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Comparing eyewitness-derived trajectories of bright meteors to instrumentally-observed data

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Abstract

The NASA Meteoroid Environment Office (MEO) is often called upon to analyze meteors of public interest observed over the United States. Data from meteor networks are often utilized to accomplish this, as are recordings from the general public. When these methods fail, eyewitness reports are the only resource which can be leveraged. The MEO developed a tool to crudely calculate the trajectories of bright meteors from the eyewitness reports submitted to the American Meteor Society. The tool was tested on eyewitness data for 33 cases and compared to observed data from the NASA All Sky Fireball Network. The tool performed better for cases with more than 75 eyewitness reports than those with fewer than 75, by almost a factor of two across all metrics except for the end height. For these cases, the eyewitness-derived trajectory was about 50 km from the observed trajectory, the radiant was within 15°, and the speed was within 20% of that observed on average. A description of the tool, example case studies, and general trends are described.

Keywords

Meteor; Fireball; Eyewitness reports; Trajectory

1. Introduction

The NASA Meteoroid Environment Office (MEO) is the only U.S. government agency tasked with analyzing meteors of public interest. When queried about a meteor observed over the United States, the MEO must respond with a characterization of the trajectory, orbit, and size within a few hours. Using observations from meteor networks like the NASA All Sky Fireball Network (Cooke and Moser, 2012) or the Southern Ontario Meteor Network (SOMN) (Weryk et al., 2008), such a characterization is often readily performed. If found, casual recordings from the public and stationary web cameras can also be used to roughly analyze a meteor trajectory if the camera's location can be identified and its imagery calibrated. Performing this sort of analysis is more time-consuming and the result may be more prone to uncertainty. The MEO utilizes casual recordings, however, when data from meteor networks is unavailable. The analyses of several meteorite falls have made use of casual recordings quite extensively, including the Chelyabinsk meteorite fall in 2013 (Borovička et al., 2013).

If the event occurs outside meteor network coverage, if an insufficient number of videos are found, or if the imagery cannot be geolocated or calibrated, a timely assessment can be difficult if not impossible. Under these circumstances, visual reports made by eyewitnesses may be the only resource available. This situation led the MEO to develop a tool to quickly calculate crude meteor trajectories from eyewitness reports made to the American Meteor Society (AMS). An assessment of the performance of this tool, accomplished by comparing the eyewitness-derived trajectory to instrumental data, is the main focus of this study. A description of the data sources utilized, the methodology behind the trajectory tool, four example case studies, and a comparison of the tool's results to meteor data observed by the NASA All Sky Fireball Network for 33 cases are discussed herein.

2. Data

Two data sources were used for this work. Instrumentally-observed meteor data was acquired by the NASA All Sky Fireball Network. Eyewitness reports were those submitted to the AMS by members of the public. Test cases for measuring the performance of the trajectory tool were identified by comparing the databases of these two data sources.

2.1. Instrumental data: NASA All Sky Fireball Network

The NASA All Sky Fireball Network was established by the MEO in 2008. It consists of 14 meteor video cameras in the United States set up to observe and study bright meteors caused by cm-sized meteoroids. As shown in Fig. 1, six camera stations are located in the southeastern United States, five are in the southwest, and three are in the north. All-sky cameras in each subcluster were placed 65–145 km apart in order to obtain overlapping fields of view.

The camera design and ASGARD real-time meteor detection and analysis software were adopted from the SOMN, run by the University of Western Ontario in Canada (Weryk et al., 2008; Brown et al., 2010) and has similar resolution¹ and sensitivity. Each all-sky station consists of a Linux desktop machine running ASGARD, with a monochrome Watec 902H2 Ultimate CCD video camera operating at 30 fps, outfitted with a 2 mm $f/1.4$ fisheye lens, an on/off daylight sensor, and a GPS receiver for time-keeping. The weatherproof camera housing consists of a PVC pipe and a clear acrylic dome, with a heater to prevent dewing. Fig. 2 shows a typical all-sky camera.

In standard operation, the ASGARD software automatically detects meteors, correlates meteors seen by multiple camera stations, and analyzes the meteor video to determine trajectories and orbits. Astrometric calibration of each camera is performed by creating a plate mapping the image coordinates to celestial coordinates using stars identified in stacked video frames and their corresponding positions in the SKY2000 catalog (Myers et al., 2002). Meteor positions are automatically chosen by ASGARD in each video frame through an intensity-weighted center-of-mass algorithm, giving subpixel resolution. To calculate trajectory solutions and orbits, ASGARD utilizes the programs MILIG (Borovicka, 1990) and MORB (Ceplecha, 1987). The data pipeline and analysis are automated and meteor results are stored in a database, reported to a public website, <http://fireballs.ndc.nasa.gov>,

and disseminated to users each morning via email. As of mid-2016, after about 7.5 years of operation, the network has automatically detected roughly 20,000 multi-station meteors.

In cases where the automated analysis routines poorly tracked the meteor's position, usually due to bad data points introduced by nearby stars or bright flares, a manual astrometric analysis was performed using the METeor AnaLyzer program, METAL (Weryk and Brown, 2012). For each camera station, a METAL user consistently picked a position near the leading edge of the meteor in each video frame, which was then refined by weighting nearby pixel intensities. MILIG was then used to compute the trajectory solution.

Uncertainties in the trajectory solutions were computed using a Monte-Carlo simulation code, as in Musci et al. (2012) and Weryk and Brown (2012). Gaussian distributions with a standard deviation of one pixel were applied to model the random and systematic errors in the meteor location picks. These were propagated through the trajectory calculations in 10,000 independent iterations. The resulting widths of the near-Gaussian distributions of height, radiant position, and speed were used as the uncertainties in those parameters.

2.2. Eyewitness data: website of the AMS

The AMS was founded in 1911 in order to promote meteor research by amateurs and professionals. Since 2005, it has also collected reports of meteors from the public via the website of the AMS, www.amsmeteors.org. For each report, eyewitnesses enter the date and time of the meteor, their location, level of observing experience, and the direction they were looking at the time of the observation. They estimate the starting and ending elevation and azimuth of the meteor, its brightness, duration, and color, and enter other observations about flaring, fragmentation, and associated sounds (Hankey et al., 2014). Reports from different eyewitnesses are correlated by observation time and location and grouped into events, each with a unique name and number. Events from each year are accessible via the AMS Fireball Log linked from the AMS homepage. As of mid-2016, the AMS website has received reports describing about 18,000 events over the United States. Roughly 2000 of these events received five or more eyewitness reports.

Coverage of the NASA All Sky Fireball Network is such that the network can detect meteors over cities like Phoenix, Detroit, Nashville, Tucson, Atlanta, Cleveland, and Pittsburgh. But the majority of meteors reported to the AMS from population centers in the northeast (New York, Philadelphia, and Boston), the Pacific coast (Los Angeles, San Diego, San Jose, and San Francisco), the midwest (Chicago, Indianapolis, and Columbus) and the south (Houston, San Antonio, Dallas, Austin, and Jacksonville) are beyond the network's range.

2.3. Data selection

This work evaluated the performance of the tool by comparing the eyewitness-derived trajectory to the corresponding instrumentally-observed trajectory for several cases. To prepare the data for comparison, events in the AMS Fireball Log were correlated with meteors in the NASA All Sky Fireball Network database.

Matching pairs were identified via a three step process. First, meteor data occurring within 30 min of AMS events having five or more eyewitness reports was selected. The minimum

number of reports was chosen as the lower limit on the number of reports necessary to determine an eyewitness-based trajectory. This initial search yielded 398 possible matches between datasets for the time period from October 2008 to May 2016. Next, the potential matches between meteor data and eyewitness data were screened through a manual inspection of a map of the eyewitness locations and the position of the observed meteor ground track. AMS events with eyewitnesses located unreasonably far from the observed ground track were discarded, narrowing the results to 96 potential data pairs. Finally, matches with poor trajectory data (i.e., the observation was solely on the edge of the cameras' field of view) were removed. This process left 33 cases for testing the tool.

3. Eyewitness-derived trajectories

The software tool used to quickly calculate crude meteor trajectories from eyewitness reports is described. The parameters used to judge the tool's performance are also addressed.

3.1. Tool I/O

The tool ingests all of the AMS reports for each event from the website. For each report this data includes the meteor date and time, eyewitness location, meteor starting and ending azimuth and elevation, meteor duration, and eyewitness experience level. The experience level is a self-reported value measured on a scale of one (least) to five (most) describing the amount of observational experience possessed by the eyewitness.

The tool outputs data describing the meteor's trajectory, apparent radiant, and average speed, and creates a map of the meteor's ground track shown alongside the eyewitness locations.

3.2. Methodology

The tool was written using the following methodology: (1) Identify eyewitness reports of interest from the AMS Fireball Log, either from the list of pending reports or cataloged reports. The minimum eyewitness experience level may be specified. (2) Import the eyewitness data from each report. (3) Remove report outliers based on the time of observation and look-direction. (4) Fill in missing data, i.e. the eyewitness elevation from their given location. (5) Remove reports with missing meteor azimuth or elevation data. (6) Calculate starting and ending sightlines for each observer, representing lines from the observer's position to the meteor's starting and ending azimuth and elevation. (7) Find a model trajectory, consisting of a starting and ending point, that minimizes the error for all observational sightlines using a distance error metric. The result is the first attempt at the trajectory, *track 1*. (8) Identify and remove outlying observations with large standard deviations. (9) Refit the model track as in step 7, yielding the second attempt at the trajectory, *track 2*. (10) Calculate the apparent radiant position from the trajectory solution and a crude, in-atmosphere speed by taking into account the length of the trajectory and the average meteor duration reported by eyewitnesses.

3.3. Performance characterization

In order to judge the performance of the tool, the tool outputs were compared to meteor data observed by the NASA All Sky Fireball Network. Several parameters were used as metrics,

including the meteor's starting and ending height, apparent radiant, average speed, and an average distance error described by the average of the vector difference between the observed and eyewitness-derived starting and ending location.

4. Results

The trajectory tool was run on 33 events in the AMS Fireball Log that had matching meteor observations in the NASA All Sky Fireball Network. Trajectory data for all 33 cases is given in Appendix A. The eyewitness-derived trajectories were compared to the instrumentally-observed trajectories and the tool's performance was evaluated as described in Section 3.3.

Presented first are four example cases: two with good results and two with poor results. Observed meteor imagery for these cases is seen in Fig. 3. Observations from only a single camera are shown here for illustrative purposes; multiple cameras detected each meteor in this study. The results for each example case are summarized in Table 1.

Following the four example cases, general trends among all 33 test cases are discussed.

4.1. Example cases: good results

The eyewitness-derived ground track output by the tool for case 1, observed on 8 November 2015 at 04:29:10 UT, is seen in Fig. 4a; the *track 1* result is pictured. This meteor received 31 eyewitness reports, 19 with good, complete data. The eyewitness-derived ground track lies on top of the observed track. The average distance between the two was only 25 km, and much of that came from the difference between the eyewitness-derived and observed height, with an error of 32% for the start height and 25% for the end height. The radiant was within 5° of that observed, and the speed was within 28%. *Track 2* results were similar: the average distance error was 15 km, the starting and ending height errors were improved to 4% and 5%, respectively, the radiant error was 7°, and the speed error was 37%.

Solution *track 1* performed better than *track 2* for radiant and speed in case 1, but *track 2s* height estimate and average distance error were an improvement. The results for both tracks were comparable to the observed data. Eyewitness reports of the event from many different vantage points benefited the solution. This fireball was considered well-characterized by the tool.

Fig. 4b shows the tool's result for case 2, observed on 3 August 2014 at 03:19:14 UT, where the *track 2* solution is given. This event received 123 eyewitness reports, though only 70 and 55 reports were used in the track solutions, *track 1* and *track 2*, respectively. A large portion of reports either had incomplete data or were rejected as outliers. For the *track 2* result, the eyewitness-derived ground track lies almost on top of the observed track. The eyewitness trajectory was shorter than the observed one, though the average distance error was 44 km. The tool performed very well in determining the radiant and speed: the radiant was within 7° of the observed radiant and the speed was within 2%. The starting height error was only 9%, but the ending height error was an unfortunate 97%. This was an improvement over *track 1*, however, as it had an average distance error of 47 km, with starting and ending errors of

24% and 122% respectively. The *track 1* radiant was within 8° of observed and it exhibited a 6% error in speed.

The two solution tracks for case 2 were comparable to each other in location, though *track 2* performed better across all metrics. Both tracks do well predicting the location, radiant, and speed and as a result, this fireball was considered well-characterized by the tool. Both solutions had difficulty, however, matching the end height; the fireball was observed quite low in the atmosphere (29.1 ± 0.3 km).

4.2. Example cases: poor results

The resultant ground track for case 3 *track 2* is seen in Fig. 5a. This event, observed on 19 November 2012 at 00:29:22 UT, received nine eyewitness reports, though only roughly half remained after outlier rejection. The average distance error was 54 km, but the starting and ending height errors were 92% and 125%, respectively. The tool failed to determine a comparable radiant and speed as well, with a radiant error of 33° and a speed error of 112%. *Track 1* had similar problems: an average distance error of 72 km, height errors of 121% and 101% for the starting and ending points, a radiant error of 36° , and an extremely large speed error of 209%.

The two solution tracks do manage to capture the approximate position of the fireball for case 3, but do not characterize the speed, direction of travel, or starting or ending heights. The start of the tracks began too high and the end heights were similarly too high, failing to capture the observed end of the trajectory. *Track 2* was an improvement over *track 1*, but still performed poorly. These issues may stem from the fact that there were simply too few eyewitnesses and/or the eyewitness reports were too inconsistent to characterize this fireball's trajectory.

The eyewitness-derived ground track for the *track 1* solution in case 4 is seen in Fig. 5b. This event, observed on 7 November 2014 at 00:45:07 UT, received 74 eyewitness reports, though only slightly more than half of those were used; the remainder either had incomplete data or were rejected as outliers. The eyewitness trajectory was quite distant from the observed trajectory, with an average distance error of 110 km. The starting and ending heights were within 11% and 14%, respectively, the radiant was 20° from that observed, and the solution had a 50% speed error. *Track 2* fared better across all metrics except average distance, with an error of 116 km. The errors in starting and ending heights were within 9% and 4% of the observed values. The radiant was 20° from the observed value and the speed error was 17%.

The two solution tracks were comparable to each other in most respects except that *track 2* better characterized the speed. Neither *track 1* or *track 2* did well determining the meteor's location. This result may be due to the fact that most eyewitnesses were located south of the fireball. Consequently the eyewitness-derived trajectory was pulled southward when compared to the observed trajectory. Due to this positional offset, this fireball trajectory was not considered well-characterized by the tool.

4.3. General trends

To find general trends among all 33 test cases, the average distance error, radiant error, and the percent error in speed were plotted as a function of the total number of eyewitness reports (Fig. 6). As the number of eyewitness reports increases, the errors in the average distance, radiant, speed, and starting and ending heights decrease. This trend implies that the tool generally performs better when more eyewitnesses report the event. This finding is expected, as the more reports a meteor has, the less a problematic eyewitness report will affect the result. Where the reports come from in relation to the location of the fireball is also an issue. The tool performs better when the meteor has widely distributed eyewitnesses, as evidenced in case 1, despite the relatively small number of reports.

Breaking up the cases into two categories, those with less than 75 total eyewitness reports (27 cases) and those with greater than 75 reports (6 cases), shows large differences between the two groups, as summarized in Table 2. Looking again at the same performance metrics, the tool better matched the observations in the latter category by almost a factor of two across the board, with the exception of end height. In the category with fewer eyewitnesses, the derived speed was typically higher than the observed, meaning that either the length of the trajectory determined by the tool was too long, or the duration given by the eyewitnesses was too short. The reverse was true for meteors with more eyewitnesses.

The tool determined starting meteor height better than ending height, though there were several cases where the eyewitness-derived trajectory heights were not realistic. More work is needed to improve the trajectory tool in this regard. The starting and ending heights are not a perfect metric, however, as there may be several issues at work. (1) Eyewitnesses may observe the start of the fireball before the cameras detect it, resulting in a higher perceived start height. (2) Eyewitnesses may observe the end of the fireball lower than the cameras detect it, resulting in a lower perceived end height. (3) Eyewitnesses are often surprised to see a meteor and may not take note of it until it has already penetrated deeper into the atmosphere, resulting in a lower perceived start height. Examining the tool's results, the majority of eyewitness-derived heights - both starting and ending - were higher than the observed meteor height. Issue 1 may explain the starting height discrepancy but it does not explain a higher ending height. The trend in higher starting and ending heights may stem from an eyewitness bias in estimating the meteor elevation that places a meteor higher in the sky than it actually was. It may be that eyewitnesses have a better grasp of compass directions (azimuth) than they do of height (elevation). This observation is reasonable, considering eyewitnesses have points of reference on the ground to indicate compass direction, but there are no such reference points for determining elevation between 0° (the ground) and 90° (straight overhead).

The quality of the track is a function of the quality of the eyewitness data and the quality of the method. Examining the relative performance of the two solution tracks yielded mixed results. On average, *track 2* performed better than *track 1*. There were several individual cases, however, where *track 1* outperformed *track 2*. In these cases, removing outlying reports negatively affected the solution. This behavior is complicated and counterintuitive and may indicate a potential area of improvement in the tool's outlier rejection methods. It also highlights the dilemma regarding the quality of the eyewitness reports: it is difficult to

determine which reports are “good” in the absence of meteor camera data (the operational mode of this tool). More work on filtering or weighting the eyewitness reports is slated for the next version of the trajectory tool.

5. Summary and future work

To quickly characterize meteors of public interest observed outside the coverage of meteor networks, a tool was created by the MEO to calculate meteor trajectories based on eyewitness reports made to the AMS. The performance of the tool was evaluated by comparing the results to meteor data collected by the NASA All Sky Fireball Network for 33 cases. Large numbers of eyewitness reports per case yielded better eyewitness-derived trajectories, as did widely-distributed observers. For cases with fewer than 75 total eyewitness reports, the eyewitness-derived trajectory was less than 100 km from the instrumentally-observed trajectory on average, the radiant was within 30° of the observed radiant, and the average speed was within 75% of the observed speed. For cases with more than 75 reports, the eyewitness-derived trajectory was about 50 km from the observed trajectory on average, the radiant was within 15° , and the speed was within 20% of that observed. Eyewitness-derived starting and ending heights were generally found to be larger than the observed heights, and were unrealistic in several cases to the point of being unreliable.

The results of this study will be used to improve the next version of the trajectory tool. Areas for future work include investigating the effects of the self-reported eyewitness experience level, improving the method for outlier rejection, developing a method for estimating confidences in the trajectory solutions given by the tool, and running more test cases as they occur.

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Appendix A. Trajectory data

The trajectory data derived from observations by the NASA All Sky Fireball Network for 33 meteors is given in Table A1. Special cases 1–4 discussed in the text in Section 4 correspond to meteor numbers 26, 13, 4, and 20, respectively.

For comparison, the eyewitness-derived trajectories for the same 33 cases determined using the MEO trajectory tool are given in Table A2; both the *track 1* and *track 2* solutions are presented where possible. For cases where no *track 2* parameters are shown, no outliers were identified (and so none were removed), and in comparisons made in the text both solutions are considered identical.

Table A1

Trajectory information for 33 meteors observed by the NASA All Sky Fireball Network. Parameters include the UT date and time of the event, the number of camera stations used to determine the trajectory (N_s), the convergence angle (Q), the starting longitude (λ_S), latitude (ϕ_S), and height (H_S), the ending longitude (λ_E), latitude (ϕ_E), and height (H_E), the apparent radiant (α_p , δ_p), and the average in-atmosphere velocity (V_{avg}), shown alongside uncertainties in each parameter.

N	Date (UT)	Time (UT)	N_{st}	Q ($^{\circ}$)	λ_S ($^{\circ}$)	ϕ_S ($^{\circ}$)	H_S (km)	λ_E ($^{\circ}$)	ϕ_E ($^{\circ}$)	H_E (km)	α_p ($^{\circ}$)	δ_p ($^{\circ}$)	$V_{avg}(\text{km s}^{-1})$									
1	20110407	01:21:57	2	39.6	-86.072	0.003	35.381	0.004	85.5	0.9	-85.953	0.003	36.026	0.009	36.1	0.5	121.89	0.08	-19.8	0.3	14.6	0.1
2	20120101	03:15:36	2	49.3	-107.43	0.01	33.003	0.009	99.5	1.0	-109.96	0.07	35.44	0.05	54	2	91.3	0.4	-33.3	0.3	25.7	0.5
3	20120213	00:02:34	3	64.0	-85.359	0.005	34.932	0.003	83.3	0.9	-84.773	0.005	35.037	0.002	36.0	0.3	8.1	0.3	13.9	0.2	14.5	0.2
4	20121119	00:29:22	4	46.3	-86.98	0.01	34.934	0.007	79	2	-86.882	0.005	34.726	0.003	21.1	0.7	324.2	0.9	55.7	0.4	11.3	0.3
5	20130317	00:49:49	3	6.5	-80.9	0.2	35.09	0.05	95	7	-82.0	0.1	36.02	0.09	53	3	154	4	-23	3	23	2
6	20130516	03:11:50	3	83.5	-84.03	0.01	33.63	0.01	92	1	-84.674	0.002	34.306	0.002	36.5	0.3	231.7	0.2	-16.8	0.2	22.6	0.2
7	20130906	09:45:34	3	44.5	-79.14	0.01	40.195	0.009	127	2	-79.28	0.01	40.908	0.007	78	1	60.4	0.5	-17.6	0.4	58.7	0.9
8	20130910	01:18:14	3	51.1	-86.654	0.007	33.45	0.01	94	1	-87.07	0.01	33.18	0.01	34	2	331	2	48.0	0.5	33.4	0.7
9	20130922	10:31:08	5	39.2	-83.963	0.009	33.33	0.02	99	2	-82.73	0.02	33.53	0.01	32.3	0.7	16.6	0.5	7.6	0.6	28.64	0.3
10	20131111	04:30:47	3	85.7	-80.870	0.004	41.067	0.005	81	1	-80.683	0.004	41.352	0.003	33.5	0.5	21.9	0.2	7.2	0.2	15.0	0.1
11	20131218	02:20:40	3	61.4	-86.016	0.006	35.461	0.004	95	1	-86.484	0.004	35.513	0.003	34.7	0.4	75.2	0.4	24.0	0.3	22.0	0.3
12	20140319	02:24:27	3	88.3	-80.097	0.009	42.740	0.002	79.4	1.0	-81.068	0.004	42.802	0.001	33	1	196.1	0.8	16.6	0.6	12.7	0.2
13	20140803	03:19:14	3	81.1	-86.146	0.004	35.613	0.007	92.0	1.0	-85.534	0.004	34.277	0.003	29.1	0.3	154.4	0.6	67.5	0.2	22.3	0.2
14	20140804	01:29:10	2	54.8	-79.358	0.008	41.069	0.006	89	1	-79.575	0.003	40.907	0.004	29.4	0.4	284.7	0.4	54.5	0.3	22.7	0.4
15	20140923	01:13:09	3	85.1	-83.12	0.05	41.367	0.006	76	4	-82.43	0.01	41.398	0.006	39	2	235	4	18	4	12.4	0.9
16	20140924	01:26:37	2	29.1	-87.93	0.02	35.121	0.004	92	1	-88.88	0.03	35.202	0.006	40	1	357.5	0.4	12.7	0.3	22.9	0.4
17	20140924	04:25:14	3	35.4	-81.97	0.01	41.129	0.009	103	4	-82.27	0.02	41.287	0.006	59	1	17	1	17	1	38	1
18	20141021	00:57:09	4	36.3	-85.67	0.01	35.86	0.01	90	2	-86.81	0.02	35.98	0.02	28.5	0.8	18.5	1.0	12.3	1.0	21.6	0.3
19	20141028	06:59:24	3	66.9	-85.449	0.007	35.623	0.004	95	1	-85.314	0.007	35.847	0.006	25	2	46.2	0.3	15.8	0.4	26.3	0.6
20	20141107	00:45:07	3	46.3	-85.067	0.02	35.402	0.005	89	2	-86.40	0.01	35.67	0.01	32	1	34.0	0.7	3.7	0.6	17.6	0.5
21	20150101	08:38:12	2	13.6	-82.64	0.03	42.27	0.02	110	3	-83.24	0.04	42.38	0.03	87	2	210	3	7	3	71	3
22	20150217	09:50:12	3	62.7	-80.287	0.007	40.798	0.003	97.9	0.9	-79.46	0.01	40.820	0.002	22	1	165.0	0.2	27.6	0.1	25.5	0.3
23	20150418	01:25:44	2	71.2	-79.41	0.02	42.21	0.01	86	1	-79.514	0.008	41.85	0.01	44	1	209	2	80.5	0.4	19.5	0.4
24	20150524	06:09:17	4	84.0	-83.389	0.005	34.69	0.01	101	1	-83.345	0.004	35.224	0.004	36.1	0.5	247.9	0.3	-7.7	0.2	25.4	0.3
25	20150730	04:40:57	4	53.4	-82.12	0.02	35.365	0.006	103	2	-82.814	0.006	35.90	0.01	65.4	1.0	339	1	-16	1	42	1

N	Date (UT)	Time (UT)	N_{st}	Q ($^{\circ}$)	λ_S ($^{\circ}$)	ϕ_S ($^{\circ}$)	H_S (km)	λ_E ($^{\circ}$)	ϕ_E ($^{\circ}$)	H_E (km)	α_p ($^{\circ}$)	δ_p ($^{\circ}$)	V_{avg} (km s $^{-1}$)									
26	20151108	04:29:10	2	14.6	-82.18	0.03	41.253	0.004	106	3	-82.45	0.04	41.435	0.006	60	2	57	3	16	3	32	1
27	20151115	04:32:12	2	43.1	-81.23	0.01	39.60	0.01	93	1	-81.381	0.008	39.70	0.01	59	1	62	2	20	1	28.0	0.7
28	20151207	01:34:33	2	12.9	-104.40	0.04	32.32	0.02	103	4	-105.70	0.02	31.81	0.02	61	2	82.0	0.9	29.8	1.0	26	1
29	20160103	03:36:44	3	35.9	-111.771	0.006	32.215	0.003	94	1	-112.68	0.02	32.146	0.003	31.7	0.7	104.7	0.3	21.9	0.2	22.4	0.4
30	20160201	01:26:10	3	39.4	-86.163	0.005	35.708	0.006	83	1	-86.612	0.007	35.766	0.006	43.3	0.5	114.7	0.5	18.0	0.5	18.1	0.2
31	20160303	04:11:45	3	14.9	-109.16	0.03	33.40	0.01	90	2	-110.106	0.010	33.29	0.01	32.3	0.7	179.6	0.4	23.1	0.5	20.5	0.4
32	20160307	04:56:25	3	86.8	-86.221	0.006	34.191	0.010	95	1	-86.317	0.004	34.891	0.004	43.3	0.5	159.0	0.2	-21.8	0.2	26.5	0.3
33	20160504	04:50:50	2	30.7	-83.91	0.01	35.411	0.006	101.3	1.0	-84.65	0.01	34.988	0.006	37.6	0.7	280.9	0.6	46.3	0.4	34.4	0.4

Table A2

Trajectory information derived from eyewitness reports for 33 meteors. Parameters and units are as in Table A1; meteor number N corresponds to meteor numbers given in Table A1. The number of eyewitness reports submitted to the AMS is shown as N_{rep} . N_{rep} with an asterisk (*) denote cases where eyewitness reports were dispersed among more than one event in the AMS Fireball Log. For meteor numbers 7 and 25, the *track 2* solution is given as “–” because it is identical to the *track 1* solution; in these two cases no additional outliers could be removed to form *track 2*.

N	N _{rep}	track 1									track 2								
		λ _S	φ _S	H _S	λ _E	φ _E	H _E	α _p	δ _p	V _{avg}	λ _S	φ _S	H _S	λ _E	φ _E	H _E	α _p	δ _p	V _{avg}
1	30	-86.13	35.47	143	-85.98	36.26	104	120	-30	30	-85.98	35.55	124	-86.01	36.20	79	132	-23	26
2	69	-109.30	33.80	135	-110.37	34.92	110	88	-34	24	-109.52	33.69	124	-110.53	34.79	98	86	-34	23
3	9	-85.23	34.81	160	-84.77	34.82	106	16	26	41	-85.36	34.88	214	-84.79	34.89	143	18	27	54
4	9	-86.19	35.05	175	-86.93	34.66	42	20	46	35	-86.74	34.74	152	-86.96	34.82	48	353	29	24
5	96	-81.84	35.06	82	-82.66	35.81	70	158	-33	24	-81.57	35.11	72	-82.47	35.90	55	157	-30	25
6	13	-83.76	34.38	66	-84.13	34.84	46	306	-29	16	-83.30	34.24	55	-83.78	34.87	43	300	-37	21
7	12	-79.04	40.87	168	-79.54	41.04	70	79	27	15	-	-	-	-	-	-	-	-	-
8	288	-86.48	33.73	71	-86.92	33.48	43	2	42	20	-86.56	33.69	64	-87.04	33.45	40	7	38	20
9	58	-83.72	34.41	96	-82.73	34.51	51	11	9	38	-83.87	34.30	89	-82.83	34.35	46	8	11	39
10	7	-80.45	40.72	122	-81.37	41.09	53	81	7	49	-80.45	40.72	122	-81.37	41.09	53	82	7	49
11	81	-86.02	35.16	105	-86.50	35.15	68	91	22	19	-85.97	35.21	98	-86.55	35.16	60	97	24	22
12	31	-80.28	42.41	99	-81.31	42.34	62	152	19	24	-80.04	42.70	92	-81.24	42.73	65	151	9	26
13	123	-86.00	35.26	114	-85.69	34.53	64	172	73	24	-85.97	35.27	100	-85.72	34.57	57	161	74	22
14	18	-79.07	41.49	186	-80.10	41.26	85	312	39	37	-79.64	41.42	91	-79.89	41.11	55	333	66	14
15	16	-83.10	41.20	164	-82.43	41.23	72	282	32	34	-83.05	41.46	138	-82.14	41.48	66	297	26	33
16	175	-87.87	35.50	100	-88.41	35.55	50	345	20	20	-87.80	35.44	91	-88.39	35.49	54	355	15	18
17	10	-82.47	40.88	193	-83.49	41.57	79	19	6	52	-82.13	40.75	186	-82.92	41.50	94	14	-1	45
18	62	-85.95	36.09	161	-86.77	35.92	96	19	32	32	-86.03	35.79	136	-86.87	35.73	89	24	21	28
19	8	-84.81	35.73	174	-85.02	36.36	113	68	-13	25	-84.56	35.07	149	-84.64	35.68	87	61	-12	24
20	74	-84.89	34.65	99	-85.74	34.60	36	30	23	26	-85.01	34.59	81	-85.67	34.56	31	29	23	21
21	13	-82.76	40.75	241	-82.71	40.88	54	146	36	82	-82.34	40.81	193	-82.77	41.05	39	163	30	70
22	131	-80.33	41.04	80	-79.89	41.03	45	158	28	15	-80.18	40.99	74	-79.72	41.00	42	157	24	14
23	71	-79.05	42.18	109	-79.23	41.85	46	180	69	20	-79.25	42.40	114	-79.49	42.13	44	180	62	21
24	25	-83.20	35.16	148	-83.34	35.60	74	279	1	27	-83.36	35.15	137	-83.40	35.53	74	285	1	23

N	N _{rep}	track 1									track 2								
		λ_S	ϕ_S	H_S	λ_E	ϕ_E	H_E	α_p	δ_p	V_{avg}	λ_S	ϕ_S	H_S	λ_E	ϕ_E	H_E	α_p	δ_p	V_{avg}
25	6	-81.34	36.03	48	-81.51	36.27	44	337	-38	11	-	-	-	-	-	-	-	-	-
26	29*	-82.16	41.24	140	-82.46	41.46	76	53	19	23	-82.19	41.09	111	-82.45	41.34	58	51	13	20
27	9	-81.08	40.06	174	-81.49	40.07	78	67	37	54	-80.95	40.31	162	-81.27	40.23	77	67	43	47
28	23*	-105.12	33.29	186	-106.49	33.29	93	53	19	42	-104.82	33.11	189	-105.95	32.88	108	58	29	36
29	8	-111.87	33.16	27	-111.99	33.32	14	76	-17	6	-111.86	33.31	11	-112.00	33.35	6	110	-3	4
30	7*	-85.99	35.63	116	-86.61	35.43	46	120	39	37	-85.77	35.71	114	-86.37	35.48	41	119	42	38
31	8	-109.67	33.32	148	-110.73	33.30	38	162	25	35	-110.59	33.08	66	-110.82	33.40	47	144	-25	11
32	6	-84.59	34.71	107	-85.96	35.75	68	156	-25	65	-84.59	34.71	107	-85.96	35.75	68	155	-25	65
33	20	-84.14	36.41	172	-85.50	36.09	107	287	28	40	-84.14	36.00	149	-85.14	35.58	88	288	38	33

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Fig. 1.

Map of the NASA All Sky Fireball Network. Each camera station is numbered and color-coded corresponding to the maps on the NASA Fireballs results webpage <http://fireballs.ndc.nasa.gov>. A range circle with a 300 km radius is also depicted for each station for reference. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article).

Fig. 2.
NASA All Sky Fireball Network meteor camera, pictured here on the roof of a building near Tucson, Arizona.

Fig. 3. Meteor observations from the NASA All Sky Fireball Network for four example cases. Left: Cases 1 (top) and 2 (bottom) Imaged from Hiram, Ohio and Tullahoma, Tennessee, respectively. Right: Cases 3 (top) and 4 (bottom) imaged from Huntsville, Alabama and Tullahoma, Tennessee, respectively.

Fig. 4.

Example cases well-characterized by the tool. The eyewitness-derived ground track (blue arrow) is shown on a map alongside the observed ground track (red arrow) for (a) case 1 and (b) case 2. The locations of eyewitnesses used in the solution are shown as black circles; cameras that observed the meteor have their locations marked by orange squares. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 5.

Example cases poorly characterized by the tool. The eyewitness-derived ground track (blue arrow) is shown on a map alongside the observed ground track (red arrow) for (a) case 3 and (b) case 4. The locations of eyewitnesses used in the solution are shown as black circles; cameras that observed the meteor have their locations marked by orange squares. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 6.

The (a) average distance error, (b) radiant error, and (c) speed error as a function of the total number of eyewitness reports submitted for the *track 1* (blue circle) and *track 2* (orange square) trajectory solutions. Generally, as the number of reports increases, the errors decrease. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1

Comparison of the eyewitness-derived trajectory determined by the MEO tool to meteor data observed by the NASA All Sky Fireball Network for four example cases. For each of case, the results for both solution tracks 1 and 2 are given alongside the number of eyewitness reports used in deriving the solutions, the average distance error, the percent errors in the starting and ending heights, H_S and H_E , respectively, the error in the apparent radiant calculation, and the percent error in the average speed. Cases 1 and 2 are considered well-characterized by the tool. Cases 3 and 4 are poorly characterized.

Case	Solution track	No. reports	Avg. dist. err (km)	H_S err (%)	H_E err (%)	Radiant err (°)	Speed err (%)
1	1	19	25	32	25	5	28
	2	17	15	4	5	7	37
2	1	70	47	24	122	8	6
	2	55	44	9	97	7	2
3	1	6	72	121	101	36	209
	2	5	54	92	125	33	112
4	1	40	110	11	14	20	50
	2	38	116	9	4	20	17

Table 2

Mean results for trajectory solutions, *track 1* and *track 2*, after categorizing the cases into two groups based on the number of eyewitnesses. Twenty-seven cases were observed by fewer than 75 eyewitnesses. The remaining six cases had more than 75 eyewitness reports. Cases with more eyewitnesses generally have better results. Column headings are as in Table 1.

Solution track	Total no. reports	Avg. dist. err (km)	H_S err (%)	H_E err (%)	Radiant err (°)	Speed err (%)
1	<75	93	61	88	27	75
2	<75	86	49	80	28	68
1	>75	50	17	68	13	20
2	>75	43	16	54	12	19