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METEOR HEAD ECHO OBSERVATIONS USING THE MILLSTONE HILL UHF INCOHERENT SCATTER RADAR SYSTEM

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ABSTRACT

We present studies of meteor head echo statistics at UHF frequencies using the megawatt-class Millstone Hill incoherent scatter radar facility during the November 1999 and November 2000 Leonid meteor shower periods. The majority of meteoroid particles observed have approximate radar cross-sections of $10^{-5} - 10^{-4} m^2$ and masses in the 70 mg range. Diurnal count rates show expected sporadic meteor peaks at local dawn and minimum at local dusk during both shower periods. However, the lack of a significant increase in counts during periods when the Leonid radiant is visible implies that Leonid showers do not possess significant enhancement in milligram-class meteoroid particles. Altitude distributions from November 2000 show significant unusual enhancements in count rates at 118 km in addition to normal 105-110 km altitude peaks. We also describe upcoming enhancements to the Millstone Hill system which will allow improved statistics as well as advanced trajectory determinations.

Key words: meteors; head echoes; incoherent scatter radar.

1. INTRODUCTION

Studies of the properties of meteors using radiowave techniques have been conducted since the mid 1940's by numerous scientific groups. Beginning with the seminal work of Evans [1] and continuing through the present day [2, 3, 4, 5, 6], a unique data set has been gathered using large-aperture, high-power radars whose primary purpose is making ionospheric measurements using the technique of incoherent scatter [7]. These megawatt-class radars are capable of detecting weak -170 dBW signals reradiated from the background ionosphere, and this level of sensitivity allows them to study so-called radar head echoes arising from scattering in the region immediately surrounding the meteoroid. In particular, these radars are sensitive to the properties of micrometeoroids with approximate mass on the order of micrograms, equivalent visual magnitudes smaller than 12th order, and radar scattering cross-section (RCS) values below $10^{-6} m^2$.

Recently, the mid-latitude U. S.-run Millstone Hill ionospheric observatory, first used for meteor investigations in the work of Evans [1], has seen a reactivation of meteor experiments prompted by the results reported at the EISCAT, ALTAIR, and Arecibo radar facilities in Europe, the Pacific, and Puerto Rico respectively. Whereas these facilities initially discovered meteor echoes within experimental results aimed at E region ionospheric diagnostics, the contemporary Millstone observations have been specifically targeted from the outset at observing meteor head echo characteristics at the radar operating frequency of 440 MHz (67 cm wavelength). Because the meteoroid itself enters the atmosphere at high speed and the radar antenna beam is of small angular size, high-resolution data capturing techniques capable of recording individual meteor echoes are crucial in obtaining good statistical determinations of micrometeor characteristics.

We report in this paper on observations made at Millstone Hill during the Leonid meteor shower periods in November of 1999 and 2000. We focus here on statistical distributions of UHF meteor head echoes with respect to altitude, RCS, and time. Doppler characteristics will be covered in a future work. In addition to the results already obtained, we describe future enhancements in meteor observations which will be made possible by upgrades to the Millstone Hill MIDAS data acquisition system.

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Table 1. Millstone Hill Radar Meteor Experiment: System Parameters

Antenna diameter	68 m
One-way antenna gain	~ 45 dB
Antenna beamwidth (FWHM)	0.6°
Beam diameter at 100 km altitude	1.1 km
Receiver system temperature	~ 120 K
Transmitter power	1 - 2 $\times 10^6$ W
Transmitter frequency	440 MHz
Transmitter wavelength	67 cm
Transmitter waveform	13 baud Barker code
Waveform baud	4 μs
Receiver bandwidth	500 kHz
Maximum observable velocity	85.5 km/s

2. OBSERVATIONAL TECHNIQUE

The observations reported here were made using the Millstone Hill incoherent scatter radar, located on the U. S. mainland at 42.6° N latitude and 288.5° E longitude in suburban Massachusetts. Relevant radar system parameters are listed in Table 1. Meteor head echo data was collected on several occasions, but we concentrate here on experiments during the Leonid meteor shower periods on November 17 - 19, 1999 and November 17 - 18, 2000. The Millstone Hill radar has two available large antennas, but for the experiments to date, the fixed 68 meter zenith antenna was employed to ensure maximum signal-to-noise ratio (SNR). As outlined in [8], the narrow 0.6° FWHM field of view of this antenna, coupled with the high velocity of the meteor target, means that meteor head echoes are visible only for < 0.1 sec and may be Doppler shifted by up to 200 kHz from the 440 MHz center frequency. Since these experiments were exploratory and the nature of the meteor selection algorithms was not known apriori, a wideband recording mode capable of saving power profiles from individual radar pulses (a "raw data" mode) was applied. This mode of operation yielded large data quantities (74 GB over 44 hours for the 1999 experiments) for later postprocessing.

Table 1 also describes the transmitter and receiver parameters. The transmitted waveform selected is a standard 13-baud Barker code [9] first applied to meteor observations at EISCAT [10]. On reception, the observed signal is passed through a matched digital decoding filter, and the decompressed echo exhibits Doppler decorrelation patterns which are a function of the instantaneous Doppler velocity of the meteor head echo. It is then possible to apply a least-squares fitting technique to derive not only the mean altitude and total RCS, but the Doppler velocity of each meteor echo observed. A future work will describe the results of this Doppler decorrelation analysis as applied to the 1999 and 2000 data. Here, we concentrate on postprocessed measurements of the mean meteor head echo altitude and RCS. Altitude is derived by estimating the middle range of the Doppler decorrelation signature, and RCS is estimated by integrating the total received signal power under the decorrelation envelope since this quantity is conserved regardless of the actual Doppler velocity [10]. The received signal is sampled at twice the transmitted waveform baud rate in order to avoid appreciable loss of signal power which would occur if the meteor Doppler shift placed the received echo outside the analog filter passband. The experiment parameters selected ensure that all meteors with velocities up to 85.5 km/s are visible, a figure beyond the Leonid shower radiant velocity of 72 km/s.

An important step in the signal processing of the recorded data is separation of valid meteor echoes from other impulsive events such as in-band radiofrequency interference and momentary receiver noise. We accomplish this by first identifying those recorded echoes with a SNR threshold of 9 dB, and then further filtering the results by assembling them into time sequences. A final filtering criterion rejects short impulses as well as long-duration satellite echoes by asserting that the meteor echo sequence be contiguous over a minimum of 10 msec and a maximum of 123 msec. The SNR threshold used, combined with the system sensitivity and antenna gain from Table 1, sets the hard-target minimum detectable RCS at approximately -60 dBsm. The upper limit of observability before reaching receiver saturation is in excess of -10 dBsm.

3. LEONID SHOWER RESULTS

3.1. SNR, RCS Statistics

For the November 2000 observations, we present meteor head echo statistics ordered by SNR and RCS in Figure 1; results for the November 1999 experiments are similar. The RCS values were calculated from the SNR statistics by assuming the meteor head echo is a point target and employing the hard-target radar equation

$$RCS = \frac{P_N (4\pi)^3 R^4}{P_T \lambda^2 G^2} SNR \qquad (1)$$

where $P_N = k_B T_{sys} BW$, T_{sys} is the system noise temperature, k_B is Boltzmann's constant, BW is the receiver bandwidth in Hz, R is the meteor echo range in meters, λ is the transmitter wavelength in meters, and G is the one-way antenna gain; parameters are taken from Table 1. The results show that at the 440 MHz frequency of Millstone Hill, the radar observes micrometeoroids with cross-sections between 3×10^{-5} and $10^{-3} m^2$. Employing the methods of Mathews [5] where the RCS is assumed to be (very roughly) equivalent to the geometric area around the

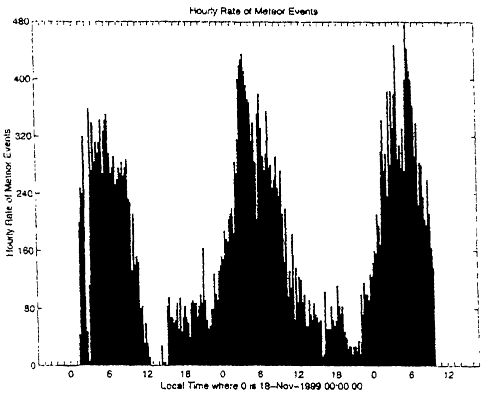

Figure 2. Millstone Hill meteor head echo count statistics as a function of local time for the November 1999 Leonid shower observations.

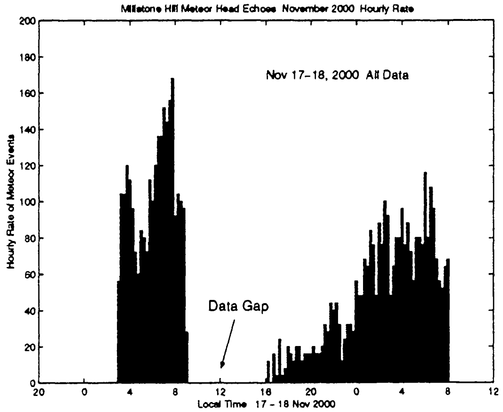

Figure 3. Millstone Hill meteor head echo count statistics as a function of local time for the November 2000 Leonid shower observations.

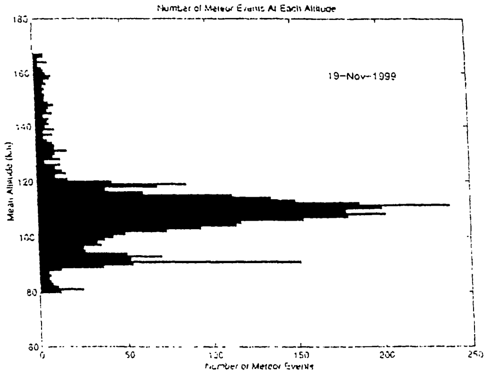

Figure 4. Millstone Hill meteor head echo count statistics as a function of altitude for the November 1999 Leonid shower observations. Sampling extends from 85 to 165 km altitude.

meteor's plasma head, we estimate this corresponds to particles with average mass of approximately 70 mg assuming a density of 3 g/cm^3.

3.2. Diurnal Statistics

We present meteor head echo count statistics, expressed in effective number of meteor counts per hour as a function of time, in Figure 2 for the November 1999 and Figure 3 for the November 2000 Leonid shower periods. The diurnal variation of the two observations peaks during local dawn at rates of 150 - 300 meteors/hour when the relative earth-meteor velocity is greatest, and becomes a minimum near dusk, in good agreement with other meteor head echo and classical trail echo results (e.g. [3]). However, observed counts do not significantly deviate from those characteristic of non-shower periods (e.g. November 10, 1998; not shown here), and no significant short-duration enhanced count rates are seen.

3.3. Altitude Statistics

We plot meteor head echo count statistics versus mean altitude in Figure 4 for November 1999 and Figure 5 for November 2000; due to an oversight in experiment setup, the receiver sampling altitudes for the latter experiment begin at 100 km. The November 19, 1999 day shown is typical of the entire data set for 1999 and shows a distribution centered near 105 - 110 km altitude, typical of meteor head echoes at UHF frequencies, as the electron density in front of the impacting meteoroid rapidly increases creating an overdense target [11]. The results from November 2000 in contrast exhibit a somewhat variable distribution, which we illustrate in Figure 5 by separating the echoes into three time periods from November 17 03 - 09 LT, November 17 16 - 22 LT, and November 17 22 - 08 LT. The first nighttime period and the intervening daytime observations show a primary peak centered on $\sim$ 105 km as in 1999, but a significant secondary peak exists at approximately 118 km. By the second evening of November 17-18 the 118 km peak has become the dominant mean center altitude for meteor head echoes, with the lower peak still visible. The upper peak cannot be ascribed to meteor echoes entering a sidelobe, as the strongest sidelobe of the Millstone zenith antenna is $\sim 2 - 3°$ off boresight and no significant antenna response exists at a 27.1° degree offset which would be implied by assuming the 118 km mean altitudes were actually 105 km echoes in a sidelobe. No other unusual systematic differences were uncovered that might lead to exclusion of the upper peak as an instrumental artifact.

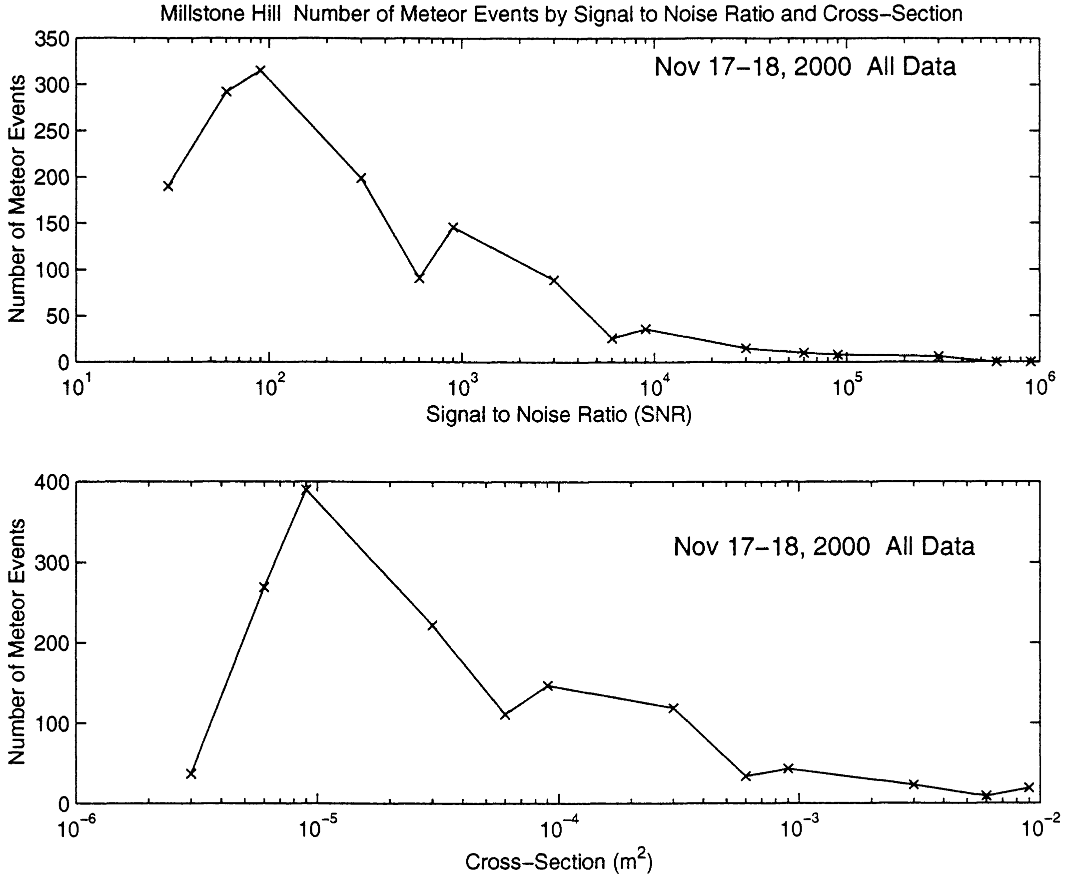

Figure 1. Millstone Hill meteor head echo count statistical distribution in SNR and RCS for the November 2000 Leonid shower observations. The data were binned in SNR before computing RCS; overall standard deviation was less than 10 percent.

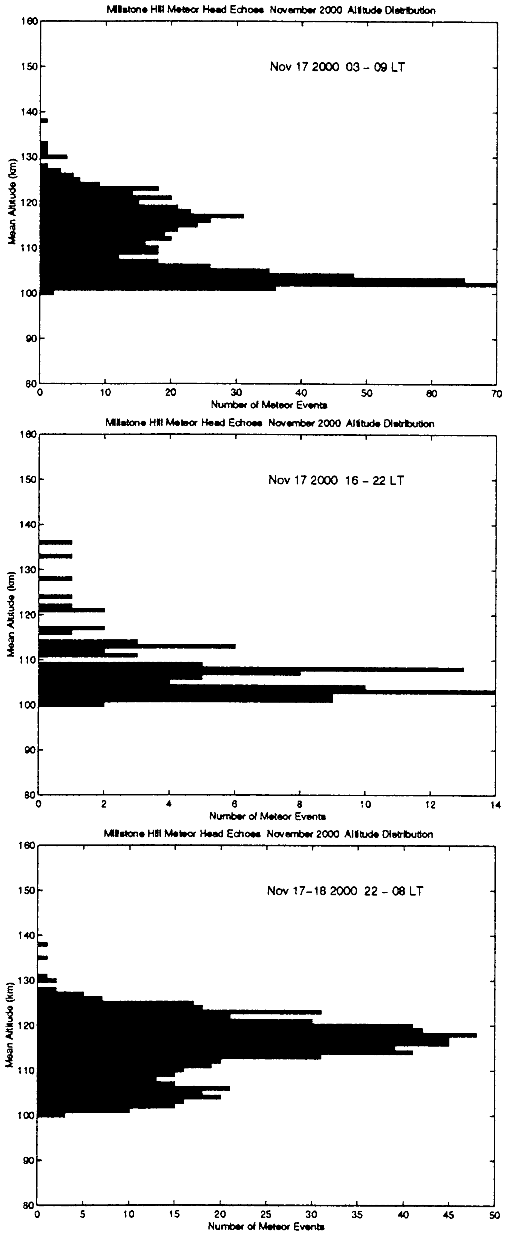

Figure 5. Millstone Hill meteor head echo count statistics as a function of altitude for three periods during the November 2000 Leonid shower observations: (a) between 03 - 09 LT November 17; (b) between 16 - 22 LT November 18; (c) between 22 - 08 LT November 18/19. Sampling extends from 100 to 140 km altitude.

3.4. Discussion

The 105 -110 km altitude distribution presented in section 3.3 for a majority of the Millstone Hill observations is in good agreement with results from Arecibo [3] and EISCAT [2]. However, the 118 km mean altitude peak in meteor head echo counts observed on the evenings of November 17 and 18, 2000 is a very high altitude for meteor head echo observations, and does not agree with theories proposed to explain the observed upper altitude cutoff for conventional meteor radar distributions [12] or meteor head echo distributions [2, 11]. The mechanism postulated by these studies predicts that the upper cutoff is due to the electrons within either the plasma cloud (for head echoes) or trail (for conventional meteor radars) cancelling one another's scattering contributions. The resulting predicted upper limit on UHF head echo observation is ~110 km, and complete cancellation of the reflected wave should occur at 118 km, as the atmospheric mean free path there is much larger than the 67 cm wavelength used at Millstone Hill. Future studies will attempt to further confirm and quantify this upper altitude peak.

We note that temporal count statistics presented in section 3.2 do not exceed those observed on typical days when only sporadic meteor populations are present. However, significant Leonid shower activity has been reported during both the November 1999 (maximum at November 18, 2202 LT) and 2000 (maximum at November 18, 0312 LT) Leonid showers by optical observations [13, 14] and lower-frequency radiowave observations (e.g. the Ondrejov backscatter radar in the Czech Republic - cf. `http://sunkl.asu.cas.cz/~koten/radar.html`). Furthermore, the Leonid radiant point was visible at Millstone Hill's location from approximately 2200 to 1300 LT during each November day, reaching a maximum altitude of 69°. The Millstone Hill observations strongly suggest, therefore, that the Leonid streams encountered by the earth during these showers do not possess significant enhancements in meteoroid particles at the milligram level.

4. MIDAS-W: ENHANCED CAPABILITIES FOR METEOR RESEARCH

The results from the 1999 and 2000 Leonid meteor periods demonstrate the capability at Millstone Hill for dedicated meteor observation experiments. Since 1992, the radar has employed MIDAS (Millstone Incoherent Scatter Data Acquisition System), a hierarchical hardware/software system based on an abstract model of a general incoherent scatter radar, for its experiment management and data acquisition needs. The MIDAS system has proved to be a versatile and robust datataking system, but is currently limited to a single-processor configuration in which each incoming radar pulse is associated one-to-one with a corresponding analysis algorithm tailored to a specific scientific goal.

The system is currently undergoing an upgrade to the MIDAS-W software radar system [8] where all signal processing functions are performed in the digital domain on general purpose computers. The observations presented in this work from November 2000 were in fact made with a prototype version of the MIDAS-W system. A fundamental goal of MIDAS-W is to flexibly extend the kinds of processing that can be done on radar signals by providing raw voltage samples across a multicast high-speed Ethernet backbone. This allows multiple attached clients to independently analyze received echoes in different ways through simultaneous access to the incoming data. Receiver system performance will also improve, and the library of accessible transmitter modulations will be greatly expanded to utilize the full ~ 1 MHz bandwidth of the klystron-based transmitter.

This system upgrade will have significant implications for meteor observation statistics. The modern revival of interest in high-frequency meteor head echoes at the EISCAT facility [2] arose in fact as a result of anomalous echoes, generated by incoming meteors, appearing in experimental data aimed instead at measuring neutral and ionized parameters in the ionospheric E region near 100 km altitude. In a similar manner, normal ionospheric observing programs at Millstone Hill also have meteor echoes embedded in data intended for other purposes. We intend in the future to construct a software meteor detection module, always present in the signal processing chain, which takes advantage of the multicast MIDAS-W received data to automatically log and classify strong point-scatter targets independently of other more ionosphere-specific analysis modes. Since Millstone Hill operates over 2000 hours per year in various coordinated and site-specific experiments, statistics of micrometeoroids will be vastly improved over reliance on dedicated meteor experiments alone, although some transmitted waveforms will by their nature produce more accurate head echo results. The improved receiver bandwidth and enhanced transmitter waveform library will also allow the meteor module to routinely process head echoes in both range and Doppler shift in real-time.

In addition to the 68 meter zenith antenna used in this work, Millstone Hill also has available a 46 meter fully steerable antenna, and the transmitter can be switched between the two antennas in approximately 1.5 seconds. Furthermore, the 46 meter steerable antenna has a four horn monopulse feed which provides two azimuth and two elevation error channels in addition to the central sum channel. We plan to instrument all four error channels and the main sum channel with high dynamic range receivers, and we will simultaneously sample these channels, using their data to construct a more sophisticated meteor orbit determination system. This technique will combine the interferometric phase information provided by the error channels to allow unambiguous trajectory angle and orbit determination on each observed meteor head echo target. Such phase angle information has already been employed successfully at the ALTAIR Pacific UHF/VHF radar [15] in dedicated experiments, but the design of the Millstone Hill/MIDAS-W software radar system combined with the large number of potential observation times will greatly increase the number of orbital determinations possible.

5. SUMMARY

We have begun to explore the characteristics of meteor head echoes at UHF frequencies from Millstone Hill using a new set of experimental modes as the micrometeors pass through the narrow-beam, high-power incoherent scatter radar. Diurnal distributions during the 1999 and 2000 Leonid meteor showers do not show significant count enhancements over normal sporadic meteor patterns, leading to the conclusion that meteoroids in the cross-section range of $10^{-5} - 10^{-4} m^2$ and estimated masses of $\sim 10 - 100$ milligrams are not a significant population within the Leonid interplanetary debris streams. Altitude distributions, particularly during the November 2000 observations, show evidence of very high-altitude meteor echoes which disagree with conventional theories predicting upper altitude cutoffs at 110 km for UHF radar frequencies. Future studies will be able to more completely explore these features and map out Doppler velocities with greatly enhanced statistics as the MIDAS-W software radar system is brought online.

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