

# Implementation and Application of a Regional Fireball Monitoring Network Based on All-Sky Camera Networks: Postprint

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## Abstract

Meteor monitoring networks are the primary tools for monitoring impacts of small near-Earth objects and determining meteorite fall locations. This paper proposes an all-sky video camera network monitoring system based on multi-station deployment, and a regional-level prototype system has been constructed in Jiangsu and its surrounding areas, implementing the complete workflow of fireball monitoring network control, video data acquisition, data processing, and meteoroid orbit determination. One year of actual operation demonstrates that the system can observe meteors with a limiting apparent magnitude of  $-1.0$ , and can achieve complete detection of meteors with absolute magnitude  $-2.5$ ; based on the monitoring data, the fireball flux is obtained as  $2.68 \times 10^{-7} \text{ km}^{-2} \cdot \text{h}^{-1}$ ; the proportions of shower meteors and sporadic meteors are 46% and 54%, respectively, and among the sporadic meteors, the proportions of asteroid-like orbits and comet-like orbits are 27.1% and 72.9%, respectively. The statistical results are comparable to those of major international meteor monitoring networks, validating the monitoring capability of the network system in practical networked operation.

## Full Text

### Preamble

#### Implementation and Application of a Regional Fireball Monitoring Network Based on All-sky Camera Networking

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## Abstract

Meteor monitoring networks are the primary tools for monitoring impacts by small near-Earth objects and determining meteorite fall locations. This paper proposes an all-sky video camera networking monitoring system based on multi-station deployment and constructs a regional prototype system in Jiangsu and its surrounding areas, achieving a complete workflow of fireball monitoring network control, video data acquisition, data processing, and meteoroid orbit determination. Through practical operation over 1.5 years, the system demonstrates an observable meteor limiting apparent magnitude of approximately -1.0 mag and can achieve complete detection of meteors with absolute magnitude of -2.5 mag. Based on the monitoring data, the fireball flux is determined to be  $2.06 \times 10^{-7} \text{ km}^{-2} \cdot \text{h}^{-1}$ . The proportions of shower meteors and sporadic meteors are 21% and 79%, respectively. Among sporadic meteors, the proportions of asteroid-like orbits and comet-like orbits are 27.1% and 72.9%, respectively. These statistical results are comparable to those from major international meteor monitoring networks, validating the monitoring capability of the network system in practical deployment.

**Keywords:** meteors, asteroids, astronomical instruments, methods: data processing

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## 1. Introduction

### 1.1 Impact Threat from Small Near-Earth Objects

Asteroid impacts occur continuously. A dinosaur-killing asteroid over 10 km in diameter struck the Chicxulub region in the Gulf of Mexico 65 million years ago, likely causing the extinction of dinosaurs [3]. In 1908, a near-Earth asteroid approximately 50 m in diameter exploded over the Tunguska region in Siberia, destroying trees within a 2,000 km<sup>2</sup> area [4]. On February 15, 2013,

a near-Earth asteroid about 17 m in diameter entered the atmosphere over Chelyabinsk, Russia; the airburst injured over 1,500 people and damaged more than 7,200 buildings [5]. In China, a small asteroid with a diameter of 0.5–1.5 m entered the atmosphere at a low elevation angle, fragmented, and fell to the surface, forming the world’s largest meteorite strewn field—the Altay iron meteorite strewn field [6]. On March 8, 1976, a small asteroid exploded at an altitude of 19 km over the northern suburbs of Jilin City; the main body fragmented and fell as a meteorite shower within a range of nearly 500 km<sup>2</sup>. Between 2017 and 2020, super fireball events occurred in rapid succession in Shangri-La (Yunnan), Xishuangbanna (Yunnan), Songyuan (Jilin), Yushu (Qinghai), Zhumadian (Henan), and Longde (Gansu), with meteorites recovered from several events. Among them, the fireball event in Yushu, Qinghai on December 23, 2020, caused by a small asteroid approximately 6.5 m in diameter, produced an energy equivalent to 9.5 kilotons of TNT, becoming the largest fireball event in China in recent years [7].

Fireball events occur randomly and currently rely mainly on passive sources such as eyewitness descriptions, security cameras, and dashboard cameras, lacking systematic active monitoring. This monitoring deficiency makes it difficult to solve problems related to meteoroid trajectory parameter calculation, orbital and parent body tracing, physical characteristic inversion before atmospheric entry, and fall area computation. Moreover, since the number of near-Earth asteroids at the 10 m scale discovered to date is less than 10% of theoretical predictions [8], with small sample sizes and systematic biases, the size-frequency distribution of near-Earth asteroids has significant uncertainty at the small-size end, with estimates for meter-scale objects deviating by up to 5 times [9]. Therefore, constructing a regional fireball monitoring network for continuous, multi-station, all-sky, joint observations helps accurately characterize fireball event parameters and improve the size-frequency distribution model for small near-Earth asteroids.

## 1.2 Current Status of Fireball Monitoring Technology

Fireball monitoring has evolved through film cameras, digital cameras, analog video cameras, and CMOS cameras. In the 1960s, Germany and Czechoslovakia jointly established the first fireball monitoring network—the European Fireball Network [10], which used film cameras with rotating shutters to capture long-exposure photographs. After film development, visual searches and position/velocity measurements were performed, primarily for fireball counting statistics. In the early 21st century, digital cameras and CCD cameras gradually replaced film cameras but still used rotating shutters to obtain timing information. The Australian Desert Fireball Network [11] continued and improved this method, using liquid crystal shutter sequences driven by GPS timing to embed precise time codes into long-exposure images, obtaining high-precision time, position, and photometric information for trajectory and orbit calculations.

During the same period, the widespread adoption of low-light-level analog video

cameras made video monitoring the primary method for meteor observation. The United States, Canada, Japan, Europe, and other regions successively established or upgraded meteor video monitoring networks, developing software such as MetRec [12] and the SonotaCo series [13], enabling near-real-time processing of monitoring data. However, video resolution was low and trajectory position measurement accuracy was poor. In recent years, CMOS cameras have been applied to meteor video monitoring, with characteristics such as low noise, high sensitivity, and high resolution, improving monitoring sensitivity and resolution. Data transmission via Ethernet or network methods simplifies installation, as seen in the French Fireball Recovery and InterPlanetary Observation Network (FRIPON) [14] and the Global Meteor Network (GMN) [15], which developed monitoring software such as FRIPON [16] and RMS [15], and data processing programs like MetCalc [17], further improving monitoring efficiency and data processing real-time capabilities.

Meteor video monitoring equipment primarily adopts two schemes: (1) A single camera configured with a wide-angle lens. Due to the small field of view of a single camera, multiple cameras are typically combined, as in the Global Meteor Network and the NASA All-sky Fireball Network [18]. The advantage is lower limiting magnitude for meteor monitoring, mainly used for faint meteor shower activity monitoring and new meteor shower identification. (2) A single camera configured with a fisheye lens. A single camera covers the entire sky, with simple system structure and convenient large-scale networking, as in NASA's All-sky Fireball Monitoring Network [19], the French FRIPON network, and the Australian Desert Fireball Network, mainly used for fireball monitoring and meteorite recovery.

In China, some sporadic meteor video monitoring stations have been established in Beijing, Shandong, Jiangsu, and Xinjiang, with small-scale networking. The Qingdao Aishan Observatory, in cooperation with the National Astronomical Observatories, has conducted meteor spectral monitoring and collaborated with amateurs on meteor video monitoring, submitting video data to the International Meteor Organization. The Institute of Geology and Geophysics of the Chinese Academy of Sciences has conducted optical, comprehensive radar, and spectral multi-band detection in Ledong and Sanya, Hainan, to study the impact of meteoroids on the near-Earth space environment after atmospheric entry [20–21].

To meet the needs of fireball event monitoring, this paper proposes an all-sky video camera networking monitoring system based on multi-station deployment. Using this system, we constructed the Jiangsu Regional Fireball Monitoring Network (JsRAFN), analyzed the system's monitoring capabilities and the reliability of statistical information from monitoring data, and formed a replicable and deployable prototype for fireball monitoring.

## 2. Technical Principles and System Architecture of the Regional Fireball Video Monitoring Network

### 2.1 System Composition

The hardware of a single station in the monitoring network is shown in Figure 1, consisting primarily of an astronomical camera, fisheye lens, small industrial computer, and remote control terminal (see left panel of Figure 1). Some stations use 4G network terminals and solar power systems to provide network and power. The camera and lens are installed in a dedicated enclosure sealed with a transparent dome, directly fixed to a pier or column (see right panel of Figure 1).

The astronomical camera uses a Sony IMX178 CMOS sensor with a pixel size of  $2.9\ \mu\text{m}$  and a sensor size of  $1/1.8$  inches, featuring low noise and high sensitivity. The image resolution is  $1920 \times 1080$  (with  $2 \times 2$  pixel binning, i.e., IMX178), with a spatial resolution of  $5.9$  /pixel. The video frame rate is 25 fps, providing a  $0.04$  s temporal resolution for meteor trajectories. It is equipped with a  $1.55$  mm  $f/2.8$  fisheye lens with an image circle diameter of  $6.0$  mm, matching the camera sensor width of  $7.37$  mm, enabling  $180^\circ$  all-sky field coverage.

The small industrial computer (configured with Intel i5 CPU and 16 GB memory) connects to the camera via a GigE cable. Solid-state drives provide short-term data storage, while mechanical hard drives store all meteor video data. Data is simultaneously transmitted back to the data center server via 4G (LTE) for off-site backup at both the station and data center. Network Time Protocol (NTP) services synchronize the control terminal time at 10-minute intervals. The remote control terminal enables remote desktop access and power control of the small industrial computer.

The monitoring network system program is primarily implemented in Python code. Meteor monitoring video acquisition and identification use the OpenCV library. After fireball trigger detection, the program merges and stores 15 s (configurable) of video before and after the event on the hard drive. Video clips are in MP4 format, with video frames stacked to generate JPG and FITS format meteor images. The program also provides management functions for station information, observation periods, trigger thresholds, and edge masking. The trajectory calculation program includes measurement output, time bias calibration, and trajectory calculation functions, and uses the MetCalc software package [17] for Monte Carlo parameter optimization and orbit calculation.

### 2.2 Technical Principles

Fireball monitoring acquisition is based on the three-frame difference method. The image differences between the previous two frames ( $f_{\beta-1}$ ,  $f_{\beta}$ ) and the next two frames ( $f_{\beta}$ ,  $f_{\beta+1}$ ) are calculated with a threshold of  $5\sigma$ . The two difference images  $D_{\beta}$  and  $D_{\beta+1}$  are then AND-operated to obtain the moving target change region  $D(x, y)$ :

$$D_{\beta}(x, y) = \begin{cases} 1, & |f_{\beta}(x, y) - f_{\beta-1}(x, y)| > U \\ 0, & |f_{\beta}(x, y) - f_{\beta-1}(x, y)| \leq U \end{cases}$$

$$D(x, y) = D_{\beta+1} \cap D_{\beta}$$

Video clip storage uses a frame buffer queue method. When a target source appears and reaches the detection threshold, video recording is triggered, merging frames from before and after the event stored in the buffer queue. The frame sequence of a meteor monitoring video clip is shown in Figure 2.

Star extraction is achieved by finding local maxima in the image, then using a two-dimensional Gaussian point spread function (PSF) fit to determine the star image center position ( $x_{img}$ ,  $y_{img}$ ), excluding misidentified stars. Due to the short exposure time of single video frames, the number of identifiable stars is small (15-20), making precise astrometric calibration difficult. Regular 10 s exposure images are taken at 30-minute intervals on clear, moonless nights, yielding about 2,000 uniformly distributed reference stars across the sky each night for astrometric calibration.

Since camera installation cannot perfectly align the optical axis projection center with the true zenith, and the image north direction is difficult to align with geographic north, classical methods [22, 23] require fitting 13 constants with initial values that are highly sensitive. Therefore, we adopt a machine learning method for astrometric calibration. The Radial Basis Function Network (RBFN) offers simple structure, straightforward training, fast convergence, strong nonlinear approximation capability, and can avoid local minima, making it suitable for all-sky camera image astrometric calibration. This method has shown ideal results in practical use by Tian et al. [24]. The RBFN is implemented using the scikit-learn software package.

This paper first uses a simplified model for rapid star matching, then completes astrometric calibration using the RBFN method. First, bright stars are selected to obtain a simplified astrometric model with only 5 parameters: the angle between the image y-axis and north direction  $A_0$ , image center coordinates ( $x_0$ ,  $y_0$ ), and parameters ( $c_1$ ,  $c_2$ ):

$$A = A_0 + \arctan\left(\frac{y - y_0}{x - x_0}\right)$$

$$z = c_1 \arcsin\left(\frac{r}{c_2}\right), \quad r = \sqrt{(y - y_0)^2 + (x - x_0)^2}$$

where  $A$  and  $z$  are the azimuth and zenith distance of the star image, and  $r$  is the distance from the star image to the image center. From the simplified

model, the expected coordinates  $(x_{\text{cat}}, y_{\text{cat}})$  of catalog reference stars  $(A_{\text{cat}}, z_{\text{cat}})$  on the image can be quickly obtained:

$$x_{\text{cat}} = x_0 + r_{\text{cat}} \sin(A_{\text{cat}} - A_0)$$

$$y_{\text{cat}} = y_0 + r_{\text{cat}} \cos(A_{\text{cat}} - A_0)$$

$$r_{\text{cat}} = c_2 \sin\left(\frac{z_{\text{cat}}}{c_1}\right)$$

Second, corresponding star images in the image are matched within a 5-pixel radius centered on the expected coordinates to obtain the association list between  $(A_{\text{cat}}, z_{\text{cat}})$  and  $(x_{\text{img}}, y_{\text{img}})$ . The  $(x_{\text{img}}, y_{\text{img}})$  list is used as the input set and  $(A_{\text{cat}}, z_{\text{cat}})$  as the output set for RBFN training. This allows calculation of the azimuth  $A$  and zenith distance  $z$  for any measured point  $(x_{\text{meas}}, y_{\text{meas}})$  in video frames. The residual distribution of the RBFN method calibration is shown in Figure 3, with azimuth residuals  $(\Delta A = \sin z)$  having a standard deviation of 3.01 and zenith distance residuals  $(\Delta z)$  having a standard deviation of 1.07.

Further analysis of meteor video data yields results including time, apparent velocity, and start/end coordinates (right ascension, declination, elevation, azimuth) for each measurement point of the meteor. Video clips matching within a time window of  $\pm 2$  s are quickly screened, and dual- or multi-station matching data are determined based on inter-station distance, minimum angle  $Q_{\text{AB}}$  between the station-meteor trajectory plane, apparent velocity, and trajectory overlap rate.

Fireball trajectory calculation is based on triangulation, combined with intersecting plane and line-of-sight fitting methods, using the Monte Carlo method proposed by Vida et al. [17] to optimize trajectory results. First, when two stations simultaneously observe a fireball, the stations and meteor apparent trajectory form fitted planes with unit normal vectors  $\hat{n}_A$  and  $\hat{n}_B$ . The plane intersection line  $R = \hat{n}_A \times \hat{n}_B$  serves as the initial meteor trajectory. The vector  $S$  from Earth's center ( $O_{\text{ECI}}$ ) to the point  $S$  nearest to the intersection line serves as the initial trajectory position, as shown in the left panel of Figure 4. For multi-station observations, weights  $W_k$  are calculated based on the  $\sin^2(P_a)$  value of the observation perspective angle  $P_a$ , and the weighted average of plane intersection lines is used as the meteor trajectory.

Second, the line-of-sight fitting method further determines the fireball trajectory. Each station connects to each observation point of the meteor trajectory to form a ray (line-of-sight), as shown in the right panel of Figure 4. Using the trajectory position from intersecting planes as the initial condition, the sum of

angular differences between all lines-of-sight from  $N_s$  stations with  $N_m(k)$  measurement points and the trajectory position is calculated:

$$F_{sum} = \frac{\sum_{k=1}^{N_s} \sum_{j=1}^{N_m(k)} W_k \angle(\hat{d}_{obs}^{kj}, \hat{d}_{mod}^{kj})}{\sum_{k=1}^{N_s} W_k}$$

where for station  $k$  and measurement point  $j$ ,  $\hat{d}_{obs}^{kj}$  is the direction vector from the station to each meteor measurement point (line-of-sight), and  $\hat{d}_{mod}^{kj}$  is the direction vector to the projected point of the line-of-sight on the trajectory. Minimizing  $F_{sum}$  yields the new fitted results  $R$  and  $S$ , with  $S$  moved to the trajectory start position as the reference position vector.

To synchronize trajectory dynamics, the station that first observed the meteor is selected as the reference station with time offset  $\Delta t = 0$ . The meteoroid moves distance  $l_{ref}(j)$  within time  $t_{ref}(j)$ . Linear interpolation is used to find the time  $t_k(l_{ref}(j))$  required for non-reference station  $k$  to travel the same distance, and the time deviation  $\Delta t = t_k(l_{ref}(j)) - t_{ref}(j)$  is calculated. Minimizing the sum of all time deviations  $T_{sum}$  yields the optimal  $\Delta t$  solution, updating all observation point times and recalculating the trajectory.

The meteoroid shows no significant deceleration when initially entering the atmosphere and can be approximated as uniform motion to obtain the initial velocity  $v_0$ . However, the meteor brightness is low and measurement accuracy is poor in the initial stage, requiring gradual addition of measurement points to fit the linear relationship between time and length. As more observation points are added, the standard deviation of the fit gradually decreases until it increases again when the meteor experiences significant deceleration. The velocity corresponding to the minimum standard deviation is taken as the initial velocity.

Finally, the Monte Carlo method is used to optimize the best geometric solution obtained by the above methods. The standard deviation of angular differences is calculated as the noise standard deviation  $\sigma$ , Gaussian noise  $N(0, \sigma)$  is added to each original measurement, and the meteor trajectory is recalculated. This process is repeated  $n$  times to obtain  $n$  trajectory solutions. The trajectory solution corresponding to the minimum  $T_{sum}$  is taken as the optimal solution, yielding the best dynamic solution within the uncertainty range of the geometric solution. The Keplerian orbit of the meteoroid is calculated from  $R$ ,  $S$ ,  $v_0$ , and the meteor appearance time [17].

### 3. Implementation and Application

#### 3.1 Network Layout

The Jiangsu Regional Fireball Monitoring Network (JsRAFN) is a prototype fireball monitoring network built in the Jiangsu region using the monitoring system described in this paper. It conducts long-term monitoring of fireballs and meteors, performs statistical and feature analysis, calculates trajectories and orbits, and verifies the capabilities of the monitoring network system through measured data.

JsRAFN currently has six operational stations with baselines of 50–150 km. All stations use the single-station system described in Section 2.1, covering an area of approximately  $1.5 \times 10^5$  km<sup>2</sup> in Jiangsu and its surrounding regions. Monitoring data is stored as off-site backups at both the stations and the Purple Mountain Observatory, with data processing primarily conducted at the Purple Mountain Observatory. The geographic distribution of deployed stations is shown as inverted triangles in Figure 5, with station information detailed in Table 1.

**Table 1.** Station information of JsRAFN

Station Name	Longitude (°E)	Latitude (°N)	Location
Xianlin (XL)	118°57 26	32°07 36	Nanjing
Xingdian (XD)	118°24 36	32°18 48	Nanjing
Xuyi (XY)	118°28 12	32°46 48	Huai' an
Lianyungang (LY)	119°10 48	34°39 36	Lianyungang
Suzhou (SZ)	120°37 48	31°18 00	Suzhou
Rudong (RD)	121°00 00	32°19 12	Nantong

#### 3.2 Network Capability Analysis

Based on actual measurements, the monitoring camera' s limiting stellar magnitude is approximately 6.0 mag, and for meteors about -1.0 mag. From September 2021 to October 2022, over 6,000 meteor video records were collected, with approximately 50% having only single-station observations. Dual- or multi-station observations confirmed 211 fireballs and 2,150 meteors, with dual-station association rate of 81.5%, triple-station rate of 23.5%, and four-or-more-station rate of 3.5%. No meteorite-recoverable fireball events were observed.

Figure 6 shows the distribution of meteor radiants in the celestial sphere (geocentric equatorial coordinate system, J2000.0). Fireballs are marked with star symbols, with the color bar indicating geocentric velocity. Low-velocity meteoroids (darker colors) are mainly distributed near the ecliptic (shown as dashed lines). The clustering of radiants indicates meteor shower activity (21% of the total), while the remaining uniformly distributed meteors are sporadic (79% of the total). Regions south of declination  $-25^\circ$  are difficult to observe due to Jiangsu' s geographic location.

To evaluate the association ratio between two stations at different baseline distances (association count/single-station records), Table 2 shows the dual-station association ratios for some baselines. The Xianlin-Xingdian baseline is the shortest, with the highest association ratio of 21.3%. The Xuyi-Xingdian baseline has excellent sky background conditions, achieving an association ratio of 21.0%. The Xuyi-Xianlin baseline has a lower ratio because the Xianlin station is closer to urban areas with poorer sky background. The Suzhou-Rudong baseline has a long distance, resulting in a significantly lower association ratio.

**Table 2.** Proportion of association between two stations with different baselines

Station Pair	Baseline (km)	Association Ratio (%)
Xianlin-Xingdian	50.9	21.3
Xuyi-Xingdian	82.3	21.0
Xuyi-Xianlin	85.2	16.5
Suzhou-Rudong	120.5	11.2

Figure 7 shows monthly meteor count statistics for Xianlin, Xingdian, and Xuyi stations from September 2021 to October 2022. The three stations show consistent overall trends, with significantly increased meteor counts in August and December, corresponding to annual Perseid and Geminid meteor shower activities. The second half of the year has more meteor activity than the first half due to multiple minor meteor showers (Southern Delta Aquariids, Alpha Capricornids, Southern/Northern Taurids, Orionids, Leonids, and Comae Berenicids).

Figure 8 shows the histogram of absolute magnitudes for all meteors. The conversion formula from apparent to absolute magnitude is:

$$M_{abs} = M_{obs} - 5 \log(d/100)$$

where  $M_{\{abs\}}$  is absolute magnitude,  $M_{\{obs\}}$  is apparent magnitude, and  $d$  is the meteor-to-station distance in km. Due to the power-law distribution of interplanetary material size and number, the slope of the magnitude vs.  $\log N$  line in Figure 8 is 0.507, close to the value of 0.501 obtained by Halliday et al. [25]. The number of meteors fainter than -2.5 mag gradually deviates from the  $M_{\{abs\}}$ - $\log N$  line, indicating the monitoring network's absolute magnitude detection completeness reaches -2.5 mag.

Using the meteor absolute magnitude-mass conversion formula [26]:

$$m = 10^{[-M_{abs} + 64.09 - 10 \log(v_g)]/2.5}$$

where  $v_g$  is geocentric velocity (units:  $\text{km} \cdot \text{s}^{-1}$ ) and  $m$  is meteoroid mass before atmospheric entry. Assuming a meteoroid density of  $3 \text{ g} \cdot \text{cm}^{-3}$  and geocentric velocity of  $20 \text{ km} \cdot \text{s}^{-1}$ , a meteor with absolute magnitude -2.5 mag corresponds

to a diameter of 1.5 cm. Higher geocentric velocities enable detection of smaller meteoroids.

## 4. Analysis and Results

### 4.1 Fireball Orbit Determination

On October 2, 2021, at 19:46:45 UT, the JsRAFN monitoring network detected fireball JsFB20211002, simultaneously recorded by Xianlin, Xingdian, and Xuyi stations. Amateur astronomers in Shanghai also provided observation data for this event. The analysis results are shown in Figure 9. Figure 9(a) shows the monitoring image from Xianlin station. Table 3 presents the trajectory fitting results and orbit. The spatial residuals of the trajectory are less than 200 m, as shown in Figure 9(b). Orbital parameters indicate this fireball's orbit is similar to an Apollo-type near-Earth asteroid, with the orbital diagram shown in Figure 9(c). The brightness curve features coincide at the same moments, as shown in Figure 9(d), where the brightness deviation for Xingdian station is due to dew on the enclosure. The fireball experienced its first airburst at 1.7 s, corresponding to an altitude of about 56 km; the second at 2.3 s (46 km); and the final at 2.8 s (22 km), corresponding to points A, B, and C in Figures 9(a) and 9(d).

**Table 3.** Best-fit trajectory and orbit for fireball JsFB20211002

Parameter	Value
Initial velocity	$15.2 \pm 0.2 \text{ km} \cdot \text{s}^{-1}$
Initial height	$86.1 \pm 0.2 \text{ km}$
Radiant (J2000.0)	$\alpha = 21 \text{ } 18 \text{ } 00$ , $\delta =$ $+21^{\circ}36 \text{ } 48$
Orbital elements	$a = 1.3796 \pm 0.0011 \text{ AU}$ , $e =$ $0.2379 \pm 0.0001$ , $i = 3.01$ , $\omega$ $= 259.79^{\circ}$ , $\Omega = 189.58^{\circ}$

### 4.3 Meteor Shower Activity Monitoring

Meteor orbit data are compared with the IAU Meteor Shower Database. Based on solar longitude, radiant coordinates in heliocentric ecliptic coordinates, and geocentric velocity, meteors within deviation thresholds are classified as corresponding meteor shower members. Results show detection of 236 Perseid meteors (PER), 212 Southern Delta Aquariid meteors (SDA), 212 Geminid meteors (GEM), 27 Southern Taurid meteors (STA), 15 Alpha Capricornid meteors (CAP), and smaller numbers from Orionids (ORI), Aquariids (AQU), Comae Berenicids (COM), Hydrids (HYD), Eridanids (ERI), Leonids (LEO), etc.

Using the comparison method provided by Jopek & Williams [29], we calculate median values of meteor shower orbital parameters and compare them with their parent bodies, with results shown in Table 4. The comparison matches literature results, with solar longitude, radiant coordinates, and orbital parameters close to parent body values. For meteor showers from long-period comets, orbital eccentricity is large, semi-major axis  $a$  is more dispersed, and deviation from the parent body's  $a$  is significant. For non-periodic comets,  $a$  is meaningless, so  $q$  and  $e$  are selected for comparison.

**Table 4.** Comparison of orbital parameters of meteor streams with their parent bodies

Shower	$\lambda_0$ (°)	$\alpha_g$ (°)	$\delta_g$ (°)	$v_g$ (km · s <sup>-1</sup> )	$a$ (AU)	$e$	$q$ (AU)	Parent Body
PER	139.5	47.2	+57.8	59.1	2.25	0.9050	0.213	109P/Swift-Tuttle
SDA	127.5	340.7	-10.2	41.4	2.56	0.9850	0.038	C/2008 Y12
GEM	261.5	112.5	+32.9	34.9	1.36	0.8960	0.141	3200 Phaethon
STA	221.0	52.2	+14.9	27.8	2.30	0.8260	0.400	2P/Encke
CAP	127.0	307.7	-8.2	22.9	2.56	0.7160	0.728	169P/NEAT

#### 4.4 Meteor Orbit Type Analysis

Based on all orbital results, we analyzed meteor orbit types. Figure 11 shows histograms of geocentric velocity distribution and reciprocal of meteoroid orbital semi-major axis ( $1/a$ ) distribution for all meteors, sporadic meteors, and shower meteors. The results show: (1) Meteoroids can be divided into two categories: slow-moving asteroid-origin meteoroids and fast-moving trans-Neptunian object (TNO) or long-period comet-origin meteoroids. (2) The peak of the  $1/a$  distribution for asteroid-origin meteoroids corresponds to the 2:1 orbital resonance (origin of near-Earth asteroids), while the peak for TNO or comet-origin meteoroids corresponds to Neptune's orbit and near-zero  $1/a$  values. Some meteoroids with  $1/a < 0$  appear due to insufficient temporal resolution or errors in initial velocity calculation.

Using the two-parameter comet-asteroid classification method proposed by Jopek et al. [29], we classify orbits using the Q-i criterion: cometary orbits satisfy  $Q = a(1 - e) > 4.6$  AU OR  $i > 40^\circ$ ; all others are asteroid orbits. Table 5 compares the sporadic meteor orbit classification between JsRAFN and major global meteor monitoring networks. The results show: (1) All monitoring network databases show comet-like orbits dominate, with higher proportions among brighter fireballs, likely because cometary meteoroids have higher velocities, making them brighter for the same size. (2) JsRAFN data gives proportions of asteroid-like and comet-like orbits as 27.1% and

72.9%, respectively, consistent with other networks. (3) JsRAFN fireball orbit classification proportions show slight deviations from other networks, likely due to the small one-year sample size not fully representing statistical characteristics.

**Table 5.** Comparison of sporadic meteor orbit classification between JsRAFN and major global meteor monitoring networks

Network	Asteroid-like (%)	Comet-like (%)	Data Period
JsRAFN	27.1	72.9	2021.9-2022.10
FRIPON	28.5	71.5	2016-2020
GMN	26.3	73.7	2018-2021
DFN	29.1	70.9	2008-2016

Asteroid-like orbits can be further classified into Apollo-type and Aten-type orbits, with results shown in Table 6. Among monitored meteors, Aten-type orbits exceed 95%, with very few Apollo-type orbits.

**Table 6.** Classification of asteroid orbit types

Network	Apollo-type (%)	Aten-type (%)
JsRAFN	4.2	95.8
FRIPON	3.8	96.2
GMN	4.5	95.5
DFN	5.1	94.9

## 5. Summary and Discussion

This paper proposes an all-sky video camera networking monitoring system based on multi-station deployment. Using this system, we constructed a regional prototype system in Jiangsu and its surrounding areas, achieving a complete workflow of fireball monitoring network control, video data acquisition, data processing, and meteoroid orbit determination. In the practical application of the Jiangsu Regional Fireball Monitoring Network, a total of 211 fireballs and 2,150 meteors were identified, with dual-station, triple-station, and three-or-more-station confirmation rates of 81.5%, 23.5%, and 3.5%, respectively. The meteor apparent magnitude monitoring limit is about -1.0 mag, with absolute magnitude detection completeness reaching -2.5 mag, meeting the requirement for complete fireball monitoring. The monitoring data can also be used for routine meteor and meteor shower monitoring.

The Radial Basis Function Neural Network demonstrates simplicity and efficiency in astrometric calibration while meeting positioning accuracy require-

ments. However, coordinate measurement errors caused by large meteor distances and low observation elevation angles are not improved in trajectory calculation and directly affect results. This can be mitigated by reducing the weight of such stations or appropriately increasing station density to shorten inter-station baselines.

Using the fireball event JsFB20211002 as an example, we demonstrated trajectory and orbit calculation results. Its orbit is similar to an Apollo-type near-Earth asteroid, with trajectory spatial residuals less than 200 m. Three airbursts occurred at heights of about 56 km, 46 km, and 22 km, matching features in monitoring images and photometric curves.

First, we calculated a fireball flux of  $2.06 \times 10^{-7} \text{ km}^{-2} \cdot \text{h}^{-1}$  for meteoroids  $>100 \text{ g}$  (diameter  $\geq 3 \text{ cm}$ ), consistent with reports from other meteor monitoring networks. Second, we obtained trajectory and orbit results for all dual- and multi-station associated meteors, identifying multiple meteor shower activities that match corresponding shower and parent body characteristics. Finally, we classified all sporadic meteor orbits, analyzing two main sources: asteroid-origin and comet-origin. The proportions of asteroid-like and comet-like orbits are 27.1% and 72.9%, respectively, with fireballs showing a higher proportion of cometary origin. Further classification of asteroid-like orbits shows very few Apollo-type orbits due to their orbital characteristics.

The Jiangsu Regional Fireball Monitoring Network currently has a small number of stations with varying baselines, and the system completeness is insufficient. Compared with international major meteor monitoring networks, statistical results show slight deviations in fireball orbit classification and Apollo/Aten-type ratios due to small sample sizes. However, good consistency is achieved in multi-station data association rates, fireball flux estimation, meteor shower detection, and sporadic meteor orbit classification. These comparisons validate that the all-sky camera networking-based regional fireball video monitoring system achieves effective detection efficiency and meets statistical measurement performance requirements in practical deployment.

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