Analysis of the June 2, 2016 bolide event

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ABSTRACT
On June 2, 2016 at 10h56m UTC, a −18.9 ± 0.5 magnitude superbolide was observed over Arizona. We present analysis of this event based on 6 cameras and a multispectral sensor observations by the SkySentinel continuous fireball-monitoring camera network, supplemented by a dash cam footage and a fragmentation model. The bolide began its luminous flight at an altitude of 104.8 ± 0.5 km at coordinates φ = 34.59 ± 0.04° N planetographic latitude, λ = 110.45 ± 0.04° W longitude, and it had a pre-atmospheric velocity of 17.6 ± 0.5 km/s. The calculated orbital parameters indicate that the meteoroid did not belong to any presently known asteroid family. From our calculations, the impacting object had an initial mass of 11.4 ± 0.5 metric tonnes with an estimated initial size of 1.89 ± 0.07 m.

Key words: meteors – meteor light curve – asteroids

1 INTRODUCTION

At 10h56m 27s UTC on June 2, 2016 a bright fireball was observed over Arizona. The American Meteor Society received 421 reports about this fireball, most of them from Arizona but people also witnessed this event in Utah, New Mexico, California, Texas, Colorado and Nevada. Sonic booms from the bolide were heard across the greater Phoenix area. Videos of the bolide from dash cams and security cameras appeared on YouTube and various media outlets. After sunrise, videos captured the dust trail that the impactor left behind.

Camera and satellite observations of meteors have been used for decades in order to help to determine the mass, trajectory and orbital parameters of the impacting body. Various satellites, NASA’s All Sky Fireball Network and the Lowell Observatory Cameras for All-Sky Meteor Surveillance (LO-CAMS) also recorded the Arizona bolide event. The Arizona Geological Survey’s seismic network picked up a signal near Payson that was consistent with an airburst event and according to the agency it marked the explosion of the asteroid. This was the largest observed bolide event over the continental United States since March 2010 that was reported by the Center for Near Earth Object Studies (CNEOS)1, and the fifth largest since 1988 when the agency began recording fireball data from US Government sensors.

The bolide was also observed by multiple nodes of the SkySentinel’s Spalding Allsky Camera Network (Figure 1) and the recorded data allow us to characterize some of the physical properties and the likely origin of the impacting body. Here, we present our analysis of the available SkySentinel observations, coupled with complementary data and modeling tools. We also compare our inferred results with data reported by other sources.

2 METHODOLOGY AND INSTRUMENTATION

2.1 The SkySentinel Network

Mr. R.E. Spalding (Sandia National Labs) developed the Allsky Camera System to monitor, track, and analyze large meteor events in order to provide “ground-truth” to assist both science (NASA) and treaty monitoring (Nuclear-Test-Ban Treaty Organization - CTBTO) operations in confirming the impact of large meteor fireballs (bolides) in Earth’s atmosphere. The collected data is also used to support the refinement of the energy calculations of those events, as well

1https://cneos.jpl.nasa.gov/fireballs/, accessed December 2, 2017
as, to improve trajectory calculations and orbit determination for the impacting bodies. Another important goal of the project was to develop a companion instrument, MultiSpectral Radiometer (MSR) for comparison to the Allsky cameras, and government-collected data, in order to improve the diagnostic capability of SkySentinel.

The network consists of a large number of wide-angle view cameras at various sites throughout the continental United States and other countries and it also includes the infrastructure that permits the archival of the observational data that is available for processing and analysis for the scientific community. Software tools were developed and added for calibration, removal of detector effects and anomalies, automatic event detection and correlation among stations, and automatic trajectory computation.

Mr. R. E. Spalding formally established the current SkySentinel Allsky Camera Network that was transitioned to SkySentinel, LLC and is now operated as a Joint Florida Institute of Technology and SkySentinel, LLC Science Education and Research Program. This paper is a demonstration of improvements made to SkySentinel under the Joint Program. The current system was renamed the Spalding Allsky Camera Network in honor of its founder. Data for recorded events and details on the camera system can be found at www.goskyssentinel.com.

### 2.2 Astrometric Calibration of SkySentinel Sensors

For the 2 June 2016 bolide event, six SkySentinel nodes reported positional data expressed in Cartesian coordinates (x, y). During the calibration of the data we convert each SkySentinel camera’s reported (x, y) measurements into horizon coordinates (z, a), where z is the zenith distance and a is the azimuth. The image calibration is accomplished by fitting a 10-parameter mathematical model to observations of calibration stars in each node’s CCD imagery. Table 1 lists the SkySentinel nodes that were calibrated, the dates of the SkySentinel images used for calibration, and the number of calibration points (stars) employed.

The method used to perform the calibration was based on a geometric solution originally developed by Borovička et al. (1995) to calibrate emulsion-based plates from all-sky cameras. Borovička’s complete solution, which employed 13 calibration parameters, achieves a residual error of just 0.015 degree. The solution’s main drawback is that it requires a “large number” of calibration stars, including stars at large zenith angles, which are “seldom available”.

The Borovička solution uses a coordinate system that differs in an important way from SkySentinel’s coordinate system. To distinguish between them, SkySentinel coordinates will henceforth be denoted using lower-case letters (x, y), and upper-case letters will denote Borovička coordinates (X, Y). The difference is that coordinates are interchanged, i.e., (X, Y) correlates to (y, x). For example, (x = 320, y = 240) in SkySentinel coordinates is the same point as (X = 240, Y = 320) in Borovička coordinates.

On the other hand, the two coordinate systems are alike in that they both define the center of the upper left pixel to be the origin of the coordinate system (0, 0). For SkySentinel cameras aligned approximately with North up, the origin (0, 0) is the center of the pixel in the Northeast corner of the image.

New Mexico State University, through grant funding, studied how to accomplish calibration of CCD-based video meteor cameras used in SkySentinel (Bannister et al. 2013). Bannister made several simplifications to the Borovička model, one of which was to replace the exponential model of zenith distance by a quadratic approximation. Applied to actual SkySentinel sensors, Bannister showed that his 8-parameter all-sky calibration model could achieve 0.21 degree accuracy in azimuth and 0.09 degree in zenith angle. For a SkySentinel sensor, this is sub-pixel precision because 1 pixel subtends about 0.3 degree on the sky.

The calibration of SkySentinel sensors is based upon Bannister’s paper, but with two significant changes. First, an exponential model replaced the quadratic model of zenith distance. This is because the quadratic model of zenith distance was leading to systematic error at zenith distances greater than 70°. Most bolides are seen at large zenith distances (i.e., low elevations), and utmost accuracy is needed in this regime. Indeed, replacement of the quadratic model by an exponential model of zenith distance was a step back to the original Borovička model (Borovička (1992); Borovička et al. (1995)).

Second, we discovered that the USB video capture devices that are used to digitize SkySentinel’s analog signal often introduced elliptical distortion, or flattening. Figure 2 illustrates the difference between a normal image and one that has elliptical distortion. This distortion created, in some cases, 1–2” residual error with period π as a function of azimuth. It became apparent that electronic circuitry inside the video capture device was responsible. A method to correct the image distortion was devised by including two additional parameters (α, φ) in the calibration model to define, respectively, the ellipse orientation and its flattening. These two parameters, in turn, defined the six coefficients of an affine transformation to restore image circularity.

### 2.3 Calibration Procedure

Calibration points (stars) brighter than visual magnitude +2 were selected from a list downloaded from the U.S. Naval
Table 1. Planetographic coordinates for the SkySentinel nodes that observed the event, and the dates and number of stars used for the astrometric calibration of the pixel positions from the cameras.

| Node | Location      | Imagery Dates | No. Cal Stars | Latitude (°) | Longitude (°) | Altitude (m) |
|------|---------------|--------------|---------------|--------------|--------------|--------------|
| 1    | Las Cruces, NM| Jun 1–4      | 130           | 32.281       | -106.754     | 1191         |
| 2    | Las Cruces, NM| May 31-Jun 2 | 54            | 32.281       | -106.754     | 1191         |
| 6    | Flagstaff, AZ | May 31-Jun 2 | 124           | 35.200       | -111.655     | 2106         |
| 14   | Los Alamos, NM| May 31-Jun 4 | 56            | 35.887       | -106.277     | 2177         |
| 37   | Parker, AZ    | May 31-Jun 2 | 109           | 34.144       | -111.656     | 1514         |
| 79   | Turkey Springs, AZ | May 31-Jun 3 | 120           | 34.233       | -111.301     | 1958         |
| 8*   | Alberquerque, NM| -           | -             | 34.951       | -106.460     | 1958         |

* MultiSpectral Radiometer (MSR)

Observatory’s Online Astronomical Almanac. Hourly Sky-Sentinel composite images were selected from a period of 4-5 days centered on the 2 June 2016 bolide event. Images were converted to TIF format, 8-bit depth, and enhanced by subtraction of a median combined image to enhance star visibility. Calibration stars were selected over a wide range of azimuths and zenith distances, limited only by availability of stars bright enough to be seen by SkySentinel. The 15-degree/hour change of hour angle made it possible to measure the same star multiple times during the course of a night.

Mira Pro x64 Windows astronomical software (MiraMetrics Inc. 2017) was used to measure calibration stars until there were 50-150 data points. Mira Pro defines the upper left (Northeast) pixel to have coordinates (1,1), which differs from SkySentinel’s convention that this same pixel has coordinates (0,0). Accordingly, Mira Pro coordinates were decremented by 1, along each axis, before data entry into the SkySentinel calibration model.

A Microsoft Excel 2011 workbook was created to solve for the 10 calibration parameters using a least-squares procedure. For each calibration point, the great circle error between cataloged (USNO Bright Stars) and calculated (Calibration Model) star coordinates was calculated. The errors were squared and summed to yield a sum of squared errors (SSE). Excel’s non-linear solver was then used to minimize SSE by varying the 10 calibration parameters until the solver converged on a solution. Table 2 lists the values of the calibration parameters found for each of the three SkySentinel nodes that were used for the analysis of the event.

Standard deviation of the great circle error, $\sigma = \sqrt{\text{SSE}/(n-10)}$, where $n$ is the number of calibration stars, ranged from 0.07-0.16 degree. Goodness-of-fit was verified by examining residual plots to ensure they were randomly distributed with no patterns or trends. The mean absolute deviation of zenith distance $|\delta z|$ ranged from 0.04-0.09 degree, and the mean absolute deviation of azimuth $|\delta a \cos z|$ ranged from 0.03-0.07 degree. These uncertainties, no greater than one-third of a pixel, show that SkySentinel cameras are capable of accurate calibration.

In summary, the 10-parameter calibration model produces accurate horizon coordinates $(z, a)$ where $z$ is the zenith distance and $a$ is the azimuth measured from cardinal South.

To get azimuth measured from cardinal North, compute $a + \pi$, and subtract multiples of $2\pi$, as needed, to get a result on the interval $[0, 2\pi)$.

3 RESULTS FROM SKYSENTINEL DATA

3.1 Fireball Trajectory

We determined the trajectory of the bolide from triangulating the observed position of the object from two sites;
Flagstaff (Node 6) and Turkey Springs (Node 79), both located in Arizona. The Turkey Springs station was the first to detect light from this event and in this paper we use the beginning of that video as a reference time. We used frames from the first few seconds of the recordings up until the saturation of the pixels made it impossible to accurately determine the location of the bolide from the camera frames. This gave us about the first 40 frames from each camera, approximately between 0.6 s and 2.0 s from the start of their respective videos.

For this limited time period, other sensors did not record simultaneous observations. This is due to the fact that those sites are located much farther away, resulting in the bolide appearing fainter and causing a delay in its initial detection (~ 2.5 s or more, depending on actual site, after the Turkey Springs station began recording). The MultiSpectral Radiometer (MSR) recorded data at 1000 frames per second and used GPS clocks for timing. Consequently, we used the MSR to calibrate the timing in the other observations by aligning the features from the respective light curves. The offsets in the Turkey Springs (Node 79), Flagstaff (Node 6) and Parker (Node 37) data were \( t = 0.225 \text{ s}, t = 0.2 \text{ s} \) and \( t = 0.25 \text{ s} \) respectively.

Triangulation from the stations that are located farther away also have significantly more error due to low viewing angles and lower accuracy in the altitude/azimuth measurement. In most of those cases the bolide also disappeared below the horizon or behind obstructing objects causing only the bloom to be seen in the videos. As a result, for the trajectory calculation we were limited to using data from the Flagstaff and Turkey Springs nodes only.

For the triangulation, for each time step we define a vector that points to the location of the bolide in a geocentric reference frame. \( \mathbf{R}_i \) is the unit vector pointing to the observation site from the center of the Earth and \( \mathbf{r}_i \) is the unit vector pointing to the bolide from the observation site. The location of the bolide is then the vector sum with \( \mathbf{R}_i \) being the distance from the observation site to the center of the Earth and \( \mathbf{r}_i \) being the free parameter which is the distance between the observation site and the bolide. The location of the bolide in terms of the site \( i \) is then:

\[
\mathbf{h}_i = r_i \mathbf{r}_i + \mathbf{R}_i \mathbf{R}.
\]

The solution to the triangulation is obtained by finding \( r_i \) and \( \mathbf{r}_i \) which minimizes the distance between the position of the bolide from any pair of observations \( i, j \), using the Gauss-Newton method. We define the difference vector \( \mathbf{d} \):

\[
\mathbf{d}(r_i, r_j) = \mathbf{h}_i - \mathbf{h}_j = r_i \mathbf{r}_i + \mathbf{R}_i \mathbf{R} - r_j \mathbf{r}_j - \mathbf{R}_j \mathbf{R}. \tag{2}
\]

Taking \( u, v \) and \( w \) to be the x-, y- and z- coordinates of \( \mathbf{d} \), we can create the Jacobian \( J \) and \( b \), given by.

\[
J = \begin{pmatrix}
\frac{du}{dr_i} & \frac{du}{dr_j} \\
\frac{dv}{dr_i} & \frac{dv}{dr_j} \\
\frac{dw}{dr_i} & \frac{dw}{dr_j}
\end{pmatrix}, \quad b = -\begin{pmatrix}
u(r_i, r_j) \\
v(r_i, r_j) \\
w(r_i, r_j)
\end{pmatrix}. \tag{3}
\]

Choosing an initial guess for \( p = (r_i, r_j) \), the solution is found iteratively by solving for the step given by \( \Delta \mathbf{p} = (J^T J)^{-1} J^T b \), until the \( |\mathbf{d}| \) is below a threshold, or \( |\Delta \mathbf{p}| = 0 \).

The position of the bolide is then the average of the respective videos.

\begin{align*}
\mathbf{h}_i &= r_i \mathbf{r}_i + \mathbf{R}_i \mathbf{R} \\
\mathbf{d}(r_i, r_j) &= \mathbf{h}_i - \mathbf{h}_j = r_i \mathbf{r}_i + \mathbf{R}_i \mathbf{R} - r_j \mathbf{r}_j - \mathbf{R}_j \mathbf{R}.
\end{align*}

and this procedure is repeated for each time stamp to yield the position of the bolide as a function of time.

The details of the trajectory parameters are listed in Table 3. The luminous flight began at \( t = 0.63 \text{ s} \) at coordinates \( \phi = 34.59 \pm 0.04^\circ \) geocentric latitude, \( \lambda = 110.45 \pm 0.04^\circ \) longitude, and a height of \( 104.8 \pm 0.5 \text{ km} \). The Arizona fireball moved closely from North to South, with the azimuth of the radiant being \( 16.44 \pm 0.01^\circ \), measured from North. From the SkySentinel observations we could not determine the altitude of the maximum brightness or the terminal height of the luminous flight due to image saturation and the obscured view that we described above.

Figure 3 illustrates the trajectory, along with along with a map of the nodes which observed the event. Figure 4 shows the distance travelled by the bolide along the track as a function of time.

### 3.2 Velocity

The velocity of the bolide was determined from a linear best-fit of the distance travelled by the bolide in the frames used in the triangulation (see red points in Figure 4). This gives an observed entry speed of \( v_{\infty} = 17.6 \pm 0.5 \text{ km/s} \). At this stage of the impact event there is no observed deceleration from the triangulation, and thus we assume a constant pre-breakup velocity. Since we do not include frames after the pixel saturation caused by the large bursts, it was impossible to determine from SkySentinel data the change in velocity.
Table 3. Trajectory parameters using triangulation of the bolide’s position from the initial frames of SkySentinel cameras, the analysis of the dash cam video and the fragmentation model.

| Parameter                        | Value                           |
|----------------------------------|---------------------------------|
| Entry Latitude                   | 34.59 ± 0.04° N                |
| Entry Longitude                  | 110.45 ± 0.04° W               |
| Pre-atmospheric Velocity         | 17.6 ± 0.5 km/s                |
| Peak brightness magnitude        | -18.9 ± 0.5                    |
| Height of peak brightness        | 42.0 ± 0.5 km                  |
| Zenith radiant                   | 42.23 ± 0.01°                  |
| Azimuth of radiant               | 16.44 ± 0.01°                  |

* from triangulation using SkySentinel cameras  
† using data from dash cam video and the fragmentation model.

![Figure 4](image1.png)  
Figure 4. The distance travelled by the bolide as a function of time. The red points near the start of the event are from the triangulation and the blue points are from the dash cam video. The solid line is from the fragmentation model.

![Figure 5](image2.png)  
Figure 5. The absolute magnitude and luminous power of the bolide from the three cameras as a function of time. The vertical dashed line indicates the peak brightness.

3.3 Light curve

We performed photometric analysis on the video frames from the cameras located at Flagstaff (Node 6), Parker (Node 37) and Turkey Springs (Node 79). The fourth source of information for the analysis was the MSR instrument in New Mexico. The former three datasets were from 8-bit grayscale cameras in the visible wavelength, observing at 30 frames per second. The radiometer observed at 5 bands: UV, Blue, Green, Red and Infrared at 1000 frames per second.

Images from the three cameras were first calibrated using the Moon. The sum of the raw pixel counts were taken to be proportional to the intensity of the light observed, and thus taking the base-10 logarithm and multiplying by a factor of $-2.5$ provided an uncalibrated instrumental magnitude. A calibration offset was calculated by multiple observations of the Moon. The calibrated magnitudes from the cameras were then converted to luminosity of the bolide at each time stamp, based on the distance from each camera. For each dataset, the magnitude values were corrected for extinction at each time stamp, with the extinction coefficients determined from calibrating an image of the Moon at different airmass. Figure 5 shows the magnitude values from these three cameras.

The quantum efficiency and responsivity of the MSR were already known and thus, it was a straightforward mat-
Figure 6. The apparent magnitude and luminous power of the bolide from the different filters of the MSR as a function of time. The vertical dashed line indicates the peak brightness.

After the initial brightening, the first notable flash occurs at around 4s, followed by multiple bright flaring events. There are two distinct peaks in the light curve, at around 5.9 s and at 6.4 s. The bolide reached maximum brightness of $-18.9 \pm 0.5$ magnitudes at 5.94 s at a height of 42.0 $\pm$ 0.5 km.

We determined the total luminous energy of the fireball from each of the sites by integrating the light curve. The corresponding total impact energy ($E$) was calculated based on the total luminous energy ($E_0$) using the empirical relation by Brown et al. (2002):

$$ E = 8.2508 \times (E_0)^{0.885} $$

The impact energy then can be used, along with the pre-atmospheric speed to calculate the mass of the object. The results for each site are shown in Table 4. The calculated average energy of the incoming bolide was about 0.42 $\pm$ 0.02 kt which yields an estimated mass of 11.4$\pm$0.5 metric tonnes.

### Table 4. Results of light curve analysis for each node.

| Site    | $E_0$ [×10^{12} J] | $E_0$ [kt] | $E$ [×10^{12} J] | $E$ [kt] | Mass [metric tonne] |
|---------|---------------------|------------|------------------|----------|-------------------|
| Node 6  | 0.155               | 0.0370     | 1.87             | 0.446    | 12.11             |
| Node 37 | 0.141               | 0.0639     | 1.72             | 0.411    | 11.15             |
| Node 79 | 0.139               | 0.0311     | 1.69             | 0.404    | 10.99             |
| MSR     | 0.145               | 0.0346     | 1.76             | 0.420    | 11.41             |

Figure 7. The diagram of the calculated orbit is shown in black, with the solid line above the ecliptic and dashed below in (a). (b) shows the view down the x-axis with the solid line before the y-z plane and dashed line, behind. The small and large black points show the peri- and aphelion respectively. The orbits of Venus, Earth and Mars are shown along with their positions on June 2, 2016. The vernal equinox is to the right in (a) and out of the page in (b).

3.4 Orbit

We determined the pre-atmospheric orbit from the velocity values measured at the earliest part of the bolide’s trajectory. First, we calculated the heliocentric position and velocity vectors at the entry point. Then we carried out a backward time-integration to determine the position and velocity outside the Hill sphere of the Earth. At this location, we obtained the heliocentric orbital parameters. These values are listed in Table 3.

Figure 7 illustrates the orbit of the impactor which was inclined and slightly eccentric. The object reached perihe- lion about 64 days before the impact event. Figure 8 shows the bolide’s orbital parameters plotted against the orbital element distributions of known asteroids and comets. The object clearly did not belong to any known main-belt asteroidal families, but was part of the Apollo category of near-Earth objects.

A search for the parent body was done using the Drummond criterion (Drummond 1981) and the modification by Jopek (Jopek 1993) and data from the MPCORB3 database. This yielded no match for any known parent body.

### 4 ADDITIONAL OBSERVATION AND MODELING

A significant number of movies became available on video sharing websites and news portals that were recorded by dash cams and security cameras. Most of these have the problem of obstructed view throughout most or all of the bolide’s flight path and show only lens flare. In a few instances the entire event was clearly visible and for one of

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3 https://www.minorplanetcenter.net/iau/MPCORB.html accessed December 2, 2017
4.1 Dash Cam Footage

Mark Olvaha recorded the event using his GoPro dash cam. Based on the land and road features seen in the video and in the video description, we were able to pinpoint the location of the car at the time of the recording as being on I-40 east of Kingsman, AZ at (35.159 N, 113.694 W). For our analysis we used a revised version of this video because in this version the authors applied image stabilization to the original source that made the bolide tracking easier. Since the position where the dash cam movie was recorded was significantly further away compared to the SkySentinel camera locations (~ 350km), we were only able to get the light curve and the track of the object close to the end of the observation (after $t \sim 3s$). We calibrated the footage timing with the MSR dataset by matching the peaks of the sum pixel values from the video.

We applied an angular calibration assuming a constant pixel scale, which is valid considering the object was very close to the centre of the field-of-view, where distortion effects are small. By calculating the centre-of-mass of the pixel intensity, we obtained a track of the pixel location of the bolide, which was converted to an angular distance from the start of the event. Due to the large distance, we used the small angle approximation to convert the angular distance to a linear distance along the track.

From the triangulation of the SkySentinel data, we already have the straight-line path of the bolide. Since the track of the bolide was nearly North-South and the car was moving east, we can assume the horizontal deviation (i.e., along the line of the sight of the camera) in distance is negligible. In reality, the bolide drifted by about 20km from the North-South line, and this caused a difference of a fraction of a percent in the results obtained. Therefore, we ignored the lateral motion in the dash cam analysis and we assume that the linear distance calculated is the true distance travelled by the bolide from the starting position. This allowed us to constrain the distance travelled and the speed of the bolide during and after the main fragmentation, where the SkySentinel cameras were saturated or their view were obstructed. The blue points in figure 4 show the results of the dash cam analysis.

The lack of precise astrometry for the post-breakup flight from SkySentinel data prevented accurate measurements of velocity during the latter part of the luminous flight. Therefore, it was not possible to constrain the deceleration of the object from observations only.

The end height of the luminous phase is around $40.3 \pm 0.5$ km. at a planetographic latitude of $34.05 \pm 0.04^\circ$ N and longitude $110.61 \pm 0.04^\circ$ W.

4.2 Fragmentation Model

To obtain information on the deceleration of the bolide and on the position of the peak brightness and the end of the luminous phase, we implemented the fragmentation model of Ceplecha & Revelle (2005) to calculate the post-breakup trajectory.

In this model, we input the times of discrete gross-fragmentation events (assumed to be local maxima in the light curve), and the duration of the fragmentation event, which is taken to be the width of the peak. The initial parameters for the model are the entry velocity, entry position, zenith distance and azimuth of the bolide radiant obtained from the SkySentinel triangulation. The free parameters are $K$ (the shape coefficient) and $\sigma$ (the ablation coefficient) between subsequent events. We approximate the mass loss during each fragmentation event to be proportional to change in brightness of the respective peak in the light curve, which allowed us to distribute the mass loss among the flaring events.

Ceplecha & Revelle (2005) used results from observations to constrain the values of $K$ and $\sigma$. In our case, there were no observations during the latter part of event, thus we carried out sensitivity test for all unconstrained parameters. We sampled about $16000$ values of $K$ and $\sigma$ for each fragmentation event. We varied the value of $K$ from 2 to 9 and $\sigma$ from $2 \times 10^{-9}$ to $7 \times 10^{-9}$, both in m.k.s. units (to be consistent with the Ceplecha & Revelle (2005) model).

To constrain the values for these parameters, we compared the distance travelled with time to the result from the triangulation for the start of the event and the analysis from the dash cam video near the end of the event. Figure 4 shows
the best fit for the distance travelled and Figure 9 shows the resulting velocity and height outputs from the model.

4.3 Recovered Fragments

Based on analysis of weather Doppler radar images, researchers from the Arizona State University’s Center of Meteorite Studies found fragments from the parent body on the lands of the White Mountain Apache Tribe. 15 fusion-crusted stones were recovered during the 2 day search with a total of 79.46g of material. The locations of the meteorites are shown on Figure 3. The tribe has chosen the official meteorite name of Dishchii’bikoh Ts’il’ilsqqo Tsee (Apache for Cibecue Star Stone) (Garvie 2017).

4.4 Size estimation

To calculate the size of the bolide from its mass, we require an approximation for the bulk density value. We adapted multiple methods to obtain this value indirectly from observations and we compare those results with properties of the actual “ground truth” value obtained from the recovered fragments.

Ceplecha & McCrosky (1976) diagnosed the structure and bulk density values of impacting objects based on the terminal height of the fireballs they produced. Following their method, we calculated a PE value of −5.2, which points to either a Type II object (carbonaceous chondrite) or a Type IIIa (weak cometary material). Similarly, Brown et al. (2016) classified fireballs based on the analysis of their peak brightness altitude values, using the same categories. Using the appropriate parameters of the Arizona bolide, this object lies close to the same threshold between a Type II and Type IIIa object as in the end height analysis. To that end, we analyzed these two categories separately. Using bulk density values of 900 kg/m$^3$ and 1700 kg/m$^3$ for Type IIIa and Type II objects respectively (Ceplecha 1988), we obtained diameters of 2.89 ± 0.04 m and 2.50 ± 0.04 m from the estimated mass of 11.4 ± 0.5 metric tonnes.

Borovička et al. (2005) performed a classification of meteors based on spectral emission features. Looking at the SkySentinel MSR observations, the data indicates a strong emission in the blue filter and a weak emission in the green. This is indicative of an Fe-poor object, as the main Fe emission lines are between 420 – 550 nm. The high starting altitude of 104.5 km points to a low material strength object but there is insufficient information to distinguish between cometary and asteroidal origin for the impacting body. For the bulk density of cometary material, we used 750 kg/m$^3$ as the mean value for Type IIIa objects listed by Ceplecha (1988, their Table 6.). For Fe-poor asteroids with low material strength, we adopted the bulk density value of 2500 kg/m$^3$ from Britt & Consolmagno (2003). Assuming spherical impactors, we calculated initial diameters of 3.07 ± 0.04 m and 2.05 ± 0.03 m for the cometary and asteroidal bodies, respectively.

Analysis of the recovered fragments categorize the object as being an LL7 chondrite with a shock stage S0 (Garvie 2017). Britt & Consolmagno (2003) performed a bulk density analysis for this material type and we adopted their value of 3220 ± 220 kg/m$^3$ which results in an pre-impact diameter for the Arizona bolide of 1.89 ± 0.07 m.

The summary of results from all analyses described above is shown in Table 5.

5 DISCUSSION AND CONCLUSIONS

We have analyzed multi-station observations of a magnitude −18.9 ± 0.5 superbolide that entered Earth’s atmosphere over Arizona on June 2, 2016. The calculated deposited energy of the fireball from the light curve analysis is 0.42 ± 0.02 kt. This is in good agreement with the value of 0.48 kt reported by CNEOS based on data from US government sensors. However, their reported peak location of 33.8°N and 110.9°W longitude (marked in Figure 3) is about 43 km off from our calculated position of the peak brightness. The site
Table 5. Result of size estimation from different methods. The errors in the sizes are carried through from the result for the total mass.

| Method               | Source                          | Type/Material       | Bulk density [kg/m$^3$] | Diameter [m] |
|----------------------|---------------------------------|---------------------|-------------------------|--------------|
| PE criterion         | Ceplecha & McCrosky (1976)      | IIIa                | 900$^a$                 | 2.89 ± 0.04  |
|                      |                                 | II                  | 1400$^b$                | 2.50 ± 0.04  |
| Peak brightness      | Brown et al. (2016)              | IIIa                | 900$^a$                 | 2.89 ± 0.04  |
|                      |                                 | II                  | 1400$^b$                | 2.50 ± 0.03  |
| Spectral analysis    | Borovička et al. (2005)         | Cometary            | 750$^a$                 | 3.07 ± 0.04  |
|                      |                                 | CI/CMM Chondrite    | 2500$^b$                | 2.05 ± 0.03  |
| Recovered analysis   | Garvie (2017)                   | LL7 chondrite       | 3220 ± 210$^b$          | 1.89 ± 0.07  |

$^a$ Ceplecha (1988)
$^b$ Britt & Consolmagno (2003)

of recovered fragments are along the line of our calculated trajectory, thus we believe that for this particular event the CNEOS reported peak brightness location is inaccurate.

From the deposited energy and the entry velocity of the bolide we estimate the mass of the object to be 11.4 ± 0.5 metric tonnes. We calculate the initial size of the object by assuming spherical shape. We use 3 different methods to obtain the bulk density of the meteor based on the observations of the peak altitude, end height, and spectral emission during the ablation. Borovička et al. (2017) noted that the method of end height analysis (Ceplecha & McCrosky 1976) for superbolides may lead to misleading results, while the use of the height of peak brightness (Brown et al. 2016) to determine material strength does not provide an adequate fit. Consequently, the object is most likely not of category Type IIIa, as this is inconsistent with the analysis from the other methods, which point to stony meteor. Therefore, the true size of the object is most likely smaller than what we obtained from the methods above.

The spectral-method points to a Fe-poor object but it does not provide enough information to distinguish between cometary or asteroid composition. Assuming cometary material yields a larger size than what we get from the peak/end height analyses, assuming Fe-poor material (CI/CMM chondrite) gives a slightly smaller diameter. The reason we test different methods is that in the absence of knowing the exact composition we would have to rely on these types of analyses. In this particular case, there were recovered fragments from this bolide and using the actual LL7 chondrite composition we estimate the diameter of the object to be 1.89±0.07 m. Our spectral analysis - assuming that somehow we can identify that the object is not a comet - is in good agreement with that value, the peak/end height methods overestimate this size by 25-50%. Dunn et al. (2013) state that a majority of Apollo-class asteroids are LL-chondrites, which suggests that this object is likely to be an Apollo asteroid.

The calculated orbit points to an origin interior to the main belt that is nearly co-orbital to the Earth. The object did not form of any known families, and a search for the parent body yielded no results.

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