Analysis of a Citizen Science Based Fireball Tracking System

Written and Prepared By Mike Hankey March 18th, 2013
Contributors: Bob Lunsford, David Meisel PhD, Vincent Perlerin, PhD

1. Introduction

The American Meteor Society (AMS) was founded in 1911 and pioneered the study of visual meteor observations. The AMS has accepted reports of bright fireballs and bolides from the public since inception and online since 2005. All online reports are analyzed, approved, and grouped into events based on the location of the witnesses and the time of the sighting. The events are published on the AMS website along with a map displaying the witness location, sighting vectors and other details. Usually when enough reports are submitted, a rough trajectory of the fireball meteor can be plotted (see Appendix). Some of the fireballs reported to the AMS are associated with meteor showers while others are the bolide type, originating from the asteroid belt and sometimes causing sonic booms and leaving meteorites. A small percentage of reports are associated with the re-entry of space debris. Another small percentage of reports are non-meteor sightings. The AMS fireball report is a free service offered to the public and scientific community. The purpose of this paper is to present a summary of the fireball reports logged with the AMS from January 1, 2005 through February 27th, 2013.

2. Data overview

As the graph below illustrates, the number of reports filed with the AMS has been increasing over the last few years. The level of traffic on the site, the popularity of the site and improvements to the software are all contributing to more reports being filed. More people are able to find the site and more easily complete the report application. These factors contribute to an increase in witness reports being filed with the AMS.

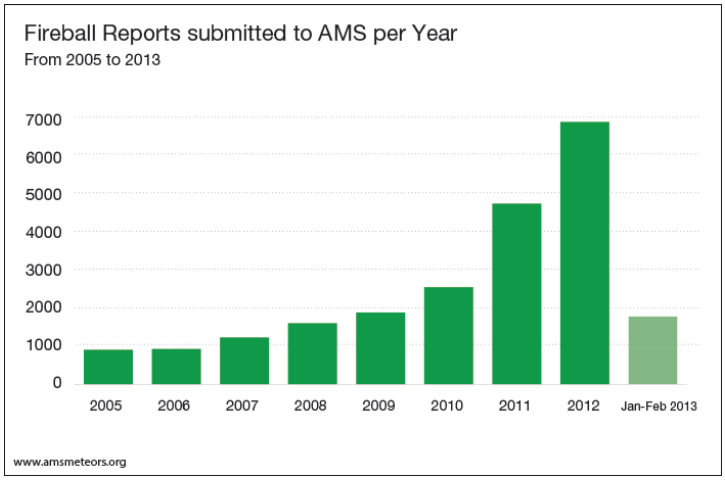
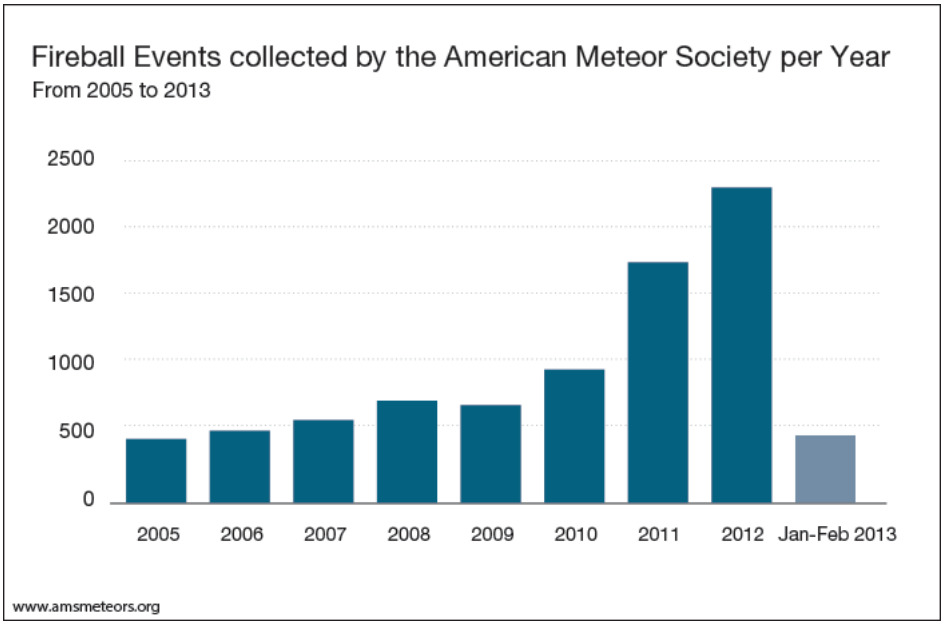


Figure 1 - Fireball Reports submitted to AMS per Year from 2005 to 2013

Not only are more reports being submitted, but also more unique events are being created. The following is a graph of unique fireball events registered by the AMS each year from January 2005 through February 27, 2013.



3. Circumstances effecting the number of reports and events collected by the AMS

There are circumstances affecting the data collected by the AMS that should be understood to prevent misinterpretation regarding the change of fireballs reported.

Things to note:

1) From January 2005 through December 2010 the AMS fireball reports system was based on the same data collection form and process created by Bob Lunsford in 2005.
2) In December 2010 the AMS fireball reporting system was upgraded to a database google maps system developed by Mike Hankey and Associates.
3) The new software made it much easier for witnesses to file reports and resulted in more witnesses successfully reporting events.
4) Internet traffic on the AMS site has increased since 2005. In current years, more people are connected with mobile devices, laptops and computers than ever before. This leads to more people reporting fireballs.
5) At least one huge event with over 100+ reports in 2009 was space trash, and there was at least 1 space trash event for 2012. The graph of 100+ events has not been adjusted to account for space trash.
6) A percentage of reports received are cloud contrails, planes, sun dogs or phenomenon other than fireball meteors. These reports are deleted when detected and generally tend to be events reported by only one witness.
7) In November 2012, the AMS fireball reporting software was upgraded again and this upgrade resulted in an immediate increase of reports received. It is believed that improvements to the user interface lessened the amount of form abandonment and other training issues that may have kept witnesses from successfully logging events on the previous version.

4. Fireball Event Classes

The AMS has recently established a method of classifying fireball events to indicate the relative size of the event. This is a simple process based solely on the number of witnesses who report the same event. The logic for this approach is based on the belief that the more noticeable the event, the more people will see it

and thus report it to the AMS. Of course this approach will not hold true for events that happen in under populated areas or odd times of night since fewer possible viewers would be present. The goal of the event classification is to add a level of differentiation between fireball events. Clearly an event reported by one person is less significant than an event reported by 100 people (regardless of how brilliant both fireballs may be). The frequency of these larger events will also be significantly less, i.e. one can agree that 100+ witness events will be less common than 1-witness events.

As total traffic to the site increases, the total number of witness reports for any given event will also increase, so viewing the data for various sized events can also be misleading. However, viewing the events by class over time provides context to the data collected by the AMS and the events the society has logged over the last 8 years.

The AMS has adopted a classification system for each event in an attempt to quantify the size of the event. The fireball classification system the AMS has chosen to adopt for this purpose follows:

Event Class	Number of Witnesses Description
Unconfirmed	Event reported by only 1 witness. The vast majority (70-80%) of events reported to the AMS are classified as unconfirmed.
Confirmed	Events reported with 2-5 witnesses are classified as confirmed events.
Mid Sized	Events with 6-20 witness reports are classed as mid-sized events.
Significant	Events with 21-50 witness reports are classed as significant.
Large	Events with 50-100 witness reports as large events.
Huge	Events with 100+ witness reports are rare and classed as huge events.
Sonic	A special class for events with sonic boom effects has been created to classify deep penetrating fireballs. 2 or more witnesses reporting a delayed boom are required to classify an event as sonic.

Table 1 – AMS Event Classification.

Below is a data table representing all of the AMS reports by event class from January 2005 through Feb 27, 2013.

Events By Class Per Year	2005	2006	2007	2008	2009	2010	2011	2012	2013
1 Witness Report (unconfirmed)	370	387	453	514	493	673	1219	1553	358
2-5 Witness Reports (confirmed)	79	118	127	186	174	242	406	590	142
6-20 Witness Reports (mid-sized)	12	21	19	36	34	47	103	122	29
21-50 Witness Reports (significant)	4	1	3	8	7	6	19	22	7
51-100 Witness Reports (large)	0	0	2	0	2	2	7	9	5
100 or more witness Reports (huge)	1	0	0	0	2	2	2	6	1
Events with Confirmed Sounds (sonic)	5	6	9	8	12	17	16	27	5
Total Events Per Year	**466**	**527**	**604**	**744**	**712**	**972**	**1756**	**2302**	**507**

Table 2 – Number of Events per class from 2005 to 2012 (with Jan-Feb 2013)

Each row in the table above shows the total fireball events recorded with the AMS by classification and year.

5. Graphs of AMS Fireball Events

Graphs for this data table have been split to compensate for scale. Below are graphs for the first 3 classes of fireball events.

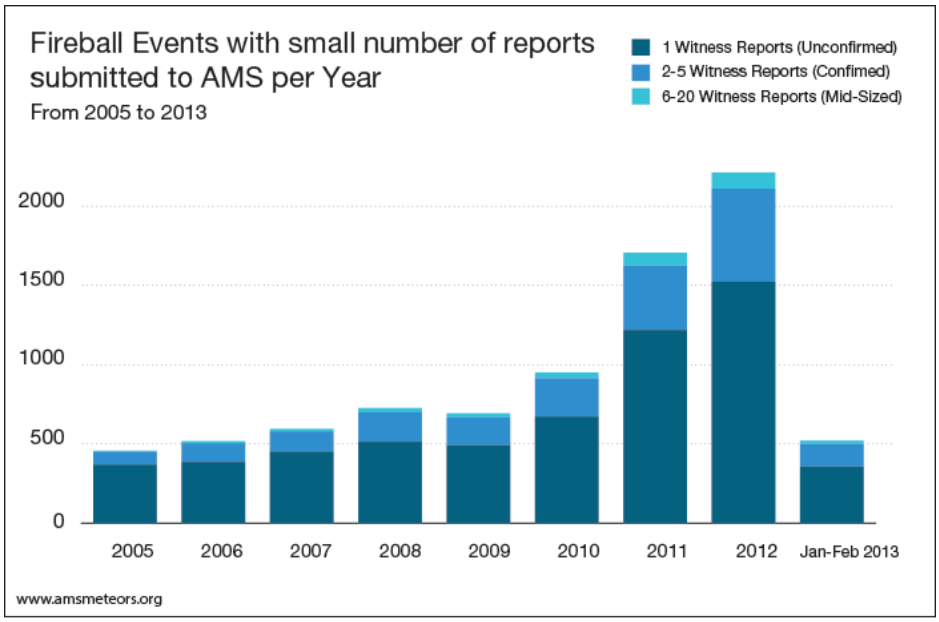


Figure 3 Fireball Events for class Unconfirmed, Confirmed and Mid-Sized submitted to AMS per Year from 2005 to 2012 (with Jan-Feb 2013)

The next graph shows the larger event classes by year.

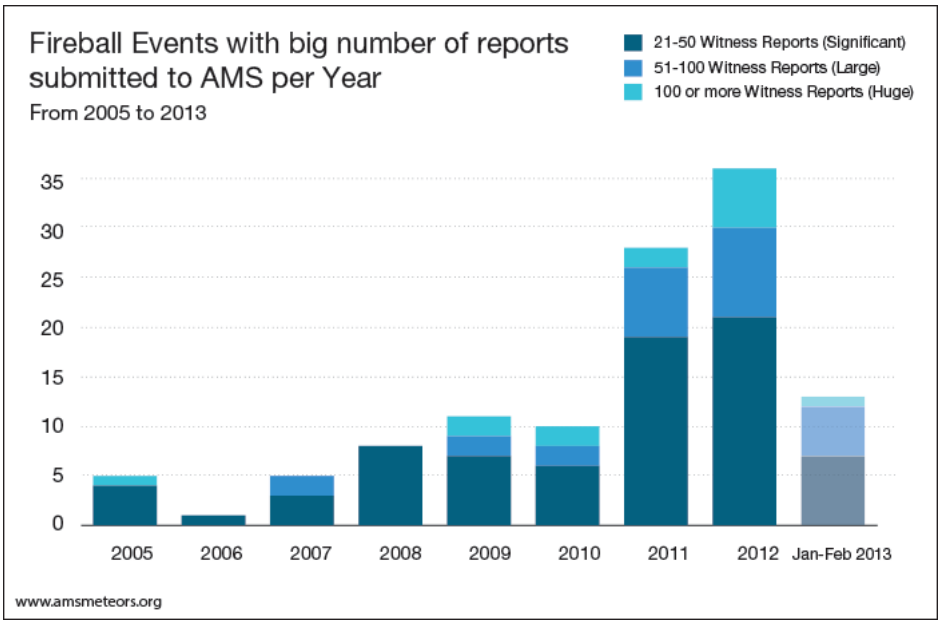


Figure 4 - Fireball Events for class Significant, Large and Huge submitted to AMS per Year from 2005 to 2012 (with Jan-Feb 2013)

Since the program's inception in 2005,the AMS has also logged flags to indicate delayed sonic booms associated with fireball events. Sonic booms sometimes accompany large bolide events when the fireball

detonates and fragments in a terminal burst, often leaving meteorites. Events with sonic booms are considered rare and a small percentage of reports with sonic booms are submitted each year. AMS events with sonic booms have risen since 2009 and doubled in 2012.

The graph below charts the sonic boom events reported by 2 and 3 witnesses.

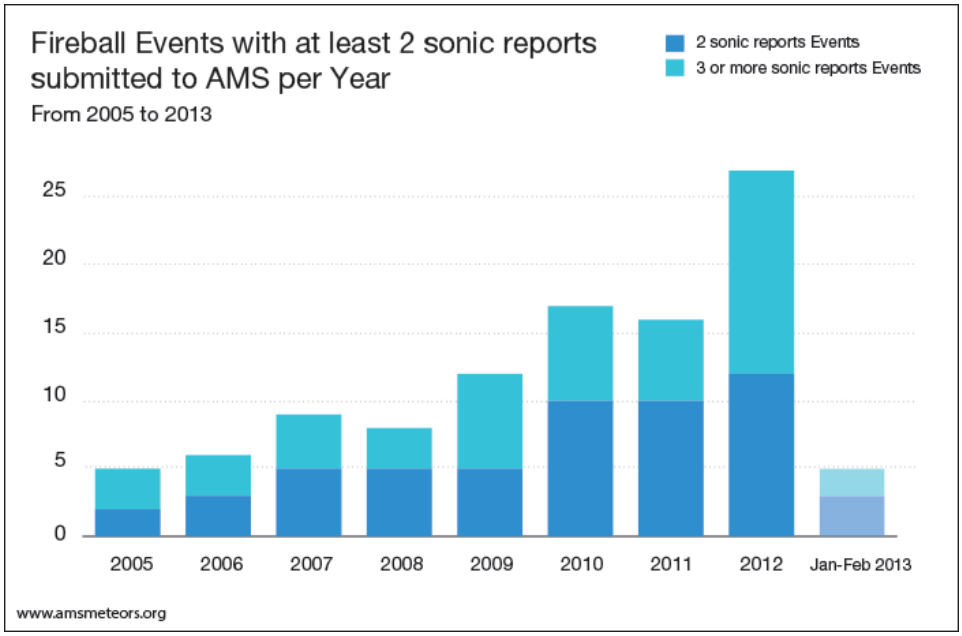


Figure 5 - Fireball Events with at least to sonic reports per Year from 2005 to 2012 (with Jan-Feb 2013)

Certainly fireball events with large numbers of witnesses are most noteworthy. The AMS has only classified 14 events as “huge” (100+ witnesses) in the 8 years of operations. 6 of those events were logged in 2012.

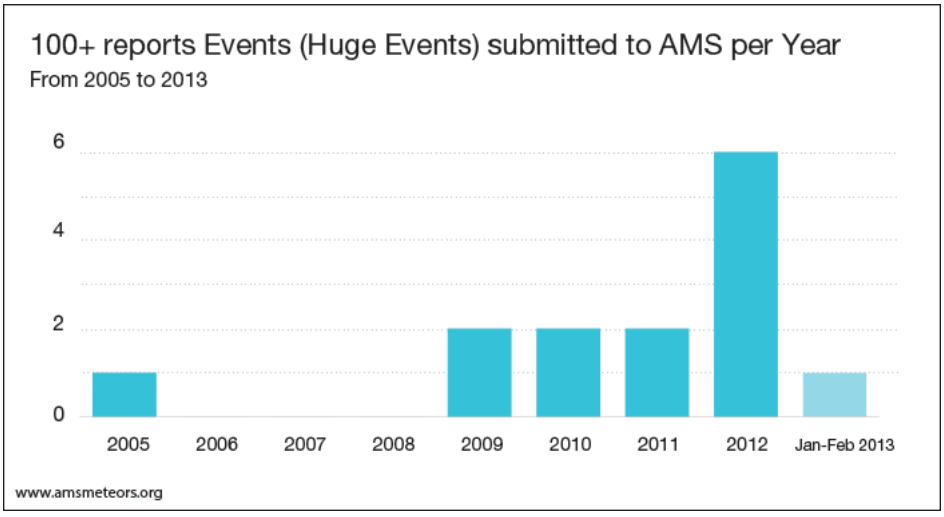
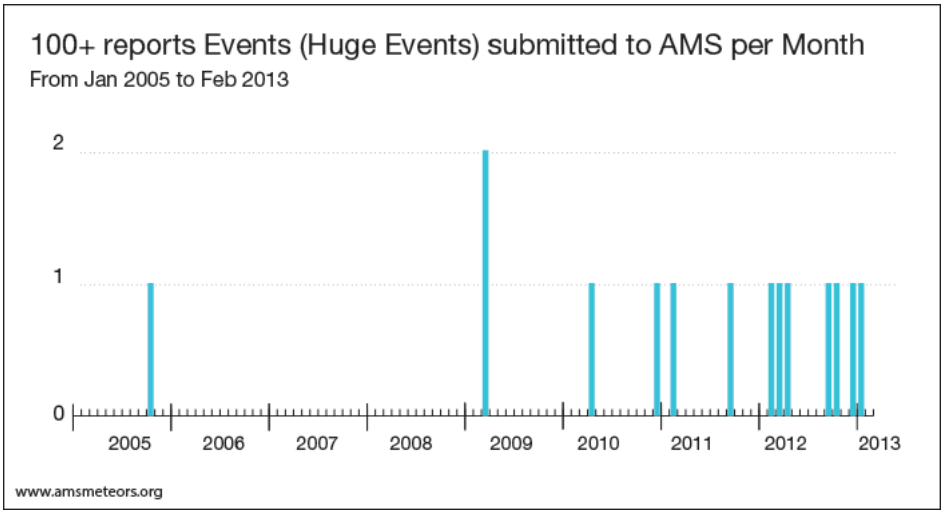


Figure 6 – Huge Fireball per Year from 2005 to 2012 (with Jan-Feb 2013)

When we look at a graph of huge events by month, we can see one huge event was reported as far back as 2005, but also a clustering of huge events was reported in 2012. We can also note that at least 4 huge events were reported to the AMS before the software upgrade at the end of 2010 (indicating that the early version of the software had enough reach and capability to register huge events).



As we can see from the graph above, the frequency of 100+ events reported to the AMS increased leading up to and including 2012.

Below is a graph of meteorite recoveries from witnessed falls from 2000 - 2012.

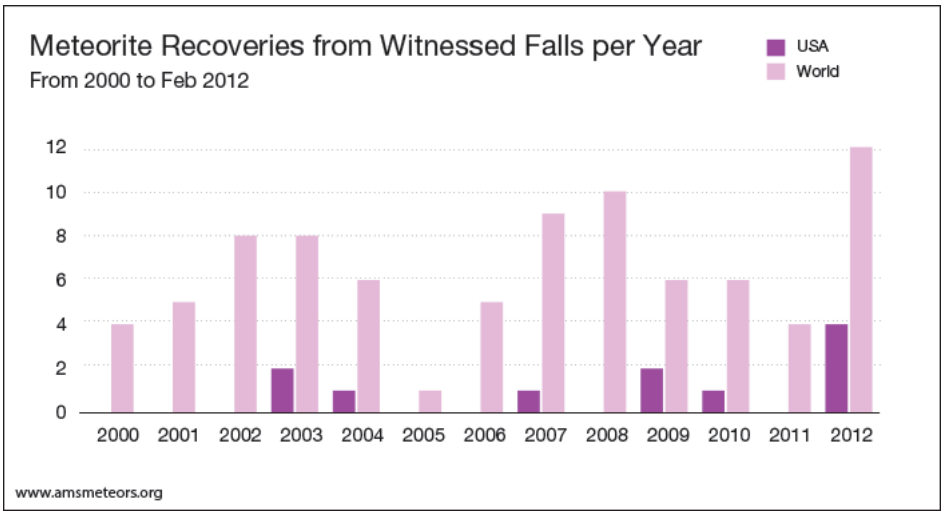


Figure 8 – Meteorite Recoveries from Witnessed Falls per Year from 2002 to 2012 – USA vs Rest of the Word

While not grossly out of proportion with past years, of coincidental interest is the fact that more meteorites from witnessed falls were recovered in 2012 than in the past 12 years. The running 12-year average for 2000-2012 is 7 meteorite recoveries per year worldwide. In 2012 there were 12.

6. Recommendations Regarding the Frequency of Fireballs Reported to the AMS

The AMS fireball reporting tool, while a useful service to the public and scientific community, is not a controlled scientific environment that one can use to reach conclusions about the frequency of fireballs. The AMS in no way suggests that the frequency of fireballs has increased or is increasing. This is not to say that fireball and bolide rates are not increasing, they may in fact be increasing, we simply cannot prove this with the AMS reports alone. We can only conclude from the data collected that more users are submitting fireball reports. It is understood that the rates of fireballs will increase and decrease year to year, but in order to

answer the question “Have the rates of fireballs been increasing lately?” a more comprehensive study is needed.

Analysis of DOD & DOE Bolide Data

As documented in, *The Flux of small near-Earth objects colliding with Earth (Letters to Nature – vol420, 2002)*, the United States Department of Defense and Department of Energy operate space-based systems that are capable of detecting bolide events across the entire globe. From the period of February 1994 to September 2002 bolide data from this system was analyzed, and based on that analysis these conclusions were made:

> *We estimate that the Earth is on average struck annually by an object of energy, 5 kton (with a possible range of 2–10 kton), and struck each month by an object with 0.3 kton of energy. Every ten years, an object of energy,50 kton strikes Earth.*
>
> Letters to Nature – *The Flux of small near-Earth objects colliding with Earth*, P. Brown, R.E. Spalding, D.O. ReVelle, E. Tagllaferri & S.P. Worden NATURE | VOL 420 | 21 NOVEMBER 2002

Re-executing this 2002 study using the DOD bolide reports from 2003-2012 would provide definitive insight into the recent perceived increase in fireball rates. Another benefit resulting from this study would be the development of a worldwide large-bolide frequency table covering a 20-year time period. It appears the DOD agrees more study of fireballs is needed and they have recently stated they will re-enable the sharing of bolide data with the public, as reported by Leonard David at space.com on February 26th, 2013.

On March 14th NASA announced the release of a Fireball and Bolide website where the analyzed results of the DOD data will be published. The AMS hopes NASA will give attention to the most significant bolide events that were recorded over the USA and reported to the AMS over the last five years. The release of bolide data relating to these events will help the AMS calibrate the reporting of our system so that future analysis will be more accurate. We will also be able to use this data to better understand past events and reach more meaningful conclusions about the size, locations and origins of these asteroids and meteoroids that have already struck Earth.

Conclusion

Since 2005, the AMS fireball report system has logged over 17,000 reports, identified more than 8,000 unique fireball events and been successfully used for different purposes by the scientific community and various government agencies including NASA, the Coast Guard, and the Air Force. Several meteorite recoveries have occurred in part due to the data collected by the AMS and the AMS fireball reports have assisted meteor and meteorite research at NASA Ames and other NASA offices. The re-entry of satellites and space debris has been confirmed by AMS reports. The Coast Guard has also used the AMS reports to vet calls about crashed airplanes off the coast of Florida (which later turn out to be fireball meteors). The AMS continues to improve the systems that collect and analyze the fireball report data. We have developed trajectory analysis programs that automatically determine the flight path of fireball meteors (within a margin of error) and we are in the process of creating orbital analysis programs for the improvement of meteorite recovery and meteor research. The AMS fireball log is the most comprehensive set of public data regarding bolide and fireball events that have taken place over the United States since 2005.

While the AMS fireball log has many uses and benefits, based on the AMS reports alone it is not possible to make conclusions about an increase or decrease in fireball/bolide events from year to year. However, the data shows that reports submitted to the society have been increasing and a significant increase in large events was specifically noticed in 2012. This warrants further study. A pairing of DOD bolide data with AMS event data would prove useful to the scientific research of meteors striking Earth. In addition, the AMS reports identify the date, time, location and relative size of significant fireball events. This information could be useful in pinpointing events inside the DOD’s data sets. The AMS makes all report data available through our website and encourages the use of our data.

The AMS appreciates criticism and review of this analysis and the fireball data presented herein. Anyone with questions regarding this article or a desire to analyze the AMS raw data for statistical purposes may contact Mike Hankey regarding their requests. Mike can be reached at mike.hankey@gmail.com.

Appendix

A .Map of Estimated Trajectories for Significant Fireball Events Reported to the AMS 2008-2013

The map below displays the trajectory (computed from witness reports) of the significant fireball events reported to the American Meteor Society from 2008 through 2013. All of these events produced sonic booms, which indicate they are associated with large deep penetrating objects. The trajectory is calculated by computing and then averaging the intersection points of all witnesses. Green dots represent the start point of the fireball and red dots represent the ending point. The red line represents the estimated flight path of the fireball.

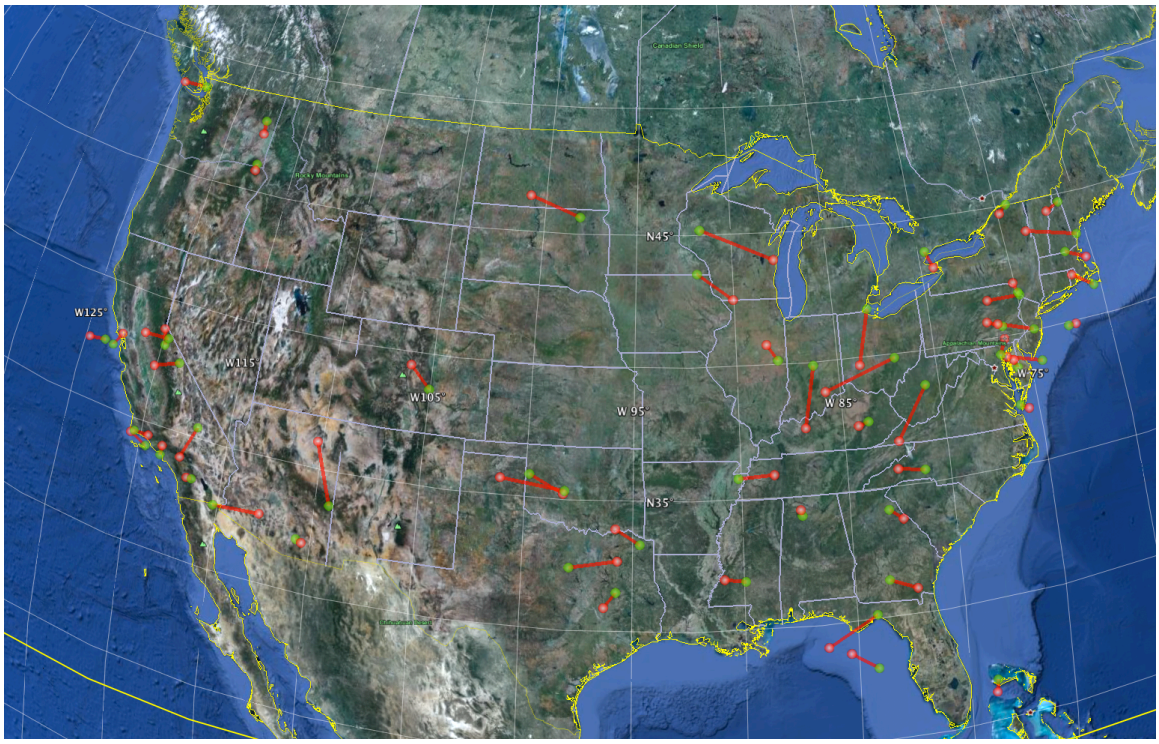


Figure 9 – Map of Established Trajectories for Significant Fireball Events Reported to the AMS between 2008 and 2013

The table below lists the events displayed in the map above. These are the most significant fireball events logged with the AMS. The AMS is seeking to pair declassified analysis of DOD bolide data for all of these events. Confirmation of the event, the energy from the event, the velocity and the location information will be very useful.

B. AMS Significant Fireball Events 2013

The following table lists the most significant events logged with the AMS in 2013. All events are associated with reports of sonic booms and represent the most significant events of the year.

AMS ID	Date Time	Estimated Starting Ending Points of Bolide*	Number of Witness Reports
2013-460	2013-02-22 06:20 UTC	34.09 -119.54 / 34.43 -120.56	68

2013-383	2013-02-17 23:59 UTC	26.78 -78.76 / 26.25 / -78.82	66
2013-326	2013-02-16 03:41 UTC	37.60 -123.56 / 37.47 -124.62	73
2013-206	2013-01-28 02:29 UTC	38.70 -80.75 / 36.71 -82.39	48
2013-166	2013-01-22 04:57 UTC	41.58 -74.95 / 41.97 -75.10	77
2013-103	2013-01-17 13:21 UTC	38.21 -119.76 / 38.81 -120.00	107
2013-63	2013-01-11 14:23 UTC	47.88 -117.76 / 47.34 -117.64	42

Table 3 – Significant events logged with the AMS in 2013

C. AMS Significant Fireball Events 2012

The following table lists the most significant events logged with the AMS in 2012. All events are associated with reports of sonic booms and represent the most significant events of the year. Note the increased number of reports in 2012 compared to other years.

AMS ID	Date Time	Estimated Starting / Ending Points of Bolide*	Number of Witness Reports
2012-2107	2012-12-08 05:15 UTC	33.39 -116.59 / 33.38 -116.88	69
2012-2085	2012-12-07 12:43 UTC	31.54 -95.73 / 30.93 -96.2	193
2012-1976	2012-11-25 04:57 UTC	37.69 -118.62 / 37.28 -120.07	40
2012-1695	2012-10-31 13:21 UTC	34.53 -120.34 / 34.53 -119.44	41
2012-1681	2012-10-30 22:34 UTC	34.29 -87.24 / 34.51 -87.33	56
2012-1677	2012-10-30 11:09 UTC	35.85 -90.50 / 35.93 -88.44	96
2012-1528	2012-10-18 02:45 UTC	37.52 -122.98 / 38.07 -122.54	292
2012-1375	2012-09-22 00:34 UTC	45.11 -74.43 / 44.67 -74.91	85
2012-1379	2012-09-21 21:52 UTC	54.46 -0.88 / 54.12 -6.74	162
2012-1252	2012-09-04 02:09 UTC	33.41 -94.72 / 33.94 -95.72	44
2012-1224	2012-08-30 01:50 UTC	35.52 -81.27 / 35.67 -82.57	54
2012-793	2012-06-06 03:17 UTC	35.33 -98.17 / 35.65 -101.03	45
2012-588	2012-04-22 14:01 UTC	38.52 -119.61 / 38.45 -121.05	118
2012-331	2012-03-06 00:58 UTC	41.46 -74.87 / 41.46 -76.76	80
2012-322	2012-03-03 21:44 UTC	55.61 -1.92 / 53.07 -1.06	181
2012-303	2012-02-29 03:14 UTC	44.69 -71.18 / 44.42 -72.03	46
2012-174	2012-02-04 03:21 UTC	38.75 -75.81 / 39.03 / -75.92	97
2012-163	2012-02-02 01:55 UTC	32.46 97.83 / 32.73 -95.69	159

Table 4- Significant events logged with the AMS in 2012

* We solve the estimated starting and ending points of the bolide by computing the intersection points of all witnesses and then averaging those locations for the start and end point of the fireball.

AMS Significant Fireball Events 2011

The following table lists the most significant events logged with the AMS in 2011. All events are associated with reports of sonic booms and represent the most significant events of the year.

AMS ID	Date Time	Estimated Starting Ending Points of Bolide*	Number of Witness Reports
2011-1626	2012-01-01 03:27 UTC	36.63 -109.41 / 36.00 -110.29	69
2011-1490	2011-12-08 04:30 UTC	39.84 -86.19 / 37.56 -86.85	60

2011-1137	2011-10-07 00:44 UTC	30.20 -84.15 / 29.12 -86.40	60
2011-1015	2011-09-15 02:45 UTC	32.60 -115.14 / 32.77 -112.69	133
2011-898	2011-08-24 02:02 UTC	45.75 -98.15 / 46.45 -100.71	49
2011-817	2011-08-12 02:38 UTC	28.06 -84.19 / 28.76 -85.38	42
2011-456	2011-04-30 02:22 UTC	31.51 -83.46 / 31.01 / -82.12	54
2011-393	2011-04-10 03:59 UTC	40.16 -87.97 / 40.76 -88.48	40
2011-331	2011-03-24 02:04 UTC	35.92 -99.81 / 35.28 -98.16	46
2011-208	2011-02-14 17:30 UTC	39.89 -72.50 / 39.90 -72.06	299
2011-86	2011-01-20 01:58 UTC	39.87 -82.13 / 38.86 -85.74	58
2011-52	2011-01-12 03:11 UTC	-31.90 -89.93 / 32.00 -90.88	61

Table 5 - Significant events logged with the AMS in 2011

* We solve the estimated starting and ending points of the bolide by computing the intersection points of all witnesses and then averaging those locations for the start and end point of the fireball.

AMS Significant Fireball Events 2010

The following table lists the most significant events logged with the AMS in 2010. All events are associated with reports of sonic booms and represent the most significant events of the year.

AMS ID	Date Time	Estimated Starting Ending Points of Bolide*	Number of Witness Reports
2010-929	2010-12-28 23:49 UTC	40.06 -74.48 / 40.53 -76.40	155
2010-705	2010-11-02 23:20 UTC	40.06 -74.48 / 40.53 -76.42	59
2010-330	2010-06-25 02:00 UTC	40.41 -76.18 / 40.66 -76.98	66
2010-194	2010-04-15 03:00 UTC	43.51 -91.84 / 42.51 -90.05	324
2010-182	2010-04-10 00:55 UTC		25

Table 6 - Significant events logged with the AMS in 2011

* We solve the estimated starting and ending points of the bolide by computing the intersection points of all witnesses and then averaging those locations for the start and end point of the fireball.

AMS Significant Fireball Events 2009

The following table lists the most significant events logged with the AMS in 2009. All events are associated with reports of sonic booms and represent the most significant events of the year.

AMS ID	Date Time	Estimated Starting Ending Points of Bolide*	Number of Witness Reports
2009-558	2009-09-26 01:03 UTC	43.72 -79.66 / 43.07 -79.32	68
2009-536	2009-09-20 04:50 UTC	42.73 -71.63 / 42.35 -70.46	21
2009-519	2009-09-13 03:15 UTC	48.64 -122.90 / 48.58 -124.63	37
2009-371	2009-07-06 05:04UTC	39.18 -76.67 39.95 76.18	41
2009-350	2009-06-24 04:22 UTC	32.14 -110.69 / 32.04 -110.40	25
2009-212	2009-03-30 01:40 UTC	37.31 -76.01 / 37.13 -75.58	156
2009-200	2009-03-20 06:30 UTC	34.18 -83.20 / 33.77 -82.56	107
2009-122	2009-02-14 02:53 UTC	37.59 -83.78 / 37.46 -84.28	32

2009-43	2009-01-19 01:33 UTC	35.44 -116.75 / 34.10 -117.45	56

Table 7 - Significant events logged with the AMS in 2009

* We solve the estimated starting and ending points of the bolide by computing the intersection points of all witnesses and then averaging those locations for the start and end point of the fireball.

AMS Significant Fireball Events 2008

The following table lists the most significant events logged with the AMS in 2008. All events are associated with reports of sonic booms and represent the most significant events of the year.

AMS ID	Date Time	Estimated Starting Ending Points of Bolide*	Number of Witness Reports
2008-715	2008-12-30 02:25 UTC	41.22 -70.45 / 41.79 -71.61	29
2008-621	2008-11-27 03:15 UTC	45.19 -91.66 / 43.97 -87.83	29
2008-474	2008-10-29 01:31 UTC	38.68 -105.02 / 39.53 -106.08	21
2008-399	2008-09-25 10:21 UTC	41.82 -83.22 / 39.74 -83.92	21
2008-239	2008-06-15 06:50 UTC	33.94 -118.59 / 34.31 -118.56	33
2008-76	2008-02-19 13:30 UTC	46.09 -117.41 / 45.84 -117.39	28
2008-317	2008-08-04 02:00 UTC	38.81 -74.39 / 39.23 -76.26	46

Table 8 - Significant events logged with the AMS in 2008

* We solve the estimated starting and ending points of the bolide by computing the intersection points of all witnesses and then averaging those locations for the start and end point of the fireball.