Simultaneous Optical and Radar Observations of Meteor Head-Echoes utilizing SAAMER

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Abstract

We present simultaneous optical and radar observations of meteors observed with the Southern Argentine Agile MEteor Radar (SAAMER). Although such observations were performed in the past using High Power and Large Aperture radars, the focus here is on meteors that produced head echoes that can be detected by a significantly less sensitive but more accessible radar system. An observational campaign was conducted in August of 2011, where an optical imager was operated near the radar site in Rio Grande, Tierra del Fuego, Argentina. Six head echo events out of 150 total detections were identified where simultaneous optical meteors could also be clearly seen within the main radar beam. The location of the meteors derived from the radar interferometry agreed very well with the optical location, verifying the accuracy of the radar interferometry technique. The meteor speeds and origin directions calculated from the radar data were accurate—compared with the optics—for the 2 meteors that had radar signal-to-noise ratios above 2.5. The optical meteors that produced the head echoes had horizontal velocities in the range of 29 km/s to 91 km/s. These comparisons with optical observations improve the accuracy of the radar detection and analysis techniques, such that, when applied over longer periods of time, will improve the statistics of southern hemisphere meteor observations. Mass estimates were derived using both the optical and radar data and the resulting masses agreed well with each other. All were within an order of magnitude and in most cases, the agreement was within a factor of two.

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1. Introduction

The use of combined optical and radar observations of meteors is an under-utilized technique, which can lead to an increased insight into the processes involved with meteor ablation as well as help to constrain key parameters such as the meteor ionization and luminous efficiencies (Weryk and Brown, 2013). The use of High-Power and Large Aperture (HPLA; aka Incoherent Scatter Radars) is currently the primary method for observing the small signals from meteor head echoes, but recently Janches et al. (2014a) demonstrated that all-sky VHF meteor radars with advanced designs such as the Southern Argentine Agile MEteor Radar (SAAMER) (Fritts et al., 2010), can also be used to detect such events. SAAMER transmits significantly less power compared to HPLA systems but 5 to 10 times more power than similar all-sky VHF meteor radars, which typically detect specular meteor trail echoes—a much larger scattering target than head-echoes. The use of a transmitting antenna array that can focus the transmitted power is also essential to detect the head echoes.

The analysis and modeling of meteor head echoes in HPLA radar observations has been used to constrain the characteristics of the incoming meteoroid flux (Mathews et al., 2001; Close et al., 2005; Dyrud and Janches, 2008; Fentzke and Janches, 2008; Close et al., 2012; Janches et al., 2014b). The utilization of HPLA systems to detect meteor head echoes is currently the most efficient way to detect and quantify large numbers of meteors, especially the most abundant, small, microgram to milligram interplanetary Dust Particles (IDP). HPLA observations of meteor head echoes can provide accurate measurements of only a limited number of meteor parameters, including the line-of-sight (LOS) velocity and deceleration as well as the backscattered power. The absolute velocity can only be determined for those systems that have interferometric capabilities (Chau and Woodman, 2004; Sparks et al., 2010; Kero et al., 2011; Pifko et al., 2013). It is from these fairly limited measurements that other parameters, such as mass can be estimated with less accuracy.

The study of meteors and their interactions with planetary atmospheres involve many aspects, including theory and modeling, such as described in McNeil (1999); Oppenheim et al. (2000); Dyrud et al. (2007); Close et al.

(2002) and more recently the techniques described in Gritsevich (2009); Bouquet et al. (2014); Moreno-Ibáñez et al. (2015) to name a few representative examples. In addition, there have been many observational studies which use radars (Reddi and Nair, 1998; Janches et al., 2003), lidars (Grime et al., 1999; Von Zahn, 2001), and spectroscopy and imaging (Shamir, 2005; Kaiser et al., 2004). However, there appears to be a lack of studies that combine optical television observations of visible meteor trails with simultaneous radar scattering signatures, until very recently (Michell, 2010; Campbell-Brown et al., 2012; Weryk and Brown, 2013). In the last decade, the availability of Electron Multiplying CCD (EMCCD) imagers have greatly increased the ease of analyzing high-time resolution, low-light-level optical imaging. Most of the observational work on radar scattering from meteors is done without optical imaging, commonly assuming that the meteors causing the radar scattering are too small to produce visible trails. Initial observations—using the Poker Flat Incoherent Scatter Radar (PFISR)—demonstrated that meteors detected optically were simultaneously observed as head echoes by the radar, even when they occurred in the side lobes (Michell, 2010). Additionally—for the case of PFISR observations—there appears to be a direct correlation between optical brightness and radar backscattered power—radar cross section (RCS)—indicating a mass dependence of the RCS (Michell, 2010; Close et al., 2012).

The focus of the observations presented here is on common-volume optical imaging and SAAMER observations of meteor head echoes, where we have identified—optically—some of the meteors that produced the head echoes in the radar data. The main purpose of these comparisons is to demonstrate that such observations can be done with more accessible and less expensive systems than HPLA radars. In addition, the added information from the optical observations is used to improve the accuracy of the radar detection and analysis techniques. Therefore the application of such radar observations over longer periods of time—when optical data are not available or not possible due to daylight and weather conditions—enables the compilation of more accurate statistics of southern hemisphere meteor observations. In the next section, the methods are described, including both optical and radar. The observations are then presented, followed by discussion and conclusions.

69 2. Methodolgy

70 The data presented in this work were obtained over a period of 12 days
71 covering 02 to 14 August, 2011. Details of the observing campaign are de-
72 scribed in Janches et al. (2014a). Due to the low sensitivity of SAAMER, we
73 did not expect meteor head-echo detection rates to be as large as is the case
74 for HPLA radars (> 10 events/minutes at the peak). In addition, because
75 these observations were performed simultaneously with the optical imager,
76 we concentrated mostly on night hours, with the inclusion of mornings to
77 cover the flux rate increase and peaks (Janches et al., 2006), thus increasing
78 the likelihood of successful observations.

79 2.1. Radar Observations

80 SAAMER is a SKiYMET system (Hocking et al., 1997) deployed at the
81 Estacion Astronomica Rio Grande (EARG) in the city of Rio Grande (53.8°
82 $45' 8''$ S; $67^\circ 45' 5''$ W), province of Tierra del Fuego, Argentina. The system,
83 which operates at a frequency of 32.55 MHz, is enhanced relative to standard
84 meteor radars, including higher transmitter peak power—60 kW, rather than
85 6-20 kW used by most meteor radar systems (Hocking et al., 2001; Brown
86 et al., 2008; Stober et al., 2011)—and a transmitter phase antenna array con-
87 figuration, specially designed by Mardoc Inc., composed of eight 3-element
88 crossed yagis arranged in an octagon of 27.6 m (3 wavelengths) in diameter.
89 This is significantly different from typical systems, which use a single an-
90 tenna. This provides the ability to change electronically (e.g. pulse to pulse)
91 the phases between antennas allowing transmission of different radiation pat-
92 terns and hence permits the operation of a number of different experiments
93 (Janches et al., 2014a). During the observing campaign reported here, we
94 utilized a transmitting mode that somewhat follows the methodology ap-
95 plied in the past for meteor head echo observations utilizing HPLA radars by
96 transmitting with all the TX antennas in phase resulting in most of the ra-
97 diated power upwards in a relatively narrow beam. As described in Janches
98 et al. (2014a), this methodology results in a near Gaussian central transmit-
99 ted beam pattern with a 3 dB decrease in gain at $\sim 8^\circ$. We refer to this mode
100 as a “relatively” narrow beam because when compared with HPLA systems,
101 SAAMER’s main beam width is approximately 3 times wider than the MU
102 and ALTAIR radars (Close et al., 2000; Kero et al., 2011), 8 times wider than
103 PFISR and Jicamarca (Chau and Woodman, 2004; Sparks et al., 2010) and

Quantity (units)	
Latitude (degrees)	53.8° S
Longitude (degrees)	67° W
Frequency (MHz)	32.55
PRF (Hz)	500
Peak Transmitted Power (kW)	60
Bandwidth (MHz)	0.05
Coherent Integrations (# of IPP)	2
Pulse Code	Monopulse
Pulse Length (μ s)	13.6
Sampling Resolution (m)	250
FWHM	8°

Table 1: SAAMER’s operating characteristics for the head-echo mode

50 times wider than the Arecibo radar (Janches et al., 2004), yet is significantly (~ 18 times) narrower than the typical all-sky pattern resulting from a single Yagi antenna utilized in most of the meteor radar systems (Fritts et al., 2012). Specifically, we transmitted a 13.5μ s monopulse at a Pulse Repetition Frequency (PRF) of 500 Hz and performed a 2 point pulse coherent integration, thus resulting in an effective Inter Pulse Period (IPP) of 4 ms. The sampling rate of the returned signal results in 250 m range resolution 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. This scheme was chosen as an initial test mode, where the data rate could be handled by the current computer. The larger area and lower transmitted power, as compared to most HPLA systems, results in lower power density and hence sensitivity to larger particles than those detected by typical HPLA radars. Therefore using the head echo observing mode with SAAMER, the size range of meteoroid observations is extended to larger masses as compared to HPLA radars, with the exception of the MU radar in Japan (Kero et al., 2011) which can also detect meteoroids of a similar size range as SAAMER.

Table 2 summarizes the orbital parameters of the six meteors reported on here. These are the semi-major axis (a) in AU, the eccentricity (ϵ), the inclination (I), the ecliptic longitude (λ) and the ecliptic latitude (β). It

Meteor #	a (AU)	ϵ	I (Deg.)	λ (Deg.)	β (Deg.)
1	1.23	0.32	168	-8.4	-6.3
2	2.6	0.83	101.9	-37.7	-30.7
3	1.8	1.5	153.4	7.52	-16.46
4	1.3	0.3	96.3	-9.6	-44.1
5	10.8	0.9	107.7	4.1	-43
6	0.6	0.8	91.7	20.4	-21.9

Table 2: Summary of the orbital parameters of the meteors, derived from the radar measurements. These include the semi-major axis (a) in AU, the eccentricity (ϵ), the inclination (I), the ecliptic longitude (λ) and the ecliptic latitude (β). Note, the ecliptic longitude (λ) is measured from the apex.

should be noted that for the data presented in Table 2, the ecliptic longitude (λ) is measured from the apex, thus Earth’s apex is 0° with the sun at 90° .

2.2. Optical Observations

One imager from the Multi-spectral Observatory Of Sensitive EMCCDs (MOOSE) suite of imagers was used to make the observations. These are Andor Ixon DU-888 EMCCD imagers that have a 1024×1024 pixel chip, with internal binning and sub-framing capabilities that allow tradeoffs between temporal and spatial resolution. For the observations presented here, the imager was operating with a narrow field of view (14°). The CCD was internally cooled to -70° C to reduce thermal noise and was set to 4×4 binning with some sub-framing, resulting in a 190×190 image at 40.7 frames per second (~ 20 ms exposure time). This setup provides an angular resolution of 0.073° per pixel or approximately 130 meters per pixel, assuming an altitude for the meteors of ~ 100 km. The imager was pointed at the local zenith (90° El.) and was located approximately 5 km from the radar transmitter in order to avoid the bright lights of the city and the airport. The center of the radar beam was therefore offset by approximately 5 km from the center of the image.

3. Observations

During the near two-week campaign the radar detected about 150 meteor head echoes (Janches et al., 2014a). Unfortunately, during this period there

Figure 1: Images showing the six meteors. The meteors are circled and the white number is the meteor number for reference. The area of the images is approximately 25 km x 25 km, at 100 km altitude.

146 were few nights with optimal weather for the optical observations. Neverthe-
 147 less, cross-referencing the times when it was clear enough for the imager to
 148 detect optical meteors, a total of six of the radar detected meteors were also
 149 detected with the imager.

150 Figure 1 shows a panel of optical images for each of the six meteors
 151 simultaneously detected by both techniques, the meteors are circled for iden-
 152 tification and numbered 1–6. Meteor #6 was traveling faster than the rest
 153 and therefore has a longer, fainter streak, due to the finite exposure time
 154 of ~ 20 ms, but is clearly identifiable in 7 frames as it passes through the
 155 image. Figure 2 shows a panel with the corresponding radar data as Range-
 156 Time-Intensity (RTI) images for each of these six meteors.

157 SAAMER used—as a receiver—the typical 5 antenna interferometer ar-
 158 rangement which allowed for the unambiguous determination of the spatial
 159 location of the detected echoes. This methodology is widely utilized and
 160 will not be described in this work. Hocking et al. (1997) and Hocking et al.
 161 (2001) described in detail the operation of the 5 antenna meteor radar inter-

Figure 2: Radar returns from the six meteors, plotted as Range-Time-Intensity plots. The numbering is in the same orientation as is in Figure 1.

ferometer. The application of interferometry for meteor head echo purposes is described in Janches et al. (2014a). The positions and velocities of the meteors can therefore be calculated from the radar observations. The radar derived meteor speeds and directions can then be compared with the speeds and directions determined from the optical observations. Figure 3 shows a panel of optical images, showing the meteors' locations from the images (white boxes) and the locations derived from the radar data (black stars). The white 'X' in the upper left corner denotes the position of the center of the radar beam. The small white arrows indicate the direction of travel of the optical meteors. The radar data are the positions of the meteors that were derived from the interferometry from different times along their paths.

The horizontal speeds and the directions of origin for these meteors can be derived from both the radar and optical data independently. Table 3 summarizes the comparison between the optical and radar derived horizontal speeds ($\pm$ estimated errors) and origin directions for these 6 meteors.

4. Discussion

The meteor head echo observations with SAAMER presented in (Janches et al., 2014a) represent a great improvement to our meteor observing capabilities in the southern hemisphere. The observations presented here build

Figure 3: Images showing the optical meteor locations (white boxes) and the locations derived from the radar interferometry (black stars). The white ‘X’ in the upper left corner of the images marks the location directly above the radar (the position of the center of the radar beam).

Meteor #	Optical $\perp$ Speed (km/s)	Radar $\perp$ Speed (km/s)	Optical Dir. (Deg.)	Radar Dir. (Deg.)
1	57.2 ($\pm$ 5.1)	53.7 ($\pm$ 13.2)	329.8°	357.9°
2	29.5 ($\pm$ 1.7)	30.1 ($\pm$ 7.3)	18.2°	36.9°
3	75.4 ($\pm$ 2.5)	67.6 ($\pm$ 8.6)	58.7°	60.4°
4	52.0 ($\pm$ 2.0)	34.3 ($\pm$ 10.4)	90.5°	52.3°
5	41.2 ($\pm$ 3.4)	42.9 ($\pm$ 10.2)	61.0°	69.0°
6	91.5 ($\pm$ 3.4)	62.3 ($\pm$ 4.6)	56.9°	41.1°

Table 3: Summary of the radar and optical comparison of speeds and directions for the meteors. The estimated errors in the speeds are listed in the parentheses (in km/s) . The direction is defined as the direction of origin of the meteor with North = 0° and East = 90°.

181 on that analysis, with the goal of improving the meteor detection and anal-
182 ysis techniques using the radar data alone. Optical observations of the same
183 meteors detected in the radar can be used to accurately determine the direc-
184 tion of motion of the meteors and—given the high frame rate of the imager
185 data—the horizontal component of the velocity.

186 The summary of the optical and radar data presented in Figure 3 shows
187 that agreement is found in the radar and optical observations, suggesting
188 that these are simultaneous radar and optical detections of the same events.
189 However, there is significant spread in the radar derived locations. In addi-
190 tion, the meteors appear to have more radar position determinations along
191 the portion of their paths that are the closest to the center of the radar beam,
192 marked by the white ‘X’ in Figure 3. This is consistent with the beam pat-
193 tern of the radar during these observations, which had a single beam with a
194 3 dB point at 8° off zenith. The size of the images is $14^\circ \times 14^\circ$, meaning that
195 most of the radar derived points were within about 5° of the beam center,
196 emphasizing the need for focused transmitted power in order to be able to
197 make head-echo detections (Janches et al., 2014a). The scattered nature of
198 these points indicates that there was not always enough signal in the radar
199 to determine a location, indicating that the data are noisy and the technique
200 utilized in this campaign has limitations.

201 The comparison between the directions and speeds determined from the
202 radar and optical data are useful in evaluating the accuracy and limitations—
203 as well as methods for improving—the radar data analysis techniques. Ta-
204 ble 4 summarizes the differences between the optical and radar horizontal
205 speeds and directions. The radar speed estimates overall appear to be slightly
206 more accurate than the direction estimates. Four out of the six speeds differ
207 by less than 10 km/s (two of them less than 2 km/s difference), while the for
208 the directions, only 2 of them differ by less than 10 degrees.

209 Meteors 1, 2, 3 and 5 all had speeds that closely matched between the
210 radar and optics, while meteors 3 and 5 had origin directions that matched
211 fairly closely. Meteor 4 and meteor 6 had significant differences in both speed
212 and direction between the optics and radar. Although the returns for these
213 meteors were centered close to the center of the radar beam, the spread was
214 significant about the meteor path, producing the larger errors.

215 The optically measured speeds tend to be more accurate because the
216 2-dimensional position of the meteor can be located to within two pixels
217 in multiple frames (between 4 and 13 different frames for these meteors),
218 leading to maximum errors in speeds of between 1 and 5 km/s. The radar

Meteor #	$\perp$ Speed Diff. (km/s)	Direction Diff. (Deg.)	Radar SNR
1	3.5	-28.1°	0.7
2	-0.6	-18.7°	1.9
3	7.8	-1.7°	2.5
4	17.7	38.2°	2.1
5	-1.7	-8.0°	2.7
6	29.2	15.8°	1.6

Table 4: The differences between the optical and radar horizontal speeds and origin directions as well as the radar signal level for the meteors, expressed as the signal-to-noise ratio.

219 data however have errors in the 5 to 10 km/s range.

220 The estimated errors in the meteor origin directions calculated from the
221 optical data range between 2° and 5°, while the estimates based on the radar
222 data have errors that range between 10° and 15°. The calculation of the
223 meteor origin directions show more variation between the optics and radar
224 than the perpendicular speeds do. This indicates that the radar method of
225 calculating directions appears to be sensitive to the errors introduced by the
226 low signal levels—from either weak backscatter or the meteor being too far
227 from the center of the radar beam.

228 The data displayed in Figure 3 show that the radar interferometry tech-
229 nique accurately captures the spatial location of the meteors on average.
230 There is some spread in the radar derived locations about the actual me-
231 teor location, which causes the errors in the speed and direction calcula-
232 tions. Two of the meteors (3 and 5) showed fairly good agreement between
233 both the optically derived and radar derived perpendicular speeds and direc-
234 tions. These events have the highest radar Signal-to-Noise Ratios (SNR) of
235 all the meteors, 2.5 and 2.7, respectively. Two of the other meteors (1 and
236 2) showed agreement between the optics and radar in only one of the param-
237 eters (speed). The remaining two meteors (4 and 6) showed large differences
238 between the radar and optically derived speeds and directions. The radar
239 head echo observations analyzed here actually represent some of the weakest
240 backscattered power head echo events detected during the campaign. These
241 six meteors are the only head echoes detected when the observing condi-
242 tions were favorable for the optical observations. In fact, many other head

243 echoes—with much stronger backscattered power—were detected at different
244 times with the radar and these had much smaller errors in the direction and
245 velocity estimations (Janches et al., 2014a), but the sky conditions at those
246 times were unfavorable for optical observations—either cloudy or snowing.

247 It is important to note that, in order to make these observations, the radar
248 was operated in a different mode than its normal operational design, which
249 is for determining mesospheric winds estimates. In light of this and the fact
250 that most of these meteors represent the weakest head echo events detected,
251 these observations show that it is possible to calculate meteor speeds and
252 directions from meteor head echoes detected by the radar. In fact, this
253 method produces accurate estimates of the meteor speeds and directions for
254 meteors with radar SNR values above about 2.5. SAAMER—operated in
255 this mode—can detect about one head echo per hour with SNR greater than
256 2.5, and if these simultaneous observations can be performed continuously it
257 will enable the collection of sufficient statistics of these relatively rare events.

258 The mass of meteors in general can be estimated from both optical and
259 radar methods (Gritsevich, 2009; Campbell-Brown et al., 2012; Weryk and
260 Brown, 2013), each of which relies on separate assumptions. The mass of
261 the meteors presented here, was estimated from both the optical and radar
262 observations, using independent techniques. The summary of the mass es-
263 timates is presented in Table 5. The optical mass was calculated using a
264 luminous efficiency of 1%, consistent with Hill et al. (2005) and a radiative
265 energy output constant of 1950 W, consistent with Ceplecha et al. (1998).
266 The radar masses were derived using a recently developed model reported
267 in Janches et al. (2014b). The model utilized the Chemical Ablation Model
268 (CABMOD) developed by Vondrak et al. (2008) to calculate the electron
269 production profiles as a function of altitude of a given particle, and the radar
270 antenna gain pattern to estimate the meteor SNR as a function of the phys-
271 ical location of the particle’s path through the radar beam. The velocity
272 and spatial information derived from the SAAMER observations are input
273 back into the model in order to estimate the mass of the particle required
274 to produced the detected signal. The possible mass ranges derived for each
275 meteor are presented in Table 5.

276 Figure 4 shows a plot of the optical masses of the meteors plotted against
277 the maximum radar SNR. The mass estimates range between 0.1 mg and
278 1.5 mg, which is consistent with the mass range determined by the radar
279 sensitivity estimates presented in Janches et al. (2014a). The data show a
280 general linear relationship, except for meteor #1 which has a low SNR and

Meteor #	Radar SNR	Speed (km/s)	Optical Mass (mg)	Radar Mass Range (mg)	Min. Mag.
1	0.7	64.3	1.46	0.3 – 0.5	2.66
2	1.9	52.0	0.90	0.3 – 0.7	4.20
3	2.5	80.0	0.88	0.6 – 0.8	3.50
4	2.1	63.7	0.64	0.2 – 0.6	3.63
5	2.7	57.1	1.10	0.2 – 0.3	2.82
6	1.6	92.3	0.10	0.5 – 0.6	5.01

Table 5: The total speeds, mass estimates and minimum magnitudes (maximum brightness) for each of the meteors.

281 a large optical mass. The correlation coefficient of the data where the SNR
282 is greater than 1.0 (5 data points) is 0.83, while the correlation coefficient of
283 the data where the SNR is greater than 2.0 (3 data points) is 0.98. While
284 a definitive relationship between optical mass and radar SNR is not possible
285 with such a small sample size, these initial observations suggest that a rela-
286 tionship exists between these two parameters. Therefore, if this relationship
287 can be quantified with further observations, it can provide a calibration for
288 the radar observations to produce improved meteor mass estimates.

289 5. Conclusions

290 The use of a relatively inexpensive and accessible radar system—such
291 as SAAMER—to detect meteor head echoes in the southern hemisphere,
292 presents a great advantage over HPLA radars in that such a system can be
293 operated continuously over long periods of time, while HPLA radars can only
294 be operated in meteor modes for short campaigns. Such long term operations
295 allow for the compilation of large statistical samples of meteor head echoes
296 as well as capture the seasonal variations in the meteor populations.

297 These observations show that this fairly low power SKiYMET radar sys-
298 tem can indeed detect meteor head echoes and that the interferometry tech-
299 nique is accurate at determining the physical locations of the meteors. The
300 comparison between the horizontal speeds and directions calculated using
301 both the optical and radar observations reveals that a radar SNR of 2.5 is
302 the lower limit for producing accurate estimates from the radar data.

303 Two of the six meteors showed good agreement between the radar and

Figure 4: Plot of optical mass versus maximum radar SNR. The dashed line is a fit to the data where the radar SNR is greater than 1.0.

optics for both the horizontal speed (< 10 km/s) and direction ($< 10^\circ$) of the meteor, these had the highest radar SNR values (2.5 and 2.7). The meteors with radar SNR less than 2.5 showed either close agreement for the horizontal speed (< 5 km/s), but not good agreement on the direction ($< 30^\circ$) or large discrepancies in both speed and direction.

The interferometry technique used at this radar is accurate at quantifying meteor parameters and has the potential to be used as a method of determining the speeds and directions of meteors in the hundred microgram to several milligram mass range, which can then be used to calculate the original orbits of the meteors. The comparison to optical observations presented here suggests that one way to ensure the accuracy of the radar determined parameters is to use a threshold backscattered power, under which, it is known that the technique produces larger errors, but over which, it can be shown that the technique produces accurate estimates of the meteor parameters. The comparison presented here provides an initial estimate of the limiting threshold of the radar interferometry technique (radar SNR > 2.5), but further optical observations would be needed in order to statistically quantify the relation between radar accuracy, number of data points, returned power and meteor mass. The optical and radar derived mass estimates agreed well with each other; all within an order of magnitude and in most cases, the agreement was within a factor of two.

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References

- Bouquet, A., Baratoux, D., Vaubaillon, J., Gritsevich, M. I., Mimoun, D., Mousis, O., Bouley, S., Nov. 2014. Simulation of the capabilities of an

338 orbiter for monitoring the entry of interplanetary matter into the terrestrial
339 atmosphere. *Planet. Space Sci.* 103, 238–249.

340 Brown, P., Weryk, R. J., Wong, D. K., Jones, J., May 2008. A meteoroid
341 stream survey using the Canadian Meteor Orbit Radar. I. Methodology
342 and radiant catalogue. *ICARUS* 195, 317–339.

343 Campbell-Brown, M. D., Kero, J., Szasz, C., Pellinen-Wannberg, A., Weryk,
344 R. J., Sep. 2012. Photometric and ionization masses of meteors with simul-
345 taneous EISCAT UHF radar and intensified video observations. *Journal of*
346 *Geophysical Research (Space Physics)* 117, 9323.

347 Ceplecha, Z., Borovička, J., Elford, W. G., Revelle, D. O., Hawkes, R. L.,
348 Porubčan, V., Šimek, M., Sep. 1998. Meteor Phenomena and Bodies. *Space*
349 *Science Review* 84, 327–471.

350 Chau, J. L., Woodman, R. F., Mar. 2004. Observations of meteor-head echoes
351 using the Jicamarca 50MHz radar in interferometer mode. *Atmospheric*
352 *Chemistry & Physics* 4, 511–521.

353 Close, S., Hunt, S. M., Minardi, M. J., McKeen, F. M., Sep. 2000. Analysis
354 of Perseid meteor head echo data collected using the Advanced Research
355 Projects Agency Long-Range Tracking and Instrumentation Radar (AL-
356 TAIR). *Radio Science* 35, 1233–1240.

357 Close, S., Oppenheim, M., Durand, D., Dyrud, L., Sep. 2005. A new method
358 for determining meteoroid mass from head echo data. *J. Geophys. Res.*
359 110, 9308.

360 Close, S., Oppenheim, M., Hunt, S., Dyrud, L., Oct. 2002. Scattering char-
361 acteristics of high-resolution meteor head echoes detected at multiple fre-
362 quencies. *J. Geophys. Res.* 107, 1295.

363 Close, S., Volz, R., Loveland, R., Macdonell, A., Colestock, P., Linscott,
364 I., Oppenheim, M., Sep. 2012. Determining meteoroid bulk densities us-
365 ing a plasma scattering model with high-power large-aperture radar data.
366 *ICARUS* 221, 300–309.

367 Dyrud, L., Janches, D., Sep. 2008. Modeling the meteor head echo using
368 Arecibo radar observations. *Journal of Atmospheric and Solar-Terrestrial*
369 *Physics* 70, 1621–1632.

370 Dyrud, L. P., Kudeki, E., Oppenheim, M., Dec. 2007. Modeling long duration
371 meteor trails. *J. Geophys. Res.* 112, 12307.

372 Fentzke, J. T., Janches, D., Mar. 2008. A semi-empirical model of the con-
373 tribution from sporadic meteoroid sources on the meteor input function
374 in the MLT observed at Arecibo. *Journal of Geophysical Research (Space*
375 *Physics)* 113, 3304.

376 Fritts, D. C., Janches, D., Hocking, W. K., Oct. 2010. Southern Argentina
377 Agile Meteor Radar: Initial assessment of gravity wave momentum fluxes.
378 *Journal of Geophysical Research (Atmospheres)* 115, 19123.

379 Fritts, D. C., Janches, D., Hocking, W. K., Mitchell, N. J., Taylor, M. J.,
380 May 2012. Assessment of gravity wave momentum flux measurement capa-
381 bilities by meteor radars having different transmitter power and antenna
382 configurations. *Journal of Geophysical Research (Atmospheres)* 117, 10108.

383 Grime, B. W., Kane, T. J., Collins, S. C., Kelley, M. C., Kruschwitz, C. A.,
384 Friedman, J. S., Tepley, C. A., Mar. 1999. Meteor trail advection and
385 dispersion; preliminary lidar observations. *Geophys. Res. Lett.* 26, 675–
386 678.

387 Gritsevich, M. I., Aug. 2009. Determination of parameters of meteor bodies
388 based on flight observational data. *Advances in Space Research* 44, 323–
389 334.

390 Hill, K. A., Rogers, L. A., Hawkes, R. L., Dec. 2005. High geocentric velocity
391 meteor ablation. *Astronomy and Astrophysics* 444, 615–624.

392 Hocking, W. K., Fuller, B., Vandepeer, B., Jan. 2001. Real-time determi-
393 nation of meteor-related parameters utilizing modern digital technology.
394 *Journal of Atmospheric and Solar-Terrestrial Physics* 63, 155–169.

395 Hocking, W. K., Thayaparan, T., Jones, J., 1997. Meteor decay times and
396 their use in determining a diagnostic mesospheric Temperature-pressure
397 parameter: Methodology and one year of data. *Geophys. Res. Lett.* 24,
398 2977–2980.

399 Janches, D., Heinselman, C. J., Chau, J. L., Chandran, A., Woodman, R.,
400 Jul. 2006. Modeling the global micrometeor input function in the upper

401 atmosphere observed by high power and large aperture radars. *J. Geophys.*
402 *Res.* 111, 7317.

403 Janches, D., Hocking, W., Pifko, S., Hormaechea, J. L., Fritts, D. C., Brunini,
404 C., Michell, R., Samara, M., 2014a. Interferometric meteor head echo ob-
405 servations using the Southern Argentina Agile Meteor Radar. *J. Geophys.*
406 *Res.* 119.

407 Janches, D., Nolan, M. C., Meisel, D. D., Mathews, J. D., Zhou, Q. H., Moser,
408 D. E., Jun. 2003. On the geocentric micrometeor velocity distribution. *J.*
409 *Geophys. Res.* 108, 1222.

410 Janches, D., Nolan, M. C., Sulzer, M., Apr. 2004. Radiant measurement
411 accuracy of micrometeors detected by the Arecibo 430 MHz Dual-Beam
412 Radar. *Atmospheric Chemistry & Physics* 4, 621–626.

413 Janches, D., Plane, J. M. C., Nesvorný, D., Feng, W., Vokrouhlický, D.,
414 Nicolls, M. J., Nov. 2014b. Radar Detectability Studies of Slow and Small
415 Zodiacal Dust Cloud Particles. I. The Case of Arecibo 430 MHz Meteor
416 Head Echo Observations. *The Astrophysical Journal* 796, 41.

417 Kaiser, N., Brown, P., Hawkes, R. L., Dec. 2004. Optical Trail Width Mea-
418 surements of Faint Meteors. *Earth Moon and Planets* 95, 579–586.

419 Kero, J., Szasz, C., Nakamura, T., Meisel, D. D., Ueda, M., Fujiwara, Y.,
420 Terasawa, T., Miyamoto, H., Nishimura, K., Oct. 2011. First results from
421 the 2009-2010 MU radar head echo observation programme for sporadic
422 and shower meteors: the Orionids 2009. *Mon. Not. R. Astron. Soc.* 416,
423 2550–2559.

424 Mathews, J. D., Janches, D., Meisel, D. D., Zhou, Q.-H., 2001. The mi-
425 crometeoroid mass flux into the upper atmosphere: Arecibo results and a
426 comparison with prior estimates. *Geophys. Res. Lett.* 28, 1929–1932.

427 McNeil, W., 1999. Modeling of Meteor Trails as Observed by LIDAR. In:
428 Jenniskens, P. (Ed.), *The Leonid MAC Workshop*, NASA Ames Research
429 Center, CA, April 12-15, 1999. Eds.: P. Jenniskens, *Meteoritics & Plane-*
430 *tary Science*, meeting abstract.

- 431 Michell, R. G., Aug. 2010. Simultaneous optical and radar measurements of
432 meteors using the Poker Flat Incoherent Scatter Radar. *Journal of Atmo-*
433 *spheric and Solar-Terrestrial Physics* 72, 1212–1220.
- 434 Moreno-Ibáñez, M., Gritsevich, M., Trigo-Rodríguez, J. M., Apr. 2015. New
435 methodology to determine the terminal height of a fireball. *ICARUS* 250,
436 544–552.
- 437 Oppenheim, M. M., vom Endt, A. F., Dyrud, L. P., Oct. 2000. Electro-
438 dynamics of meteor trail evolution in the equatorial E-region ionosphere.
439 *Geophys. Res. Lett.* 27, 3173–3176.
- 440 Pifko, S., Janches, D., Close, S., Sparks, J., Nakamura, T., Nesvorny, D.,
441 Mar. 2013. The Meteoroid Input Function and predictions of mid-latitude
442 meteor observations by the MU radar. *ICARUS* 223, 444–459.
- 443 Reddi, C. R., Nair, S. M., 1998. Meteor trail induced backscatter in MST
444 radar echoes. *Geophys. Res. Lett.* 25, 473–476.
- 445 Shamir, L., Jun. 2005. Analysis of meteor trails using the Night Sky Live
446 network of panoramic CCD cameras. *WGN, Journal of the International*
447 *Meteor Organization* 33, 75–80.
- 448 Sparks, J. J., Janches, D., Nicolls, M. J., Heinselman, C., Oct. 2010. De-
449 termination of physical and radiant meteor properties using PFISR in-
450 terferometry measurements of head echoes. *Journal of Atmospheric and*
451 *Solar-Terrestrial Physics* 72, 1221–1230.
- 452 Stober, G., Jacobi, C., Singer, W., Jun. 2011. Meteoroid mass determina-
453 tion from underdense trails. *Journal of Atmospheric and Solar-Terrestrial*
454 *Physics* 73, 895–900.
- 455 Von Zahn, U., Nov. 2001. Lidar observations of meteor trails: evidence for
456 fragmentation of meteoroids and their subsequent differential ablation. In:
457 Warmbein, B. (Ed.), *Meteoroids 2001 Conference*. Vol. 495 of ESA Special
458 Publication. pp. 303–314.
- 459 Vondrak, T., Plane, J. M. C., Broadley, S., Janches, D., Dec. 2008. A chemi-
460 cal model of meteoric ablation. *Atmospheric Chemistry & Physics* 8, 7015–
461 7031.

462 Weryk, R. J., Brown, P. G., Jun. 2013. Simultaneous radar and video
463 meteors-II: Photometry and ionisation. Planetary and Space Science 81,
464 32-47.