PRECISE FIREBALL TRAJECTORIES USING LIQUID CRYSTAL SHUTTERS AND DE BRUIJN SEQUENCES.
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Introduction: Meteor camera networks have been used since the late fifties to characterise meteoroid orbits and calculate meteorite fall positions [1]. Previous designs used large format sheet film cameras to capture images of a meteoroid's luminous trajectory during ablation. Advances in digital imaging technology have enabled the transition from large format photographic film based systems to systems based on digital still cameras like the Desert Fireball Network (DFN) [2].

Previous stills based meteor cameras used rotating or oscillating mechanical shutters to chop or periodically interrupt the light recorded on the film plane [3],[4]. This breaks the streak on the long exposure image into short segments or dashes; the timing of which is precisely known and allows the determination of the meteor velocity after triangulation.

Exposure times can range from a few seconds to one night, so networks using long exposure images with periodic shutters for velocity determination still require a method of establishing absolute timing along a fireball path in order to determine a trajectory. Prior designs used various approaches including a combination of fixed and guided cameras [5] or photomultiplier tubes to log meteor luminosity [4], [6]. Video based systems such as [7],[8],[9] do not require an additional periodic shutter due to the high rate of image capture, nor do they require external hardware to provide absolute timing, but the resolution of video meteor cameras is poor compared to stills based systems leading to larger errors in fall position estimation.

This abstract presents a technique for encoding absolute trajectory timing with relative timing without additional hardware using a liquid crystal shutter modulated according to a de Bruijn sequence. This allows the development of high resolution, smaller, less expensive and simpler meteor cameras than previously possible.

Meteor Velocity: The tight tolerances and bulk of mechanical shutter assemblies used to interrupt light transmission for velocity determination significantly increase system complexity, size, cost and manufacturing time. These factors need to be minimised whilst maintaining imaging performance in order to maximise network coverage area to enable the observation and recovery of as many meteorites as possible.

The proliferation of consumer liquid crystal technology in displays and more recently active 3D display shutter glasses has made inexpensive liquid crystal (LC) shutters readily available. These shutters provide a solid-state alternative to mechanical periodic shutters, significantly simplifying the system. They do, however, have limited light transmittance in their open state, approximately 36% for those in use on the DFN. Testing has shown that the LC shutters are a suitable replacement for mechanical shutters as long as the light loss in open state transmittance is acceptable. They are a good fit with digital image sensors where the contamination from dust and dirt is of higher concern than in film based systems. The LC shutters on DFN cameras operate at a rate of 10 Hz providing 20 luminous trajectory data points per second.

Absolute Trajectory Timing: The DFN stations use coded operation of the LC shutter to determine the absolute timing for the start and end of the luminous trajectory. The time is encoded by modulating the LC shutter according to a de Bruijn sequence or cycle. A de Bruijn sequence is the shortest cyclic sequence containing all possible subsequence for a given alphabet size and subsequence length making it the optimal encoding for this sort of problem [10]. For example, the de Bruijn sequence generated using the prefer high method for an alphabet size of two and a subsequence length of three is '00011101'. As long as three consecutive elements in the cyclic sequence are known, it is possible to determine exactly where in the sequence the subsequence of three elements is. The LC shutter runs according to a de Bruijn sequence at a rate of ten elements per second throughout the 25 second exposure. Currently, the sequence parameters are 10 elements per second, a subsequence length of nine and an alphabet size of two, but this can be modified remotely for the network connected systems. The sequence is long enough that it doesn't repeat itself during the 25 second exposure. At least nine elements or dashes must be visible in the fireball's luminous trajectory for the start time of the trajectory to be determined. In practice, it is preferred to have more elements visible to validate the position in the sequence. Validated timing is available for all meteors clearly visible for one second or longer.

Sequence Encoding: The de Bruijn sequence is encoded using pulse width or dash length. A '1' is represented by leaving the shutter open longer which results in a longer dash and a '0' corresponds to a shorter open time and therefore a shorter dash in the image.

The advantage of this approach compared to previous techniques is that the absolute trajectory and relative timing data are collected together on the same sensor without any additional hardware. The LC shutter is required to chop the meteor trail for velocity data; modulating it according to a de Bruijn sequence provides the absolute timing without requiring the integration, synchronisation and calibration of additional sensor subsystems. This simplification allows the production of much smaller, lighter, lower power and more economical meteor cameras than previously possible.

Timing precision: A microcontroller ensures the exposure start time and the LC shutter waveforms are synchronised with UTC via a GPS module. This module is accurate to within a few tens of nanoseconds. The shutter opens regularly every 0.1 s and closes either 0.02 s later for a short '0' dash or 0.06 s later for a long '1' dash. This system therefore enables sub-millisecond, absolute timing resolution during fireball entry. This level of precision allows reliable velocities to be calculated. The deceleration of a meteoroid is essential for determining its mass during bright flight with such a simple system, and subsequently any potential fall locations. Although only relative timing is required for meteorite fall predictions, the absolute start time of the luminous trajectory is required for accurate determination of pre-atmospheric entry due to the spin of the Earth. The sub-millisecond precision offered by the DFN cameras is well in excess of the requirements for calculating meaningful orbits.

Example meteor: A meteor was captured over South Australia by three DFN camera systems on 26 September 2014 at 16:42:2.80 UTC. Figure 1 shows the dashes in the fireball trail from the de Brujin shutter sequence. Decoded timings are from the start of the exposure and some examples are given in the inset. The beginning of the de Bruijn sequence used is shown at the bottom, with the inset section highlighted. The altitude and azimuth of the start and end points of the fireball dashes are determined on each of the images and after calibration, triangulation software determines their absolute latitude, longitude and height. This fireball entered the atmosphere at 135.620° E, 28.529° S, with a height of 75.93 ± 0.15 km. Its entry velocity was 16.6 ± 1.3 km/s and its very shallow angle (~9° from the horizontal) meant that although the total duration was 6.68 s, it only penetrated 15.4 km into the atmosphere, ending with a velocity of 15.2 ± 1.3 km/s. At the end of the fireball's bright flight (135.51° E, 27.77° S) the angle to the horizontal had reduced to ~7°. Orbital parameters were also obtained for this event using the absolute entry time decoded from the sequence.

Summary: The combination of a liquid crystal shutter modulated by a de Bruijn sequence and synchronised via GPS makes it possible to record absolute trajectory timing data within a long exposure image without additional hardware. This enabled the development of a smaller, simpler and more economical meteor observatories than previously possible. The implementation allows the calculation of fireball trajectories with very precise timing data coupled with the high spatial resolution of 36 megapixel image sensors. The low per system cost and ease of manufacture of the automated observatories has driven rapid growth of the DFN to 30 stations covering ~1.5 million km^2. We are currently developing a simple 'kit' system, based on this technology, that will allow colleagues and interested amateurs to make high resolution fireball observations at low cost, see http://www.fireballsinthesky.com.au for details.

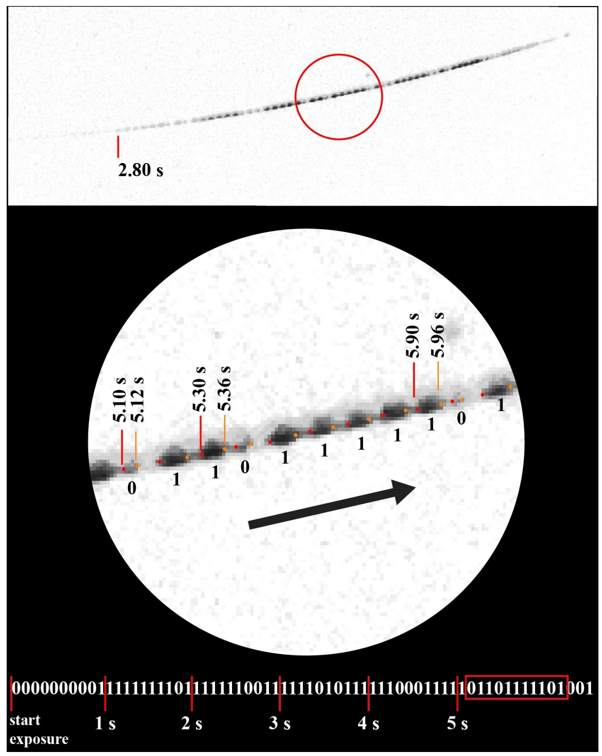

Figure 1: Trajectory with decoded de Bruijn sequence

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