SIMULTANEOUS DUAL-FREQUENCY OBSERVATIONS OF METEOR HEAD ECHOES USING ALTAIR

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ABSTRACT
We present a sample of radar meteors detected during the November 1998 Leonid shower that were collected using the ARPA Long Range Tracking and Instrumentation Radar (ALTAIR) at 160 and 422 MHz. A total of 900 VHF and 500 UHF head echoes were collected near the peak of the shower; these data produced a detection rate of approximately 1 VHF head echo every 2 seconds, which is the highest rate recorded by any sensor. These data were analyzed to determine frequency-dependent radar cross-section (RCS) and true 3-D velocity, as well as altitude and aspect angle trends. These data are the first to reveal that the shape and strength of the head echo varies as a function of detection angle. In addition, the azimuth and elevation data were used to compute the deceleration as a function of time, which can be utilized to compute the radius/density of the meteoroid itself. The majority of these meteoroids had mass ranges between 10^{-6} and 10^{-3} grams and diameters less than 2 mm.

1. INTRODUCTION

Meteoroids that enter the Earth's atmosphere collide with the neutral air molecules and generate localized ionization regions. These plasma regions are formed primarily within the *E* region of the ionosphere (approximately 80- to 140-km altitude) and are grouped into two categories, including the ionization trail and a locally ionized region surrounding the meteor called a head echo. These head echoes travel with the same velocity as the meteoroid itself [1] with radar cross-sections that are dependent upon the size, shape, composition and velocity of the meteor. The instantaneous size of the meteoroid is dependent upon the rate of mass dissipation, which, in turn, is dependent upon air density and meteoroid velocity. Radar cross sections will vary between particles and change rapidly as a meteoroid travels through the ionosphere. From the analysis of head echoes, one can deduce meteoroid decelerations and densities, which are independent of ionization assumptions in the formulation applied here.

A renewed interest in meteors resulted from the expected increase in the Leonid meteor flux, due to the passage of the comet Tempel-Tuttle in February 1998. The last Leonid meteor storm occurred in 1966, commensurate with Temple-Tuttle's 33- year orbital period, and at that time, there were few satellites in orbit. Because of the large increase in the satellite population, which currently exceeds 700 operational spacecraft, a worldwide meteor data collection effort was initiated in 1998 to help characterize the Leonid storm and its potential threat [2]. Consequently, shower and sporadic meteor data were collected using ALTAIR.

ALTAIR (Figure 1) resides in the central Pacific at 9^{o} N and 167^{o} E on the island of Roi-Namur in the Kwajalein Atoll, Republic of the Marshall Islands. ALTAIR is a high-power, dual-frequency radar that capable of collecting precise measurements on small targets at long ranges. ALTAIR has a 46-m diameter, mechanically steered, parabolic dish that transmits a peak power of 6 MW simultaneously at two-frequencies. A complex transmit and receive radio-frequency (RF) antenna feed system arrangement allows the simultaneous operation at both VHF and UHF. Targets are illuminated with right-circularly (RC) polarized energy in a narrow half-power beam-width of 2.8^{o} and 1.1^{o} at VHF and UHF, respectively. The reflected signal energy is focused by the dish into the dually polarized feed horn. The feed horn receives the left-circularly and right-circularly polarized signal energies separately. These two channel measurements are denoted sum left circular (SLC) and sum right circular (SRC). ALTAIR also has four additional receive horns that collect LC signal returns for the purpose of angle measurement. These horns are offset from the focus of the dish, and their signal energies are differenced to produce two additional channels of data, including the left circular azimuth difference (ALC) and left-circular elevation difference (ELC). ALC and ELC are combined in a process known as amplitude comparison monopulse, a form of phase interferometry, to measure the angle of arrival of the radar return (for each pulse) to a small fraction of the beam width. Combined with a range measurement

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derived from the time delay of the target return, ALTAIR can determine the position of an object in three dimensions.

Fig. 1. Photograph of ALTAIR.

ALTAIR is part of the Kwajalein Missile Range (KMR), whose mission areas include support of missile testing (such as operational tests of fielded ballistic missile systems) and developmental testing of missile defense systems. ALTAIR itself has a second and much larger mission area, which is to provide support to U.S. Space Command for space surveillance. ALTAIR dedicates 128 hours per week to Space Command and provides data on nearly every space surveillance event involving satellites. ALTAIR's high peak power and large aperture combine to create high system sensitivity. Using the most sensitive waveforms available, ALTAIR can reliably detect a target –74 decibels-relative-to-a-square-meter (dBsm) at VHF (–80 dBsm at UHF) at a range of 100 km. This high system sensitivity makes ALTAIR very well suited for the detection of small head echoes. Because head echoes provide direct measurements of meteoroid velocities, important meteor parameters can be inferred, such as size and density [3].

2. LEONID OBSERVATIONS

Leonid data were collected on November 18, 1998, during a 3-hour period, which was chosen to span the predicted peak of the Leonid storm (07:30 AM local time); Table 1 contains a summary of KMR observation times and the estimated flux rates. Over 26 GB of ALTAIR data corresponding to 30 minutes of actual measurements were collected during this period, including both on-radiant and off-radiant observations (the radiant is the position in the sky from which the head echoes appear to emanate). While the radar is pointing at the radiant, Leonid particles follow paths roughly aligned with the antenna beam and will therefore endure longer in the observe more of the sporadic meteors and to have a greater chance of observing returns from specular meteor trails. For this activity, ALTAIR operated simultaneously at VHF (160 MHz) and UHF (422 MHz). Amplitude and phase data were recorded for each frequency and four receive channels: sum right-circular (SRC), sum left-circular (SLC), azimuth difference left-circular (ALC), and elevation difference left-circular (ELC). Measurements were collected for radar slant-ranges corresponding to altitudes spanning 70 to 140 km using two different waveforms (one waveform per frequency). The two waveforms used to collect most of the data were a 40 μsec VHF pulse (30 meter range sample spacing), and a 150 μsec UHF pulse (7.5 meter range sample spacing). We used a 333 Hz pulse-repetition frequency to provide a high sampling rate in order to better study a meteor's deceleration. Different waveforms (V260M/U1000) were also applied for their high sensitivity to obtain the best estimate of the meteoroid flux. The parameters associated with these waveforms are contained in Table 2.

Table 1. Summary of activity during the Leonid '98 storm.

Time	Elevation	Position	Flux
15:00 GMT[1]	28°	Radiant	0.35 / sec
15:15 GMT[1]	28°	Off-radiant	0.15 / sec
18:20 GMT[2]	72°	Radiant	0.68 / sec
20:20 GMT[2]	69°	Off-radiant	0.38 / sec
20:40 GMT[2]	65°	Radiant	1.20 / sec
21:00 GMT[2]	**62°**	**Radiant**	**1.65 / sec**
21:20 GMT[2]	60°	Off-radiant	0.39 / sec
21:30 GMT[2]	55°	Radiant	0.36 / sec

[1] *Min Detectable RCS: -74 dBsm (VHF), -80 dBsm (UHF)*
[2] *Min Detectable RCS: -55 dBsm (VHF), -75 dBsm (UHF)*

Table 2. Summary of waveform parameters for the Leonid '98 storm.

	V40H	U150	V260M	U1000
Frequency (MHz)	160	422	158	422
Bandwidth (MHz)	3	18	1	1
PRF (Hz)	333	333	50	50
Range Spacing (m)	30	7.5	75	75
Sensitivity (dBsm)	-55	-75	-74	-80

3. LEONID DATA ANALYSIS

To obtain the range-time-intensity data, the radar amplitude and phase measurements were reduced using signal processing algorithms developed at MIT Lincoln Laboratory. The first step in the process involved the calculation of the system noise floor and receiver channel was estimated by averaging the amplitude for a noise sample region for each data collection interval. System thermal noise and background sky-noise are included in the estimates. The receiver biases were estimated by determining the offset of the system noise floor from zero-mean for each receiver value (SLC, SRC, AZ, EL). A 10-dB SNR threshold (above the noise floor) is applied to the SLC and SRC amplitude, and the data from all four channels are saved whenever either of the thresholds is exceeded. Digital samples of the received radar pulses are then interpolated to determine the range to the peak amplitude of the SLC measurement. The SRC, AZ and EL receiver measurements are subsequently interpolated to the range of the interpolated SLC peak to provide a consistent measurement for all four channels for a given pulse.

A variation of the Hough Transform is applied to automatically search the range-time images to associate a series of pulse detections (in straight lines) as one head echo. Head echo pulse "detection sequences" with range rates values characteristic of meteors bound in solar orbit (-72 to 0 km/s) were included. A threshold on the length of a pulse detection sequence was also used. (This threshold is a function of radar pulse-repetition-frequency (PRF) and was set to five for a PRF of 333 Hz). The resulting head echo detections were then used to compute histograms of meteor head echo parameters, including RCS.

ALTAIR is calibrated to the RCS of a known target, such as a conducting sphere; the absolute RCS measurement capability of ALTAIR is within 0.5 dB. The final step in the data reduction process was to use the computed range rates to correct the target ranges for range-Doppler coupling. Range-Doppler coupling results from a chirp-type pulse. Doppler shifts of the radar echo cause an offset in the apparent range of the echo. The relationship between target range rate and the range-Doppler coupling range offset is $Dr = (Tf_0 v_r)/B$, where Dr is the range offset, T is the pulse width, f_0 is the radar RF frequency, v_r is the target radial velocity, and B is the chirp bandwidth. The quantity $(Tf_0)/B$ has units of time and is called the range-Doppler coupling constant. The range-Doppler coupling constant for the ALTAIR waveforms primarily used in this study are 2.13×10^{-3} s (VHF) and 3.52×10^{-3} s (UHF).

To obtain meteor decelerations, we extracted each head echo and fit a polynomial curve to its associated time-of-flight velocity profile, interpolating to obtain finer resolution. The data from the two angle processed to determine the angular offset of the detections from the radar boresite (in units of radians). By applying the angular offsets, the true 3-d position of the head echo was determined. Once the position of the head echo was calculated, the time rate of change of position was computed to obtain the true velocity; a second differentiation resulted in an estimate of the meteor's deceleration. (ALTAIR is a coherent radar, and Doppler processing of the head echo data to directly measure closing velocity was considered. However, the Doppler processing was not pursued because the PRF and the ALTAIR wavelength of approximately 2 m (VHF) and .7m (UHF) give an unambiguous velocity interval of 0.31 km/s and .12 km/s, respectively. This was considered too small of an interval for targets with range velocities of the order of 72 km/s.)

Monopulse angle measurements are only valid when detections are made in the main beam; therefore care was taken to ensure that the detections that were used did not occur in angle sidelobes. The gain of the two-way ALTAIR antenna falls by more than 30 dB outside the main beam. When the meteor head passes from the main beam into the first sidelobe, the apparent RCS would decrease, and the arithmetic sign of the angle error of one or both of the channels would suddenly change (as if the detection "hopped" to the other side of the beam).

The final goal was to estimate the radius and density of the meteor particle. This was first accomplished by John Evans [5] and was explained in reference to ALTAIR data in [6]. The final result is

$$rd = \frac{3}{2} v_m r \sec(c) \left(\frac{dv_m}{dh}\right)^{-1} \qquad (1)$$

where r and d are the radius and density of the meteoroid, respectively, n_m is the velocity of the meteoroid (or head echo), r is the air density (as a function of altitude), and c is the elevation.

4. LEONID DATA RESULTS

Three experiments were conducted using the ALTAIR system, including the Perseid 1998, Leonid 1998 and Leonid 1999 meteor showers. Of the three data sets, the Leonid 1998 measurements provided observations of head echoes with the most intense ionization and corresponding greatest head echo signal-to-noise measurements. The head echo ionization from these meteors tends to persist for longer periods of time and allows a better determination of their characteristics. This ionization is presumably due to the viewing of a cometary debris stream composed of physically larger meteorites. The presence of larger particles, coupled with the fact that Leonid meteors (~72 km/s) have a greater velocity than Perseid meteors (~60 km/s) lead to a more energetic interaction with the E-region of the of the atmosphere relative to the other viewing periods. The kinetic energy given off in the form of ionization energy was most pronounced during the Leonid 1998 campaign because of these factors. These high SNR head echo returns are likely complicated by the presence of dust fragmentation from the larger meteors as they disintegrate during their passage through the atmosphere. The effects of the plasma being dusty versus dust-free (on the radar measurements) is not considered in the treatment here. Figure 2 contains histograms for head echo data collected when ALTAIR was pointed at the Leonid radiant. The plotted results include 570 VHF echoes and 300 UHF echoes, although the detected rate was 906 VHF echoes in 29 minutes of data and 496 UHF head echoes in 17 minutes of data. This corresponds to an average rate of one head echo detected every two seconds. This detection rate was affected by the presence of intense specular and spatially distributed oblique ionization trails that dominated our return signal strength and masked the head echoes. If we removed the ionization trails, the head echo rate for Leonid 1998 would likely exceed the rate seen during the Perseid shower (1 head echo every second).

Figures 2a and 2b are histograms of the mean detection altitude and radial velocity of the head echoes. The radial velocity distribution indicates peaks near 60 km/s for both the VHF and UHF data. Although this is contrary to the expected peak of 72 km/s for a Leonid, this number does not reflect the true velocity of the meteoroid particle. Also, note that several head echoes were detected with a velocity greater than 72 km/s, suggesting at orbits that are not bound in solar orbit or were gravitationally accelerated by a third body. These data are currently being examined further. Figure 2c contains a histogram of the duration times for both the VHF and UHF head echoes, and indicates that a typical head echo persists for approximately .1 seconds in the ALTAIR VHF beam (2.8^{o}). The longest head echo endured for nearly 2.3 seconds in the VHF beam, and in contrast only 0.4 seconds in the UHF (1.1^{o}) beam.

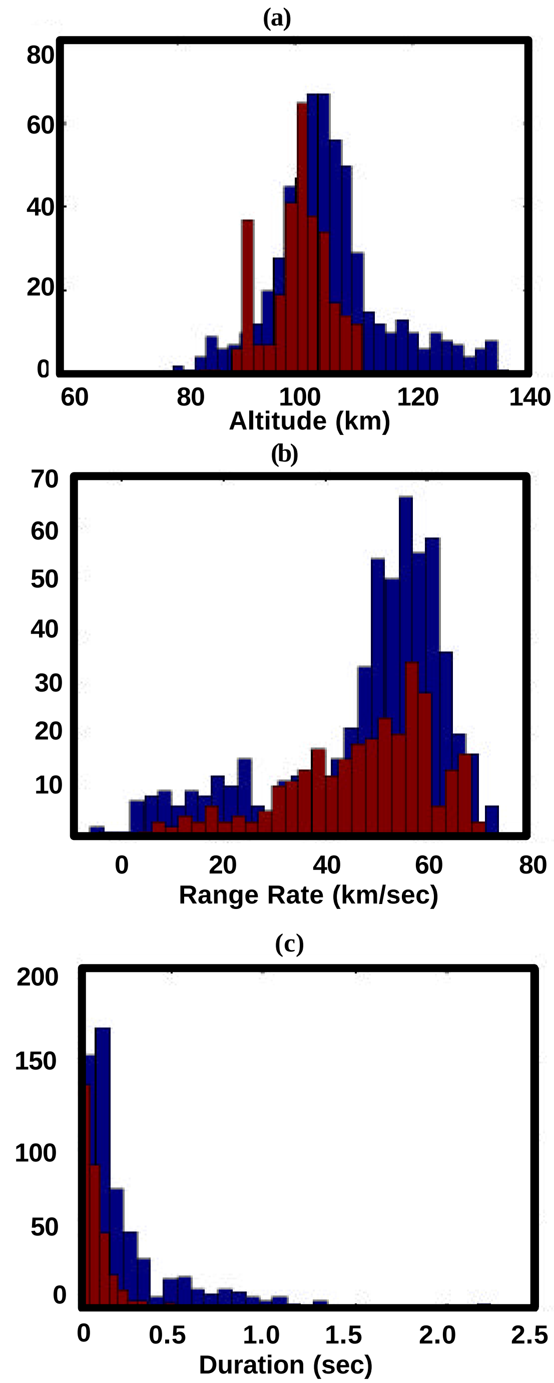

Fig. 2. Leonid radiant histograms, including (a) mean detection altitude, (b) range rate and (c) duration.

Figure 3 contains the VHF and UHF RCS histograms for both the LC (a) and the RC (b) RCS data. Both graphs indicate that the average difference between the VHF and UHF data is approximately 24 dBsm. This frequency dependent scattering characteristic of the meteors are transparent (underdense) at the shorter wavelengths. A similar characteristic is true for the majority of meteor trails [7].

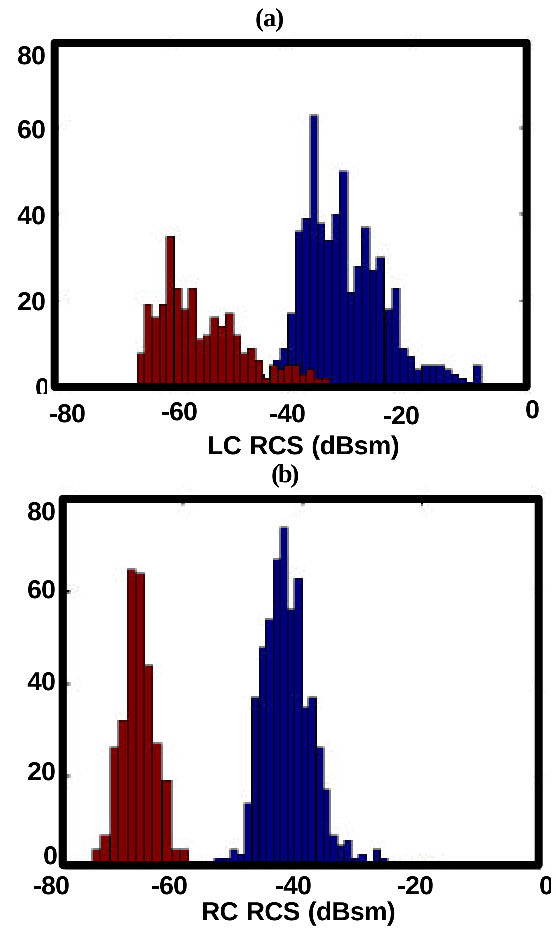

Fig. 3. Leonid radiant histograms, including (a) left-circular RCS and (b) right-circular RCS.

Figure 4 contains the first results that show that deceleration is not constant over the lifetime of a head echo. The time varying deceleration is presumably due to the spatially distributed atmospheric density coupled with the shape and composition of the meteor itself. Figure 4 shows the deceleration, varying between 5 and 100 km/s^2. These data were also color-coded to show the variation in RCS of the head echo as it decelerates. As a meteor traverses the ALTAIR beam, the returned signal energy will tend to track the spatial distribution of the intensity of the beam pattern. Near the center of the main radar beam, the signal intensity as a function of solid angle distance from the center, is approximately sin(x)/x. To characterize the head echo relative to the beam center. For this particular case, the head echo's peak RCS does not coincide with the center of ALTAIR's beam (peak SNR) and reveals that this sin(x)/x distribution in RCS is due to the time evolution of the meteor as opposed to a radar artifact.

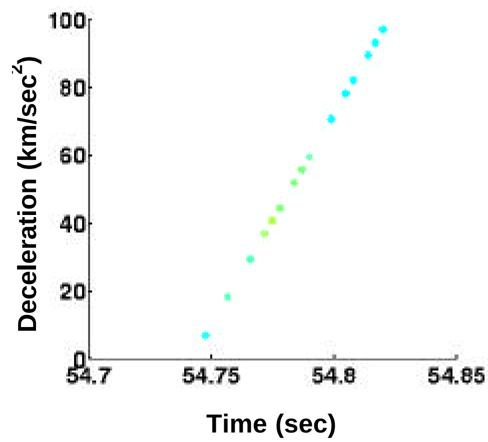

Fig. 4. An example head echo showing its deceleration as a function of time (lighter shading indicates peak RCS).

Figure 5 contains the results of analysis on 20 VHF head echoes. Figure 5a shows the velocity as a function of altitude, where each head echo is indicated by a different symbol. The average velocity (averaged over the lifetime of a head echo and then over all 20 head echoes) is 69 km/s. The average duration is .1 seconds and the average RCS (LC only) is –27 dBsm. These values are contained in Table 3. The statistical data begin to provide a calibrated sample (RCS and position) of the overall characteristics of the meteor shower dynamics and distribution with the shower itself. Figure 5b shows the deceleration as a function of the radius*density product and indicates that as the radius*density decreases, the deceleration increases. This result is intuitive: the radii of the meteoroids decrease (assuming a constant density) as they penetrates further into our atmosphere.

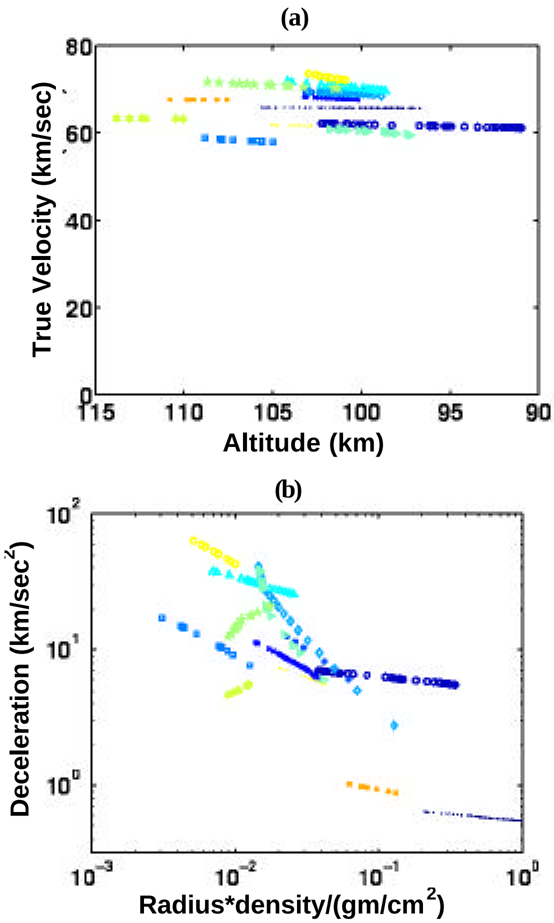

Figure 5. The (a) true velocity corrected by monopulse angle data as a function of altitude and the (b) associated deceleration as a function of the meteoroid's radius-density product for 20 head echoes.

Table 3. Summary of Parameters Averaged Over 20 Head Echoes

Parameter	Value
Duration	0.1 s
Maximum RCS	-27 dBsm
Mean apparent velocity	-69 km/s
Deceleration	15 km/s^2
Mean meteor radius-density	0.08 g/cm^2
Mean radius*	0.08 cm
Mean mass	10^{-3} - 10^{-4} g

**Assume meteor density is 1g/cm^3*

5. SUMMARY

Although the 1998 Leonid meteor shower did not reach its expected peak flux, ALTAIR detected numerous dual-frequency head echoes that were used to calculate the first calibrated frequency dependence on RCS. Our high detection rate achieved during the Perseid shower in 1998 was once again seen during the Leonid shower, indicating that ALTAIR's sensitivity is very valuable in estimating a true meteoroid flux. The monopulse angle data permitted determination of the true three-dimensional position of the head echoes that resulted in decelerations, as well as estimations of the radius-density product of the meteor particle. As a result, we have achieved the first results to show how a meteoroid's deceleration varies as it penetrates the Earth's atmosphere. Analysis of the Leonid 1999 storms is in progress. A collection campaign designed to characterize sporadic meteors is also currently planned.

6. ACKNOWLEDGMENTS

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