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Interferometric Meteor Head Echo Observations using the Southern Argentina Agile Meteor Radar (SAAMER)

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Abstract.

A radar meteor echo is the radar scattering signature from the free-electrons in a plasma trail generated by entry of extraterrestrial particles into the atmosphere. Three categories of scattering mechanisms exist: specular, non-specular trails, and head-echoes. Generally, there are two types of radars utilized to detect meteors. Traditional VHF meteor radars (often called all-sky radars) primarily detect the specular reflection of meteor trails traveling perpendicular to the line of sight of the scattering trail, while High Power and

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Large Aperture (HPLA) radars efficiently detect meteor head-echoes and, in some cases, non-specular trails. The fact that head-echo measurements can be performed only with HPLA radars limits these studies in several ways. HPLA radars are very sensitive instruments constraining the studies to the lower masses, and these observations cannot be performed continuously because they take place at national observatories with limited allocated observing time. These drawbacks can be addressed by developing head echo observing techniques with modified all-sky meteor radars. In addition, the fact that the simultaneous detection of all different scattering mechanisms can be made with the same instrument, rather than requiring assorted different classes of radars, can help clarify observed differences between the different methodologies. In this study, we demonstrate that such concurrent observations are now possible, enabled by the enhanced design of the Southern Argentina Agile Meteor Radar (SAAMER) deployed at the Estacion Astronomica Rio Grande (EARG) in Tierra del Fuego, Argentina. The results presented here are derived from observations performed over a period of 12 days in August 2011, and include meteoroid dynamical parameter distributions, radiants and estimated masses. Overall the SAAMER's head echo detections appear to be produced by larger particles than those which have been studied thus far using this technique.

1. Introduction

The collision of asteroids and disintegration of comets are the main source of dust in the Solar System. These processes give rise to a thick circumsolar disk of small debris known as the Zodiacal Dust Cloud (ZDC). Several physical effects produced by larger Solar System bodies result in the dust having relatively short lifetimes, maintaining a partial balance in their distribution and preventing this cloud from becoming dustier. For example, dust particles can be ejected from the Solar System by Jupiter, thermally obliterated by the Sun, or physically fragmented by additional collisions amongst themselves. Also, a portion of the cloud is swept up by the planets, and for the case of those with atmospheres will produce the familiar phenomena of ionization and light production termed meteor. We now know that similar processes occur in other systems as circumstellar disks of dust have been observed, for example, around Beta Pitcoris [*Okamoto et al.*, 2004] and Formalhaut [*Currie et al.*, 2012]. Thus, studying the ZDC enables the understanding of its nature, shedding light into the history and development of the Solar System as well as extra solar planetary environments [*Malhotra*, 1995; *Johansen et al.*, 2007; *Walsh et al.*, 2011; *Nesvorný et al.*, 2010; *Wiegert et al.*, 2009].

The ZDC is the source of meteoroids originating from the so-called Sporadic Meteor Complex (SMC) formed by six apparent sources: Helion, Anti Helion, North and South Apex and North and South Toroidal [*Jones and Brown*, 1993, and reference therein]. The study of the ZDC, SMC and their relation is fundamental for a number of areas of research within the Solar System and Planetary Sciences realms and many basic questions regarding their nature still remain an unsolved puzzle [*Nesvorný et al.*, 2011b]. Issues of importance include the relative contribution of comets and asteroids to the overall dust budget, clarification of the dynamical processes that make particles of different sizes produce the observed light scattering and thermal emissions, and the causes of the differences in relative strength of the sources [*Galligan and Baggaley*, 2005; *Campbell-Brown*, 2008a, b; *Brown and Jones*, 1995; *Galligan and Baggaley*, 2005; *Nesvorný et al.*, 2010; *Wiegert et al.*, 2009]. In addition, the fact that knowledge of the ZDC can be utilized to estimate the amount of dust accreted by planets and satellites [*Nesvorný et al.*, 2010, 2011a] makes it a compelling tool for the additional study of the composition and chemistry of planetary atmospheres. The daily ablation of billions of interplanetary dust particles (IDPs) produces layers of neutral and ionized metal atoms in planetary atmospheres [e.g. $\sim$ 90 km of altitude on Earth and Mars, $\sim$120 km on Venus; and $\sim$550 km on Titan; *Plane*, 2003; *Pätzold et al.*, 2005, 2009; *Withers et al.*, 2008; *Kliore et al.*, 2008]. Once the meteoric metals are injected into the atmosphere they are responsible for a diverse range of phenomena, including: the formation of layers of metal atoms and ions, nucleation of noctilucent clouds, impacts on stratospheric aerosols and O_3 chemistry, and fertilization of the ocean with bio-available Fe, which has potential climate feedbacks [*Plane*, 2003].

Ground-based meteor observations with radars detect thousand of sporadic, as well as shower, events every day, providing data sets with excellent statistics and a variety of dynamical and physical information regarding the particles that produced the observed meteors. This makes radar meteor science an optimal tool to study the ZDC. The radar scattering signature produced by the interaction between the transmitted pulse and the ionized region generated by entry of extraterrestrial particles into the atmosphere gives rise to the radar meteor echo. Three categories of scattering mechanisms exist: specular trails, non-specular trails, and head-echoes. Generally, there are two types of radars utilized to detect meteors. Traditional VHF meteor radars (often called all-sky radars) primarily detect the specular reflection of meteor trails traveling perpendicular to the line of sight of the scattering trail while High Power and Large Aperture (HPLA) radars efficiently detect meteor head-echoes and, in some cases, non-specular trails. Trails are generally semi-stationary echoes that originate from the ionization left behind by the meteoroid [*Baggaley*, 2002]. The specular or non-specular nature of the trails depends on the viewing geometry and their position with respect to the magnetic field lines [*Dyrud et al.*, 2002]. While specular trails produce echoes that are confined to one altitude, non-specular reflections occur from Field Align Instabilities (FAIs) that are spread in many range gates. Head-echoes, on the other hand, are reflections from the plasma immediately surrounding the meteoroid itself traveling at, or near, its speed [*Janches et al.*, 2000a, 2003].

The first head echo detection was reported by *Hey et al.* [1947] who made observations with a 150 kW VHF radar system during the Giacobinid meteor storm of 1946, while *Evans* [1965] used the Millstone Hill incoherent scatter radar system to conduct the first head echo measurements using HPLA radars. However, routine operational worldwide head echo observations utilizing HPLA radar only began in earnst almost 3 decades later [*Pellinen-Wannberg and Wannberg*, 1994; *Mathews et al.*, 1997; *Close et al.*, 2000; *Sato et al.*, 2000; *Chau and Woodman*, 2004; *Janches et al.*, 2006; *Sparks et al.*, 2009]. Because head echoes allow direct detection of the meteoroid flight in the atmosphere, they provide information about meteoroid changes during the actual entry process, and so provide key information for understanding mass loss mechanisms [*Kero et al.*, 2008; *Janches* *et al.*, 2009], electromagnetic plasma processes [*Dyrud et al.*, 2002], as well as enabling the quantification of the mass range of detected particles [*Close et al.*, 2012] and their effect in the upper atmosphere [*Fentzke and Janches*, 2008; *Gardner et al.*, 2011]. HPLA radars are characterized by their high peak transmitter power ($\geq$1 MW) at VHF and UHF frequencies that range between 50 and 1200 MHz, and antenna apertures, in the form of arrays or dishes, that have areas ranging between $\sim$800$-$9$\times$10^4 m^2 [*Janches et al.*, 2008, see also Section 5 and Table 2]. This focuses most of the radiation into narrow beams with patterns characterized by Full Width Half Maximum (FWHM) between 0.16 and 3 degrees. In comparison, meteor radars generally transmit with a single Yagi or dipole antennas at VHF frequencies ranging from 17 to 50 MHz and peak power of the order of 6$-$20kW [*Galligan and Baggaley*, 2004; *Brown et al.*, 2008; *Younger et al.*, 2009]. Thus, over the past decade, two distinct areas of research have developed separately in radar meteor science. The first one is based on the more classical detection of specular reflections of meteor trails using meteor radars and the second is based on detection of head echoes and non specular trails utilizing HPLA radars. Results from both areas have shown significantly different observed meteoroid dynamical property distributions [*Janches et al.*, 2008] and trying to elucidate the origins of these differences has been a major undertake.

The fact that head-echo measurements can be performed only with HPLA radars limits these studies in several ways. HPLA radars are very sensitive instruments constraining the studies to the lower masses within the spectrum of terrestrial atmospheric aeronomical interest [*Mathews et al.*, 2001]. In addition, meteor observations with HPLA radars are scarce because they are radars at national observatories, and as such the allocated observing time in these instruments is limited. To date, only the Arecibo and MU radars has been used extensively to study seasonal effects in the observed meteor flux properties [*Janches et al.*, 2006; *Kero et al.*, 2011]. If head echo detections can successfully be made with meteor radars, such observations can potentially addresses these limitations. In addition, the fact that the detection of all different scattering mechanisms, only possible now using an assorted class of radars, can be made with the same instrument can contribute to the explanation of the observed differences. Thus in this manuscript we demonstrate that such observations are now possible with the Southern Argentina Agile Meteor Radar (SAAMER) enabled by its enhanced design. Section 2 discusses in detail the system characteristics while Section 3 describes our data analysis methodology. In Section 4 we present a summary of the most representative results and distributions from the head echo observations utilizing SAAMER, and compare them with past HPLA radar observations in Section 5. In particular we will compare our results with the Arecibo 430 MHz radar in Puerto Rico, The 440 MHz Poker Flat Incoherent Scatter Radar (PFISR) in Alaska, the 46 MHz Middle and Upper (MU) radar in Japan, the 160 MHz ARPA Long-Range Tracking and Instrumentation Radar (ALTAIR) in the Marshall Islands, and the 50 MHz Jicamarca radar in Peru.

2. SAAMER: System description

SAAMER is a SKiYMET system [*Hocking et al.*, 1997] deployed at the Estacion Astronomica Rio Grande (EARG) in the city of Rio Grande (53.8^o 45' 8" S; 67^o 45' 5" W), province of Tierra del Fuego, Argentina. SAAMER has being operational continuously since May, 2008 at a frequency of 32.55 MHz. It is enhanced relative to standard meteor radars, in order to enable Gravity Wave (GW) momentum flux measurements in the Mesosphere and Lower Thermosphere (MLT) atmospheric region [*Fritts et al.*, 2010a, b]. These enhancements over the more traditional systems were driven by two important new requirements: 1) the need for significantly higher count rates and 2) a need for the majority of meteor detections to be at small zenith (high elevation) angles. Both needs were addressed with SAAMER, which additionally was designed for greatly enhanced transmitter peak power (60 kW, rather than 6-20 kW used by most meteor radar systems).

Of particular interest for this work, is that SAAMER uses a transmitter phase antenna array configuration, specially designed by Mardoc Inc., composed of eight 3-element crossed yagis arranged in an octagon of 27.6 m (3 wavelengths) in diameter (Figure 1). This is significantly different from typical systems, which use a single antenna. In addition, the ability to change electronically (e.g. pulse to pulse) the phases between antennas provides great flexibility to the system, since it allows transmission with different radiation patterns and hence permits performance of a number of different experiments. This makes SAAMER not only an operational instrument but also a system with which additional radar experiments can be implemented.

In the normal mode of operation (hereafter referred as Mode 1), designed to measure mesospheric winds, SAAMER transmits with opposite phasing of every other yagi, directing the majority of radar power into eight beams at 45^o azimuth increments with peak power at $\sim 35^o$ off zenith (Figure 2a). This results in a majority of meteor specular trail detections at off-zenith angles between 15^o and 50^o [*Fritts et al.*, 2012a]. During the first 16 months of operation, SAAMER transmitted a 2-km (13.4 μs) long monopulse at 2140 Hz pulse repetition frequency (PRF) and a bandwidth of 0.3 MHz resulting in an excess of 10,000 meteor trail specular reflections detected daily. In September of 2009, however, the transmitting scheme was changed to a 2-bit Barker code pulse of total length of 26.8 microsec at a PRF of 1765 Hz. This change resulted in a ∼40% increase in the daily counts, that is in 15,000 to 25,000 daily detected underdense specular meteor trail events [*Janches et al.*, 2012].

For the purpose of the work described herein, enabled by the agility of SAAMER's new transmitter design, we utilized a transmitting mode that somewhat follows the methodology applied in the past for meteor head echo observations utilizing HPLA radars (hereafter called Mode 2). As opposed to the semi-stationary nature of specular reflections from meteor trails, the head echo originates from the plasma surrounding the meteoroid, moving at or near its speed [*Janches et al.*, 2000a]. Its radar cross section is much smaller than the trail [*Close et al.*, 2004], requiring far better detection sensitivity as well as improved temporal resolution. For these reasons, Mode 2 transmits with all the TX antennas in Phase resulting in most of the radiated power upwards in a relatively, narrow beam [*Janches et al.*, 2000b, 2002, 2003; *Sparks et al.*, 2009; *Pifko et al.*, 2012]. As displayed in Figure 2b, Mode 2 results in a near Gaussian central transmitted beam pattern with a 3 dB decrease in gain at $\sim 8^o$. We refer to this mode as a "relatively" narrow beam because when compared with HPLA systems, SAAMER's main beam width is approximately 3 times wider than the MU and ALTAIR radars [*Close et al.*, 2000; *Kero et al.*, 2011], 8 times wider than PFISR and Jicamarca [*Chau and Woodman*, 2004; *Sparks et al.*, 2010] and 50 times wider than the Arecibo radar [*Janches et al.*, 2004], yet is much narrower than the typical all-sky pattern resulting from a single yagi antenna utilized in most of the meteor radar systems [*Fritts et al.*, 2012a]. Specifically, we transmitted a 13.5 μs monopulse at a PRF of 500 Hz and performed a 2 point pulse coherent integration, thus resulting in an effective Interpulse period (IPP) of 4 msec. The sampling resolution of the return signal was 250 m and the bandwidth was 0.05 MHz. The vertical altitude range covered was between ~75 km and 130 km. Table 1 presents a summary of SAAMER's operation characteristics in Mode 2. As it will be discussed in more detail in the following sections, the larger area and lower transmitted power, as compared to HPLA systems, will result in lower power density which will result in sensitivity to larger particles than those detected by HPLA radars. Hence the ability to utilize SAAMER in head-echo observing mode extends the size range of meteoroids for which this technique can be applied.

The data presented in this paper were obtained during an observing campaign performed between August 2 and 14, 2011. During that time we also performed simultaneous optical observations that will be presented in a future paper. We transmitted in Mode 2 generally from evening hours until noon so as to cover the early morning meteor rate rise and peak [*Janches et al.*, 2006]. The return echoes are received by both the TX array and the receiving (RX) array, where the latter is formed by a modified version of the typical five antennas interferometer arrangement [Figure 1, *Hocking et al.*, 1997], all of which are also 3 – element crossed yagis. Due to physical constrains at the location where SAAMER operates, the southernmost RX antenna was shifted off the cross axis toward the east by a distance equal to a wavelength. Such modification preserves all the characteristics of the interferometric antenna arrangement developed by *Hocking et al.* [1997] and demonstrates that the "cross" arrangement is just one of many antenna positioning options available to form a RX interferometer that enables redundant position definition of the detected echoes. For example, a clone system to SAAMER operating in the Brazilian Antarctic Base Comandate Ferraz in King George Island uses a "T" antenna arrangement [*Fritts et al.*, 2012b]. Using the interferometer, the position for each detected range gate at every

IPP is determined with errors less than 0.5^o, ultimately enabling the determination of absolute meteoroid velocities as discussed in the next section.

3. Data Analysis

SAAMER uses the basic real-time echo detection and analysis algorithms for the SKiYMET systems developed by *Hocking et al.* [2001], independently of what transmitting mode is been utilized. These algorithms simultaneously stream raw data into memory, detect occurrences of meteors and identify and store those produced by underdense specular reflections [*McKinley*, 1961; *Ceplecha et al.*, 1998]. From these selected events, the location of meteor trails (range and angle) are determined, as well as their radial drift speeds and decay times. Underdense specular meteor trail events are semi-stationary targets drifting with the background wind at speeds that range typically from a few to ∼100 m/s. Thus, when analyzing raw data, these events are detected in the same range gate during many IPPs until the returned signal strengths falls below the noise floor due to their diffusion in the background atmosphere [*Lau et al.*, 2006]. Head echoes, on the other hand, move at hypersonic speeds (∼ km/sec) and therefore they will be detected over several range gates with increasing time (i.e. IPP) [*Janches et al.*, 2000a]. Thus, for the case of this work, additional data analysis and processing were required to be performed off line. For this, we recorded the in-phase and quadrature components of the voltage of the returned signal for each range gate, coherently integrated over 2 IPPs for each of the 6 receiving channels, five from each of the antennas that form the RX array and one from the TX array used as a receiver. Initially, we performed a running average of the noise floor and searched through the raw data for enhancements greater than 3 sigmas above the noise. Due to the presence of thousands of trail events which are detected hourly by

SAAMER, this simple approach is not efficient for identification of single head echoes, requiring that we perform a visual inspection among the detected candidates. Figures 3 and 4 show the Range-Time-Intensity (RTI) images for two examples of such events. The first five panels from each figure correspond to the data recorded on each of the RX array antenna. The sixth panel corresponds to data recorded with the 8-Yagi TX array utilized as a receiver. A common feature of the radars is that the echo return is range aliased and, for the case of meteor radars, the interferometric results as well as the assumption that meteors occur between 70 and 140 km of altitudes are needed to obtain the corrected altitudes. This step is not yet applied for the data presented in Figures 3 and 4 and that is why the vertical axis show uncorrected ranges.

Once the head echo events had been identified we proceeded to determine the meteoroid motion vector. For this, we performed interferometric calculations for every IPP by determining the phase differences between receiving channels for a selected range gate. As can be seen from the detailed RTI images displayed in Figures 5 of the two examples shown in Figures 3 and 4, for a given IPP, the events show a vertical spread of range gates which in many cases is longer than the pulse length. We then determine, for each IPP in which the meteor is present, the lowest range gate of the vertical signal range spread (i.e. leading edge) and select among ten range gates (about the length of the pulse in ranges) from the lowest one, the gate with maximum signal strength. This is represented by the black dots in this figure. The use of the 5 antenna interferometer arrangement allows for the unambiguous determination of the spatial location for each IPP. This methodology is widely utilized and will not be described in this work. *Hocking et al.* [1997] and *Hocking et al.* [2001] described in detail the operation of the 5 antenna meteor radar interferometer. The application of interferometry for head echo purposes has been reported by *Sato et al.* [2000]; *Chau and Woodman* [2004]; *Hunt et al.* [2004] and *Sparks et al.* [2010]. The results of the inteferometry calculation for both examples are displayed in Figure 6 where the vertical, eastward and northward positions for each IPP are shown as black dots. It is evident from these panels that the interferometric results are noisier than those reported in the past by HPLA radars [*Sparks et al.*, 2010, and reference therein]. However, a clear trend is present in the data and a linear fits can be applied in order to obtain an estimate of each component of the vector velocity. An interesting point to note from these panels is that both events were detected at heights greater than 110 km, somewhat greater than average altitudes reported in previous HPLA observations [$\sim$ 105 km *Janches et al.*, 2002, 2003; *Sparks et al.*, 2009; *Pifko et al.*, 2012]. In addition, the distance traveled in some of the planes, in some cases greater than 10 km, are relatively larger than previous HPLA observations. Although some dependency on the lower transmitted frequency and radar beam size exists, both factors also suggest that these head echoes are produced by relatively larger particles than those detected by HPLA systems [*Janches et al.*, 2008; *Pifko et al.*, 2012]. In the next section we present a summary of the results obtained throughout the observing campaign.

4. Results

As described in Section 2, the data presented in this work were obtained over a period of 12 days covering August 2 to 14, 2011. Due to the low sensitivity of SAAMER, we did not expect meteor head-echo detection rates to be as large as is the case for HPLA radars. In addition, because these observations were performed simultaneously with an optical campaign aimed at observing the same events with radar and optical techniques, we concentrated mostly on night hours, with the inclusion of mornings to cover the flux rate increase and peaks [*Janches et al.*, 2006], thus increasing the likelihood of successful observations. Figure 7 displays the observing interval times for each day of observations. Figure 8 provides information on the head echo detection rate observed by SAAMER. Over the 12 days of observations, an average of ∼15 head echoes where observed (Figure 8a) during each observing period that lasted on average ∼14 hrs (Figure 8b), resulting in, approximately, one detection every hour (Figure 8c). Figure 8d displays the number of head echoes detected through out the day for all the days combined. Although observations were stopped after local noon (Figure 7), Figure 8d indicates that most of the detections occur between 5 am and noon, consistent with the diurnal behavior of meteor head echoes observed by radars [*Janches et al.*, 2006; *Fentzke et al.*, 2009; *Sparks et al.*, 2009]. As can be derived from Figure 8, the SAAMER head echo detection rate is up to 2 order of magnitude lower than those resulting from HPLA radar observations [*Janches et al.*, 2006; *Sparks et al.*, 2009; *Pifko et al.*, 2012]. Although the much reduced detection rate is in part due to the significantly lower sensitivity of SAAMER compared to that of HPLA systems, this is also indicative that the particles producing SAAMER's detected head echoes may be significantly larger than those detected by HPLA radars [*Janches et al.*, 2008; *Fentzke et al.*, 2009; *Pifko et al.*, 2012]. First, larger particles will produce larger electron concentrations, so that they may be detected by the lower sensitivity SAAMER system [*Fentzke and Janches*, 2008], and second, the influx rate of meteoroids decreases with increasing size resulting in the lower detected rate [*Ceplecha et al.*, 1998]. In addition, it is worth noting that these observations were performed near the southern hemisphere spring equinox, which according to models and observations is the period during which the meteor count-rates reach a minimum at a given location [*Janches et al.*, 2006]. This seasonal variability is enhanced, in particular, at higher latitudes [*Sparks et al.*, 2009]. Thus it is likely the observed rate may increase significantly during the fall equinox period.

Figure 9a presents the initial meteor head echo altitude distribution, that is the altitude at which the first meteor IPP is recorded [*Janches and ReVelle*, 2005]. Although the counts are low, limiting statistical reliability, (in particular when compared with HPLA observations), a peak at about ∼110 km of altitude is evident from this figure. In addition, more than 45% of SAAMER's detections are between 110 and 120 km. Both the peak as well as the large percentage of high altitude events are significantly higher than similar studies utilizing HPLA observations [*Chau and Woodman*, 2004; *Janches et al.*, 2003; *Chau et al.*, 2007; *Sparks et al.*, 2009; *Pifko et al.*, 2012; *Close et al.*, 2012]. One must be cautious when doing these comparisons, however, due to the large differences in system sensitivity, transmitted frequency and even detected particle size range. We will discuss this in more detail in the next section.

The geocentric velocity distribution resulting from SAAMER's head echo observations is presented in Figure 9b. Due to the low statistical sample a clear distribution shape is not evident from this panel. However a slight dominance of higher velocities ($\geq$30 km/sec) meteors can be observed that is generally typical of head-echo observations [*Janches et al.*, 2003; *Janches et al.*, 2008; *Sparks et al.*, 2010; *Pifko et al.*, 2012]. Uncertainties of these estimates are obtained by propagating the errors of the individual linear fits (Figure 6). Overall, the methodology presented here provides the absolute velocity estimates with errors of the order of a few to 20 %, with a few cases with higher errors. This is observed in Figure 10 where the distribution of the absolute velocity uncertainty is displayed. The median in this distribution results in 14.6 %. Also, Figure 9b, shows the presence of a few meteor samples with velocities greater that the Solar System escape velocity (i.e. 72 km/sec). These particles are also seen in HPLA observations, specially those with interferometric capabilities [*Sato et al.*, 2000; *Chau and Woodman*, 2004; *Chau et al.*, 2007; *Pifko et al.*, 2012]. There are many factors that can produce such detections, such as inaccuracies in the observing methods, acceleration processes due to the giant planets, and indeed true interstellar origin. This issue however, is currently beyond the scope of this investigation.

The horizontal projections of the vector velocities are displayed in Figure 11. The circles in these figure represent 5, 10 and 20 degrees off zenith at ∼110 km of altitude. As can be observed from this figure, most of the detection occurred overhead within 10 degrees off zenith which is the region of higher transmitted power density, with no detections beyond 20 degree of zenith, from any of the side lobes (Figure 2b). It is important to note that the horizontal projections displayed in Figure 11 are unambiguous meteor positions. This is possible due the use of the five antenna interferometer [*Jones et al.*, 1998]. Furthermore, it can be derived from Figure 11, that most of these observations are relatively long lived, compared to other HPLA observations, with some events producing significant amount of electrons along distances greater than 20 km. This can also be seen in more detail in Figure 12, where distributions of the horizontal, vertical and absolute distances through which the meteor is observed are displayed. In particular, it can be seen in the third panel of Figure 12 that the majority of observed meteors have typical vertical extents of between half to one atmospheric scale height at those altitudes ($\sim 7 - 10$ km). This once again suggests the these meteors are produce by large meteoroids, as will be discussed in the next section.

As a final measured result reported in this section, we present the distribution of the meteor entry angles (i.e. the zenith angle of the meteoroid trajectory) derived from the velocity components, This distribution is displayed in Figure 13. In the figure, an entry angle of 0^o corresponds to a trajectory that was aligned with the local vertical (i.e. the meteoroid was travelling straight downward), while 90^o corresponds to a horizontal velocity vector. The results in this figure indicate that most of the observations are produced by particles entering at angle smaller or equal to 45^o with respect to the local zenith. A sharp decrease of meteoroids entering the atmosphere at higher angle values then occurs, and almost no particles with angles higher than $\sim$75 degrees. This observation agrees with past modeling results reported by *Janches et al.* [2006]; *Fentzke and Janches* [2008] and *Fentzke et al.* [2009]. In order to obtain agreements between modeled and observed head echo rates by different radars and locations, those authors argued for the need to reject most of the meteoroids entering at these large zenith angles. Recently, *Pifko et al.* [2012] reported interferometric measurements of head echoes using the MU radar in Japan and showed similar results, where the number of meteors decrease rapidly for entry angles greater than $\sim 60^o$, and incoming meteors at angles of $\geq 75^o$ are, in practical terms, negligible.

5. Discussion

In Section 4 we presented a summary of the most representative results and distributions from the head echo observations utilizing SAAMER. In this section we discuss these results in the context of previous head-echo observations utilizing HPLA radars and determine how SAAMER's observations compare to and/or complement those obtained with the more powerful and sensitive systems. In Section 2 we discussed the difference in beam width between SAAMER's transmitting in Mode 2 and HPLA radars and argued that SAAMER's wider beam will result in sensitivity to larger particles than those generally detected by HPLA radars. We will now attempt to quantify this hypothesis. Table 2 presents a comparison of several figures of merit between SAAMER and a selected group of HPLA systems for which meteor head echo observations have been performed and reported repeatedly (column 1). Columns 2 and 3 list the radar operating wavelength and frequency while the fourth column provides the peak transmitted power. Note that even though SAAMER is a high power system when compared to other all-sky meteor radars, it is still 2 orders of magnitude lower than any of the more powerful HPLA radars. The fifth column provides the aperture of each radar. For the case of SAAMER we calculate its aperture as the area in a circle of diameter equal to 3λ. MU, ALTAIR and Arecibo are also circular areas with diameters equal to 103, 46 and 300 m respectively. PFISR and Jicamarca are rectangular areas with dimensions equal to 27.5×31.5 m and 300×300 m respectively. If we assume that this aperture is the effective aperture, A_{eff}, we can then calculate the Gain (G) as

$$G = 4\pi \frac{A_{eff}}{\lambda} \tag{1}$$

This quantity is listed in the sixth column. The last column of Table 2 provides the power density (P_d) calculated from

$$P_d = \frac{P_t \times G}{4\pi \times R^2} \tag{2}$$

where R is range chosen to be 110 km for this comparison. We note that, for the case of SAAMER, this may result in an overestimation of its aperture because the array is only sparsely filled, but even if its A_{eff} is reduced to half, it will result in only a 3 dB decrease in G (∼7.3 dB), which is comparable to the gain of a single 3-element Yagi antenna, and a one order of magnitude decrease in P_d. Thus, for the purpose of this discussion, we believe that the results presented in Table 2 are reasonable representations of SAAMER's "best case scenario" performance.

If we utilize P_d as a proxy for the radar sensitivity for the case of head echo observations, the results in Table 2 show that while there is a variability of 3 orders of magnitude of this value among the HPLA systems, SAAMER differs by 4 to 7 orders of magnitude with respect to these sensitive instruments. Thus while there may be an overlap between the meteoroid mass range detected by each of the HPLA radars, the much smaller sensitivity of SAAMER suggests that the particles producing the head echoes reported here must be a different class (i.e. larger). Recently, *Pifko et al.* [2012] reported a comparison of detected sensitivity as a function of meteoroid mass between the Arecibo, PFISR, MU and ALTAIR radars. Utilizing the head echo Radar Cross Section (RCS) model developed by *Close et al.* [2005] combined with the same radar sensitivity approach introduced by *Janches et al.* [2008], the authors estimated the minimum velocity that a meteoroid with a given mass must have to be detected by any of these radars, and the results are reproduced in Table 3. As described by *Close et al.* [2005], the model and, therefore, determined sensitivity is strongly dependent on radar frequency. Taking this into account, we first concentrate on the UHF frequencies by comparing Arecibo and PFISR. Both radars transmit essentially the same frequency (430 and 440 MHz respectively), have a 2 order of magnitude difference in P_d (Table 2) and 1 order of magnitude difference in meteoroid mass sensitivity (Table 3). That is, PFISR can detect meteoroids traveling at 15 km/sec with masses equal to 10 μg, unlike Arecibo, which can detect meteoroids at the same velocity but smaller in mass by an order of magnitude. A similar trend can be observed for VHF frequencies when we compare MU and ALTAIR, although caution must be taken in this case because their frequencies are significantly different. This indicates that, given a meteoroid velocity, a difference of two orders of magnitude in radar P_d translates to one order of magnitude in mass range detected sensitivity. Applying this conjecture to SAAMER and utilizing MU as a reference, since their frequencies are comparable, we can estimate that SAAMER will be able to detect particles with minimum masses of the order of 10^2 μg if the particle travels at very high speeds (∼60 km/sec) and 10^4 μg if they travel at 15 km/sec.

On the other hand, because the number of meteors per unit area per unit time decreases as the particle mass increases [*Ceplecha et al.*, 1998], the maximum mass that each of these radars can detect will be limited by their beam size. For example, *Fentzke and Janches* [2008] and *Fentzke et al.* [2009] determined, using modeling and observed results, that Arecibo's detected mass range, considering all velocities, is 10^{-4} to 10 μg while PFISR's will be 1 to 250 μg. Similarly, *Pifko et al.* [2012] determined a detected mass range by the MU radar of also 1 to 250 μg. This agrees with recent results reported by *Kero et al.* [2011] who, utilizing RCS calculations, determined a MU detected mass range of 1 to 1000 μg. For the case of ALTAR, *Close et al.* [2012] estimated a detected mass range between 1 to 10^4 μg utilizing an improved technique for calculating bulk densities of low-mass meteoroids using a plasma scattering model. Given the very small collecting area of ALTAIR's VHF system (beam width$\sim 2.8^o$), it is somewhat surprising to see detection of particles greater then 1000 μg if we assume the mass flux reported by *Ceplecha et al.* [1998] to be correct. However, when looking at the mass distribution in detail, the number of particles decreases abruptly for masses greater than 10^2 μg and values larger than those are simply part of the distribution tail ($\leq$15%, S. Close, Personal Communication, 2012), which suggests they can be outliers of the model. In any case, it is evident that the minimum masses determined to be detected by SAAMER are equal or greater than the maximum masses detected by HPLA radars as reported by these various authors, and that overall the SAAMER's head echo detections are produce by larger particles than those which are commonly studied using this technique.

As a final result, we present meteoroid radiant information enabled by the interferometric determination of the vector velocity. Until now, this has only been possible utilizing the ALTAIR, Jicamarca, MU and PFISR radars [*Sato et al.*, 2000; *Hunt et al.*, 2004; *Chau and Woodman*, 2004; *Chau et al.*, 2007; *Sparks et al.*, 2010; *Kero et al.*, 2011; *Pifko et al.*, 2012]. Figure 14 displays the calculated meteoroid radiant color coded to their velocity plotted in terms of Sun-centered ecliptic longitude ($\lambda - \lambda_0$) and latitude (β). These data represent the point in the sky that the meteoroids entered into a hyperbolic geocentric orbit [*Jones and Brown*, 1993]. The radiant angles are defined such that the ecliptic longitude is the angle of rotation about the ecliptic normal measured from the Earth-Sun direction, and the ecliptic latitude is the angle of rotation out of the ecliptic plane (i.e., the Sun is located at $\lambda - \lambda_0 = 0^o$, $\beta = 0^o$). The plots in Figure 14 are oriented such that the center point corresponds to the Apex direction (i.e., the direction of Earth's velocity relative to the Sun). The locations of the six sporadic meteoroid sources are also displayed in the figure as ellipses, with the coordinates as specified in *Pifko et al.* [2012]. The North and South Apex (NA and SA) sources lie just above and below the figure center point, respectively. Likewise, the North and South Toroidal (NT and ST) sources are above and below the respective Apex sources. To the left of the Apex is the Helion (H) direction, and the Anti-Helion (AH) is symmetrically opposite to the Helion source about the Apex. As expected given SAAMER's location and the time period during which these observations were performed, the majority of the detections appear to come from the SA and ST source region and a minority originating from the NA and AH regions. Note that most of the radiants lie below 30^o in ecliptic latitude, which is expected due to SAAMER's high southern geographical latitude.

6. Conclusions

We have presented meteor head echo observations using SAAMER and demonstrated that, enabled by the enhanced design of this system compared to typical meteor radars, studies that are not based on the commonly detected specular trails are possible. There are many reasons why these results are compelling. Over the past decade, studies of the microgram-size meteoroid mass input in the upper atmosphere have benefited tremendously with the introduction of meteor head echo observations using HPLA radars [*Janches et al.*, 2008]. These observations have enabled us to develop and validate modeling essential for our understanding of the temporal and spatial variability of the meteoric flux, physical characteristics of the meteors and meteoroids, and how they relate to layered phenomena in the Earth's mesopause region [*Janches et al.*, 2006; *Fentzke and Janches*, 2008; *Fentzke et al.*, 2009; *Plane et al.*, 2010; *Gardner et al.*, 2011]. Furthermore, these highly resolved measurements have contributed to identifying the mass loss mechanisms that these particles undergo upon atmospheric entry, allowing us to relate small scale features of the detected radar light curves with the precise moment that a particular chemical constituent is released from the meteoroid body [*Dyrud and Janches*, 2008; *Janches et al.*, 2009; *Close et al.*, 2012]. The fact that these measurements can be performed only with HPLA radars limits these studies in several ways. First, since HPLA radars are very sensitive instruments, the studies are generally constrained to the lower masses within the spectrum of Terrestrial atmospheric aeronomical interest. Secondly, meteor observations with HPLA radars are scarce because they are made at national observatories and as such the allocated observing time on these instruments is shared among many other type of experiments. In fact, only the Arecibo and MU radars have been used extensively to study seasonal effects in the observed meteor diurnal properties [*Kero et al.*, 2011; *Pifko et al.*, 2012; *Janches et al.*, 2006]. The routine utilization of enhanced meteor radars, such as SAAMER, to observe and detect head echoes addresses both issues. First we have shown that the observational technique can be extended to larger masses, expanding the mass range of particles that can be studied using the same methodology. Second, these systems, even with SAAMER's enhancements, are two to three orders of magnitude less expensive than HPLA radars, in addition to being easily deployable and almost 100% autonomous. That implies that these observations can be performed continuously and the potential for more deployments at different locations is attainable. This also addresses the low detection rate drawback, since 24 hr long observation periods may not provide a statistical significant sample, a problem at this mass range, but because these instruments are operated continuously the collection of large data sets over long periods of time is now possible. A methodology to achieve this objective is under current development.

In addition to measurements of the head-echo, HPLA radars have been instrumental in the detection and understanding of the plasma phenomena surrounding the non-specular (i.e. field aligned) meteor trails [*Dyrud et al.*, 2002, 2007a, b]. Although most of the HPLA radars can be used to detect head-echoes, only three [out of 11; *Janches et al.*, 2008] can successfully detect non-specular trail echoes, all of which are at low to mid latitudes (ALTAIR in the Marshall Islands, the MU radar in Japan and the Jicamarca radar in Peru). The characteristics of these echoes (i.e. duration, spatial extend, etc), which provide key information on meteoroid physical properties [*Dyrud et al.*, 2005], are expected to have a strong dependence with latitude [*Dyrud et al.*, 2011]. Because these echoes are also detected by SAAMER, its location will provide valuable new information regarding this phenomena. These results are under current analysis and will be presented in a future paper.

Finally, over the past decade, there has been a controversy regarding the differences in measured velocity distributions and consequently orbital distributions of meteors resulting from HPLA head echo and meteor radar specular trail detections. These differences are in part due to different observational biases introduced by the detection of different scattering mechanisms using an assorted class of radars. The fact that we can perform measurements of all these mechanisms simultaneously with the same instrument will undoubtedly contribute to clarification of these issues.

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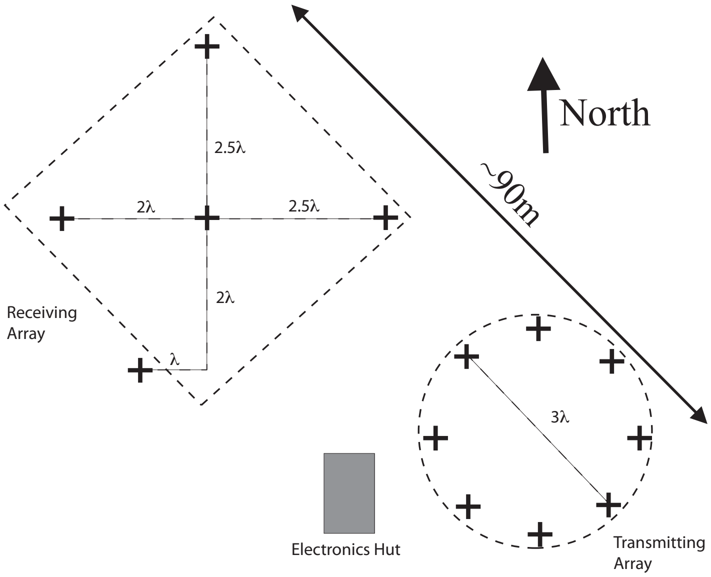

Figure 1. Antenna transmitter and receiver layout at Rio Grande, Tierra del Fuego (with individual antennas indicated with plus symbols).

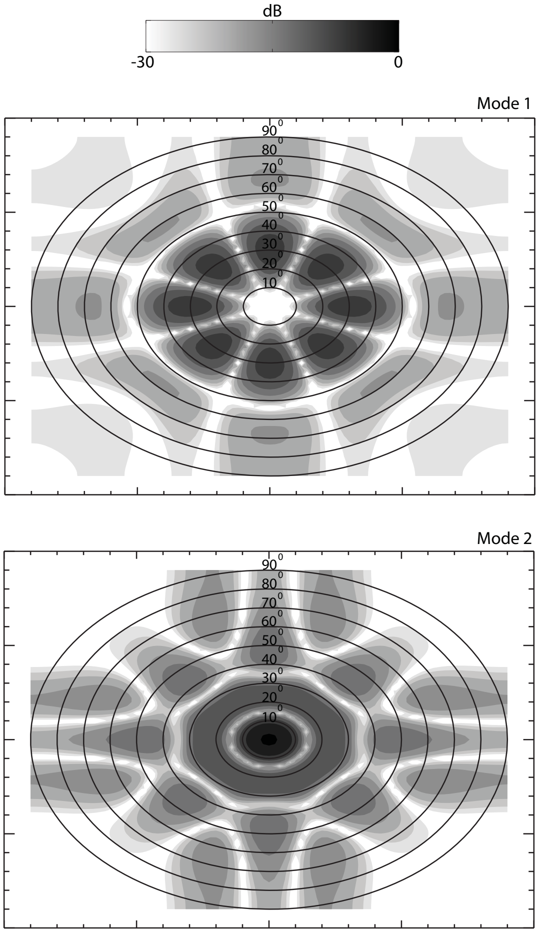

Figure 2. SAAMER's radiation patterns transmitting a) Mode 1: 180^o off phase and b) Mode 2: all antennas in phase.

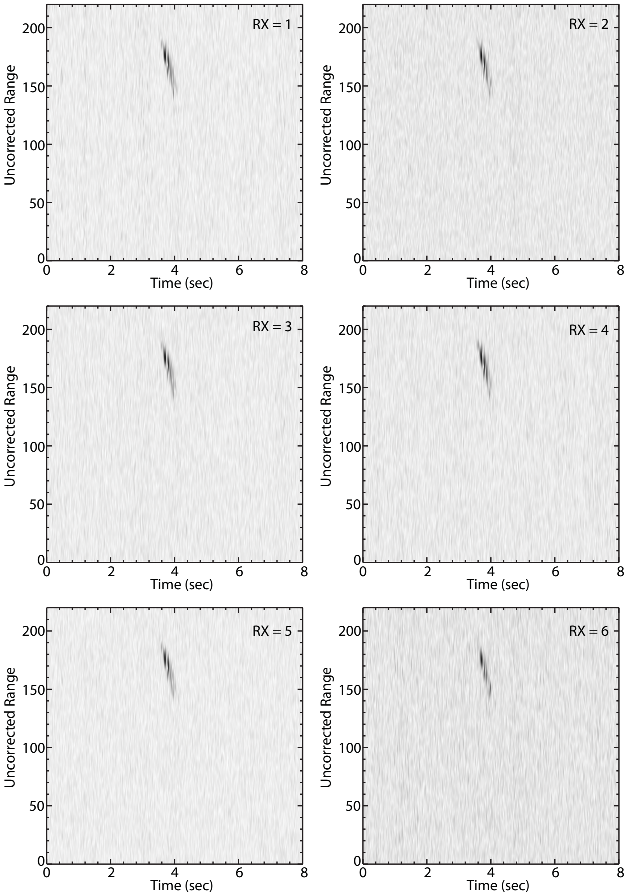

Figure 3. RTI Images of a head echo event observed by SAAMER. The first 5 panels represent the signal detected by each of the receiving antennas while the last panel displays the signal recorded by the transmitting array utilized as a receiver.

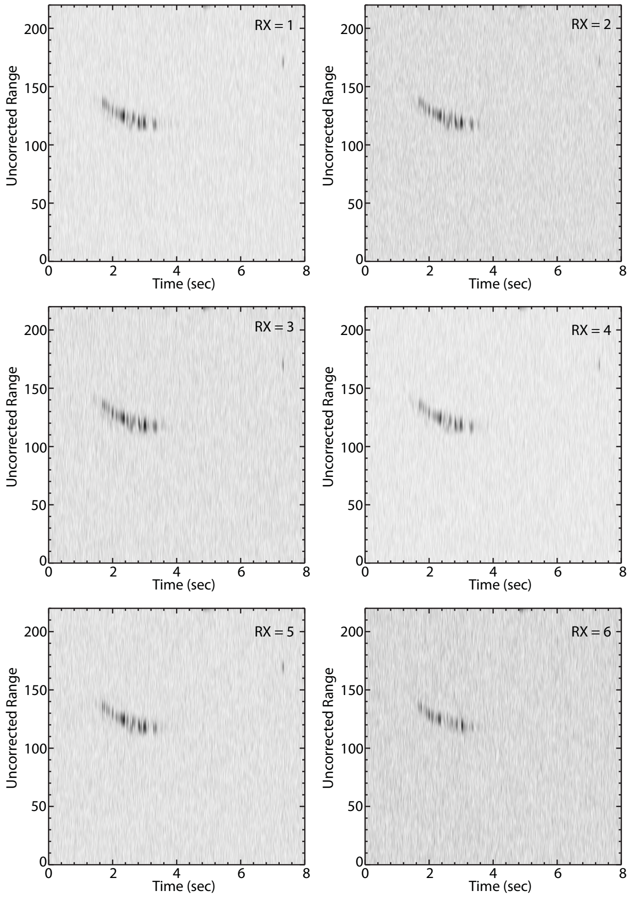

Figure 4. Same as Figure 3 for a second event which also displays the beginning of a specular trail.

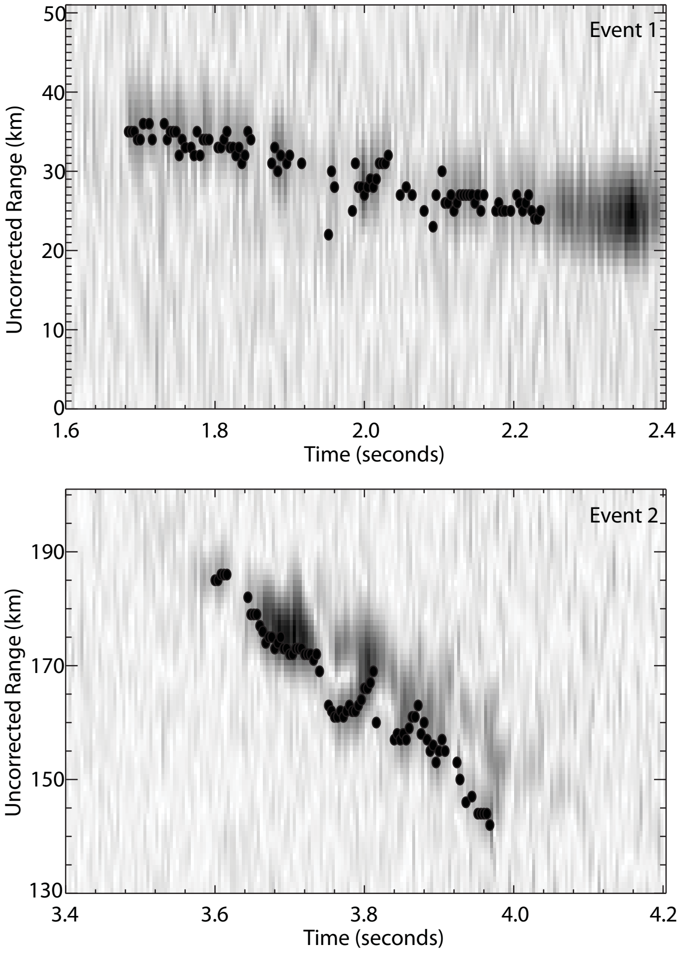

Figure 5. Detail RTI images of the events displayed in Figures 3 and 4. The black dots show the range gates that were utilized for interferometric calculation purposes.

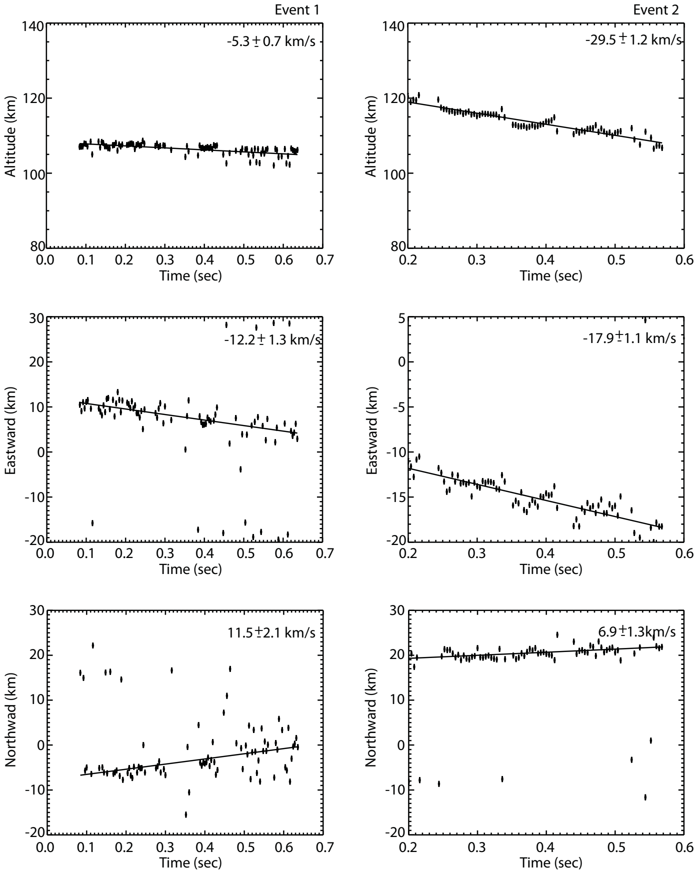

Figure 6. Interferometric spatial and velocity determinations of the events displayed in Figures 3 and 4.

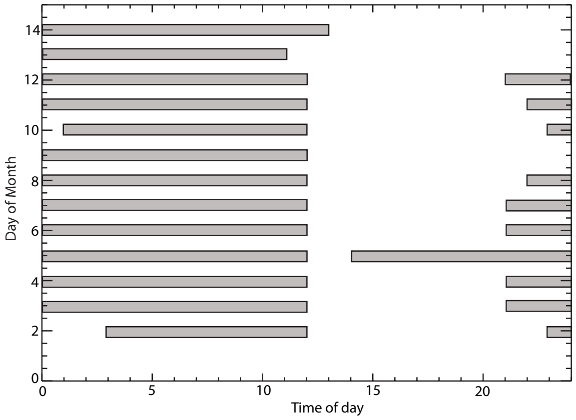

Figure 7. SAAMER's observing periods for the head echo experiment performed in August 2011.

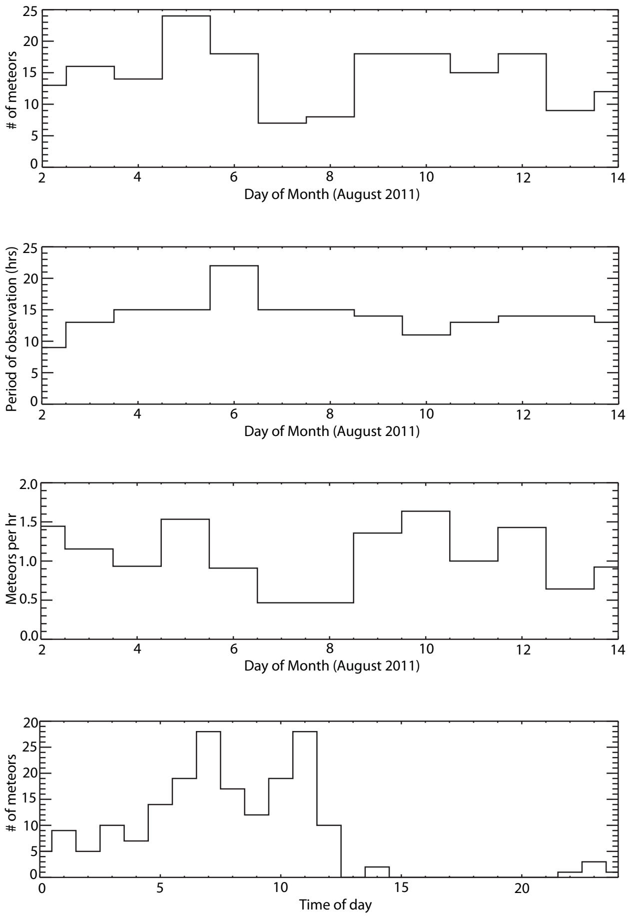

Figure 8. a) Number of meteors detected per day of observations; b) number of observed hours per day of observation; c) average number of meteors per hours observed; and d) number of meteors observes as a function of time of the day with all days compiled.

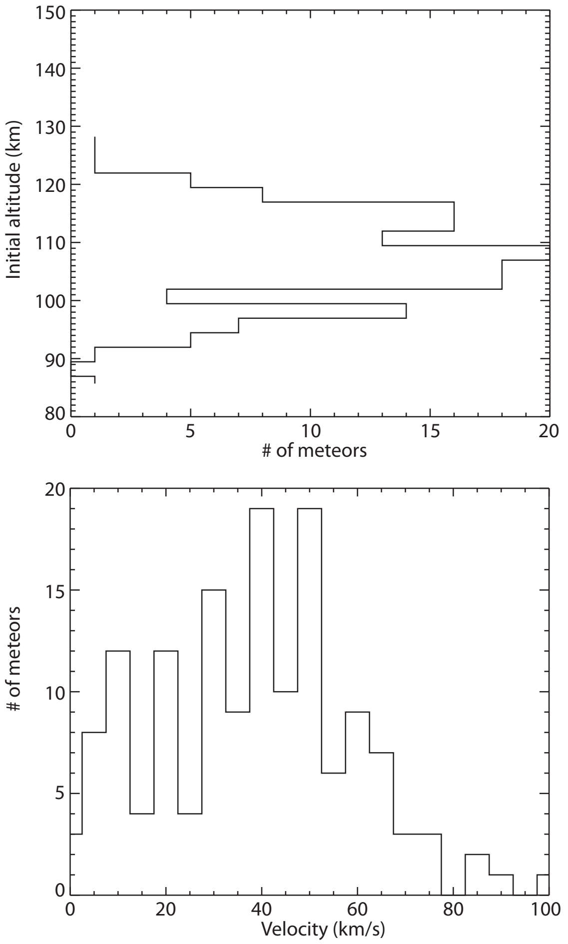

Figure 9. Top panel: observed initial altitude distribution; bottom panel: Observed absolute velocity distribution.

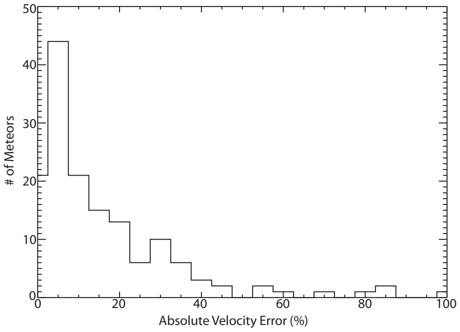

Figure 10. Distribution of calculated errors on the velocity determination

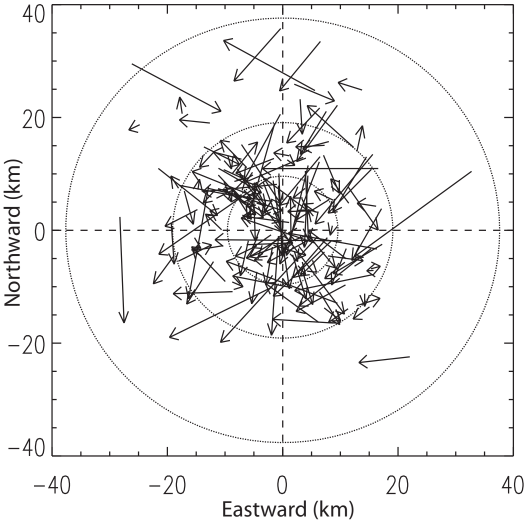

Figure 11. Horizontal projections of the vector velocities displays as arrows. The circles represent 5, 10 and 20 degrees off zenith at 110 km of altitude.

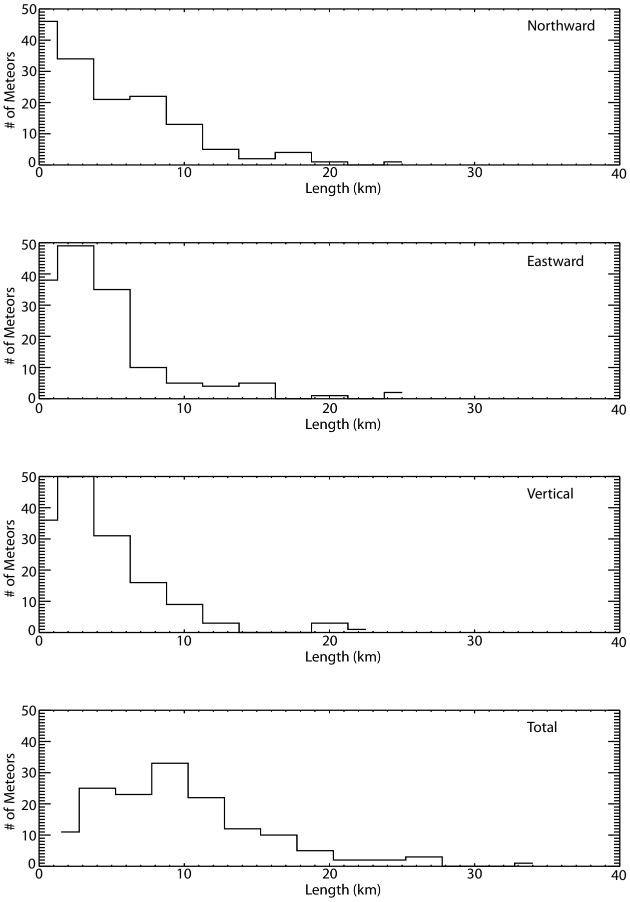

Figure 12. Top three panels display the distribution of the spatial coverage of the head echo events in the three directions. The bottom panel displays the distribution of the absolute observed displacement.

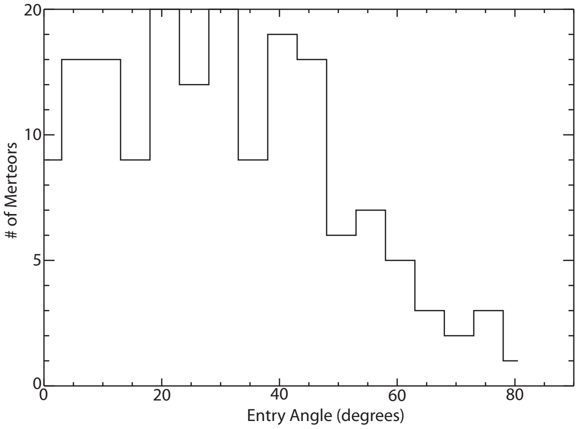

Figure 13. Distribution of calculated entry angle measure from the local Zenith.

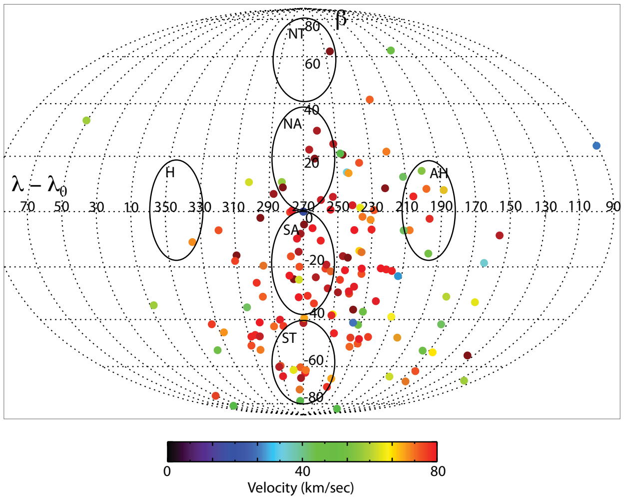

Figure 14. Calculated meteoroid radiant color coded to their velocity plotted in terms of Sun-centered ecliptic longitude ($\lambda - \lambda_0$) and latitude (β). The ellipses represent the location of the six apparent sporadic meteoroid sources.

Quantity (units)	
Latitude (degrees)	53.8^o
Longitude (degrees)	67^o
Frequency (MHz)	32.55
PRF (Hz)	500
Peak Transmitted Power (kW)	60
Banwidth (MHz)	0.05
Coherent Integrations (# of IPP)	2
Pulse Code	Monopulse
Pulse Length (μs)	13.6
Sampling Resolution (m)	250
FWHM	8^o

Table 1. SAAMER's Operating characteristics for Head-Echo mode

RADAR	λ (m)	f (MHz)	P_t (kW)	Aperture (m^2)	G (dB)	P_d (W/m^2)
SAAMER	9.7	32.55	60	74	10	5×10^{-6}
MU	6.5	46	1000.	8332.3	34	0.02
Jicamarca	6	50	2000	90,000	45	0.5
ALTAIR	1.8	160	6000	6648	44	1.23
Arecibo	0.69	430	2000	70,686	63	28.9
PFISR	0.68	440	1500	866.25	43	0.3

Table 2. Comparison of various figures of merit between SAAMER and HPLA radars

Mass	**Minimum Speed (km/s)**				
(log$_{10}$ g)	**MU**	**ALTAIR**	**Arecibo**	**PFISR**	**SAAMER**
-7	80	40	25	–	–
-6	60	25	15	25	–
-5	25	15	5	15	–
-4	10	All	All	All	60
-3	10	All	All	All	40
-2	All	All	All	All	15

Table 3. Minimum meteoroid speed required for radar detection as a function of meteoroid mass for several HPLA radar systems reproduced from *Pifko et al.* [2012]