# Meteor Shower Characterization at Kwajalein Missile Range

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**Approximately one billion meteors enter the Earth's atmosphere daily, and their potential impact on spacecraft is not yet well characterized. Kwajalein Missile Range radar systems, because of their high sensitivity and precise calibration, have contributed new information on meteor phenomena, including observations of the Perseid and Leonid meteor showers of 1998. Initially, Perseid data were collected by using the Advanced Research Projects Agency (ARPA) Long-Range Tracking and Instrumentation Radar (ALTAIR), which is a two-frequency radar (VHF and UHF) uniquely suited for detecting meteor head echoes. ALTAIR transmits right-circular (RC) polarized energy and records four channels: left-circular (LC) sum, RC sum, LC azimuth difference, and LC elevation difference. The four channels facilitate the determination of apparent target position and the calculation of polarization ratios. Shortly after the Perseid observations demonstrated ALTAIR's capabilities for meteor detection, Leonid data were simultaneously collected by using ALTAIR and other Kwajalein sensors at microwave and optical frequencies. This article contains an analysis of Perseid data collected at VHF. Meteor head-echo statistics are presented, with an in-depth analysis of a few select head echoes to estimate decelerations and densities. Head-echo data collected at three frequencies (UHF, VHF, and L-band) and ionized meteor-trail data from the Leonid shower are also presented. Radar cross-section measurements for both head echoes and ionized meteor trails illustrate the frequency dependence of plasma reflections.**

The Earth is continually bombarded by particles of debris in solar orbit. Most of these particles are small meteoroids (i.e., meteors in solar orbit), typically the size of a grain of sand, which are captured by the Earth's gravitational field and destroyed in the atmosphere before they reach the Earth's surface. These meteoroids are often a great danger to orbiting satellites in the upper atmosphere. The collision of a meteoroid and a satellite can result in significant damage, including mechanical cratering of the satellite surface or plasma and electromagnetic pulse generation, which can lead to electronic noise, sudden current and voltage spikes, and software anomalies. Meteoroids enter the Earth's atmosphere with considerable energy, between 11 and 72 km/sec. The lower limit represents the kinetic energy of a particle, initially at rest, that has fallen into the Earth's gravitational field. The upper limit is a sum of the Earth's orbital velocity and the solar escape velocity. This article examines meteor data collected at radar frequencies in order to estimate meteor decelerations, densities, and size, which are used to characterize the danger of the meteoroids to orbiting satellites.

Meteor activity consists of either sporadic meteors or meteor showers. Sporadic meteors, which can be encountered anywhere in the Earth's orbit, and at any time, create a constant background flux. Meteor showers are a heightened level of meteor activity that occurs when the Earth's orbit intersects the orbit of a debris stream, typically created by a comet. Meteor showers occur at the same time every year, and the meteors appear to an observer to be radiating from a single point called the radiant. This effect occurs because all the meteors, originating from a single object, are traveling on roughly parallel paths. Meteor showers take their name from the star constellation that contains the radiant point; for example, the Leonid shower takes its name from the constellation Leo.

When meteoroids enter the Earth's atmosphere, they collide with and ionize (i.e., produce a transfer of energy that frees an electron) neutral air molecules and atoms, which generates localized plasma regions. Ionization takes place in the E region of the ionosphere (between approximately 80 to 140 km in altitude). Above 140 km the neutral particle density tends to be too low to ionize, and below 80 km the meteor usually has been destroyed. Meteor ionization in the E region is classified into two categories—the ionized meteor trail and a localized spherical ionized region surrounding the meteor [1]. The meteor trail is cylindrical in shape and typically kilometers in length and meters in diameter; at radar frequencies, trails are often modeled as a long conducting wire. Trail duration varies but is typically less than one second (although some trails last for many minutes) [2]. Trails are stationary except for motion due to atmospheric winds. Specular reflection from these trails occurs if incident radio waves are perpendicular to the cylindrical trail, producing strong returns that have been studied since the 1940s.

The localized spherical ionization surrounding the meteor produces a much weaker type of reflection known as the *head echo*. Head echoes travel with the same velocity as the meteor, with cross sections that depend on the size and shape of the meteor. Because the size of the meteor subsequently depends on the rate of mass dissipation, which in turn depends on the air density and meteor velocity, cross sections vary among meteors and change rapidly as a meteor travels through the ionosphere. By analyzing head echoes we can deduce meteor decelerations and densities, which are independent of assumptions about ionization.

The current high interest in meteors is due to the recent Leonid meteor storm in 1998. The annual Leonid meteor shower, which occurs in November and was created from the comet Tempel-Tuttle, developed into a meteor storm in 1998 and 1999 and is expected to develop into equally intense storm-like activity in 2000. The higher flux of these meteor storms arises because comet Tempel-Tuttle crossed the orbital path of the Earth in February 1998, as illustrated in Figure 1, and the greatest density of meteoroids is collocated in the proximity of the comet. In addition, comet Tempel-Tuttle is inclined only 17° to the Earth's orbital plane, which increases the duration of the meteor shower. Finally, the comet's retrograde orbit around the sun (opposite the direction of the Earth's orbit) increases the brilliance and visible numbers of the meteor shower because the Earth is colliding with the meteoroids at their maximum velocity.

Comet Tempel-Tuttle has a thirty-three-year orbital period; thus the last Leonid storm occurred in 1966, when few satellites were in orbit. At that time, a peak flux rate of forty meteors per second was detected by visual observations [3]. Because of the increased risk of a meteor shower to the current satellite population of over seven hundred operational spacecraft, a worldwide meteor data-collection effort was initiated to help characterize the Leonid storm and its potential threat to satellite safety [4]. The Advanced Research Projects Agency (ARPA) Long-Range Tracking and Instrumentation Radar (ALTAIR), which was requested by the U.S. Air Force Office of Scientific Research to support this effort, collected data on both the Perseid shower and the Leonid storm in 1998.

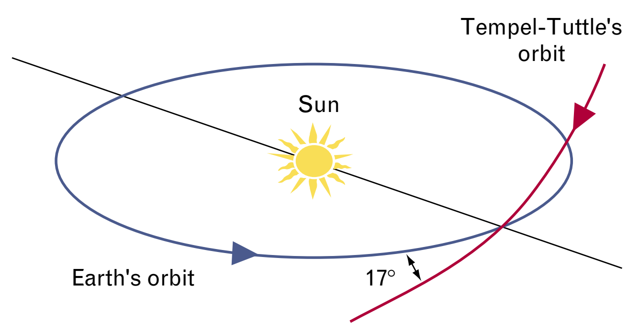


**FIGURE 1.** The intersection of the Earth's orbit with the comet Tempel-Tuttle in February 1998. This intersection, in combination with Tempel-Tuttle's retrograde motion and low orbital inclination of 17°, produced an intense meteor storm in November of 1998 and 1999 and is expected to produce a similarly intense meteor storm in 2000. These storms are actively studied by radar researchers for information on meteor head echoes and meteor trails.

ALTAIR is located in the central Pacific Ocean on the island of Roi-Namur in the Kwajalein Atoll, Republic of the Marshall Islands, at 9° N latitude and 167° E longitude. Shown in Figure 2, ALTAIR has a mechanically steered, 46-m-diameter dish antenna that transmits a peak power of 6 MW with a 2.8° beamwidth at VHF and a 1.1° beamwidth at UHF. ALTAIR is part of a system of radars known as the Kiernan Reentry Measurements Site (KREMS). KREMS mission areas include the support of missile testing activities, such as operational tests of fielded ballistic missile systems and developmental testing of missile defense systems.

ALTAIR has a second and much larger mission area, providing support to U.S. Space Command for the space-surveillance mission. ALTAIR dedicates 128 hours per week to providing data to Space Command on nearly every aspect of space surveillance. The remaining forty hours per week are devoted to system maintenance and development. However, ALTAIR is available with a fifteen-minute recall for high-priority tasks even during these maintenance periods. Lincoln Laboratory fills the role of scientific advisor to the U.S. Army Kwajalein Atoll, which operates the entire radar range. In particular, Lincoln Laboratory has responsibility for the quality of ALTAIR's space-surveillance mission.

ALTAIR's high peak power and large antenna aperture combine to create high system sensitivity. By using the most sensitive waveforms available, ALTAIR can detect a –74-dBsm (decibels relative to a square meter) target at VHF and a –80-dBsm target at UHF at a range of a hundred kilometers, which is a typical range for meteor observations. This high system sensitivity makes ALTAIR uniquely suited for the detection of small head echoes, which so far have been neglected relative to radar research on larger trail echoes. Because head echoes give direct measurements of meteor velocities, important meteor parameters such as size and density can be inferred.

**FIGURE 2.** The Advanced Research Projects Agency (ARPA) Long-Range Tracking and Instrumentation Radar (ALTAIR), located on the island of Roi-Namur in the Kwajalein Atoll, Republic of the Marshall Islands, in the Pacific Ocean. ALTAIR has a mechanically steered, 46-m-diameter dish antenna that transmits a peak power of 6 MW with a 2.8° beamwidth at VHF and a 1.1° beamwidth at UHF. ALTAIR's primary mission area is space surveillance, including observations of meteor activity, but it also contributes to operational testing of fielded ballistic missile systems and developmental testing of missile defense systems.

## Perseid Meteor Observations

The first meteor data collection discussed in this article occurred during the Perseid meteor shower. The purpose of the data collection was to determine the suitability of ALTAIR for meteor observation. Data were collected at two different times during the early morning hours of 12 August 1998. First, the ALTAIR antenna was pointed at the radiant point in the constellation Perseus when it was at its maximum elevation of 40°. Ten minutes of data were recorded. While the radiant point was still at its peak elevation, five minutes of off-radiant data were collected after moving the antenna 30° in azimuth. While the antenna is pointing at the radiant, Perseid meteors follow paths roughly aligned with the antenna beam, and they therefore endure longer in the beam. The purpose of collecting the off-radiant data was to observe more of the sporadic meteor head echoes and to have a greater chance of seeing returns from meteor trails.

Amplitude and phase data were recorded for each of four receive channels: sum right circular (SRC),

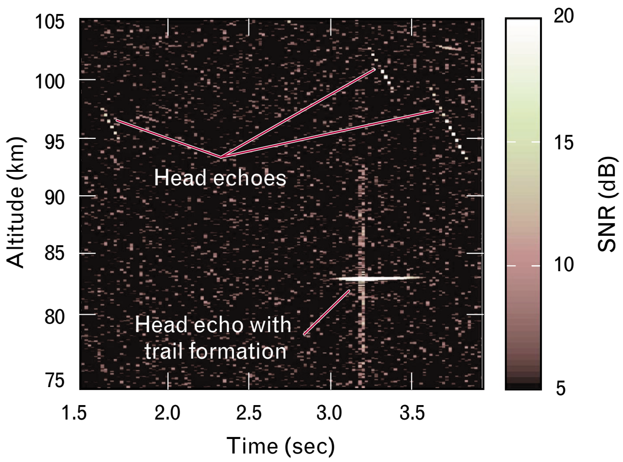


**FIGURE 3.** Range-time-intensity (RTI) image showing three meteor head echoes and a head echo with an associated trail formation.

sum left circular (SLC), azimuth-difference left circular (ALC), and elevation-difference left circular (ELC). Data samples were collected every seventy-five meters for ranges corresponding to altitudes between 70 and 140 km. ALTAIR radiated a VHF 260-$\mu$sec (V260M) pulse fifty times per second. The pulse was modulated with a 1-MHz linear frequency modulation, which allowed the pulse to be compressed to 1 $\mu$sec after receive filtering. By using this waveform, ALTAIR can detect a –72-dBsm target at a range of a hundred kilometers.

## Perseid Data Analysis

Figure 3 shows a representative range-time-intensity (RTI) image of 3.5 sec of SLC channel data. Image color in the figure corresponds to the received signal-to-noise ratio (SNR). This data sample, which contains both meteor head echoes and an ionized trail return, represents the raw data that we processed to detect and measure meteor head echoes (note the range sidelobes resulting from the strong return off the trail). The amplitude and phase data were reduced by using MATLAB scripts. First, receive biases were estimated for all four data channels by averaging the data over an 80,000-sample region that was devoid of detections. After the receive biases were removed, the noise floor in the SLC channel was estimated by averaging the data amplitude over the same window. A 12-dB threshold (above the noise floor) was applied to the SLC amplitude data, and the data from all four channels were saved whenever the threshold was exceeded in the SLC channel. A high threshold was chosen to reduce the huge amount of data (on the order of gigabytes) to a manageable data set. Also, real-time observation of the data indicated a wealth of detections, so we felt there was no need to search the data for small signals.

Next, we interpolated the SLC range samples to find the peak signal strength and associated range. An automated search of the range-time maps was implemented to detect lines corresponding to meteor range rates between –72 and –4 km/sec. Meteor head echoes with fewer than six detections were discarded. The resulting head-echo detections were then used to compute histograms of meteor head-echo parameters. A final step was to use the computed range rates to correct the target ranges for range-Doppler coupling[1].

To obtain meteor decelerations we extracted each head echo, fit a polynomial curve to its associated velocity profile, and interpolated the data samples to obtain finer resolution. The monopulse angle-offset data were then applied to each head echo to compute its apparent position from the radar slant range. Many head-echo returns were excluded because of poor-quality monopulse angle data that resulted from low SNR and low angle sidelobe detections.

Once the head-echo position had been calculated, the time rate of change of position was computed to obtain the apparent velocity of the meteor; a second differentiation resulted in an estimate of the meteor's deceleration.

The next goal was to estimate the radius and density of the meteor particle [5]. The meteor momentum reduction per unit time is

[1] Range-Doppler coupling is a property of 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 $\Delta r = (Tf_0 v_r)/B$, where $\Delta r$ is the range offset, $T$ is the pulsewidth, $f_0$ 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 coupling constants for the ALTAIR waveforms used in this study are $4.16 \times 10^{-2}$ sec for V260M, $1.83 \times 10^{-3}$ sec for V40H, and $3.17 \times 10^{-3}$ sec for U150.

$$\frac{dv_m}{dt} = \frac{\sigma \gamma \rho v_m^2}{m}, \qquad (1)$$

where $\sigma$ is the physical cross section of the meteor, $\rho$ is the air density, $\gamma$ is the dimensionless drag coefficient, $v_m$ is the velocity of the meteor, and $m$ is the meteor mass. The velocity is further defined as

$$v_m = \frac{dh/dt}{\cos\chi}, \qquad (2)$$

where $h$ is the altitude of the meteor and $\chi$ is the elevation angle. After substituting Equation 2 into Equation 1 we obtain

$$\frac{dv_m}{dh} = \frac{\sigma v_m \rho \sec\chi}{m}.$$

If we estimate the physical cross section to be $2\pi r^2$ and calculate the mass $m$ of the meteor to be

$$m = \frac{4}{3}\pi r^3 \delta,$$

where $\delta$ is the density of the meteor, the final result for the radius-density product is

$$r\delta = \frac{3}{2} v_m \rho \sec\chi \left(\frac{dv_m}{dh}\right)^{-1}.$$

Note that the velocity, air density, altitude, and elevation change as a function of time.

## Perseid Data Results

Figure 4 contains histograms showing head-echo data collected when ALTAIR was pointed at the Perseid radiant [6]. Over 692 head echoes were detected in eleven minutes of data; again, this significantly high number includes only meteors approaching the radar and those with duration greater than six pulses (0.12 sec). Meteors traveling perpendicular to the beam or with positive range rates were excluded.

Figures 4(a), 4(b), and 4(c) are histograms of the mean detection altitude, radial velocity, and radar cross section (RCS) of the 692 head echoes. The altitude profile in Figure 4(a) is roughly Gaussian in shape and is consistent with previous Perseid data taken at other sensors [7]. The radial velocity distribution in Figure 4(b) illustrates two peaks; the distribution with a velocity near zero may be attributed to

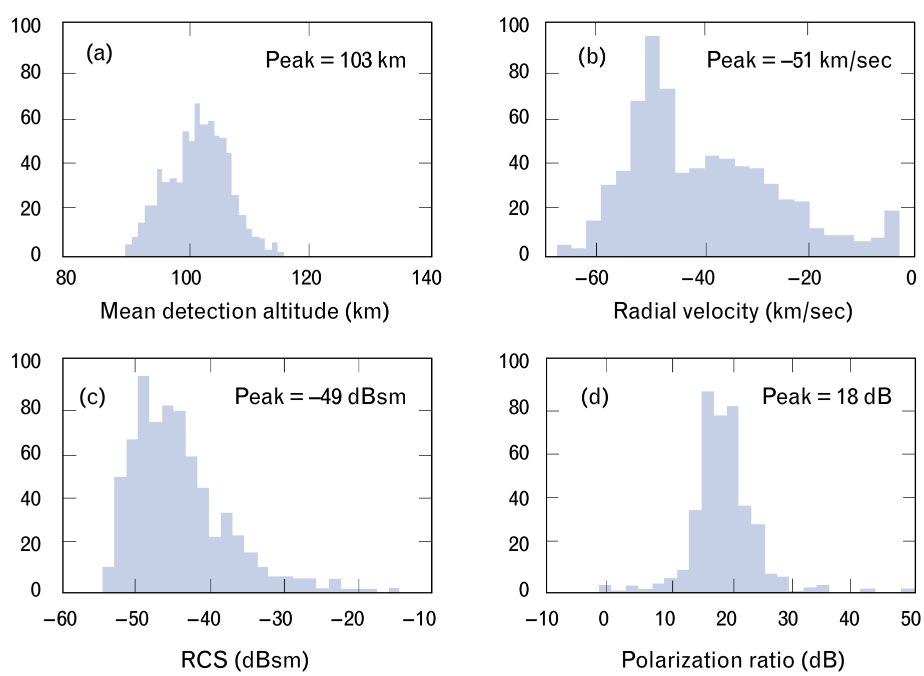


**FIGURE 4.** Perseid meteor-shower radiant histograms, including (a) mean detection altitude, (b) radial velocity, (c) radar cross section (RCS), and (d) polarization ratio.

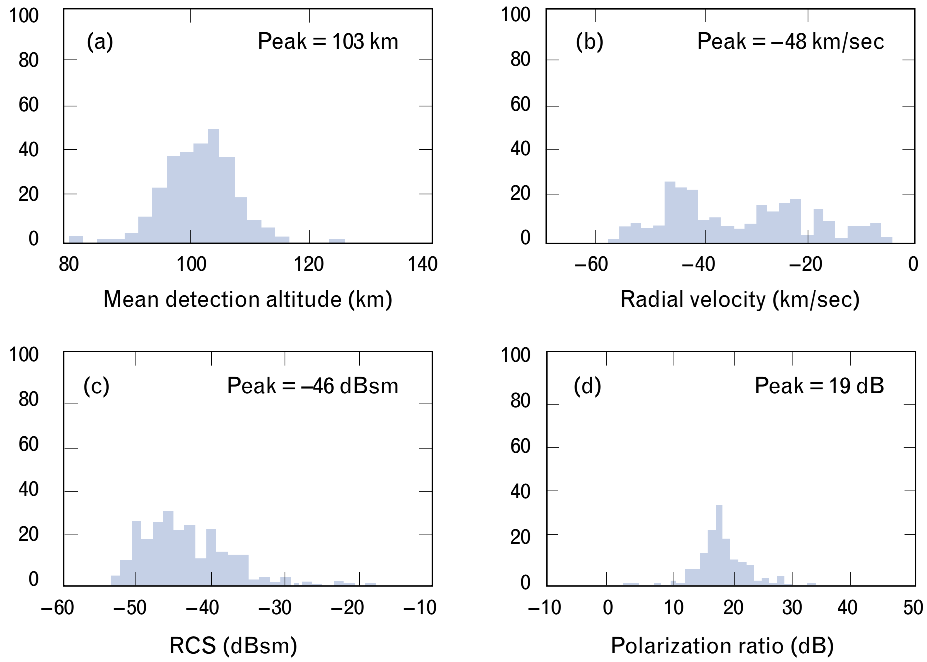


**FIGURE 5.** Perseid meteor shower off-radiant (30°) histograms, including (a) mean detection altitude, (b) radial velocity, (c) radar cross section (RCS), and (d) polarization ratio.

the background sporadic meteor detection. The RCS histogram in Figure 4(c) shows that the RCS with the highest count is somewhat lower than previously published data taken at other sensors [7]. This lower count reflects the fact that ALTAIR's sensitivity allows the observation of smaller head echoes. The sharp cutoff at low RCS is due to thresholding the data to 12-dB SNR and is an artifact of the data-processing procedure. The polarization ratio histogram in Figure 4(d) represents the ratio of the LC and RC received power. Head echoes with an SLC SNR less than 20 dB are excluded from the histogram because the SRC-channel data must be above the noise floor to calculate the polarization ratio. The peak count, which occurs at approximately 19 dB, is consistent with the expected returns from a sphere-like object such as a meteor.

Figure 5 contains histograms for the 30° off-radiant Perseid observations; 281 meteor head echoes were detected in five minutes of data. The distribution of the altitude histogram in Figure 5(a) remains unchanged from the radiant data shown in Figure 4, as does the polarization ratio data in Figure 5(d). The radial velocity samples in Figure 5(b) are more spread, due to the relative radar detection angle. The variation in RCS in Figure 5(c) can be attributed either to the fundamental variations in head-echo shape and strength, or to the broadside view of the Perseid head echoes (sporadic meteors show a more random distribution independent of pointing). The exact shape of a typical head echo is unknown at this time; it is possible, however, that the head echo is spherical in front and spreads to a more teardrop shape in its wake.

As noted earlier in the Perseid data-analysis section, the monopulse angle data were used to compute the apparent position of the head echo. This computation represents the true three-dimensional position of the meteor in a radar-based reference frame. Most of the head-echo detections had to be discarded because of uncertainties (for example, in angle sidelobe and noise) in the monopulse data; many other data values were omitted because of low SNR and short durations. After this data-filtering process was complete, focus was placed on twenty head echoes to compute decelerations and densities.

Figure 6 contains the apparent meteor velocity as a function of time and the radius-density product as a function of altitude for a single head echo that remained in the 2.8° VHF beam for nearly one second. The apparent velocity plot shows at least two distinct

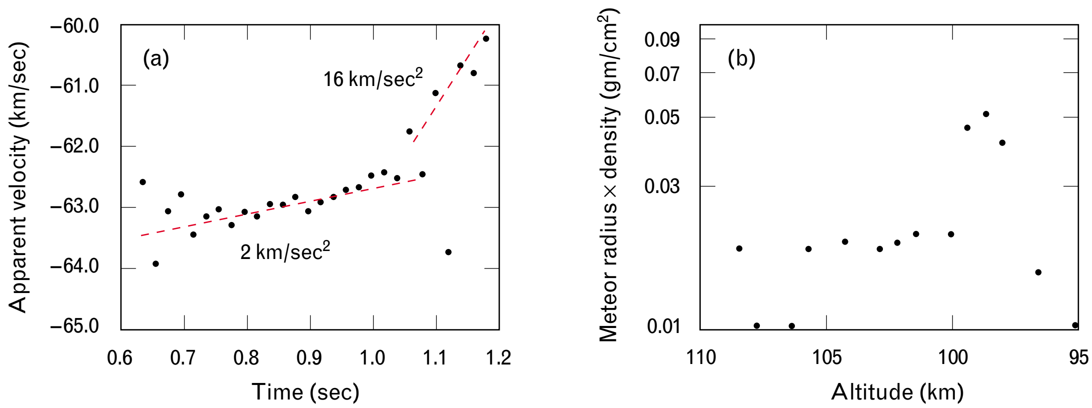


**FIGURE 6.** (a) The apparent velocity for a single head echo (corrected by monopulse angle data) in the ALTAIR VHF beam as a function of time. These data show two distinct decelerations of 2 km/sec$^2$ and 16 km/sec$^2$. (b) The associated radius-density product as a function of altitude remains relatively constant at 0.02 gm/cm$^2$ until just before the meteor burns up.

decelerations, namely, 2 km/sec$^2$ and 16 km/sec$^2$. The point-to-point fluctuations at the beginning of the data set are due to noise in the monopulse angle data and were excluded from the estimation. This curve is then utilized to calculate the radius-density product. Figure 6(b) shows that this product stays near a value of 0.02 gm/cm$^2$, except for a few outlier points. Table 1 summarizes the measurement parameters associated with this head echo.

Figure 7 contains the results from the same analysis applied to twenty head echoes. Figure 7(a) shows the apparent meteor velocity as a function of altitude (each meteor is represented in the figure by a distinct color). The average velocity is about 56 km/sec; this number represents an average value over the lifetime of each head echo, which is further averaged over all twenty meteors. These data were then used to calculate the radius-density product shown in Figure 7(b). Table 2 summarizes the averaged measurement parameters for these twenty head echoes. Note that the average duration of 0.3 sec is representative of the meteor head echoes detected by ALTAIR.

## Leonid Meteor Observations

Because of the successful collection of data during the Perseid shower, data were also collected during the Leonid meteor storm. Several adjustments were made to the data-collection techniques. First and foremost we decided to collect UHF data as well as VHF data. Some theoretical models of radar observations of meteors predict that the RCS of a head echo follows an $f^{-2}$ dependency [8]. Therefore, head-echo observations have been infrequently attempted at UHF because head echoes are difficult to detect at such high frequencies. Despite this theoretical difficulty, however, the combination of an unusually high number of head echoes, the high RCS of the target meteors, and the sensitivity of ALTAIR at UHF indicated that many head echoes would indeed be seen. Dual-frequency detections of head echoes are rare in the literature [9]; such detections would be extremely useful for validating theories of meteor RCS.

Discussions with staff members of the Institute for Meteor Studies at the University of Ottawa indicated

**Table 1. Measurement Parameters for a Single Head Echo**

| | |
|---|---|
| Duration | 0.95 sec |
| Maximum radar cross section | –40 dBsm |
| Mean apparent velocity | –62 km/sec |
| Deceleration | 2 and 16 km/sec$^2$ |
| Mean meteor radius × density | 0.02 gm/cm$^2$ |
| Mean radius * | 0.02 cm |
| Mean mass | $10^{-3}$ to $10^{-4}$ gm |

* We assume meteor density is 1 gm/cm$^3$

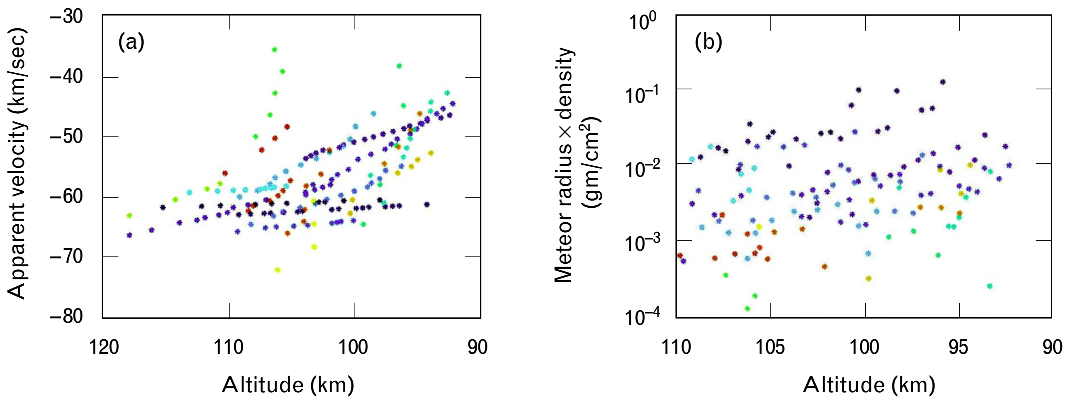


**FIGURE 7.** (a) The apparent velocity (corrected by monopulse angle data) for twenty head echoes. Each meteor is represented by a distinct color; the average velocity over the lifetime of each head echo is approximately 56 km/sec. (b) The associated radius-density product as a function of altitude for these twenty head echoes.

there was an interest in studying meteors during the final moments before they burned up in the ionosphere. To examine these meteors, researchers at ALTAIR selected shorter waveforms to increase the pulse-repetition frequency (PRF) to 333 Hz in order to have a higher detection rate during the meteors' final moments. Although higher PRF waveforms have less energy, ALTAIR had sufficient return sensitivity to satisfy data-collection requirements.

Leonid observations were taken on 18 November 1998 during a three-hour period designed to span the predicted peak of the Leonid storm [10]. ALTAIR recorded over 26 GB of data during this period. Both on-radiant and off-radiant data were collected when Leo was at 28° elevation and 77° elevation; Leo was at its highest elevation during the predicted peak. For this data-collection activity, ALTAIR collected simultaneously at VHF (160 MHz) and UHF (422 MHz,), and the PRF was increased to 333 Hz. The waveforms chosen for this experiment (V40H and U150) have a range sample spacing of 30 m at 160 MHz, and 7.5 m at 422 MHz. The sensitivity of ALTAIR with these waveforms allows it to reliably detect a –55-dBsm target at 160 MHz and a –75-dBsm target at 422 MHz, at a range of a hundred kilometers.

As part of KREMS, ALTAIR has several sister radars. The TRADEX radar operates at 1320 and 2951 MHz, and ALCOR operates at 5664 MHz. Both radars have narrower beams and somewhat less sensitivity than ALTAIR. TRADEX and ALCOR were also operational during the Leonid meteor storms, and simultaneous data were collected at L-band, S-Band, and C-Band frequencies, as well as at optical sites.

During the Perseid meteor shower, ALTAIR detected a total of twelve head echoes with an RCS of –20 dBsm or greater. Assuming an $f^{-2}$ falloff in RCS, those head echoes could have been detected by both TRADEX and ALCOR if they had passed through the TRADEX and ALCOR beams. The Leonid meteor storm was predicted to have ten times to a hundred times higher meteor activity compared to standard meteor showers such as the Perseids. A hundredfold increase in meteor flux would mean a hundred detectable meteors might pass through the ALTAIR VHF beam every minute, so the likelihood of at least one also passing through the ALCOR beam

**Table 2. Measurement Parameters Averaged over Twenty Head Echoes**

| | |
|---|---|
| Duration | 0.3 sec |
| Maximum radar cross section | –42 dBsm |
| Mean apparent velocity | –56 km/sec |
| Deceleration | 0.54 km/sec$^2$ |
| Mean meteor radius × density | 0.01 gm/cm$^2$ |
| Mean radius * | 0.02 cm |
| Mean mass | $10^{-3}$ to $10^{-4}$ gm |

* We assume meteor density is 1 gm/cm$^3$

or the TRADEX beam was believed to be significant. The chances of a detection at a higher frequency warranted the use of TRADEX and ALCOR.

## Leonid Data Analysis

To date, the Leonid data have not yet been reduced to obtain statistical information. From the real-time RTI display at ALTAIR, we noted numerous head echoes and trails collected at both VHF and UHF. Figure 8 is an example of an RTI display that was recorded near the end of the data-collection period, when ALTAIR was pointed at the Leonid radiant. An expanded view of the RTI display shows the meteor head echo associated with the trail. This trail is most likely not a typical specular reflection, but instead is a view as we look down the tube of the trail. Its duration was extremely long, nearly three minutes (most ionized trails last less than one second). The frequency dependence of the signal return from the ionospheric plasma is apparent.

Because of the large quantity of data, at this time we have completed an analysis of only one head echo, which was recorded during observations of the Leonid radiant. Although many head echoes and trails were visible at VHF and UHF, real-time observation of A-scopes (a display of amplitude versus range) and RTI displays at ALCOR and TRADEX revealed only one detection at a frequency higher than UHF. A single head echo was detected by TRADEX at L-band (1320 MHz). ALTAIR data were examined at the same data-collection time and range as the TRADEX L-band detection. As expected, a large head echo was recorded at both UHF and VHF. This detection is significant because we believe it is the only head echo detected simultaneously at three frequencies [11].

Figure 9 illustrates this three-frequency head-echo detection in the UHF, VHF, and L-band LC data. The slanted line that extends for less than 0.2 sec in each of the three RTI images in the figure represents the meteor head echo. The ionized trail is spread in both range and time, and, again, most likely represents a non-orthogonal view of the meteor trail. The spacing between the head echo and the trail is due to range-Doppler coupling (range-Doppler coupling offsets for a target range velocity of –59,000 m/sec are –108 m in VHF and –187 m in UHF). The Doppler measurement of the trail is due to atmospheric winds and is typically less than 100 Hz at VHF, while the Doppler measurement of the head echo is associated with the velocity of the meteor and is between 12 and 77 kHz. In Figure 9(d), a slice of the head echo is extracted from both the VHF and UHF data at both LC and RC polarization. As with the Perseid data, a polarization ratio of approximately 20 dB is apparent for both frequencies. (The VHF sensitivity is down approximately 6 dB because of operation at reduced transmitter power.)

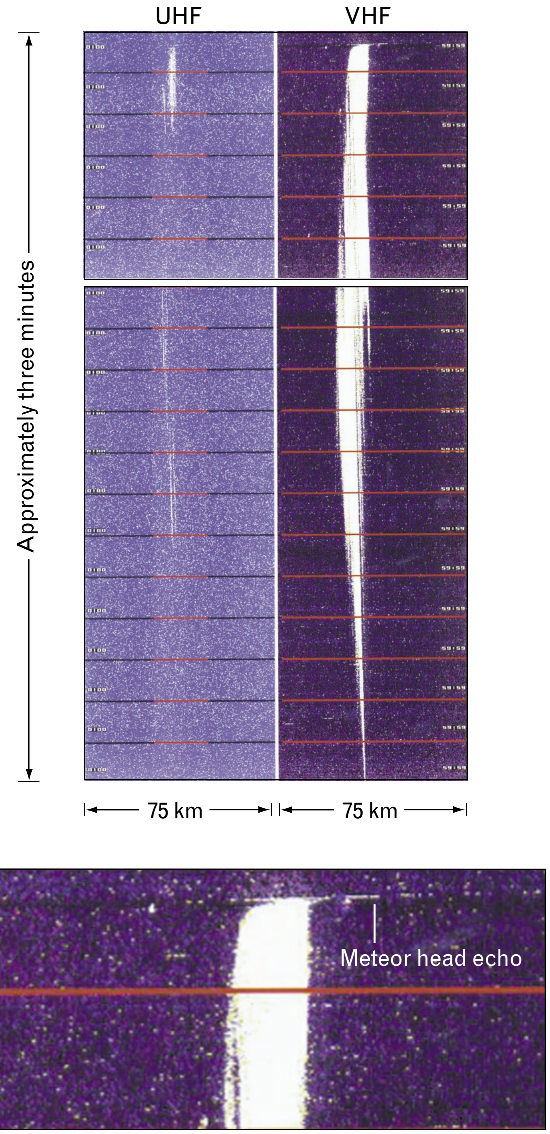


**FIGURE 8.** Snapshot of the RTI display at ALTAIR. The upper image shows a long-duration ionized trail visible in both UHF (left) and VHF (right). The expanded view of the VHF data in the lower image shows the meteor head echo.

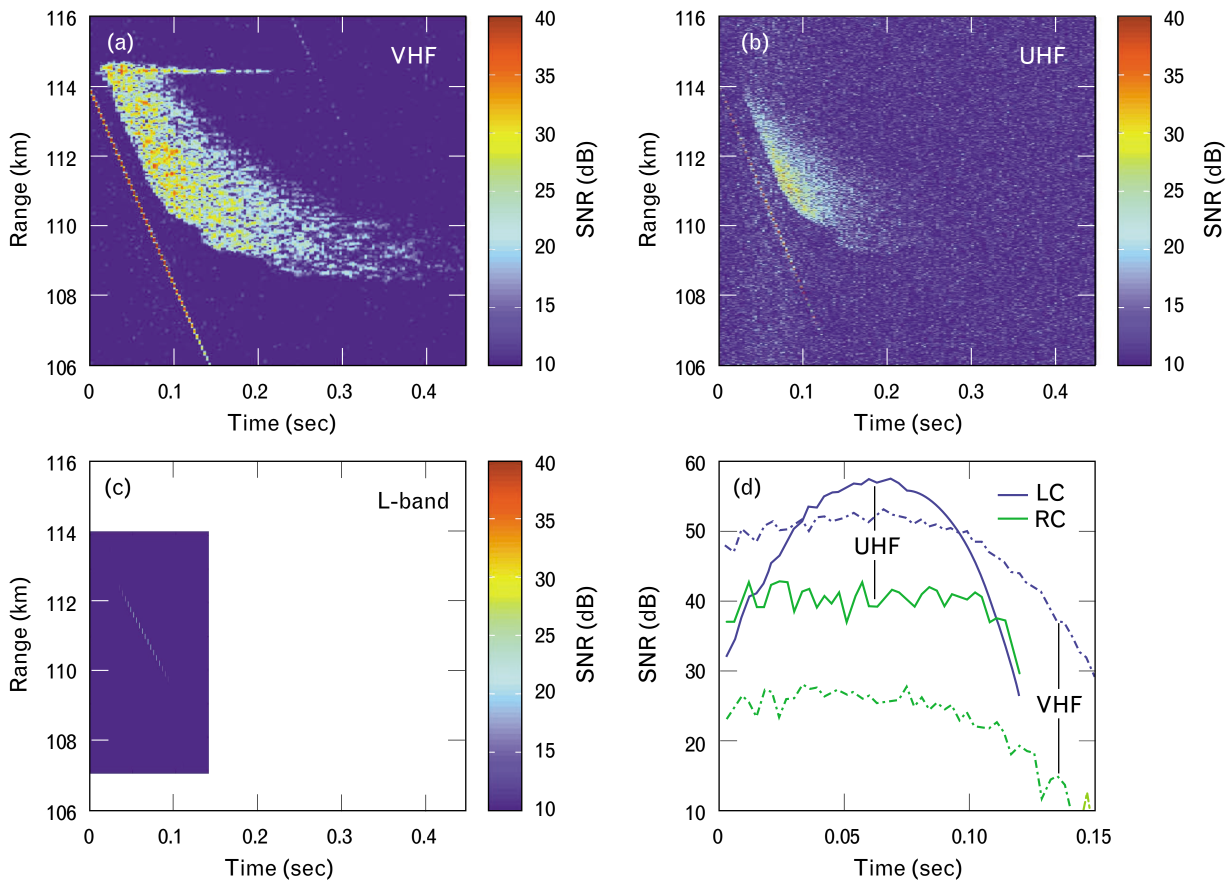


**FIGURE 9.** RTI images for left circular (LC) data at (a) VHF, (b) UHF, and (c) L-band. (d) The signal-to-noise ratio (SNR) of the head echo was extracted at UHF and VHF for both LC and right circular (RC) data and is plotted as a function of time.

From these RTI images, we can see that the SNR of both the head echo and the trail is reduced as the frequency increases. Table 3 contains the RCS values for both detections as a function of frequency. We also estimated the radius-density product for the VHF return of this head echo. Figure 10 shows the apparent velocity of the meteor as a function of time; Table 4 shows the corresponding meteor measurement parameters. Note that the duration of the head echo is only 0.15 seconds. This head echo has a much higher RCS and a much shorter duration than the Perseid head echo shown in Figure 6, with significantly less noise in the monopulse data (illustrated by the relatively smooth apparent velocity curve in Figure 10). The mean meteor radius-density product of 0.05 gm/cm$^2$ is also larger than the typical Perseid meteor.

**Table 3. Radar-Cross-Section Dependence on Frequency**

| *Frequency* | *Head Echo* | *Trail* |
|---|---|---|
| VHF | –5 dBsm | –18 dBsm |
| UHF | –23 dBsm | –51 dBsm |
| L-band | –36 dBsm | None detected |

## Summary

The Perseid meteor shower demonstrated the capabilities of ALTAIR for detecting head echoes. The high sensitivity of ALTAIR resulted in an extremely high number of head-echo detections, compared to those seen by other radars. The altitude histograms are consistent with data in the literature. The RCS

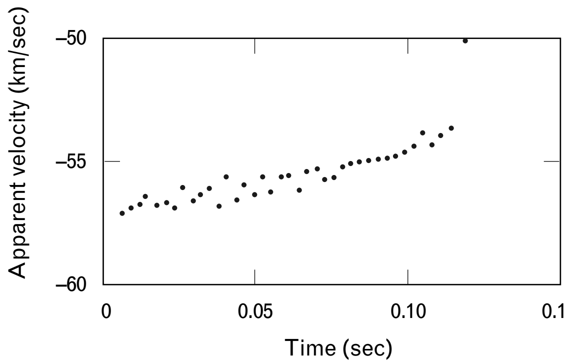


**FIGURE 10.** The apparent velocity corrected by monopulse angle data.

histogram shows a peak count at a much lower RCS than previously seen, most likely because of ALTAIR's high sensitivity. The radial velocity distribution shows a peak consistent with what is expected for Perseid meteors. Some of the spread in the velocity distribution is most likely due to the presence of sporadic meteors. The polarization ratios of meteor head echoes were reported for the first time. High polarization ratios (the peak of the distribution is near 20 dB) are consistent with returns from a sphere-like object, supporting the theory that head echoes are approximately spherical in shape. The monopulse angle data permitted the determination of the true three-dimensional position of the head echoes that resulted in decelerations, and estimates of the radius-density product of the meteor particle.

The Leonid data-collection activity, including other sensors at the Kwajalein Missile Range, has yet to be fully analyzed. By examining selected real-time observations, we detected numerous head echoes and trails at both VHF and UHF. One head echo, detected at VHF, UHF, and L-band, has been analyzed to determine RCS dependence on frequency, as well as its deceleration and radius-density product.

**Table 4. Measurement Parameters for Leonid Three-Frequency Head Echo**

| | |
|---|---|
| Duration | 0.15 sec |
| Mean apparent velocity | –56 km/sec |
| Deceleration | 10 km/sec$^2$ |
| Mean meteor radius × density | 0.05 gm/cm$^2$ |
| Mean radius * | 0.05 cm |
| Mean mass | $10^{-3}$ to $10^{-4}$ gm |

* We assume meteor density is 1 gm/cm$^3$

## Acknowledgments

The authors would like to acknowledge the following people for their contributions: William Ince and Kurt Schwan, the site managers at Kwajalein; Tom White, the ALTAIR sensor leader; Tim Kirchner, the technical evaluator for the Kwajalein Missile Range; Jeff Delong, the KREMS technical leader; Scott Coutts and Mark Corbin for valuable input in both data collection and analysis; Andy Frase and Wil Pierre-Mike for software and hardware support; and Peter Brown and Andrew Taylor for technical direction and input. The Leonid data collection effort, in particular, involved many Lincoln Laboratory and Raytheon Range Systems Engineering staff, including Bill Riley, Bob Foltz, Tim McLaughlin, Glen McClellan, Dave Gibson, LeRoy Sievers, and Dave Shattuck.

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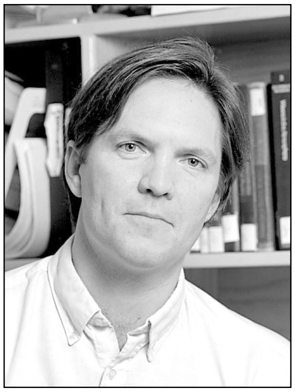

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