The Observations of Meteor Trail Made with Chung-Li VHF Radar

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ABSTRACT

Chung-Li VHF radar is a low power (average transmitted power is only 3.6 kw) and small aperture (physical antenna area is 4800 m^2) coherent ST radar. This radar can effectively observe the mesospheric meteor events if the appropriate radar parameters are set. In this paper, some results of meteor events observed over Taiwan area by Chung-Li VHF radar (operating frequency is 52 MHz) are obtained. We find that the height distribution of meteor trail is between 80 km and 120 km, and the peak value is occurred at about 93 km. There is a remarkably diurnal variation in the appearance of meteor event, maximum at the morning hour and minimum around the dusk. The average life time of the meteor trail is about 0.35 s. Furthermore, the diffusive coefficients in the meteor zone, calculated from the information of life time of meteor tail, are also estimated and between 0.1 $m^2\ s^{-1}$ to 1 $m^2\ s^{-1}$. These results are quite consistent with the others' observations.

1. INTRODUCTION

It is well-known that VHF radar can measure effectively many atmospheric parameters, such as three dimensional wind field, turbulent strength, tropopause height, gravity wave events, terminal velocity of precipitation, and so on (Woodman and Guillen, 1974; Balsley and Gage, 1980; Wakasugi *et al.*, 1985). However, the meteor events, which are occurred in the lower ionosphere due to the ablation of the extra-terrestrial objects, e.g., the debris of comet or fragments of asteroid, can also be observed by VHF radar if the specific radar parameters are set and appropriate signal analysis process is performed (Avery *et al.*, 1983; Wang *et al.*, 1988). From the echoes generated from the meteor-associated ionic trails, the upper atmospheric features, e.g., wind field, diffusion coefficient, and wave event can then be estimated (Aso *et al.*, 1979a, 1979b; Brown and Lovell, 1962; Hawkins, 1964; Millman and McKinley, 1963, Davies, 1965).

According to the original design concept, Chung-Li VHF radar is ST radar, that is, this radar can observe stratosphere and troposphere only. However, in this paper we will show that this radar can efffectively observe the meteor trails occurred in the upper atmosphere, i.e. in the height range between 80 km and 120 km. In section 2, the theory of the echo mechanism of meteor trail observed with VHF radar will be reviewed briefly. In section 3, the observation scheme of the meteor trail used by the Chung-Li VHF radar will be illustrated, and the observation results are also presented in this section. The discussion and the conclusion will be made in the section 4 and 5, respectively.

2. ECHOING PROCESS OF METEOR TRAIL

According to the free electron content, the meteor trail can be divided into the overdense and underdense trail. For the overdense trail, assume that (a) the radius of the trail is far smaller than the incident wave length, (b) the electron line density, q_0, is constant, (c) the trail is perpendicular to the radar beam direction, and (d) the distribution of the electron concentration of the trail is Gaussian, the radar equation can then be described as follows if the initial radius of the trail is zero (Davies, 1965; Brown and Lovell, 1962; Hawking, 1964; Millman and McKinley, 1963)

$$P_r = \frac{P_t G^2 L^2}{32\pi^2 r^3}\left(4Dt ln\left(\frac{R_e q_0 L^2}{4\pi^2 Dt}\right)\right)^{\frac{1}{2}} \tag{1}$$

where P_r is the received echo power, P_t is the transmitted power, G is the antenna gain (the radar is assumed to be monostatic), r is the range, L is the radar wavelength, R_e is the classical electron radius (about 2.8×10^{-15} m), D is the diffusive coefficient, and t is the time measured from the formation of the trail. From Eq. (1) it is easy to show that P_r will be vanished after the time T_0, where T_0 is defined as

$$T_0 = \frac{R_e q_0 L^2}{4\pi^2 D} \tag{2}$$

Therefore T_0 can represent the lifetime of the overdense meteor trail. Moreover, from Eq. (1) the maxium radius of the trail can be obtain, after differentiating Eq. (1) with respect to t, as follows (Millman and McKinley, 1963)

$$R_d = \frac{L}{\pi}\left(\frac{R_e q_0}{e}\right)^{\frac{1}{2}} \tag{3}$$

where e ~ 2.7183. While for the underdense trail, if we assume that the free electrons in the first Fresnel zone contribute to most of the received echo power, and the waves scattered by the free electrons are coherent. Furthermore, if the trail is orthogonal to the radar beam direction and the initial radius of the trail is zero, the radar equation of the underdense trail can then be obtained as follows (Millman and McKinley, 1963)

$$P_r = \frac{P_t G^2 L^3}{128\pi^3 r^3} A q_u^2 exp(-2t/T_u) \tag{4}$$

where A is the scattering cross section of electron $(8\pi R_e^2/3)$, and T_u is defined as

$$T_u = \frac{L^2}{16\pi^2 D} \tag{5}$$

Same as the derivation of Eq. (3), the radius of the underdense trail at the time T_u will be (Davies, 1965; Crank, 1967)

$$R_d = \frac{L}{2\pi} \tag{6}$$

Thus, as long as the radius of underdense meteor trail reaches R_d due to the diffusive expansion, the echo power will be so weak that the meteor trail can not be detected by the radar any more. The application of the above equations to the observation results of Chung-Li radar will be discussed in the section 4.

3. THE OBSERVATION OF METEOR TRAIL WITH CHUNG-LI VHF RADAR

According to the earlier studies (Brown and Lovell, 1962; Millman and McKinley, 1963; Hawking, 1964; Davies, 1965; Aso *et al.*, 1979a; 1979b; Avery *et al.*, 1983), it is well known that, if the observation of meteor trail is carried out by a VHF radar, the meteor trails always occur in the height range from about 80 *km* to 120 *km* (this atmospheric region is termed as meteor zone), and the lifetime of the echo signal is only a fraction of a second. These features should be taken into account if the observation of meteor trail is carried out at Chung-Li VHF radar. In this section, the characteristics of Chung-Li VHF radar will be introduced first. The observation scheme of meteor trail designed for Chung-Li radar will then be illustrated in detail. Finally, some observation results obtained by Chung-Li radar will be presented.

a. The characteristics of Chung-Li VHF radar.

The Chung-Li VHF radar was constructed in June, 1985, located at the campus of the National Central University in Taiwan (R.O.C.) (25° N, 121° E). This radar consists of three identical and independent modules. Each module of antenna is composed of 64 (8×8) Yagi antenna in a 40×40 m^2 and arranged as an equilateral triangle with the apex pointing toward north by west 24°. The peak transmitted power for each module is 60 *kw*. The operating frequency is 52 *MHz* (radar wavelength is 5.77 *m*), and the pulse width can be set as 1, 2, 4, 8, and 16 μs arbitrarily. The maximum duty cycle, which is defined as the ratio of pulse length to the inter-pulse period (IPP), is 2 %. The phase code used in the Chung-Li VHF radar is complementary code with 2, 4, 8, or 16 μs elements. The direction of the radar beam for each antenna module or for full antenna aperture can be steered independently from zenith toward northeast, southeast, northwest and southwest with fixed zenith angle 17° and the beam can also be pointed vertically. The half power beam width (HPBW) for each module is 7.4° and for the full aperture 5° . The maximum probing range for neutral atmosphere is about 1 to 23 *km*. However, occasionally, the echoes of mesospheric irregularities can be observed (Chu *et al.*, 1989). Besides, in this paper, we will show that the Chung-Li VHF radar can effectively observe the echoes generated from meteor trail. The results will be shown in the following.

b. The scheme of radar signal analysis

The data of meteor trail signals used in this paper were taken from January 6, 1989, 1500LT to January 9, 1989, 1700LT observed with Chung-Li VHF radar. The peak transmitted power of all three modules were identical and was about 35 *kw*. The receiver bandwidth was 62.5 *kHz*. The other radar parameters of this observation were set as follows: pulse width was 16 μs (the corresponding range resolution is 2.4 *km*). Delay was 100 μs and 40 range gates were set (i.e. the first and last detectable altitude is 16.2 *km* and 112.2 *km*, respectively). IPP was set as 1000 μs, and the number of coherent integration was 80 (these two parameters determine the time resolution of echo signal as 0.08 *s*). The three radar beams were all pointed toward zenith.

After radar signals were received by the radar, in order to abstract the actual echoes of meteor trail from the background noise, the following steps of radar signal processing in this paper are performed: First step, calculate the mean and variance for each 4 records data (there are 16 data points contained in one record). Second step, pick up the signals as the quasi- meteor echoes if their values are larger than the sum of mean and double standard deviations. Note that each quasi-meteor event is usually consisted of several consecutive data points. If the number of data points is larger than 40, i.e. the duration of this event is longer than about 3 seconds, this set of signals will be discarded because these data seem to be not the real echoes of meteor trail. Third step, estimate the Doppler frequency spectrum of the quasi-meteor echoes by using maximum entropy spectral analysis method (Ulrych and Bishop, 1975). Before doing that, the following modification of the data is carried out in this paper. If the number of the data points of a quasi-meteor event is less than 11, a few additional data points, which are the neighboors of this event, will be appended to the head or tail of this quasi-meteor signal such that the number of the rearranged data points is equal to 11 and the position of the data point with maximum amplitude is located at the center of this modified data segment. Fourth step, calculate the power, mean and width of the Doppler frequency spectrum by using moment method. If the spectral width is so large that the shape of Doppler spectrum is close to the uniform distribution, this set of data should be given up because these signals are characterized by the white noise. Fifth step, accumulate all the ture echoes of meteor trails for the further statistical analysis and calculation.

c. The observation results

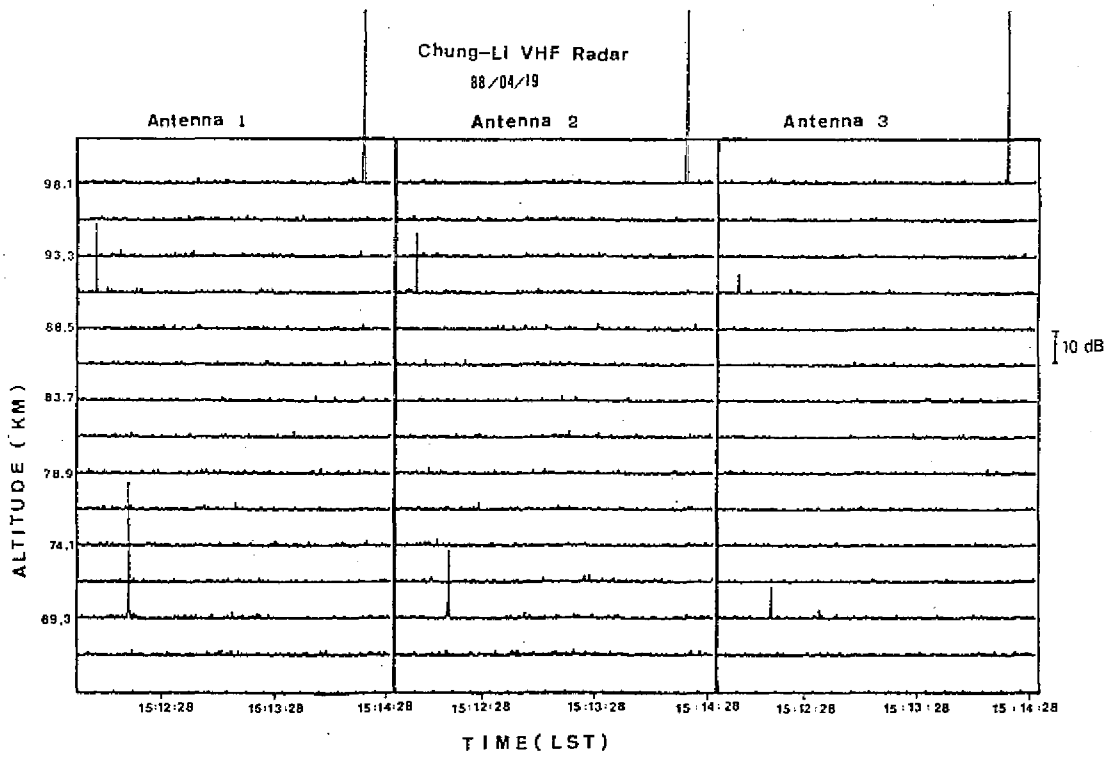

Fig. 1. The typical record of the echoes of meteor trail observed with Chung-Li VHF radar with coarse time resolution (0.25 *s* for one data point).

Fig. 1 is a typical record of the echoes of meteor trail observed by Chung-Li VHF radar with coarse time resolution, i.e. 0.25 *s* for one data point, on

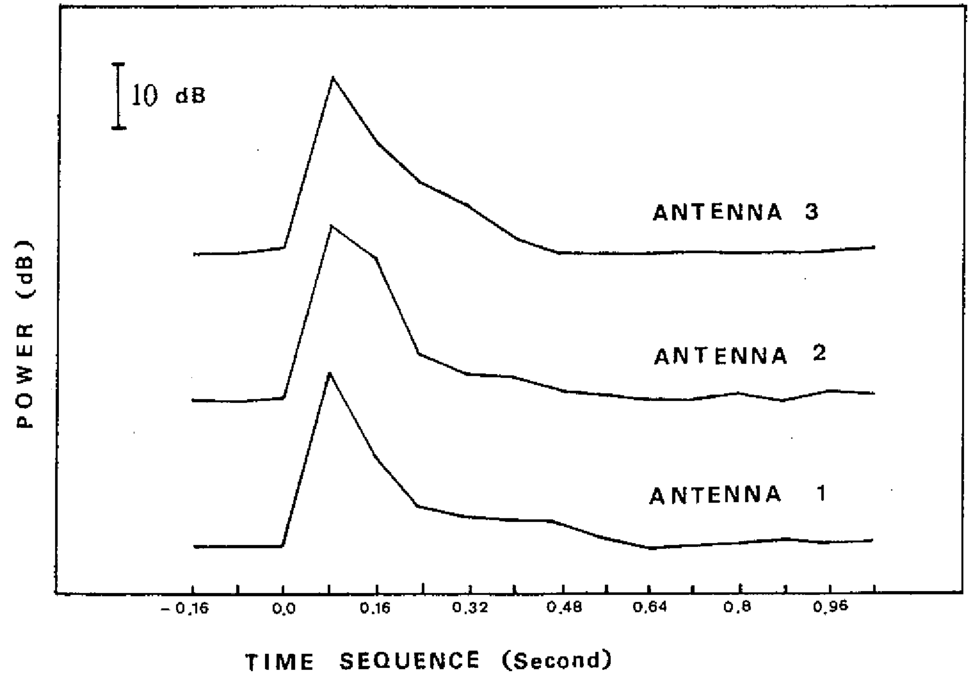

Fig. 2. The typical fading patterns of the echo signals of meteor trail observed by Chung-Li VHF radar with better time resolution (0.08 *s* for one data point).

April 19, 1988, 1512LT-1515LT (Chu *et al.*, 1989). The antenna 1, 2 and 3 are corresponding to the antenna module of Chung-Li VHF radar located at north, east and west side, respectively. It is clear that three antenna modules record the meteor trail events at the same time and altitude. The S/N ratio of meteor trail signals are also high and, in general, larger than about 10 *dB*. However, the detailed structure of meteor trail signal can not be found in Fig. 1 because of the poor time resolution. Fig. 2 shows the typical fading patterns of the echo signals of the meteor trail obtained by Chung-Li VHF radar with better time resolution (i.e. 0.08 *s* each data point). The observation time of this meteor trail event is around January 7, 1989, 0532LT, and the altitude of this signal occurred is about 93 *km*. It is obvious that the amplitude of signals are decayed exponetially and the lifetime, which is defined as the time difference measured from the initial amplitude to the 1/e maximum amplitude, is about 0.3 *s*. The Doppler frequency spectra of these three signals, by using maximum entropy spectral analysis method, are shown in the Fig. 3. It is apparent that the shapes of these spectra are Gaussian-like, and the mean Doppler frequency shifts are about 0.13 *Hz*. Note that although the antenna beams are pointed vertically, these mean Doppler frequency shifts can not be explained as the result of vertical motion of meteor trail relative to the antenna. Actually, these

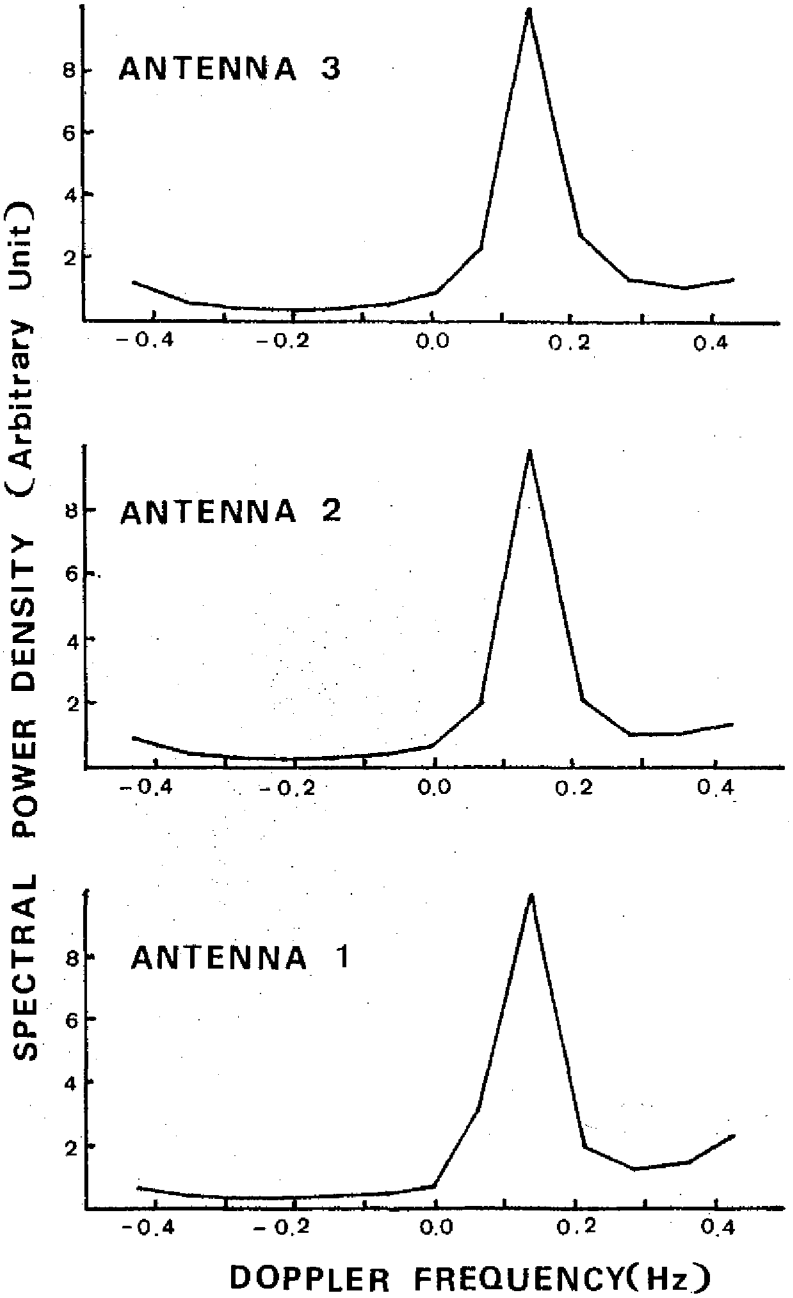

Fig. 3. The Doppler frequency spectra of *Fig.* 2 by using maximum entropy spectral analysis method.

Doppler frequency shifts are caused by the so called beam broadening effect (Chu, 1988; Woodman and Chu, 1989).

After collecting all the echoes of meteor trails, the statistics of lifetime of

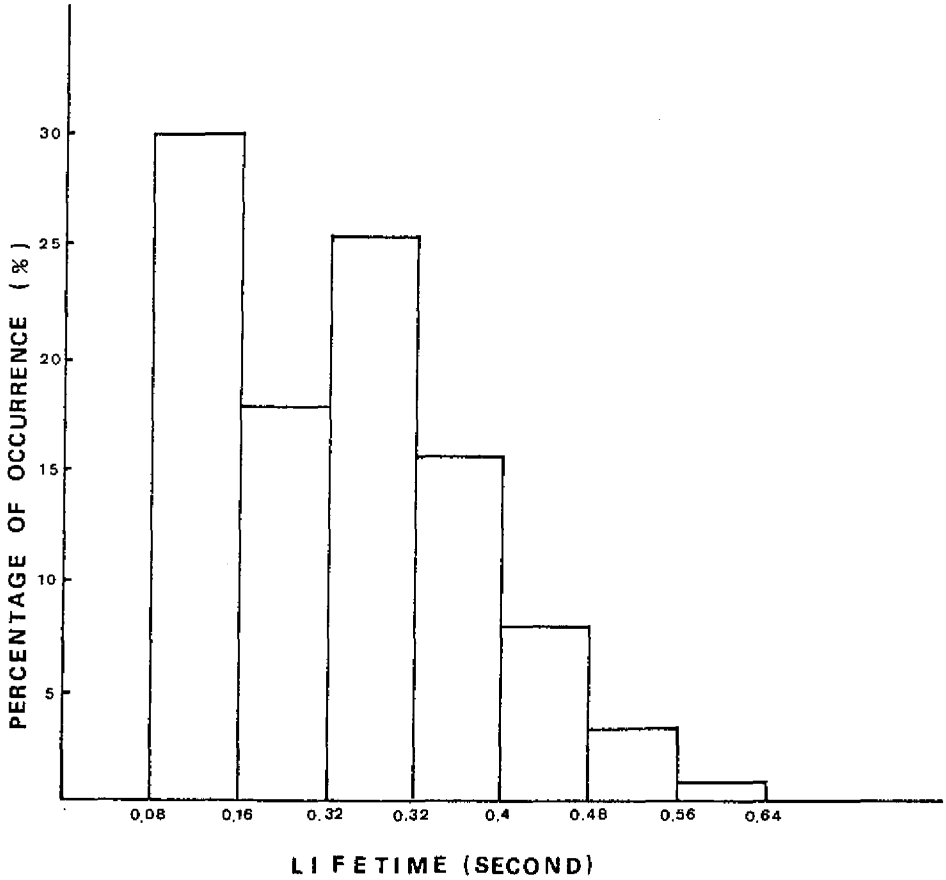

Fig. 4. The frequency distribution of the lifetime of meteor trail echoes.

meteor trail signals can be obtained and shown in the Fig. 4. Fig. 4 shows that the lifetimes of meteor trails obtained in this study are distributed from about 0.1 s to 0.7 s and, in average, the mean lifetime is about 0.35 s. This result is quite similar with the earlier observations (Brown and Lovell, 1962; Hawkins, 1964).

In most of the cases, the echoes of meteor trails are appeared only in one range gate, as shown in the Fig. 1. However, occasionally, the echoes of a meteor trail can occur in more than one range gate, Fig. 5 shows an example of this kind of signal. It is noted from Fig. 5 that there are time delay between the occurrence of the echoes at different altitudes. Thus, the vertical component of meteor falling speed can be estimated from the time delay and the range resolution. The value is about 30 $km\ s^{-1}$ in this case. Fig. 6 is the histogram of the number of the range gate in which the echoes of the same meteor trails are occurred. It is shown that most of the meteor trail (larger than 85 %) appear in one range gate, and only small portion (about 15 %) of that occur in

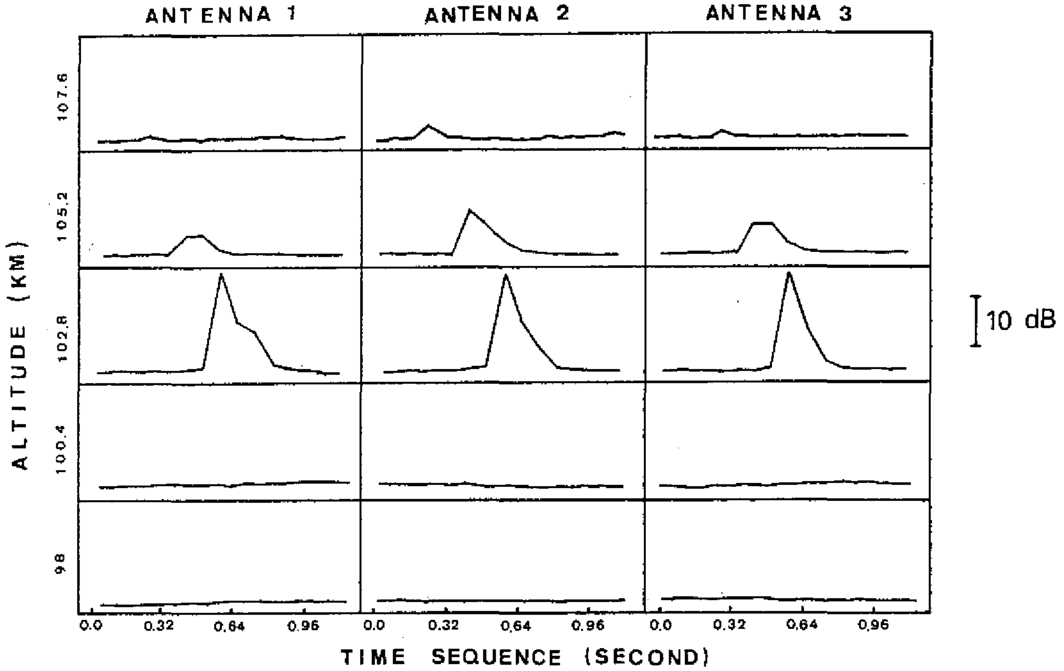

Fig. 5. The hight-time plot of a meteor trail event which appears more than one range gate.

more than two range gate. This feature will be discussed in the next section.

Fig. 7 shows the height distribution of the meteor trails. It is obvious that the meteors are occurred in the height range form 80 *km* to 120 *km* and the peak is located at about 93 *km*. These results are very consistent with the other observations carried out by 50 *MHz* radar, such as Brown and Levell (1962), Hawkins (1964), Davies (1965), Avery *et al.* (1983), Aso *et al.* (1979a), Aso *et al.* (1979b, Wand *et al.* (1988), and so on. However, if the operating radar frequency is not in lower VHF band (i.e. 50 *MHz*), but in HF band (3-30 *MHz*), say, 6 *MHz*, the height distribution of meteor trail will be different. This will be discussed in the next section.

Fig. 8 is the diurnal variation of the occurrence rate of the meteor trail. It shows that the occurrence rate is maximum in the morning and minimum in the evening. This phenomenon can be explained as follows. It is well-known that the earth rotates around the sun with velocity about 30 $km\ s^{-1}$. If there are debris of comet distributed on the path of earth, as the earth moves into these comet debris, the meteor flux will be maximum at the forward side, i.e. in the morning side, of the earth movememt and minimum at the rear side, i.e. in the morning side, of that. This fact results in the diurnal variation of meteor occurrence.

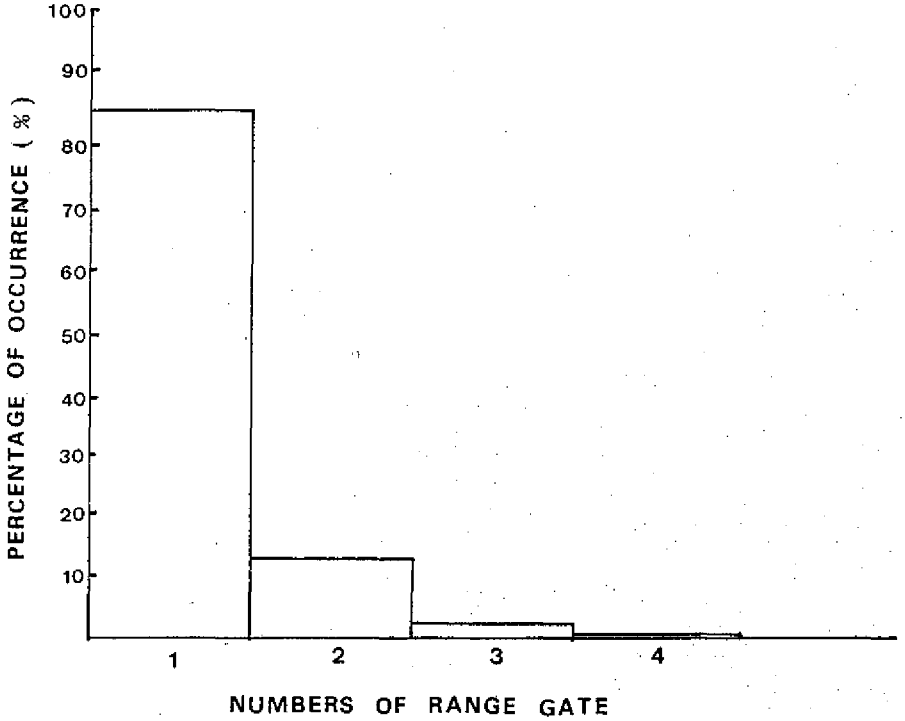

Fig. 6. The histogram of the numbers of the range rate in which a meteor trail occurs.

4. DISCUSSION

In section two, the echoing mechanism of overdense and underdense meteor trail have been illustrated. Because the former is reflection, while the latter is scattering, it is interesting to compare which echo power is significant. From Eq. (1), after differentiating P_r with respect to t, it is easy to find that the maximum echo power of overdense trail can be represented as follows

$$P_m = \frac{P_t G^2 L^3 q_0^{\frac{1}{2}} R_e^{\frac{1}{2}}}{32 r^3 e^{\frac{1}{2}} \pi^3} \tag{7}$$

From Eq. (4), the echo power of underdense trail will be maximum at $t = 0$, and is denoted by P_n. Thus, the power ratio of these two peak values, i.e. $R = P_m/P_n$, can be obtained as follows

$$R = \frac{q_0^{\frac{1}{2}}}{3.71 R_e^{\frac{3}{2}} q_u^2} \tag{8}$$

Typically, for overdense trail, q_0 is about 5×10^{14} (m^{-1}), while for underdense trail, q_u is about 5×10^{12} m^{-1} (Davies, 1965; Brown and Lovel, 1962; Millman

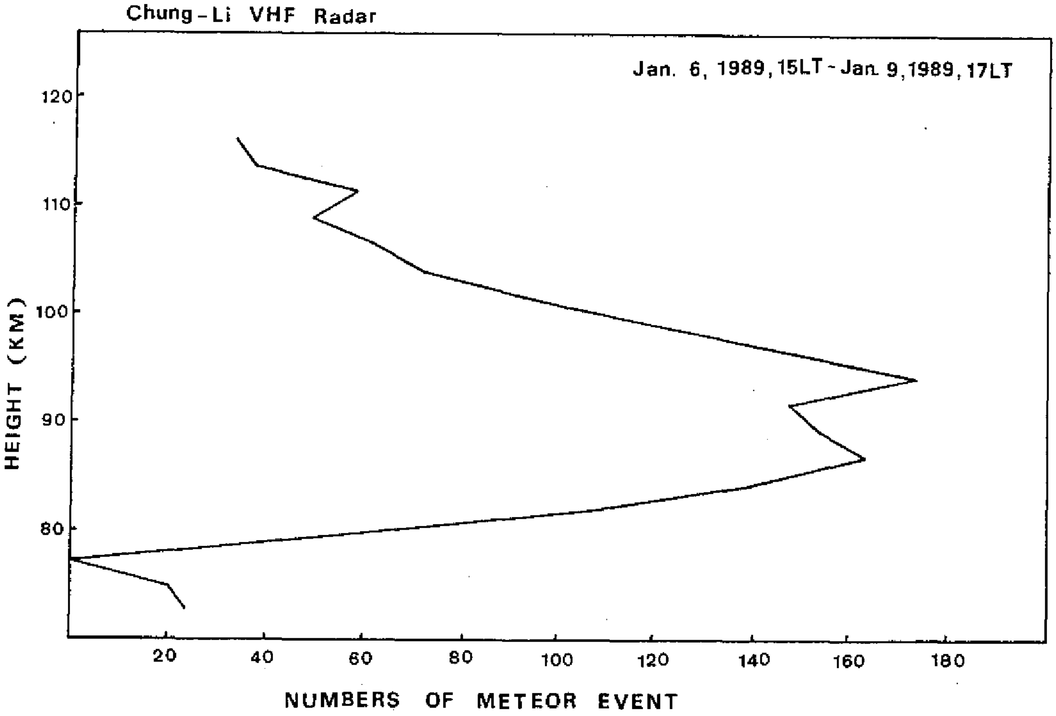

Fig. 7. The height distribution of the meteor trail.

and McKinley, 1963). Substituting these data into Eq. (8), we obtain that, after taking logarithm,

$$R \sim 40\ (dB) \tag{9}$$

This means that in typical case the echo power of overdense trail will be significantly larger than that of the underdense trail.

As mentioned in the last section, the height distribution of echoes of meteor trail, when observed with lower VHF (i.e. 50 *MHz*) radar, is between 80 *km* and 120 *km*, and the peak is centered at about 93 *km*. However, if the radar frequency is changed to lower HF (3 *MHz* to 30 *MHz*) band, i.e. 6 *MHz* or 2 *MHz*, the height distribution of meteor trail will be different from the results obtained in this study. Under this circumstance, the height range of meteor trail occurrence will be between 100 *km* and 140 *km*, centered at about 104 *km* (Olsson-Steel and Elford, 1987; Elford and Olsson-Steel, 1988). This feature can be illustrated as follows. It is apparent that, as the radius of underdense meteor trail is larger than R_d, this trail will be impossible to be detected by the radar. This is because at this moment (1) the destructive interference will occur between the signals scattered from the electrons located at the opposite side of the trail, (2) the electron density in the column of meteor

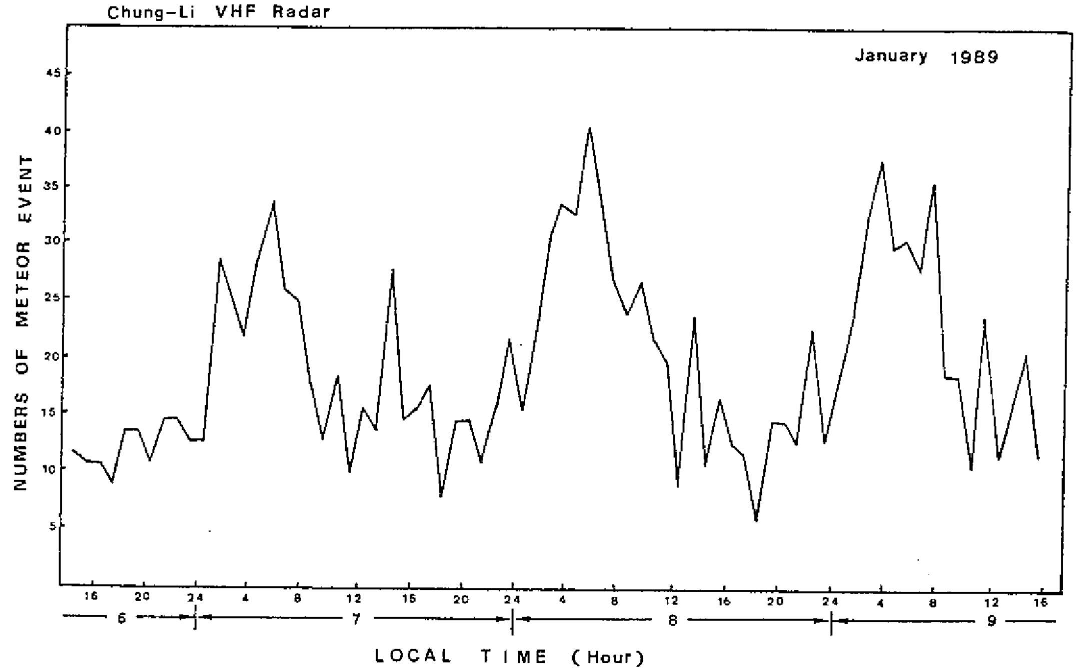

Fig. 8. The diurnal variation of the occurrence tate of the meteor trail.

trail will become so small that the echo power of meteor trail is too weak to be detected. For example, if the 50 MHz and 6 MHz radar are both used to observe the underdense meteor trail, from Eq. (6) R_d will be 0.96 m and 7.96 m, respectively. Usually, the initial radius of an underdense meteor trail, R_c, is not zero, e.g., R_c is about 0.5 m at 90 km and 3 m at 115 km (Davies, 1965; Olsson- Steel and Elford, 1987). Thus, the underdense meteor trail occurred at 115 km can be detected effectively by 6 MHz radar because $R_c < R_d$, however, for 50 MHz radar this kind of meteor trail can't be detected because $R_c > R_d$. Moreover, from Eqs. (2) and (5) it is clear that the lifetime of the meteor trail is inversely proportional to D. According to the theoretical calculation (Rishbeth and Garriott, 1969), D increases with height exponentially. This implies that the lifetime of meteor trail occurred at lower altitude will be greatly larger than that of meteor trail occurred at higher altitude. For example, for 50 MHz radar, T_u is about 0.38 s at 90 km where $D \sim 0.6\ m^2\ s^{-1}$ and about 2.9 m s at 115 km where $D \sim 80\ m^2$ (Brown and Lovell, 1962). However for 6 MHz radar T_u is about 26.4 s at 90 km and about 0.2 s at 115 km. The above discussions explain the fact that the height of radio meteor celling (Olsson-Steel and Elford, 1987) varies with the operating radar frequency.

Figs. 5 and 6 show that a few meteor trails will appear in more than one range gate. This kind of trail was also reported by Millman and McKinley

(1963), Avery *et al.* (1983), Olsson-Steel and Elford (1987), Wang *et al.* (1988), etc. The echoing theories of meteor trail presented in the section two are based on the assumption that the meteor trail is orthogonal to the radar beam direction. Under this circumstance, the range gate in which the meteor trail will appear must be one. Thus the echo mechanism of these non-orthogonal meteor trails seem to be unable to be explained by these theories. However, from the theory of wave propagation in random media (Tatarskii, 1961; Doviak and Zrnic, 1984), it is shown that the radar returns will be generated if the spatial Fourier component of refractive index fluctuations has size with the Bragg scale. This mechanism can explain the echoes generated from the non-orthogonal meteor trail (Avery *et al.*, 1983).

In this experiment, the vertical radar beams have been used for meteor trail observations. However, the care must be taken as the observations are carried out by using the oblique beams. This is because there are many factors which will contaminate the oblique echo signals, e.g., the cosmic noise coming from the Cygnus A radio star will degrade the S/N of northward pointed beam at specific time (Pan, 1987), the sidelobe effect resulted from the 58^o sidelobe will contaminate the signal quality of the mainlobe (Fu, 1988), etc.

Many atmospheric parameters, such as meso- and lower thermospheric wind fields (including gravity waves and tidal waves), diffusive coefficient, electron line density of overdense trail, falling speed or trajectory of meteor, etc., can be estimated from the study of meteor trail signals. From Eq. (5), according to the observation of lifetime as shown in the Fig. 4 the diffusive coefficients are about from 0.1 $m^2\ s^{-1}$ to 1 $m^2\ s^{-1}$. These estimations quite agree with Brown and Lovell (1962). And from Fig. 3 the horizontal wind can be abstracted from the informations of mean Doppler frequency shift and the spectral width if both the assumption of zero vertical motion of meteor trail is made and the angular position of meteor trail is known (Chu, 1988). The results of this kind of study will be presented in the other paper.

5. CONCLUSION

In this paper, some results of meteor trail events observed with Chung-Li VHF radar are presented and discussed. The distribution height of meteor trail is between 80 km to 120 km when lower VHF band radar is used. The mean lifetime of meteor trail echoes is about 0.35 s, and the diffusive coefficients estimated from the informations of lifetime is between 0.1 $m^2\ s^{-1}$ to 1 $m^2\ s^{-1}$. In this study, the vertical component of meteor falling speed is estimated from the time delay of signal and is about 30 $km\ s^{-1}$. Finally, the diurnal variation of meteor occurrence is also presented and found that there is maximum in the morning and minimum in the evening.

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利用中壢VHF雷達進行流星尾的觀測

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摘　　要

中壢VHF雷達雖是一個低功率（平均發射功率只有3.6 KW）小面積（天線面積爲4800 m^2）的ST雷達，但若適當的選取雷達參數，則仍可對發生在80到120公里之間的流星尾進行有效的觀測。結果顯示流星尾均發生在80到120公里之間的流星區內，並且集中在93公里附近，流星尾的發生次數有一明顯的日變化，最大值發生在日出時分，而最小值則發生在傍晚。流星尾的平均存在時間約爲0.35 秒。藉此所計算出的中氣層擴散係數則爲0.1 m^2/s到1 m^2/s之間。這些結果與國外的觀測十分一致。