A Method for Mathematically Analyzing Fireball Reports

Frank Sanders, DMNS/DESS Department Associate

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1.0 INTRODUCTION

Eyewitnesses frequently observe fireballs, and in the future a DMNS camera network may perform such observations [Sanders A, 2000]. There is reason to believe that such events typically deposit meteorites on the earth's surface [Sanders B, 2000]. Infrasound and satellite data are only infrequently available. But careful analysis of eyewitness and camera data from such events may closely localize the positions of resulting falls. As a corollary, orbital elements of fireball source meteoroids may be derived. This paper describes a method for mathematically analyzing eyewitness reports of fireball events to most nearly identify the locations of resulting falls.

1.1 Overview

Assuming it is large enough to survive ablation effects, a meteoroid entering the earth's atmosphere experiences two distinct flight phases: A straight-line segment at high altitude and supersonic velocity, and a modified parabolic segment during which the meteoroid falls from high altitude to the earth's surface at subsonic velocity [Sanders B, 2000]. To localize the most likely coordinates of a meteoroid fall on the earth's surface, it is necessary to perform the following analyses:

1) Determine the initial flightline orientation in the atmosphere;
2) Determine the initial flightline lateral and vertical position in the atmosphere;
3) Determine the position of the point of retardation in the atmosphere;
4) Optionally determine the meteoroid velocity at the point of retardation, or at least place upper and lower bounds on the velocity at this point;
5) Calculate the path of fall from the point of retardation to the earth's surface [Sanders B, 2000];
6) Calculate a circular error probable (CEP) for the fall coordinates.

The first two steps determine the position, heading, and horizontal and vertical velocity components of the meteoroid at the point of retardation. The third step determines the point at which the meteoroid is launched into the lower atmosphere on a modified parabolic trajectory. The fourth and fifth steps determine the most probable amount of forward distance that the meteoroid traverses between the point of retardation and the ultimate fall location. Given a resulting circular error probable (CEP) ellipse for the fall on the earth's surface, it may be possible to engage in a search for the fall with a small but reasonable chance of success.

2.0 MATHEMATICAL THEORY

The mathematics required for this analysis are those of equations for lines and planes, including parametric analysis. A combination of polar and rectangular coordinate systems is required.

2.1 Determination of fireball flightline orientation and position

The key to computation of the flightline orientation is the assumption that a fireball initially travels on a straight line prior to the point of retardation. This assumption is justified by the fact that the meteoroid experiences a deceleration force directed opposite to its velocity vector as it enters the atmosphere. It is not expected to experience significant lift effects during this flight phase. This theoretical assumption is supported by Prairie Network camera records and eyewitness observations that indicate straight flightlines for high-altitude meteoroids.

Each fireball observer should provide two azimuths and two elevation angles pointing toward the visible track of the flightline. These are represented as ordered pairs (Az_1, El_1) and (Az_2, El_2). These may possibly point from the observer's location to the beginning of the visible event and the point of retardation, respectively. But it is not necessary that they encompass these two points on the flightline. Any two points along the flightline are adequate for subsequent analysis, on the condition that they be at or before the point of retardation.

Taking the observers' position at coordinates to be

$$(x_0, y_0, z_0) = (0, 0, 0) \qquad (1)$$

the azimuth and elevation angle ordered pairs form two vectors extending from the observer's position through the specified angles. Setting the lengths of these vectors to unity, the coordinates of the resulting vector tips are then

$$(x_n, y_n, z_n) = ((\sin Az_n \cos El_n), (\cos Az_n \cos El_n), (\sin El_n)) \qquad (2)$$

where n = 1, 2.

The three points determined by (Eqs. 1-2) define a plane, and the fireball flightline must lie somewhere within this plane if the observer's data are accurate. The equation of the plane is derived from the canonical parametric equations

$$\begin{aligned} x &= x_0 + s(x_1 - x_0) + t(x_2 - x_0) && \text{(a)} \\ y &= y_0 + s(y_1 - y_0) + t(y_2 - y_0) && \text{(b)} \\ z &= z_0 + s(z_1 - z_0) + t(z_2 - z_0) && \text{(c)} \end{aligned} \qquad (3)$$

Reducing (x_0, y_0, z_0) to (0, 0, 0); eliminating t from 3(a) and 3(c) and from 3(a) and 3(b); and then eliminating s from the two resulting equations yields an equation for the observer's plane in the form (ax + by - z = 0):

$$\frac{(x_2 y_2 z_1 - x_2 y_1 z_2)}{(x_1 x_2 y_2 - x_2^2 y_1)}\, x + \frac{(x_1 x_2 z_2 - x_2^2 z_1)}{(x_1 x_2 y_2 - x_2^2 y_1)}\, y - z = 0 \qquad (4)$$

If the observer's coordinate is generalized from (0, 0, 0) to (Δx, Δy, Δz), the resulting equation is of the form (ax + by - z = d):

$$ax + by - z = \left[(a\,\Delta x) + (b\,\Delta y) - \Delta z\right] = d \qquad (5)$$

The fireball flightline is contained somewhere within this plane. The line formed by the intersection of two observers' planes must be the flightline path prior to the point of retardation. This flightline can be defined parametrically. It can also be defined in terms of the points where it crosses the xy, yz, and xz planes of the selected coordinate system. If the two observers' plane equations are

$$a_1 x + b_1 y - z = d_1$$
$$a_2 x + b_2 y - z = d_2 \tag{6}$$

then the points $(x_1, y_1, 0)$; $(0, y_2, z_2)$; and $(x_3, 0, z_3)$, where the flightline passes through the xy, yz, and xz planes, are defined by:

$$x_1 = \frac{(d_2 b_1 - d_1 b_2)}{(a_2 b_1 - a_1 b_2)} \qquad \text{(a)}$$

$$y_1 = \left(\frac{d_1}{b_1}\right) - \left(\frac{a_1}{b_1}\right)\frac{(d_2 b_1 - d_1 b_2)}{(a_2 b_1 - a_1 b_2)} \qquad \text{(b)}$$

$$y_2 = \frac{(d_1 - d_2)}{(b_1 - b_2)} \qquad \text{(c)}$$

$$z_2 = b_1 \frac{(d_1 - d_2)}{(b_1 - b_2)} - d_1 \qquad \text{(d)}$$

$$x_3 = \left(\frac{d_1}{a_1}\right) + \left(\frac{1}{a_1}\right)\frac{(d_2 a_1 - d_1 a_2)}{(a_2 - a_1)} \qquad \text{(e)}$$

$$z_3 = \frac{(d_2 a_1 - d_1 a_2)}{(a_2 - a_1)} \qquad \text{(f)} \tag{7}$$

The fireball flightline heading relative to true north is

$$\theta_{\text{heading}} = \frac{\pi}{2} - \tan^{-1}\left(\frac{-y_2}{x_3}\right) \tag{8}$$

and the descent angle relative to the local horizon is

$$\phi_{\text{descent}} = -\tan^{-1}\frac{(z_2 - z_3)}{\sqrt{y_2^2 + x_3^2}} \tag{9}$$

The fireball flightline translational position in space is defined by the points given in (Eq. 7). Using the values from (Eq. 7), the flightline can be specified by a set of parametric equations of the form

$$
\begin{aligned}
x &= x_1 + p_1\Delta \\
y &= y_1 + p_2\Delta \qquad (10) \\
z &= z_1 + p_3\Delta
\end{aligned}
$$

where Δ is an arbitrary distance parameter along the line, and the coefficients $p_{1\text{-}3}$ are

$$
\begin{aligned}
p_1 &= \frac{x_2 - x_1}{\alpha} \\
p_2 &= \frac{y_2 - y_1}{\alpha} \qquad (11) \\
p_3 &= \frac{z_2 - z_1}{\alpha}
\end{aligned}
$$

$$\alpha = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \qquad (12)$$

2.2 Determination of fireball flightline orientation and position for a set of m observers

If m observers each report a pair of vectors (Eqs. 1-2), then a set of m planes of the form (Eq. 5) are defined, one for each observer. Every possible pair of observers defines a possible fireball flightline with position and orientation defined by (Eqs. 7-9).

For a set of m observers, the total number of possible pairs, M, is

$$M = \frac{m(m-1)}{2} \qquad (13)$$

These can be computed as a set of M possible headings, a set of M possible descent angles, and a set of M possible positions in space. From this group of sets, a most probable flightline orientation and position must be determined.

Various procedures might establish the most likely path. An effective method is to first determine the most likely heading and descent angle, and also the standard deviation of those quantities. The orientation can be determined by rejecting the largest and smallest heading and descent angles from consideration. Then the arithmetic mean and standard deviation of the remaining set of (M-2) headings and descent angles are computed. (An arithmetic rather than geometric mean is suggested with the assumption that the values to be compared are reasonably close together.)

A subset of observations is then selected to determine the most likely position in space. This subset consists of all computed flightlines for which the headings and orientations lie within plus-minus one standard deviation of the mean heading and descent angles. The number of elements, N, in this subset will be N ≤ (M-2). This subset of N flightlines will be nearly parallel to one another. Since they are nearly parallel, the mean position in space of the fireball flightline can be computed from this subset. As with orientation computations, it is recommended that the most extreme heights and lateral positions be rejected from consideration. The arithmetic mean of the remaining (N-2) altitude values and (N-2) lateral position values are then computed.

2.3 Determination of the location of the point of retardation

In principle, the location of the point of retardation may be determined from the initial set of m observations. The pertinent observations are those for which the end of the straight-line flight are noted. The azimuths of those observations are plotted across the computed flightline, and the weighted mean crossing point is assumed to represent most nearly the subpoint on the earth's surface of the point of retardation.

In practice, the location of the point of retardation may be determined more precisely by methodically searching for observers who were in the near vicinity of the meteoroid break-up. These observations are then used to fine-tune the most likely lateral position of the fireball flightline. Presumably this lateral position lies within the earlier computed standard deviation of the lateral position. The fireball's originally computed flightline orientation is retained, as is its originally computed altitude.

2.4 Determination of meteoroid velocity (optional)

If video, motion-picture, or chopped still-frame camera data are available, the meteoroid initial velocity may be computed directly from a conversion of angular rate at the camera to absolute initial velocity along the flightline. The initial velocity, when combined with the date, time, and orientation of the initial fireball flightline, can be used to determine the heliocentric orbit from which the meteoroid originated.

If no camera data are available, then the best estimate is an upper and lower bound on possible velocities. If it assumed that the meteoroid originated from an orbit of at least 1 AU mean radius from the sun, then the minimum velocity, v_{min}, is that of a circular heliocentric orbit at 1 AU. The maximum possible velocity, v_{max}, cannot be any greater than $\sqrt{2} \cdot v_{min}$.

2.5 Calculation of the path of fall from the point of retardation to the earth's surface

This calculation is described in detail in [Sanders B, 2000]. The meteoroid is assumed to be launched into the lower atmosphere from the point of retardation at an initial speed about equal to the speed of sound. The speed of sound is assumed because modelling indicates that the point of retardation marks the approximate location at which the meteoroid goes subsonic [Sanders B, 2000].

The initial speed is reduced to horizontal and vertical components, based upon the descent angle of the initial flightline. Each of those components is then reduced by atmospheric resistance. The forward component eventually drops to zero, while the vertical component is modulated by the downward force of gravity and the upward resistance of the atmosphere. Eventually the two vertical forces balance, resulting in a constant downward velocity at the end of the fall.

The complete fall is computed from a numerical analysis method. This method is described in detail in [Sanders B, 2000].

2.6 Calculation of most likely circular error probable (CEP) for the fall

The standard deviations of the heading, orientation, altitude, and lateral position of the fireball's initial flightline are used to compute upper and lower bounds on range and lateral position of the fall relative to the subpoint of the point of retardation. These bounds may be substantially tightened by accurate determination of the point of retardation by terminal observations, as described above.

The upper and lower bounds on range and lateral position should be converted into an ellipse on the earth's surface. Two standard deviations may be used to compute an even larger, but lower-probability, CEP ellipse on the earth's surface. When the CEP ellipse(s) is/are plotted, the analysis is complete. Taking into account the size of the CEP, the type of terrain in the area, and the extent and nature of local vegetation, it can then be decided by the principal investigator whether a search for the fall is warranted.

3.0 EXAMPLE: THE COLORADO FIREBALL OF 26 MAY 2000

This section illustrates the application of the mathematical principles described above to an actual fireball event. The flightline and probable fall location were computed, and a ground search in the fall vicinity may be undertaken in the near future.

3.1 Preparation

Beginning in 1995, the DMNH (now DMNS) Curator of Geology, Jack Murphy, developed a Department of Earth and Space Sciences (DESS) Meteorite Workshop for the study of all physical aspects of meteors and meteorites. The workshop was conducted several times between 1995 and 1999. In conjunction with these workshops, several key objectives were achieved under Murphy's leadership. These included:

1) Training a volunteer network, called the Meteor Posse, for in-field acquisition of critical vector data (see Section 2.1) and related fireball information from eyewitnesses;
2) Development of forms for the collection and tabulation of data from eyewitnesses, both over the telephone and at field observation locations;
3) Development of the theory of fireball flight [Sanders B, 2000];
4) Development of the mathematical theory presented in this paper;
5) Development of software to perform the computations described in this paper for a large number of eyewitnesses.

3.2 Chronology and description of the 26 May 2000 Colorado fireball event

On 26 May 2000 at 2250 hours Mountain Daylight Time (27 May at 0450 UT), a very bright fireball was observed in Colorado and adjacent states. Subsequent to this event, a DMNS Geology telephone number was provided to local news media for the collection of fireball reports from eyewitnesses. Hundreds of eyewitnesses called this number. People saw the fireball from such distant points as Moab, UT; Liberty, KS; Laramie, WY; and south of Cañon City, CO. Custom-designed forms were used to record critical information from the initial reports. Jack Murphy and his staff used initial information to identify the most potentially valuable eyewitnesses. Murphy called a meeting of the DMNS Meteor Posse and provided a briefing on the initial reports.

These reports indicated that the meteor had travelled nearly south to north above east central Colorado in the vicinity of Tarryall Reservoir and west of Mt. Evans. Jack Murphy assigned Meteor Posse members to collect detailed reports from selected eyewitnesses, in accordance with procedures developed during previous DESS meteor workshops.

Over the next two weeks, Meteor Posse volunteers collected reports from witnesses at field locations. These reports are summarized in Table 1. The reports came from people who had been nearly broadside to the trajectory, as well as persons who saw the fireball from a nearly head-on aspect angle.

The object was described as being exceptionally bright. People within 10-20 miles of the point of retardation said that it illuminated the ground like automobile headlights. Its color was usually noted as appearing red-orange at the beginning of the flight, changing to blue-white as it progressed. The visible flight was noted as being at least several seconds in length. Two witnesses at separate locations noted the time on their watches.

A sonic boom was heard by a number of witnesses. It was generally noted as being low-pitched. One group of witnesses stated that they felt an earth tremor in association with the boom. Electrophonic[1] sound, reported as being similar to that of frying bacon, was reported by some witnesses at separate locations.

By 30 June 2000, the witness reports were ready for quantitative analysis to determine the fireball's flightline orientation and spatial location. The author undertook this analysis using software that he had written in conjunction with a museum meteorite workshop. The analysis is detailed below.

3.1 Data Analysis Step 1: Generation of a planar equation for each observer

As applied to the problem of solving the meteor's initial flight path, the author's software was used to generate a planar equation from the raw data provided by each observer (Table 1). Each plane was defined by the observer's location at (x0, y0, z0) = (0, 0, 0) and by the tips of unit-length vectors for each observers' first and last sightings as points (x1, y1, z1) and (x2, y2, z2) from (Eqs. 2-5). Each plane equation incorporated the observer's coordinates in latitude, longitude, and altitude above sea level relative to an arbitrarily chosen xy coordinate origin (Eq. 6). A convenient coordinate origin for this fireball was selected to be 39° N latitude; 106° W longitude.

3.2 Data Analysis Step 2: Generation of the set of all possible intersections (possible flightlines) between observers' planes

The plane equations from each pair of observers (there being a total of m=9 witnesses) were processed by the author's software to yield an intersection line (Eq. 7 and related parametric equations for the lines) for each pair of observers, as summarized in Table 2. Each plane-intersection line was a possible solution to the fireball's path in space.

[1]Electrophonic sound is heard simultaneously with the visual apparition of a fireball. Since acoustic energy does not travel that fast, another phenomenon must occur. The origin is unknown.

3.3 Data Analysis Step 3: Determination of the best-fit solution for the fireball's flightline orientation from the set of solutions generated in Step 2

Of the observers correlated in Table 2, one witness' data fit very poorly with all others, as noted from visual inspection of the results. That witness' data were excluded from further consideration, reducing the number of usable observers to m =8. A total of 28 flightlines should have resulted (Eq. 10), but only 27 were obtained because one pair of observers had a pair of exactly parallel azimuth vectors that would yield a degenerate solution. The computed flightline orientations are plotted in Figure 1. Of the total of 27 flight paths, 24 fit within a box bracketed by headings (true) between 357° and 20°, and descent angles between -32° and -47°. This grouping is shown in detail in Figure 2. The largest and smallest headings and the largest and smallest descent angles were excluded from further consideration), and the arithmetic means of the remaining heading and descent angles were computed. A root-mean-square standard deviation was also computed for each parameter. The computed mean heading and descent angles are plotted with the data in Figure 3.

The results for the May 26 fireball were (Eqs. 8-9):

Mean heading = 10.6° ± 5°;
Mean descent angle = -35° ± 3°.

3.4 Data Analysis Step 4: Determination of the fireball flightline's most likely location in space

The fireball orientation vectors lying within one standard deviation of the mean heading and descent angle are summarized in Table 3, and were used to compute the spatial location of the fireball path in space. As discussed in Section 2.2, these particular vectors were used to compute spatial location because they were all nearly parallel and presumably were close to the fireball's actual flightline orientation. The significant difference between them was that they were translated laterally and vertically in space relative to one another. Thus it was possible to find a mean spatial location between them where the fireball probably travelled.

In this step, the three-dimensional spatial locations of the selected observer's flightlines were computed by the author's software and were graphed as piercings of the XZ plane in space, as shown in Figure 4. The XZ plane has its origin at latitude 39° N, 106° W. The 39th parallel is the X-axis, and Z is measured vertically from sea level. Distances are in statute miles. The XZ plane piercings were averaged for mean elevation above sea level and mean displacement along the X-axis. Standard deviations were computed to produce probable error bounds. The result for the May 26 fireball was:

Mean X displacement = 16.2 miles ± 5.3 miles along 39th parallel east of longitude 106°;
Mean altitude = 23.8 miles ± 4.3 miles above sea level at that point.

Taken together, the Step 3 and Step 4 results defined the best-fit solution for the path that the 26 May 2000 fireball followed through the earth's atmosphere. The error bars for heading, descent angle, altitude, and lateral position of the fireball were reasonably tight, given the inherent uncertainty in eyewitness observations.

3.5 Data Analysis Step 5: Determination of the point of retardation and most likely fall location (preliminary determination as of July 5, 2000)

A preliminary look at Jack Murphy's map for atmospheric entry and point of retardation indicates that the 26 May meteor flight probably lasted about 20 statute miles across the earth's surface north of the 39th parallel before the point of retardation was reached. Given the altitude of 24 miles above sea level at the 39th parallel and the descent angle of -35°, this implies that the point of retardation occurred at an altitude of about 10 miles above sea level, east of Kenosha Pass.

Further analysis of eyewitness accounts from the South Park area (ongoing at this time) is expected to yield a more precise determination of the location of the point of retardation on the 26 May meteor flightline. That information will in turn make it possible to compute the most likely location of the 26 May meteorite fall using an algorithm developed two years ago in conjunction with a DMNH/DESS Meteor Workshop. Our preliminary determination is that meteorite fall of May 26, 2000 fall is in a rugged, wooded area NE of Kenosha Pass.

ACKNOWLEDGMENTS

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REFERENCES

Sanders, F. H., 2000, A proposed DMNS all-sky surveillance network for observation of fireballs and meteors; in preparation for publication as of July 2000.

Sanders, F. H., 2000, Fireball physics and determination of meteorite fall locations; in preparation for publication as of July 2000.

Table 1. Observational raw data for 5/26/00 fireball.

Name	Location	#	Lat	Lon	Alt.	Az 1	El 1	Az 2	El 2	Comments
Ron Slater	e. of Estes Park	93	40.3569	105.4459	8300’	190°	21°	191°	10°	85° descent angle; saw end of flight
Julie Dunbar	Erie	151	40.0608	105.0594	5000’	197°	35.5°	203°	26.3°	Missed end
Jerry Krenz	Gold Hill	153	40.0564	105.4192	8000’	190°	20°	191°	10°	Vertical, missed end of flight
Greg Hammer, Lloyd Mills	Whiteside campground	163	39.4814	105.6931	9000’	137°	62°	189°	42°	Saw end of flight
Tom Dielman	Franktown	176	39.38	104.75	6300’	159.5°	28°	257.5°	19°	
Greg Hill	Rampart Reservoir	179	38.98	104.98	9000’	265°	45°	275°	15°	
Cole Frank	Castle Rock	178	39.375	105.02	6500’	178.5°	35°	238.5°	20°	
Brad Mugleston, Gary Marshall	Lake Wellington	174	39.31	105.30	8000’	238°	38.5°	262°	25° to 32°	32° gives best fit to other data
Trish Boylen	Larkspur	177	39.25°	104.9997	7500’	248.5°	21°	263.5°	13°	

Table 2. Intersections of 5/26/00 observer's planes, yielding flightline orientations.

Name and Location	#		A 93	B 151	C 153	D 163	E 176	* 179	F 178	G 174	H 177
Ron Slater east of Estes Park	93	A	______	______	______	______	______	______	______	______	______
Julie Dunbar Erie	151	B	Az= 6.7° ø= -47.0°	______	______	______	______	______	______	______	______
Jerry Krenz Gold Hill (near Boulder)	153	C	Parallel vectors	Az= 6.1 ø= -47.0°	______	______	______	______	______	______	______
Greg Hammer, Lloyd Mills Whiteside campground	163	D	Az= 7.2° ø= -44.°	Az= 29.° ø= -15.9°	Az= 6.8° ø= -44.°	______	______	______	______	______	______
Tom Dielman Franktown	176	E	Az= 8.6° ø= -34.°	Az= 18.° ø= 34.°	Az= 8.4° ø= -33.8°	Az=16.3° ø= -34.2°	______	______	______	______	______
Greg Hill* Rampart Reservoir	179	*	Az= 352° ø= -76.°	Az=309.° ø= 65.°	Az=350.° ø= -76.°	Az=305.° ø= -62°	Az=277.° ø= -7.46°	______	______	______	______
Cole Frank Castle Rock	178	F	Az= 8.5° ø= -34.7°	Az=18.4° ø= -33.6°	Az= 8.3° ø= -34.7°	Az=16.6° ø= -33.9°	Az=14.4° ø= -34.1°	Az=280.° ø= -7.3°	______	______	______
Brad Mugleston,Gary Marshall Lake Wellington	174	G	Az= 8.4° ø= -35.2°	Az= 15.8° ø= -37.1°	Az= 8.2° ø= -35.2°	Az=14.1° ø= -36.8°	Az= 2.1° ø= -33.2°	Az=272° ø= -28.°	Az= 7.0° ø= -34.8°	______	______
Trish Boylen Larkspur	177	H	Az= 8.7° ø= -33.4°	Az=18.5° ø= -33.5°	Az= 8.4° ø= -33.4°	Az=16.9° ø= -33.5°	Az=357.° ø= -32.4°	Az=97.7° ø= -4.1°	Az=19.4° ø= -33.4°	Az=1.48° ø= -33.0	______

*Poor data correlation

Table 3. Observer's vectors within +/- 1 s.d. of average fireball azimuth and descent angle.

Name and Location	#		A 93	B 151	C 153	D 163	E 176	F 178
Ron Slater east of Estes Park	93	A	______	______	______	______	______	______
Julie Dunbar Erie	151	B		______	______	______	______	______
Jerry Krenz Gold Hill (near Boulder)	153	C			______	______	______	______
Greg Hammer, Lloyd Mills Whiteside campground	163	D				______	______	______
Tom Dielman Franktown	176	E	Az= 8.6° ø= -34.°		Az= 8.4° ø= -33.8°		______	______
Cole Frank Castle Rock	178	F	Az= 8.5° ø= -34.7°		Az= 8.3° ø= -34.7°		Az=14.4° ø= -34.1°	______
Brad Mugleston,Gary Marshall Lake Wellington	174	G	Az= 8.4° ø= -35.2°	Az= 8.7° ø= 37.1°	Az= 8.2° ø= -35.2°	Az=14.1° ø= -36.8°		Az= 7.0° ø= -34.8°
Trish Boylen Larkspur	177	H	Az= 8.7° ø= -33.4°		Az= 8.4° ø= -33.4°			

Table 4. Lateral position and vertical elevation of 5/26/00 fireball. X=miles east of 106˚ at 39˚ lat; A=altitude in miles above sea level.

Name and Location	#		A 93	B 151	C 153	D 163	E 176	F 178
Ron Slater east of Estes Park	93	A	______	______	______	______	______	______
Julie Dunbar Erie	151	B		______	______	______	______	______
Jerry Krenz Gold Hill (near Boulder)	153	C			______	______	______	______
Greg Hammer, Lloyd Mills Whiteside campground	163	D				______	______	______
Tom Dielman Franktown	176	E	X = 12.5 A = 29.6		X = 18.3 A = 28.4		______	______
Cole Frank Castle Rock	178	F	X = 11.6 A = 19.3		X = 17.5 A = 19.3		X = 61.3 A = 19.4	______
Brad Mugleston,Gary Marshall Lake Wellington	174	G	X = 12.4 A = 28.8	X = 12.7 A = 28.6	X = 18.1 A = 25.7	X = 9.9 A = 30.1		X = 29.8 A = 19.4
Trish Boylen Larkspur	177	H	X = 11.6 A = 19.3		X = 17.4 A = 18.3			

Figure 1. Flightline orientation overview for 5/26/00 fireball.

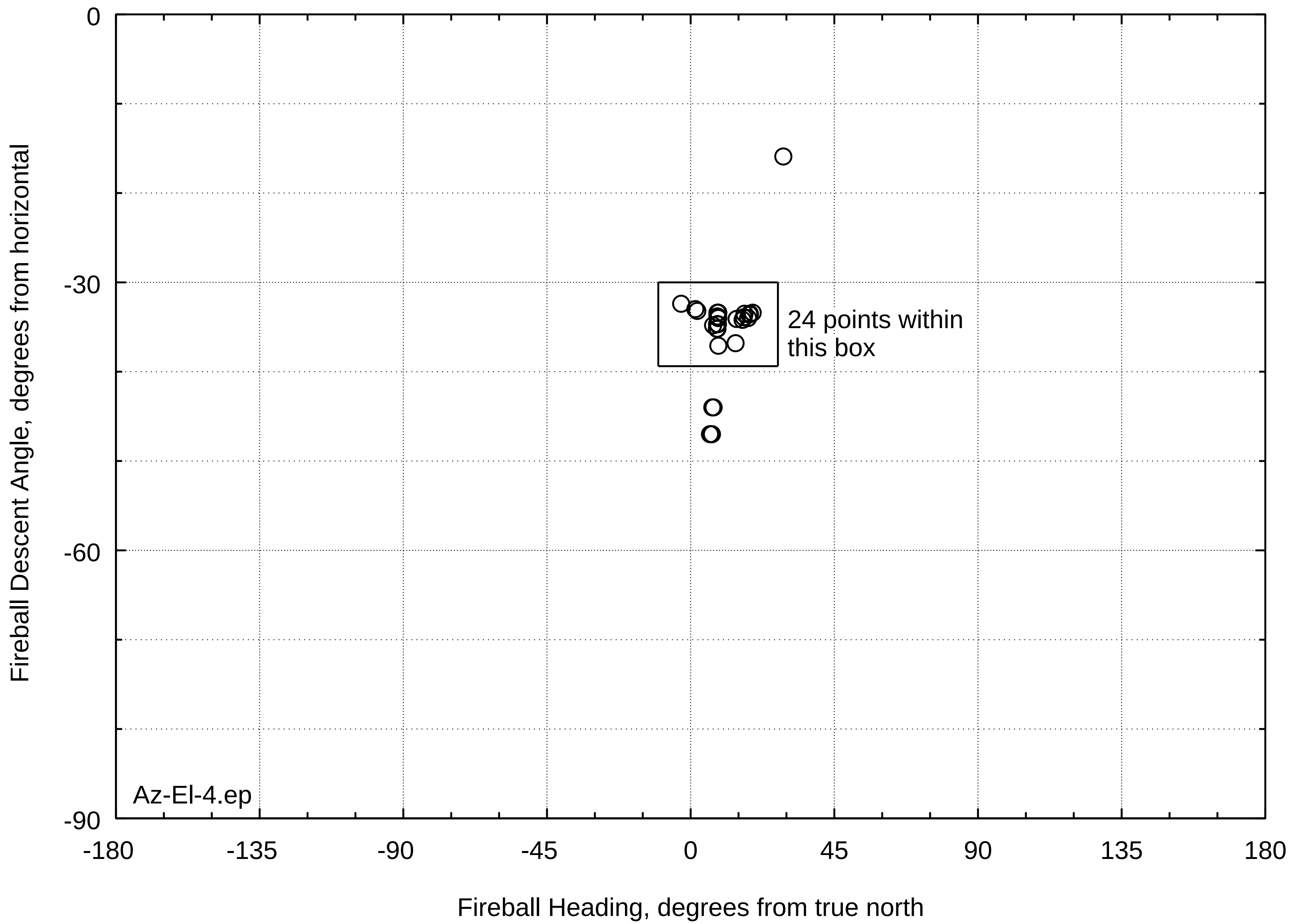

Figure 2. Orientation analysis of 5/26/2000 fireball.

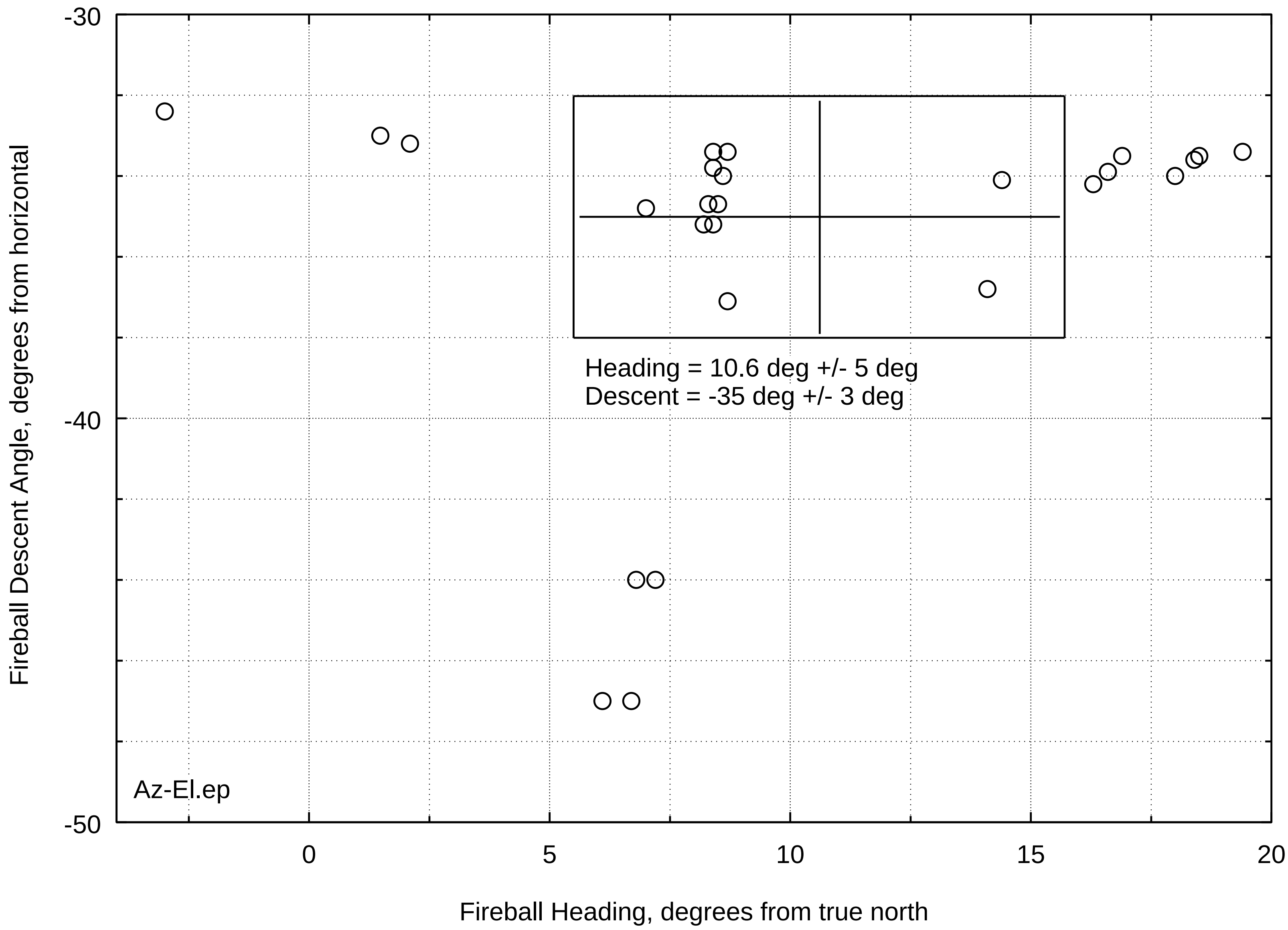

Figure 3. Observer pairings within standard deviation of mean flightline orient.

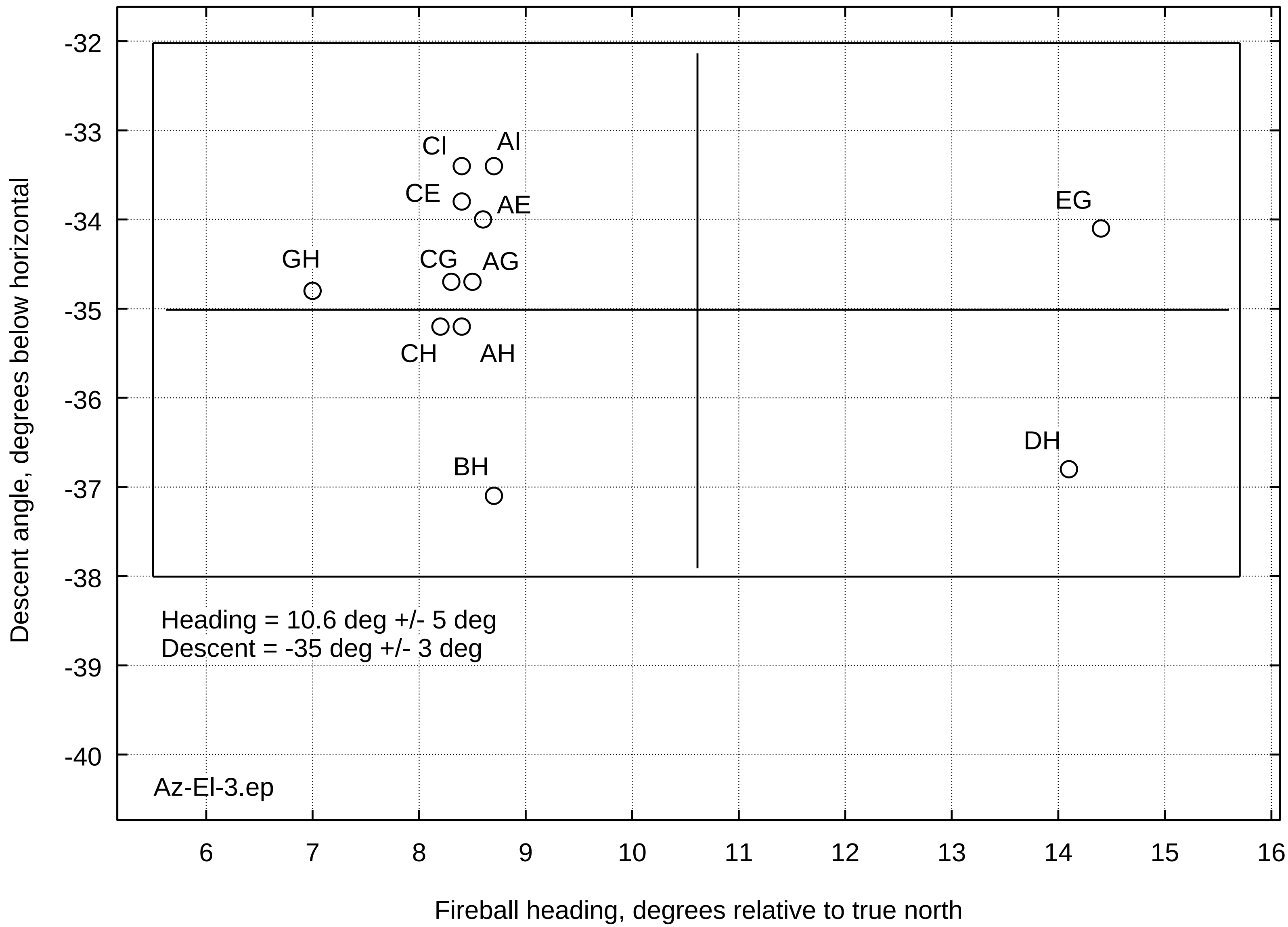

Figure 4. XZ Plane piercings relative to 39 N 106 W on 39th parallel.