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Radio and Meteor Science Outcomes From Comparisons of Meteor Radar Observations at AMISR Poker Flat, Sondrestrom, and Arecibo

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Abstract Radio science and meteor physics issues regarding meteor "head-echo" observations with high power, large aperture (HPLA) radars, include the frequency and latitude dependency of the observed meteor altitude, speed, and deceleration distributions. We address these issues via the first ever use and analysis of meteor observations from the Poker Flat AMISR (PFISR: 449.3 MHz), Sondrestrom (SRF: 1,290 MHz), and Arecibo (AO: 430 MHz) radars. The PFISR and SRF radars are located near the Arctic Circle while AO is in the tropics. The meteors observed at each radar were detected and analyzed using the same automated FFT periodic micrometeor searching algorithm. Meteor parameters (event altitude, velocity, and deceleration distributions) from all three facilities are compared revealing a clearly defined altitude "ceiling effect" in the 1,290 MHz results relative to the 430/449.3 MHz results. This effect is even more striking in that the Arecibo and PFISR distributions are similar even though the two radars are over 2,000 times different in sensitivity and at very different latitudes, thus providing the first statistical evidence that HPLA meteor radar observations are dominated by the incident wavelength, regardless of the other radar parameters. We also offer insights into the meteoroid fragmentation and "terminal" process.

Keywords Radar meteors · Headechoes · Meteor fragmentation · Radio science

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1 Introduction

Observations of sporadic radar meteors have been of increasing interest to the scientific community as the role of meteoroids in planetary astronomy, space weather, in the aeronomy of the meteor zone, and in various aspects of the plasma physics and radio science surrounding the meteoroid interaction with the atmosphere have become increasingly apparent (Janches et al. 2001; Mathews 2004; Mathews et al. 1997). Here we consider "head-echo" observations in which radar returns are from the distribution of plasma immediately surrounding the meteoroid and traveling with the meteoroid itself. The high power, large aperture (HPLA) radars at the 32 panel Advanced Modular Incoherent Scatter Radar at Poker Flat Alaska (PFISR-32), the Sondrestrom Research Facility (SRF) in Greenland, and at Arecibo Observatory (AO) all observe meteor head-echo scattering. We report on observations using these radars. Radar parameters are given in Table 1.

While several theories for the exact mechanism of the head-echo scattering have been proposed, all find that head-echo scattering is highly frequency dependent (Close et al. 2002; Mathews 2004). As such the ideal method for study of the scattering mechanism would employ a common-volume radar using multiple frequencies that could study individual meteor events. The only current radar with these capabilities (AO had this capability as described by Zhou et al. 1998) is ALTAIR (Kwajalein Atoll, Marshall Islands), which is largely inaccessible due to military applications although Close et al. (2002) and other papers including S. Close as an author, employ ALTAIR meteor observations in their results. In order to achieve similar ends, we employ observations at multiple locations but at nearly coincident time and examine the results statistically to provide insight into the meteor head-echo scattering mechanism.

In order to best compare meteor observations from different radars we employ observations from nearly the same calendar dates and local times and we apply the same automated FFT (Fast Fourier Transform) searching technique used at AO (Briczinski et al. 2006; Mathews et al. 2003) to nearly common observing strategies. The automated search routine provides minimal false positives (<1%) while still identifying events with

Table 1 Comparison of the operating parameters of the three radars used in this study

	PF AMISR-32	SRF	AO
Location	65.12° N, 147.47° W	66.99° N, 50.95° W	18.47° N, 66.73° W
Beam width	~2°	~1/2°	~1/6°
Transmit frequency (MHz)	449.3	1,290.0	430.0
Effective aperture (m^2)	180	800	73,000
System temperature (K)	135	110	80
Pulse length (μs)	50	82	45
Sampling rate (MHz)	1	1.25/2	1
Operating power (MW)	~0.5	~2.6	~1.6
Quality factor (MW-m^2/K)	0.667	18.9	1,460
Initial range (km)	84.0	75.5	75.0
Final range (km)	140.0	170.0	142.5
IPP (ms)	1	3.3	1
Observing time (h)	8	8	2
Meteors detected	443	271	2,486

signal-to-noise ratios (SNR) below unity thus maximizing the number of events positively identified.

The AO, SRF, and PFISR radars were chosen for our study for several reasons. (1) The PFISR and SRF radars can be configured with observation parameters similar to that at AO. (2) PFISR (449.3 MHz) and SRF (1,290 MHz) are widely different in frequency but have very similar latitudes (just below the Artic Circle), thus maximizing the frequency range of our results while minimizing possible spatial (latitude) dependency in meteor rates and sources. (3) AO (430 MHz) and PFISR (449.3 MHz) are very similar in frequency but vastly different in sensitivity thus likely involving different populations (mass and energy) of meteoroids. In this paper we compare the observed characteristics of radar meteors seen at the three radars. The results presented from (32 panel) PFISR and SRF are the first reports of altitude and Doppler measurements from campaigns at these facilities and are thus unique. For AMISR Poker Flat this is also the first meteor campaign at the facility. We also uniquely apply the same automated searching algorithm to all data sets to eliminate analysis disparities. In this paper we statistically compare the observed characteristics of radar meteors observed at the three radars to provide insight into the head-echo scattering mechanism and meteoroid properties.

2 Observations

Observed radar meteor parameters such as rates and speeds are seasonally varying (Janches and Chau 2005). Consequently, we conducted the meteor observations reported here within the same few weeks during the calendar year to minimize this source of variation. The zenith-pointed SRF 1,290 MHz radar system was used to observe meteors during the mornings of 31 July and 04 August 2005. Each observation window lasted approximately 4 h, 04.00–08.00 local time (LT). The PFISR-32 meteor observations occurred on 01 and 02 August 2006, and each observing window was 04.00–08.00 LT. In both instances this time period was chosen to be centered around local dawn at lower (non-polar) latitudes when the sporadic meteor event rate is a maximum (Mathews et al. 2001). The PFISR-32 beam was pointed 9° off of zenith at due north.

The AO micrometeors observations used here are for a 20 August 2004 2 h period (05.00–07.00 LT), again centered on local dawn, using the zenith-pointed Arecibo 430 MHz radar system The properties of the three radars are summarized in Table 1 with particular emphasis on sensitivity.

At all of the facilities the received “head-echo” signals were Doppler shifted due to the 10–70 km/s meteoroid radial speed. The vector meteoroid encounter speed cannot be deduced as interferometric capabilities are currently unavailable at these three radars. Doppler speeds were obtained by fitting a complex exponential to the returned voltages, resulting in instantaneous (single-pulse) measurement errors on the order of 100 m/s (Briczinski et al. 2006).

Figure 1 gives the Range-Time-Intensity (RTI) and SNR (analogous to the optical “light curve”) of events typical of the PFISR (left panel) and SRF (right panel) radars. AO meteor events are very similar in appearance to those at PFISR but sometimes different in character, as we will discuss. The Fig. 1 PFISR result shows a abrupt fragmentation event near 65 ms. Fragmentation and terminal—the meteor signal disappears in 1 ms—events are common in both PFISR and AO results. Fragmentation events consistent with two or three major fragments remaining—with each producing headechoes that produce distinctive interference patterns—are often observed at PFISR. The Fig. 1 SRF event represents

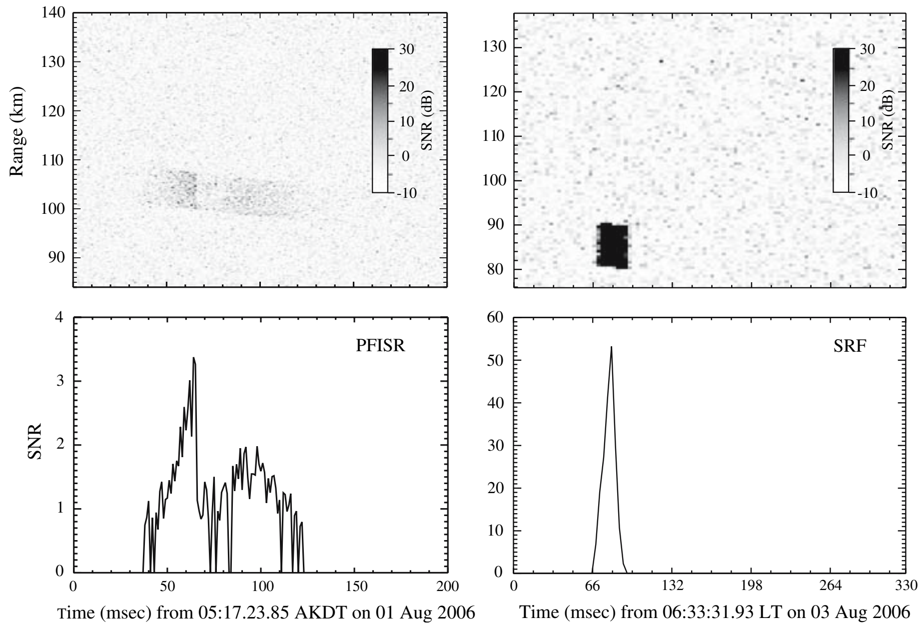

Fig. 1 RTI (Range-Time-Intensity; top) and SNR (Signal-to-Noise Ratio; bottom) versus time (analogous to light curves) plots showing meteor events typical to PFISR (left) and SRF (right). The PFISR meteor is also typical of AO meteors and shows a fragmentation event at ~65 ms. The abrupt decrease in signal strength at fragmentation is presumed to be due a now smaller meteoroid that generates less scattering plasma (Mathews 2004). The fragment is assumed to have terminally "flared" (see Fig. 6, Mathews 2004) as is often observed with much larger optical meteors. The strong SRF event occurs over ten radar pulses (IPPs) and is characteristic of nearly all SRF events

the vast majority of events observed with the 1,290 MHz radar. The SRF SNR (light) curve shows little if any structure and appears/disappears in one IPP—we give interpretation of this result in the conclusions. It is important to note that the fragmentation/terminal features are in no way associated with the respective antenna patterns. These features occur on time scales of order 1 ms or less during which even a 100 km/s meteoroid traveling horizontally would only traverse 100 m—a scale on which even the narrow Arecibo beam pattern does not change dramatically.

Figure 2 gives the altitude distributions of the meteor events observed at the three radars. Note that the AO (430 MHz)/PFISR (449.3 MHz) altitude distributions are quite similar with the AO distribution sharply centered at 105 km and the broader PFISR distribution centered at 100 km. The SRF distribution is centered 5–10 km below the other distributions at ~95 km and is asymmetric with a sharp onset at 100 km and a gradual decrease to 80 km. Also note that with common automated analysis software, the SRF detected just 60% of the number of meteor events seen with the much less sensitive PFISR system in the total of 8 h of observations. The much more sensitive AO system recorded ~4 times more events in 2 h as the combined PFISR/SRF systems.

The Fig. 3 speed distributions show that PFISR and SRF, at the same latitudes and local time, largely agree but with the SRF distribution peaking ~5 km/s faster. It is unclear if this small difference is significant to the processes discussed later. The AO distribution is fastest as it is closest to the apex of Earth's way (Janches and Chau 2005). We interpret

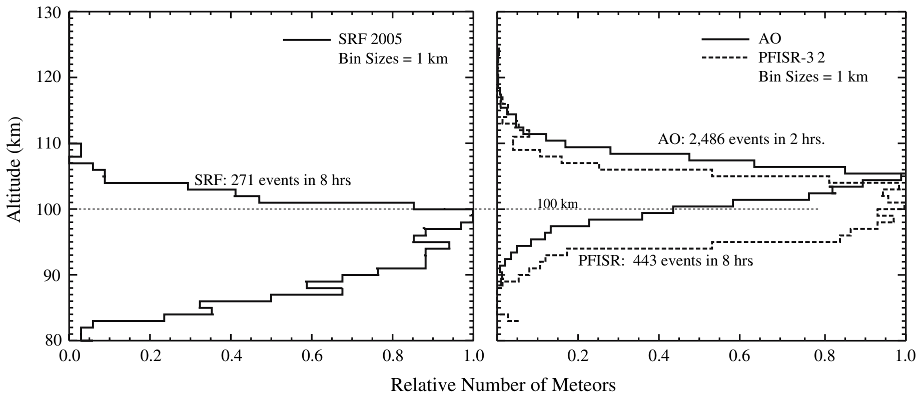

Fig. 2 The altitude distributions for the PFISR, SRF, and AO meteor events. Note the relative event numbers and that while the AO and PFISR results peak at nearly the same altitude, the SRF distribution peaks 5–10 km lower exhibiting the oft-noted upper-UHF "ceiling effect." Note that the PFISR distribution is ~3–5 km below the sharper AO distribution

these results as evidence that most of the high latitude events have a large across-the-beam component. Future interferometric capabilities at PFISR will allow this effect to be studied.

Figure 4 compares the decelerations and speed versus altitude and each other for the three radars. Note from all panels that high deceleration events are in the majority at SRF and are common at PFISR but are relatively rare at AO. The usual momentum equation (Mathews et al. 1997, 2001, 2003; Mathews 2004) interpretation of high meteor deceleration, especially deep in the atmosphere, is that the single-body meteoroids producing the observed ionization are very small. However from Table 1 it is clear that AO is ~2,100 times more sensitive than PFISR and ~77 times more sensitive than SRF while SRF is ~28 times more sensitive than PFISR. Additionally, as relative sensitivity decreases, the antenna beam width increases (except for transmitter power differences) so that the probability of seeing the lower-flux larger meteoroids increases. Note that the AO speed versus altitude distribution shows a clear tendency for higher speed events to be observed at higher altitudes. The PFISR results hint at the same outcome while the SRF results appear to be "flat" in this regard. We agree that the statistics are marginal for both SRF and PFISR—coordinated 24 h observations at both radars are planned.

3 Conclusions

AO (430 MHz) is ~2,100 times more sensitive than PFISR (449.3 MHz) and ~77 times more sensitive than SRF (1,290 MHz). Yet the event rate is lowest at SRF (~34 per hour) relative to PFISR (~55 per hour) and AO (~1,000 per hour) and the height distribution is also ~10 km below that observed with AO/PFISR. Both SRF and PFISR show a high proportion of high deceleration events relative to AO. We conclude that SRF sees a different class of events from AO with PFISR seeing both event classes.

The Fig. 1 "light curves" and Fig. 2 height distributions with different "ceilings" for SRF relative to AO/PFISR both point to different processes producing the large radar scattering cross-sections (RCS) necessary to observe these meteor events with the less sensitive SRF and PFISR radars. The observed high decelerations, especially at SRF, provide the final clue. These high decelerations would—under standard interpretation—

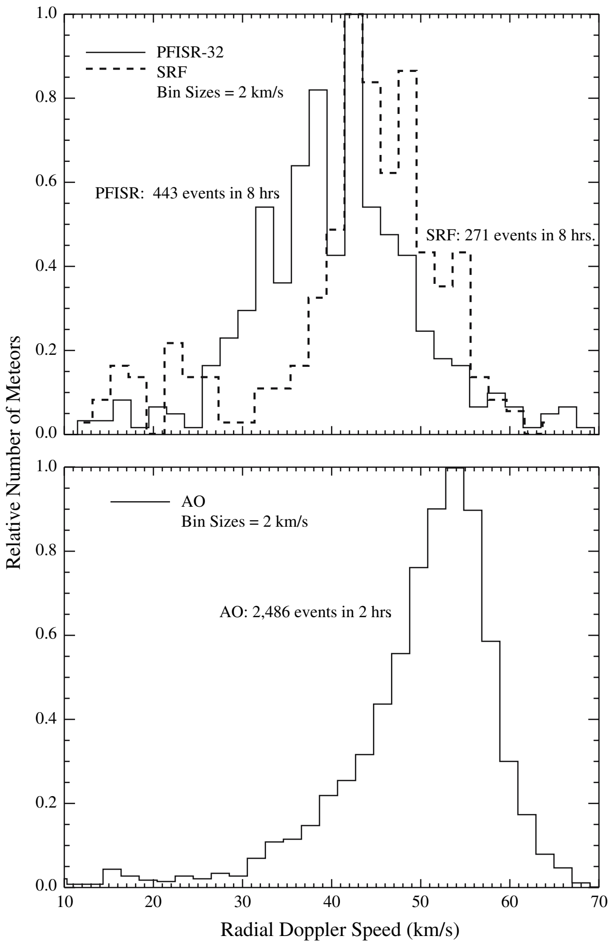

Fig. 3 The meteor radial speed distributions for the three radars

point to very small meteoroids. However, we surmise that the events seen at SRF and to somewhat lesser extent at PFISR are likely representative of a meteoroid fragmentation and/or terminal process yielding a highly confined distribution of small particles that decelerate rapidly while producing the RCS (from a compact, high-concentration plasma) necessary to appear as radar meteors in the—relative to AO—low sensitivity SRF and PFISR radars. This scenario also offers the explanation for the "height ceiling" effect noted in upper UHF radars (Westman et al. 2004; Pellinen-Wannberg 2004). That is, that relatively large meteoroids are invisible at higher altitudes because of the size relative to wavelength of the plasma scattering volume (Mathews 2004) but, upon fragmentation at lower altitudes, produces the observed radar meteor properties—in particular, high deceleration—with large, observable, RCS. Westman et al. (2004) report the existence of a UHF radar "ceiling" relative to the VHF radar. However, their results are difficult to interpret due to relatively small number of events at 224 MHz (VHF) relative to 931 MHz (UHF). Possible seasonal differences in the fluxes also cloud their results. Hunt et al. (2001) also demonstrate a weak ceiling effect when meteor results from the ALTAIR 160 and 422 MHz radars are compared. In both cases the deceleration distribution was not reported. Also note from Fig. 4 that the speed versus altitude correlation seen in the AO

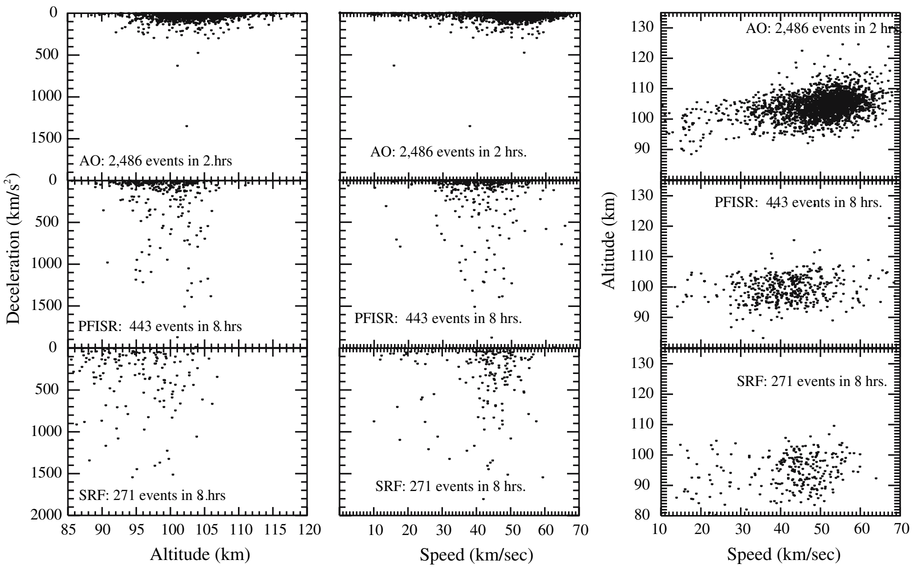

Fig. 4 Meteor deceleration and speed plotted versus altitude and each other for the three radars. Note that the SRF (1,290 MHz) results exhibit a high proportion of high deceleration events relative to AO and that the PFISR deceleration results lie between AO and SRF. If high decelerations were taken to represent, via the meteoroid momentum equation, a very small meteoroid, we would conclude that the SRF and PFISR radars proportionally "see" more smaller meteoroids than the much more sensitive AO radar

results and, perhaps, weakly in the PFISR results is not apparent in the SRF results. Future coordinated SRF/PFISR observational campaigns will address this issue.

It is the Fig. 4 deceleration results that provide the critical clue that forms the final basis for our conclusions. That is, we cannot argue that high deceleration events point to small single meteoroids, as this would imply that the less sensitive SRF and PFISR radars see smaller meteoroids than the very sensitive AO radar. Thus we conclude that fragmentation of the larger meteoroids that we expect to observe in the, relative to AO, wide-beam SRF/PFISR radars produces a radar scattering cross-section from a compact volume of plasma that is sufficient to be seen by these, relative to AO, low sensitivity radars. Recent meteor head- and trail-echo observations from Jicamarca offer further insights into meteoroid fragmentation processes (Malhotra et al. 2007). Further joint observations among the carefully cross-calibrated SRF, PFISR, AO, and—hopefully—the EISCAT radars should shed further "light" on these processes.

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