Analysis of Meteor Trails Using the *Night Sky Live* Network of Panoramic CCD Cameras

Lior Shamir

Michigan Technological University, Department of Computer Science
1400 Townsend Drive, Houghton, MI 49931, USA
E-mail: lshamir@mtu.edu

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Abstract

The analysis of meteor trails using a publicly accessible array of two panoramic all-sky CCD cameras is presented. Located at Mauna Kea and Haleakala, Hawaii, the array captures meteor showers as well as sporadic meteors, and provides information regarding meteor atmospheric trajectories and light curves. The system also allows light curve analysis using the FITS data and the absolute distances between specific points of interest in the trail. Data collected by the system are available to the public in real-time, and can be accessed using a simple internet browser.

1 Introduction

Observing meteors is commonly done using arrays of cameras (Ceplecha 1986; Ceplecha et al. 1999). These arrays can consist of narrow-field optics allowing imaging of faint meteors, or wide-field optics that capture only the brighter meteors, but covers a larger portion of the sky.

By using two (or more) cameras located far enough from each other, a 3D analysis of the meteor trail is obtained by using parallax (Molau 1995; Koten et al. 2004; Spurny et al. 2004). However, while meteor research is a field of scientific interest, deploying and operating on-going arrays of cameras is a logistically demanding task. In this paper, a technique of using the *Night Sky Live* (Nemiroff & Rafert 1999) network for the purpose of meteor science is presented. The twin all-sky CCD cameras constantly operated at Mauna Kea and Haleakala observatories are used for obtaining altitude, absolute length and light curves of meteors. Archived and real-time data collected by the Night Sky Live network are available to the public.

In Section 2 we briefly present the *Night Sky Live* network, in Section 3 the analysis of meteor trails is presented, in Section 4 the estimated error is discusses and Section 4 presents the analysis of meteor light curves.

2 The Night Sky Live Network

The Night Sky Live (Nemiroff & Rafert 1999) consists of 10 nodes called *CONCAM* located at some of the world's premier observatories. Each node incorporates an SBIG ST-8 or ST-1001E CCD camera, a Nikon FC-E8 or SIGMA F4-EX 8mm fish-eye lens and an industrial PC. Each *CONCAM* takes one 1024×1024 180-second exposure all-sky image every 3 minutes and 56 seconds. The FITS files are then transmitted to the main server where they are copied to the public domain and can be accessed at http://nightskylive.net. The Night Sky Live network provides features such as bright star monitoring (Shamir & Nemiroff 2004) and all-sky opacity maps (Nemiroff & Shamir 2003). FITS frames are stored in the main server for two months, after which they are archived on DVDs and removed from the server, but are still available upon specific request.

Currently there are 10 *CONCAM* nodes located in Mauna Kea and Haleakala - Hawaii, Cerro Pachon - Chile, Kitt Peak - Arizona, Mt. Wilson - California, Rosemary Hill - Florida, Siding Spring - Australia, Wise Obs. - Israel, Canary Islands and South Africa. Among the operating *CONCAM*s, the ones discussed in this paper are the twin *CONCAM*s located at Mauna Kea and Haleakala, which are close enough to capture the same meteors.

3 Analysis of Meteor Trails

Mauna Kea CONCAM is located at Lon=$-155°28'8.7''$, Lat=$19°49'21.1''$, and Haleakala CONCAM is located at Lon=$-156°15'21.2''$, Lat=$20°42'25.9''$. The distance between the two stations is 128.14 km. In order to analyze the trajectory of a meteor trail, the celestial coordinates of the start and end of the meteor trail are required. These coordinates are obtained by manually finding the image (X, Y) coordinates of the start and end of the light curve in both images, and then converting the image coordinates into (Alt, Az) topocentric celestial coordinates using a fuzzy logic-based transformation formula (Shamir & Nemiroff 2005). The source code of the computer program that implements the transformation formula can be downloaded at http://nightskylive.net/wolf/source/, and the algorithm is thoroughly discussed in (Shamir & Nemiroff 2005).

Figures 1 and 2 show the same meteor recorded by Mauna Kea and Haleakala CONCAMs at 2004 October 18, $13^h36^m07^s$ UT.

The image coordinates of the meteor are given in Table 1.

	Mauna Kea	Haleakala
Start	(339,670)	(219,483)
End	(329,695)	(203,483)

Table 1: Image coordinates (in pixels) of the start and end of the meteor trail in the images taken at Mauna Kea and Haleakala

The topocentric celestial coordinates calculated by applying the fuzzy logic-based transformation formula are given in Table 2.

	Mauna Kea	Haleakala
Start	Az=44.30°	Az=99.84°
	Alt=44.24°	Alt=32.70°
End	Az=41.84°	Az=99.66°
	Alt=39.72°	Alt=28.47°

Table 2: Topocentric coordinates of the start and end of the meteor trail

The azimuth of Haleakala from Mauna Kea is 320.35°. Given the distance from Mauna Kea to Haleakala and the azimuths of the meteor from both stations, the horizontal distance of the end of the meteor trail from Mauna Kea can be easily obtained by calculating the side y in Figure 3.

The horizontal distance of the end of the meteor trail from Mauna Kea can be calculated using Equation 1.

$$y = \frac{x \cdot \sin(180 - \delta - \alpha)}{\sin(\alpha - \beta)} \tag{1}$$

Given that $x = 128.14$ km, $\alpha = 99.66°$, $\beta = 41.84°$, and $\delta = 39.65°$, y can be calculated to be 98.7 km. The horizontal distance z from Haleakala to the end of the meteor trail can be calculated using Equation 2

$$z = y \cdot \frac{\sin(\delta + \beta)}{\sin(180 - \delta - \alpha)} = 149.72km \tag{2}$$

Using the angular altitude of the end of the meteor trail measured in Mauna Kea (which is 39.72°), the altitude of the end of the meteor trail is $H_{end} = \tan(39.72)y = 81.9$ km above the Mauna Kea.

Using the altitude and the horizontal distance, the absolute distance of the end of the meteor trail from Mauna Kea is $D_{mk} = \sqrt{H_{end}^2 + y^2} = 128.25$ km

Similarly, the horizontal distance of the start of the meteor trail from Mauna Kea can be obtained using Equation 3.

$$v = \frac{x \cdot \sin(180 - \delta - \gamma)}{\sin(\gamma - \phi)} \tag{3}$$

Where γ is the azimuth of the start of the meteor trail from Haleakala and ϕ is the azimuth of the start of the meteor trail from Mauna Kea. Using the values from Table 2, $\gamma = 99.84°$ and $\phi = 44.30°$, gives $v = 100.9$ km.

The horizontal distance from Haleakala to the start of the meteor trail can be calculated using Equation 4.

$$v \cdot \frac{\sin(\delta + \phi)}{\sin(180 - \delta - \gamma)} = 154.5km \tag{4}$$

Using the angular altitude of the start of the meteor trail measured in Mauna Kea (44.24°), the altitude of the start of the meteor trail is $H_{start} = \tan(44.24)v = 98.2$ km above the Mauna Kea.

The horizontal length of the meteor trail can be obtained by calculating the side w using Equation 5.

$$w = \sqrt{(\sin(\phi - \beta)y)^2 + (v - \cos(\phi - \beta)y)^2} \tag{5}$$

where ϕ is the azimuth of the start of the meteor trail measured in Mauna Kea, y is the horizontal distance of the end of the meteor trail from Mauna Kea and v is the horizontal distance of the *start* of the meteor trail from Mauna Kea. Given that $\phi = 44.30^\circ$, $\beta = 41.84^\circ$, $y = 98.7$ km and $v = 100.9$ km, the horizontal length of the meteor trail is 4.7 km.

Given the altitudes of the start and end of the trail and the horizontal length, the absolute length of the trail (assuming linear trajectory) can be calculated simply by $L = \sqrt{(98.2 - 81.9)^2 + 4.7^2} = 16.96$ km.

4 Estimated Error

The fuzzy logic-based transformation formula is accurate to a level of 3.2 pixels (Shamir & Nemiroff 2005). Since each pixel in a NSL frame is approximately $10'$, the maximum difference between the computed celestial coordinates and the true celestial coordinates would be $3.2 \cdot 10' = 32'$. Due to sub pixel positioning, an extra error of $0.5 \cdot 10'$ should be added so the total error is $32' + 5' = 37' \simeq 0.617^\circ$.

The coordinates of the meteor trail with the estimated error are given in Tables 3 (in degrees) and 4 (in radians).

	Mauna Kea	Haleakala
Start	Az=44.30$\pm\frac{0.617}{\cos(44.24)}$	Az=99.84$\pm\frac{0.617}{\cos(32.70)}$
	Alt=44.24±0.617	Alt=32.70±0.617
End	Az=41.84$\pm\frac{0.617}{\cos(39.72)}$	Az=99.66$\pm\frac{0.617}{\cos(28.47)}$
	Alt=39.72±0.617	Alt=28.47±0.617

Table 3: Topocentric coordinates (in degrees) of the start and end of the meteor trail and their estimated error

	Mauna Kea	Haleakala
Start	Az=0.7732$\pm\frac{0.0108}{\cos(0.7721)}$	Az=1.7425$\pm\frac{0.0108}{\cos(0.5707)}$
	Alt=0.7721±0.0108	Alt=0.5707±0.0108
End	Az=0.7302$\pm\frac{0.0108}{\cos(0.6932)}$	Az=1.7394$\pm\frac{0.0108}{\cos(0.4969)}$
	Alt=0.6932±0.0108	Alt=0.4969±0.0108

Table 4: Topocentric coordinates (in radians) of the start and end of the meteor trail and their estimated error

4.1 Estimated Error of the End of the Meteor Trail

The horizontal distance y of the end of the meteor trail from Mauna Kea is calculated based on α and β (the azimuths of the end of the meteor trail measured in Mauna Kea and Haleakala) using Equation 1.

Let $y_n = x \cdot \sin(\pi - \delta - \alpha)$ and σ_α be the estimated error of α specified in Table 4. The estimated error of y_n is defined by Equation 6.

$$\begin{gathered}\sigma_{yn} = x \cdot \cos(\pi - \delta - \alpha) \cdot \sigma_\alpha = \\ 128.14 \cdot \cos(\pi - 0.692 - 1.7394) \cdot \frac{0.0108}{\cos(0.4969)} \simeq 1.193\end{gathered} \tag{6}$$

Let $y_d = \sin(\alpha - \beta)$. The estimated error σ_{yd} of y_d is defined by Equation 7.

$$\sigma_{yd} = \cos(\alpha - \beta) \cdot \sqrt{\sigma_{\alpha}^2 + \sigma_{\beta}^2} = \\ \cos(1.7394 - 0.7302) \cdot \sqrt{(\frac{0.0108}{\cos(0.4969)})^2 + (\frac{0.0108}{\cos(0.6932)})^2} \\ \simeq 0.0099 \tag{7}$$

Using the estimated error provided by Equations 6 and 7, the estimated error σ_{y} of y is defined by Equation 8.

$$\sigma_{\mathrm{y}} = \frac{x \cdot \sin(\pi - \delta - \alpha)}{\sin(\alpha - \beta)} \cdot \sqrt{(\frac{\sigma_{\mathrm{y}n}}{y_n})^2 + (\frac{\sigma_{\mathrm{y}d}}{y_d})^2} \simeq 1.82 \tag{8}$$

The estimated error σ_{y} introduces an error of ~1.84% in y.

Let $t = \tan(\psi)$, where ψ is the altitude of the end of the meteor trail measured in Mauna Kea. The estimated error of t is defined by Equation 9.

$$\sigma_{\mathrm{t}} = \sigma_{\psi} \cdot \cos^{-2}(\psi) = 0.0108 \cdot \cos^{-2}(0.6932) \simeq 0.0183 \tag{9}$$

Let $\sigma_{\mathrm{H}e}$ be the estimated error of H_{end}, defined by Equation 10.

$$\sigma_{\mathrm{H}e} = \tan(\psi) y \cdot \sqrt{(\frac{\sigma_{\mathrm{y}}}{y})^2 + (\frac{\sigma_{\mathrm{t}}}{\tan(\psi)})^2} \simeq 2.35 \tag{10}$$

$\sigma_{\mathrm{H}e}$ introduces an estimated error of $\frac{2.35}{81.9} \simeq 2.87\%$ in H_{end}.

4.2 Estimated Error of the Start of the Meteor Trail

Let $v_n = x \cdot \sin(\pi - \delta - \gamma)$. The estimated error $\sigma_{\mathrm{v}n}$ of v_n is defined by Equation 11.

$$\sigma_{\mathrm{v}n} = x \cdot \cos(\pi - \delta - \gamma) \cdot \sigma_{\gamma} = \\ 128.14 \cdot \cos(\pi - 0.692 - 1.7425) \cdot \frac{0.0108}{\cos(0.5707)} \simeq 1.25 \tag{11}$$

Let $v_d = \sin(\gamma - \phi)$. The estimated error of v_d is defined by Equation 12.

$$\sigma_{\mathrm{v}d} = \cos(\gamma - \phi) \cdot \sqrt{\sigma_{\gamma}^2 + \sigma_{\phi}^2} = \\ \cos(1.7425 - 0.7732) \cdot \sqrt{(\frac{0.0108}{\cos(0.5707)})^2 + (\frac{0.0108}{\cos(0.7721)})^2} \\ \simeq 0.0112 \tag{12}$$

Using the estimated error provided by Equations 11 and 12, the estimated error of v is defined by Equation 13.

$$\sigma_{\mathrm{v}} = \frac{x \cdot \sin(\pi - \delta - \gamma)}{\sin(\gamma - \phi)} \cdot \sqrt{(\frac{\sigma_{\mathrm{v}n}}{v_n})^2 + (\frac{\sigma_{\mathrm{v}d}}{v_d})^2} \simeq 2.04 \tag{13}$$

σ_{v} introduces an error of $\frac{2.04}{100.9} \simeq 2.02\%$ in v.

Let $q = \tan(\xi)$, Where ξ is the altitude of the start of the meteor trail measured in Mauna Kea. The estimated error of q is defined by Equation 14.

$$\sigma_{\mathrm{q}} = \sigma_{\xi} \cdot \cos^{-2}(\xi) = 0.0108 \cdot \cos^{-2}(0.7721) \simeq 0.0210 \tag{14}$$

Let $\sigma_{\mathrm{H}s}$ be the estimated error H_{start}, defined by Equation 15.

$$\sigma_{\mathrm{H}s} = \tan(\xi) v \cdot \sqrt{(\frac{\sigma_{\mathrm{v}}}{v})^2 + (\frac{\sigma_{\mathrm{q}}}{\tan(\xi)})^2} \simeq 2.90 \tag{15}$$

This introduces an estimated error of $\frac{2.90}{98.2} \simeq 2.95\%$ in H_{start}.

The procedure described in Section 3 was tested by measuring the altitude of known satellites such as the International Space Station and several Iridium satellites with accuracy of less than 1%.

5 Meteor Light Curves

FITS frames provide an effective infrastructure for pixel-by-pixel analysis of meteor light curves (Campbell et al. 2001; Cordell et al. 2004; Brosch & Manulis 2002; Brosch et al. 2004). A 3D plot of the pixel values of the meteor recorded in Figure 1 is illustrated in Figure 4.

The light curve presented in Figure 4 has two peaks of maximal brightness. The first peak is at image coordinates (334,681) and the second is at the end of the trail at (329,695). Using the analysis presented in Section 3, the first peak is at altitude of 91.2 km above Mauna Kea and occurred when the meteoroid was 7.29 km away from where it started its luminous trail. The second peak is at altitude of 81.9 km above Mauna Kea and 16.96 km away from where the luminous trail started.

The limiting stellar magnitude of CONCAM is approximately 6.8. Assuming a meteor duration is 0.4 seconds and the length of the trail is 20 pixels on the CCD chip (such as the meteor in the paper), the duration on each pixel would be $\frac{0.4}{20} = 0.02$ seconds, and the limiting magnitude of the meteor would be $6.8 + 2.5 \log \frac{0.02}{180} \simeq -3.08$.

6 Conclusion

The twin CONCAM stations located at Mauna Kea and Haleakala provide data that can be used for the purpose of meteor research without the need to set up and operate a dedicated array of cameras. The fish-eye images cover the whole 2π view of the night sky, and the stations are active 24/7 year round. Data recorded in real-time, as well as archived data are copied to the public domain and can be accessed and used easily. The analysis presented in this paper allows obtaining the altitude and total length of meteor trails, which can be used for light curve analysis.

References

Brosch N. and Manulis I. (2002) “Light curves of Geminids in 2001”, Proceedings of Asteroids, Comets, Meteors – ACM 2002. International Conference, 29 July - 2 August 2002, Berlin, Germany. Ed. Barbara Warmbein. ESA SP-500. Noordwijk, Netherlands: ESA Publications Division, pp. 209 – 212

Brosch N., Helled R., Poolishook D., Almoznino E. and David N. (2004) “Meteor light curves: the relevant parameters”, Monthly Notices of the Royal Astronomical Society, Volume 355, Issue 1, pp. 111 – 119.

Campbell M., Theijsmeijer C., Jones J., Hawkes R. L. and Brown P. (2001) “Ground-based observations of the Leonids 1999 - 2000”, Proceedings of the Meteoroids 2001 Conference, 6 - 10 August 2001, Kiruna, Sweden. Ed.: Barbara Warmbein. ESA SP-495, Noordwijk: ESA Publications Division, 2001, pp. 197 – 201

Ceplecha Z. (1986) “Photographic Fireball Networks”, Asteroids, comets, meteors II; Proceedings of the International Meeting, Uppsala, Sweden, June 3-6, 1985. Uppsala, Sweden, Astronomiska Observatoriet, 1986

Ceplecha Z., Spalding R. E., Jacobs C., ReVelle, D. O., Tagliaferri, E. and Brown, P. (1999) “Exact dynamical behaviour of meteoroids in the atmosphere”, Meteroids 1998, Proceedings of the International Conference, Tatranska Lomnica, Slovakia, August 17-21, 1998, pp. 37

Cordell D., Tilvi S. V. and Nemiroff, R. J. (2004) “The 2004 Perseids Meteor Shower as Captured by Night Sky Live CONCAMs”, American Astronomical Society Meeting 205, San Diego, CA, 2004, #56.08

Koten P., Borovicka J., Spurn P., Betlem H. and Evans S. (2004) “Atmospheric trajectories and light curves of shower meteors”, Astronomy and Astrophysics, Volume 428, pp. 683–690

Molau S. (1995) “MOVIE - Analysis of Video Meteors”, Proceedings of the International Meteor Conference, Belogradchik, Bulgaria, 22-25 September 1994, International Meteor Organization

Nemiroff R. J. and Shamir L. (2003) “CONCAM All–Sky Maps of Airglow and Opacity”, American Astronomical Society Meeting 203, Atlanta, GA, 2003, #38.14

Nemiroff R. J. and Rafert, J. B. (1999) “Toward a Continuous Record of the Sky”, The Publications of the Astronomical Society of the Pacific, Volume 111, Issue 761, pp. 886–897

Nemiroff R. J., Shamir L., Muzzin V., Merlo M. and Tilvi S. V. (2004) “Exhaustive Monitoring of Polaris in Night Sky Live CONCAM Data”, American Astronomical Society Meeting 205, San Diego, CA, 2004, #54.12

Shamir L. and Nemiroff R. J. (2004) “CONCAM’s Fuzzy-Logic All-Sky Star Recognition Algorithm”, American Astronomical Society Meeting 204, Denver, CO, 2004, #76.07

Shamir L. and Nemiroff R. J. (2005) “A Fuzzy Logic Based Algorithm For Finding Astronomical Objects in Wide-Angle Frames”, Publications of the Astronomical Society of Australia, Volume 22(2), pp. 111–117

Spurny P., Olech A. and Kedzierski P. (2004) “Trajectory and orbit of the EN200204 Laskarzew fireball” WGN – Journal of the International Meteor Organization, Volume 32, No. 2, pp. 48–50

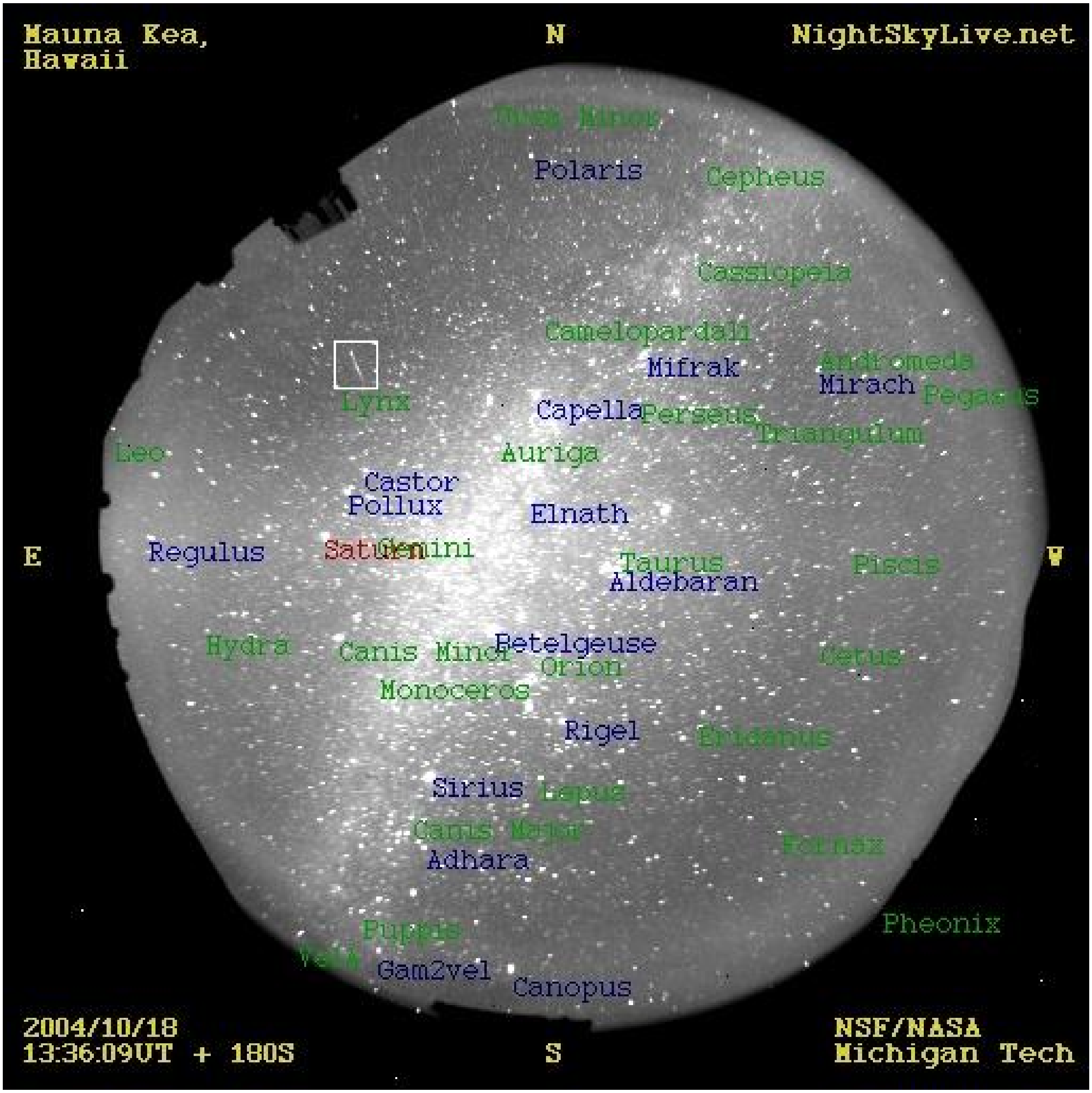

Figure 1: A meteor (in the white rectangular frame) recorded at Mauna Kea

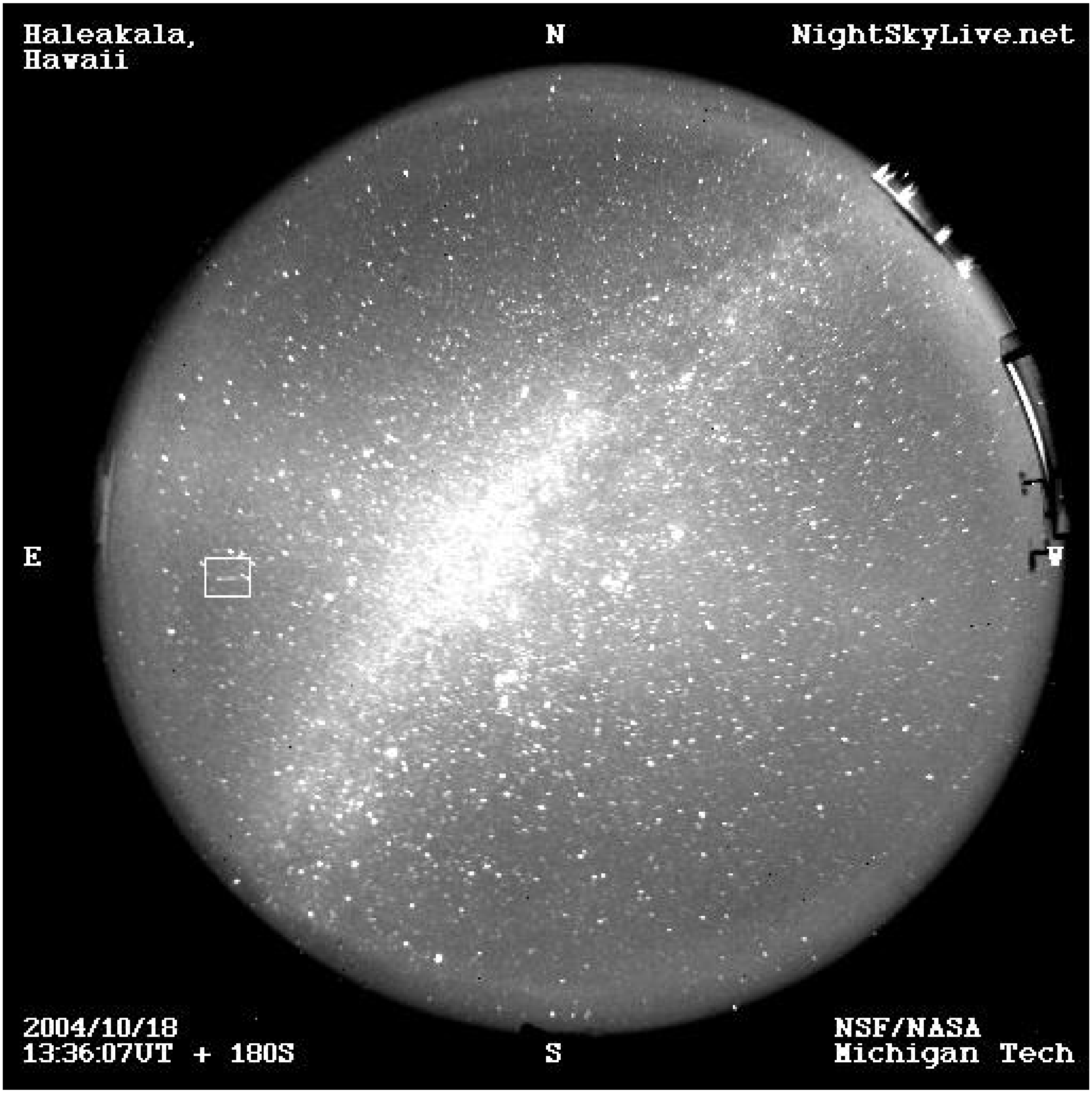

Figure 2: A meteor (in the white rectangular frame) recorded at Haleakala

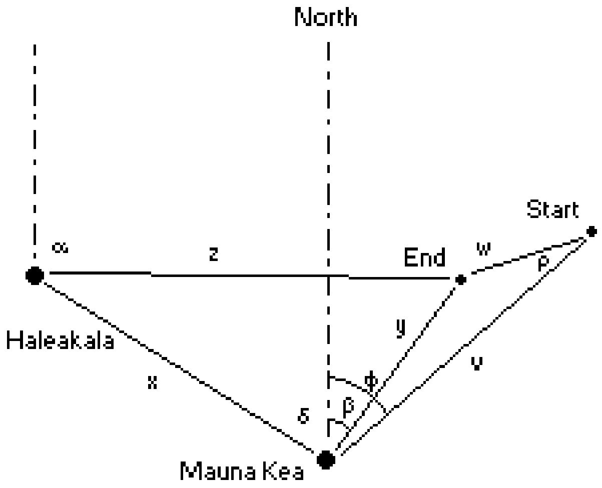

Figure 3: Illustration of the meteor trail as seen from above. α is the azimuth of the end of the meteor trail from Haleakala, β is the azimuth of the end of the meteor trail from Mauna Kea, x is the distance from Mauna Kea to Haleakala and δ is the azimuth of Haleakala from Mauna Kea.

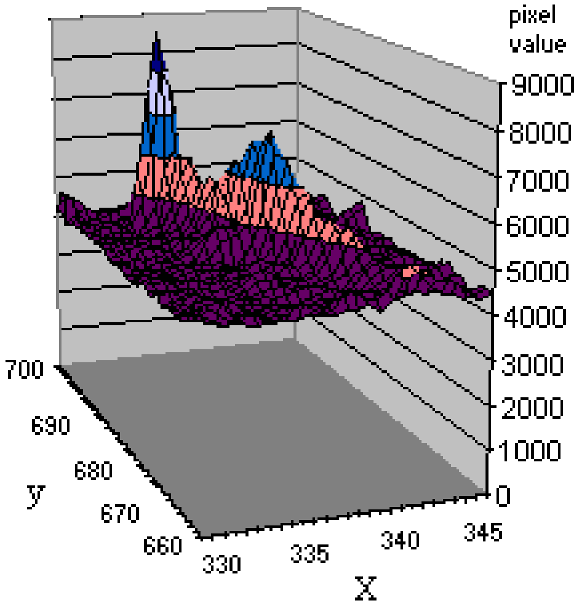

Figure 4: Light curve of the meteor recorded in Figure 1.