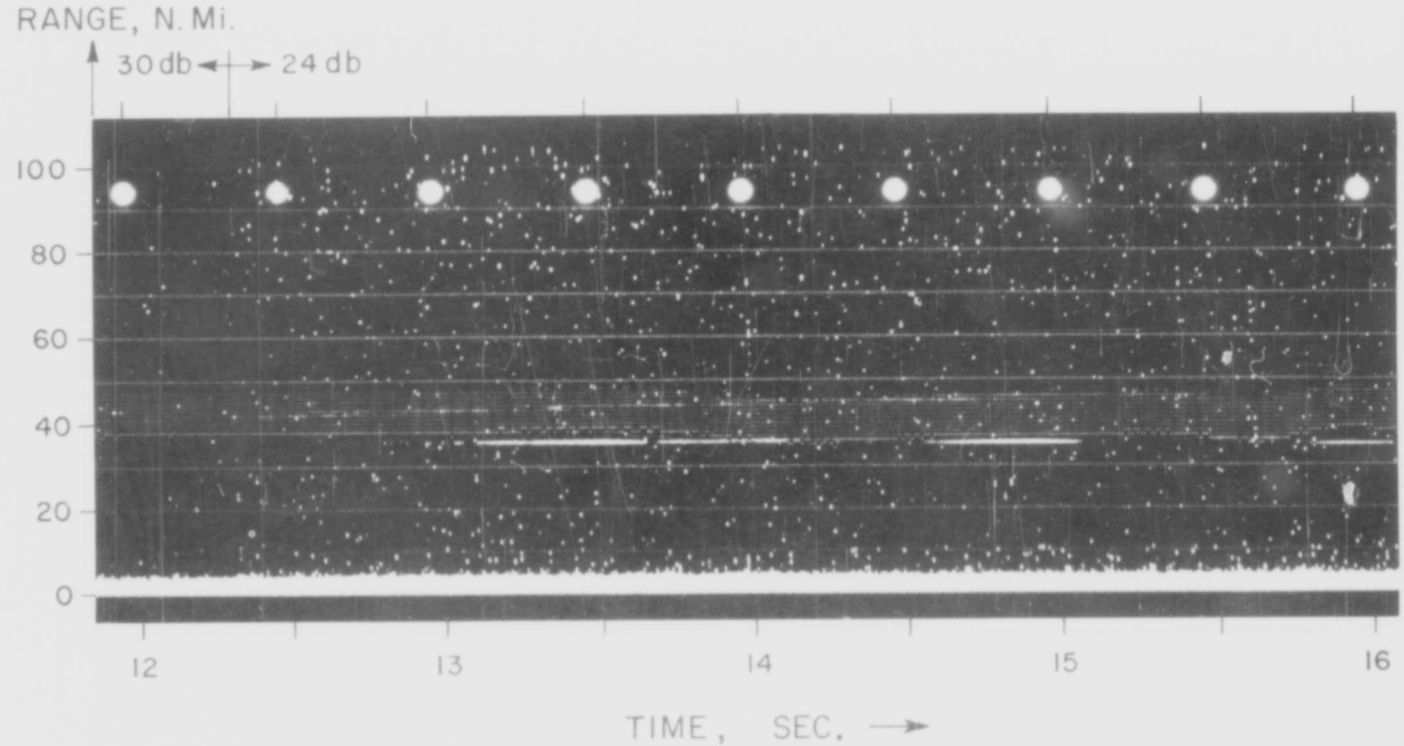

Fig. 4 (d)

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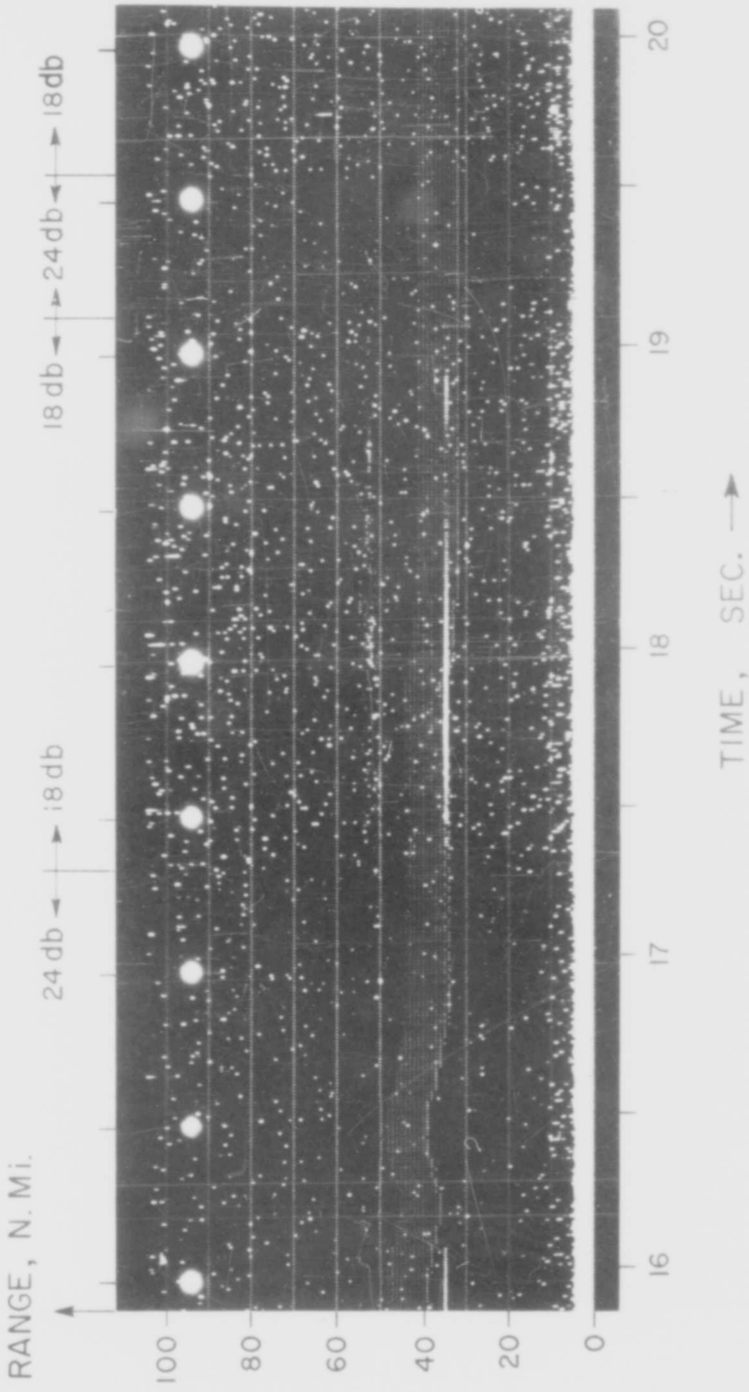

RANGE, N. MI.
100
80
60
40
20
0
24 db
18 db
18 db
24 db
18 db
16
17
18
19
20
TIME, SEC.

Fig. 4 (e)

8099

Fig. 5 (a) through (j)

Pulse amplitude record of the radar echoes from the ionized trails produced by the MA-6 Mercury re-entry on February 20, 1962, as seen within the fine range gate of the omnidirectional pulsed radar of 30.25 megacycles/sec radiated frequency (see Fig. 4). The peak radiated power was 200 kilowatts and the pulse duration at the half-power point was approximately 1.5 μ-sec. The time scale in seconds refers to the time after the moving-film-strip recording cameras were turned on, which took place at 14 hr, 33 min, 00 sec, Eastern Standard Time. The sudden change in background noise level at various times was due to sudden changes in the receiver input attenuator setting, which is marked accordingly on the right side of the film strip. The receiver sensitivity corresponding to each input attenuator setting, which is also given on the right side of the film strip, was obtained from calibration against a standard pulse generator and from measurement of the antenna mismatch just before the experiment. Note that the apparently irregular movement of the echoes within the range gate was primarily due to tracking motion of the range gate by the operator during the experiment.

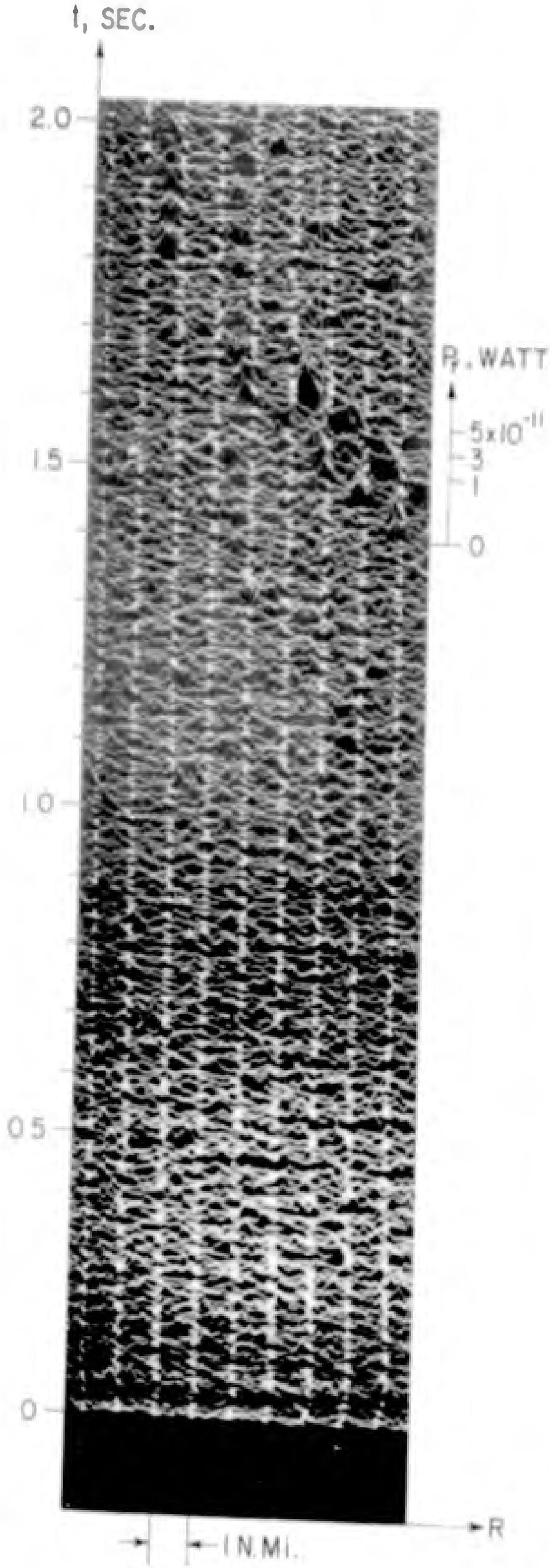

Fig. 5 (a)

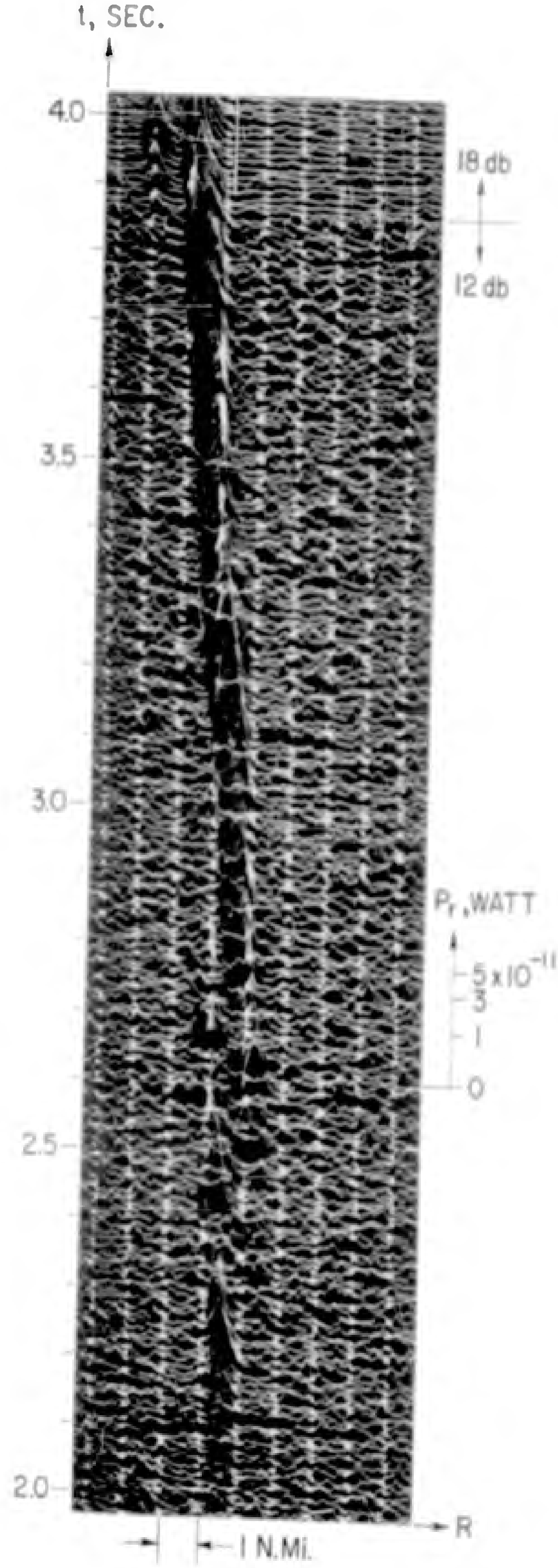

Fig. 5 (b)

8100

8101

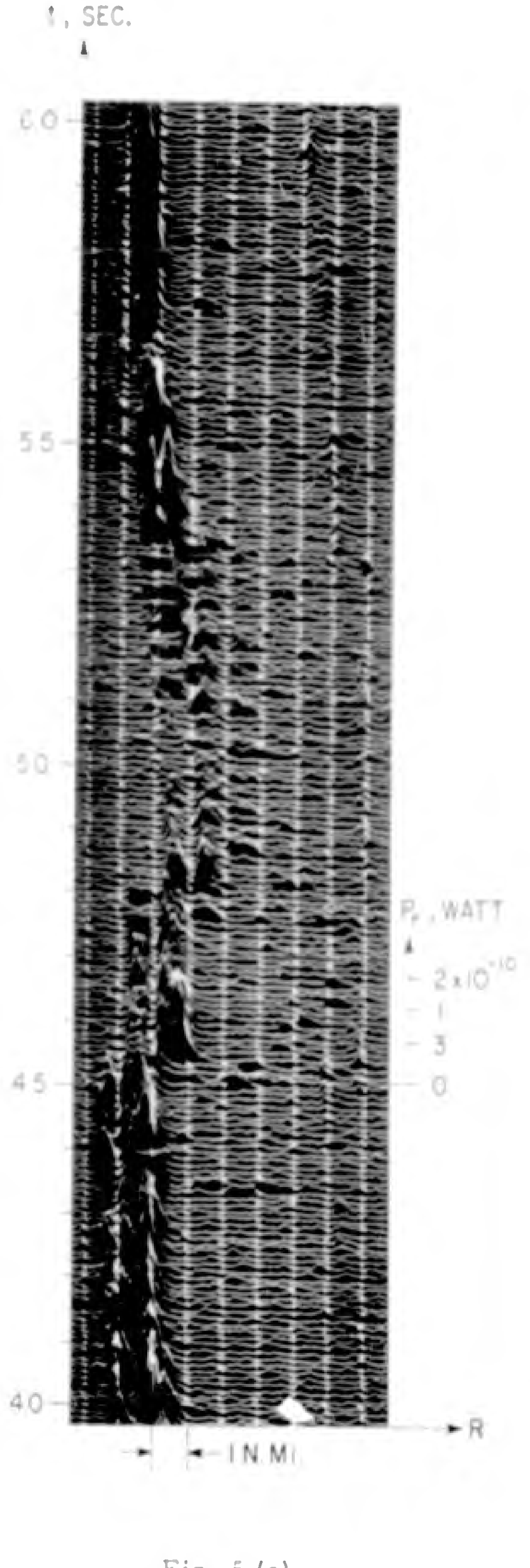

Fig. 5 (c)

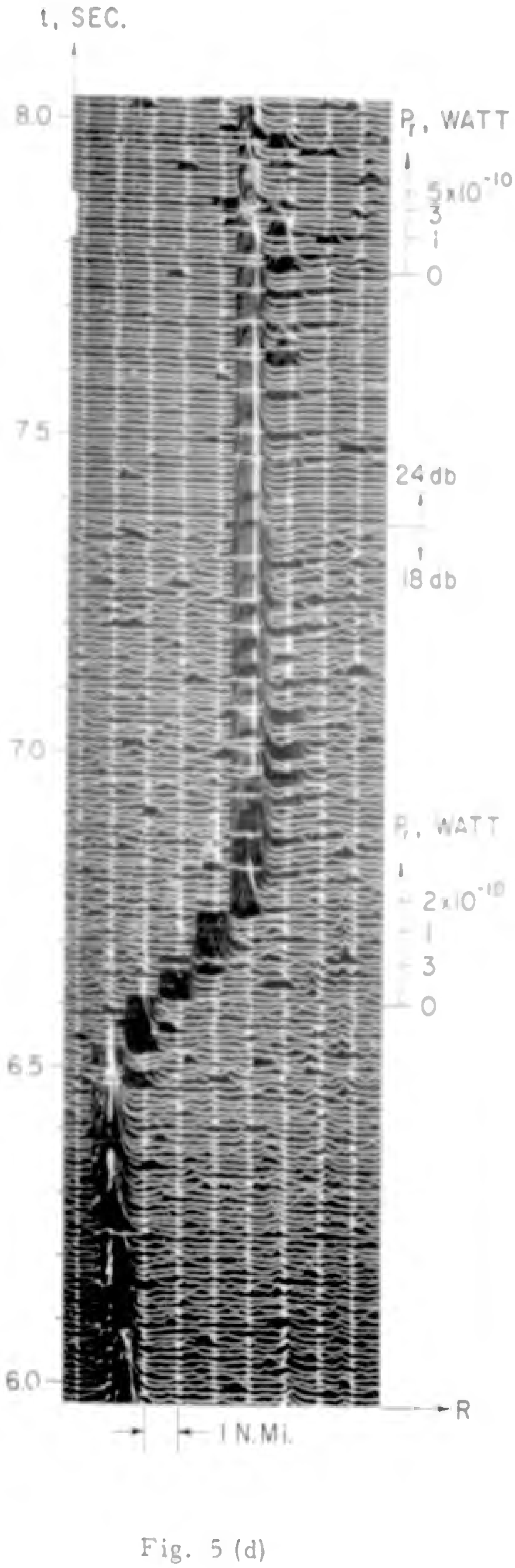

Fig. 5 (d)

8102

8103

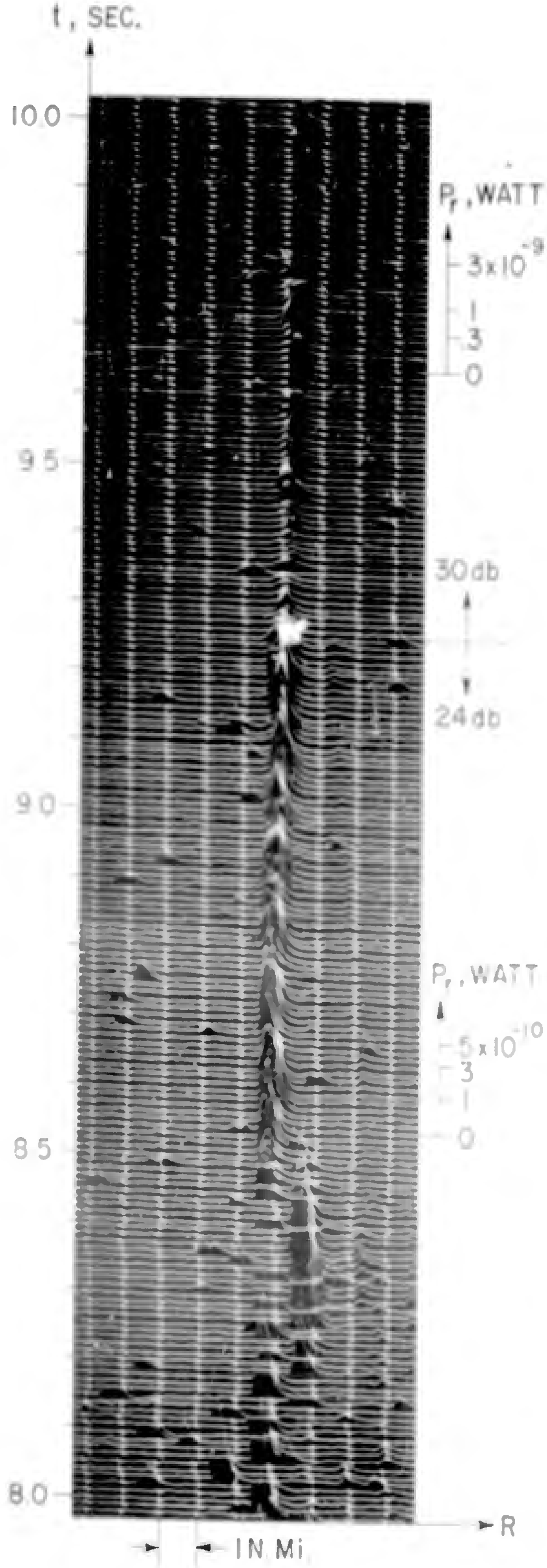

Fig. 5 (e)

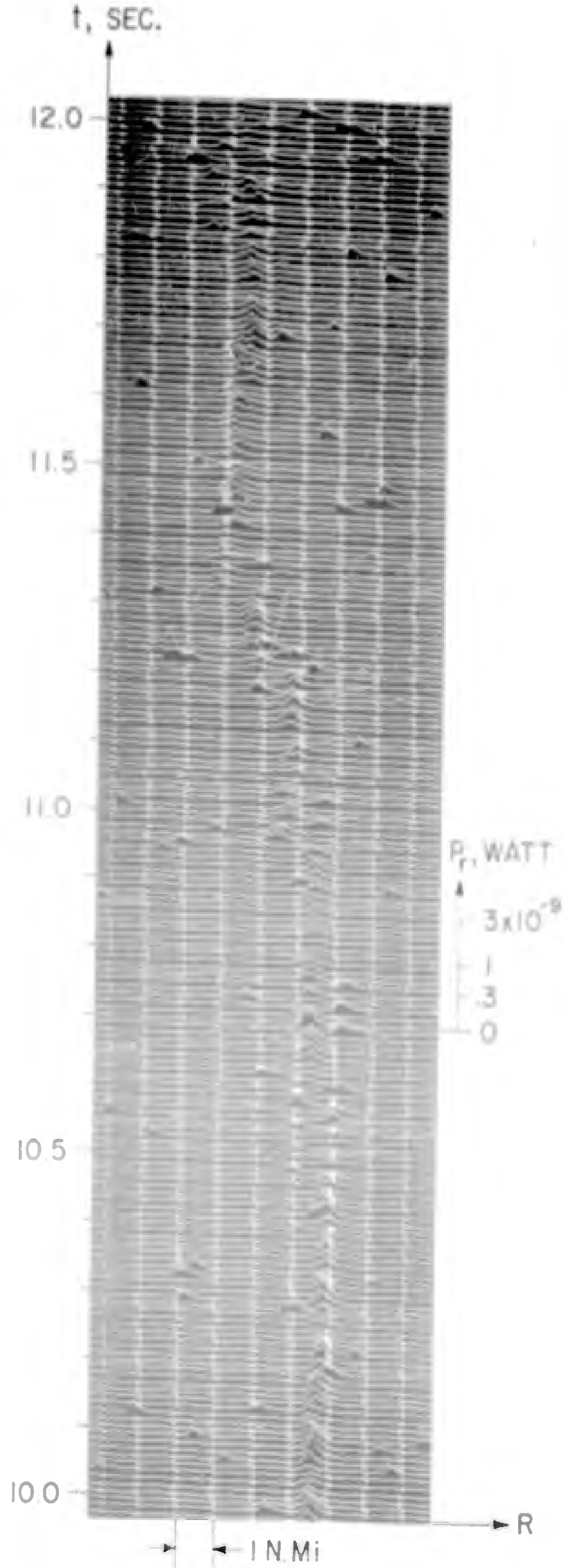

Fig. 5 (f)

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8105

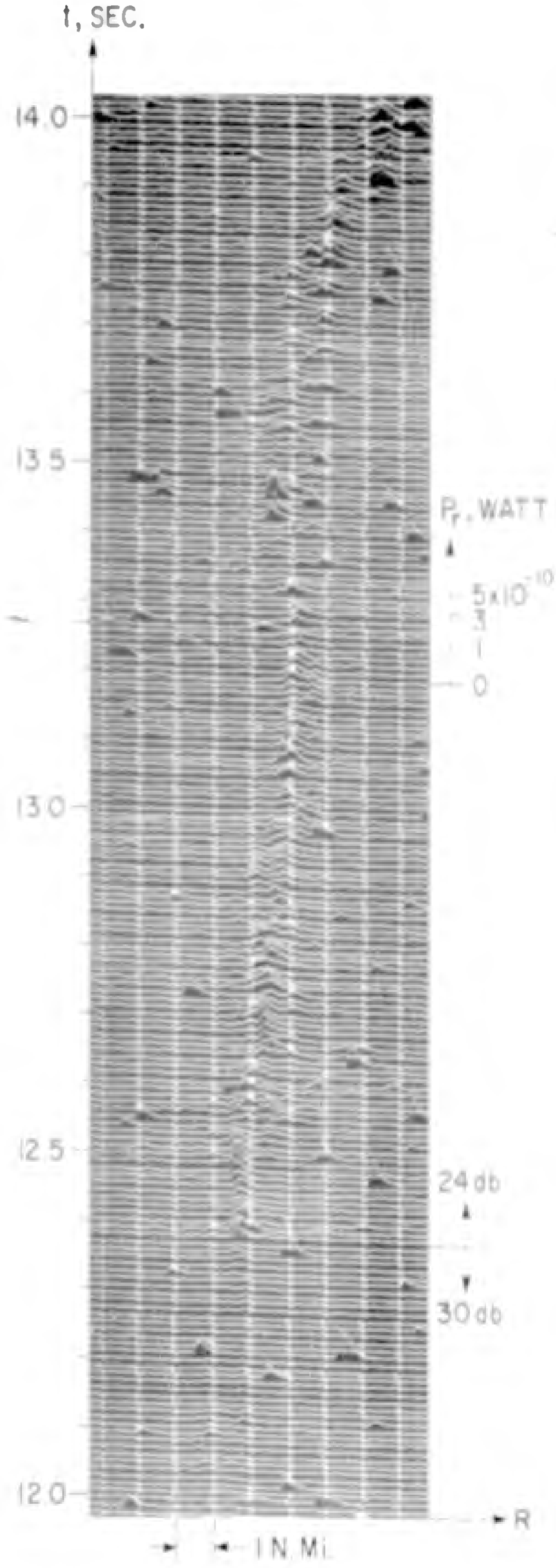

Fig. 5 (g)

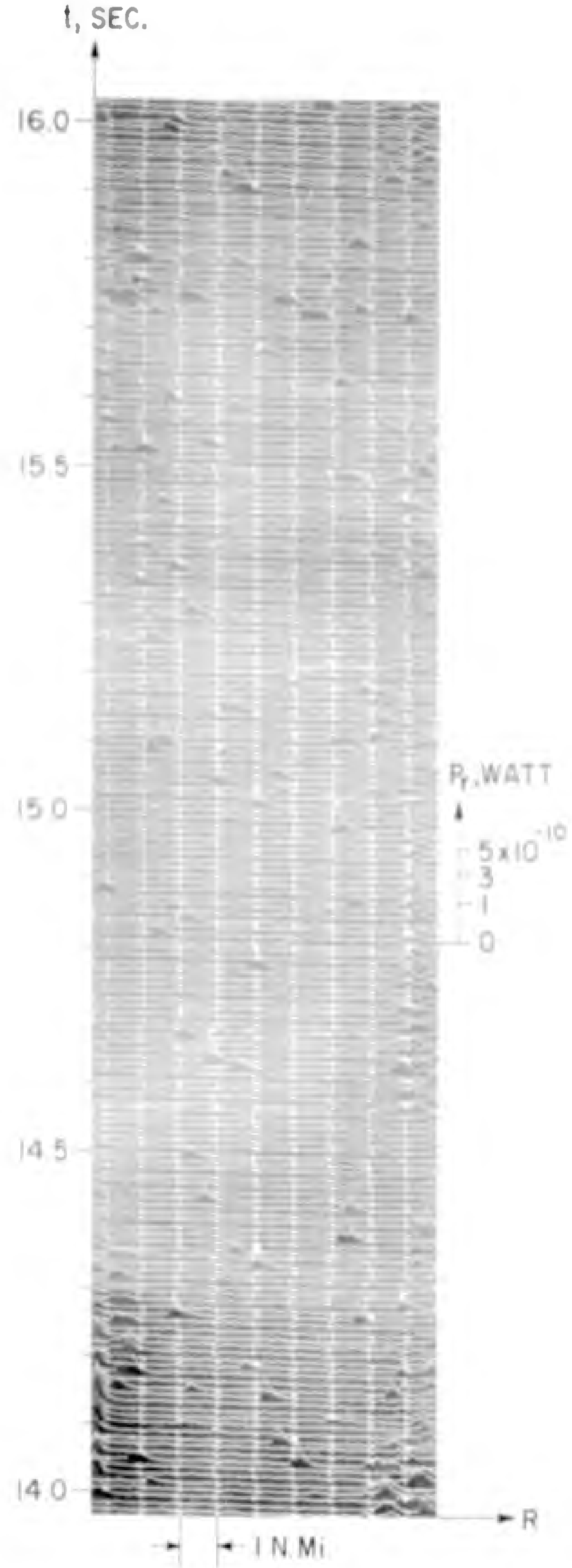

Fig. 5 (h)

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8107

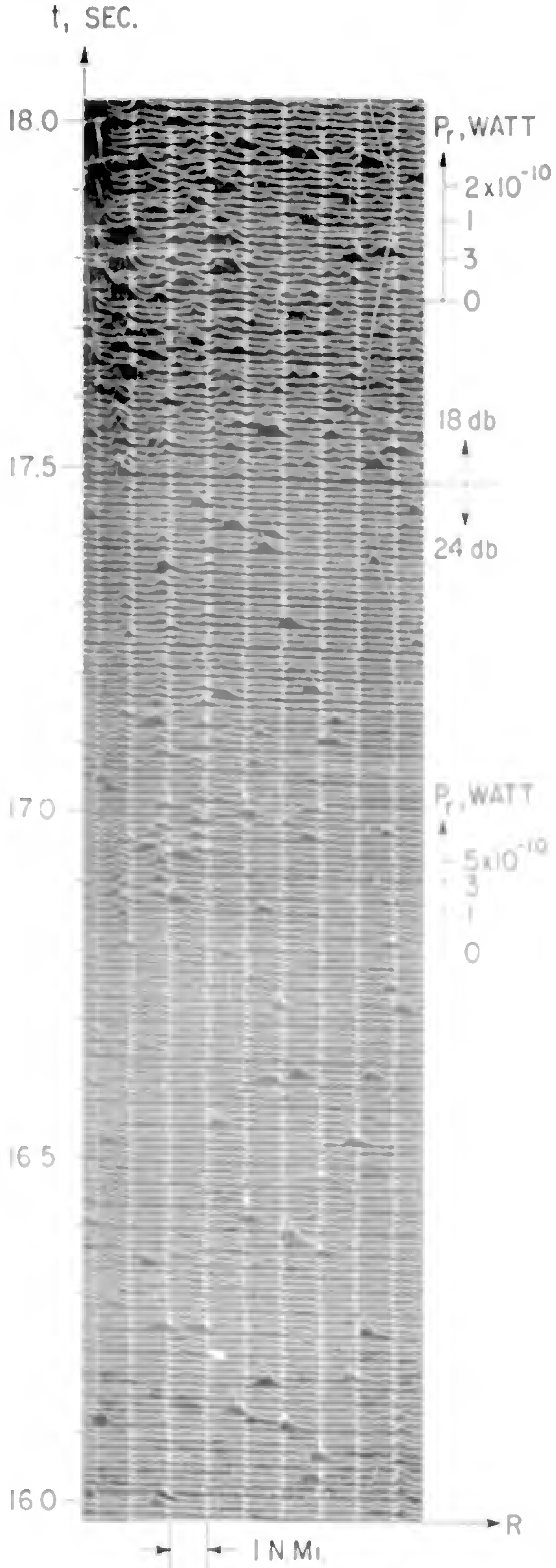

Fig. 5 (i)

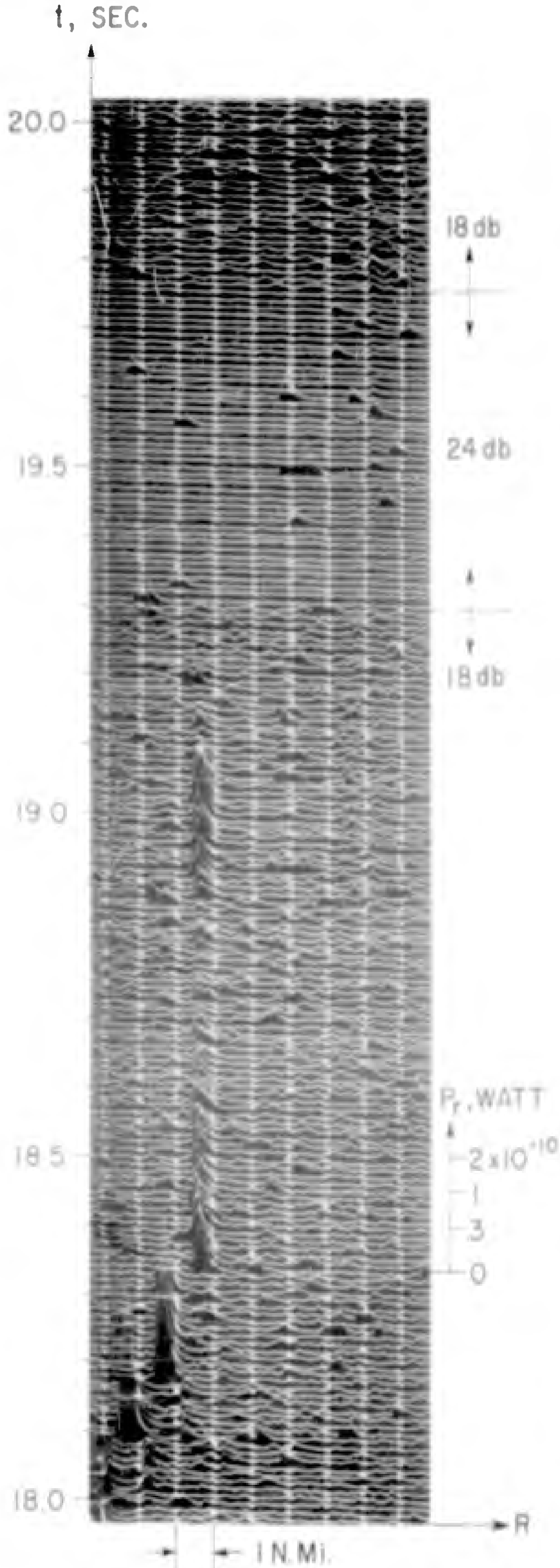

Fig. 5 (j)

8108

8109

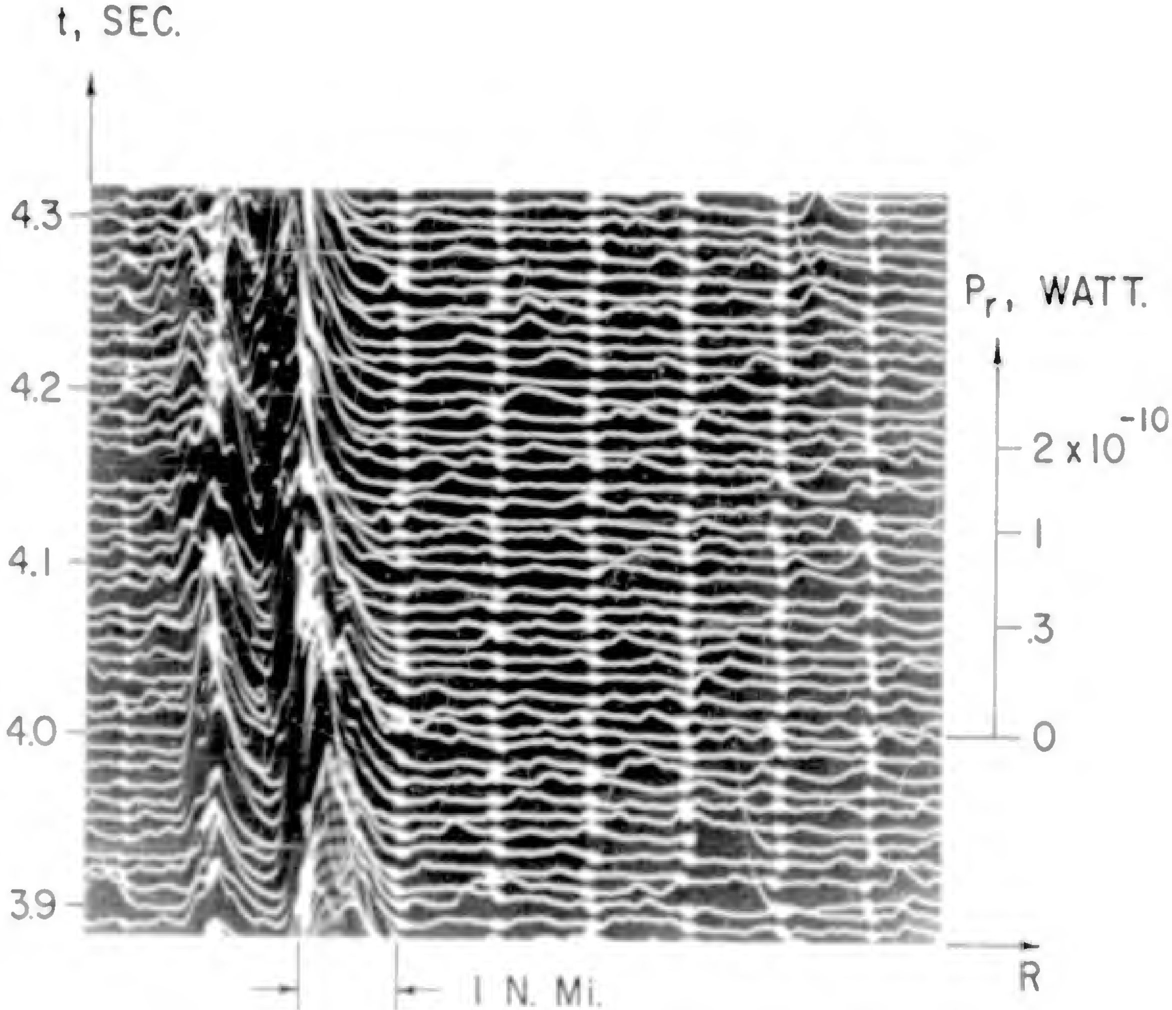

Fig. 6 (a) Selected magnified segment of pulse amplitude record showing splitting of main echo at about 4 sec after 14:33:00 E.S.T.

8178

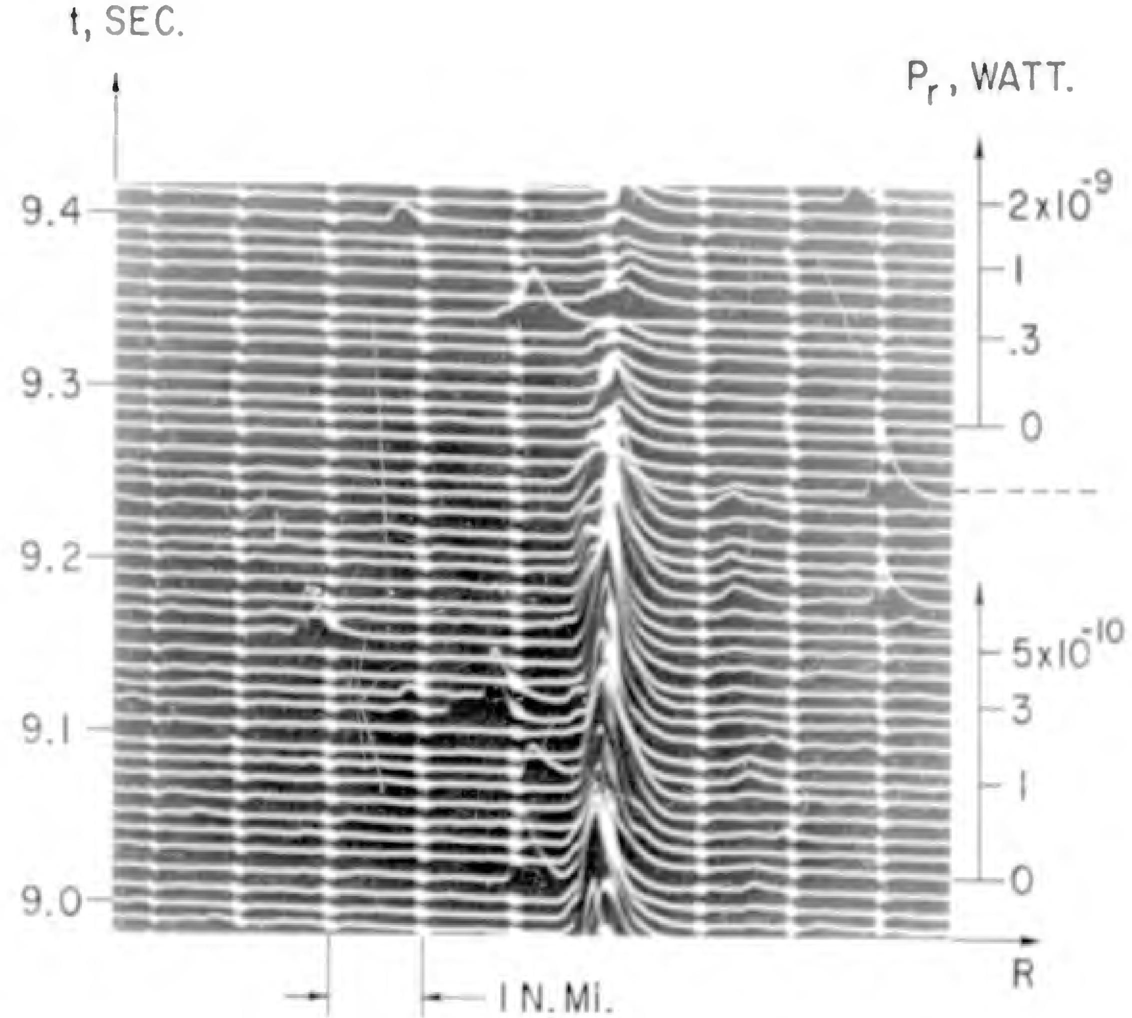

Fig. 6 (b) Selected magnified segment of pulse amplitude record showing single main echo at about 9 sec after 14:33:00 E.S.T.

8177

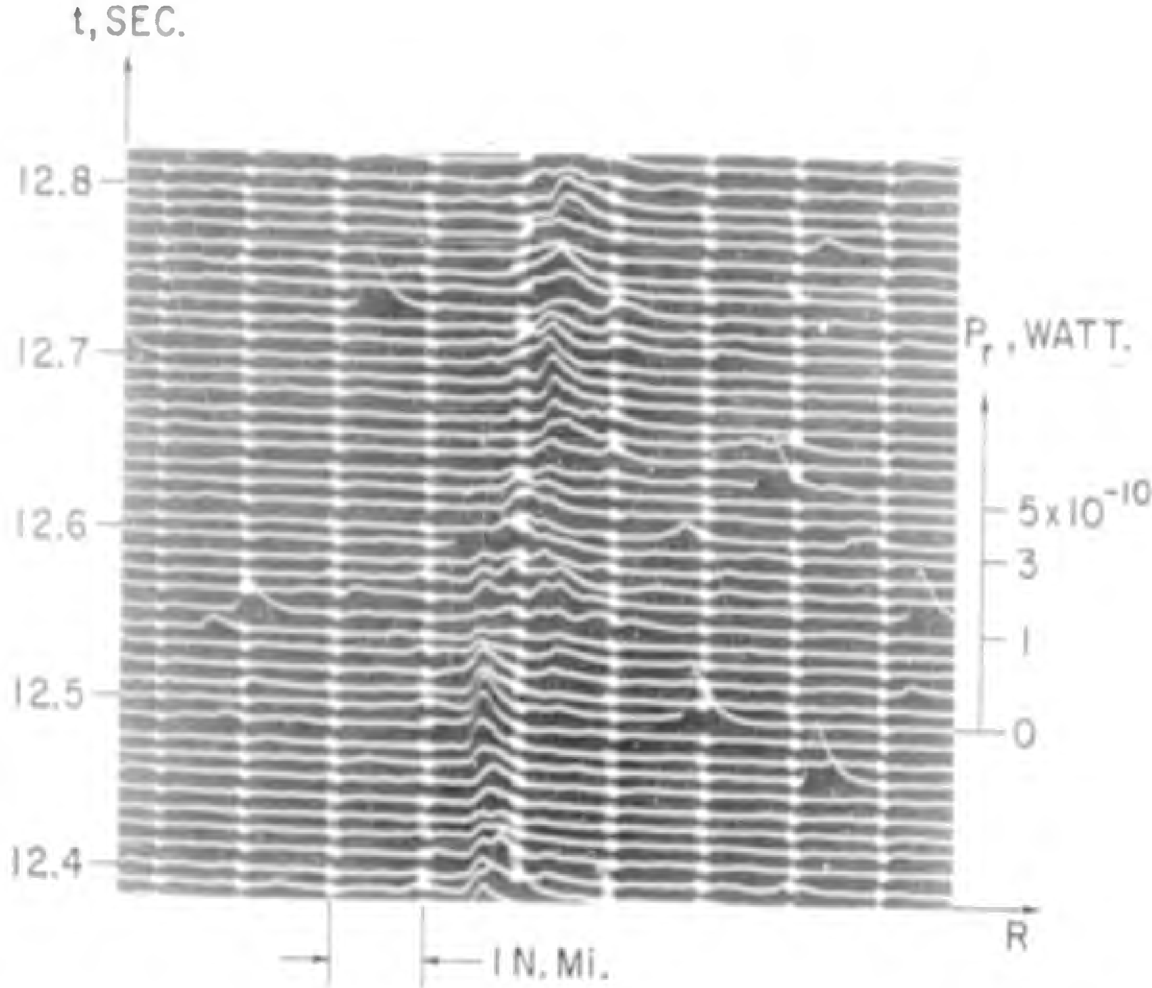

Fig. 6 (c) Selected magnified segment of pulse amplitude record showing fading and range spread of main echo at about 12.5 sec after 14:33:00 E.S.T.

8179

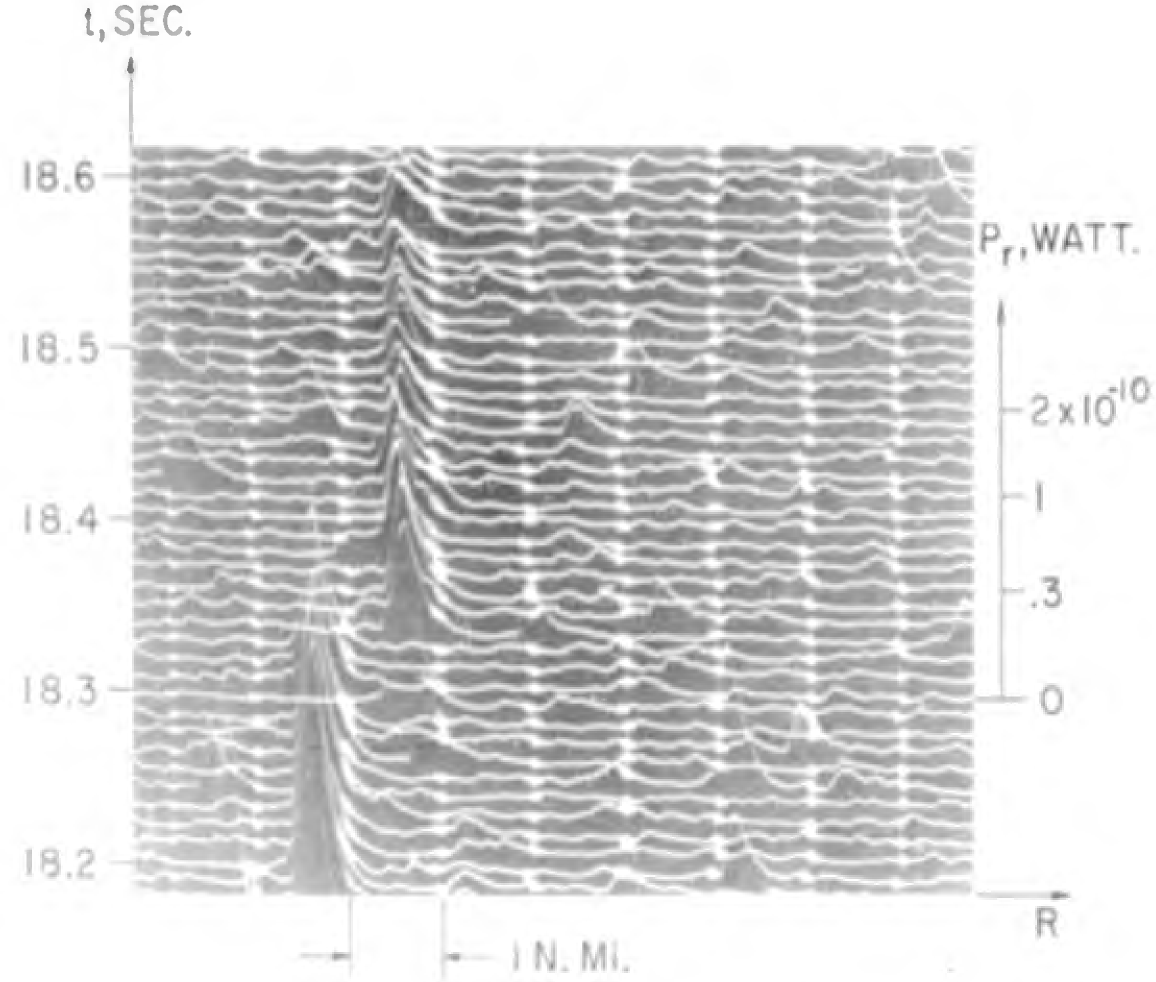

Fig. 6 (d) Selected magnified segment of pulse amplitude record showing range persistency of one of the short duration echoes at about 18 sec after 14:33:00 E. S. T. Note that the sudden jumps in range between 18.2 and 18.4 sec was due to shifting of the fine range gate by the operator and was not due to the echo (see Fig. 4 (e)).

8180

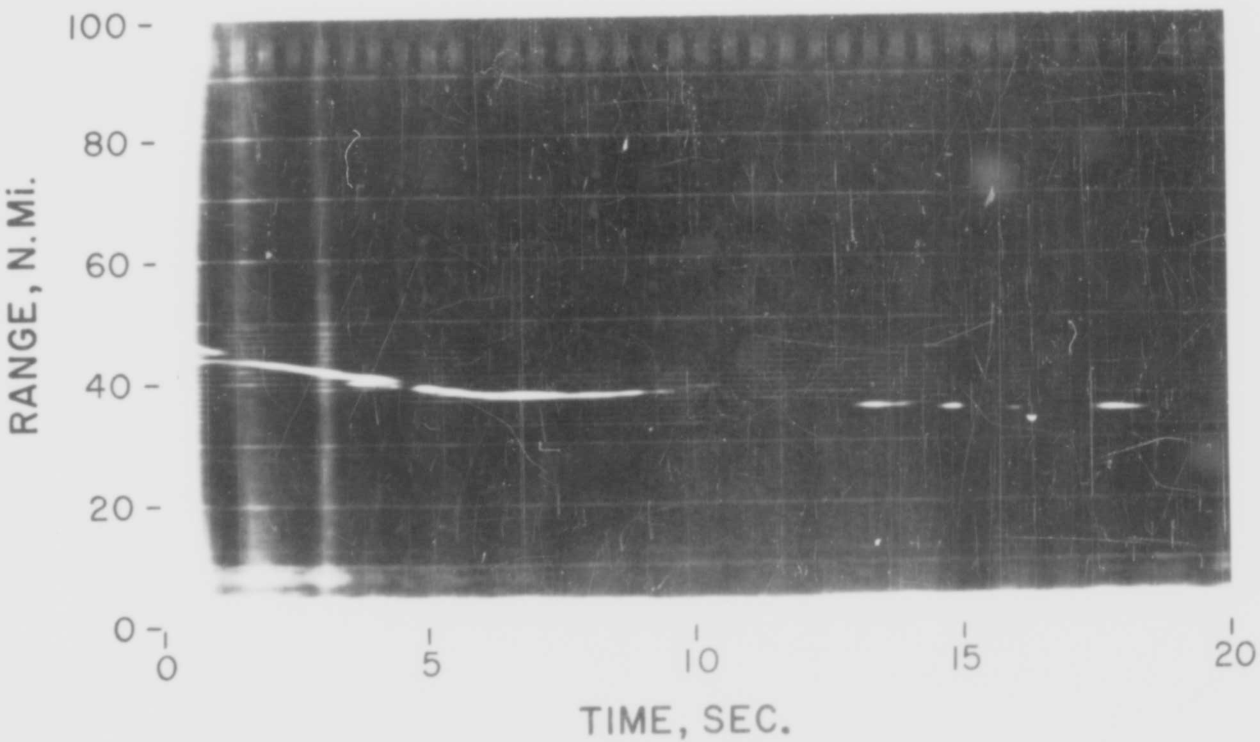

Fig. 7 A condensed time scale display of the intensity modulated range-time record showing the overall characteristics of the radar echoes from the ionized trails generated by the MA-6 Mercury re-entry. The parabola-like range time variation of the main echo similar to those observed for large meteors (i. e., "head-echoes"), and the short duration glints of the weaker echoes similar to those observed for faint meteors, are quite evident in this picture.

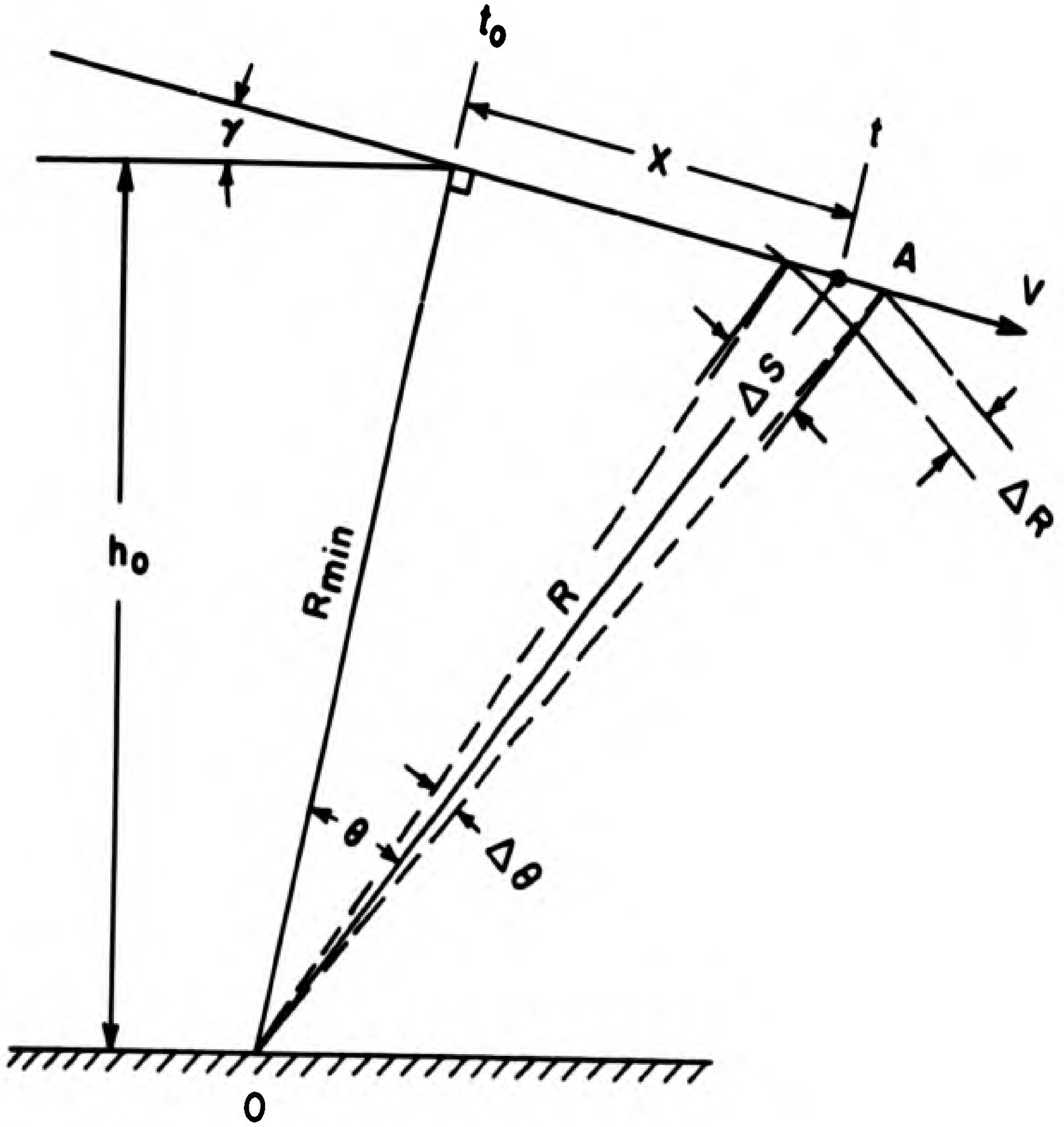

Fig. 8 Schematic diagram showing range-time relationship for a point target in uniform rectilinear motion as seen from a fixed point on the ground.

8111

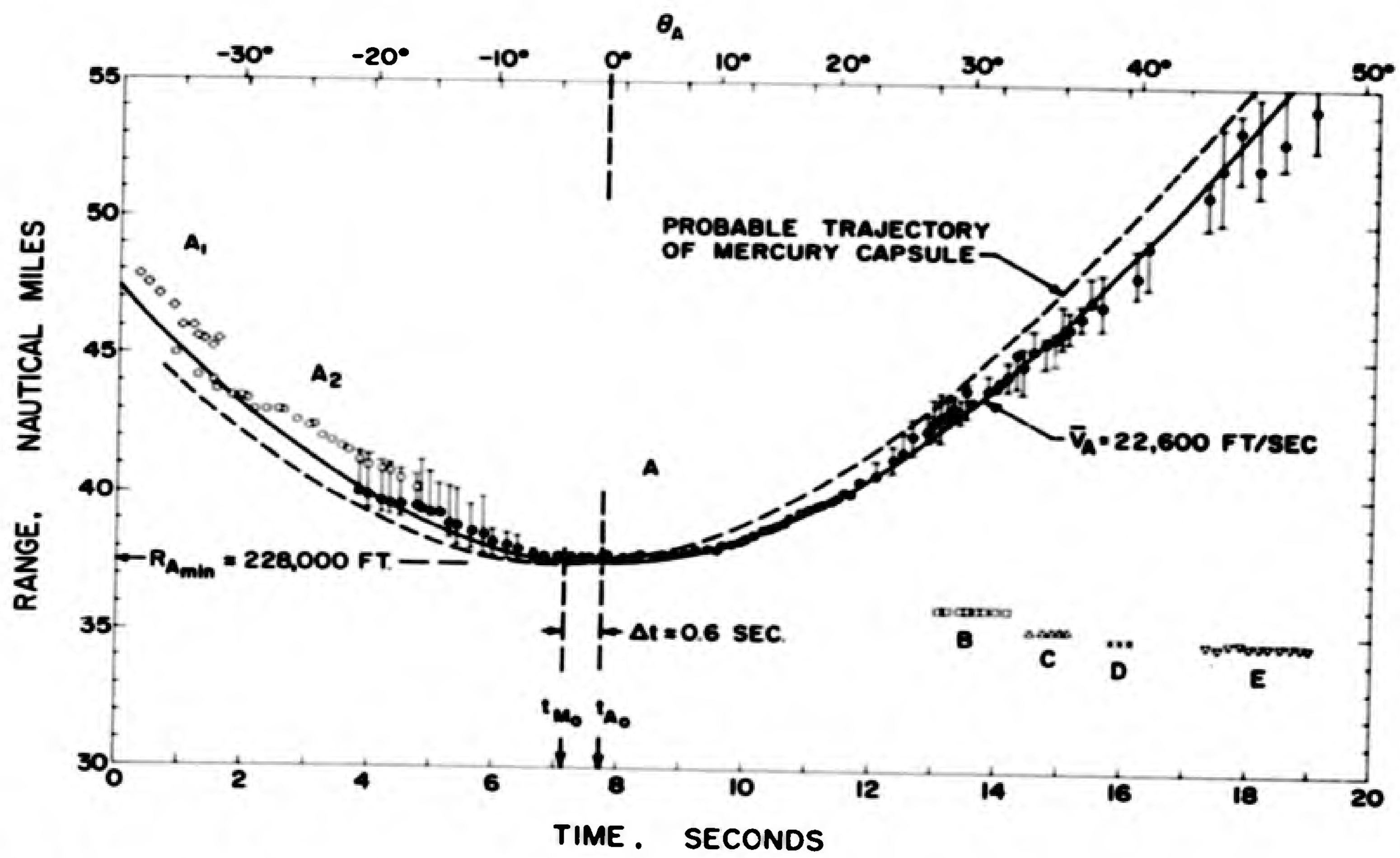

Fig. 9 Range vs time plot for the various identifiable ionized trails as determined from a correlation between the film strip records shown in Figs. 4 and 5. The plotted points correspond to the brightest spot on the trail (i. e., the point of maximum echo amplitude), and the vertical bars correspond to the discernible range spread of the pulse. Note that the aspect angle scale marked on top of this figure for convenient reference is only applicable to the main trail A.

8112

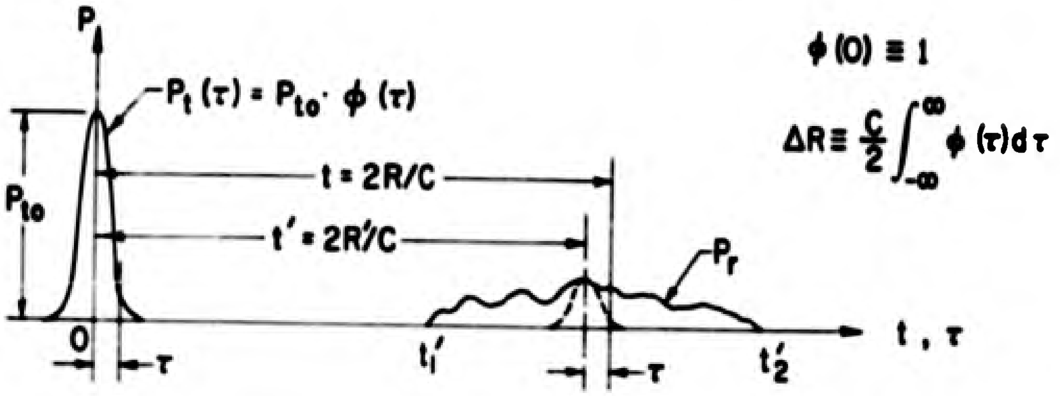

Fig. 10 Schematic diagram showing range-propagation time relationship between the transmitted pulse and the returned signal for an extended echoing region.

8113

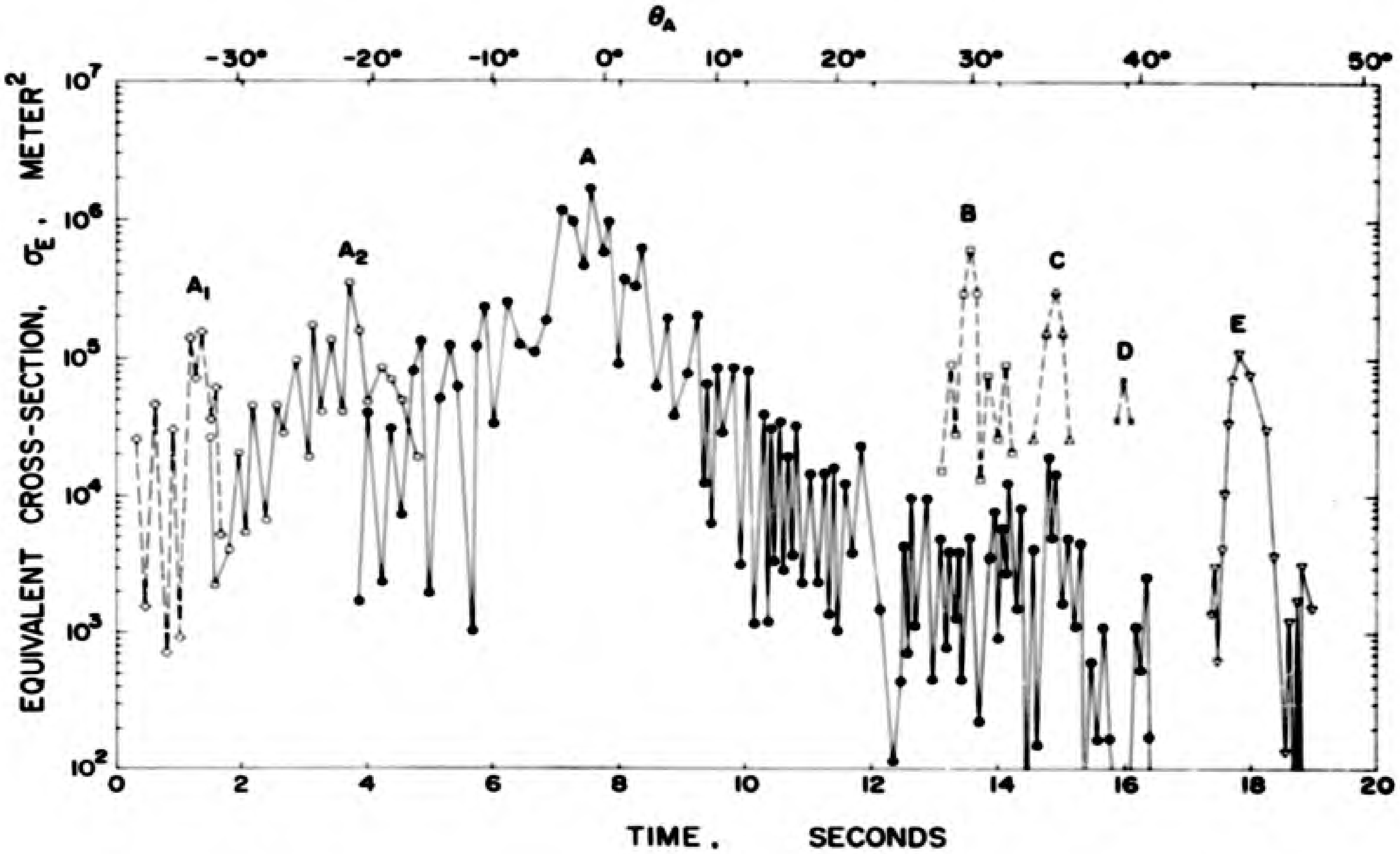

Fig. 11 Equivalent isotropic scattering cross-section corresponding to the brightest spot (i.e., the point of maximum echo amplitude) of the various trails as a function of time. The time scale in seconds refers to the time after the recording cameras were turned on, which took place at 14 hr, 33 min, 00 sec, E.S.T. Note that the aspect angle scale marked on top of this figure for convenient reference is applicable only to the main trail A.

8114

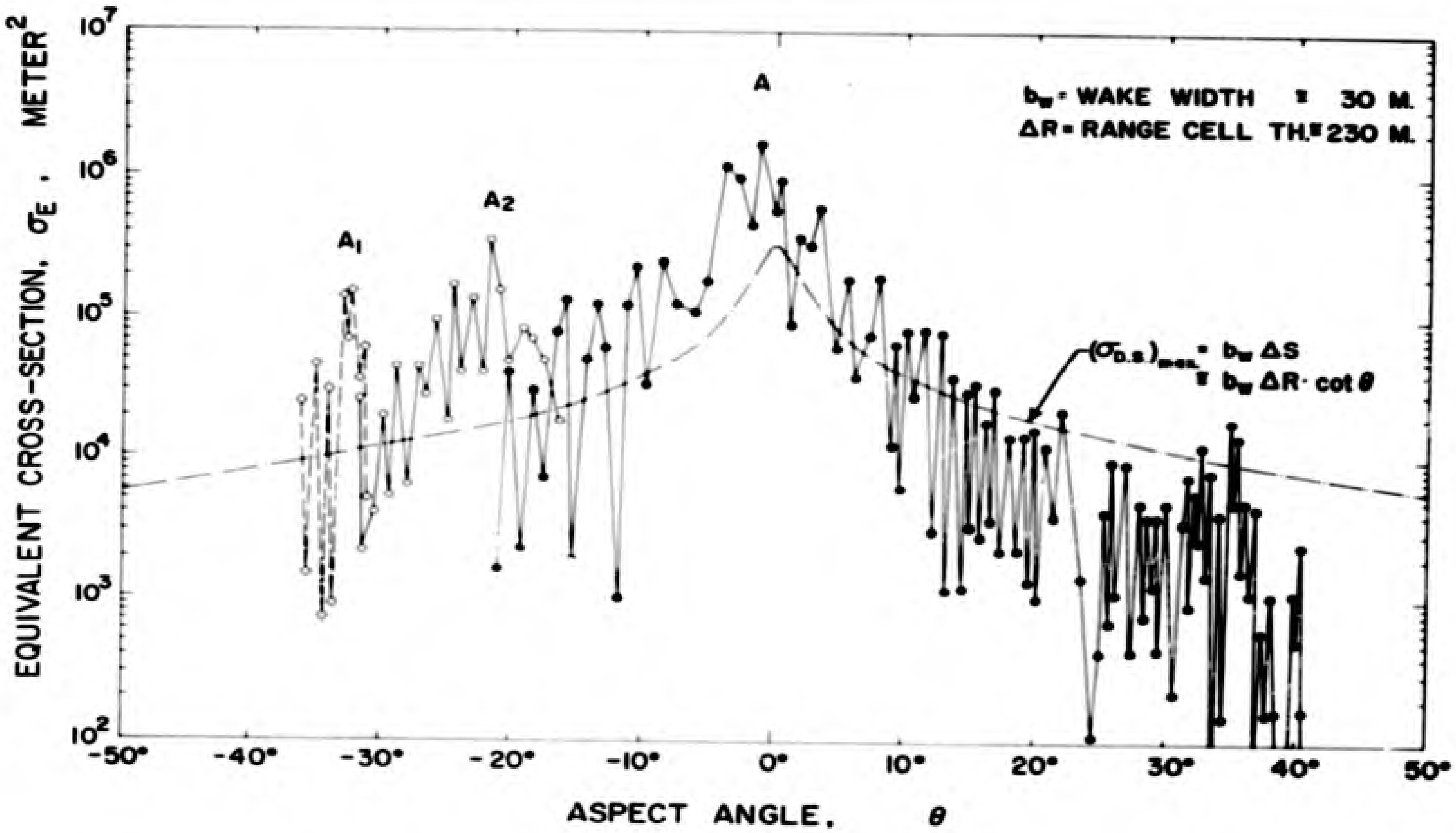

Fig. 12 A re-plot of the equivalent isotropic scattering cross-section corresponding to the brightest spot of the main trail as a function of aspect angle θ (see Fig. 7). The theoretical curve plotted for rough comparison with experiment was simply the geometrical projected area of the trail within the range cell in the direction normal to the line of sight, assuming an effective wake width of 30 meters.

8115

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I. Reentry vehicles - Ionized trails.
2. Satellites - Ionized Trails.
3. Mercury MA-6 - Reentry.
4. Trails, Ionized - Radio echoes.
5. Reentry vehicles - Radio echoes.
I. Title.
II. Lin, S. C.
III. Goldberg, W. P.
IV. Janney, R. B.
V. Avco-Everett Research Report 127.
VI. BSD-TDR-62-54.
VII. Contract AF 04(694)-33.

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