OPTICAL STUDIES OF METEORS AT MT. HOPKINS OBSERVATORY

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March 1 to November 30, 1974

Final Report

Principal Investigator:

Dr. Trevor C. Weekes

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1. INTRODUCTION

The conventional detection of optical meteors using the photographic technique does not extend to objects much fainter than +4: use of the low-light-level television significantly reduces the detector threshold. With SEC Vidicons, it is estimated that, under ideal conditions, 50% of the meteors brighter than $M_V = +8.15$ will be detected with a simple optical system that subtends a 13° by 16° field.

Although radar techniques can detect even fainter meteors, it is difficult to translate the fluxes into an absolute rate of meteor mass per unit area per unit time. Since the design of spacecraft destined to spend long periods in the space environment depends critically on the precise value of these fluxes, the measurement in the 10^{-4} to 10^{-1} g range is extremely important. For very low masses, 10^{-8} to 10^{-6} g, the fluxes can be determined directly by use of penetration experiments on satellites. In the intermediate range, the fluxes are estimated by interpolation over many orders of magnitude.

Using the 10-m optical reflector and an array of phototubes, we have attempted to extend the optical measurements beyond the present limit achieved by the Vidicon system. We report here the first detection of optical meteors with $M_V = +12$. It is hoped that this system can be used to determine intermediate points in the meteor frequency mass curve for sporadic meteors and to study in detail the faint components of meteor showers. We report here preliminary observations made on three nights in September 1974.

2. DETECTION SYSTEM

The 10-m reflector at the 7600-ft level of Mt. Hopkins in southern Arizona has been used in studies of cosmic radiation since 1968 (Fazio et al., 1968). It consists of 248 hexagonal spherical mirrors, which are front-surfaced with aluminum and SiO_2 overcoating. The reflector has an overall focal length of 7.3 m and is designed to concentrate 90% of the reflected light from a point source at infinity into a circle of 5-cm diameter in the focal plane. A phototube with a 12.5-cm photocathode effectively subtends a field of view of 1° (full field). The reflector sits on an altitude-azimuth mount that can be programed to track at a sidereal rate.

The gamma-ray program normally utilizes one or more RCA 4522 tubes at the focus of the reflector; these 12.5-cm tubes have high quantum efficiency in the near ultraviolet. For the meteor work, we used the same tubes in the configuration shown in Figure 1. The center tube was on the optical axis of the reflector and was the principal channel for meteor detection; it shall be referred to hereafter as the detector. The remaining six tubes were distributed symmetrically in a ring of diameter of 1°2 about the center tube. The voltage on the tubes that constitute the guard ring was adjusted so that their gains were comparable.

The outputs of the two systems, detector and guard ring, were taken through 150 m of cable to the control room. The detector channel was split between two amplifiers with bandwidths D.C. to 10 Hz (slow) and D.C. to 100 Hz (fast). The combined guard ring signals were taken through an amplifier with bandwidth D.C. to 10 Hz. The upper limit to the wider bandwidth was set by the desire to reject the 120-Hz signal from back-scattered man-made light sources. The outputs of the three amplifiers were displayed on three channels of a six-pen chart recorder. The output of the fast detector amplifier was split between two recorder channels, one of which had a gain 10 times lower than the other. The remaining two channels were used to display a time code generator signal.

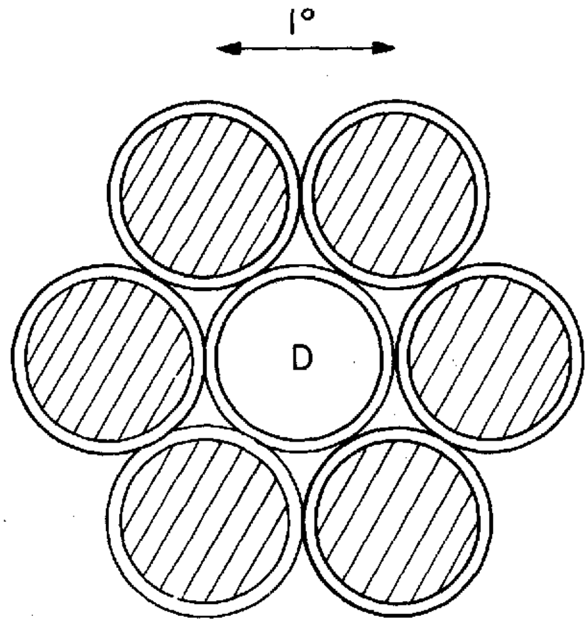

Figure 1. Phototube configuration at focal plane of the 10-m reflector. D = detector. Separation between tube centers is 1°2. Cross-hatched areas are covered by guard ring.

3. OBSERVATIONS

Observations were scheduled during the moonless nights of September and at the maximum of the Leonid shower in October 1974. Unfortunately, an unusually wet fall limited observations to three partially clear nights in September. All the observations were made with the reflector in the sidereally tracking mode with the detector directed at an arbitrary region of dark sky. Since the detector sensitivity is ultimately limited by fluctuations in the night-sky background, the maximum sensitivity in the detector is obtained by keeping its star field fixed. The sensitivity is significantly less if the reflector is kept fixed or oriented in a direction such that the phototubes observe distant, variable, man-made light sources on the horizon.

Since the tracking is not perfect, some slow variations will occur that make it necessary for an observer to adjust the zero setting of the chart recorder to keep the outputs on scale.

3.1 Sensitivity Estimate

The sensitivity of the detector channel to optical meteors of 10-msec duration can be estimated assuming that the light fluctuations in the sky background are only statistical.

The detectable signal is given by:

$$S = 10 \left(\frac{B_\lambda \cdot \Delta\lambda \cdot Q \cdot r \cdot A \cdot R \cdot T}{h\nu} \right)^{1/2} ,$$

where

B_λ = background light = 1.7×10^{-7} erg/cm^2 sec ster (Allen, 1973),

$\Delta\lambda$ = effective bandwidth = 1500 Å,

Q = quantum efficiency = 0.20 from 3000 to 4500 Å,

r = field of view = 2×10^{-4} ster,

A = mirror area = 75 m^2,

R = mirror reflectivity = 0.8,

$h\nu$ = effective photon energy = 4.8×10^{-12} erg,

T = resolving time = 10^{-2} sec,

$\therefore$ S = 3.57×10^4 photoelectrons/resolving time.

This corresponds to an optical flux of 0.06 photon per 10 msec or 1.9×10^{-14} erg/cm^2 sec Å. Using the expression log f (B) = $-0.4\ m_V - 8.21$ (Allen, 1973), we get $m_V = +13.8$. In practice, the limiting detectable magnitude will be greater than this since we have not taken into account atmospheric absorption, tracking jitter, non-statistical sky fluctuations, etc.

3.2 Calibration

A relatively simple calibration procedure was used to determine the peak pulse height in terms of stellar magnitudes of A0 stars. These particular measurements were not corrected for atmospheric extinction: This correction can be done accurately by using one of the astronomical telescopes nearby, enabling the meteor pulse heights to be expressed in absolute units.

The 10-m reflector was oriented to point at a bright A0 star. A lamp mounted on the reflector so that it was visible to the detector tube was adjusted to give the same current. The lamp was then covered by a known number of neutral density filters, and the reflector was oriented at a typical region of the sky. The neutral density filters in front of the lamp were removed until the lamp was just detectable by the detector. A chopping wheel in front of the lamp was used to simulate meteor pulses; the filter density was adjusted until the chopped signal was just detectable above the background night-sky noise on the chart. The threshold for pulse detection P_T is then given by

$$P_T = M + N \quad ,$$

where M = magnitude of the A0 star and N = neutral density factor in stellar magnitudes.

Using this technique, we found $P_T = +12.0\ M_V$ with an estimated uncertainty of ±0.7 mag. If sufficient stars are observed at a range of wavelengths, this uncertainty can be reduced to ±0.1 mag.

A pulsed L.E.D. in front of the phototubes was used to compare the sensitivity of the detector tube to the individual guard ring tubes. Since we had used the most sensitive tube available for the detector, and since the noise in the Guard Ring output is greater because of larger area of sky viewed, we estimated that the sensitivity of an individual tube on the guard ring to a meteor was 1/3 that of the detector. Since the center of the phototubes cannot be positioned any closer than $1^\circ\!.2$, the guard ring is not completely efficient. However, the angular response of a phototube is not flat-topped but Gaussian in shape so that the holes in the guard ring are partially filled in.

3.3 Background Pulses

The major virtue of the guard ring was that it enabled several potentially troublesome sources of background pulses to be rejected. We noted three main sources: (1) distant lightning gave simultaneous bursts of fast pulses in the detector and guard ring; (2) under windy conditions, the tracking of the 10-m reflector was uneven, causing simultaneous slow variations in both channels, and (3) in certain orientations, the phototubes could see the light beacon at Nogales Airport some 20 mi distant; these pulses were simultaneous, slow, and periodic and therefore could be easily rejected.

Since genuine meteor pulses are expected to appear either in one channel only or in both channels with a time delay, we do not consider that these or any other spurious sources made any significant contribution to our meteor data.

4. RESULTS

For the purposes of this report, we have examined briefly all the data from the three nights of observations but have performed a detailed analysis on only one 40-min run, which is typical of all the observations. We believe that the results obtained on this run accurately represent those that can be obtained on sporadic meteors (there were no large showers at the time). The observations were made with the reflector sidereally tracking a dark region of the sky close to the zenith from 2:45 to 3:25 local time.

The fast channel of the detector was used to select meteor events; a threshold pulse height of two chart divisions was used, which was well above the background light fluctuations on the 10- to 15-msec scale. There were many events below this threshold that were probably also meteor events, but they have not been considered in this analysis. Since the selected events were well above noise, there is no subjectivity in their selection. Our subsequent calibration showed two chart divisions $\equiv +12.0 \pm 0.7\ m_V$.

In 40 min, we detected 105 events. Figures 2 and 3 show the integral distribution of pulse heights and the distribution of pulse width (at 3-db points), respectively. Figure 4 shows some of the largest pulses.

Because the guard ring is significantly less sensitive than the detector, most of the events in the fast channel have no counterpart in the guard ring. We have examined the 18 pulses with a height of 10 scale divisions or more. Allowing for a difference of three in sensitivity, these events would have given a detectable signal in the guard ring if the meteor train was as bright as when it passed through the detector field of view. Of the 18 events, 7 had a guard ring component that was less than 0.4 times as bright as its detector component. Figure 4 shows an event that has clearly developed and died entirely in the field of view of the detector. As we go to smaller events, we expect the ratio of detector-only events to increase, but it is not possible to estimate the proportion from this small sample.

A preliminary search for after-pulse components (green line from oxygen) or for nonstatistical spacing between adjacent events (fragmentation perhaps) did not show any significant effects.

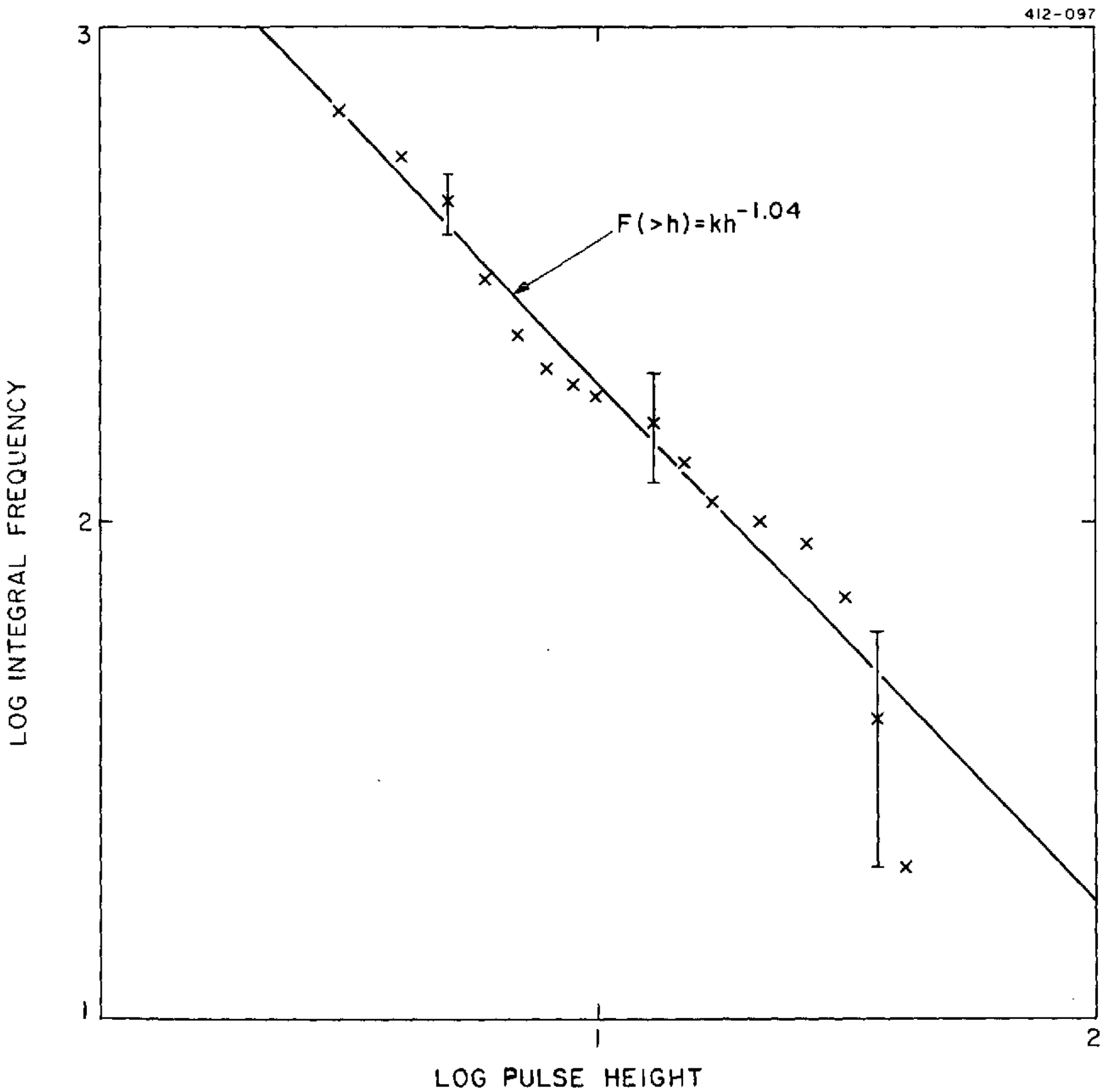

Figure 2. Integral frequency versus pulse height for 104 pulses. Pulse height is in chart-scale divisions; 2 divisions $\equiv +12\ M_V$.

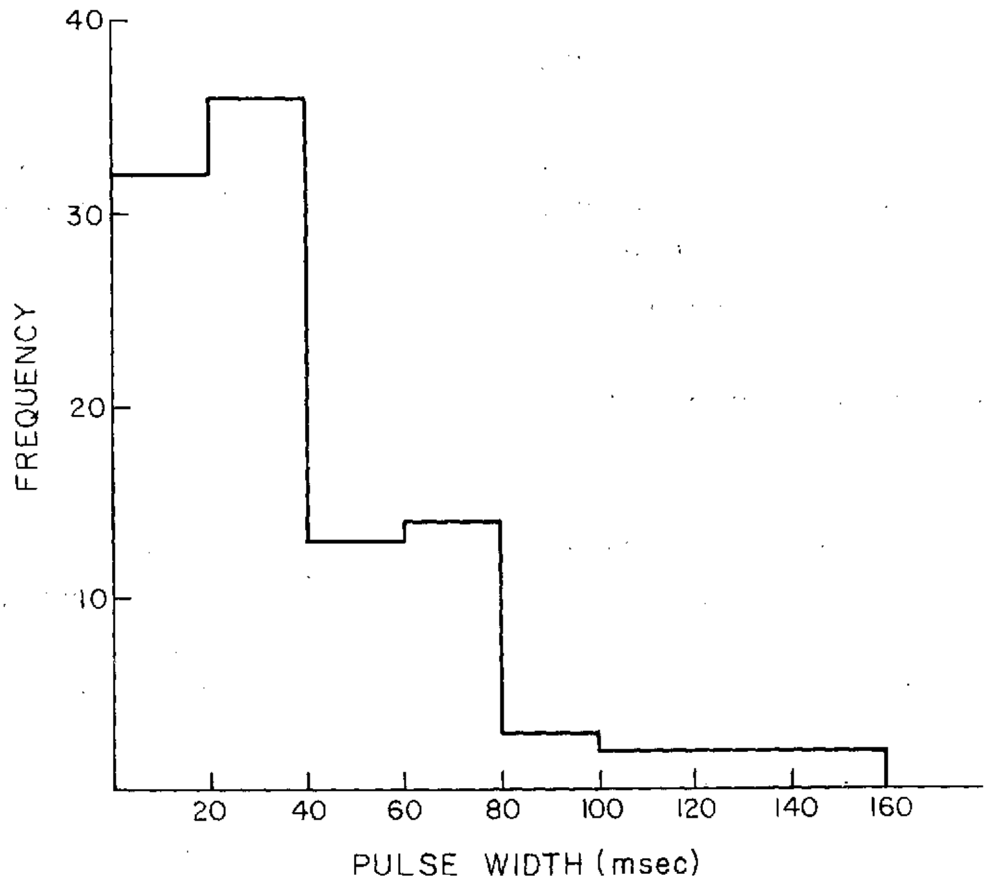

Figure 3. Frequency versus pulse width (at half-maximum).

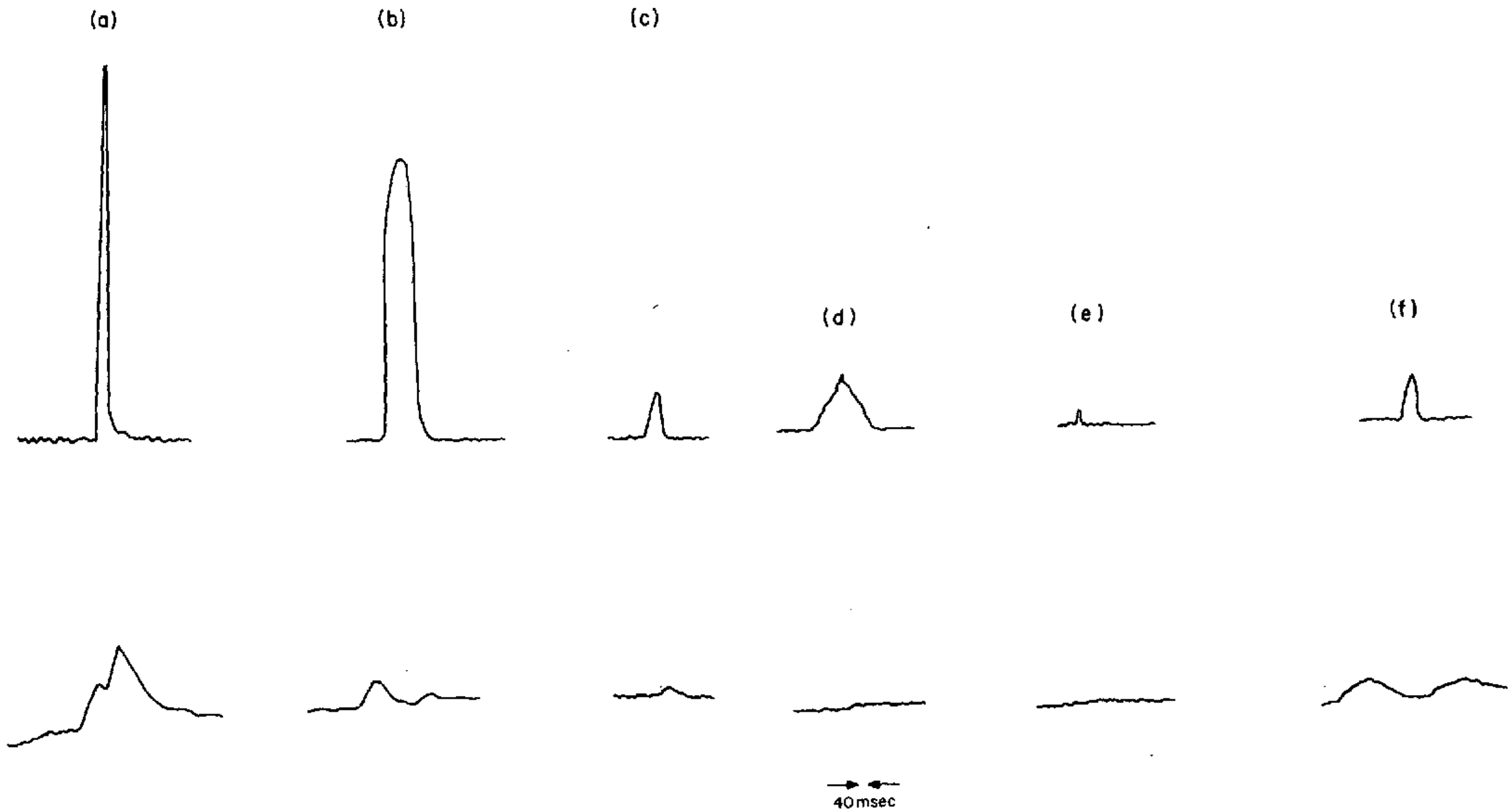

Figure 4. Sample of pulses detected. Upper curve is output of detector channel. Lower curve is corresponding guard-ring output. Pulse (e) is a threshold event of two chart divisions.

5. ANALYSIS

The efficiency of a one-degree-beam depends critically on the train length of faint meteors. From Jones and Hawkes (1974), the train length at $M_V = +7.5$ is 4 km, and it decreases with decreasing brightness. If these faint meteors typically ablate between 90 and 100 km, the target area is 2.2 km^2; when the track length is less than 2 km, most of the track will be seen if the impact angle is within a solid angle π of the optic axis. If the threshold is +12.0 mag, then the rate is given by $\phi\ (> +12.0) = 0.02/km^2$ sec. Inserting $M_V = 12.0$ into the expression $\log \phi = -15.294 - 0.5008\ M_V$ (Clifton, 1973) gives $\phi = 5.2 \times 10^{-4}/km^2$ sec. Hence, either the sensitivity or collection area of the 10-m system is greater than the values used above or this expression cannot be extrapolated over this range of stellar magnitudes. This may indicate that the flux of very faint meteors is much larger than the extrapolation would indicate or that the luminosities are greater, thus implying a change in the physics of the ablation process at these small masses.

The collection area—solid angle factor for this system for sporadic meteors can probably be best estimated with a Monte Carlo program for the meteor arrival directions and impact points. Further observations will show the diurnal and seasonal variations and give a more accurate frequency-pulse height spectrum.

It is obvious, however, that the chief value of this technique will be in the study of meteor showers where the impact angle is fixed and directed along the optical axis of the detector channel. The rate of detection of meteors seen only in the detector channel should increase substantially during a large shower, so that the frequency-pulse size spectrum can be calculated directly for that shower. In this case, there will be little uncertainty about the collecting area so that absolute fluxes can be measured. With the velocity and entry angle fixed, the meteor mass can be determined unambiguously.

Without any major modification, the 10-m reflector could be equipped with an array of 100 two-inch-diameter tubes, which would give a spatial resolution of about

$0\overset{\circ}{.}5$ over a field of 5° diameter. This combination of high sensitivity with spatial resolution seems the optimum system for the study of meteors with M_V from +10 to +13 magnitude.

Acknowledgment

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6. REFERENCES

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