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High Sensitivity Radar-Optical Observations of Faint Meteors

Koji NISHIMURA†*, **Toru SATO**†, **Takuji NAKAMURA**††, *Members, and* **Masayoshi UEDA**†††, *Nonmember*

SUMMARY In order to assess the possible impacts of meteors with spacecraft, which is among major hazard in the space environment, it is essential to establish an accurate statistics of their mass and velocity. We developed a radar-optical combined system for detecting faint meteors consisting of a powerful VHF Doppler radar and an ICCD video camera. The Doppler pulse compression scheme is used to enhance the S/N ratio of the radar echoes with very large Doppler shifts, as well as to determine their range with a resolution of 200 m. A very high sensitivity of more than 14 magnitude and 9 magnitude for radar and optical sensors, respectively, has been obtained. Instantaneous direction of meteor body observed by the radar is determined with the interferometry technique. We examined the optimum way of the receiving antenna arrangements, and also of the signal processing. Its absolute accuracy was confirmed by the optical observations with background stars as a reference. By combining the impinging velocity of meteor bodies derived by the radar with the absolute visual magnitude determined by the video camera simultaneously, the mass of each meteor body was estimated. The developed observation system will be used to create a valuable data base of the mass and velocity information of faint meteors, on which very little is known so far. The data base is expected to play a vital role in our understanding of the space environment needed for designing large space structures.

key words: meteor observation, MU radar, ICCD video camera, sensor fusion, space environment

1. Introduction

Impacts of meteors with spacecraft are among major sources of possible troubles in the space environment. Leonid meteor shower observed in 1998 and 1999 invoked world-wide attention to meteors as a possible hazard in the space[1]. Although the average mass of meteor bodies is much less than artificial space debris, relative velocity of high-speed meteors against the earth reaches to 72km/s, which far exceeds that of artificial objects. It is thus very important to establish statistics of meteors along the earth's orbit around the sun in order to make reliable data base for designing large scale spacecraft such as space stations.

Since the mass and the impinging velocity are the key parameters for impact assessment, it is essential to measure these quantities for each meteor. Radar and optical observations are the most effective tools for meteor observations. Especially, the head echo, which is the radar echo from the plasma generated around the meteor body when it impinges the earth's atmosphere, provides direct information on the velocity through its Doppler frequency shift[2]. We have developed a special scheme for meteor head echo observations with the MU (Middle and Upper atmosphere) radar, which is a powerful VHF Doppler radar located in Shiga prefecture, Japan[3]. Combined with its high peak output power of 1 MW and the large antenna size of 100 m in diameter, a special signal enhancement scheme called Doppler pulse compression enabled a much higher sensitivity than previous radar observations.

On the other hand, optical observations have the advantage of precise determination of directions[4]. Accurate instantaneous direction can be determined from the relative location of the meteor on the image against the background stars. The absolute magnitude can also be determined relatively easily by comparing it to that of the stars. Empirical relations have been established to give the mass of meteor body from its absolute visual magnitude assuming its velocity is known, as we discuss in details later. Although it is possible to determine the velocity of meteors by simultaneous optical observations from two locations, the chances for such events are quite limited.

It is thus advantageous to combine the radar and optical techniques which provide velocity and absolute visual magnitude, respectively, for the estimation of the mass of meteor bodies. The purpose of the present paper is to develop a combined radar-optical system consisting of the MU radar and an ICCD video camera for the purpose of studying velocity and mass distributions of faint meteors. Description of the systems and their performance evaluations are given. Preliminary results of the mass estimates and the relations of the radar echo power and the absolute visual magnitude derived from test experiments are also presented.

2. MU radar system and signal processing

The MU radar is a pulse Doppler radar operating at 46.5MHz, and is equipped with an active phased array antenna of 100 m size and 1 MW peak output power. The one-way antenna beamwidth is 3.6°, and the pointing direction can be switched in 10 μsec to any direction within 30° from the zenith. The aperture of the MU radar consists of 25 antenna groups, each of which consisting of 19 crossed Yagi antennas.

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†The authors are with Department of Communication and Computer Engineering, Graduate School of Informatics, Kyoto University, Kyoto 606-8501, Japan.
††The author is with Radio Science Center for Space and Atmosphere, Kyoto University, Uji 611-0011, Japan.
†††Nippon Meteor Society, 43-2 Asuka, Habikino-shi, Osaka, 853-0842, Japan
*Presently, the author is with SONY Corporation.

Moreover the MU radar has a capability to simultaneously use 4 sets of sub-arrays, each of which is an arbitrary combination of antenna groups, and their output signals are transferred to 4 receiver channels. However, the processing required for the meteor head echoes is beyond the capability of the real time data processing unit of the MU radar. It is thus necessary to record all of the raw data for off-line data processing. Recording of 4 channels of the raw data needed for interferometric observations described below became available in January 2000, when the tape drive is updated.

In order to detect weak head echoes from faint radio meteors at the range of around 100 km, we made use of a long transmission pulse of 256 μs which has a narrow bandwidth of 4 kHz. Although the meteor head echoes have large Doppler shifts of up to 24 kHz, their spectral width is narrow enough so that the signal is confined in the bandwidth of 4 kHz. We developed a scheme called Doppler pulse compression[3], which is equivalent to have 32 receivers whose center frequency is staggered at an interval equal to the bandwidth of 4 kHz. Doppler velocities, echo powers and ranges are determined from range-frequency spectra derived with the Doppler pulse compression. The rangewise sections of the spectra at each frequency is the correlation functions of the transmitted and received signals.

It is necessary to find peaks in the range-frequency spectra in order to determine the range and velocity of the meteor. The precise range of meteors are determined by interpolating the rangewise sections through the point of peak power. While the Doppler velocity can also be determined by interpolating the frequency bins around its peak as is done in [3], we found that a higher precision can be achieved by interpolating the frequency spectra after oversampling 16 times along the frequency axis.

The received echoes also contain coherent Bragg scattering from meteor trails as well as the desired meteor head echoes. The coherent trail echoes is characterized by a very small Doppler velocity of less than about 100 m/sec, corresponding to the background wind velocity. In processing the data the meteor trail echoes are removed by rejecting three central points of the Doppler spectra. The minimum detectable velocity of the meteor head echoes becomes 25.2 km/sec because of this filtering.

3. Optical observation system

We developed a high-sensitive video camera system with an image intensified CCD (ICCD) for simultaneous meteor observations with the MU radar. In contrast to conventional optical observations of meteors, our radar field of view is limited to about an angle of 6° due to the beamwidth of the MU radar. On the other hand, a very high sensitivity of the MU radar requires the optical observations also has a sensitivity as high as possible. We thus designed our system to achieve sensitivity by limiting the field of view to about 10°.

The camera system consists of a primary lens for 35 mm size camera, ICCD camera unit and video recorder of NTSC signal. In the ICCD camera unit (C5909-12, Hamamatsu), two stages of MCP (Micro Channel Plate) intensifies an image collected by the primary lens and then it is transfered to the CCD chip through a tapering fiber with a reduction ratio of 2:1. The photocathode of GaAs is sensitive to a wavelength between 370 and 920 nm, with an image size of 12.8 mm $\times$ 9.6 mm. Comparing with a conventional system with a single image intensifier used in the previous cooperative observations with the MU radar [6], its sensitivity is improved by two orders of magnitudes. A small distortion (less than 1 %) with a fiber coupling enables accurate measurement of meteor directions relative to the background stars. Comparisons between tracks of meteors observed by both the radar and the video systems therefore provide a measure for the absolute accuracy of directions determined by the radar. In our current experiment, we utilized a primary lens of f=85 mm and F=1.4 (Nikkor), which produces the field of view of 7.5° $\times$ 5.7° in the ICCD camera unit.

Simultaneous observations of sporadic meteors with both the radar and the video systems were made on November 23 and 24, 2000. The antenna beam of the radar, and also the center of the field of the video camera, was pointed to the azimuth and the zenith angles of 135° and 30°, respectively, which is near the apex of the earth's motion at around 4:30 JST, expecting to observe the fastest part of the sporadic meteors relative to the earth. Nine time slots of 20–30 minute period shown in Table 1 were used for the simultaneous observations.

4. Radar interferometry for precise determination of directions

In our previous study[3], the sequential beam lobing (SBL) method with the MU radar was applied for determination of the directions of meteors. In this method, the antenna beam direction is slightly offset by 2°–3° from pulse to pulse, and the direction of a target is determined from the echo power ratio of two adjacent pulses. SBL method has an advantage of being insensitive to the absolute power or the receiver gain, and provided precise orbits of space debris[5], whose precision in the direction and the range is about 0.1° and 200 m, respectively. In the observation of meteor head echoes, however, it was found that the direction of meteors determined with the SBL method has a random error of about 11°. This large error is apparently due to fast variations in the back scattering cross section (RCS) of the meteor head echoes, because the SBL method assumes that RCS is con-

Table 1 Parameters of the observation of sporadic meteors on November 23 and 24, 2000.

November 23, 2000 Local time(JST)	November 24, 2000 Local time (JST)
1:38-1:58	0:37-0:58
2:30-2:58	1:32-1:58
3:30-3:58	2:32-2:58
4:30-4:58	3:32-3:58
	4:32-4:58

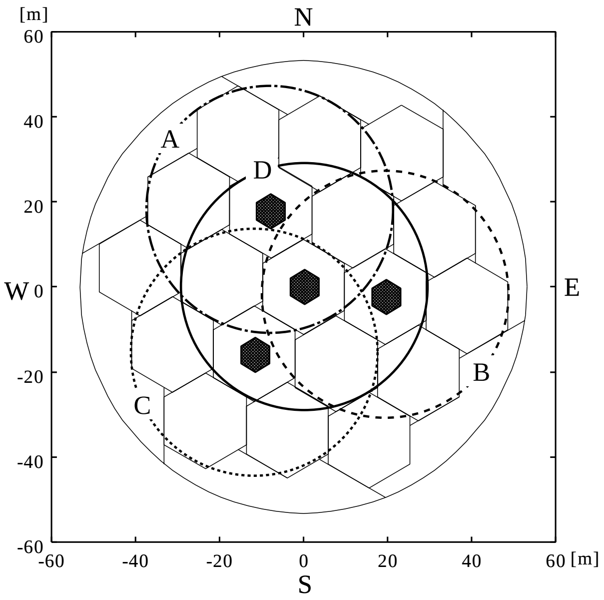

Fig. 1 Configuration of sub-arrays. Thin solid lines separate 25 antenna groups, and black hexagons indicate the center of gravity of each sub-array.

stant over the inter-pulse-period of 5-10 msec.

In this study, we employed a radio interferometry for more precise orbit determinations of meteors with the MU radar. By making use of 4 output channels available for the MU radar, we configured the radio interferometry with 4 sets of sub-arrays, each of which consists of 7 antenna groups. The transmission is made using the entire array with half-power beamwidth of 3.7°, while the receiving sub-array has the beamwidth of 8.0°. Figure 1 shows the shapes of the sub-arrays. The centers of the sub-arrays A, B and C constitutes an equilateral triangle and the center of the sub-array D is located at the center of the triangle. The distance of A, B and C is 34.0 m, and that of D and other three is 19.6 m.

Directions of targets are calculated from phase differences of echoes between two sub-arrays and the baseline length which corresponds to the length between the centers of the two sub-arrays. A two-dimensional determination of directions requires at least two independent phase differences which are calculated from three independent receiver outputs. We use the outputs of sub-arrays A, B and C for this purpose.

Phase differences between the channels are given by

$$\left\{ \begin{array}{lcl} \psi_{12} & = & (\boldsymbol{d}_1 - \boldsymbol{d}_2) \cdot \boldsymbol{k} \\ \psi_{13} & = & (\boldsymbol{d}_1 - \boldsymbol{d}_3) \cdot \boldsymbol{k} \\ \psi_{14} & = & (\boldsymbol{d}_1 - \boldsymbol{d}_4) \cdot \boldsymbol{k} \end{array} \right. , \tag{1}$$

where $\boldsymbol{k} = (k_x, k_y, k_z)$ is wave number vector of the echo, $\boldsymbol{d}_i - \boldsymbol{d}_j = (x_{ij}, y_{ij}, z_{ij})$ is displacement vector from the center of sub-array j to that of i, and ψ_{ij} is the phase difference observed between sub-arrays i and j.

Desired wave number vector $\boldsymbol{k}$ is obtained by minimizing the total error

$$E = \sum \{(\boldsymbol{d}_i - \boldsymbol{d}_j) \cdot \boldsymbol{k} - \psi_{ij}\}^2 \ , \tag{2}$$

which gives the MMSE (minimum mean-square-error) solution $\boldsymbol{k}_{\text{MMSE}}$. Noting that $z_{ij} = 0$ for an antenna located on $x - y$ plane, we obtain

$$\begin{pmatrix} k_{x\text{MMSE}} \\ k_{y\text{MMSE}} \end{pmatrix} = \begin{pmatrix} \sum x_{ij}^2 & \sum x_{ij}y_{ij} \\ \sum x_{ij}y_{ij} & \sum y_{ij}^2 \end{pmatrix}^{-1} \tag{3}$$

$$\begin{pmatrix} \sum \psi_{ij}x_{ij} \\ \sum \psi_{ij}y_{ij} \end{pmatrix} . \tag{4}$$

By using the relation $\sum x_{ij}y_{ij} = 0$, we finally get

$$k_{x\text{MMSE}} = \frac{1}{\Delta} \sum y_{ij}^2 \sum \psi_{ij}x_{ij} \tag{5}$$

$$k_{y\text{MMSE}} = \frac{1}{\Delta} \sum x_{ij}^2 \sum \psi_{ij}y_{ij} \ . \tag{6}$$

Assuming the white Gaussian random noise, the standard deviation of each component is estimated as

$$\left\{ \begin{array}{lcl} \sigma_{k_x} & = & 0.039\sigma_\psi \\ \sigma_{k_y} & = & 0.028\sigma_\psi \end{array} \right. , \tag{7}$$

where σ_ψ is the phase error of received echo in each channel.

Here we further try to make use of the redundancy of the fourth receiver channel D for a more precise determination. We first examine a symmetrical arrangement with minimum mean square method using the phase differences between sub-arrays A–D, B–D and C–D. By similar manipulation as stated above, we obtain

$$\sigma_{k_x} = \sigma_{k_y} = 0.049\sigma_\psi \ . \tag{8}$$

These values are worse than those of Eq. 7, which seems to imply that the effect of adding extra information is less important than making the length of the baselines as long as possible.

An alternative way is to add a short baseline A–D with some weight to the long baselines A–B and A–C in finding a MMSE solution. We examined the optimum weighting for this solution, which is found to be zero. We thus use only the output of A, B, and C for determining the direction.

On the other hand, the maximum zenith angle of unambiguous directioning by an interferometer is given by

$$\theta_{\text{max}} = \sin^{-1}\left(\frac{\lambda}{2d}\right) \ , \tag{9}$$

where d is the length of the baseline. For the long-baseline triangle ABC, $\theta_{\text{max}} = 5.44°$, while it is 9.47° if we employ the short baselines between D and others. The output of D is thus used to resolve the ambiguity inside the main beam region of the receiving sub-arrays, which covers 8.3°from the center of the beam to the first null.

Next we examine the procedure to determine the phase difference between two receiver channels. The phase difference between the complex output $z_i(n)$ and $z_j(n)$ of the two channels is given by

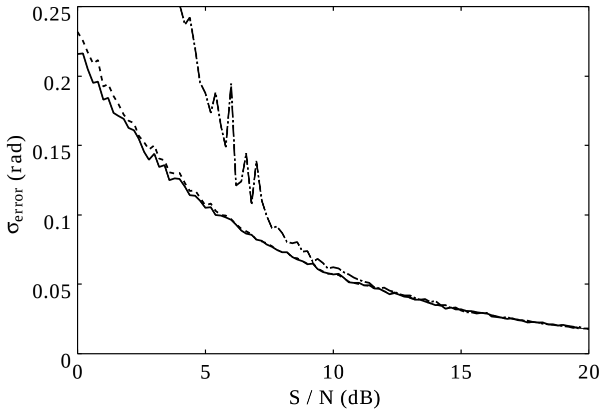

Fig. 2 Accuracies of ψ''_{ij} (solid line), ψ'_{ij} (dashed line) and ψ_{ij} (dash-dot-line) versus SNR.

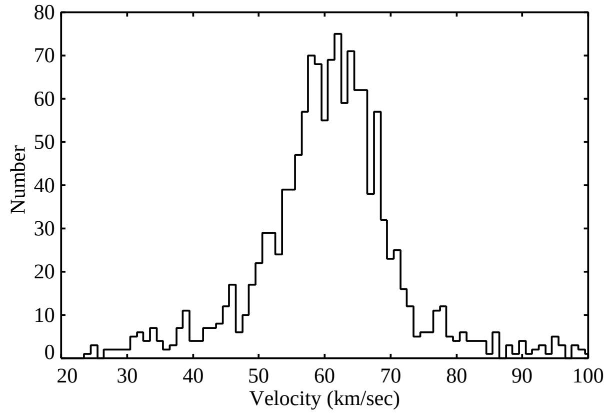

Fig. 3 Velocity distribution of the meteors observed by the MU radar.

$$\psi_{ij} = \angle \sum_n z_i(n)/z_j(n) \ . \tag{10}$$

However, this expression becomes unstable when $z_j(n)$ is small. We consider two alternate ways of calculating phase differences with different weighting, which are given by

$$\psi'_{ij} = \angle \sum_n \frac{z_i(n)/z_j(n)}{|z_i(n)/z_j(n)|} \tag{11}$$

$$\psi''_{ij} = \angle \sum_n \frac{z_i(n)}{z_j(n)} |z_j(n)|^2 \tag{12}$$

Figure 2 compares the accuracy of these three methods by numerical simulations. This result indicates that ψ''_{ij}, which is the mean of instantaneous directions weighted by the power of each sample, gives the best estimate, so it is used throughout this work in calculating the phase difference.

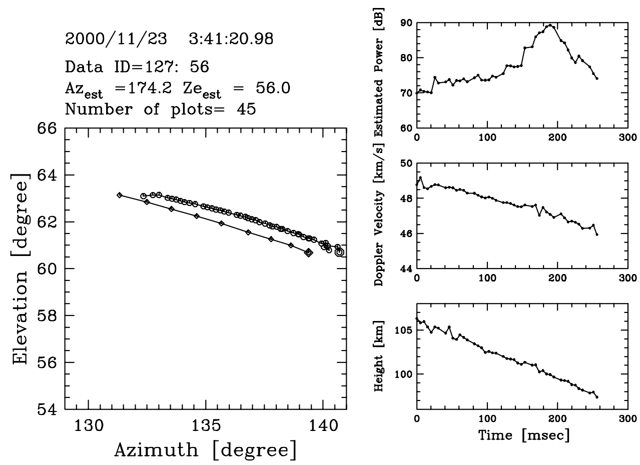

Fig. 4 A meteor observed by both the radar and the ICCD video camera system. The left panel shows tracks of the meteor in an angular plane observed by the radar (open circle) and the ICCD video camera system (open square).

5. Results of simultaneous observation

During the observation period shown in Table 1, 1393 meteor head echoes which last for more than 50 msec were detected by the MU radar. Figure 3 shows the velocity distribution of these meteors. While the majority of the distribution is within the velocity limit of 72 km/sec, which is the maximum velocity relative to the earth of an orbital body inside the solar system, there is a substantial tail extended beyond this limit. Although some of these values may due to errors in determination of direction when multiple meteors are simultaneously observed at an overlapping range, most of such high-velocity meteors are likely due to interstellar dusts.

Among these meteors, 34 cases were also observed with the video camera system. Since the current video recording system does not have the absolute timing, identification of meteors for the comparison is made manually.

Fig. 4 shows an example of the echo power, the Doppler velocity and the height of a meteor observed by the MU radar, and its instantaneous directions observed by both the radar and the optical systems. Instantaneous directions of the meteors observed by the video camera system is calibrated with the background stars, and the typical absolute accuracy is estimated as 0.009°.

As evident from the figure, there is an apparent offset of about 0.5° between the traces observed by the radar and the video camera system, which indicates the existence of angular offset error in the radar data. The major source of the offset errors in the interferometric observation is the intrinsic phase difference between the receivers. In order to compensate for this error, the same signal was fed to all four receivers prior to the observation, and the mean difference of the phase value of each receiver, which was about 10°, is subtracted from the observed phase differences.

The observed angular offset of about 0.5° suggests that there is another phase difference of about 16° between the receivers. Although the source of the error is yet to be identified, feeder lines and the antenna elements seems to be among possible causes.

However, as also clear from Fig. 4, relative directions

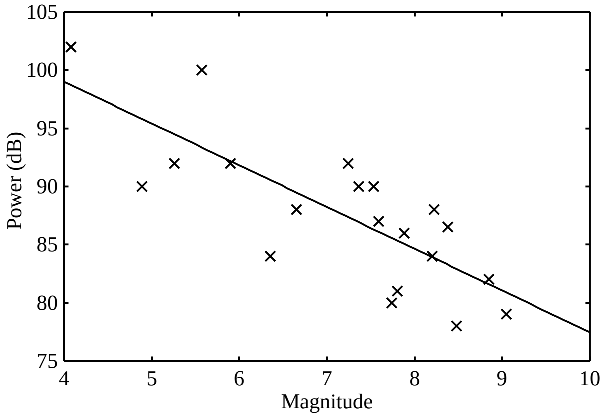

Fig. 5 Relation between the peak echo power and the absolute visual magnitude.

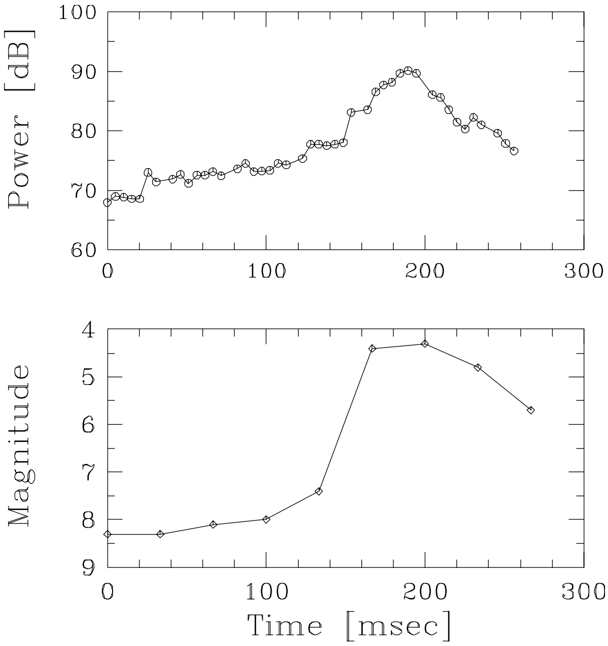

Fig. 6 An example of the echo power observed with the MU radar (upper panel), and the absolute visual magnitude observed with the ICCD video (lower panel).

determined by the MU radar have a rather high accuracy of 0.05°, if the mean offset is compensated for. Thus the velocity vector can be determined correctly, which is more important than determining instantaneous locations in assessing the effect of meteors as a space hazard.

The random error of the direction and the magnitude of the velocity vector is estimated as about 0.5°and 200m/sec, respectively for the data with good S/N ratio. As will be examined in the next section, precise determination of the velocity vectors is essential in estimating the mass distribution of meteors along the earth's orbit around the sun.

We also examined the relation between the absolute visual magnitude and the radar echo power from the simultaneously observed data. Fig. 5 shows a scattering diagram of the peak echo power versus absolute visual magnitude for each event. Among the 34 cases of the simultaneous observations, 20 cases for which both the radar and the video camera detect clear peak of the echo power and the magnitude, respectively, in their field of view are selected. The straight line is the linear regression determined by the least squares fitting, which yields

$$P = -3.6M + 113.4 \ , \tag{13}$$

where P is the peak radar echo power in dB, and M is the peak value of the absolute visual magnitude. Each point is an average of about 60 msec around the peak value, in which the radar and optical data contain 12 and 3 points, respectively. The deviation of data in this period largely varies among the cases, but is typically 3 dB for the radar echo power and 1 magnitude for the optical data. The absolute visual magnitude also has an extra error of about 0.5 magnitude due to the calibration procedure with background stars.

Figure 6 shows an example of the temporal variation of the radar echo power and the absolute visual magnitude with time. It should be noted that the horizontal axis for the optical data is adjusted so that its time of the peak agrees with that of the radar, since the optical observation does not have the absolute time reference.

It is also worth noting that temporal difference of radar echo power and optical magnitude of the meteor shown in Figure 6 between the time of 50 and 200 msec is up to about 18 dB and 4 magnitude, respectively. This corresponds well with the coefficient of 3.6 in Eq. 13. Thus, this coefficient expresses not only the relations between different meteor bodies but also the relation in a time variation of a single meteor.

The large scattering of the data seen in Fig. 5 is mainly due to the fact that we do not consider other parameters such as the velocity, height, and spectral characteristics of each meteor. Inclusion of these parameters, and establishment of the multi-parameter relation is our future task after a much larger data base is accumulated.

If we set the sensitivity limit of the MU radar to signal-to-noise ratio of 15 dB, at which reliable estimates of the orbit is obtained, it corresponds to 60 dB on the ordinate of Fig. 5. Given that Eq. 13 is correct, the sensitivity limit in terms of the absolute visual magnitude is +14.8.

It is reported that the limiting magnitude of the existing radar systems for meteor head echoes are +10.5 for EISCAT VHF/UHF (224/930MHz) radar[7], and +16 for Arecibo UHF radar (430MHz)[8]. As an orbit determination radar, AMOR(Advanced Meteor Orbit Radar, 26MHz) in New Zealand can detect +14 magnitude of meteors[9], although it observes meteor trail echoes, not head echoes. Comparing the above radars, our current radar head echo measurement with a capability of measuring meteor orbit down to +14.8 magnitude is quit sensitive, and useful for the study on characteristics of faint meteors.

It is also noteworthy that the velocity determination from meteor trail echoes depends on the temporal variation of the echo power when a meteor body passes through the

Fresnel region, so that the precision of velocity determination decreases as the velocity increases. Thus the head echo measurement presented here has an advantage in precision of high-speed meteors, since the precision of Doppler measurement is basically independent on meteor velocity itself.

6. Estimations of mass

The mass m of each meteor body before entering the atmosphere can be estimated by integrating the energy consumed to evaporate the mass, which is proportional to the optical radiation power I. An empirical relation is known between I and the absolute visual magnitude M in the wavelength region of 450–570 nm[10] as

$$M = 6.8 - 2.5 \log I \quad . \tag{14}$$

The proportionality between I and the rate of energy loss is expressed as

$$I = -\frac{1}{2}\tau v^2 \frac{\mathrm{d}m}{\mathrm{d}t} \quad , \tag{15}$$

where v is the instantaneous speed, and τ is a dimensionless constant representing the efficiency of conversion from the kinetic energy to the optical radiation, for which an empirical relation

$$\log \frac{\tau}{v} = -8.02 + 0.156M \tag{16}$$

is known[11].

Using these three equations, we can determine m in terms of v and M by integrating the following formula for the entire duration of the optical observation.

$$\frac{\mathrm{d}m}{\mathrm{d}t} = -2v^{-3}10^{10.74-0.556M} \tag{17}$$

As a first order approximation, we take v as the average value of the observed speed in integrating this equation to estimate the initial value of m.

Table 2 lists the estimated mass of the 34 cases. The first case is very likely an example of an interstellar dust, since its mean velocity is faster than the limit of 72 km/sec. This case was observed for more than 200 msec, and shows a linear deceleration of about 10% during this period. Although its initial velocity cannot be determined because it obliquely traversed the antenna beam, it is at least faster than 81 km/sec, which is the velocity when it enters the radar field of view.

It should be noted that it is of course difficult to examine the validity of the empirical relations used in the above calculation, and other forms are also proposed. However, difference in the estimated mass is within a factor of 3 for the range of M in the current case. A previous study[12] using a meteor radar system estimated the mass from the ionization curve to fall in a range of 10^{-6}–10^{-2}g for a group of meteors, whose mean velocity is 34.5km/sec, with the peak of distribution at 10^{-4}g. Our estimate, which is based on less assumptions, seems to be detecting objects of about one order of magnitude lighter, probably due to the fact that we observe much faster meteors.

Table 2 Estimated initial mass of meteor bodies before entering the atmosphere observed on November 23 and 24, 2000. Velocity is an average over the given duration.

Day	Time (JST)	Magnitude (peak)	Velocity (km/sec)	Duration (sec)	Mass (10^{-6}g)
23	01:46:11	5.6	76.83	0.300	22.96
23	02:43:47	6.0	61.75	0.267	25.38
23	03:32:13	7.6	70.65	0.267	3.02
23	03:41:20	4.3	58.57	0.300	194.33
23	03:43:00	7.6	66.89	0.200	3.27
23	03:43:27	7.9	58.59	0.167	3.37
23	03:43:56	7.4	57.63	0.200	5.65
23	03:47:32	7.7	87.86	0.233	1.46
23	03:53:16	7.5	64.38	0.233	4.31
23	03:57:41	6.5	63.76	0.300	13.45
23	04:38:54	7.6	70.23	0.133	1.61
23	04:45:59	6.3	68.48	0.267	11.14
23	04:46:26	7.0	62.54	0.267	7.97
23	04:47:59	5.2	70.22	0.400	43.23
23	04:48:30	5.7	68.84	0.400	35.71
24	00:42:40	6.4	65.08	0.167	5.72
24	00:53:41	8.4	55.14	0.167	1.25
24	01:43:51	8.6	57.59	0.233	1.34
24	01:57:02	8.2	67.58	0.367	1.94
24	02:32:28	6.6	70.88	0.433	9.17
24	02:42:07	8.7	70.34	0.233	0.65
24	02:44:59	9.2	63.77	0.200	0.53
24	02:51:15	9.0	72.66	0.133	0.25
24	02:54:05	8.9	66.68	0.200	0.53
24	02:55:54	8.7	69.43	0.267	0.59
24	03:32:48	5.9	64.18	0.333	37.61
24	03:35:17	7.2	67.31	0.133	1.99
24	03:37:18	9.0	56.37	0.200	0.71
24	03:37:37	8.1	68.22	0.100	0.74
24	03:40:31	8.2	71.63	0.267	0.82
24	03:40:48	8.7	51.50	0.167	0.95
24	03:46:01	7.9	65.19	0.133	1.29
24	03:55:39	9.3	54.84	0.100	0.34
24	04:53:13	7.6	67.03	0.233	3.20

7. Summary

We developed a radar-optical combined system for detecting faint meteors consisting of a powerful VHF Doppler radar and an ICCD video camera. Although the system has a limited view angle of about 5° around a specified direction of 30° from the zenith, a very high sensitivity of more than 14 magnitude and 9 magnitude for radar and optical sensors, respectively, has been confirmed.

Instantaneous direction of meteor body observed by the radar is determined with the interferometry technique. We examined the optimum way of the receiving antenna arrangements, and also of the signal processing. Its absolute accuracy was calibrated by the optical observations with background stars as a reference. Although it was found by the comparison that the absolute direction of meteor bodies derived by the radar has an offset error of about 0.5°, the velocity vector was estimated very accurately.

By combining the impinging velocity of meteor bodies derived by the radar with the absolute visual magnitude determined by the video camera simultaneously, the mass of each meteor body was estimated, including a case which is very likely an interstellar dust.

The developed observation system will be used to create a valuable data base of the mass and velocity information of faint meteors, on which very little is known so far. The data base is expected to play a vital role in our understanding of the space environment needed for designing large space structures.

Our current problem is the processing of optical data, which is carried out manually. In order to accumulate the large amount of observations for the data base, automatic determination of the direction is necessary. Next important step is to establish a clear relation between the radar scattering cross section and the absolute visual magnitude. If it becomes possible to derive the absolute visual magnitude from the echo power and the velocity information obtained by the radar, the mass estimate can be made with the radar sensor alone, down to the limit of its extremely high sensitivity.

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Koji Nishimura received his B.E. in electrical engineering from Ritsumeikan University, Kyoto, Japan in 1999, and M.E. in informatics from Graduate School of Informatics, Kyoto University, Japan in 2001. He is currently working for Sony Corporation.

Toru Sato received his B.E, M.E., and Ph.D. degrees in electrical engineering from Kyoto University, Kyoto, Japan in 1976, 1978, and 1982, respectively. He has been at Kyoto University since 1983 and is currently a Professor of Department of Communications and Computer Engineering, Graduate School of Informatics. His major research interests have been system design and signal processing of atmospheric radars, radar remote sensing of the atmosphere, observations of precipitation using radar and satellite signals, radar observation of space debris, and signal processing for subsurface radars. He was awarded Tanakadate Prize in 1986. He is a member of the Institute of Electrical and Electronics Engineers, the Japan Society for Aeronautical and Space Sciences, the Society of Geomagnetism and Earth, Planetary and Space Sciences, and American Meteorological Society.

Takuji Nakamura received his B.E., M.E., and Ph.D. degrees in electrical engineering from Kyoto University, Kyoto, Japan in 1984, 1986, and 1992, respectively. Since 1986, he worked for Mitsubishi Electric Co. and since 1989 he has been with Radio Atmospheric Science Center, Kyoto University. In April 2000, the name of the center was changed as Radio Science Center for Space and Atmosphere. Currently, he is an associate professor in the center. His major research interests have been system design and signal processing of atmospheric radars, radar and optical remote sensing techniques of the atmosphere, dynamics and aeronomy of the earth's middle atmosphere, and radio scattering mechanism of meteor phenomena. He was awarded Obayashi Prize of the Society of Geomagnetism and Earth, Planetary and Space Sciences in 1997. He is a member of the Society of Geomagnetism and Earth, Planetary and Space Sciences, the Meteorological Society of Japan, the Astronomical Society of Japan, the American Geophysical Union, and the International Astronomical Union.

Masayoshi Ueda is currently working for Habikino city hall. He is a member of the Astronomical Society of Japan and the Nippon Meteor Society.