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CCD modification to obtain high-precision orbits of meteoroids

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ABSTRACT

Few high-resolution video cameras have been used for observing meteors, so the orbits obtained have high uncertainty. Precise orbits are necessary so that the meteors can be integrated backwards in time and be identified with their parent body. Also, by comparing these orbits with a theoretical evolution model, the meteors can be associated with a particular dust trail. An electronic shutter system has been developed to enhance the temporal resolution for large CCD sensors. For the first time, an LH100 camera with an electronic shutter system has been tested for observing meteors. This new innovational technique has removed the theoretical upper limit – resulting from slow frame rates – to the size of CCD that can be used for the detection of meteors. Three such cameras will be installed in southern France to create a network for determining the orbits of meteors; this will be called the CAmera for BETter Resolution NETwork (CABERNET). Here, we present preliminary results from the Geminid test campaign, which made use of this camera.

Key words: instrumentation: miscellaneous – methods: observational – meteorites, meteors, meteoroids.

1 INTRODUCTION

During the past decade, for meteor astronomy, video techniques have been implemented for all-night observations, in addition to visual and photographic techniques. The International Meteor Organization (IMO) Video Meteor Network (Molau 2005), the Polish Fireball Network (Olech et al. 2006), the Spanish Meteor Network (Trigo-Rodríguez et al. 2007), the Dutch Meteor Society (Miskotte & Johannink 2006), the Czech Meteor Network (Koten et al. 2006), the Canadian All-Sky Network (Weryk et al. 2008), the California Cameras for All-Sky Meteor Surveillance (CAMS) network (Jenniskens et al. 2011) and the Northern Irish Network (Atreya & Christou 2008) are a few of the meteor networks actively operating in Europe, and North America. Detection and analysis software such as METREC, METEORSCAN and UFO-CAPTURE can ease the tedious set-up and encourage professional and amateur astronomers alike to set up meteor stations.

These networks have thrived from off-the-shelf video cameras (Watec, Mintron, etc.) and lenses. Even though they are inexpensive, the major drawback is the astrometric quality of data acquired. Typical cameras (640×480 pixels), with medium-angled lenses ($\sim 50^\circ$), have a spatial resolution of $0.08 \text{ deg pixel}^{-1}$. This corresponds to a resolution of 140 m if the meteor is at a distance of

100 km from the camera. This causes a large uncertainty in velocity, and thus in the semimajor axis of the meteoroids.

Modellers now need more precise orbital elements for meteoroids. Fig. 1 shows the node of the Draconid meteoroid stream with different trails (1817–1913 AD) for the 2011 outburst. It is only possible to identify the exact trail that caused the outburst on 2011 October 8 with high-resolution observations and a precise semimajor axis. Similarly, the 2009 Leonid outburst was predicted because of trails from 1533 and 1466 AD (Jenniskens 2006), whose radiants differ by 0.9° . However, the observations made with current instruments were not able to identify the exact trail from which the outburst occurred (Koten, Borovicka & Kokhirova 2011). So, there is a need for better accuracy, and we can achieve this improved accuracy by increasing the resolution of the instruments used.

In traditional astronomy, if we want to increase resolution, this usually means using larger CCDs or using narrower lenses, both of which increase the pixel resolution. However, in meteor astronomy, if larger CCDs are used, then the temporal resolution is decreased (this is discussed further at the end of this section). Similarly, if narrower lenses are used, then the total field of view (FOV) of the system is decreased, which subsequently decreases the number of meteors observed.

A simple simulation was performed to identify the spread of meteors in a single image for a fixed high-resolution of $0.01 \text{ deg pixel}^{-1}$ for various frame rates. Fig. 2 shows the length of a meteor (in pixels) for different temporal resolutions for slow (angular speed of 10° s^{-1}) and fast (angular speed of 30° s^{-1}) meteors. For a typical

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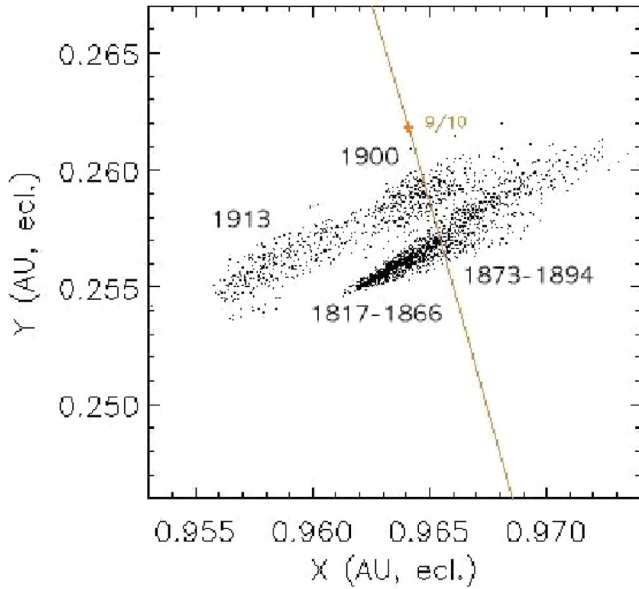


Figure 1. The node of the Draconid meteoroid stream with trails from 1817–1913 AD for the 2011 outburst.

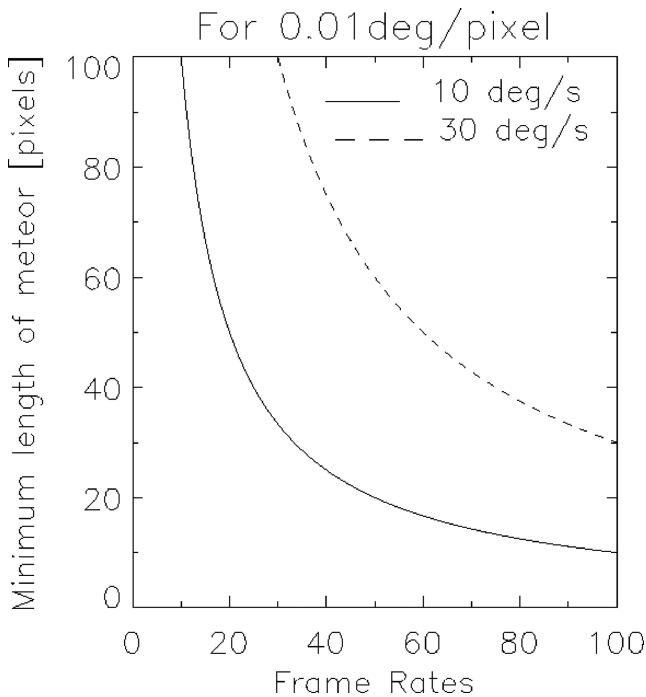


Figure 2. The length of a meteor with different temporal resolutions for two typical meteor speeds. The spatial resolution is set to $0.01 \text{ deg pixel}^{-1}$.

video frame rate of 25–30 fps, a slow meteor will be spread out across 40 pixels, whereas a fast meteor will be spread across more than 100 pixels. Thus, it is difficult to compute the position of a meteor within an accuracy of 1 pixel, because it is spread across too many pixels. When the frame rate is increased to 100 fps, the meteor is spread across only 10 pixels (fast) or 30 pixels (slow), which makes it easier for software to detect the meteor’s position in a single frame more accurately. Thus, it is essential to increase the frame rate if the spatial resolution is increased in order to estimate the meteor’s position accurately in the images. Because of this, even

Table 1. The frame rates for CCDs of different sizes.

Camera ID	Size of CCD (pixels)	Maximum frame rate (fps)
RM-6740CL	648 × 484	200
CM-140GE	1392 × 1040	31
CM-200GE	1628 × 1236	25
BM-500GE	2456 × 2048	15
AM-1600GE	4872 × 3248	3

if narrow lenses are used with CCDs with a normal video frame rate, there will still be computational disadvantages.

There are also several disadvantages to using large CCDs. The time taken to read a single frame in a CCD is inversely proportional to the size of the CCD. Table 1 shows the frame rates for different sizes of CCDs from the JAI camera company. Thus, large CCDs have very low frame rates and they are not useful for observing meteors. One option is to use an external mechanical rotating shutter (to increase the temporal resolution) with large CCDs.

2 LHERITIER CAMERA

Lheritier, a French camera and system vision company, has developed an interline progressive scan camera, LH11000. This uses a Kodak Kai 11002 sensor with 4008×2672 active pixels of $9 \mu\text{m}$. The CCD contains ~ 35 times more pixels compared to Wattec cameras, which thus increases the spatial resolution. The readout noise is only $\sim 30 e^-$. The images can be saved in a 16-bit format. The minimum and maximum shutter speeds are 0.8 and 52 428 ms, respectively. This camera was tested in military and aviation environments and it can withstand temperatures of -10°C to 50°C and a humidity of 100 per cent without condensation.

The fast shutter speed (0.8 ms) of this camera can, in theory, result in a frame rate of up to 1250. However, the maximum continuous frame rate is merely 6.7. This is because the readout time of a single image is 149 ms. So, there is still the problem of a slow frame rate in this camera. To tackle this problem, the CCD was modified to mimic a rotating shutter effect.

The top part of Fig. 3 shows the general procedure of CCD systems. During the integration or exposure, the shutter opens and the photons enter the CCD sensor plane. The photodiodes in the sensor plane accumulate charges, which are linearly dependent upon the light level and the duration of the integration. The charges

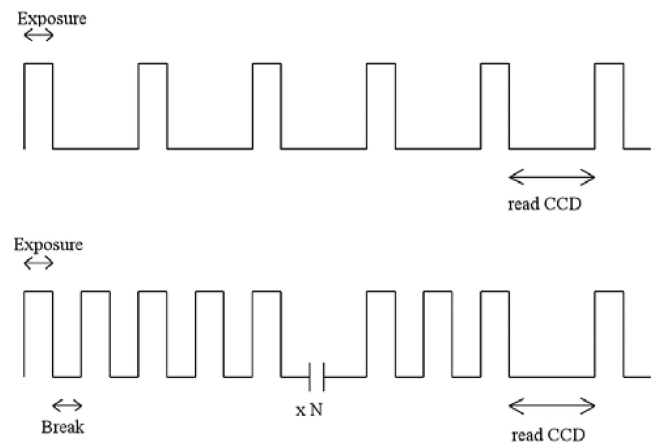


Figure 3. Modification of the basic CCD readout method to mimic the electronic shutter system.

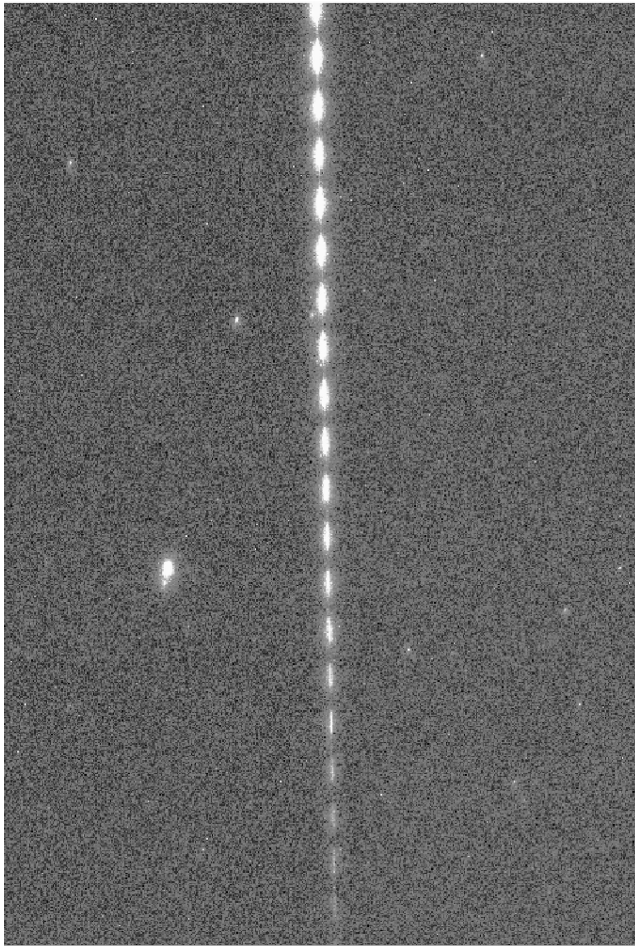


Figure 4. Example of a meteor (raw image) with a 10-ms signal, a 10-ms break and a total exposure of 1 s.

are then shifted in a combination of parallel and serial transfer to the readout area. The photodiodes are then reset before the next exposure to remove any residual charges.

A modification to the CCD system was made by introducing a ‘break’ phase, as shown in the bottom part of Fig. 3. During this phase, the shutter is closed, and the charges are dumped into the storage electrodes, but they are not sent to the readout area. Storing the charges does not take time, compared to reading the charges. The residual signal of the photodiodes is reset, and then the photodiodes are ready to accumulate charges from the next exposure. The loop of ‘exposure’ and ‘break’ continues until the charges from the storage area are shifted to the readout area. The CCD is read only once after the total integration. This method is possible only in half-well CCDs, where extra charges can be stored before they are read out.

If the camera is fixed, and pointing in a fixed direction, the movement of the meteor tracking across the CCD creates a dashed line, as in Fig. 4. The stacking of images causes the meteor to look like a solid line, whereas the inclusion of a ‘break’ causes it to look like a dashed line.

This method is very similar to having an external mechanical rotating shutter, but without the mechanical moving parts, and it is more robust and portable. The durations of the individual integration, ‘break’ and total integration can be modified to suit fast and slow meteors. This method can only be used with half-well CCDs pointing in a fixed direction. A CCD has limits on the maximum number of electrons it can store before they are read out, which can

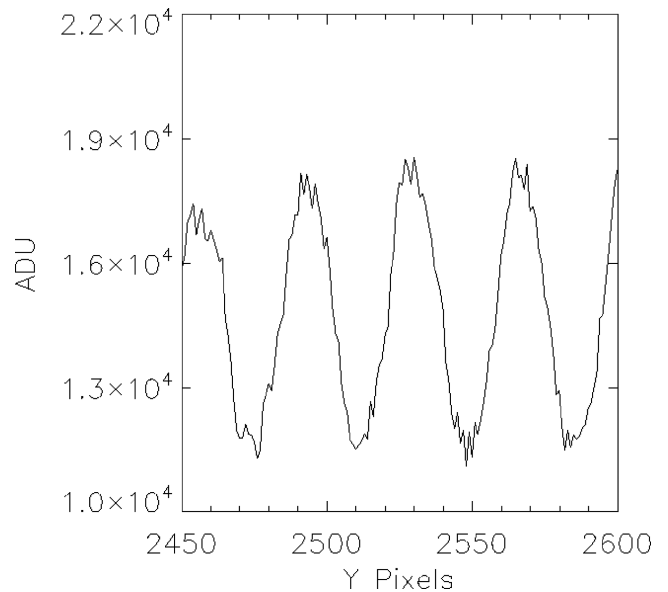


Figure 5. The intensity of meteor breaks along the y-axis.

be exceeded by observing bright objects or having long exposures. The excess charge is spilled over to the neighbouring pixel, causing bright spots on the images, which is called the blooming effect. Regardless, this new innovational technique has removed the theoretical upper limit – resulting from slow frame rates – to the size of CCD that can be used for the detection of meteors.

Fig. 4 shows an example of a meteor detected (a cropped section of the full raw image) with the LH11000 camera, a modified shutter system and a Nikon 85-mm F1.4 lens (FOV $28^\circ \times 18^\circ$). The meteor was captured during the Lyrid observation campaign on 2010 April 22 at 00:56:50 UT from the Observatory of Haute Provence (OHP), France. The spatial resolution is ~ 0.007 or ~ 25 arcsec. The signal and break duration was set to 10 ms, and the total exposure of the image was 1 s ($N = 50$ loops).

Fig. 5 shows an intensity plot of the raw image without any processing for a few breaks. The minimum of the curves represent the break phase and its value corresponds to the sky background. The distances between the peaks are ~ 40 pixels. With a 10-ms break and exposure, the time difference between the peaks is 20 ms. With spatial and temporal resolutions of $0.0070 \text{ pixel}^{-1}$ and 10 ms, respectively, the angular velocity is $\sim 14 \text{ deg s}^{-1}$, which agrees with those of general meteors. Simulation results from Richardson (2000) show that a meteor with a velocity of 42 km s^{-1} – for the Lyrids, $V_\infty = 43 \text{ km s}^{-1}$ – can have an angular velocity between 0 and 25 deg s^{-1} , depending on the distance from the radiant.¹ The precise position and velocity can be computed by fitting different types of curves in the reduced data.

Figs 4 and 6 show the quality of the CCD and the electronic shutter. The electronic shutter seems to be a clear on–off process for fainter meteors, as seen from Fig. 4. However, as the meteor becomes brighter, there is also a fine trail of signal during the break phase. This is also clearly seen in the bottom image of Fig. 5. This fine trail of signal is a result of the blooming effect, when the capacity of the storage electrodes to store electrons exceed their limit (90 000 electrons for this camera) and the charge spills over to the nearby electrodes. One way to lower the blooming

¹ <http://www.amsmeteors.org/richardson/angspeed.html>



Figure 6. Example of a Geminid observed from the Pic du Midi and Guzet on 2010 December 13 at 22^h39^m43^s.

effect would be to decrease the total duration of the exposure. A second option would be to remove the effect of the blooming by using computational methods during the preprocessing of the data. Although the positions of the dashes can be located with a fair degree of accuracy, improvements can still be made to make it possible to observe bright meteors.

3 FRENCH METEOR NETWORK

The PoDET (the French acronym for Pôle sur la Dynamique de l’Environnement Terrestre) project aims to provide an overview of the Earth’s natural and artificial environments, and the PoDET-MET project deals only deals with meteors. The first video meteor

network has been started in France under the PoDET-MET project. The primary aim of this network is to obtain high-precision orbits of meteoroids. The Lh11000 camera is equipped with a Cannon 50-mm F1.2 lens (FOV 40° × 27°) and it has a spatial resolution of 0.01, which is ~ eight times higher than the numerous off-the-shelf systems. This corresponds to a 17.4-m resolution if the observed meteor is at a distance of 100 km. This camera system is called the CAmera for BEtter Resolution NETwork (CABERNET).

During the 2010 Geminids, a double-station observing campaign was organized in collaboration with the Czech group. The stations were set up at the Pic du Midi (42°94′N, 0°14′E, 2800 m) and Guzet (42°78′N, 1°3′E, 1530 m). The observations were carried out on the night of December 12 and 13. One of the primary objectives of this observing campaign was to test the CABERNET and to compare it with the Watec camera and cameras with intensifiers. A detailed comparison of all the camera systems and an analysis of Geminid shower will be presented in a later publication. However, here, we present the preliminary result in order to illustrate the use of the electronic shutter system.

Fig. 6 shows a double-station meteor observed from both the Pic du Midi and Guzet stations on 2010 December 13 at 22^h39^m43^s. The time difference between the breaks in the image is 20 ms, and the total exposure of the image is ~1 s. This meteor was manually reduced using the SPARVM software (Atreya & Christou 2008) to compute its radiant, its trajectory and its heliocentric orbit. The radiant was computed to be RA = 113°12, Dec. = 33°16, which is comparable with the predicted RA = 113° and Dec. = 33°. The velocity, V_{∞} , was computed to be $35.8 \pm 1.2 \text{ km s}^{-1}$, which matches the Geminid velocity of 35 km s^{-1} . However, the uncertainty in the velocity of 1.2 km s^{-1} is still a magnitude higher than our expectations for this camera system. The angle between the meteor’s trajectory and the station plane from both locations is $Q_{AB} = 52^{\circ}9$.

There are various reasons for the cause of this uncertainty in velocity. One of the major reasons is the reduction method used to estimate the breaks in the meteor’s position. A single break is spread across ~50 × ~20 pixels. Thus, to identify an area of ~1000 pixels by a single point produces high uncertainty. For this computation, a basic centroiding method, along with manual estimation, was used. A more dedicated approach is being developed to identify the meteor’s position with better certainty. It can also be seen that the meteor breaks are not clearly separated in the top image (Pic du Midi) of Fig. 6. This is because the transverse velocity of the meteor with respect to the camera’s line of sight is comparatively low. Using a longer break duration in the camera setting will solve this effect. Another possible reason could be that the lens used (Canon F1.2 50 mm) is not optimized for astrometry but is focused on photography, and thus a third-degree polynomial fitting might not be sufficient.

Fig. 7 shows the heights of the meteor as seen from both locations, and these are matching. Table 2 shows the heliocentric orbital elements (q , a , e , i , ω , Ω) of the example Geminid with that of 3200 Phaethon, the parent object of the Geminid meteor shower. The orbital parameters shows a very good match, with just 0.20 au difference in the semimajor axis, caused mainly by the uncertainty in the velocity. In our next paper, we will give a detailed analysis of the Geminid meteor shower, with double-station meteors observed by the CABERNET, the Watec and the Czech intensified cameras.

The first dedicated triple station network will be set up in the south of France during early 2012. The first station will be set up at the Pic du Midi Observatory, at a height of 3000 m. The second station will be set up in Guzet, while the location of the third station

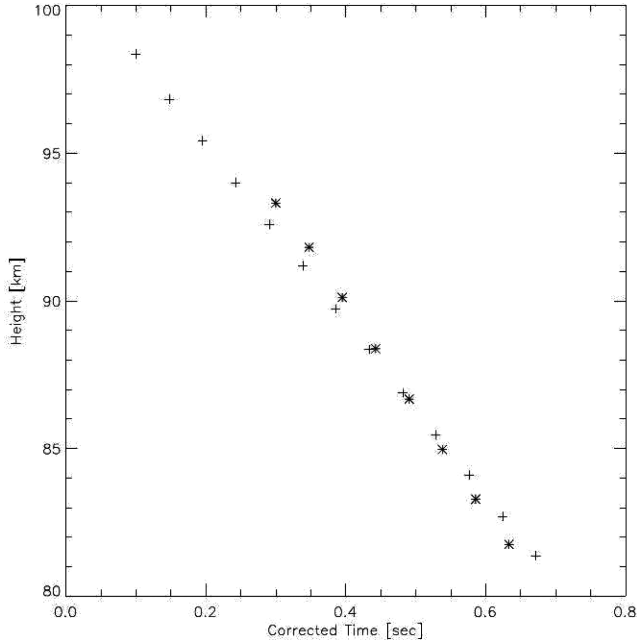


Figure 7. Height of the example Geminid from the Pic du Midi (asterisks) and Guzet (plus signs). The x -axis shows the corrected time in seconds.

Table 2. The orbital elements of the example Geminids.

	q (au)	a (au)	e	i (deg)	ω (deg)	Ω (deg)
Example Geminid	0.130	1.47	0.911	27.2	261	325
3200 Phaethon	0.139	1.27	0.890	22.1	273	322

has yet to be decided. A detailed camera housing is being designed specifically for this camera and this is currently being tested. An all-sky camera DMK41AU02 (1/2 inch, 1280×960 pixels) with a fish-eye lens has been installed to complement the high-precision cameras.

4 CONCLUSION

A newly developed electronic shutter system has been integrated in the LH11000 camera. This camera system was tested for the first time for observing meteors. The accuracy achieved with this camera is significantly higher compared to other general meteor cameras. With this new method, there is also no need for an external manual rotating shutter. This method can be implemented in even larger CCDs, which thus eliminates the theoretical upper limits – resulting from slow frame rates – on the size of CCDs used for observing meteors.

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