Earth Moon Planet (2008) 102:269–275
DOI 10.1007/s11038-007-9161-7

Algorithms and Software for Meteor Detection

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Received: 27 June 2007 / Accepted: 25 September 2007 / Published online: 12 October 2007

Abstract An ever increasing variety of electronic instrumentation is being brought to bear in meteor studies and analysis, with unique meteor detection challenges arising from the attempt to do automated and near real-time processing of the imagery. Recent algorithm developments in the literature have been applied and implemented in software to provide reliable meteor detection in all-sky imagers, wide-field intensified video, and narrow field-of-view telescopic systems. The algorithms that have been employed for meteor streak detection include Hough transforms with phase coded disk, localized Hough transforms with matched filtering, and fast moving cluster detection. They have found application in identifying meteor tracks in the Spanish Fireball Network all-sky images, detailed analysis of video recordings during the recent Leonid meteor storms, and development of a detection/cueing technology system for rapid slew and tracking of meteors.

Keywords Meteor detection · Transient detection · Meteor tracking

1 Introduction

As meteor astronomy advances, it is relying more heavily on electro-optical (EO) instrumentation in place of human visual observations. Development of intensified low light video (Hawkes and Jones 1986) has extended the limiting magnitude of EO meteor detection beyond the normal human visual range and can be used for mass index estimation, flux, orbit calculation, and light curve analysis. Spectroscopy and high frame rate imaging of meteors is now possible with the demonstration by (Gural et al. 2004) of meteor tracking hardware providing composition and fragmentation information. With the advent of more sensitive focal planes, non-intensified applications are arising as well. Large format CCDs are used in all-sky fireball tracking with the potential for meteorite recovery as in the SPanish Fireball Network or SPFN (Trigo-Rodriguez et al. 2004) and Marshall Space Flight Center has begun a program in telescopic lunar meteoroid flash

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monitoring (Suggs 2007), to examine the number density of boulder class meteoroids. All these represent transient detection problems in multi-frame image processing with a range of response times, image characteristics, noise statistics, and signal features.

2 Design Criteria and Software

In these examples, signals or the meteor's illuminated track, can last from milliseconds to seconds producing a spatial flash, a moving streak in video, or a line in a single image frame. The noise can be comprised of speckle features from an intensifier, cosmic ray artifacts, thermal, and dark current. Detection of signals in a noisy environment always involves a trade of probability of detection (Pd) for probability of false alarm (Pfa) and thus use of a priori knowledge can help decide the best algorithmic choice. However, processing throughput and the timeliness of detection can result in a less than optimal algorithm selection. Thus several questions must be answered in formulating any particular detection solution. Does the detection need to be done in real-time at the camera frame rate, or in near-real-time with a small latency, or at a later time offline in post-collection at the user's convenience? Must the detection be fast which usually requires a high SNR or robust to very low SNR events? What are the tolerance for and mitigation approach to false alarms? What are the processing capacity, storage needs, and interface requirements of the proposed computing system? What are the goals of the collection and the needs for calibration, post-analysis, and science exploitation that can drive the detection requirements?

To address these unique image processing needs, a variety of software packages have been developed such as MeteorScan, MetRec, UFOCapture (Molau and Gural 2005) for real-time video meteor detection, the SPFN MeteorDetector for all-sky fireball surveying, MeteorCue for meteor tracking and instrument pointing, LunarScan and LunaCon for lunar meteoroid impact flash detection, MachoScan for star occultation detection, and MeteorSim for meteor flux and human/video ZHR calculation. This does not represent a complete list of software (see Cheselka 1999 for an IRAS software package add-on for linear feature detection in astronomical imagery), but inherent in all is a requirement that transient detection algorithms be very fast, process large volumes of imagery, robust, and tuned towards the specific characteristics of the data and collection system. To maintain brevity in this paper only the meteor streak detection algorithms will be discussed and the reader is advised to check the references (Gural 2001, 2007; Parker et al. 2004) for discussions on flux simulation, lunar flash detection, and occultation detection respectively. In addition, a simple web search on the software names will turn up sites for downloading the aforementioned packages or alternatively contact this paper's author.

3 Detection Algorithms

The most common form of detection problem faced in the last decade has been to discover meteor tracks in video streams either live or pre-recorded. A typical meteor track is comprised of a streak lasting up to several video frames propagating in a linear fashion across space and time. There exists a variety of line detection algorithms published in the literature. The one with the best Pd, Pfa ratio is the matched filter (MF), where an object's motion is hypothesized for a particular starting point, speed, and direction, and has been applied to moving satellite and asteroid detection in a cluttered star field (Mohanty 1981;

Gural et al. 2005). Each frame set is shifted and stacked according to the motion hypothesis and the resultant summed frame tested against a threshold. However, the large number of potential motion hypotheses for meteors limits this technique except in those circumstances where the entire set of candidate motions is small. An alternative pseudo matched filter approach applied to meteors was published that included an angle hypothesis, median filter and sum technique (Torii et al. 2003) that again requires large hypothesis sets and is suitable for single frame processing but is too computationally burdensome for video frame rate processing.

Thus it is more common to see the application of the Hough Transform (HT) to the meteor line detection problem due to its relative speed improvement over the MF with only a slight loss in Pd. Unfortunately, there are a wide variety of HT algorithms to choose from and only those that the author has found to be relatively successful in meteor detection will be discussed herein. The basic concept behind the HT is to threshold an image, transform the pixel point exceedances from image space to Hough space (line orientation angle, origin offset), and finally locate peaks which have a correspondence to lines in the original image. Each HT can also be summed across several images to obtain the signal integration gain from a meteor with multi-frame duration. Depending on the HT algorithm chosen, the execution time can scale either linearly or quadratically by the number of pixel exceedances, trading speed, robustness, and sensitivity.

For even greater throughput in situations requiring real-time response, one can dispense with searching for linear features and instead simply locate clusters of pixels. Again one thresholds pixels, applies a fast cluster search algorithm, and searches for motion consistency between clusters found across several frames. The detection requires high SNR to mitigate false alarms and can be extended to situations where the transient leaves no temporal response as in meteoroid flash detection where one tries to match only a spatial signature.

Inherent in the above discussion is the underlying need to threshold the image for pixels containing a signal exceeding a noisy background level. The first stage of processing usually removes stationary features such as stars and background. This can be done through (1) removal of a mean or median which has lower noise characteristics but is harder to track in shifting scenes, (2) differencing adjacent in time frames resulting in a zero mean and finite variance estimate for each pixel with faster processing but higher noise levels, or (3) computationally loaded clutter suppression where the noise statistics are estimated and the image whitened through covariance estimation and inversion. With the stationary features removed and variance estimated, a threshold can be defined to flag the subset of pixels that then feed the detection algorithm. The next few sections will take these general concepts and apply them uniquely to each meteor detection problem.

4 All-sky Fireball Detection

The SPanish Fireball Network (SPFN) has begun operating a series of large format focal plane cameras (4 K $\times$ 4 K pixels) to detect fireballs and obtain atmospheric trajectories (Trigo-Rodriguez et al. 2004). The large number of pixels results in slow readout times so video rates are not possible in this setup. Instead the all-sky cameras integrate the star field for 3 min with a single exposure and rotating shutter, repeating this through the entire night. The all-sky nature of the scene contains a stationary horizon, star field rotation and trailing during the exposure, and has a changing background arising from the long time delay between frames. Initially failed approaches at detection included co-alignment

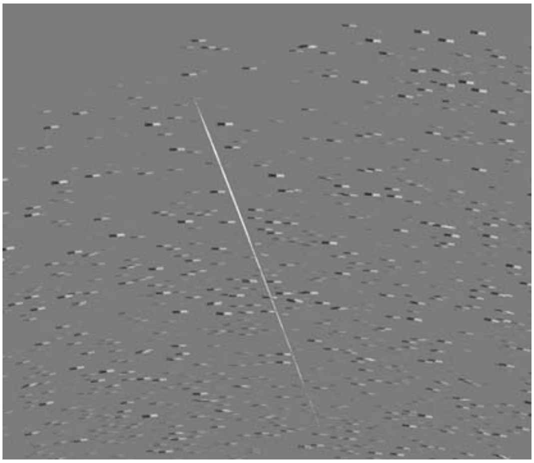

Fig. 1 Difference image of SPFN showing positive and negative star trails

(rotational registration) of frames to remove stars and the addition of a mask to screen out the background. However, bright star column bleed, lack of flat fielding, and residual registration errors caused a high level of false alarms.

The current algorithmic approach avoids the background subtraction and flat fielding issues by differencing two adjacent-in-time images directly. The trailed star tracks and meteors remain but the stars have both positive and negative trail components that over short time scales and equal exposure lengths appear as straight lines as in Fig. 1. The HT applied to the difference image results in each star effectively summing to near zero, whereas a meteor which appears in only one image has a net positive or negative Hough peak. To determine which subset of pixels to transform, a two-sigma clipped local mean and standard deviation is computed iteratively using a sliding window to obtain the estimate of the residual background noise statistics. Since the meteor detection can be processed off-line and reported on later, the algorithm uses a slower but more robust version of the Hough transform on each exceedance pixel where the orientation is obtained through the kernel convolution of a phase coded disk or PCD (Clode et al. 2004). Furthermore, false alarm mitigation and the desire to ensure that only a single detection of the same meteor is achieved, the peak finding algorithm employs Hough space region exclusion after each meteor is detected in the image.

5 Medium to Narrow Field Video Meteor Detection

The workhorse for EO meteor detection and analysis has been the medium field of view (FOV) camera system with fast low f-number lens, image intensifier, and frame-rate CCD macro-focused to the output face of the intensifier. Using standard off-the-shelf video components results in 25–30 frames per second (fps) with various image sizes depending on format (e.g. 480×640 pixels for NTSC). The limiting magnitude for these systems typically reaches +7 to +8 for a 40 degree FOV. One can trade FOV for sensitivity to fainter meteors, accuracy of track, and flux statistics. Software has been developed for real-time detection of meteors, but with the large storage capacity in modern day personal computers and/or the use of camcorders, the option for later off-line reduction of the imagery is possible and now done regularly.

The imagery is characterized by little to no change in the background between frames due to the high frame rate and slow movement of the star field in a wide FOV. For intensified systems there is a high noise speckle component which in earlier generation II systems was predominant near the center. A meteor typically appears in multiple frames propagating as a linear streak across the FOV. To remove stationary components, mean estimation and removal is preferable due to its lower noise variance, but frame differencing is usually done due to its legacy back to fast runtime in real-time operations. In either case, a variance is tracked for every pixel through an updating first order response filter that can be used to "whiten" the current image and threshold the frame for pixel exceedances. For linear time Hough transforms, the classic HT should not be used due to its "self-noise" issue and the PCD method is computationally too heavy to provide an analysis in a reasonable amount of time for the data volume of video imagery. A quadratic-in-time HT can be used that limits the transform to only local neighbor pixel pairs since a meteor's exceedance pixels are typically adjacent to each other (two points provide orientation and center offset and avoids Hough self noise). Summing multiple HTs in a short image sequence provides signal gain but requires that the absolute value of the difference be computed to avoid the meteor from canceling itself. To reduce false alarms, a subset of HT detected tracks are passed through a matched filter to enhance the robustness of the detection. The HT algorithms have difficulty with short and slow meteors since they do not produce spatial signal integration gain and lowering the detection threshold simply raises the Pfa to undesirable levels. As PC capabilities improve and the use of graphical processing units for image processing becomes more prevalent, the migration will be back to real-time processing and more robust algorithms like the PCD.

For ablation studies, narrow FOV video imaging has been tried recently which presents a slightly different signal environment for detection. The meteor may last at most two frames, can be electronically chopped (gated), and will have a longer streak in each frame. The same HT processing can be applied but the multi-frame integration must be limited to avoid adding too much noise when there is no signal present in non-meteor video frames.

6 Telescopic Meteor Tracking

To enhance the collection probability of capturing a meteor in narrow FOV instruments like spectrometers or high spatial resolution cameras, a meteor tracking system needs to be incorporated into a collection system's design. An approach using computer controlled mirrors to redirect the meteor's light to the instrument, requires very rapid response motors and a fast meteor detection/tracking system (Gural et al. 2004). The software must function on a medium FOV sensor matched to the steering system motion limits and operate at standard frame rates. The response time to capture a meteor before it fades out must include detection, mirror movement, and settle time to all occur within 100 ms of a meteor's first light. Such rapid response rules out the HT and thus a very fast clustering approach is called for. Although a clustering algorithm suffers from requiring high SNR for reliable detection, the nature of narrow FOV meteor work also requires bright meteors, so is compatible with the algorithm's poor light sensitivity. Frame differencing is chosen for its speed of stationary background removal coupled with noise variance tracking to provide thresholding for pixel exceedances. A fast region based clustering algorithm as demonstrated in Fig. 2, locates clumps of pixels in the odd and even fields separately of the interlaced video to provide higher time resolution for a meteor tracker. Cluster centroids are passed to an alpha-beta tracker which converts these positions to mirror angles.

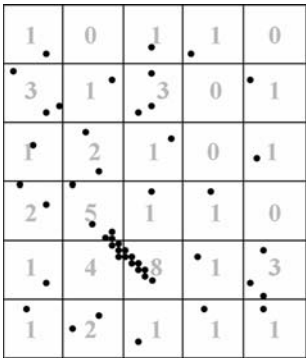

Fig. 2 Fast cluster counting in 32 × 32 blocks whose size corresponds to the maximum meteor motion for the typical intensified video image scale

Detection of a true track is declared early (after 2 out of 3 fields detected) to minimize the time to move the mirrors. This is feasible since one is willing to accept a higher Pfa to achieve a high Pd for the narrow FOV instrument.

7 Conclusion

In summary, this paper briefly discussed the algorithms used in many meteor detection systems in operation today accounting for trades in detection Pd, false alarm Pfa, sensor, signal, and noise characteristics, throughput requirements, and reporting timeliness. Details on the performance comparisons and quantitative analysis of these algorithms is beyond the scope of this paper with the goal having been to highlight the various algorithmic approaches possible given the wide operating characteristics of meteor imaging systems. Furthermore, detection is only the first phase of analysis in all meteor work, and calibration for mass index, flux estimation, and orbital elements requires application of additional image processing techniques and the refinement of high fidelity meteor simulation and analysis software.

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