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)

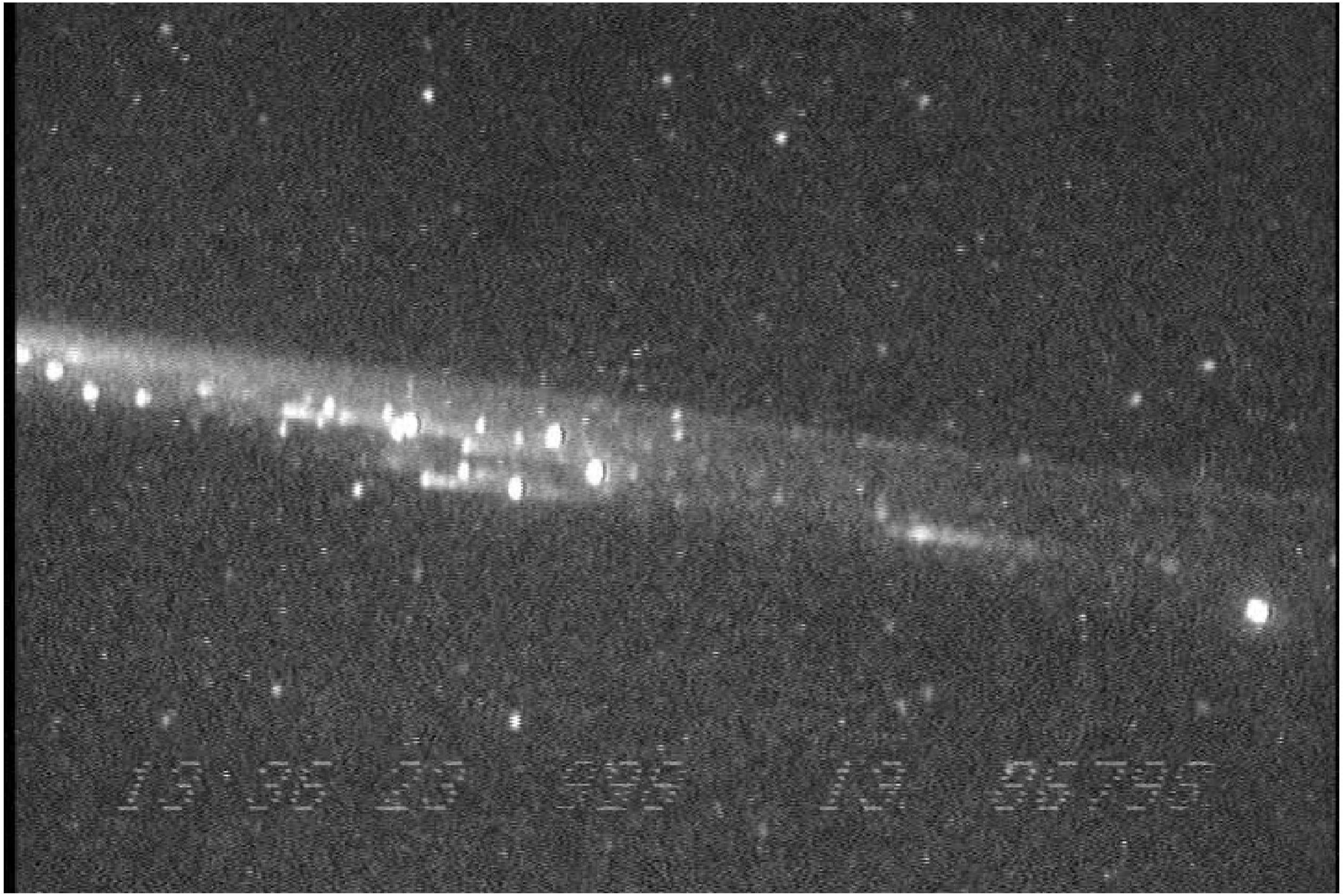
Optical coupling to COTS CCD Camera

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)



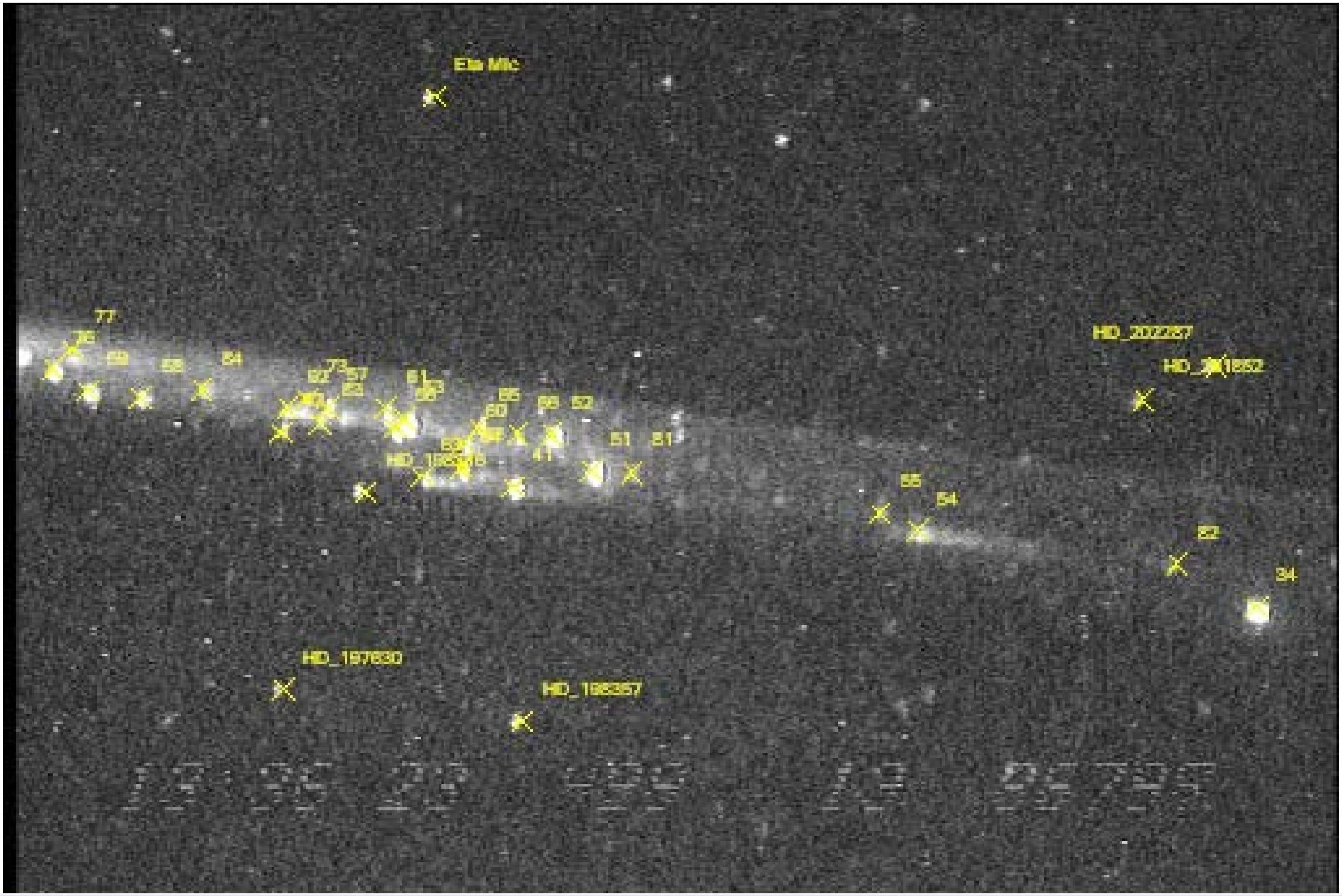
Data Extraction I

- 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 ~ 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 ~ 4 arcminute (6 digitized pixels)
- Relative photometric accuracy is ~ 0.5 astronomical magnitude (due to saturation and the analog nature of the video). Absolute ~ 1 magnitude with a limit of 10 (V Band)

Data Extraction II

- 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)

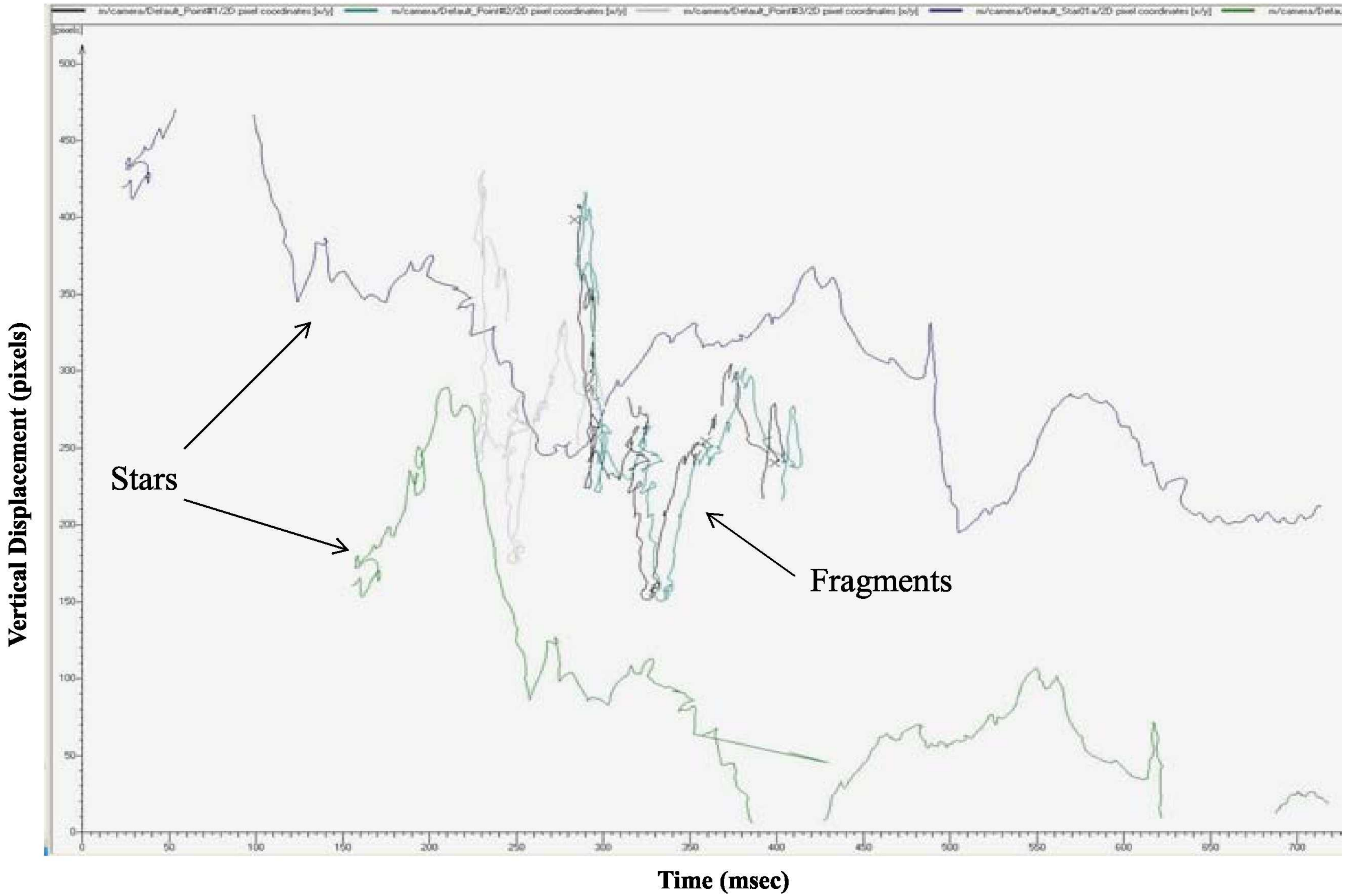


Raw Tracking Data

0.75 sec Sequence; Vertical Traverse

(Two reference stars & Three debris fragments)

Erratic target motion is removed using fiduciary reference stars

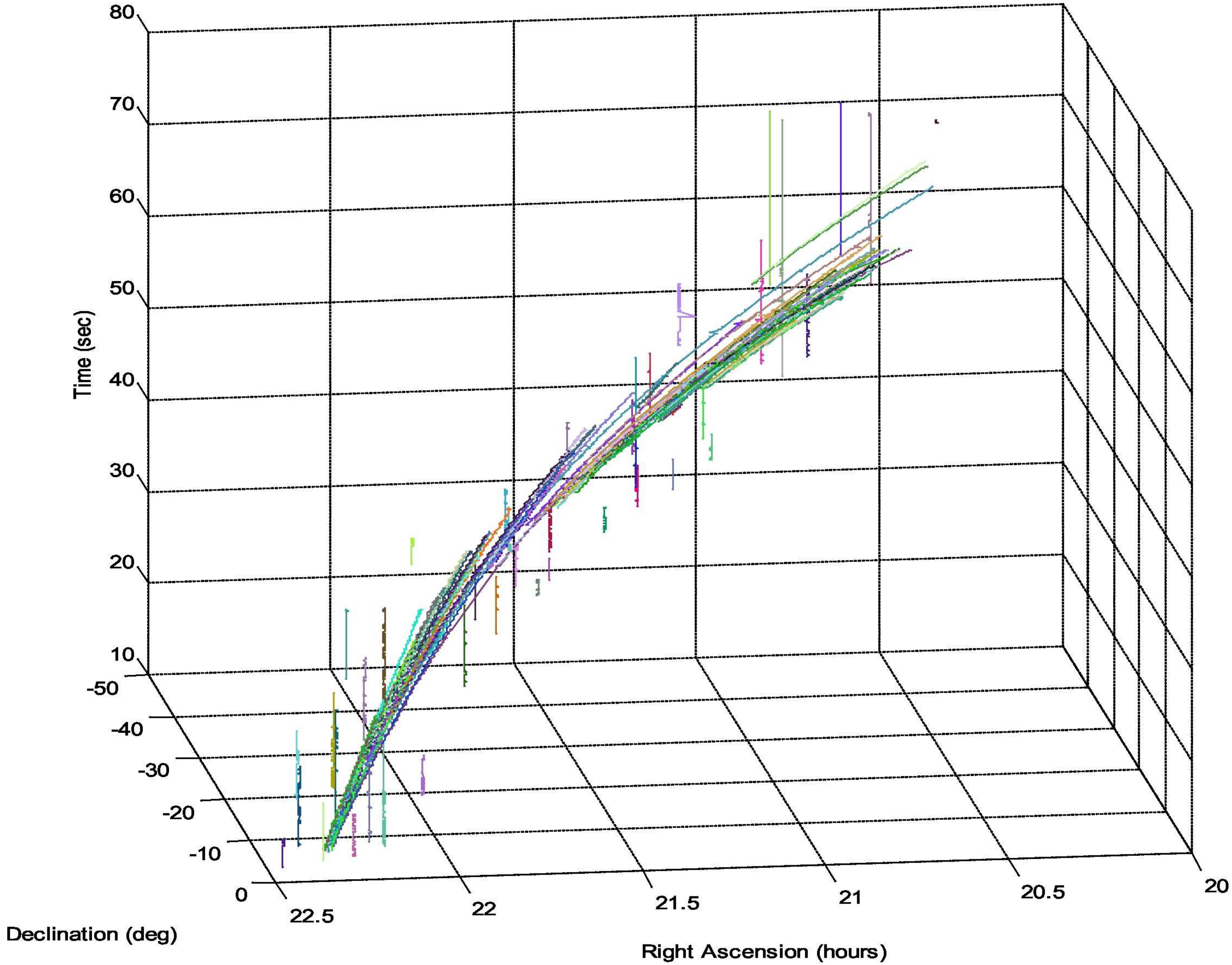


Coordinate transformation: Cartesian Image coordinates to Celestial RADEC

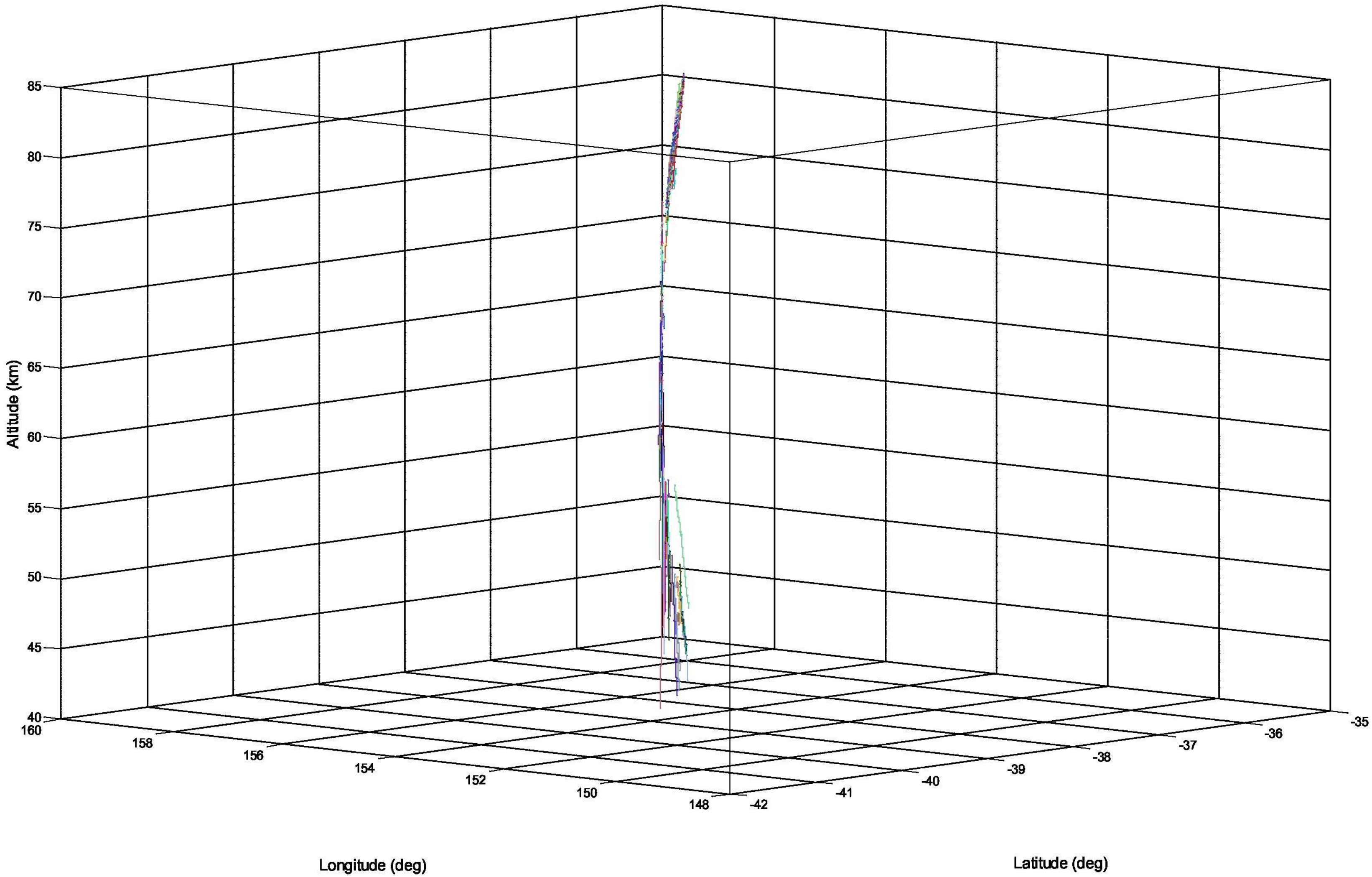
Reference Stars (vertical streaks) and Fragments (arcs)

RA DEC vs Absolute Time (T plus13:35:34 GMT)

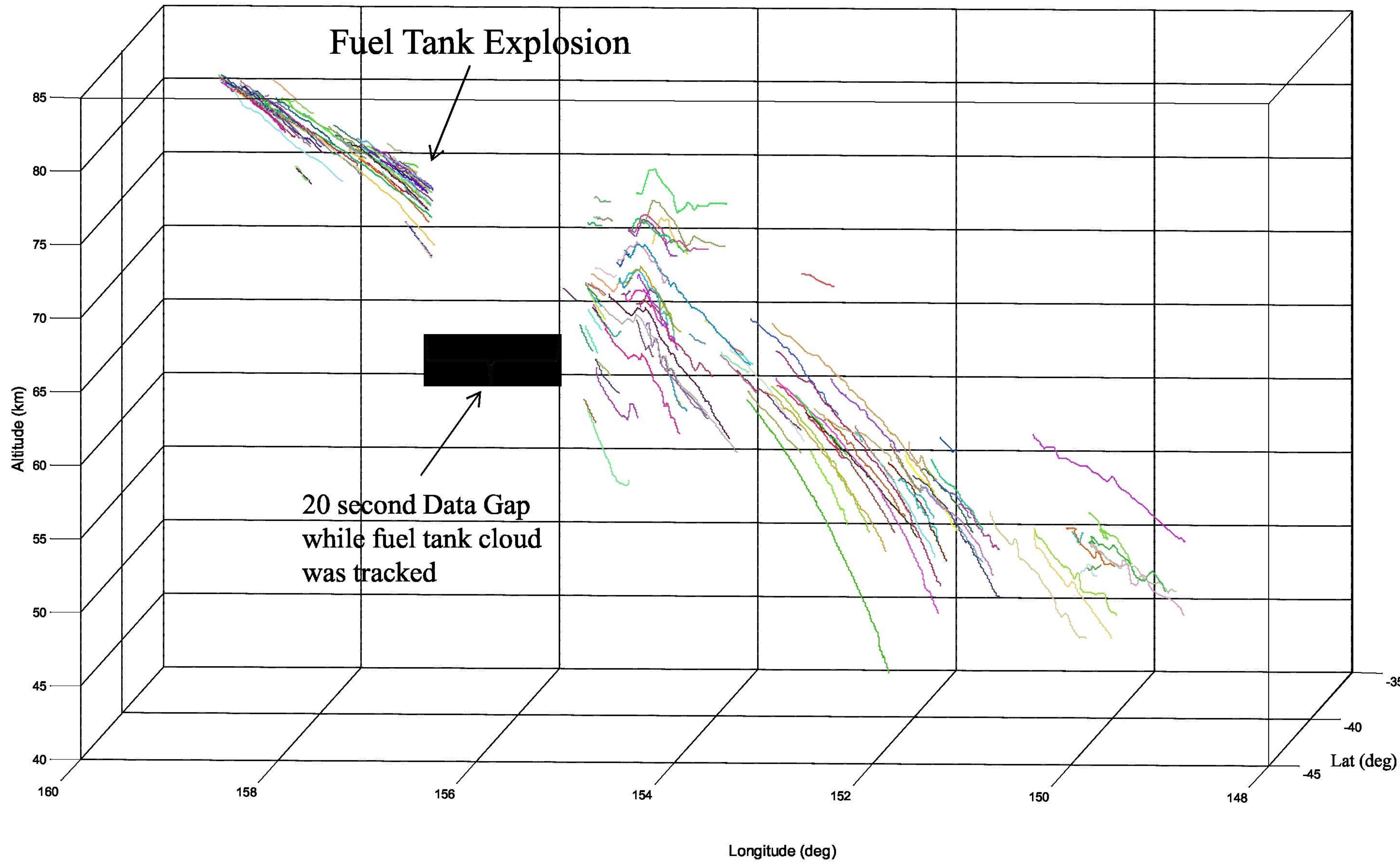
(71 fragments – first video segment)



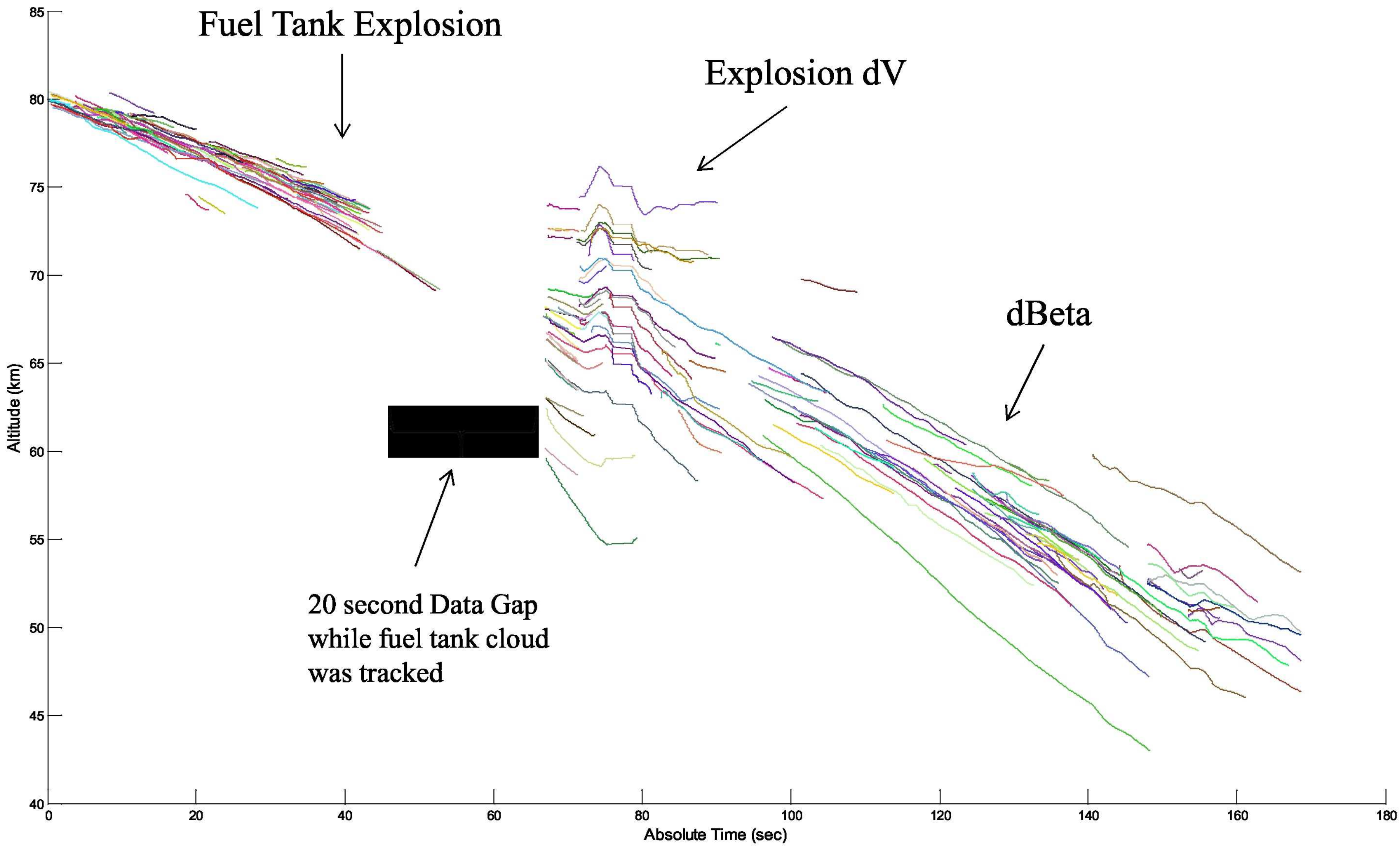
Coordinate transformation:
Celestial RADEC to Topocentric Lat Long plus Altitude
(Plane View; All data) – Curvature due to Earth Rotation; Separation due to varying Beta values



Coordinate transformation:
Celestial RADEC to Topocentric Lat Long plus Altitude
(Orthogonal View; All data) –Separation due to Explosion and varying Beta



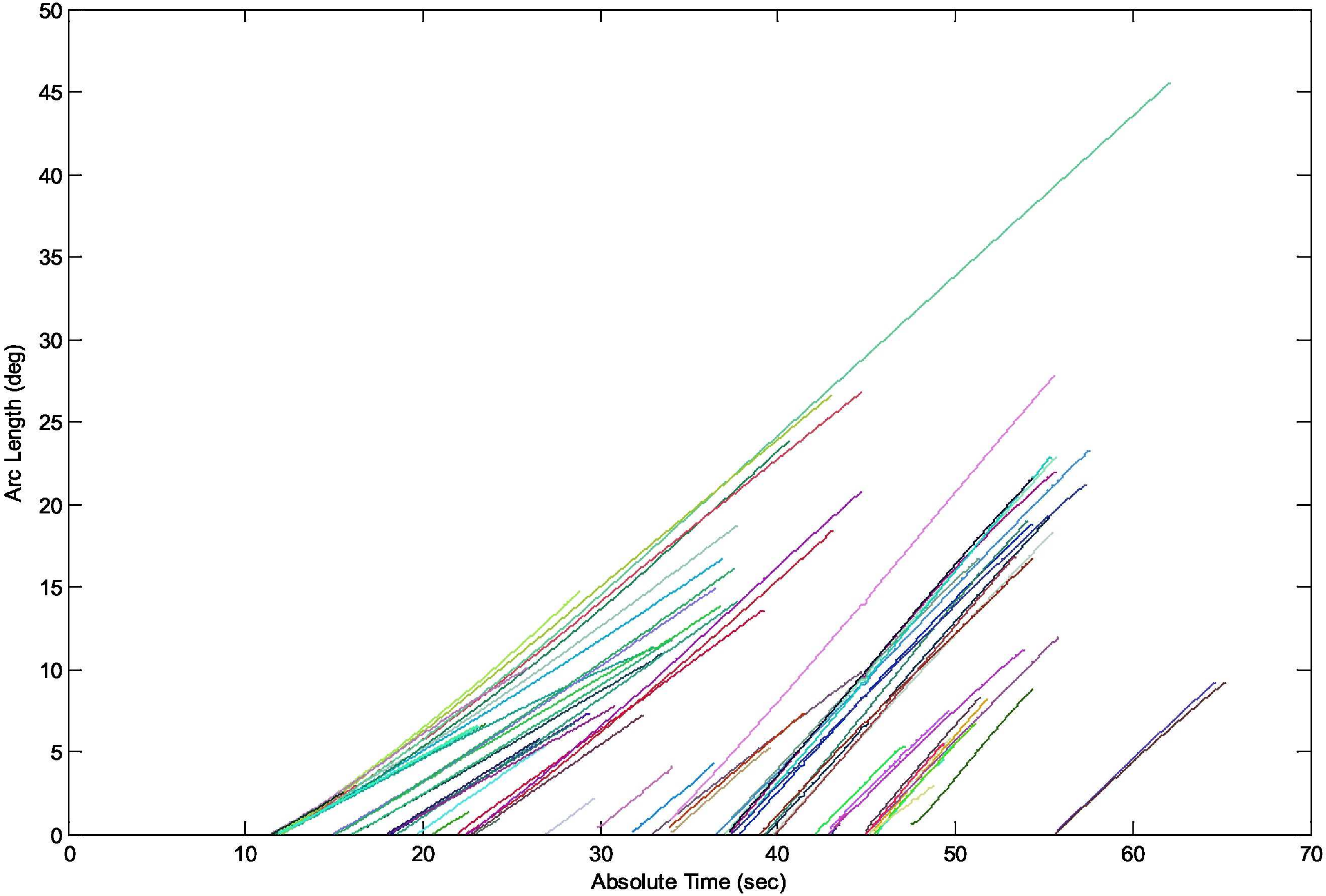
ATV Reentry - Altitude v Time



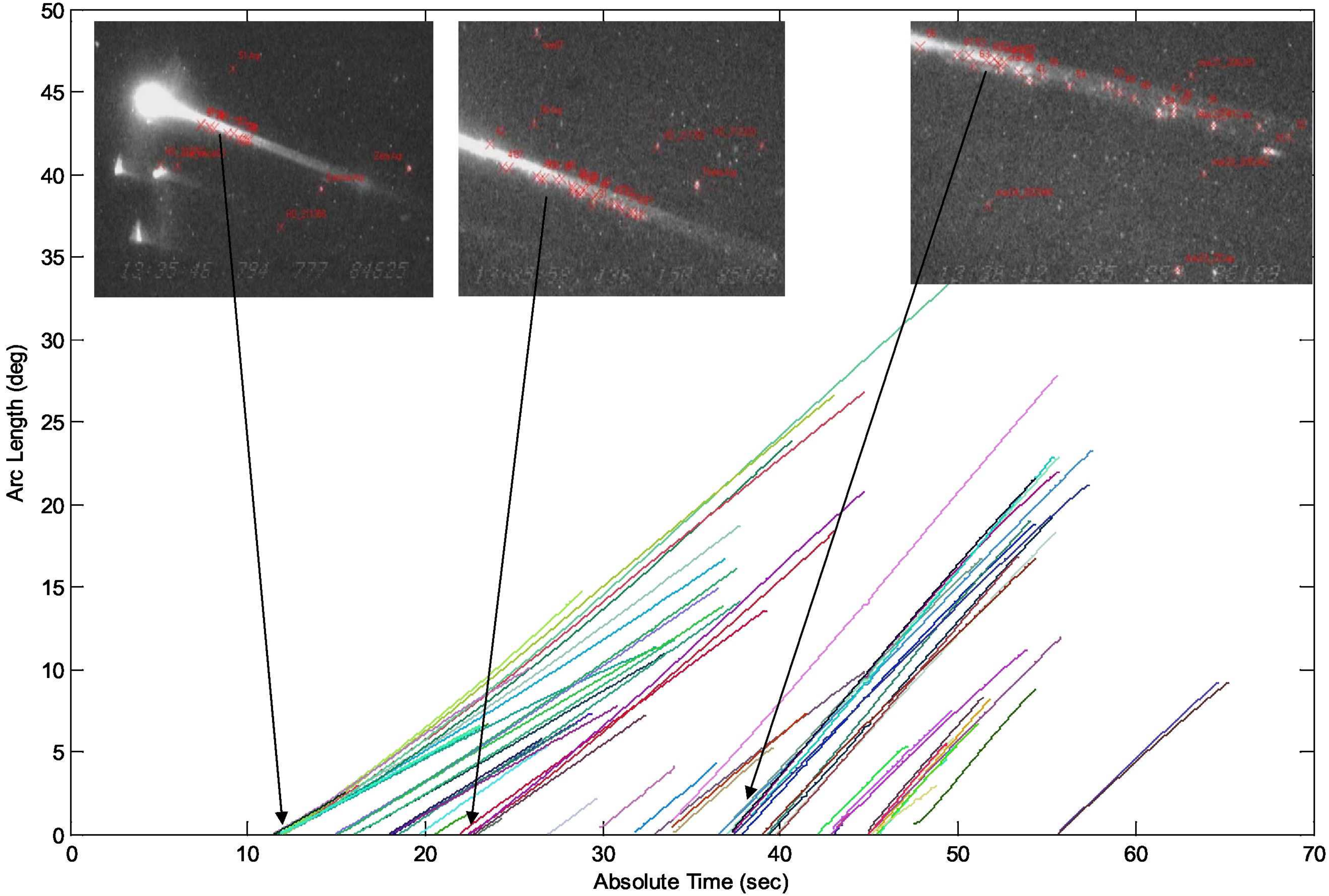
Arc Length (deg) vs Absolute Time (T plus13:35:34 GMT)

(Segment 1; 71 fragments; Arc Length along Great Circle)

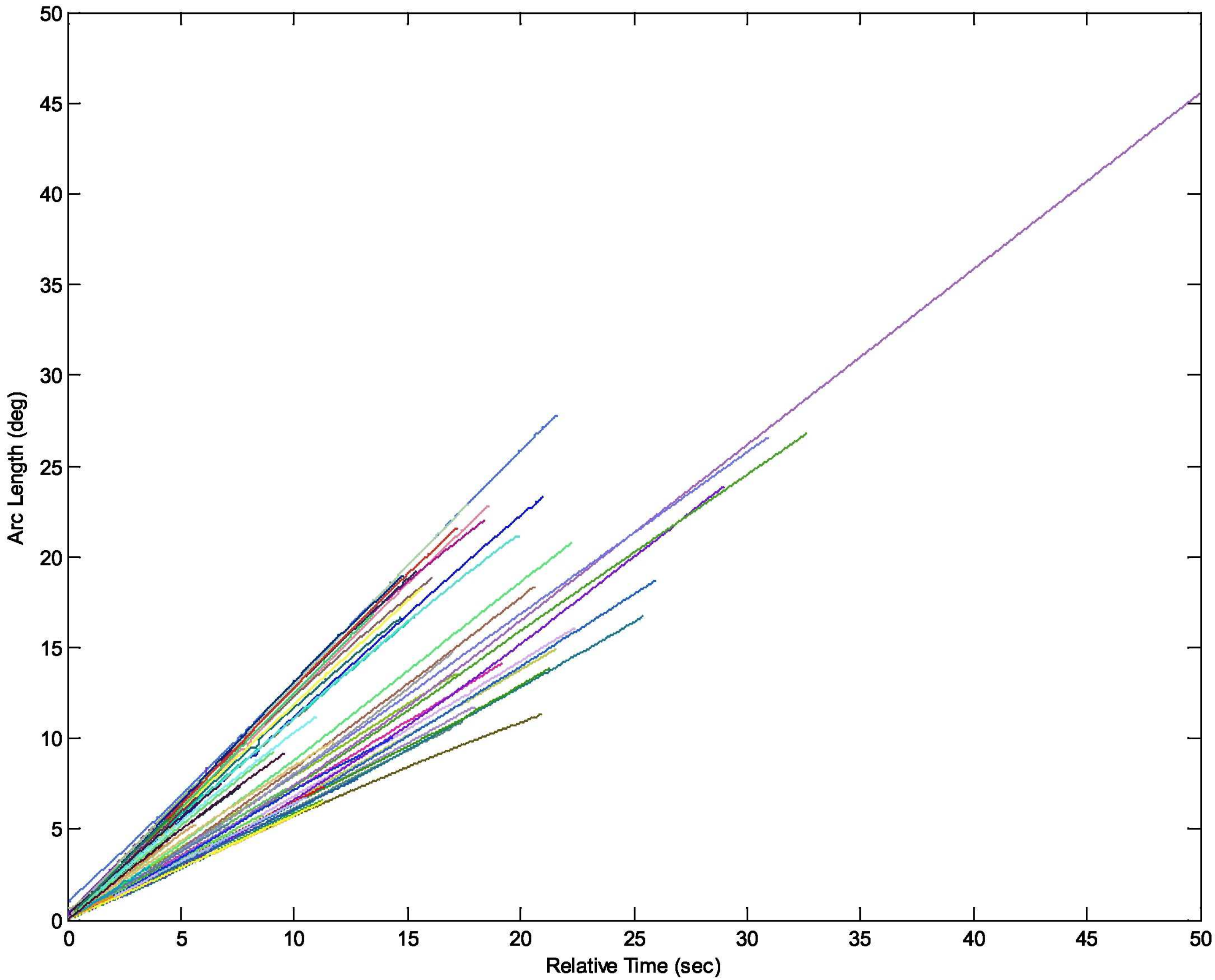
Beta ~ slope; A/m ~ 1/slope



Arc Length (deg) vs Absolute Time (T plus13:35:34 GMT)
Clustering events (fragment clumps) indicated (Segment 1; 71 frags)



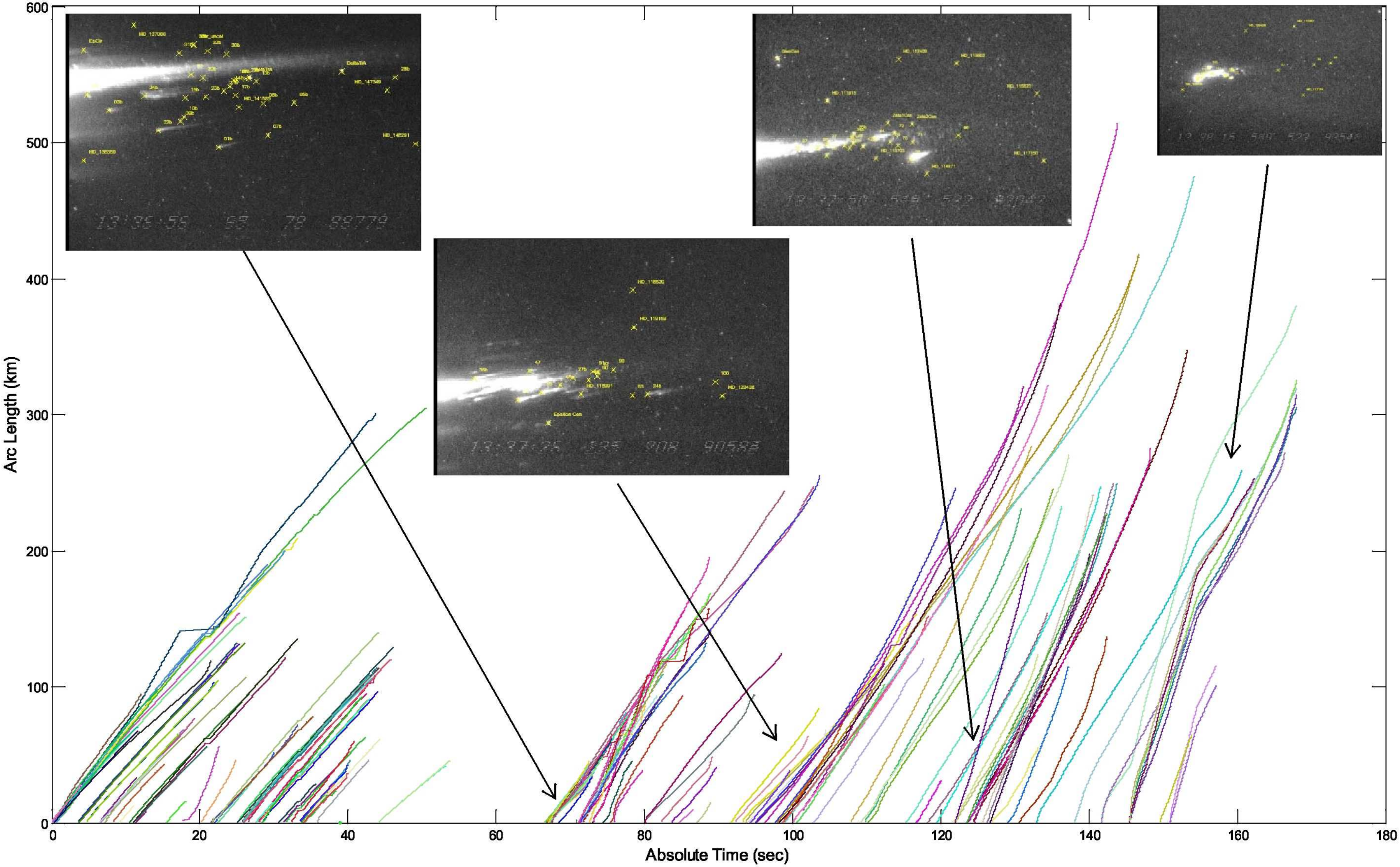
Arc Length vs Relative Time
(71 fragments; Beta ~ slope; A/m~1/Slope)



Arc Length (km) vs Absolute Time (T plus13:35:46 GMT)

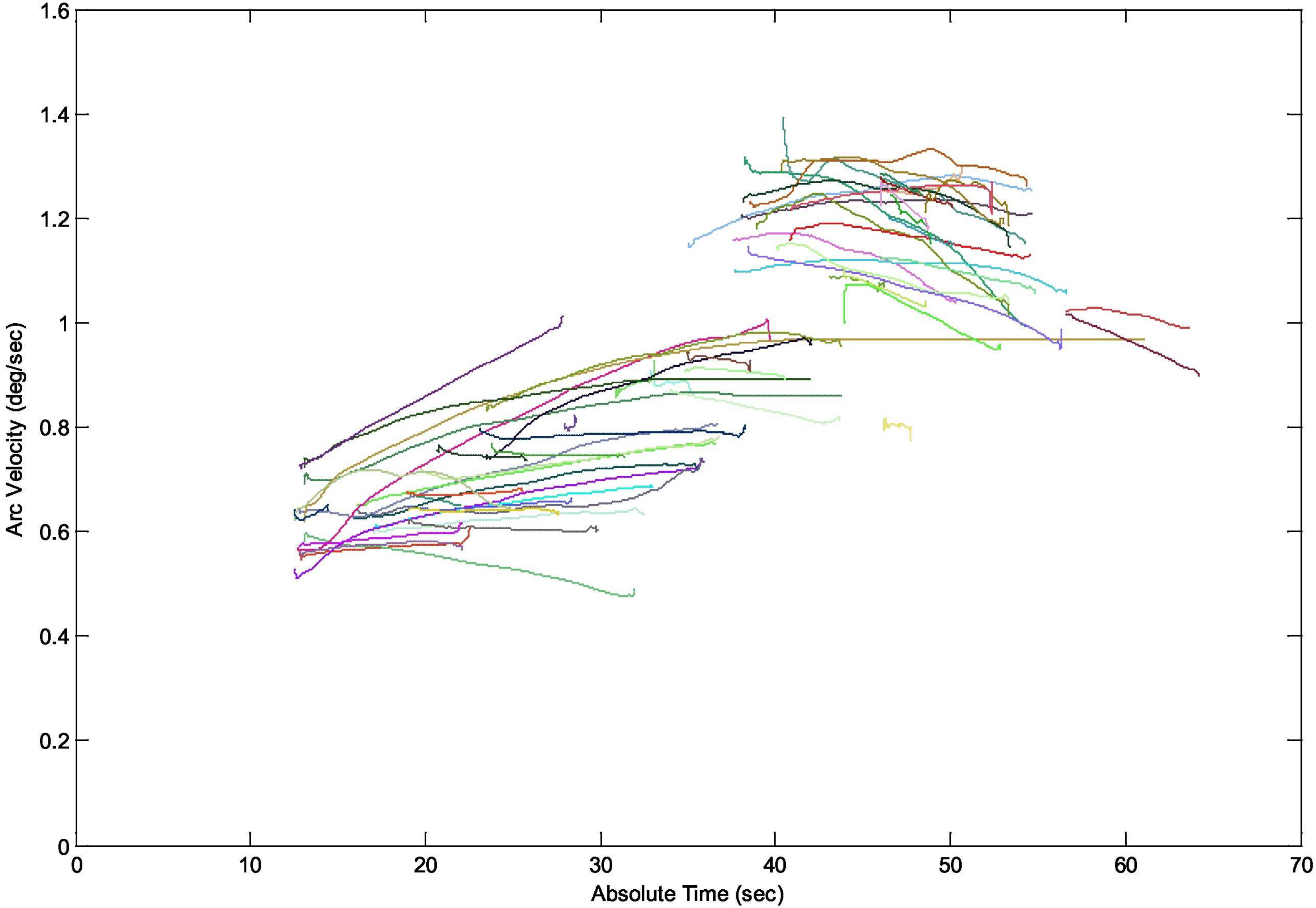
Clustering events (fragment clumps) indicated; Differential Motion is readily evident

(Segments 1&2; All 184 frags)

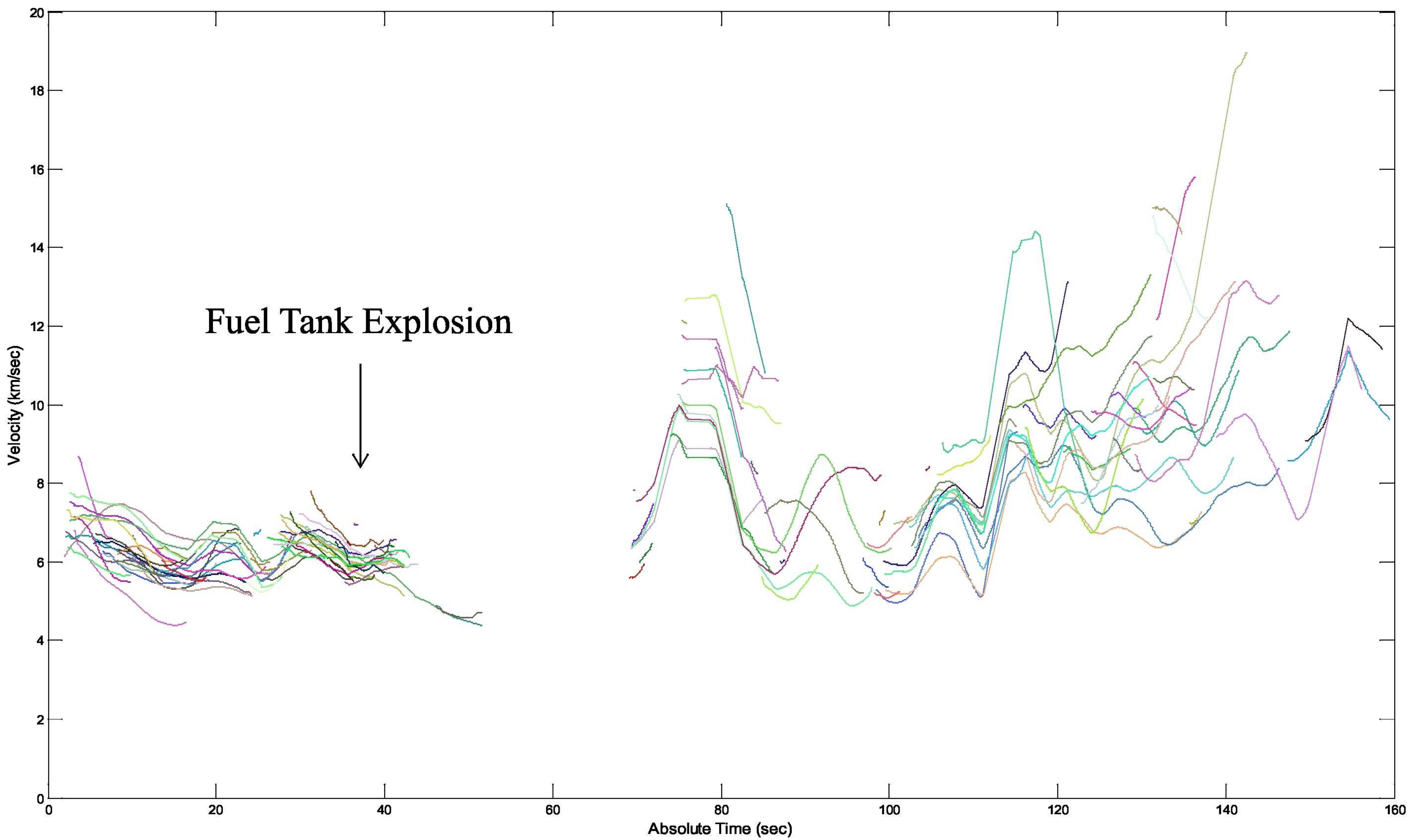


Arc Velocity vs Absolute Time (T plus13:35:34 GMT)

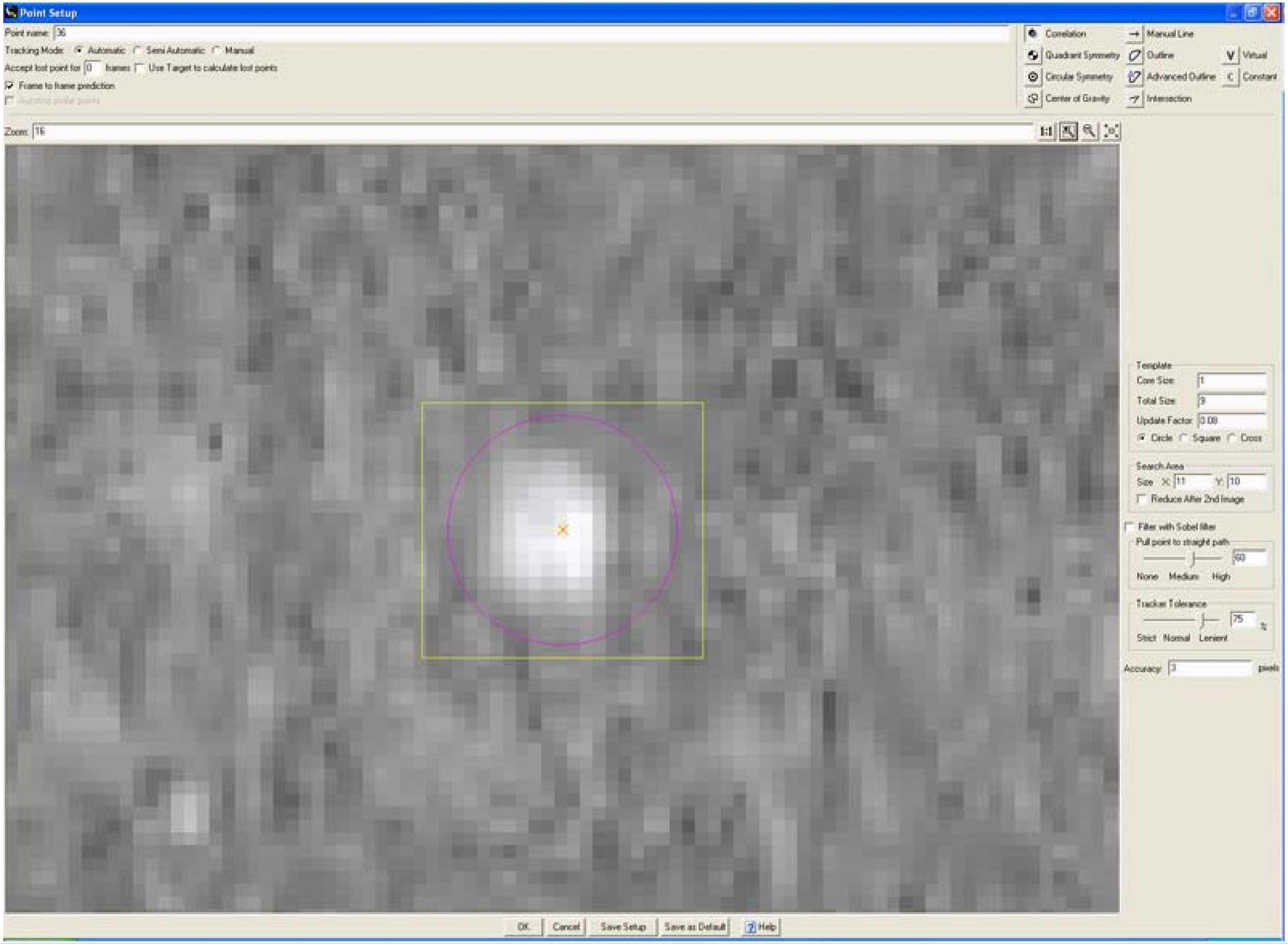
71 fragments; A/m~1/V



ATV Reentry - Velocity v Absolute Time
(T plus13:35:46 GMT)

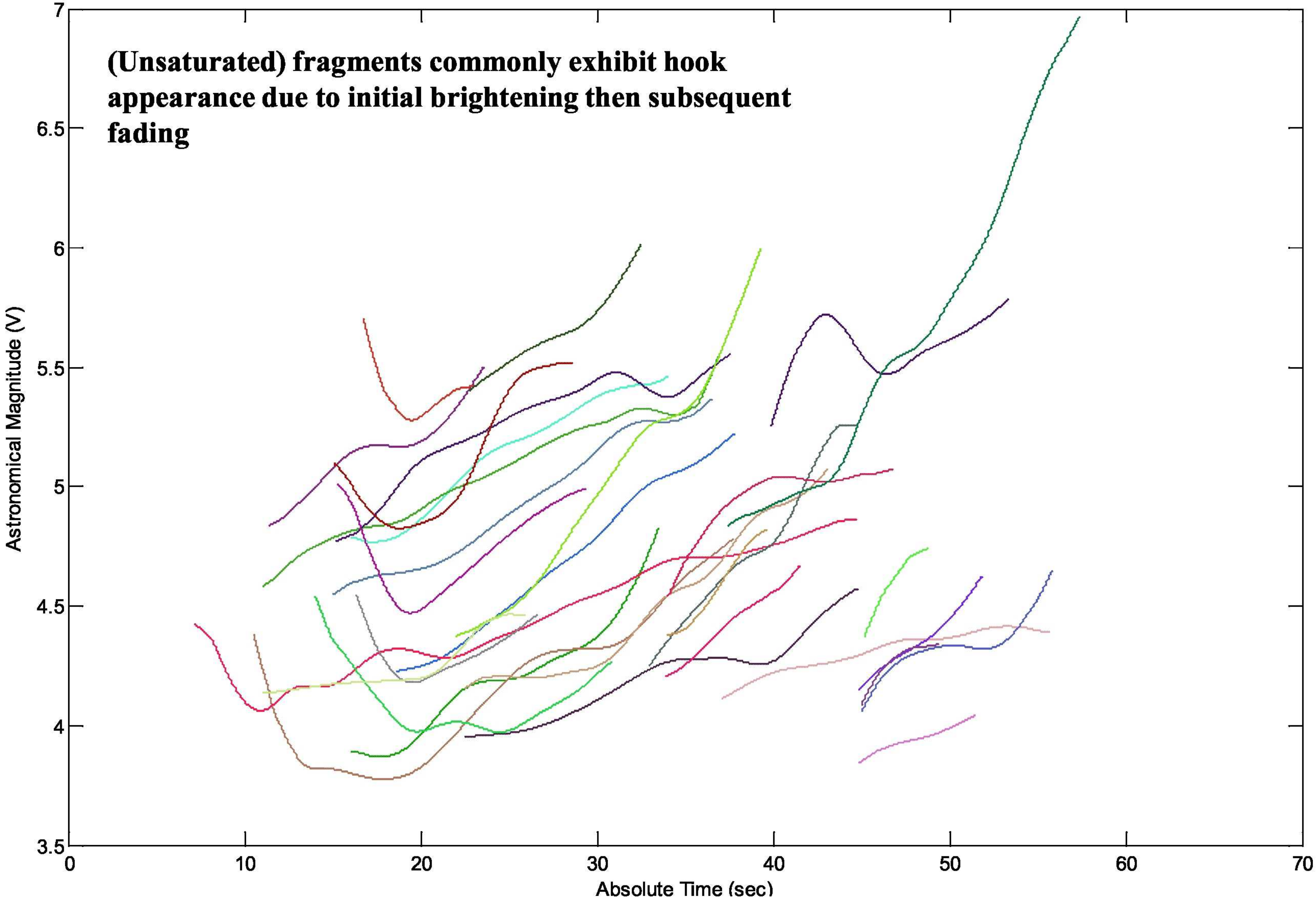


Circular Aperture Photometry via Trackeye



Brightness vs Absolute Time (T plus13:35:34 GMT)

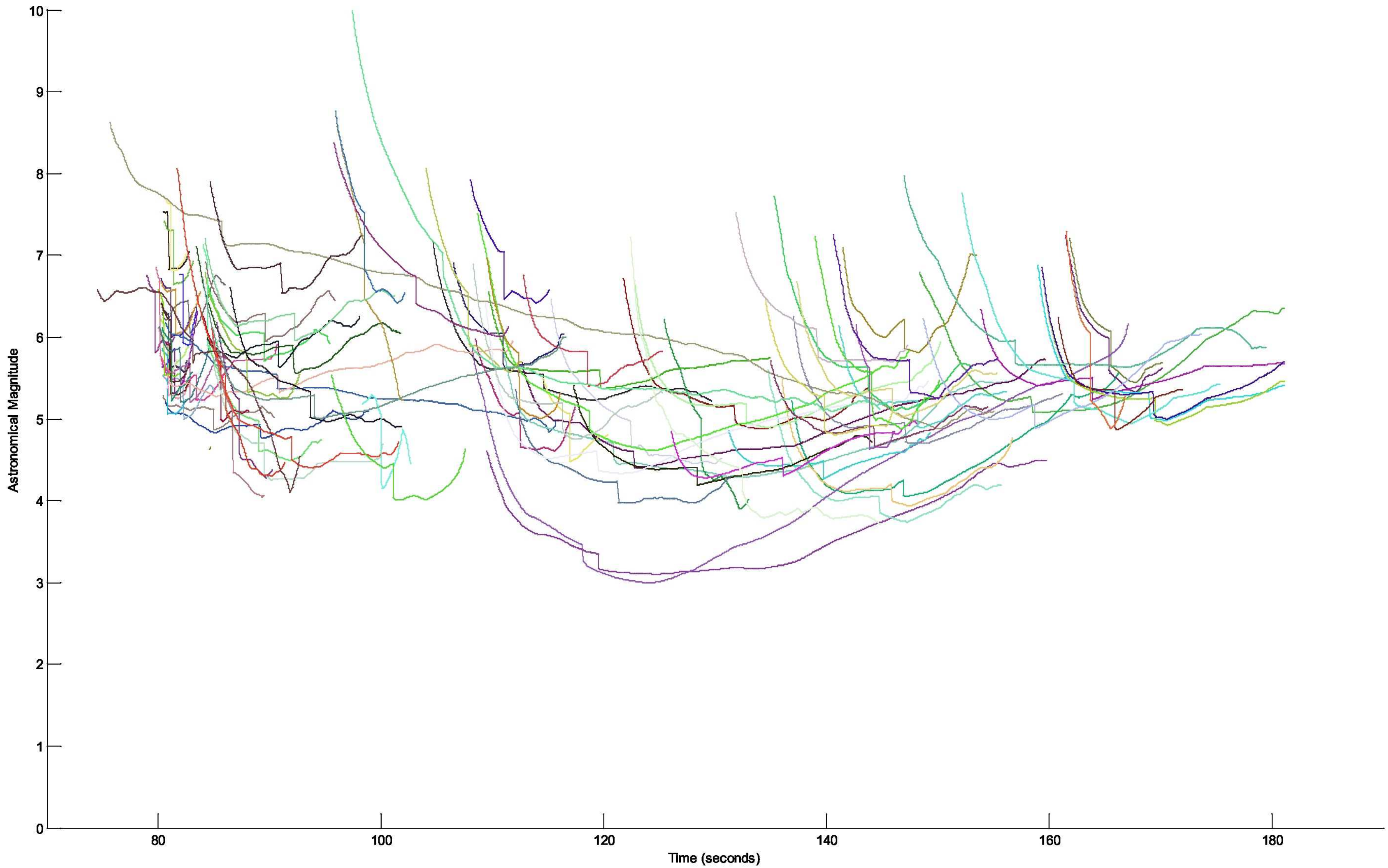
Subset of 39 (unsaturated) fragments



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.**