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RESULTS FROM THE AIM-IT METEOR TRACKING SYSTEM

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Abstract. The recent development and data collection results of the Astrobiology Instrumentation for Meteor Imaging and Tracking (AIM-IT) system, has demonstrated an ability to point narrow field-of-view instruments at transient events such as meteors. AIM-IT uses the principle of tracking moving objects via a paired set of relay mirrors along with an integrated hardware/software solution, to acquire and track meteors in real-time. Development of the instrument has progressed from a prototype rocker-box system through more recent use of a fast response mirror system during several meteor shower campaigns. Several narrow field of view instruments have been deployed using AIM-IT including high spatial resolution video, high frame rate video, and meteor spectrographic equipment. Analysis of the imagery shows evidence for meteor fragmentation in as many as 20% of the meteors tracked thus far. The success of the AIM-IT technology in tracking meteors during their luminous flight provides a new tool in enhancing the capabilities and data volume that can be obtained with existing narrow field of view instruments.

Keywords: Meteor, meteor instrumentation, meteor tracking, meteor imaging, meteor spectroscopy

1. Introduction

The analysis and understanding of meteor stream orbits, dynamics, composition, and ablation physics has very often come from the application of narrow field of view instrumentation to meteor observations. These include high spatial resolution cameras for meteoroid orbital parameter estimation and stream evolution studies, high frame rate imaging for light curve analysis and ablation structure, and high resolution slit spectroscopy for composition and thermal studies. The issue that arises is that the probability a meteor will pass within a narrow field of view instrument is extremely low and thus long-term observational periods are required and the quantity of collected data is low. Recent airborne campaigns during the Leonid meteor storms of 1999, 2001, and 2002 (Jenniskens et al., 2000; Jenniskens 2002; Jenniskens and Russell 2003) attempted to take advantage of high meteor flux rates to increase the volume of data collected from a variety of instruments. However, meteor storms are rare events and an innovative means to enhance the collection rate from a given instrument is required to help answer questions in meteor astronomy.

One solution is to physically point an instrument towards a meteor to obtain the necessary information. Most instruments of interest however possess high inertia and thus make it extremely difficult to reposition them on the time scales of tenths of seconds – the typical luminous duration of an ablating meteor. An alternative solution is to steer the light from the meteor via a set of relay mirrors to a stationary instrument, thus lowering the inertial mass that must be repositioned. This concept requires very high-speed hardware and software to successfully acquire and track meteors on very short time scales. Through recent developments, these technologies are now available with the use of state-of-the-art galvanometer motors and advances in automated video meteor detection.

Such a rapid response instrument was developed under NASA's Astrobiology program element to help answer questions about meteors and their pre-biotic contributions to Earth's early development and thus the instrument was named Astrobiology Instrumentation for Meteor Imaging and Tracking (AIM-IT). The name is a slight misnomer however in that the AIM-IT system can be used to study much more than astrobiology issues in meteor astronomy.

2. Instrument Description

The AIM-IT system consists of a set of integrated hardware components and high-speed detection software for rapid meteor acquisition and tracking. The core of the hardware is a pair of Cambridge Technologies 6900 galvanometers with mirrors configured to steer anywhere within a $40° \times 40°$ patch of sky and provide a minimum of 50 mm clear aperture for a stationary mounted narrow field instrument. The mirrors are moved by commands from a laptop computer through a digital I/O board interfaced to a pair of motor controllers as functionally illustrated in Figure 1.

The system achieves a total repositioning and vibration settling time of 10 ms when commanded to move $\pm 20°$ and requires only 2 ms for 1° shifts. This is much less than the single-field frame-time of 16 ms in standard NTSC video and the 200 ms duration of a typical meteor. To direct the mirror positioning, the meteor must be acquired and tracked in a wide field video camera that covers the entire observable area of the mirror system. Intensified video cameras with a 40° field of view are typically used in meteor

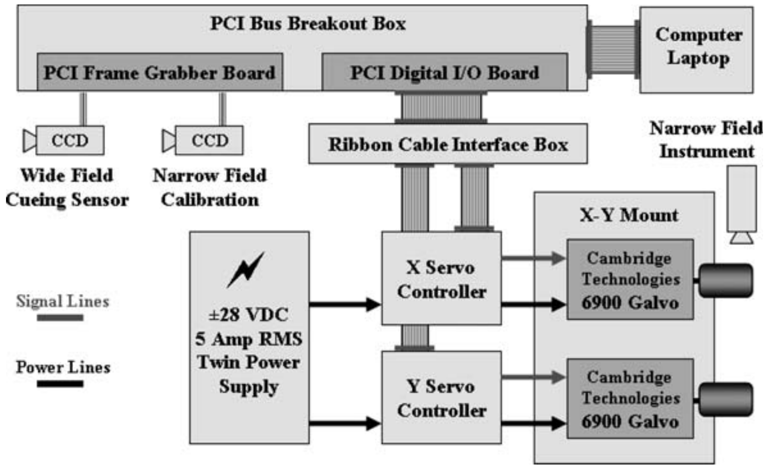

Figure 1. Block diagram of the AIM-IT system equipment interfaces.

astronomy and form the basis of the "cueing" imager for AIM-IT. The mirrors are steered towards the cue (meteor track) to relay the emitted light towards a narrow field of view instrument of the researcher's choice. For example, a picture illustrating the equipment setup during the 2003 Leonids, using a high frame rate camera as the narrow field instrument, is depicted in Figure 2.

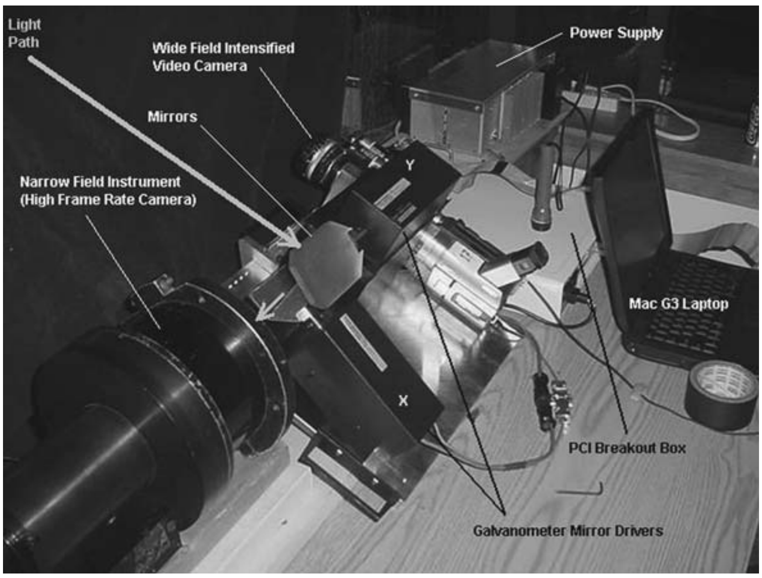

Figure 2. AIM-IT system configuration showing wide field cueing camera and mirror relay coupled to a narrow field of view instrument (high frame rate camera).

3. Image Processing

A laptop computer processes the wide field video after image capture by a LG-3 frame grabber commercially available from Scion Corporation. The LG-3 permits asynchronous image processing of previously digitized frames while grabbing the next available frame into memory on a Macintosh computer. Each digitized frame is examined for evidence of a meteor using a variant of the MeteorScan automated meteor detection software developed by one of the authors (Gural, 1999). MeteorScan's near noise limit sensitivity utilized a Hough transform/matched filter detector that contained a half second latency – a delay that would be unacceptable in the current application. Thus a re-engineered software package named MeteorCue was developed specifically for AIM-IT that employs a high speed, very low latency meteor detection algorithm that trades off some magnitude sensitivity for rapid acquisition. The current MeteorCue software detects magnitude +4 meteors in +7 stellar limiting magnitude imagery. This was deemed acceptable since the narrow field instruments to be used with AIM-IT, such as slit spectrometers, would require meteors of at least second magnitude brightness to reach sufficient signal-to-noise ratios in their sensors.

The software algorithm used for acquiring meteors is based on a custom-designed cluster detection method. The image frames are continuously passed through a first order response filter to obtain the image mean and standard deviation on a pixel-by-pixel basis. Each new frame that is digitized is then thresholded with respect to the mean image plus a user factor times the standard deviation. The exceedances are flagged and passed through a highly efficient cluster detector. The clustering algorithm involves counting the number of exceedances within 32×32 pixel accumulator cells spread across the 480×640 pixel wide field camera image. The cell dimension was based on the maximum meteor angular rate of 28 pixels per frame expected for non-hyperbolic meteors and the wide field sensor resolution of 3.75 arc minutes. Finally summed 2×2 (50% overlapping) super-cell counts are searched for a maximum whose effective 64×64 pixel region ensures a meteor will be entirely contained within a single super-cell. A cluster is considered a valid candidate if it exceeds a super-cell count threshold.

Valid clusters have their centroids computed for both the even and odd fields separately, thus providing position measurements at an effective 60 Hz update rate (NTSC video). The positions are fed to an alpha–beta tracker that first performs an association test with any previous tracks and then either initializes a new track or updates a currently active track. If there is an active track, the meteor's position is predicted ahead to the next measurement (digitizing frame) time and the pixel coordinates in the wide field coordinate system are computed. These are converted to mirror angles via a set of closed form transformation equations whose coefficients were determined in an earlier calibration stage. The current latency of MeteorCue on a 300 MHz Macintosh G3 laptop is only 100 ms from first appearance of the meteor in the wide field camera to tracking the meteor in the narrow field instrument. Further work using odd and even row fields rather than full image frames at both the threshold and cluster stages should reduce this latency to 60 ms.

A calibration is performed to tie wide field camera pixels to mirror angles by selecting a star in the wide field and adjusting the mirrors until the same star is centered in the narrow field. For 40° fields of view the relationship can be restricted to linear plate coefficients and transformations via standard coordinates. Several stars are selected across the wide field and a least squares fit is made to determine the plate constants. As long as the wide field camera is kept rigidly fixed with respect to the mirror system, this calibration will remain valid even if the entire instrument setup is repositioned. That is, it is not necessary to re-calibrate the mirror angle transform coefficients when a different overall system orientation is chosen or a different star field is present. This makes the AIM-IT system amenable for use on a moving inertial platform such as an aircraft with continuous attitude changes.

4. Development and Design Trades

During the development of the instrument, the AIM-IT system evolved through various configurations. The initial prototype was based on a rocker box approach that physically moved a lightweight imager via two orthogonally mounted stepper motors. This provided the initial proof of concept and was flown during the Leonid Mac mission of 2002 (Jenniskens, 2002). A comparison of the design choices in the AIM-IT system is shown in Table I where the rocker box capabilities are compared to the mirror based approaches. Clearly trades can be made for cost, response time, instrumentation weight, clear aperture, and field of view coverage. Stepper motors with mirrors yield a low cost solution for long duration meteors and fireballs allowing the use of high spatial resolution video for orbital element estimation. Such a system can rival photographic resolution and enlarge the two-station viewing volume ten-fold relative to a single pair of 40° intensified video cameras. The galvanometer system with mirrors provide very accurate pointing for slit spectroscopy and high frame rate video and the fast response needed to image more typical meteors that are fainter and shorter duration. Note that the costs include a computer and all sensors required with the implication that there is an intermediate level of design that falls between the two cost extremes shown.

TABLE I
Comparison of system capabilities for various AIM-IT design options

Design feature	Stepper motor rocker box	Stepper motors with mirrors	Galvanometers with mirrors
Wide-field sensor	Intensified CCD	Intensified CCD	Intensified CCD
Wide field of view	Up to all-sky	70° × 70°	40° × 40°
Narrow-field sensor	Small/light <0.5 kg	Moderate size/heavy	Moderate size/Heavy
Aperture limitation	None	35 mm	50 mm
Maximum slew rate	150°/s	800°/s	2000°/s
Max time to meteor	250 ms	50 ms	10 ms
Pointing resolution	1.8°	1.8°	2 arc seconds
Applications	Fireball tracker high-res trains	Video triangulation orbital elements	High-res spectroscopy high frame rate video
Cost ($US)	$2500	$2500	$17500

5. Narrow Field Imaging

The prototype rocker box system was flown on NASA's DC-8 Airborne Laboratory during the Leonid Mac mission of 2002 to monitor the Leonid meteor storm. Although far slower to respond than the galvanometer system under development at the time, the rocker box system provided validation of the basic AIM-IT concept by acquiring 380 meteors in the wide field camera and tracking 180 meteors in the narrow field imager. In particular, it acquired and tracked a magnitude −8 fireball that was a highlight of the entire mission (Jenniskens, 2002).

The galvanometer-based system with mirrors was ready for initial trials the following summer of 2003. Unfortunately, poor weather put a hold on "first light" for three weeks. Finally, on August 12, 2003 at 8:28 UT in Sterling, Virginia, USA, the first meteor tracked was a magnitude +2 Perseid with six more meteors obtained in two hours of observations. Further tests were then relocated to Freemont Peak Observatory, California where eight hours of observations yielded 75 meteors on the nights of August 26 and 30, 2003. This was followed by an observing run again at Freemont Peak where 33 meteors were tracked when the Orionids were active covering one and one-half hours of observations. An interesting result of some of the early observations that employed a CCD video camera for the narrow field of view sensor, has been that about 20% of the meteors imaged show twin illumination centers just prior to fade out as illustrated in Figure 3. Note that this result is from a sample taken near the times of major meteor showers without each meteor having been associated to an active radiant and therefore the

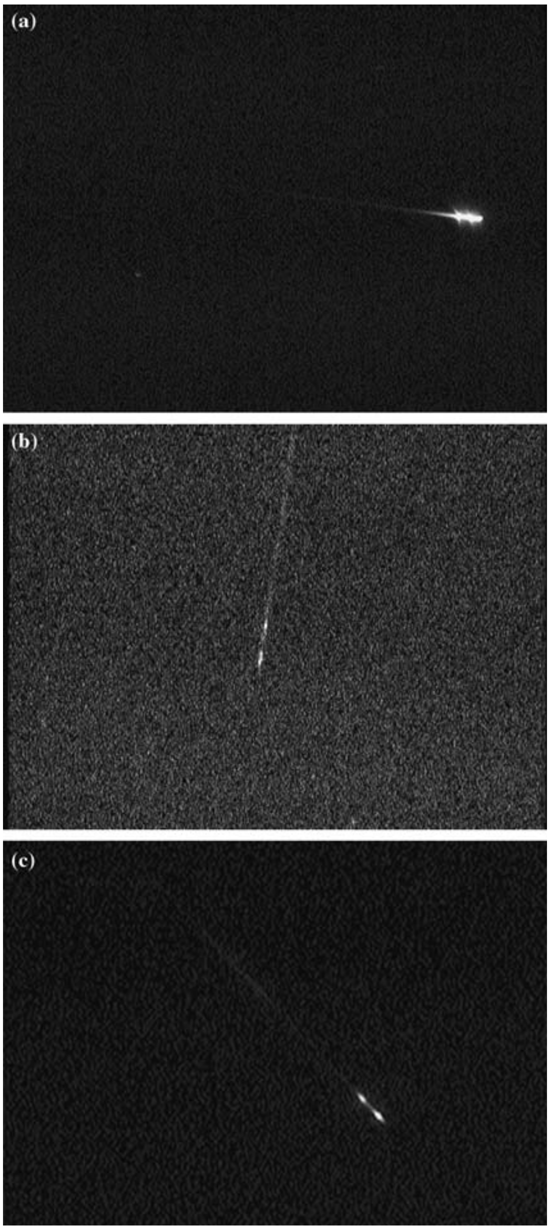

Figure 3. Examples of fragmented meteors captured in a narrow field of view imager.

20% fragmentation rate should not be generalized to all meteors or any particular shower stream at this time.

Nonetheless it is intriguing evidence for meteor fragmentation during ablation. Note that we have ruled out both multiple reflections in the mirrors (these are first surface mirrors) and lens reflections since the paired light peaks are typically of equal intensity and don't appear in earlier and brighter portions of the meteor video record. Thus, the ability to image meteors with high spatial resolution has provided additional evidence for fragmentation in a variety of shower streams other than the Leonids. Further statistical evidence will need to be accumulated to more accurately comment on the fragility of meteors associated with other streams and sporadics.

In general, the initial tests were successful and work was begun on interfacing a spectrometer to the output of the mirror light path. This latter part has encountered difficulties in obtaining sufficient intensity of a light source on the slit of the spectrograph. A mirror pointing bias correction needed to be introduced to account for the off-axis position of the slit relative to the nominal light path. An alternative fiber-optic coupling approach was also tried to permit the spectrometer and a small CCD imager to share the narrow field of view opening. This configuration has required significant rework to improve the optical train characteristics and performance of the combined sensors. These interface problems have now been worked out and the first spectrum was obtained for the AIM-IT system in July 2004 when it successfully tracked and recorded the aircraft landing lights of a passing aircraft. First meteor spectra are expected during the fall of 2004.

6. High Frame Rate Imaging

During the Leonids meteor shower of November 2003, the AIM-IT galvanometer/mirror system was deployed at Poker Flat Research Range near Fairbanks, Alaska. This campaign was specifically aimed at obtaining high frame rate imagery of meteors using a 1000 frame per second (fps) camera developed by Hans Staebeck-Nielsen of the University of Alaska. The goal was to obtain both high spatial and high temporal resolution imagery of fireball shocks as first reported in (Jenniskens and Russell, 2003).

Several issues arose during the campaign associated with the detection aspects of the AIM-IT MeteorCue software. The overall system detection sensitivity was seriously reduced due to extremely strong aurora activity that produced a rapidly changing background and large false alarm rate in the wide field sensing system. Necessarily the thresholds for detection needed to be raised thus lowering the probability of detection. Unfortunately the Leonid shower was dominated by a faint meteor component this particular epoch and thus the number of meteors acquired was significantly less than expected. In total, only eight meteors were both tracked by the AIM-IT system and were of sufficient brightness to be recorded by the 1000 fps camera. An issue involving a 10 Hz background variability from the wide field intensifier, that created a further loss in sensitivity, has since been resolved. In addition, a mirror angle drift with pointing angle was discovered that was not significant enough to cause a problem due to the available 6° field of view in the high frame rate camera. The drifting issue was later resolved by deriving a more exact closed form solution to the mirror angle transformations.

Three interesting results arose from the high frame-rate imagery of the meteors. The first involves a 162 and 172 Hz periodicity evident in the light curve of one of the meteors. Initial analysis indicates that it was caused by the meteor crossing in and out of the inter-pixel spacing of the high frame rate camera system. The camera's CCD chip has only an 84% fill factor, thus a moving steady light source displays a sensor induced flickering of the light curve. There remains however an unaccounted for 90 Hz oscillation in the light curve of the meteor that does not appear when modeling the actual meteor track on the CCD with inter-pixel voids and appropriate point spread function. Scintillation was ruled out as well since a simultaneously imaged star only shows significant spectral energy below 50 Hz with a flat response above that frequency. Possible explanations for the 90 Hz component are only conjecture and include the possibility of a rapidly rotating meteoroid or a periodic wake instability manifesting itself in a pulsating light curve. Further testing of the imaging system is required however, to rule out any sensor-based causes for the periodicity seen. The second interesting feature was that several meteors were saturated in the high frame rate camera while staring (mirrors motionless), but became unsaturated when the mirrors moved every 33 ms and the meteor smeared across the CCD by several pixels. When the integrated counts from all pixels containing the meteor were added, the smeared meteor frames had anywhere from the same number to twice the counts of the saturated frames. This evidence demonstrates the non-linear response of CCDs when in saturation and that not all the energy on a saturated pixel bleeds over to adjacent pixel sites. Thus careful consideration must be taken when calibrating meteor light curves for those meteors that are bright enough to be saturated on a CCD.

The last result involves a magnitude −1 meteor that fragmented into two pieces during one of the longer (0.75 s) high frame rate collections. In Figure 4 are shown the frames from 0.2, 0.4, and 0.5 s relative to the start of initial tracking. The meteor is clearly split into two parts during its ablation. Based on the relative angle rate of the diverging pieces, the meteor fragmented approximately one-tenth second before maximum brightness. There is no evidence to indicate this was two separate meteors that were co-aligned at one point in the trail, as the spatial spread prior to the time of fragmentation does not show any elongation or splitting of the intensity profile. Also perfect alignment of two meteors along the line of sight would be a highly improbable event. Since there were numerous frames available and the meteor is of long duration with a reference star visible in the narrow field

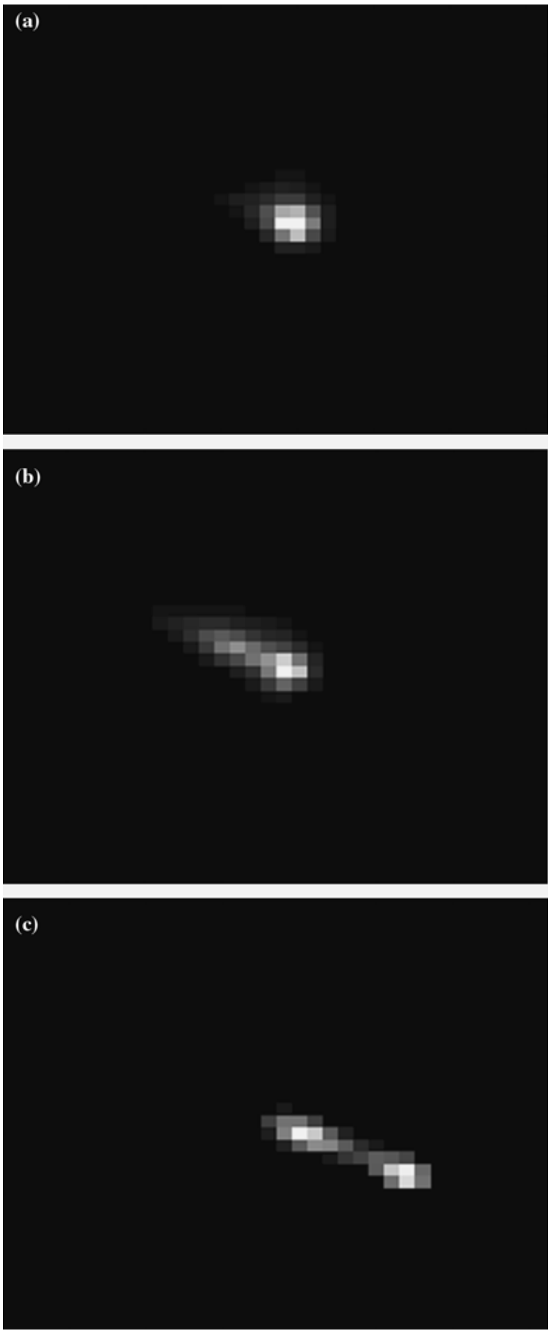

Figure 4. Selected frames of a fragmenting meteor collected with a high-speed imager on November 16, 2004 at 13:48:51 UT.

imagery, it was possible to discern not only the radiant direction but also the radiant angular distance based upon the apparent angular velocity rate of change. This latter calculation is possible from the geometric effects of angle rate change for a moderate length meteor track and was computed using the formulae published in Shiba (1995). This yielded a radiant distance for the meteor at its end height of 108° from its radiant. Attempts at association with the active meteor showers on the night of November 16 however places the meteor radiant more than 15° from the closest stream (Northern Taurids) and thus was categorized as a sporadic.

Unfortunately this classification makes it more difficult to place values on the incoming speed and distance. Note however that the nearly perpendicular motion of this meteor to the camera's line of sight (108° from radiant) permits us to place an approximate value on the relative speed between the two particles since there was negligible foreshortening effect from geometry. If one assumes the end height of this meteor to fall between 75 and 95 km, the range to the meteor is between 168 and 212 km, and the entry velocity is estimated to have fallen between 39 and 49 km/s which provided further evidence for not associating the meteor with any of the active radiants. Under these assumptions the relative speed of the two particles is between 2.0 and 2.5 km/s. This is approximately 5% of the mean angular velocity of the meteor and represents a significant change in velocity between the two pieces. Further modeling and analysis is required to understand the physics behind such dramatic acceleration changes in the flight profile due to the meteoroid's fragmentation.

7. Summary

The AIM-IT meteor tracking system has been demonstrated to provide high quality acquisition and tracking of meteors during several meteor-imaging campaigns. Through the use of a rapidly slewing mirror relay, the luminous portion of a meteor's track can be directed into a narrow field-of-view instrument within 100 ms of a meteor's first appearance. The success of the AIM-IT technology provides a new tool for meteor astronomy in enhancing the capabilities and data volume that can be obtained with existing narrow field meteor instrumentation.

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