Characterizing the Reentry Prediction Uncertainty of Tiangong-1

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Tiangong-1 Background
8,500 kg space station telemetry ceases March 2016

• Launched in Sept 2011
• Weighed 8,500 kg at launch
• Two crewed Shenzhou missions in 2012 and 2013
• Communications cease in March 2016
• Media interest begins:
  – “Tiangong-1 Space Lab Will Fall to Earth Next Year, China Says”, Space.com, Sept. 2016
  – “China's Tiangong-1 space station is expected to fall to Earth in 2017, but don't worry”, TheVerge.com, Sept. 2016
Tiangong-1 Background Cont.

Reentry far from initial analysis, plenty of unknowns

• Initial rough estimate for reentry indicated Q4 2017 (many months away)

• To provide an accurate reentry prediction, characteristics of the spacecraft / environment must be defined:
  – Coefficient of Drag ($C_d$): Based on geometric shape in velocity direction (unknown due to lack of tumbling profile)
  – Mass: Mass at launch known, not mass at time of analysis (propellant mass depletion / crew visit mass exchange)
  – Cross-Sectional Area (CSA): Same issues as $C_d$
  – Solar Activity: Forecasting can only be done so well

$B = \frac{C_d A}{M}$

Unknown characteristics must be investigated to provide more accurate and confident prediction
Ordinary v. Unconventional Reentry Analyses

Tiangong-1 provides a unique challenge

• Typical rule of thumb for declaring an uncertainty in a reentry prediction time is ±20% of the time-to-go, i.e., ±20% × (hours/days between orbit epoch used in analysis and predicted reentry time)
  – Example 1: Ordinary reentry 5 days out = ±24 hours uncertainty
  – Example 2: Tiangong-1 reentry 10 months out = ±2 months uncertainty

• Large uncertainties are not necessarily a bad thing; they are unavoidable with a prediction so far away for an object with so many unknowns

• It is important that these unknowns are studied in depth so that there is high confidence in the stated reentry prediction uncertainty

To gain confidence in stated prediction uncertainty, unknowns must be scrutinized
Uncertainty Parameters Breakdown - $C_d$

Coefficient of drag

- Ordinarily, a $C_d$ of 2.1 - 2.5 is used in orbit propagations
- Dependent on geometry of spacecraft and altitude
- TG-1’s altitude changing, probably velocity-direction geometry as well (tumbling)
- Based on TG-1’s current / future altitude and shape, $C_d$ values in green box would be used
  - Implementation shown later

Moe, K. and M. M. Moe, “Gas-Surface Interactions and Satellite Drag Coefficients"
Uncertainty Parameters Breakdown - Mass

Mass

• TG-1 mass at launch = 8,500 kg
• Decided that changes in mass due to maneuvers over lifetime would be more dominant in overall mass change than mass exchanges during crewed missions
• 15 maneuvers: approximate total $\Delta V$ used $\rightarrow$ approximate $\Delta$ fuel mass

Modeling propulsion and orbit maneuvers to raise altitude, estimate propellant mass of 599 – 691 kg
Uncertainty Parameters Breakdown – CSA
Cross-Sectional Area

• Dimensions of habitable module, service module, and solar panels known
• Two extreme cases:
  – “Streamlined” flying where TG-1 is flying with docking port facing velocity-direction and solar panels aligned parallel
  – “Flat plate” flying where TG-1 is flying with long face of cylindrical body facing velocity-direction and solar panels aligned perpendicular

“Streamlined” = 9.08 m²

“Flat plate” = 77.7 m²
Uncertainty Parameters Breakdown – Solar Activity
F10.7 and Ap

- NASA MSFC forecasts solar activity values used in orbit propagation
**Reentry Prediction Approach**

Parameters characterized – How can they be used?

- 7,000-propagation Monte Carlo run set up to use the newly characterized parameters

- Normal distributions used per parameter to generate input values for the propagator
  - $C_d$ mean of 2.3, one-sigma of 0.1 (from $C_d$ shape/altitude plot)
  - Mass mean of 7855 kg, one-sigma of 46 kg (from $\Delta V$ and ISP analysis)
  - CSA mean of 43.4 m$^2$, three-sigma (99.7% of values) of 34.3 m$^2$ (from dimensions overview)

- Each propagation run until reentry, saved reentry time along with associated inputs generated from distributions

*Monte Carlo approach to investigate unknown parameter characterization*
Reentry Prediction Approach Cont.

Initial results (March 2017)

- Nominal Reentry (12/09/2017)
- 1 sigma error bar (+/- 126 days)
Reentry Prediction Approach Cont.

Initial results
Reentry Prediction Approach Cont.
Which parameter uncertainties dominated?

• 1,000-propagation Monte Carlo run set up per ballistic coefficient related parameter where others were held constant
• CSA’s effect much larger than $C_d$ and mass
Process Reformulation

Ballistic coefficient must be characterized better

• Calculated ballistic coefficients part of Vector Covariance Messages (VCMs)
• Time history of these ballistic coefficients could provide a more accurate distribution to be used in the Monte Carlo runs
Process Reformulation Cont.

New method used to produce published reentry predictions
Results
New method led to smaller uncertainties

• Published predictions had smaller uncertainties than original method
• Process was corrected in Nov. 2017 for even better results
Results Cont.

New method led to smaller uncertainties
## Results Cont.

New method led to smaller uncertainties

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For each prediction made since the correction, the final true reentry time fell within at most ±1.5 sigma
Conclusions

Future uses of this approach

• Reentries far in the future are hard to predict

• Scrutinizing unknown parameters led to a greater understanding of reentry prediction uncertainty

• More information on a hard to define parameter led to accurate predictions

• Future high profile reentries can follow this method
Final Prediction

Off by 16 minutes
Questions?
References


