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DESIGN AND APPLICATION OF A PHOTOMULTIPLIER DETECTION SYSTEM FOR ARTIFICIAL METEORS

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Introduction

In recent years a series of rocket-borne artificial meteor experiments have been conducted by NASA Langley Research Center in cooperation with the Smithsonian Astrophysical Observatory as part of a continuing program in meteor research. These experiments are designed to reenter objects of known mass and chemical composition into the earth's atmosphere at velocities equal to the velocities associated with slow natural meteors. The purpose of these experiments is to obtain photographic and radar signatures of the phenomena associated with these artificial meteors to better understand similar phenomena associated with natural meteors. A photograph of an artificial meteor is shown in figure 1. The photograph also shows the luminous reentry of two rocket motor cases.

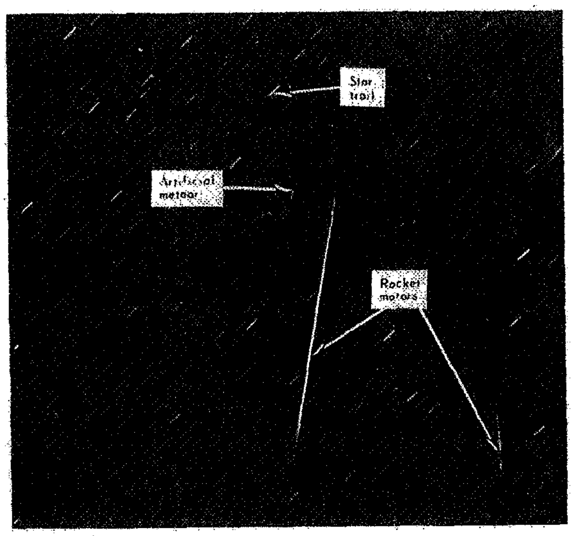

Figure 1.- Luminous reentry of an artificial meteor and vehicle rocket motors.

It was recognized early in the program that there was a need for correlation of the photographic and radar data. Since the radar signals were recorded against a real time standard (WWV), it was decided that a basis for correlation could be obtained by recording the optical signals against the same time standard as that used by the radar.

Successful photoelectric detection of natural meteors using photomultiplier systems with no optical components by McKinley in Canada (Ref. 1) and Davis in England (Ref. 2) suggested that a photomultiplier system could be used for this application. A simple electro-optical device using a photomultiplier tube as a detector was designed and constructed to detect and record in real time the optical radiation from the artificial meteors. The design was later modified to increase the dynamic range and detectivity of the basic instrument.

The purpose of this paper is to describe some of the constraints that governed the design of the instrument, the basic design and subsequent modifications, and the performance characteristics of the instrument with and without the modifications.

Design Constraints

The nature of the artificial meteor experiments placed several, sometimes conflicting, constraints upon the design of the detection system. Each experiment has several reentry objects of interest which are separated in space and time and which produce visible reentries with widely varying degrees of luminous intensity. It is practically impossible to track the artificial meteors because of the uncertainty in their reentry position and the

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short duration of their luminous existence. Multiple reentries, uncertainty in reentry positions, and the inability to track individual reentries governed the design of an instrument with a large field of view. The low light levels and wide dynamic range of the luminosities associated with the reentries governed the choice of a photomultiplier tube as the detector.

Logistical considerations were of prime importance in the design of the instrument. A short lead time for development of the instrument governed the decision to develop the instrument "in-house" and from "off-the-shelf" components. The instrument had to be portable and it had to be compatible with the real time recording equipment located at the optical stations. The necessary accuracy in time recording was determined to be on the order of 0.01 second.

It was decided that an instrument utilizing imaging optics with a 40° field of view, a photomultiplier tube, and paper strip chart recording could be designed to meet these requirements.

The Basic Instrument

Optical Network

A schematic representation of the basic instrument design is presented in figure 2. The use of imaging optics enabled the design of a compact, portable instrument; but, more importantly, provided a method of discriminating between reentry source and the stellar background. With a stationary detection system, images of the reentry sources will move in the image plane at much greater velocities than the star images. Placing a parallel bar reticle in the image plane provides a means of modulating the signals at a frequency which is proportional to the image velocity. This modulation provides a means of distinguishing the reentries from the background and from each other. Since approximately half of the total light entering the optical system is blocked by the reticle, the reticle has the added advantage of enabling the instrument to be operated with a larger field of view than would be possible without the reticle in the system.

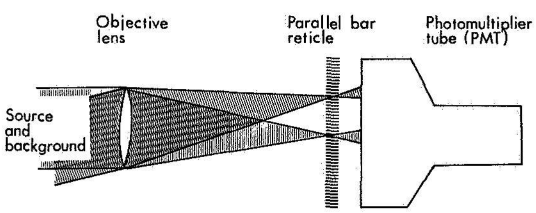
The photomultiplier tube was chosen to have the desired sensitivity, to have a spectral response similar to the photographic emulsions, and a photocathode surface large enough to accommodate the field of view of the objective lens.

Electrical Network

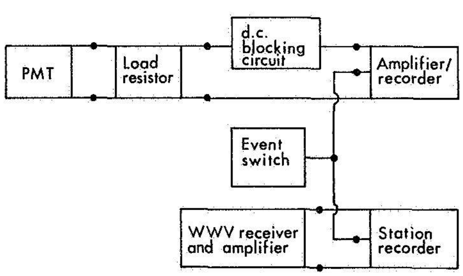
The anode current from the photomultiplier tube is proportional to the total amount of light falling on the photocathode. This current consists of the sum of the currents produced by the background, the reentry sources, and the dark current of the tube. The background current will, in general, have a large dc component and a smaller ac noise component. The noise component is due primarily to star scintillation. The signal from the reentry sources will, in general, consist of an ac component associated with the modulated frequency of the signal and a smaller very low-frequency component associated with the duration of the signal. The component associated with the duration of the signal will be present if the image of the source is larger than the width of an opaque bar in the reticle, or if an appreciable amount of reflected light from the source is collected by the optical system.

In practice, the dc component from the background limits the sensitivity at which the system can operate, its field of view, and dynamic range. This component cannot exceed the maximum mean anode current rating of the PMT. The noise component of the background has, in general, a peak-to-peak value of approximately 5-10 percent of the dc component. It is the noise component of the star background that limits the detectivity of the system.

The anode current from the PMT is passed through a load resistor to ground.



(a) Optical network.



(b) Electronic network.

Figure 2.- Schematic representation of basic detection system.

A dc blocking circuit consisting of a battery and variable resistor is used to bias out the dc component of the background from the recorders. After passing through the blocking circuit the signal is recorded on a multichannel paper recorder at various levels of amplification.

The basic instrument was designed to be portable enough to be transported to any of the optical stations. Since each station had its own WWV time receiver and recording equipment, it was decided that the optical signal record could be synchronized to the WWV time signal station record by simultaneously marking the optical strip chart and the station time strip chart. This is done several times during an experiment to allow a measure of any deviations in chart speed from either of the recorders. It has been found in practice that the desired accuracy in timing of ±0.01 sec was readily obtainable using this method.

A summary of the design data for the basic instrument is given in table I.

TABLE I.- BASIC INSTRUMENT DESIGN DATA

Objective lens	Type: Aerial camera Focal length: 178 mm Focal ratio: f/2.5 Field of view: $40^\circ \times 40^\circ$, max.
Reticle	Type: Parallel bar Overall dimensions: 127 × 127 mm Bar space: 20 pairs/cm Clear to opaque ratio: 1.0
Photomultiplier tube	Type: Flat-face; end window Spectral response: S-11 Photocathode diameter: 111 mm Overall sensitivity: 2000 Amps/lumen, max. Peak linear output: 50 ma Mean anode current: 1 ma, max. Dark current: 2 μa, max.
Load resistor	Type: Variable, 500-10,000 ohm
Blocking circuit	Type: Variable voltage, 0-6 V
Amplifier/recorder	Type: Paper recording oscillograph Amplification: 0.05 V/cm, max. Chart speed: 250 mm/sec, max.

Typical Results

Portions of a strip chart record showing the recorded signals from the reentries shown in figure 1 are presented in figure 3. The portions of the record selected for presentation are from different channels at different values of amplification. Amplification of the meteor signal is 25 times that of the first rocket motor signal and 2.5 times that of the second rocket motor signal.

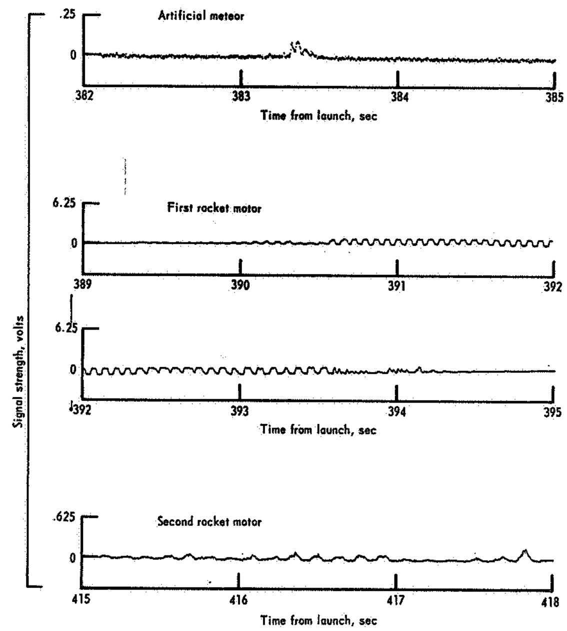


Figure 3.- Recorded signals from the three reentries shown in figure 1.

The peak magnitude of the artificial meteor, as viewed from the optical station, was equivalent to a zero magnitude star on a photographic magnitude scale and produced a signal approximately five times as great as the background noise signal. The first rocket motor reentry was several magnitudes brighter than the artificial meteor and produced a signal which exceeded the linear dynamic range of the photomultiplier tube. This is evident by the "clipped" appearance of the recorded signal. The second rocket motor produced a peak signal approximately twice that of the meteor.

The basic instrument was used in several experiments and in most instances performed satisfactorily by recording in real time the optical signals from the reentry events. In addition, the records provide useful data on the performance of the vehicle such as the time sequence of rocket motor firings (deduced from the times of reentries), and the relative velocities of the reentry objects (deduced from the modulation of the signals).

Modifications to the Basic Instrument

Although the basic instrument performed satisfactorily in the experiments where it was used, some of its performance characteristics were less than desired.

The detectivity of the instrument was limited to approximately +2 magnitude by the background noise level. This is about two magnitudes brighter than the limiting magnitude of the fastest meteor cameras. The sensitivity and dynamic range of the instrument were limited by the high dc currents generated by the background. Variations in the response of the instrument with field angle limited the total field of view to approximately 30°.

The instrument was redesigned to improve these characteristics and measurements on laboratory sources and star backgrounds have been performed to compare the performance of the modified instrument with the performance of the basic instrument. The modified instrument has yet to be tested in a reentry experiment.

A schematic representation of the modified instrument is presented in figure 4. There are three modifications to the basic design: a spectral filter, a field lens, and a low pass electrical filter.

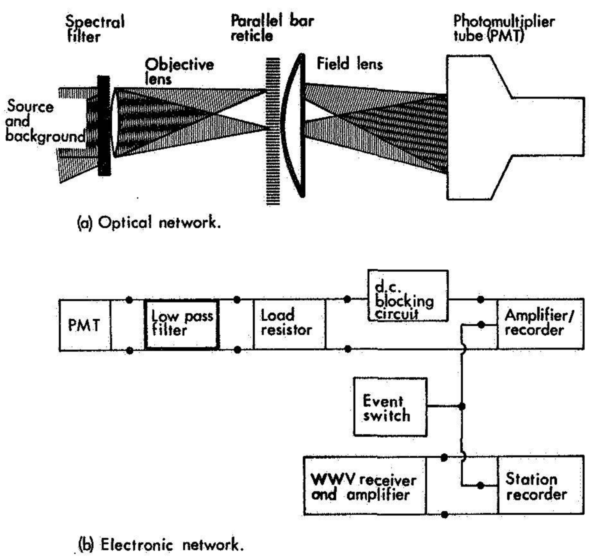


Figure 4.- Schematic representation of modified detection system.

Most of the reentry objects have been of iron or steel. Spectra from some of these reentries indicate that a large portion of the radiation in the photographic region of the spectrum is from atomic iron and concentrated in a few bright lines between 0.36 and 0.40μ. An ultraviolet filter was selected to isolate this region of the spectra. Background measurements with and without the filter indicate that the dc and noise components of the background are reduced by approximately 60 percent by use of this filter. The reduction of the signal from an iron reentry should be considerably less than 50 percent and may be as little as 20 percent. The introduction of the ultraviolet filter in the system is expected to increase the dynamic range of the instrument by decreasing the dc background level and to increase the signal to noise characteristics of the system by preferential filtering of the signal. The spectral response characteristics of the two instruments are compared in figure 5(a).

A field lens was introduced into the system to image the exit pupil of the objective lens onto the face of the photomultiplier tube. This was done so that the light passing through any point in the

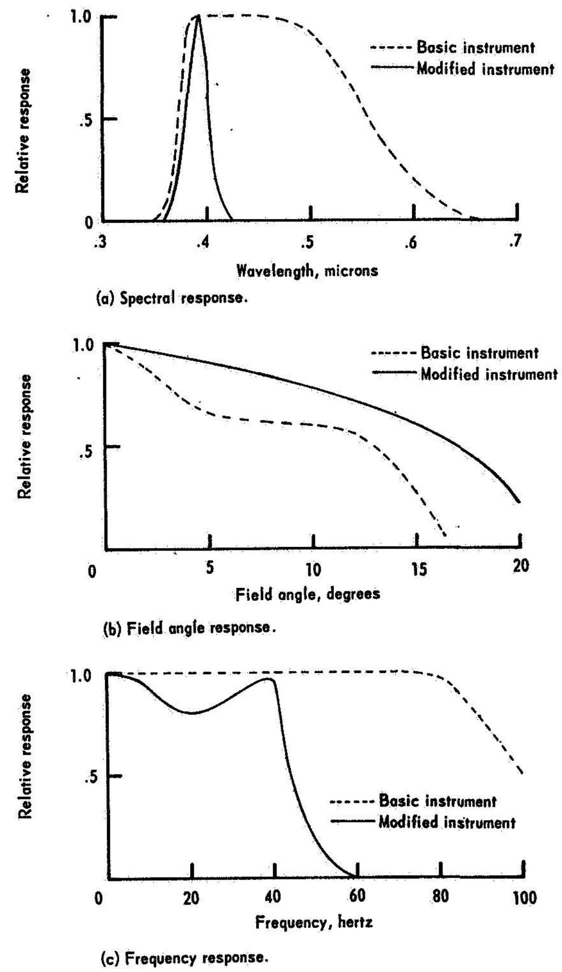


Figure 5.- Comparison of the performance characteristics of the basic instrument and the modified instrument. Ordinate values have been normalized to the maximum output values.

image plane would be spread evenly over the same area of the photocathode surface. Introduction of the field lens improved the sensitivity versus field angle characteristics of the instrument to a point where the variation of sensitivity with field angle is due to the characteristics of the objective lens and not the PMT. A comparison of the field angle characteristics of the two instruments is shown in figure 5(b).

The fundamental frequencies associated with the electrical signals produced by the reentries are generally less than 40 hertz. The frequency spectrum of the recorded background noise signal is limited only by the recording system which responds to frequencies in excess of 100 hertz. A simple low pass filter network was introduced into the system to attenuate frequencies greater than 40 hertz. Measurements on star backgrounds with and without this filter indicate that introduction of the filter into the system reduces the noise component of the background by more than 50 percent. This filter should have no appreciable effect on the reentry signals. A comparison of the frequency response of the two instruments is presented in figure 5(c).

A summary of the operating characteristics of the two instruments for a 40° field of view and a typical star background is presented in figure 6 in terms of anode current and stellar magnitudes based on a photographic scale. The data were derived from background measurements, manufacturer's data, and measurements obtained with the basic instrument during reentry experiments. The data are presented for an average star background and do not represent those cases where one or more of the brightest stars (brighter than 1.0 mag) would appear in the field of view. With average star backgrounds, the basic instrument has a dynamic range extending from +2 to -3.5 magnitudes and the modified instrument has a dynamic range from +4 to -3.5 magnitudes. Under these conditions, the modified instrument should be able to detect any artificial meteor bright enough to be photographed by the fastest meteor cameras.

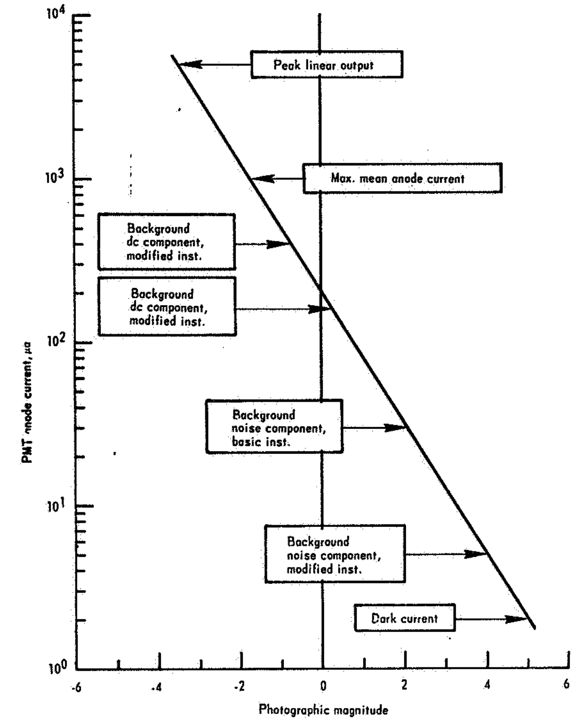


Figure 6.- Operating characteristics of the detection system with a typical star background.

Backgrounds

Background measurements indicate that the greatest background noise occurs when a single bright star dominates the background. Because of scintillation, the radiation from an individual star is almost all noise. However, the average radiation from several stars will produce a signal with a dc component considerably larger than the ac noise component. This is because the noise signals from different stars are incoherent with respect to each other.

The worst background condition that has been measured was the background having the brightest star, Serius, at the center of the field. This star increased the background by a factor of 10. In contrast, the planet Jupiter, which is an extended source, while brighter than Serius (-1.6 versus -1.4), increased the noise background level by a factor of 2. One method of reducing both the ac and dc components of the background would be selective obscuration in the image plane the most dominant background sources.

Concluding Remarks

The basic instrument performed satisfactorily in the experiments where it was used. In addition to providing a record of optical radiation from the reentry objects that could be correlated with radar record, the instrument has provided "quick-look" data for vehicle performance evaluation.

Modification of the basic instrument has increased its dynamic range to a point where it can with typical background conditions detect any artificial meteor bright enough to be photographed by the meteor cameras.

The basic design of the instrument lends itself well to signal processing by spectral, spatial, and electrical filtering techniques. These attributes make it a potentially useful instrument in other areas of research that require the detection of untrackable, low intensity sources across wide fields of view which include a large background component of radiation.

References

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2. Davis, J.: On the Color Index of Meteors. Smithsonian Contributions to Astrophysics, vol. 7, 1963, pp. 233-236.

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