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SUMMARY

A brief description is made of the Trailblazer Ig artificial meteor experiment at a reentry velocity of 9.8 kilometers per second. The methods of obtaining data during the visible reentry and the corrections to the photographic data necessary for the final analysis are developed. A value of the luminous efficiency, or the percent of kinetic energy converted into visible light, is computed from the observed photographic data and is compared with that obtained by a classical meteor theory. The observed luminous efficiency of 9.55×10^{-4} is about 80 percent of the luminous efficiency of 1.17×10^{-3} computed from Öpik's 1958 classical meteor theory at an average velocity of 9.41 kilometers per second. The luminous efficiency for the artificial iron meteoroid is extrapolated to natural stony meteors of 15 percent iron at the same velocity, and it is found that the lower limit of the luminous efficiency of a stony meteor is 1.44×10^{-4}.

INTRODUCTION

A stainless-steel pellet was fired from a rocket vehicle to study the phenomena associated with meteor entry into the earth's atmosphere. This was the first known solid artificial meteor to be observed at an altitude and velocity within the range of natural meteor entries: altitudes from 60 to 130 kilometers and velocities from 8 to 72 kilometers per second. The main purpose of this experiment was to obtain a value of the luminous efficiency of a meteor-like body of known mass and composition moving at a known speed. The value of the luminous efficiency of natural meteors, both iron and stone, is essential for interpretation of the extensive meteor observations in terms of the mass distribution of meteoroids in space. (See refs. 1, 2, and 3.) The present paper describes the experiment and the analysis of the optical data to determine the luminous efficiency, and the results are compared with some previous estimates based on theoretical considerations. Although the results of this test are by no means conclusive, they have provided, for the first time, a data point which may be compared with existing theories.

SYMBOLS

h	heat of ablation, ergs/gram
I	intensity, ergs/sec
m	mass, grams
M	stellar magnitude
R	range (units of 100 km)
t	time, sec
V	velocity, cm/sec
β_1	luminous efficiency for impact radiation of diluted coma
β_2	luminous efficiency for impact radiation of compact coma
β_c'	luminous efficiency for impact at gas kinetic velocity in coma
b_v	fraction of energy comprised in the visible spectral region
γ	heat-transfer coefficient
ϵ	fraction of the thermal energy lost in inelastic transitions
θ	ratio of radiation to evaporation heat expenditure
ν_c	number of inelastic collisions with a half-energy target in coma
σ_β	dilution factor of coma
τ	luminous efficiency, $\frac{\text{Luminous energy}}{\text{Kinetic energy}}$
τ_b	thermal-radiation efficiency
τ_i	impact-radiation efficiency
τ_o	luminosity coefficient, sec/cm
τ_t	coma-radiation efficiency
ψ	fraction of total inelastic energy remaining after ν_c collisions

DESCRIPTION OF TEST

The artificial meteor injection into the earth's atmosphere at 9.8 kilometers per second was accomplished with a seven-stage Trailblazer I rocket vehicle launched from the NASA Wallops Station on the night of April 12, 1961. A standard six-stage Trailblazer I vehicle was modified to include a seventh stage and was identified as Trailblazer Ig. (See ref. 4.) The vehicle consisted of three solid-propellant booster stages which placed a velocity package containing four rearward-firing stages to an altitude of 304 kilometers. Three successive firing reentry stages accelerated the artificial meteor to 7 kilometers per second. The final, or seventh stage, was a shaped-charge accelerator, shown in figure 1(a), which propelled a stainless-steel disk (fig. 1(b)), back into the atmosphere almost vertically. The shaped charge, which was built by the Air Force Cambridge Research Laboratory, added a velocity of 3 kilometers per second to that produced by the three Trailblazer reentry stages. The nominal trajectory of the Trailblazer Ig vehicle is shown in figure 2. The vehicle placed the reentry event approximately 110 miles from the launch site and 93 miles from the nearest observation site. Figure 3 is a map showing the projection of the vehicle path and the location of the reentry point with respect to the observation sites.

The mass and shape of a pellet emerging from the blast of a shaped-charge accelerator is dependent on the original mass, shape, charge type, and geometry. The mass and shape of the pellets from guns of the type used for the meteor test were obtained from ballistic range tests prior to actual flight. From these tests it was found that the 5.8-gram disk was reduced to 2.2 grams of essentially the same shape after being projected by the charge. The repeatability of the reduced mass was ±0.1 gram. Reference 5 gives the performance characteristics of similar type guns. The value of 2.2 grams of mass was used in the computations of the luminous efficiency of the pellet in actual flight. A sample of the bar stock from which the stainless-steel disk was machined for the flight test was analyzed and found to contain 69.7 percent iron, 18.8 percent chromium, and 8.62 percent nickel by weight. The composition of the simulated meteor material must be known in order to compare the observed luminous efficiencies from the flight with luminous efficiencies given by existing theories for natural meteors.

Data from the flight test for the simulated-meteor luminous-efficiency measurements were derived from photographs of the reentry event, which occurred at night. The photographic equipment for observing the pellet entry consisted of Super-Schmidt meteor cameras located at Wallops Island (fig. 4) and Eastville, Virginia, and ballistic and modified K-24 aerial cameras (figs. 5 and 6) located at Wallops Island, Eastville, and Coquina Beach, North Carolina. Some of each of these cameras were operated as "streak" cameras with the shutters opened prior to the visible entry and closed after the event was concluded. On these cameras the image of the visible portion of the artificial meteor entry was a continuous streak from which the total intensity was obtained. Other cameras were operated as "chopped" cameras with shutters opened and closed automatically at a known rate. These cameras produce a broken, or dashed, image from which velocity may be obtained. The Super-Schmidt cameras were operated by personnel from the Massachusetts Institute of Technology under the direction of Dr. Richard E. McCrosky of the Harvard College Observatory. The other photographic equipment was operated by personnel of the Langley Research Center. Figures 4, 5, and 6 show some of the equipment set up for the meteor experiment. An enlarged photograph of the visible entry of the simulated meteor as observed from Coquina Beach, North Carolina, is shown in figure 7. The short streaks in this photograph are star trails resulting from the fact that the shutter was open for 3 minutes to cover the period of visibility of the artificial meteor and the sixth stage. The short break in the star trails resulted from a 20-second shutter closure for ballistic data reduction purposes. The shorter reentry trail is that of the stainless-steel disk at a velocity of approximately 10 kilometers per second, and the larger reentry trail is that of the sixth stage, a 5-inch-diameter aluminum rocket case which reentered at a later time at a velocity of 7 kilometers per second.

ANALYSIS

The method of analysis is similar to the method used by astronomers to analyze the characteristics of natural meteors from optical measurements. (See refs. 6, 7, 8, and 9.) The position, the intensity, and the velocity of the meteors are determined as a function of time from the ballistic and the photometric reduction of photographs taken by cameras located at two or more sites. The initial mass, composition, and shape of natural meteoroids are generally unknown, but in this experiment these quantities were determined prior to the flight test. From these data it is possible to obtain the luminous efficiency of a meteoroid of known properties, or the ratio of the luminous energy of the pellet to the kinetic energy of the pellet. Many steps and a few basic assumptions must be made before the luminous energy may be derived from a photograph; the density of the reentry trail must be compared with the density of the trails of stars of known magnitude and spectral class; atmospheric absorption of the stars must be normalized to some point along the reentry trail, the reentry trail must be normalized to an altitude of 100 kilometers at the zenith of the camera, and the exposure of the reentry trail must be corrected for writing speed. (See ref. 7.) All intensities must be reduced to a comparable magnitude scale to compute the variation of the artificial meteor's visible intensity with time. The standard meteoric approach is then used to calculate the luminous efficiency, and this value is compared with a value computed by classical theory developed by Öpik (ref. 3).

Flight Test

The stars in the reentry photographs were identified and their exact positions at the time of the observations were established from existing star catalogs with corrections for both precession and proper motion. The positions of desired points along the reentry trail with respect to selected stars were measured on the photographic plates with a comparator to an accuracy of 2 microns or about 5 meters along the trail. The space coordinate, velocity, altitude, and deceleration of the pellet at points along the visible reentry trail were found from the measurements of the point positions on photographs from two stations. These measurements were used in a computer program similar to the meteor data reduction program employed by the Smithsonian Observatory. (See ref. 6.)

Curves of the velocity and altitude against time for the visible portion of the pellet reentry are shown in figures 8 and 9. The velocity, decreasing from 9.8 to 5.5 kilometers per second during the visible trail, is typical of an object entering the earth's atmosphere almost vertically, and the altitude of 69 kilometers at the onset of visible radiation is comparable to that of natural meteors at this velocity.

In order to compute the luminous efficiency of the simulated meteor, the visible intensity of the reentry trail must be known. The method employed to obtain the intensity differed from the eye-comparison technique usually employed for natural meteor work. A densitometer was used to measure the transmittance of the photographic film along the reentry trail, and these measurements were then compared with the transmittances of the star streaks produced on the film by stars of known spectral class and magnitude. Calibration photographs were taken of both the reentry area and the zenith from all optical stations immediately after the flight test. The calibration plates provided the correction due to atmospheric absorption at low elevation angles for the comparison stars and the desired points along the trail.

As stated previously three intensity corrections are necessary. (See refs. 7 and 10.) Trail-range corrections are necessary to change the observed photographic magnitude to absolute photographic magnitude, which is the trail's stellar magnitude at 100 kilometers at zenith. This correction involves normalizing the trail range from the observation station to 100 kilometers at zenith and increasing or decreasing the observed magnitude depending on whether the actual trail was farther or closer than 100 kilometers from the station. The formula for the range correction is

$$M = M_a - 5 \log_{10} R \tag{1}$$

where M is the absolute magnitude, M_a is the apparent magnitude, and R is the range in units of 100 kilometers. The "writing speed" correction, which in this case is the largest correction, is due to the difference in the trailing velocities of the stars and the trailing velocity of the reentry object on the photographic plate. A correction is also necessary because of the reciprocity-law failure of photographic emulsions for different exposure times of the same intensity. From these measurements and corrections, a light-intensity curve of absolute photographic magnitude as a function of time along the trail was obtained for the visible portion of the reentry.

The intensity history for the visible pellet reentry is shown in figure 10. The reason for the erratic nature of the intensity is not known at this time. The intensity variations that show up in figure 10 and also in reference 11 are not found in natural meteor phenomena. One explanation is that the complex body motions of the disk may affect the ablation rate and therefore the intensity.

The results shown in figure 10 were obtained from ballistic camera photographs, and the fluctuations in intensity may be partly due to the low photographic signal-to-noise ratio of the reentry trail to the background. McCrosky and Soberman's light curve of this same artificial-meteor experiment (ref. 11), obtained from Super-Schmidt photographs show fewer fluctuations and less magnitude extremes than are shown in figure 10; however, only about one-half as many points were plotted in their figure.

Some consideration must be given to the ablation process in determining the reentry intensity. Ablation of the pellet by either vaporization on the spot or surface vaporization without spraying is not likely to occur because of the high rotational velocity and drag forces on the pellet. A rotational velocity of 36 cycles per second is imparted to the pellet by the spinning sixth stage. The pellet velocity is too low for ablation by sputtering, which is a temperature independent phenomena in which vibration energies imparted by high-speed impact with atomic particles eject surface atoms from the lattice. For a more complete explanation of types of meteor ablation, see references 3 and 11. The ablation process realized in this test is certainly one of spraying of the liquid melt in small droplets which are eventually vaporized.

For the purpose of this investigation, the total mass of 2.2 grams is considered to be reduced to liquid drops and eventually to be vaporized during the time of the visible trail. This assumption will result in an underestimate of the artificial meteor's luminous efficiency if some mass remains after the visible radiation has ceased. The average mass-loss rate was

$$-\frac{dm}{dt} = \frac{\text{Mass lost}}{\text{Time of visible trail}} = \frac{2.2}{0.74} = 2.97 \text{ grams/sec} \tag{2}$$

The intensity of the visible trail was found from the following relation as given by Öpik (ref. 3):

$$\log I = 9.72 - 0.4M_o \tag{3}$$

where I is the intensity in ergs/sec and M_o is the average absolute visual magnitude of the simulated meteor at a distance of 100 kilometers at zenith. The light curve in figure 10 is in terms of absolute photographic magnitude (M_{pg}) and therefore a "color" correction, as derived by Jacchia (ref. 8), is used to convert the measured photographic magnitude to visual magnitudes. The correction is given by

$$\left.\begin{aligned} M_o &= M_{pg} + 1.65 \\ \log I &= 9.72 - 0.4(M_{pg} + 1.65) \end{aligned}\right\} \tag{4}$$

The value of 1.65 for the color-correction factor, interpreted from reference 8, is for blue sensitive film with spectral response limits between 3600 Å and 5500 Å. Panchromatic film with a response between 3600 Å and 6500 Å was used for observations of the simulated meteor. However, the correction factor that should be used with this film has not been established and Jacchia's value of 1.65 (ref. 8) was used for this experiment. An average value for M_{pg} of -0.1 was obtained by measuring the area under the light curve in figure 10 and dividing by the time of the visible trail. The corresponding value of I, by equation (4), is 1.26×10^9 ergs per second.

The luminous efficiency τ of a meteor is defined as the fraction of the kinetic energy that is converted into visible radiation and is usually considered to be given (ref. 9) as:

$$\tau = -\frac{2I}{V^2 \frac{dm}{dt}} \tag{5}$$

The value of τ is considered to be proportional to velocity so that (see ref. 9):

$$\tau = \tau_o V \tag{6}$$

where τ_o is the luminosity coefficient with units of seconds per centimeter and is assumed to be constant over the flight of the meteor. Combining these two equations gives

$$\tau_o = -\frac{2I}{V^3 \frac{dm}{dt}} \tag{7}$$

Substituting the previously derived value of 2.97 grams per second for the average mass-loss rate and a value for velocity of 9.41 kilometers per second (the measured velocities shown in fig. 8 were cubed and then averaged by the integral method to give $(9.41)^3$), gives the luminosity coefficient of the simulated meteor as

$$\tau_o = 1.02 \times 10^{-9} \text{ sec/cm} \tag{8}$$

The corresponding value of the luminous efficiency would be

$$\tau = 9.55 \times 10^{-4} \tag{9}$$

or about one-tenth of 1 percent of the kinetic energy of the artificial meteoroid.

The average atomic weight of the stainless steel is very nearly the same as that of iron; hence, if the different kinds of atoms in the stainless steel are assumed to be equally effective in producing light, these values of τ_o and τ obtained from the Trailblazer flight test are at present our best estimate for a natural iron meteor at an entry velocity of 9.8 kilometers per second. For an estimate of the luminosity coefficient τ_o for a natural stony meteor, considered to be 15 percent iron (ref. 1), it is assumed that the luminosity is produced by the iron alone. On this basis, the luminosity coefficient of a natural stony meteor (15 percent iron) is 1.53×10^{-10} second per centimeters at 9.8 kilometers per second; this value, however, would be a lower limit because the other material in the stony meteor would contribute to the total luminous intensity.

If it is assumed that there is no contribution to the luminous intensity from either chromium or nickel, then the total observed intensity was produced by 69.7 percent iron; therefore, a natural iron meteor of 100 percent iron would have a luminosity coefficient of 1.45×10^{-9} second per centimeter and a luminous efficiency of 1.37×10^{-3} at the reentry velocity.

Theory

Öpik, in his theoretical estimate of the luminous efficiency of natural meteors, gives a set of tables and equations from which the luminous efficiency may be derived for meteors of known composition and mass. (See ref. 3.) In the application of this theory to the simulated meteor, it was assumed, because of complex body motions, that the meteor was spherical with the same mass of 2.2 grams as the actual disk-shaped artificial meteor. It was necessary to extrapolate the values given in Öpik's table LII for the coma-dilution factor σ_β because the lowest velocity tabulated was 10.4 kilometers per second, and the simulated meteor's average velocity was only 9.41 kilometers per second. The theoretical luminous efficiency is an estimate obtained from Öpik's tables and equations.

The total luminous efficiency τ is the sum of three components, corresponding to three processes; namely, the impact of meteor-vapor atoms with air molecules and also with other meteor atoms rebounding at high speed after such collisions with air molecules, producing radiation from highly excited or ionized meteor atoms τ_i; the radiation in discrete wavelengths arising from inelastic collisions between atoms in the coma, or the "temperature radiation" τ_t; and the thermal radiation from the meteor surface τ_b. The total luminous efficiency is then

$$\tau = \tau_i + \tau_t + \tau_b \qquad (10)$$

Impact-radiation efficiency.- Öpik's equation (eq. (8-10) of ref. 3)

$$\tau_i = \frac{\beta_1 + \beta_2\sigma_\beta}{1 + \sigma_\beta} \tag{11}$$

was used with his tables LI and LII extrapolated to determine the impact efficiency. For the artificial meteor the value was found to be

$$\tau_i = 3.9 \times 10^{-4}$$

Coma-radiation efficiency.- The value for the inelastic collision efficiency is found (ref. 3) in table LIII with equation (8-13)

$$\psi = 1 - \exp(-\epsilon\nu_c) \tag{12}$$

and equation (8-14)

$$\tau_t = 50\beta_c{}'\psi(1 - \psi) \tag{13}$$

where

$$\psi \leqq 0.5$$

From this relation, a value of

$$\tau_t = 6.2 \times 10^{-4}$$

was found for the artificial meteor. In Öpik's table LIII the value of $\epsilon\nu_c$ is given in terms of an assumed spherical mass with a radius of r_o. For this estimate, $0.0979m^{2/3}$ was substituted for $r_o{}^2$ because the artificial meteor mass was known.

Thermal-radiation efficiency.- The thermal radiation efficiency from the artificial meteoroid surface is found from Öpik's equation (8-19)

$$\tau_b = \frac{b_v\theta}{\dfrac{\frac{1}{2}V^2}{h} + \dfrac{2\theta}{\gamma}} \tag{14}$$

Öpik's values of $b_v = 1.25 \times 10^{-3}$ at 2100° K, $h = 8 \times 10^{10}$ ergs per gram for vaporization, $\theta = 0.19$ at 2100° K, and $\gamma = 0.6$ were used. From these values, the black-body thermal-radiation efficiency is

$$\tau_b = 1.6 \times 10^{-4}$$

The theoretical total luminous efficiency is given as the sum of the estimates of the three preceding components

$$\tau = \tau_i + \tau_t + \tau_b$$

$$\tau = 1.17 \times 10^{-3}$$

The value of $\tau = 9.55 \times 10^{-4}$ found from observations of the Trailblazer I artificial iron meteor reentry, with equal efficiencies per atom assumed for iron, nickel, and chromium, is about 80 percent of the estimate obtained from Öpik's theory. The value of $\tau = 1.37 \times 10^{-3}$ found from the experiment by assuming no contribution to the light intensity from either chromium or nickel is about 17 percent greater than that predicted from Öpik's 1958 theory of an iron meteor at the same velocity.

RESULTS AND CONCLUSIONS

Observations of an artificial iron meteor indicate that the fraction of the meteor kinetic energy that is converted into visible light during the meteor's reentry into the earth's atmosphere is about 80 percent of that predicted by Öpik's 1958 theoretical estimate. Since the mass-loss rate was probably overestimated by the assumption that the total mass was consumed during the visible portion of the trail, the efficiency found from observations of the artificial meteor experiment is probably an underestimate.

A luminous efficiency of 9.55×10^{-4} was estimated for natural iron meteors at a velocity of 9.8 kilometers per second. From this value an estimate of 1.44×10^{-4} was obtained for the luminous efficiency of natural stony meteors at this velocity with the assumption that the stone is 15 percent iron and the visible light is produced by the iron alone. This value is an underestimate since the other material in the stone would also contribute to the luminosity.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., January 6, 1964.

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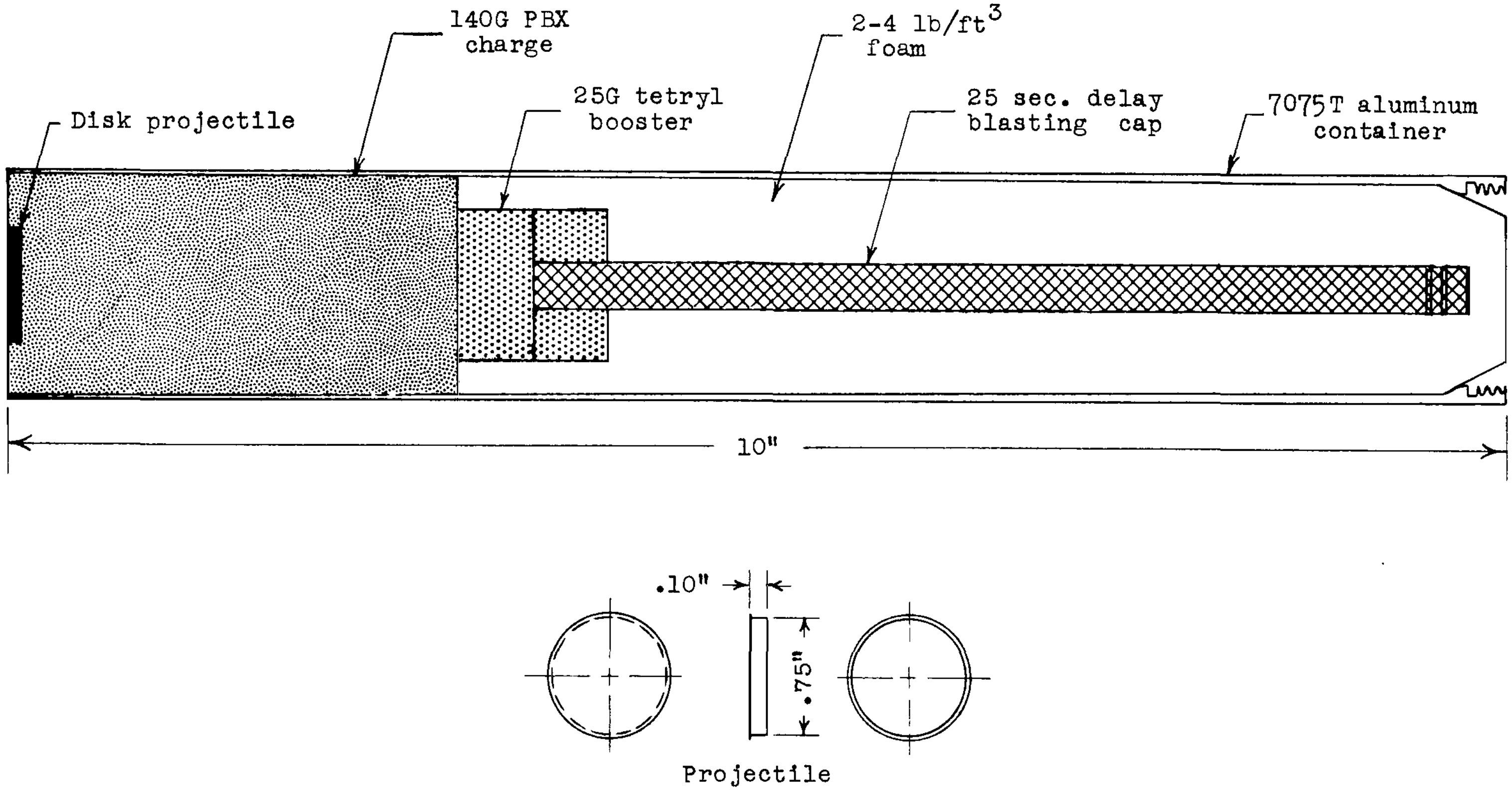

(a) Shaped-charge gun with a 5.8-gram stainless-steel projectile.

Figure 1.- Trailblazer Ig seventh stage.

Before

After

(b) Projectile before and after being accelerated by a shaped charge. L-63-6898

Figure 1.- Concluded.

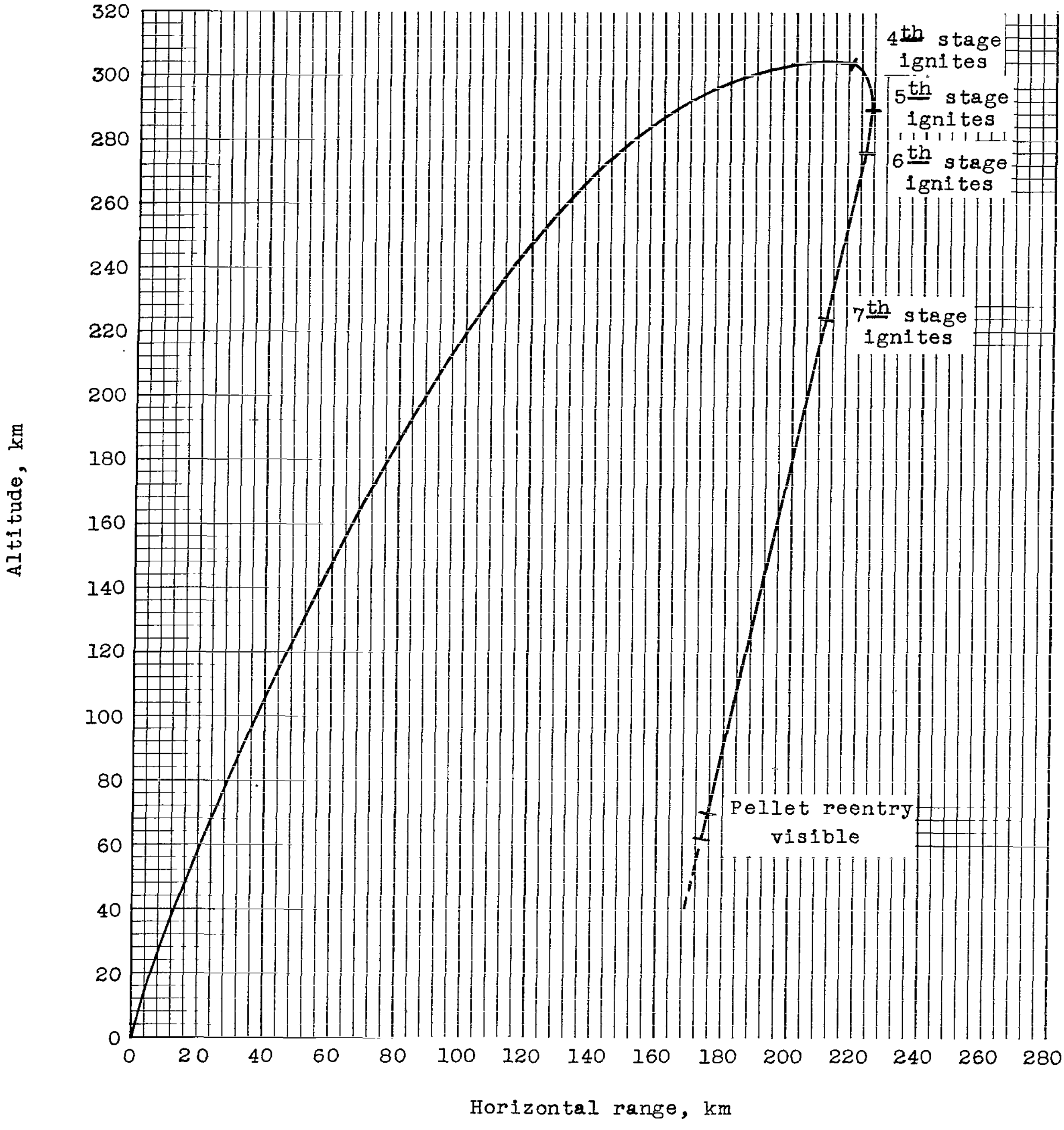

Figure 2.- Altitude as a function of horizontal range for the Trailblazer Ig nominal trajectory.

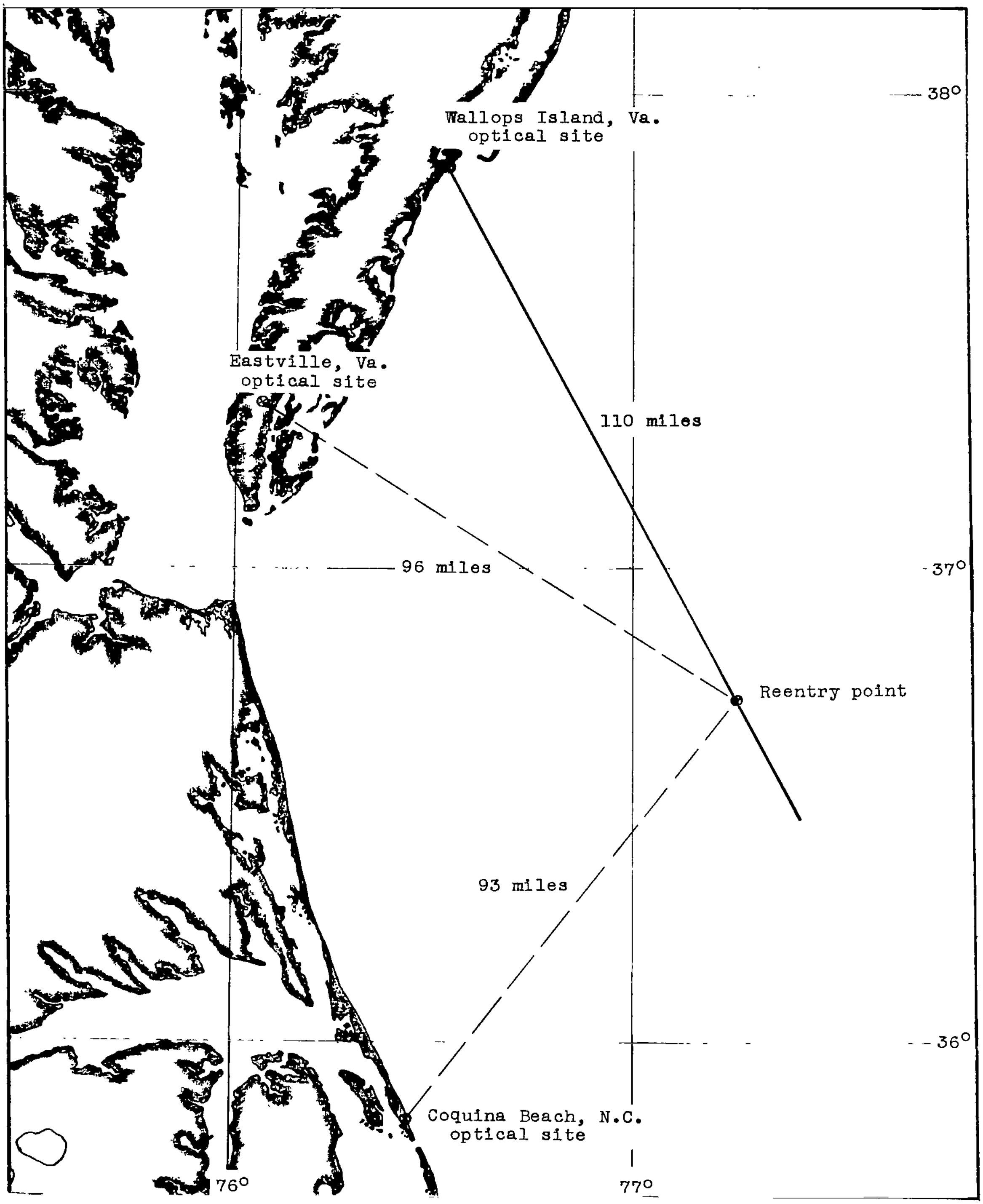

Figure 3.- Map showing vehicle azimuth and reentry point with respect to optical sites.

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Figure 4.- Super-Schmidt cameras located at the NASA Wallops Station.

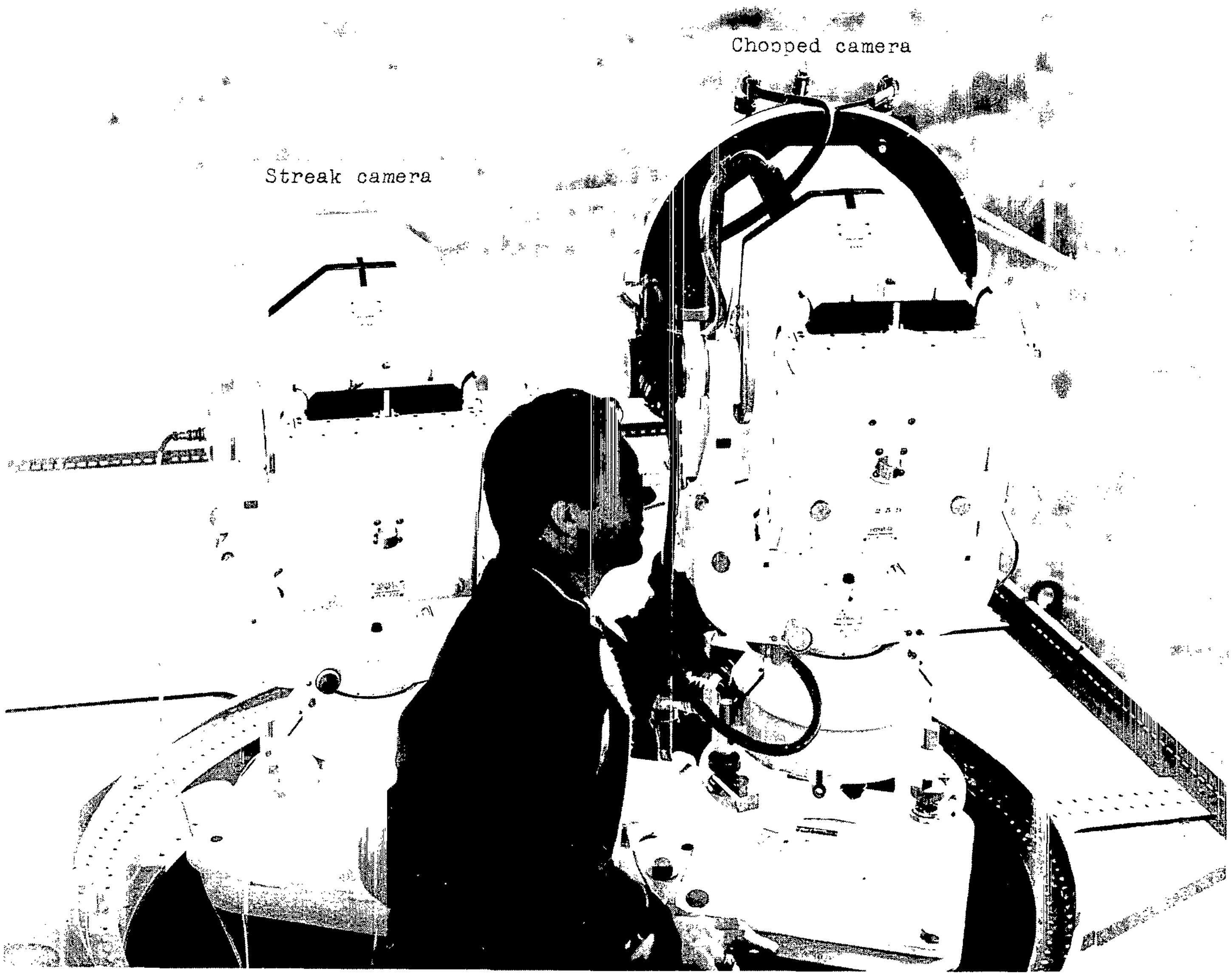

Figure 5.- A chopped and a streak-ballistic camera mounted on a trailer turret and used to obtain optical data. L-64-368

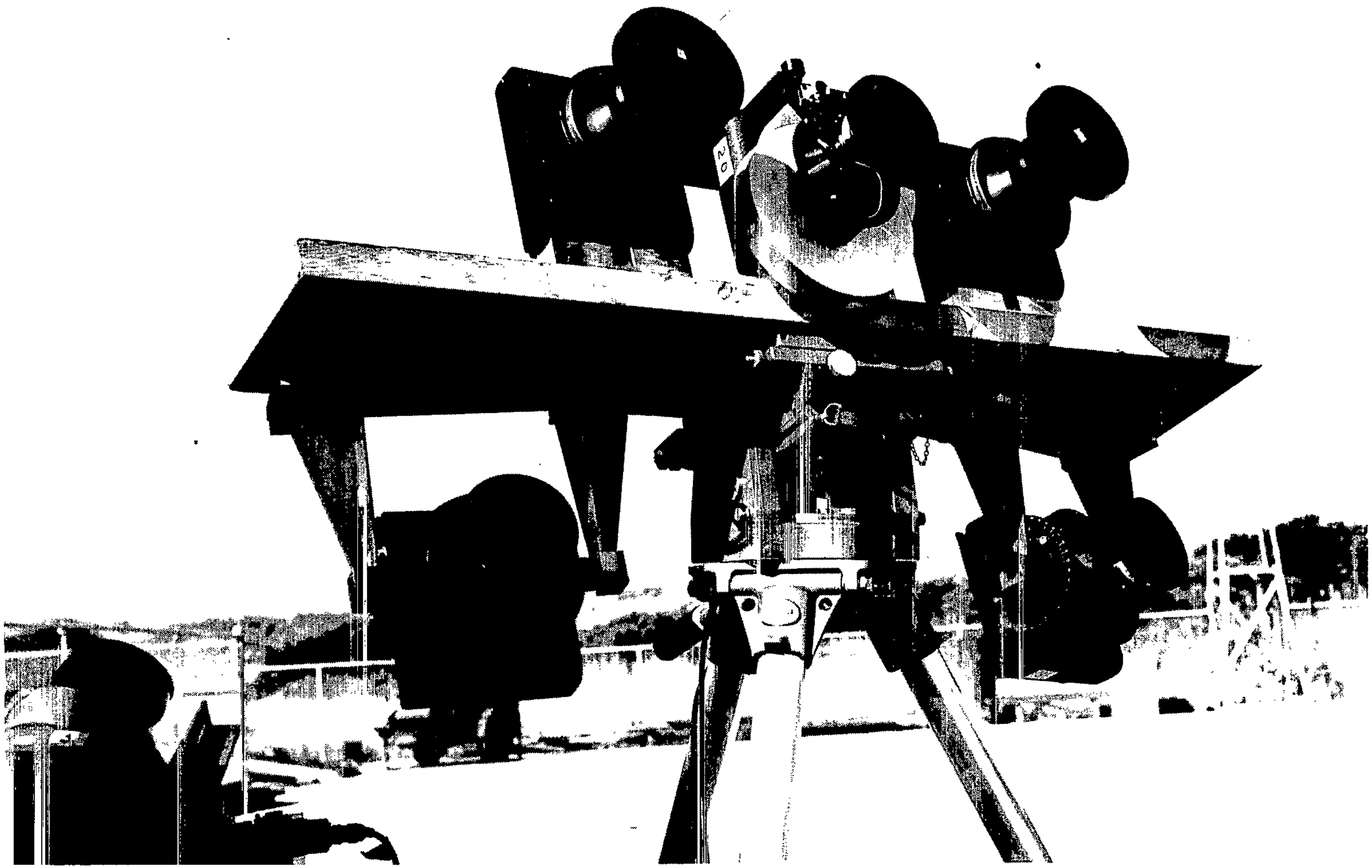

Figure 6.- An array of modified K-24 aerial cameras located at Coquina Beach.

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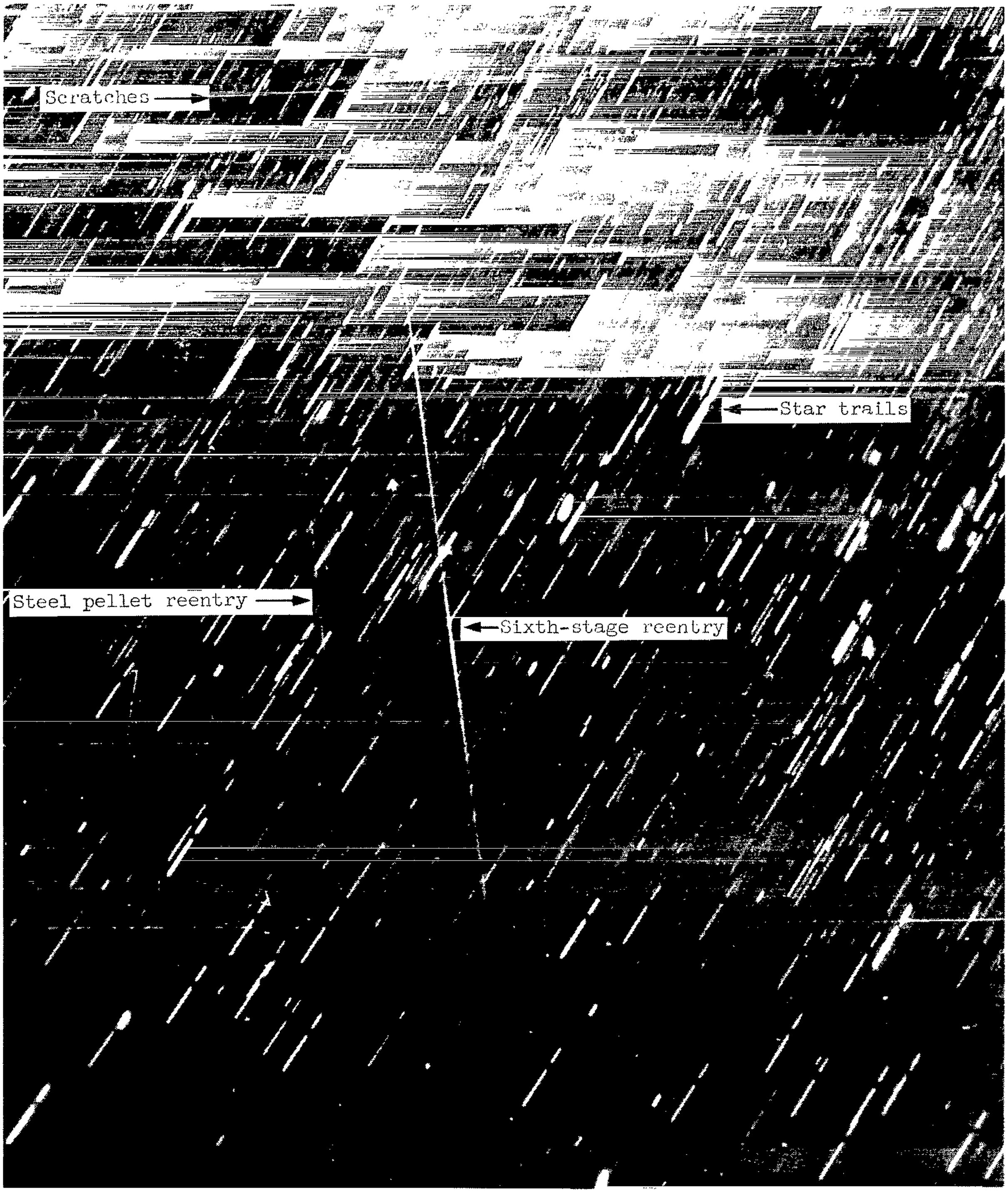

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Figure 7.- Photograph of the Trailblazer Ig reentry taken with a K-24 camera at Coquina Beach.

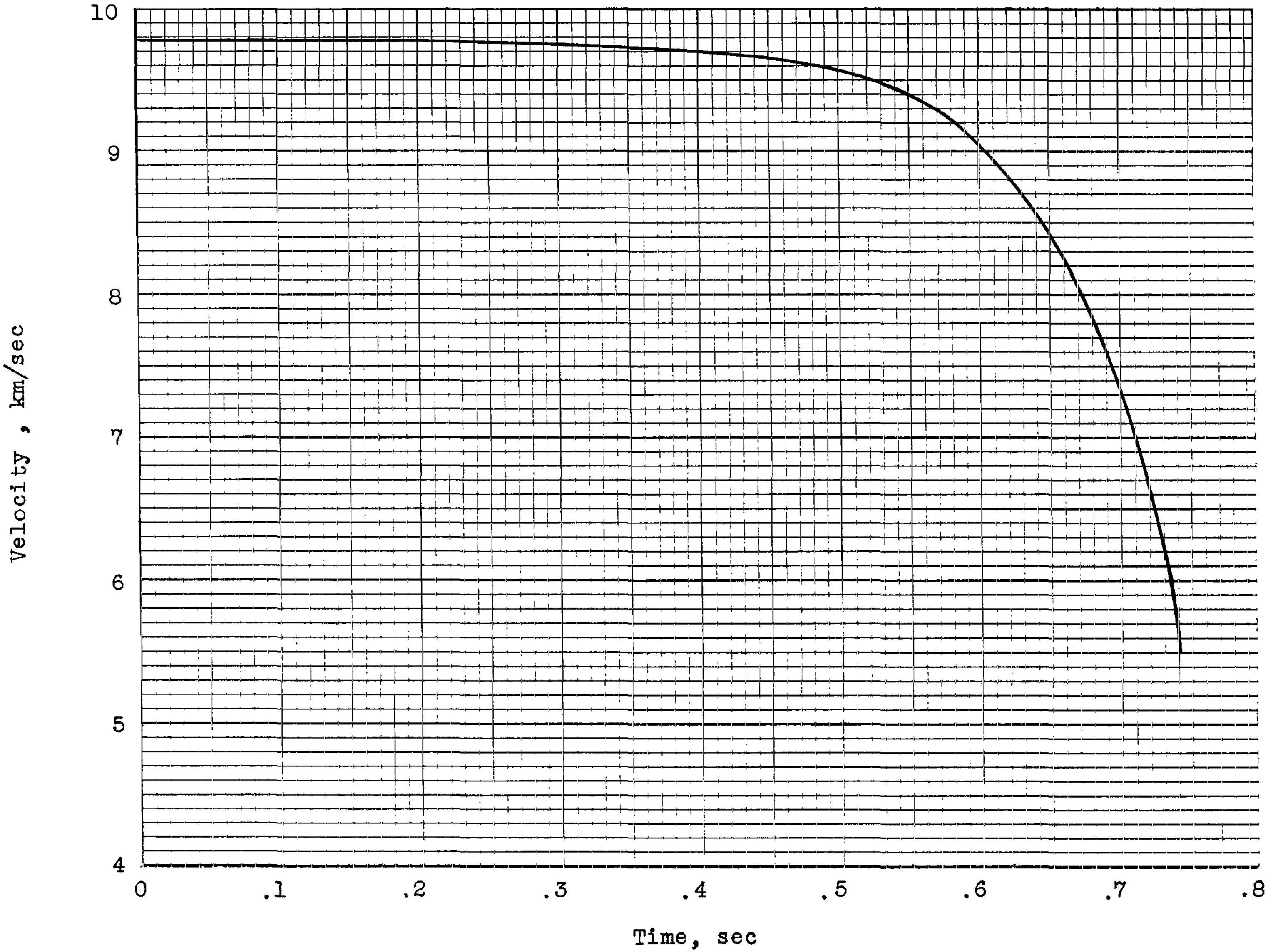

Figure 8.- Velocity as a function of time during projectile reentry.

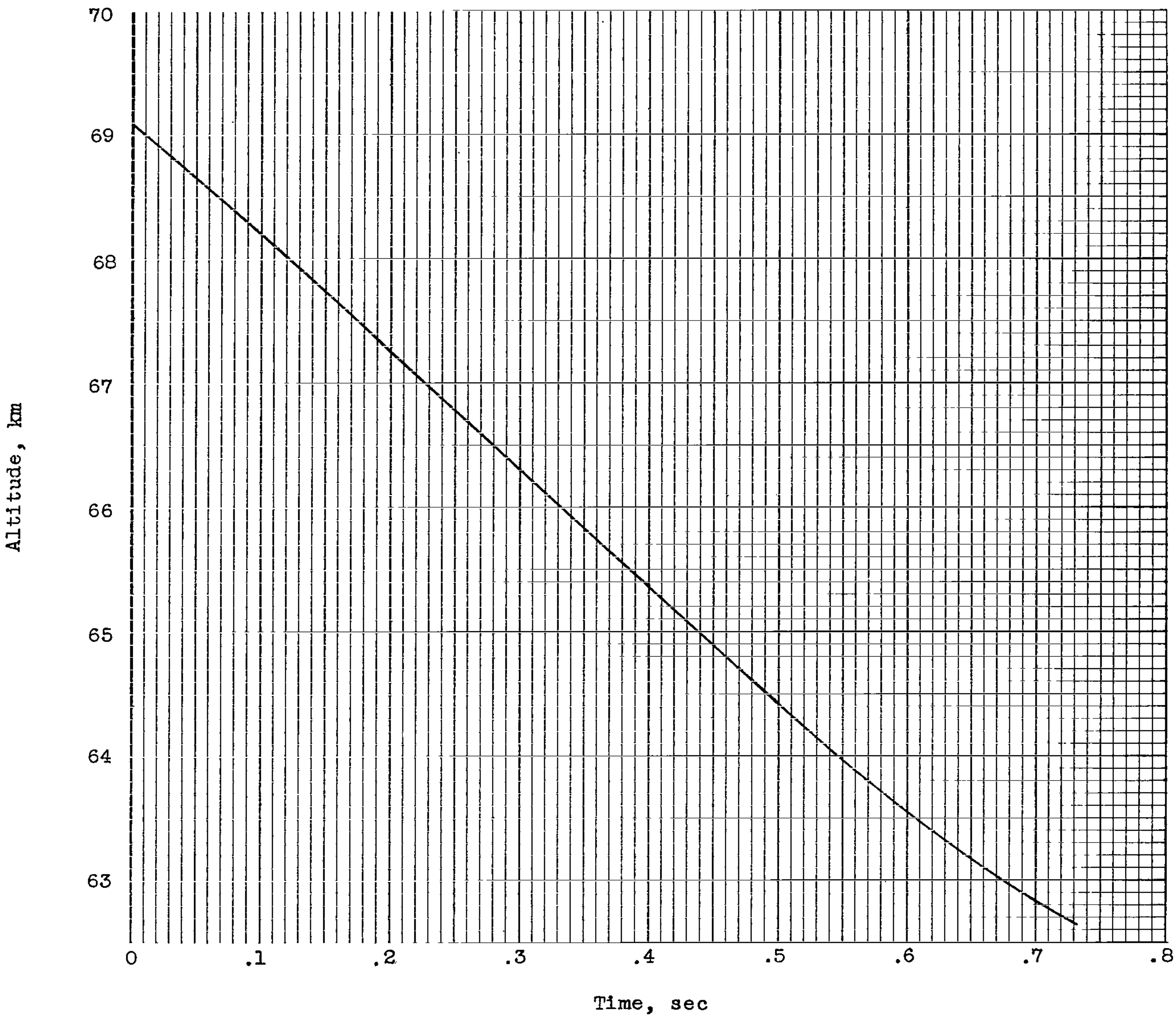

Figure 9.- Altitude as a function of time during visible projectile reentry.

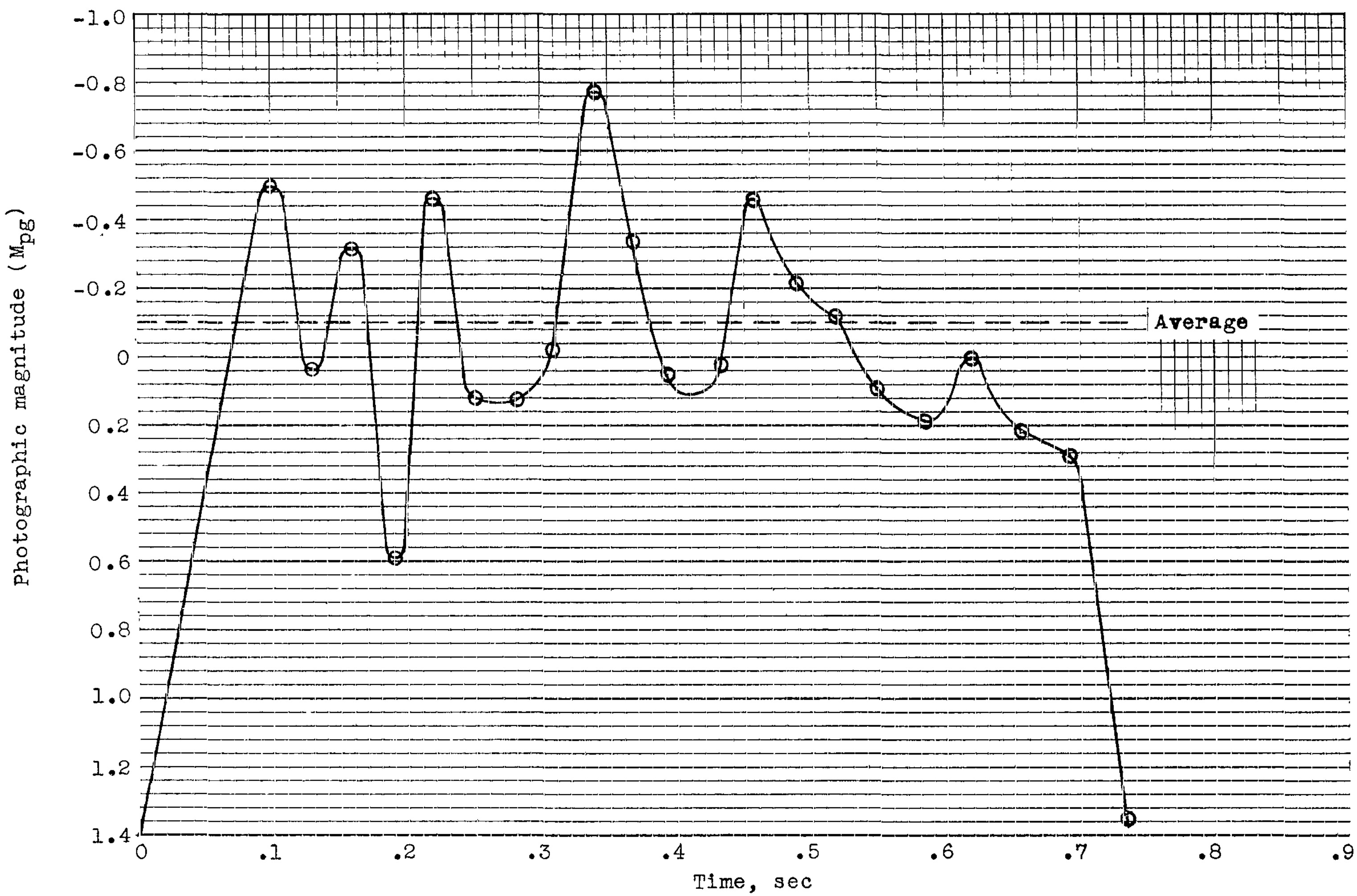

Figure 10.- Photographic magnitude as a function of time during projectile reentry.

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