Belstead

Impact of Late Aerodynamic Alignment on the Re-entry of Rocket Bodies

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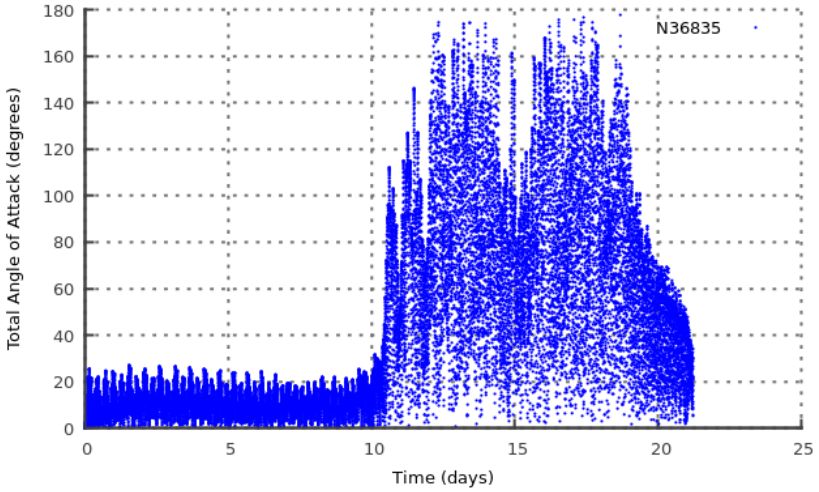
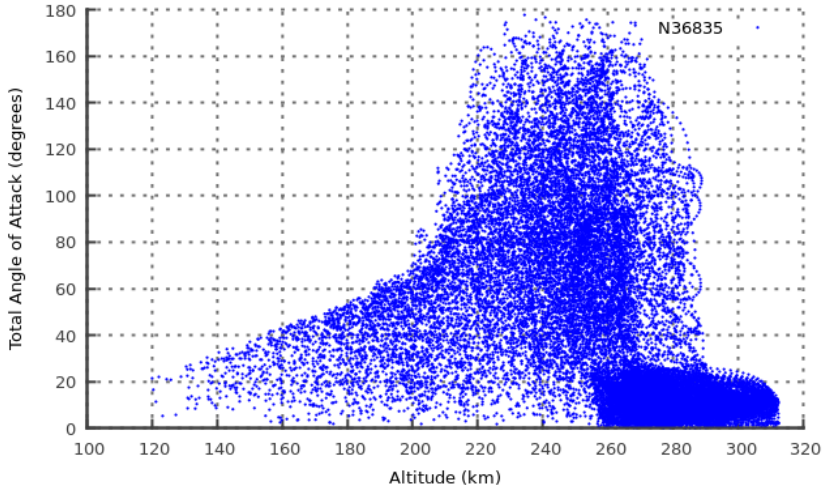
Aerodynamic Alignment - Background

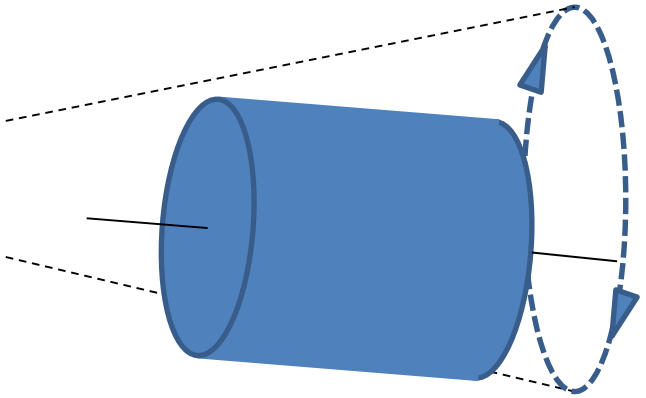
- GOCE Benchmarking Re-entry ESA Activity
  - Alignment during final days of orbit decay was seen in 6dof analysis of rocket body re-entries
  - Increase in ballistic coefficient and delayed entry versus 3dof predictions
- Is this a general phenomenon?
  - Requires vehicles with a low drag preferred aerodynamic attitude
  - Cylindrical profile of rocket bodies with offset mass may exhibit behaviour
  - How large is the impact, can it be accounted for in 3dof simulations?

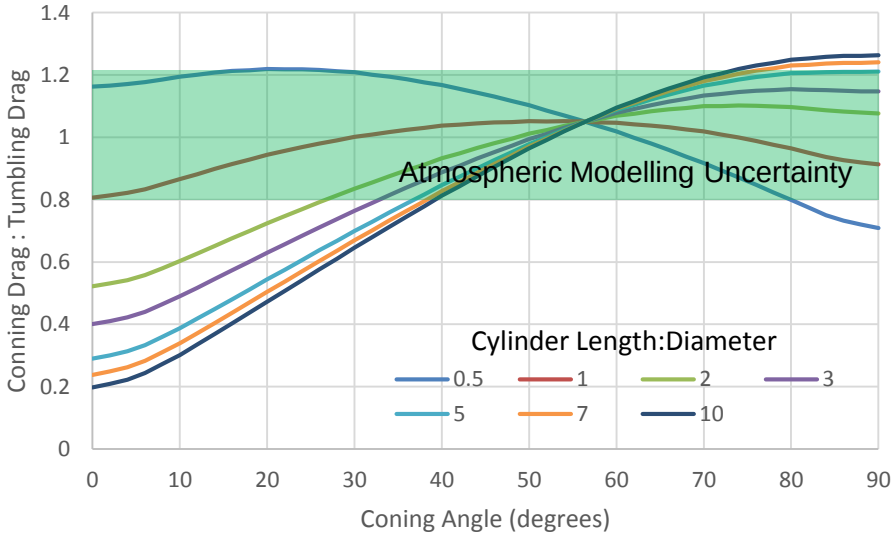




Aerodynamic Alignment - Theory

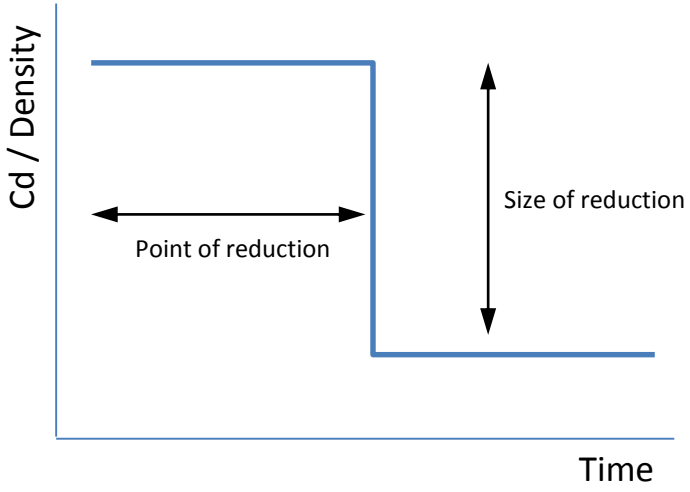
- Impact of alignment on drag
  - Assume vehicle transitions from randomly tumbling to coning motion
  - Alignment can have a significant impact on drag for long cylinders with small coning angles
  - Coning angles greater than 30 degrees are expected prior to 120km entry
  - Uncertainties could be similar to atmosphere variations, making separation of signal difficult

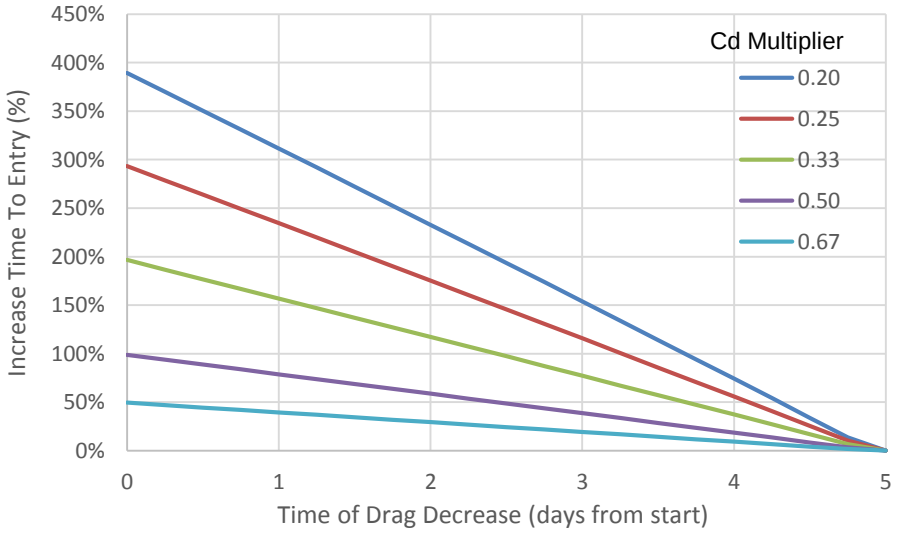




Aerodynamic Alignment - Theory

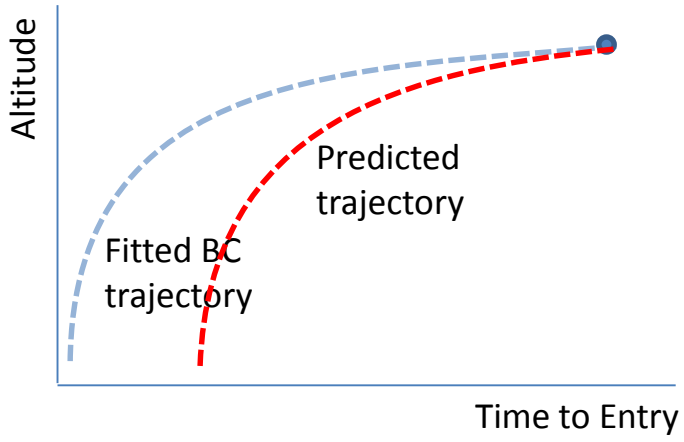
- First order impact of alignment on entry epoch
  - Step change in drag during 5 day entry, different start points & reductions
  - Percentage increase in remaining time to proportional to the ballistic coefficient increase
- Alignment may have a large impact on rocket body drag
- This could lead to a significant change in the predicted time to entry if alignment occurs in the final few days of decay

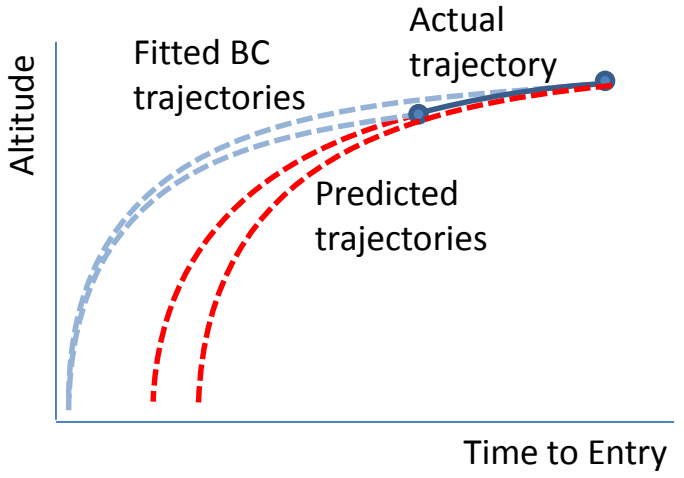




Approach

- Review public catalogue objects with high resolution decay epochs
  - Acquire TLEs for the final 25 days of orbit decay
  - Fit a ballistic coefficient starting at each TLE to the nominal 80km entry epoch within +/- 30seconds
  - Assume the vehicle is tumbling early in the data and normalise each fitted ballistic coefficient to the median value of the BCs fitted during first 5 days
- What does a alignment imply?





Initial Approach

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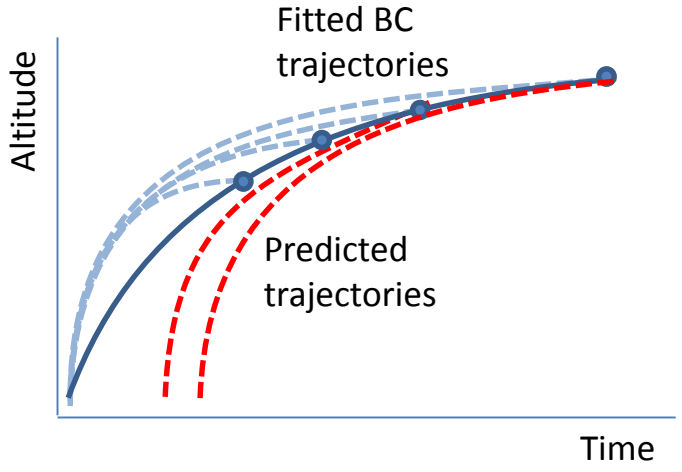
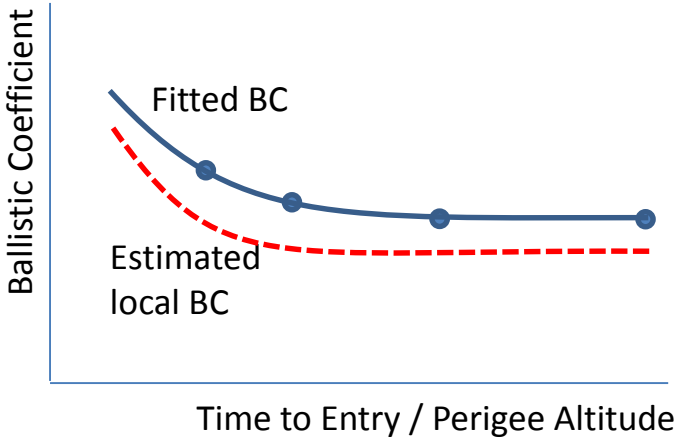
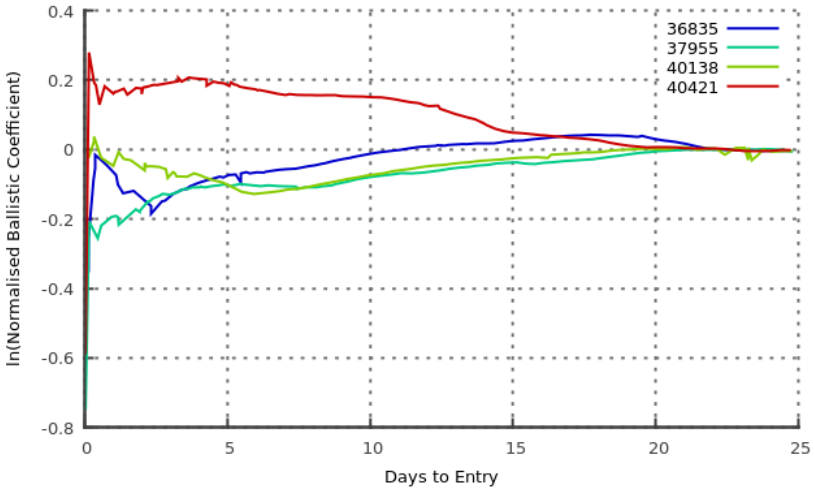


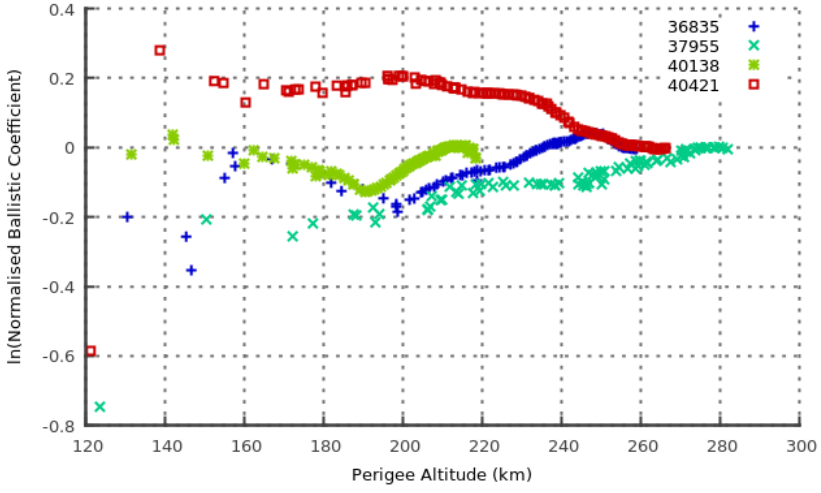


Ballistic Coefficient Evolution

- Three datasets considered
  - Rocket bodies in original study
  - IADC re-entry campaign objects
  - All rocket bodies in the public catalogue with high precision entry epochs
- Objects from original study
  - Suggestion of rising ballistic coefficient in 3 of the 4 original objects
  - Initiated at 200km – 160km perigee altitude

GOCE Study Rocket Bodies

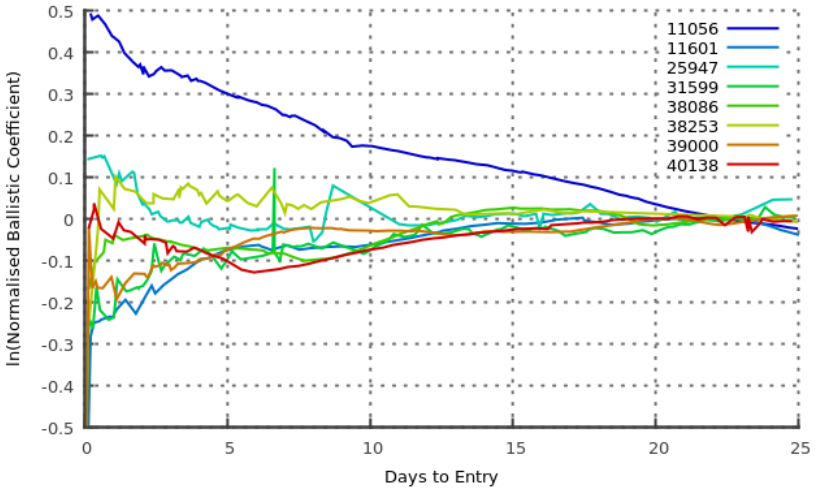


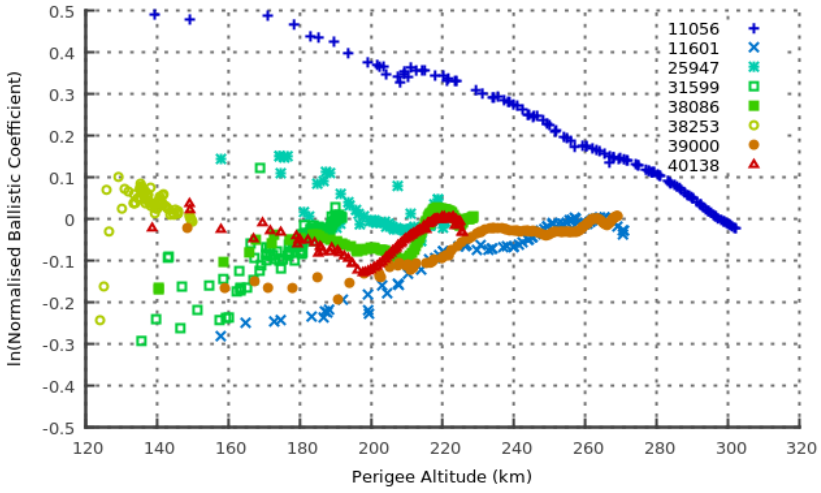


Ballistic Coefficient Evolution

- IADC dataset shows a wider range of behaviours
  - Rising trend or reversal of falling trend seen in 5 of the 8 examples
  - Change in trend occurs in the 160-220km perigee altitude range
- Also examined IADC payloads where similar behaviours were seen

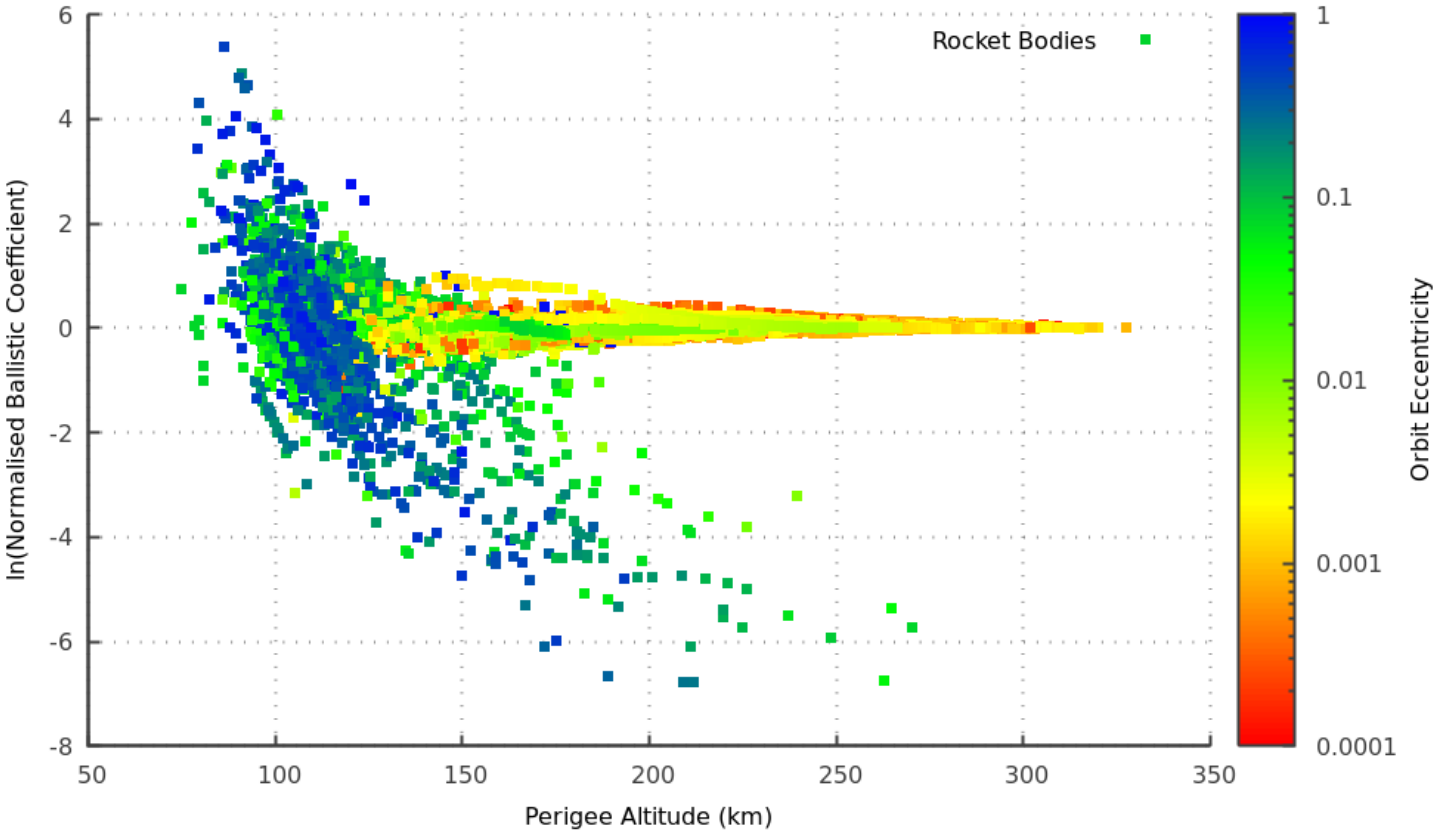
IADC re-entry campaign rocket bodies





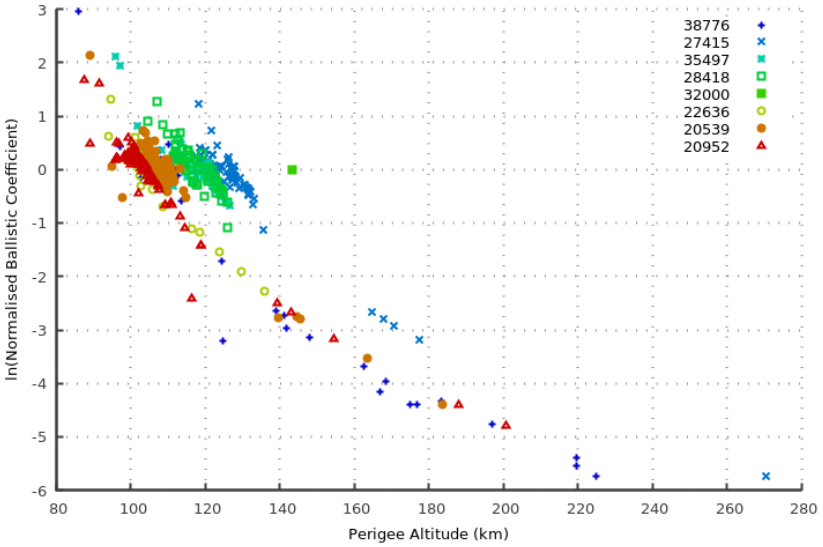
Ballistic Coefficient Evolution

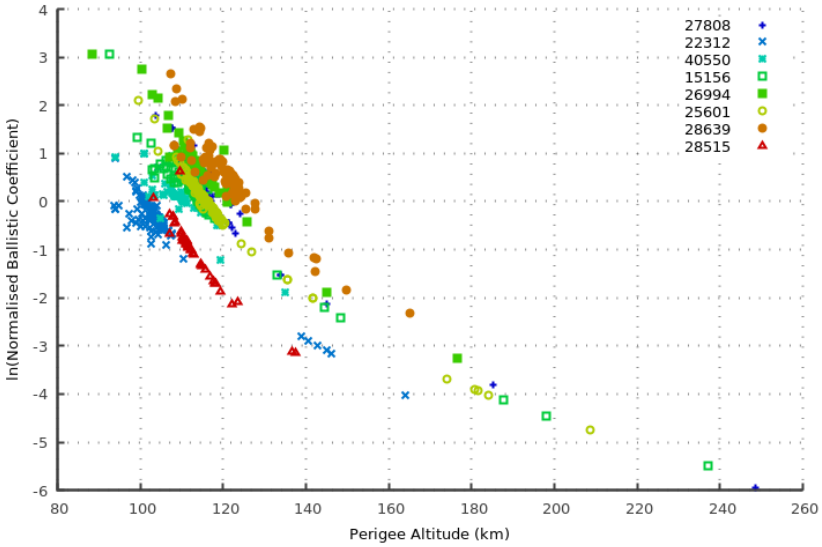
- Full population dataset comprises 273 rocket bodies



Rocket Body Regimes – High Eccentricity

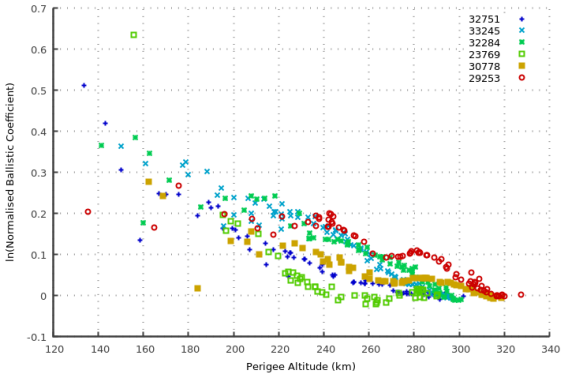
- 25 day eccentricities of greater than 0.075
  - Low initial perigee altitudes
  - Wide range of initial ballistic coefficient (20kg/m^2-4000kg/m^2)
  - Clear relationship of ballistic coefficient with perigee altitude
- High perigee altitudes are seen to be outlier TLEs
  - Observation errors for highly eccentric orbits
  - Perigee altitude drives re-entry time and therefore fitted ballistic coefficient

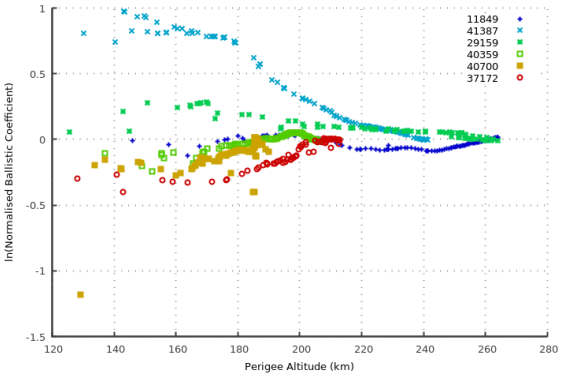


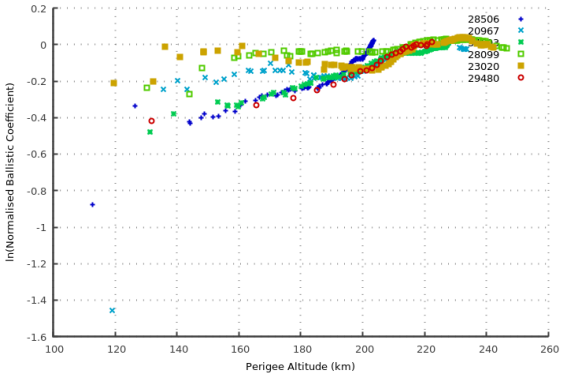


Rocket Body Regimes – Low Eccentricity

- Order by initial ballistic coefficient general trend becomes apparent
  - High initial perigee altitude results in low ballistic coefficient and leads to rising trend over time
  - Majority exhibit reversion to ballistic coefficients of 80-300kg/m^2
  - Potentially suggests that uncertainties are skewed based on initial ballistic coefficient



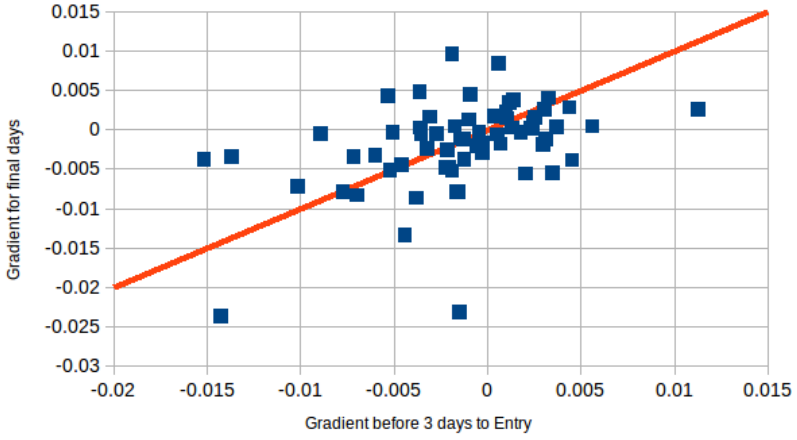




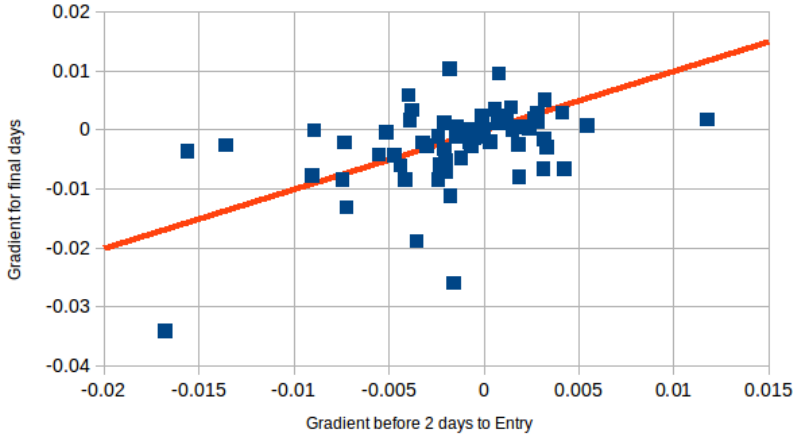
Low Eccentricity Hypothesis Testing

- High eccentricity entries are problematic
- Quantitative assessment of low eccentricity entries
  - Comparison of gradient of ballistic coefficient evolution before and after fixed points in the orbit decay
  - No evidence of increasing gradient
  - Does not account for different points of gradient change

Split 3 days to entry



Split 2 days to entry



Low Eccentricity Hypothesis Testing

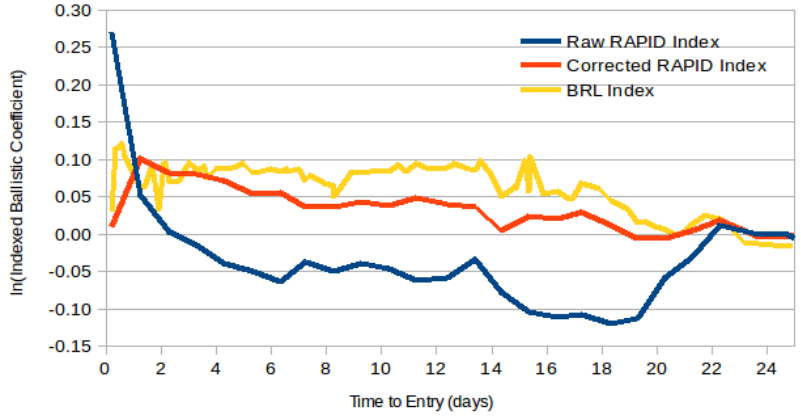
- Qualitative approach
- Visually inspect final change in gradient and categorise before and after as level, increasing, decreasing
- Identify time, altitude and BC at point of change
- 60 low eccentricity rocket body entries identified with reasonable confidence
- Small bias toward increasing ballistic coefficient

Category	Low Eccentricity
Increasing BC trend	**33**
Continuously rising	11
Falling -> rising	11
Level -> rising	4
Falling -> level	7
Decreasing BC trend	**27**
Continuously falling	12
Rising -> falling	6
Level -> falling	5
Rising -> level	4

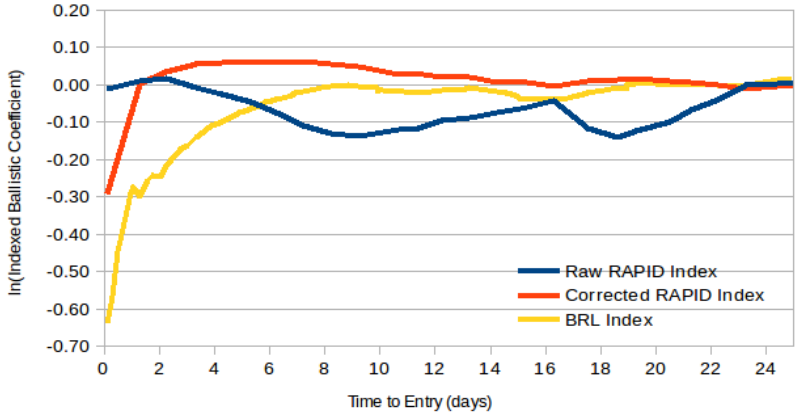
Low Eccentricity Hypothesis Testing

- Some evidence of increasing ballistic coefficient
- Forward averaging leads to interpretation being complicated
- Identified 10 rocket bodies that display characteristic profiles
- ESA Debris office generated equivalent profiles using RAPID
- Can RAPID profiles inform the fitted equivalent or vice versa?

#39137 - Rising



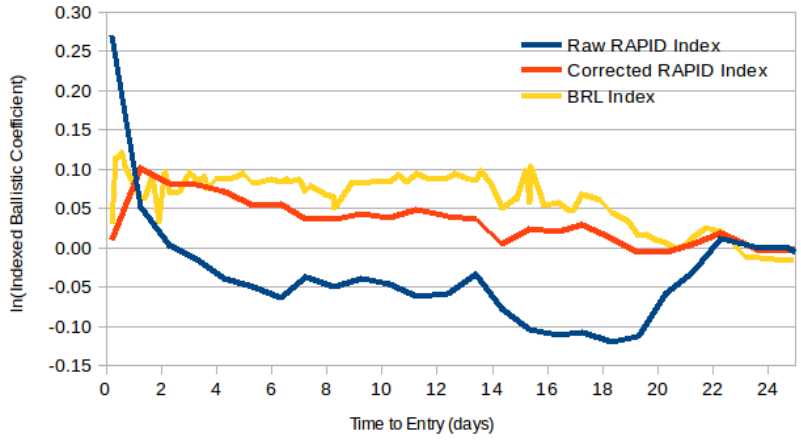
#32059 - Falling

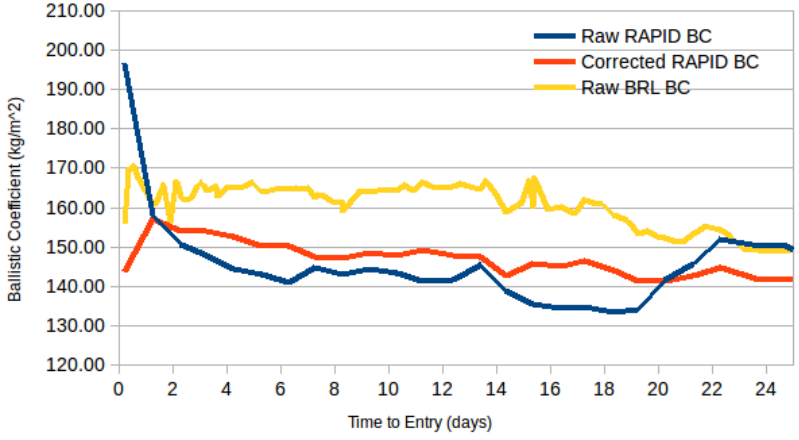


Characteristic Profiles

- Typically, once RAPID is corrected for known error in predicted entry epoch, a good match seen between indexed profiles
  - Percentage error in remaining time to epoch is equal to percentage error in predicted ballistic coefficient
- Some examples where tentative causal links can be made
  - Fall in raw RAPID prediction related to rise in fitted BC from a common estimate
  - These are the exception

#39137 (SL-4)





Conclusions

- Initial case study and IADC entries suggest aerodynamic alignment of rocket bodies in the final days of orbit decay may occur
- Theoretical analysis suggests that this might have a significant impact on drag and therefore, predicted re-entry epoch
- If the degree of alignment could be predicted a-priori, it might provide a significant improvement in the later entry predictions of 3dof codes
- Examination of the public catalogue
  - Eccentric re-entries show strong correlation of ballistic coefficient with perigee altitude; likely noise from TLEs
  - Convergence of ballistic coefficient in circular re-entries to intermediate values; might be possible to adjust predictions
- Extraction of signal from noise remains a problem
  - Observations: Predicted perigee altitude for eccentric orbits
  - Atmosphere models: Use of multiple models, or columns?