ASTRONOMICAL AND PHYSICAL DATA FOR METEOROIDS RECORDED BY THE ALTAIR RADAR

P.Brown[1], S. Hunt[2], and S. Close[2]

[1]Los Alamos National Laboratory, MS J577, Los Alamos, NM 87545 USA email:pbrown@lanl.gov
[2]MIT Lincoln Labs, 244 Wood Street, Lexington, MA 02420 USA email:hunt@ll.mit.edu

ABSTRACT

We present preliminary results of orbital and physical measurements of a small selection of meteoroids observed at UHF frequencies by the ALTAIR radar on Kwajalein island on November 17, 1998. The head echoes observed by ALTAIR allowed precise determination of velocities and decelerations from which orbits and masses of individual meteoroids derived from numerical modelling have been measured. During these observations, the ALTAIR radar detected average head echo rates of 1665 per hour. The effective system limiting magnitude is found to be between magnitude +10.5 and +11 corresponding to masses near 6×10^{-10} kg using an observed mean velocity of our analyzed sample of 56 kms^{-1}. This compares favorably to a mean modelled initial mass from the observed decelerations of the largest events of near 2×10^{-9} kg. All observations were made with the antenna beam pointing very near the center of the north apex sporadic source. The resulting orbits determined from modelling are largely consistent with the orbital characteristics of that source derived from other radar orbital surveys. Despite these observations occuring near the time of the expected Leonid maximum in 1998, no definite Leonids were detected in our analyzed sample.

1. INTRODUCTION AND EQUIPMENT

The observation of meteor head-echoes with large aperture radars offers several advantages over other radar meteor observations. Due to the nature of the scattering (cf. Jones and Webster, 1991), the radar return actually reflects off a small region of plasma in the vicinity of the meteoroid and hence can precisely follow the path of the ablating meteoroid. This affords very precise measurements of velocities and may also yield useful decelerations of the impinging meteoroid. This information may be used to compute a pre-atmospheric orbit for the meteoroid and also provide an estimate of the mass of the meteoroid. The meteoroid masses accessible by these large radars are typically intermediate between normal VHF backscatter meteor radars and spacecraft dust measurements.

One such large aperture radar is the Advanced Research Projects Agency Long-Range Tracking and Instrumentaion Radar (ALTAIR) located on the island of Roi-Namur in the Kwajalein Atoll which is part of the Republic of the Marshall Islands (9°N, 167°E). The principle function of ALTAIR is as a contributing sensor to the US Space Command satellite-tracking network. ALTAIR is a dual-frequency, high-power (6 Mw peak at both frequencies), narrow beam (half-power beamwidths are 2.8° at 160 MHz and 1.1° at 422 MHz) system using a 46-m diameter mechanically steered dish. ALTAIR transmits right circular polarized energy and records left circular with a range resolution of 15 m at VHF and 7.5 m at UHF. The 46-m diameter antenna employs a focal point VHF feed and multi-mode Cassengrain UHF feed in conjunction with a frequency selective sub-reflector (5.5 m diameter), giving a monopulse angle tracking capability at either frequency. This allows precise azimuth and elevation angle measurements which together with range contribute to the accurate determination of target position in three dimensions. The aforementioned characteristics allow ALTAIR to reliably detect a -62 dBsm target in VHF and a -81 dBsm target at UHF at a range of 100 km.

For these interferometric measurements, the ALTAIR receivers 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. The average angular measurement accuracy (standard deviation) of the ALTAIR system is 11.2 mdeg in azimuth and elevation at UHF as determined from control measurements of radar calibration spheres. More information on the ALTAIR system is given in Close et al. (2000).

Here we examine the basic astronomical and physical characteristics from a short sequence of data collected at UHF by ALTAIR on November 17, 1998. This data collection interval was originally designed to detect Leonid meteoroids.

2. DATA COLLECTION

Head echo data were collected from 15 - 21 UT on 17 November, 1998 to coincide with expected heightened activity from the Leonid meteor shower. The ALTAIR beam was pointed at the Leonid radiant as well as off-radiant (by about 20 degrees). Although data were gathered at a total of five frequencies (UHF and VHF from ALTAIR, plus TRADEX, which operates at 1320 and 2951 MHz and ALCOR, which operates at 5664 MHz) only UHF ALTAIR data are analyzed here. Table 1 contains the pointing directions in elevation and azimuth, in sun-centred coordinates, the total head echo rate plus main beam rate, estimated collecting area and equivalent limiting magnitude. Each data collection lasted a total of two minutes from the stated time. Note that some echoes have significant portions of their paths in sidelobes rather than the main beam and these are generally removed from our more detailed physical analysis.

Only echoes more than 10 dB above the noise-floor were examined. For each echo, the range, amplitude, polarization and position in the beam were measured every 3×10^{-3} s and these data saved for later analysis.

3. DETERMINATION OF LIMITING SENSITIVITY

The absolute limiting sensitivity for ALTAIR UHF observations is of considerable interest from the standpoint of physical modelling. Here we have taken two approaches to the problem. The first is to model the velocity vs. height curve for each meteoroid using the gross-fragmentation model of Ceplecha et al. (1993), to provide an approximate minimum mass for the larger events (which have the best SNR and show clear deceleration). The second approach relies on the high head echo rate for ALTAIR to compute flux from the observed rates and calculated collecting areas. Many of the head echoes detected by ALTAIR intersect the main radar beam at considerable angles; as a result the effective beam collecting area is not just the top of the beam cylinder, but includes much of the sides as well.

3.1. Using the observed radar rate to determine limiting mass

For the sporadic sources sampled by ALTAIR for this data collection (mainly the north apex source), most

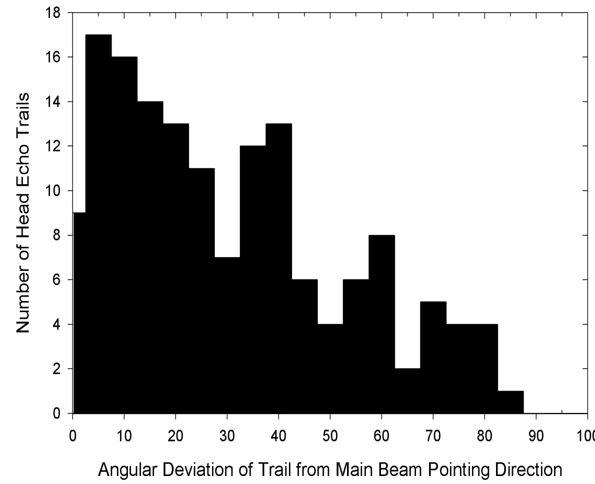

Figure 1. Angular deviation (in 5° bins) of individual trails from the beam pointing direction for all head echoes with measured trail orientations. From this figure it is apparent that few meteor head echoes travel directly down-the-beam; this is an expected result based solely on the very small solid-angle subtended by the beam at UHF.

radiants are within 30° of the pointing direction of the beam. The physical collecting area of the beam cylinder (top+sides) is approximately 130 km^2 for our observations, most of this area belonging to the sides of the beam. Figure 1 shows the distribution of trail orientations relative to the beam direction.

To verify that these measurements of trail orientation are physically reasonable (and hence that the monopulse measurements of the azimuth and altitude for the head-echoes in the beam are believeable) we also examine the variation in trail length with trail orientation. We expect a priori that those trails coming closest to down the main beam will have the longest trails. For trails intersecting the beam at larger angles we expect nearly constant trail lengths reflecting the beam width only. For our average range (near 110 km), the beam has an approximate linear width (to the 3 dB points) of 2 km. In general we expect those trails at large angles to the main beam to have lengths of $\leq$ 2 km. Figure 2 shows the measured distribution of trail lengths versus trail orientation. The basic distribution is as expected, verifying our monopulse angle measurements as essentially correct. The scatter at lower angles begins to reflect growing numbers of head echoes which actually end in the main beam and hence the population of smaller trail lengths.

As a first approximation we take the average radiant deviation as the mean angle between meteoroids impinging on the beam and the cylinder sides and derive an equivalent collecting area of 67 km^2. As ALTAIR sees effectively ($\geq$ 90% of all head echoes) only the highest velocity meteor component ($\geq$40 kms^{-1}) as head echoes, the sporadic population sampled for our pointing directions is almost exclusively that of

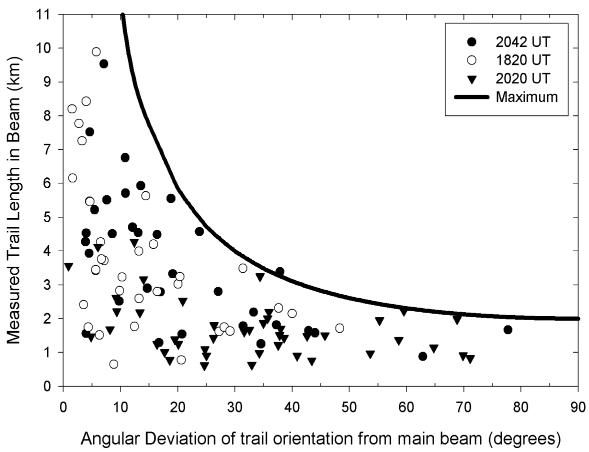

Figure 2. Measured trail length as a function of trail orientation relative to the main beam. The echoes recorded for all three measurement intervals are labelled. The solid curve shows the expected maximum trail length at a range of 110km to the 3 dB points of the beam as a function of trail orientation.

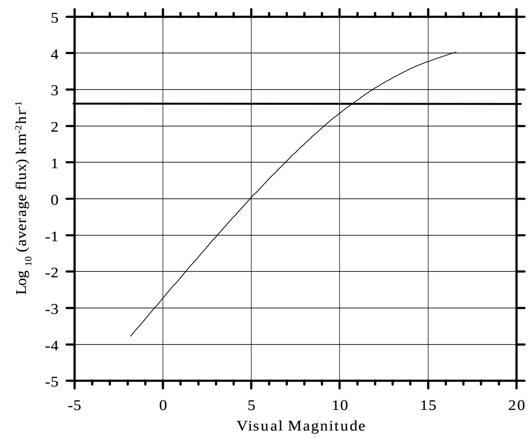

Figure 3. Comparison of the equivalent total flux from the interplanetary flux model of Grun et al. (1985) normalized to an encounter velocity of 60 kms^{-1} with the corrected flux (assumed to be that of the apex source only) measured by ALTAIR. The bold horizontal line shows the overlap near +11 as the equivalent sensitivity of the system.

the apex source. To a constant mass threshold, Taylor and McBride (1997) show the north apex source to represent 4% of the total integrated flux and covering the velocity interval from 40-70 kms^{-1}. Using a mean velocity of 60kms^{-1} for ALTAIR head echo observations and scaling the Grun et al (1985) total interplanetary flux to this velocity we derive the curve shown in Figure 3. Using the observed average ALTAIR head echo flux of 18 km^{-2} hour^{-1} and scaling to the interplanetary flux curve for the total meteoroid population we get an equivalent total flux of 443 km^{-2} hour^{-1}, which from the curve is appropriate to a limiting magnitude near +11. Given all the uncertainties, the total integrated flux from the north apex source to a constant limiting mass could be a factor of two different from this 4% value, implying an uncertainty in the determination of the limiting magnitude of one stellar magnitude.

3.2. Numerical modelling applied to the question of limiting mass

The second approach to estimating masses for the ALTAIR head echo population is to model the deceleration curves for individual meteoroids. For each meteoroid we need v_{inf}, the ablation coefficient (σ), initial mass and density (assuming a known shape factor), as well as the orientation of the trajectory to fully characterize the particle physically and compute an orbit. ALTAIR data only provides a small segment of the trail showing velocity as a function of height as well as providing the trail orientation. Hence we need to compute v_{inf}, m_{inf},density and the ablation coefficient. There are insufficient data from each head echo to compute all of these quantities uniquely. We therefore choose a very low ablation coefficient (0.0015 s$^2km^{-2}$) to provide a lower limit on the minimum mass and a maximum for the initial velocity for each echo. This is done using the gross fragmentation model of Ceplecha et al. (1993), which provides model output in the form of velocity as a function of height. As well, we assume a density appropriate to the observed apex population, which is almost certainly cometary, of 800 kgm^{-3}. We then iteratively match the observed velocity vs. height profile to provide an estimate of the minimum initial mass and upper limit for the velocity. We also determine the ballistic parameter (surface area/mass) defined as (Evans, 1965)

$$\eta = 2v\rho cos\theta\{\frac{dv}{dh}\}^{-1} \qquad (1)$$

where η is the ballistic parameter, v is the velocity as a function of time, ρ is the air density (determined from the MSIS-E model), θ is the elevation of the radiant and h is the height. In Eq (1) we have assumed the meteoroid to be spherical and hence η is equivalent to the product of the meteoroid radius and density. An example of an echo with a modelled fit is shown in Figure 4. For echoes showing largely linear decelerations, the modelled ballistic parameters range from $0.03\leq \eta \leq 0.3$ kgm^{-2}, with an average near 8.5×10^{-2}kgm^{-2}. The range of minimum masses measured for our small sample of 18 UHF echoes vary from 2×10^{-11} kg to 1×10^{-8} kg with an average value of 1.8×10^{-9} kg based on this modelling approach.

4. ORBITS

The orbits found for our small subset (18) of UHF head echoes are similar to the orbital distribution of north apex source sporadic meteoroids as given in

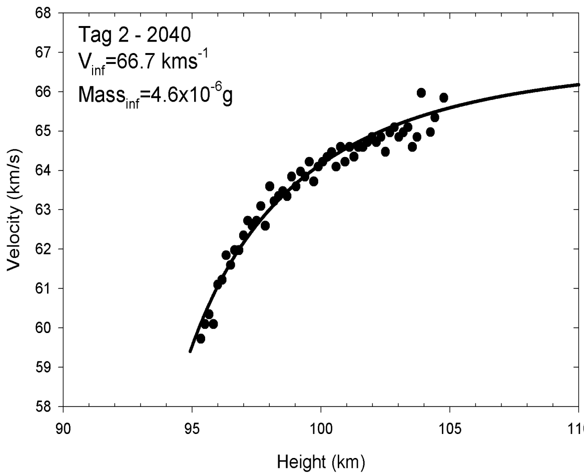

Figure 4. An example of the observed measurements of head-echo velocity as a function of height (black dots) and the numerical entry model fit following Ceplecha et al. (1993) (line).

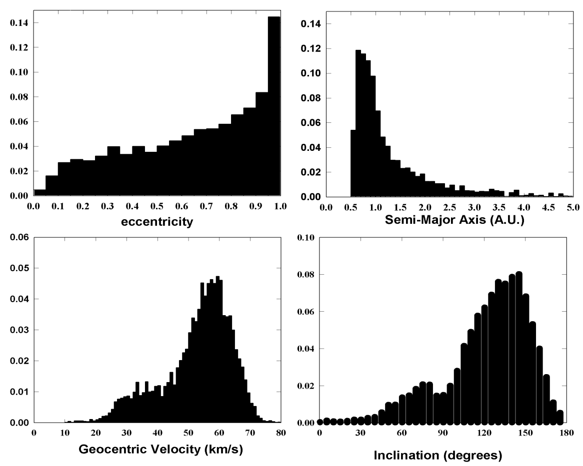

Figure 5. The normalized distribution of orbital elements for meteoroids from the north apex source taken from Jones and Brown (1993).

Jones and Brown (1993). Figure 5 shows the distribution of north apex meteoroids from orbital surveys taken from Jones and Brown (1993), while figure 6 is from our small ALTAIR orbital dataset. Table 2 shows all orbital data derived from our ALTAIR measurements.

The dominance of small number statistics in the ALTAIR data is apparent, but there exists gross similarities in semi-major axis and inclination between these data. The eccentricity is less comparable between these datasets and might reflect a true difference between the source character of the smaller ALTAIR population. One meteoroid orbit was interstellar and examination of the original monopulse data in detail does not show any unusual features (such as measurements which might indicate the echo occurred in a sidelobe). Based on the modelled initial velocity this meteoroid was 7.4 kms^{-1} beyond the interstellar velocity limit for its computed radiant. Indeed, the actual measured velocity is fully 2 kms^{-1} beyond the interstellar limit for the measured radiant. We

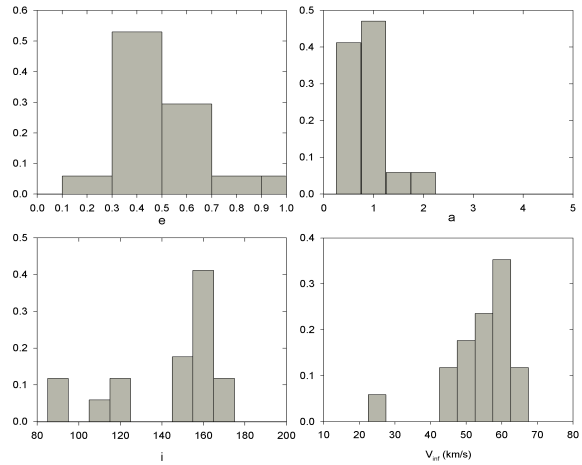

Figure 6. Normalized orbital element distirbutions for the population of ALTAIR observed meteoroids taken with the beam directed toward the north apex source. Compare to figure 5.

believe this to be a true interstellar meteoroid detection.

The original intent of the observation campaign, namely to record Leonid head echoes, has proven an elusive goal. In none of the orbits yet analyzed has any evidence of Leonid meteoroids been detected. This is perhaps in part due to the main beam being pointed within a few degrees of the nominal Leonid radiant. Such a geometry provides only a very small (of order a few km^2) effective collecting area through the top of the beam for detection of Leonids. Indeed, using the measured Leonid flux in 1998 as given by Brown and Arlt (1998) of 0.03 Leonids km^{-2}hour^{-1} and extrapolating directly using a mass-index value of 1.75 to our estimated limiting magnitude of +11, the equivalent Leonid flux at the time of our observations in 1998 corresponded to a Leonid rate coming down the main beam of 2 Leonids per hour.

Given that a total of only 17 minutes of UHF Leonid data have been analyzed to date, the lack of Leonids is not surprising. We also note that this computed Leonid rate is really an upper limit; in fact the effects of radiation pressure will completely remove Leonid meteoroids with a ratio of radiation pressure to gravitational force (β) greater than 0.05. This represents a spherical Leonid of approximate magnitude +13, but the roll-off in number will certainly begin several magnitudes higher than this value due to nonspherical shapes for some meteoroids. Sato et al. (2000) also undertook observations of the Leonids on the same date as our ALTAIR data collection using the MU-radar in Japan and from 235 determined orbits also found no evidence for a signature from the Leonids.

5. CONCLUSIONS

Observations using the ALTAIR radar over a 17-minute period on 18 November, 1998 have been analyzed for orbital determination and mass of observed head-echoes. From the observed rates and an estimate of the collecting area in the main beam, a limiting magnitude sensitivity at UHF frequencies for the ALTAIR system of +11±1 has been computed. The mean velocity of meteor head echoes recorded by ALTAIR was found to be 56 kms^{-1}. At this velocity, the flux-determined limiting sensitivity corresponds to $3.6\pm^{6.4}_{2.3} \times 10^{-10}$ kg. The distribution of head echo trail orientations with respect to the main beam was found to average 30°, with no head echoes coming closer than 2° to the main beam pointing direction.

Applying the model of Ceplecha et al. (1993) to the velocity and height data we were able to determine lower bounds for the initial mass and upper limits for the velocity of a subset of the observed head echoes outside the sidelobes of the radar and with the best signal-to-noise ratios. These largest 18 echoes were found to have minimum modelled masses of $1.8\pm2.8 \times 10^{-9}$ kg in reasonable agreement with the absolute detection limit mass found independently from flux considerations.

The orbital distribution for the ALTAIR observed population is consistent with that determined from other techniques for larger meteoroids. The population represents a sample of the north apex source and we have found no evidence for any Leonids in the sample analyzed.

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Time (UT)	θ, ϕ	Sun-centred	Total Rate	Main-beam rate	Collecting Area km^2	Limiting Magnitude
18:20	72, 43	10, 270	0.33	0.31	63	10.8
20:20	68, 357	9, 261	0.50	0.34	68	10.8
20:42	64, 302	9, 268	0.43	0.30	71	10.6

Table 1. Pointing directions for the ALTAIR radar on 17 November, 1998. The time of the start of each two minute data collection is given in the first column. The second and third columns given the pointing direction in local altitude (θ), azimuth (ϕ) and ecliptic sun-centred coordinates respectively (with the sun at zero degrees and the apex of the Earth's way at 270 degrees). The total measured head echo rate (per second) and the rate in the main beam only are also shown. Finally, the collecting area and equivalent limiting stellar meteor magnitude (see section 3.2) are given in the last two columns.

V_∞	ϕ	θ	a	e	i	ω	Ω	q	Q	α_G	δ_G	M_∞
62.0	300.6	62.4	1.18	0.223	163.9	233.1	235.317	0.9166	1.44	146.17	22.34	8.80E-10
63.6	306.5	66.7	2.03	0.518	160.3	194.2	235.317	0.9784	3.09	149.09	24.08	4.60E-09
62.0	283.6	66.5	1.73	0.446	179.4	204.5	235.302	0.9612	2.50	144.06	14.64	3.20E-09
49.8	278.1	59.1	1.04	0.507	167.6	115.1	55.318	0.5151	1.57	131.11	12.29	9.60E-10
73.3	317.5	63.1	1.37	0.363	156.5	122.9	235.317	0.8684	1.86	160.17	21.49	5.60E-09
63.1	314.5	61.8	1.23	0.213	151.6	207.6	236.326	0.9687	1.50	151.80	27.36	2.50E-10
77.5	303.0	63	1.32	0.423	165.0	102.4	235.316	0.7579	1.87	161.38	16.00	1.10E-08
55.2	285.4	61.6	1.14	0.387	180.0	93.3	55.607	0.6985	1.58	137.06	16.43	5.50E-10
63.5	310.9	25.4	0.52	0.905	33.0	358.7	235.317	0.0500	0.99	148.22	26.30	1.90E-11
32.3	3.8	58.6	-1.59	1.609	91.1	192.7	235.305	0.9738	-	175.31	67.46	6.30E-10
59.7	5.8	50.5	0.96	0.217	111.6	70.1	235.305	0.7523	1.17	171.54	39.95	2.70E-10
68.8	355.7	51.4	0.79	0.366	129.0	31.5	235.304	0.4976	1.07	165.61	30.80	2.70E-10
82.5	68.9	53.3	0.89	0.763	153.6	35.1	235.304	0.2106	1.57	174.78	12.08	3.40E-10
69.5	123.4	47.3	1.04	0.101	98.1	113.8	235.307	0.9343	1.14	173.14	48.76	2.00E-10
71.6	6.3	47.9	0.70	0.565	125.0	24.2	235.304	0.3057	1.10	169.65	27.93	1.30E-10
75.2	25.2	58.5	0.89	0.247	162.8	307.9	235.220	0.6727	1.11	144.37	22.84	2.90E-09
70.4	56.1	56.4	0.79	0.288	160.5	22.5	235.220	0.5636	1.02	155.08	19.92	1.70E-10
75.2	16.9	60.2	1.01	0.284	162.8	281.6	235.220	0.7261	1.30	142.34	23.65	1.20E-10

Table 2. Head echo trail orientation, orbital elements and modelled initial mass. ϕ and θ are the radiant local azimuth and altitude respectively; V_∞ is the computed initial velocity in kms^{-1}; a is the orbital semi-major axis in A.U.; e is the eccentricity; inc is the inclination; ω is the argument of perihelion; Ω is the longitude of the ascending node; q is the perihelion distance in A.U. ; Q is the aphelion distance in A.U.; α_G and δ_G is the geocentric location of the radiant and M_∞ is the modelled initial mass in kilograms.