Astrometric and Photometric Analysis of the September 2008 ATV-1 Re-Entry Event

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NASA utilized Image Intensified Video Cameras for ATV Data Acquisition

Platform:
- Gulfstream V Aircraft
  - 12.8 km altitude
  - Manual (Hand) Tracking

Instrument Pair:
- 75 and 12 mm lenses (8 and 20 deg FOV)
- Gen 3 Micro Channel Plate Intensifier
- S20 Photocathode (400-800 nm)
- Optical coupling to COTS CCD Camera
- Hi-8 (NTSC analog) recorder
- Video Encoded Time via GPS
ATV Raw Video Data
The high resolution/narrow field (75mm) data was used for this analysis (NTSC 480x720 pix; 8 deg Horizontal FOV; 0.7 arcminute/pix)
170 seconds of analog video were acquired

The video was digitized to .AVI, then analyzed with a modified commercial SW package: Image System’s Trackeye.

NASA sponsored SW modifications included a circular aperture photometry option and coordinate transformation from Cartesian image coordinates to celestial (RA DEC) using field reference stars.

Approximately 300 fragments were visible in the full motion video

184 fragments were actually measureable in the video still frames. Only the narrow field (75mm; 8 deg) data was analyzed due to excessive saturation in the wide field video.

Astrometric and photometric measurements were obtained for each fragment in each video frame: totaling \( \sim 10^6 \) independent fragment measurements. Fragments were tracked and measured until they faded to near still frame background levels.

84 reference stars (a minimum of 4 in each video frame) were identified for astrometric and photometric calibration of the fragment data.

Astrometric accuracy is \( \sim 4 \) arcminute (6 digitized pixels)

Relative photometric accuracy is \( \sim 0.5 \) astronomical magnitude (due to saturation and the analog nature of the video). Absolute \( \sim 1 \) magnitude with a limit of 10 (V Band)
The video is divided into two segments – delimited roughly by the ATV tank explosion

- The first segment is 76 seconds in length and contains 71 fragments and 43 reference stars
- The second segment is 94 seconds in length and contains 113 fragments and 41 reference stars

In each video segment we derived time-dependent fragment angular trajectories, velocities, accelerations, and luminosities.

Hans C.S. Nielsen (University of Alaska) kindly provided the coordinate transformation to Inertial Geocentric XYZ from our RA-DEC-Time measurements.

With Nielsen’s transformation we derived time-dependent fragment spatial trajectories, velocities, accelerations.

Ballistic Coefficients (Beta) were derived for each time step based on fragment velocity, acceleration, and altitude dependent atmospheric density.
ATV Tracked Video Data – Extracted Still Frame
(Trackeye Output w/ Markers for Fragments and Stars)
Raw Tracking Data
0.75 sec Sequence; Vertical Traverse
(Two reference stars & Three debris fragments)
Erratic target motion is removed using fiduciary reference stars
Coordinate transformation: Cartesian Image coordinates to Celestial RADEC
Reference Stars (vertical streaks) and Fragments (arcs)
RA DEC vs Absolute Time (T plus13:35:34 GMT)
(71 fragments – first video segment)
Coordinate transformation:  
Celestial RADEC to Topocentric Lat Long plus Altitude  
(Plane View; All data) – Curvature due to Earth Rotation; Separation due to varying Beta values
Coordinate transformation:
Celestial RADEC to Topocentric Lat Long plus Altitude
(Orthogonal View; All data) – Separation due to Explosion and varying Beta

Fuel Tank Explosion

20 second Data Gap while fuel tank cloud was tracked
ATV Reentry - Altitude v Time

Fuel Tank Explosion

Explosion dV

dBeta

20 second Data Gap while fuel tank cloud was tracked
Arc Length (deg) vs Absolute Time (T plus 13:35:34 GMT)
(Segment 1; 71 fragments; Arc Length along Great Circle)
Beta ~ slope; A/m ~ 1/slope
Arc Length (deg) vs Absolute Time (T plus13:35:34 GMT)
Clustering events (fragment clumps) indicated (Segment 1; 71 frags)
Arc Length vs Relative Time
(71 fragments; Beta ~ slope; A/m~1/Slope)
Arc Length (km) vs Absolute Time (T plus13:35:46 GMT)
Clustering events (fragment clumps) indicated; Differential Motion is readily evident
(Segments 1&2; All 184 frags)
Arc Velocity vs Absolute Time (T plus 13:35:34 GMT)
71 fragments; A/m ~ 1/V
ATV Reentry - Velocity v Absolute Time
(T plus13:35:46 GMT)

Fuel Tank Explosion
Circular Aperture Photometry via Trackeye
(Unsaturated) fragments commonly exhibit hook appearance due to initial brightening then subsequent fading.
ATV Reentry – Astronomical (V) Mag v Time
Segment 2 Only – Same Luminosity Hook as Segment 1
Separation => Enhanced Frictional Heating => Dissipation
Conclusions I

- Camera and platform motion were well compensated via our analysis software
  - Astrometric results were limited by saturation, plate scale, and imposed linear plate solution based on field reference stars

- Analog video (8-bit dynamic range, read noise, AGC) limited the accuracy of the photometry
  - 0.5 astronomical magnitude for the subset of unsaturated fragments; ~1 mag absolute

- It is readily evident that individual fragments behave differently
  - Differential velocity a dominant feature
  - There are derived trajectory families with a common spatial origin, this is clear evidence of fragment clustering (multiple fragments emanating from a common parent), unfortunately video saturation prevented extension of fragment tracks back to a common source
  - Fragment linear velocities range from 4 to ~20 km/sec
  - As time progresses fragments trend toward linear velocity. As they lose altitude the exchange of potential for kinetic $E$ dominates drag losses
  - Almost all unsaturated fragments exhibit hook appearance due to initial brightening then subsequent fading
Conclusions II

The fuel tank explosion at T=13:36:10 significantly affected subsequent fragment behavior:

- While the camera was trained on the dissipating fuel cloud, the fragments immediately behind the ATV parent body were not tracked for ~20 seconds after the explosion, hence the gap in fragment trajectory figures.
- ~25 seconds after the explosion (~5 seconds after the fragments were reacquired with NASA's camera) a +-5 km/s velocity dispersion was evident in the fragment field (versus +-1 km/sec prior)
- ~25 seconds after the explosion (~5 seconds after the fragments were reacquired with NASA’s camera) a +-10 km altitude dispersion was observed in the fragment distribution
- A large time window emerged as fragments descended – those with fastest descent passed through 55 km ~50 seconds earlier than the slowest

- Unfortunately photometric accuracy was insufficient to confidently assess correlations between luminosity and fragment spatial behavior (velocity, deceleration). Use of high resolution digital video cameras in future should remedy this shortcoming.

- Via ATV-1, we have developed a comprehensive pipeline enabling us to conduct future re-entry event analysis in a more timely and efficient manner.