Bolide AIDA was in a near-earth asteroidal orbit with $V_\infty \sim 15.5$ km/sec, a period of $\sim 1.4$ yrs, aubritic composition, $\sim 30$ kg initial mass. The meteorite may still be discovered in the jungles of the Arecibo river valley south of Arecibo...

Although the event was not seen by the radar, its debris apparently drifted through the radar a few minutes later. Thus the modern era of meteor observation at Arecibo began with a -12$^m$ flourish!
A brief history of radar meteor observations!

FIRST we need radar....

- Breit, G., and Tuve, M.A. 1925, A radio method of estimating the height of the conducting layer, Nature 116, 357. (just missed Appleton’s Nobel by weeks....)

The first published head-echo and classical anomalous trail-echo radar meteor results.

- RTI-display/recording techniques catch-up with radar @ 5 m wavelength, 150 pps, 3 μsec pulses, 150 kW power.

Ionospheric E-region details of processed ISR results at 10 sec & 600 m resolution. Note that the background photochemical E-region is clearly revealed for the first time. The aircraft/ship/meteor returns (fine vertical lines mainly in the 80-120 km zone) are not totally removed because of receiver saturation. Results from meteors alone are shown next.
The diurnal radar meteor radial speed distribution (in atmosphere) derived from vertical-looking incoherent scatter measurements of the ionosphere. Note the strong modulation of speeds and flux from dawn with the radar looking near to the apex of Earth’s way to dusk with the radar looking at the antapex. The curves indicate the top-of-atmosphere parabolic limit for meteoroids entering the atmosphere at the indicated zenith angles.
The radar meteor head-echo altitude distribution for three observing periods. The great sensitivity of AO 430 MHz radar system—over 70 times that of the next most sensitive radar—allows detection of meteors over the 80-135 km altitude range; a much greater range extent than for any other radar. Due to radio science issues, “classical” VHF meteor radars (using trail reflections only) usually miss high speed/high altitude (>105 km) events.
What is the AO meteor event rate?

Whereas most meteor showers have rates measured in events per hour, at AO the rate is normally measured in events per minute. The event rate is highly variable but with the diurnal maximum near sunrise (apex-crossing) and diurnal minimum near sunset - antapex of Earth’s way.

What does this imply?
A (micro)meteor storm every sunrise!

This 4-hour all-sky (120°) exposure from Modra Observatory (Slovakia) shows 156 Leonid bolides from the 1998 maximum. The faintest events are about -2 magnitude. The peak AO micrometeor event rate is 30-60 per minute in each 1/6° (300 m @ 100 km) patch of sky. The central dot is 1° or about 1.75 km across and would display ~1100-2200 events/min while the 10° circle would display ~110,000-220,000 event/min. This “storm” occurs each sunrise but is only visible to the 430 MHz AO radar.
Signal Processing Advances Enable Pulse-by-Pulse Studies!

Early dual-pulse VHF/UHF observations of a radar meteor terminal event. UHF meteors are always observed as head-echoes associated with the “plasma” in the immediate region of the meteoroid. The low-power VHF radar sees the plasma “blob” following the terminal event. This event underscores radio science aspects of radar meteor observations and may well be important to the metal aeronomy of the meteor zone.

RTI plot showing a meteor event that begins at 102 km altitude with a range extent corresponding to the 45 μsec uncoded radar pulse—the IPP is 1 msec. The inset shows the “real” voltage for the same event—the pattern in the voltage is due to the ~158 kHz Doppler frequency offset corresponding to the ~55.3 km/sec speed. The pattern in the noise background is due to “elemental” incoherent scattering from the ionosphere.
New science enabled by instantaneous Doppler measurements! Deceleration ➞ Mass!!

The instantaneous/fitted radial Doppler speed for the event shown above. The RMS fitting errors are about 10 m/sec for this 55 km/sec event that displays a deceleration of 20.96 km/sec$^2$. Also shown is the relative “pulse” energy for each IPP (dashed curved line). Assuming that the particle is spherical with a “rocky” 3 gm/cc mass density, the classical meteor drag equation yields a 0.054 μgm particle with a radius of 16.26 μm. This indicates that most AO meteors deserve to be called micrometeors with corresponding visual magnitudes often fainter than 16th(!), a brightness range not presently available to any other radar. Because of the prodigious hourly numbers of events, recently devised statistical analysis techniques have enabled the recovery of mass density, beam inclination, and related quantities from most meteor runs of the AO radar.
AO micrometeoroid mass fluxes to the upper atmosphere extended to whole earth annualized mass fluxes with comparisons to the Ceplecha et al. (1998) estimates. Also shown are estimates based on LDEF cratering per Love & Brownlee (1993)—corrections to this estimate based on the AO velocity determinations is also shown. One of the BIG surprises to the community is that micrometeor in-atmosphere speeds average ~50 km/sec while LB assumed effectively 12 km/sec!
We see hyperbolic orbit particles deemed ESPs and ISPs.

- AO “Geminga” and Ulysses ISP (InterStellar Particles) cumulative mass distributions compared with that of the Ulysses/Galileo spacecraft particles observed at ~5 AU. The “turn-over” at small masses seen in both curves result from particles being excluded by solar processes including radiation pressure and electromagnetic interaction with the solar wind. The effect is more dramatic at 1 A.U. than at 5 A.U.

- ESPs (ExtraSolar Particles) are defined as hyperbolic particles (usually “large”) of likely solar system origin such as from hyperbolic comets or some Oort cloud or Kuiper belt object(s). ESPs are not included in the above plot and the one that follows.
So here’s the (nearby) Galaxy via AO ISPs.

Positional dependence of LSR referenced ISP velocity in system II Galactic coordinates as a contour map with the actual 108 ISP positions superposed. The mean AO ISP radiant is near the LSR parabolic convergence point where heliocentric zero velocity objects (parabolic relative to the sun) converge in the LSR. Particles which are observed to be only slightly hyperbolic relative to the sun and which are uncoupled from the galactic gas flow will cluster around this point.
Summary & Conclusions!

- New automated signal processing techniques now allow complete analysis of each radar pulse. This enables separation of ISR and meteor signal paths as well as separate meteor observation modes. We are building “signal classifiers” into the process with the hope of finding hyperspeed meteor events as well as new classes of signals (rare events?).

- UHF radar meteor observations—especially those at AO—have established that there exists a high speed (including ESPs and ISPs), small particle mass component in the zodiacal band that may contribute significantly to its total mass at 1 AU. Because the AO micrometeors are so small, they are sensitive probes of the solar wind at the edge of the solar system as well as near the sun and earth. Solar cycle effects seen so far need future confirmation to rule out simple secular fluctuations of the solar system micrometeor flux. The ISPs allow direct study of the local galactic environment.

- Aeronomic and radio science issues addressed by AO micrometeor observations include determination of the micrometeoroid mass flux to the upper atmosphere over particle sizes ranging from about 1-100 microns and studies of radar scattering from confined “plasmas”. The study of “terminal events”, apparently due to fragmentation, will enable us to produce more refined models of micrometeor ablation in the atmosphere in support of better heliocentric orbit determination.

- Head/trail-echo results need to thoroughly reconciled. This appears to be possible only with multi-frequency radar studies of the same meteor events coupled with a model of the radar scattering process. There is a discrepancy between trends of micrometeor mass and radar signal strength that needs resolution. Again this affects both mass influx and solar influenced orbit calculations.

- What instruments next at AO? A 430 MHz interferometer to determine where particles are in the beam thus enabling better speed/deceleration (mass/orbit) determinations and perhaps obtaining the meteor-zone atmospheric density profile as a fitted parameter. An enhanced 50 MHz radar to extend the mass flux measurements to the milligram region with significant other uses.