Characterizing the Reentry Prediction Uncertainty of Tiangong-1

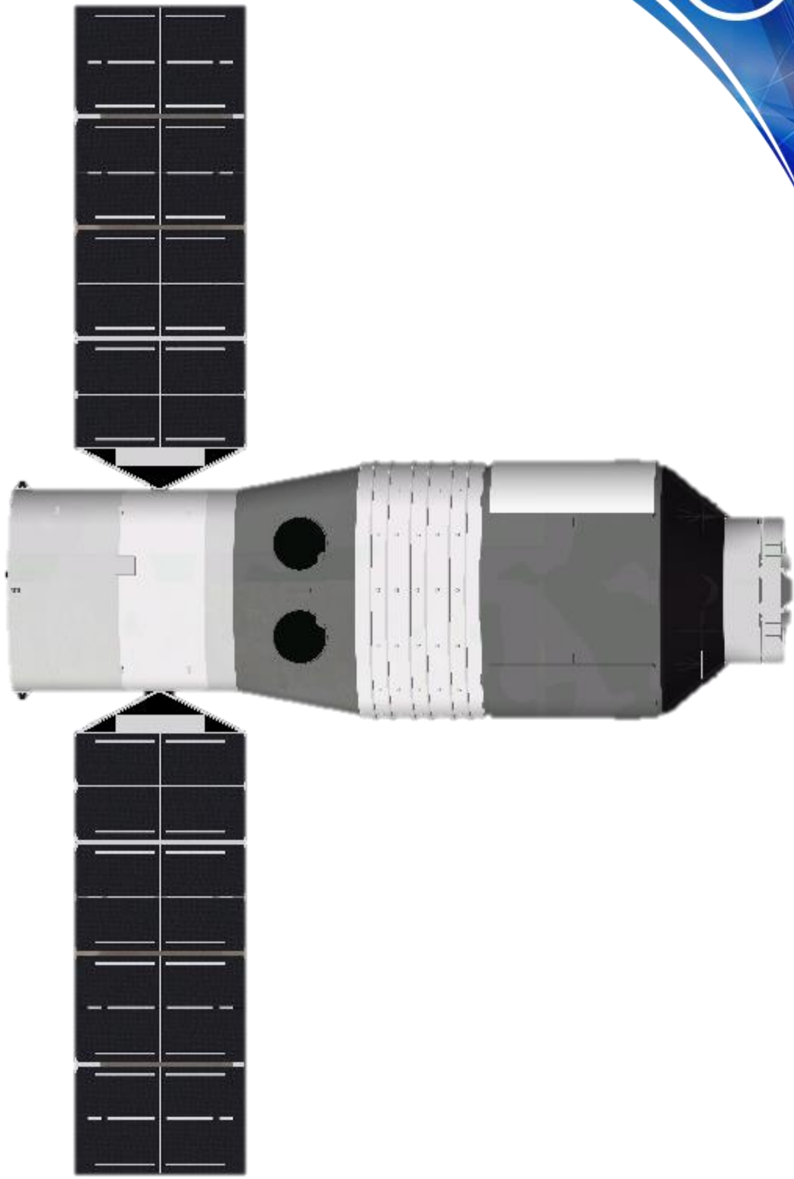
Eric Eiler
Andrew Abraham
Mission Analysis and Operations
The Aerospace Corporation

November 13, 2018

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*
  - *“Is Tiangong-1 Going To Fall On My Head?”, AsianScientist, Oct. 2016*
  - *“China's Falling Space Station Is Not Going to Hit You on the Head. Unless it Does”, TIME, Sept. 2016*

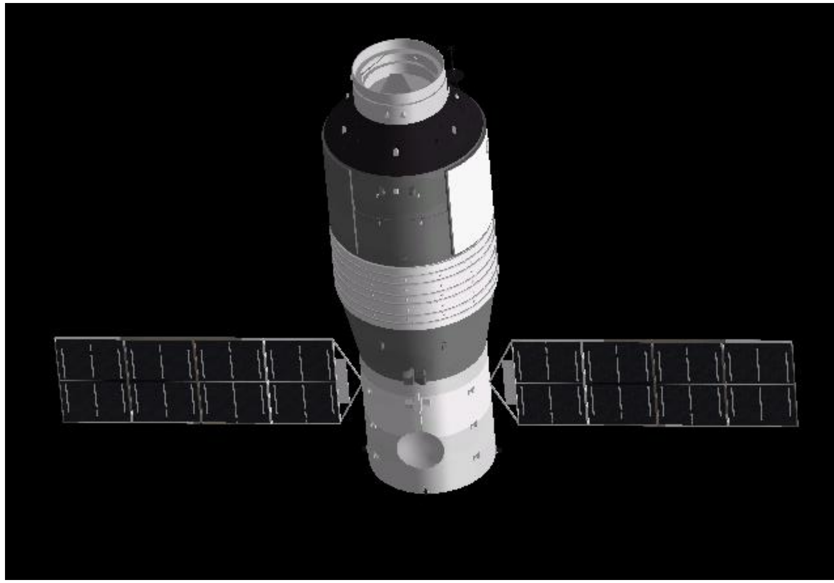


Tiangong-1 Background Cont.

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

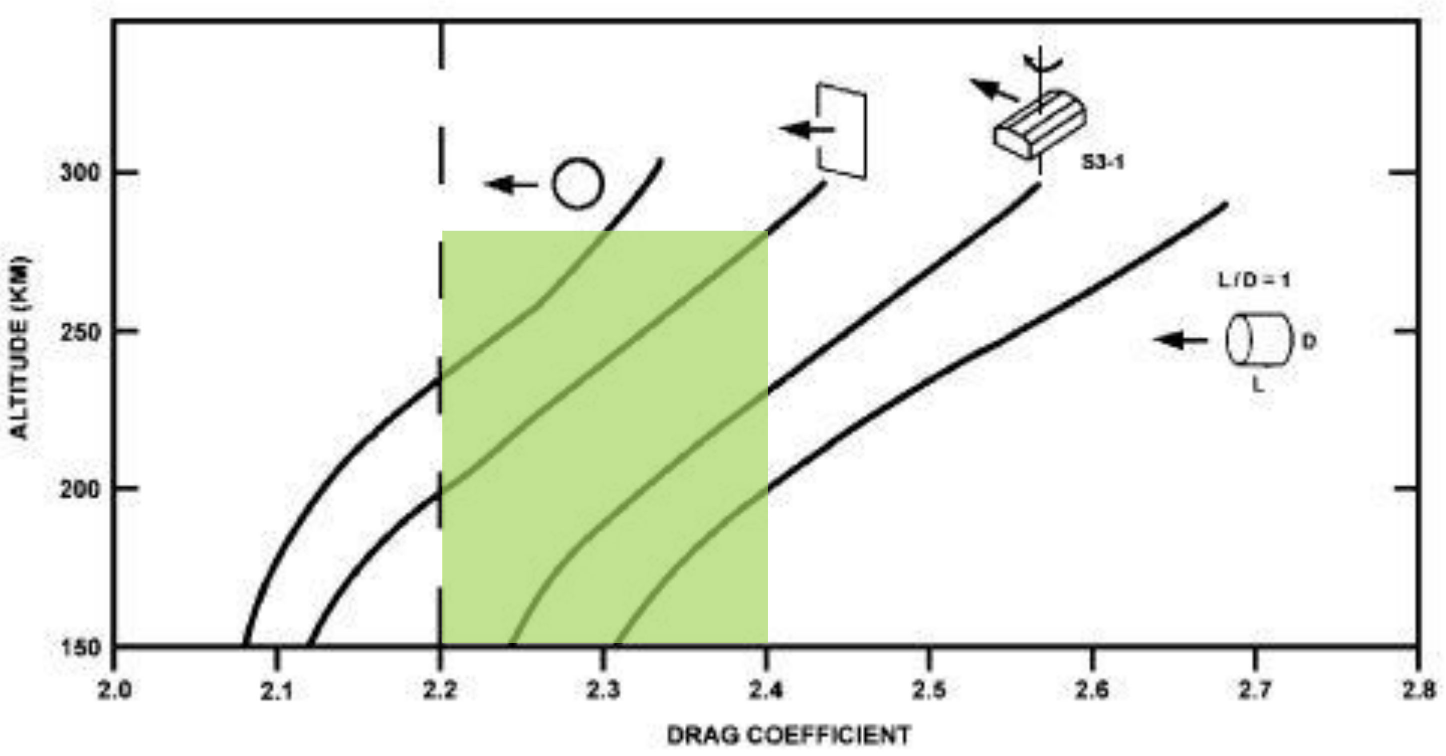
- It is important that these unknowns are studied in depth so that there is high confidence in the stated reentry prediction uncertainty

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*

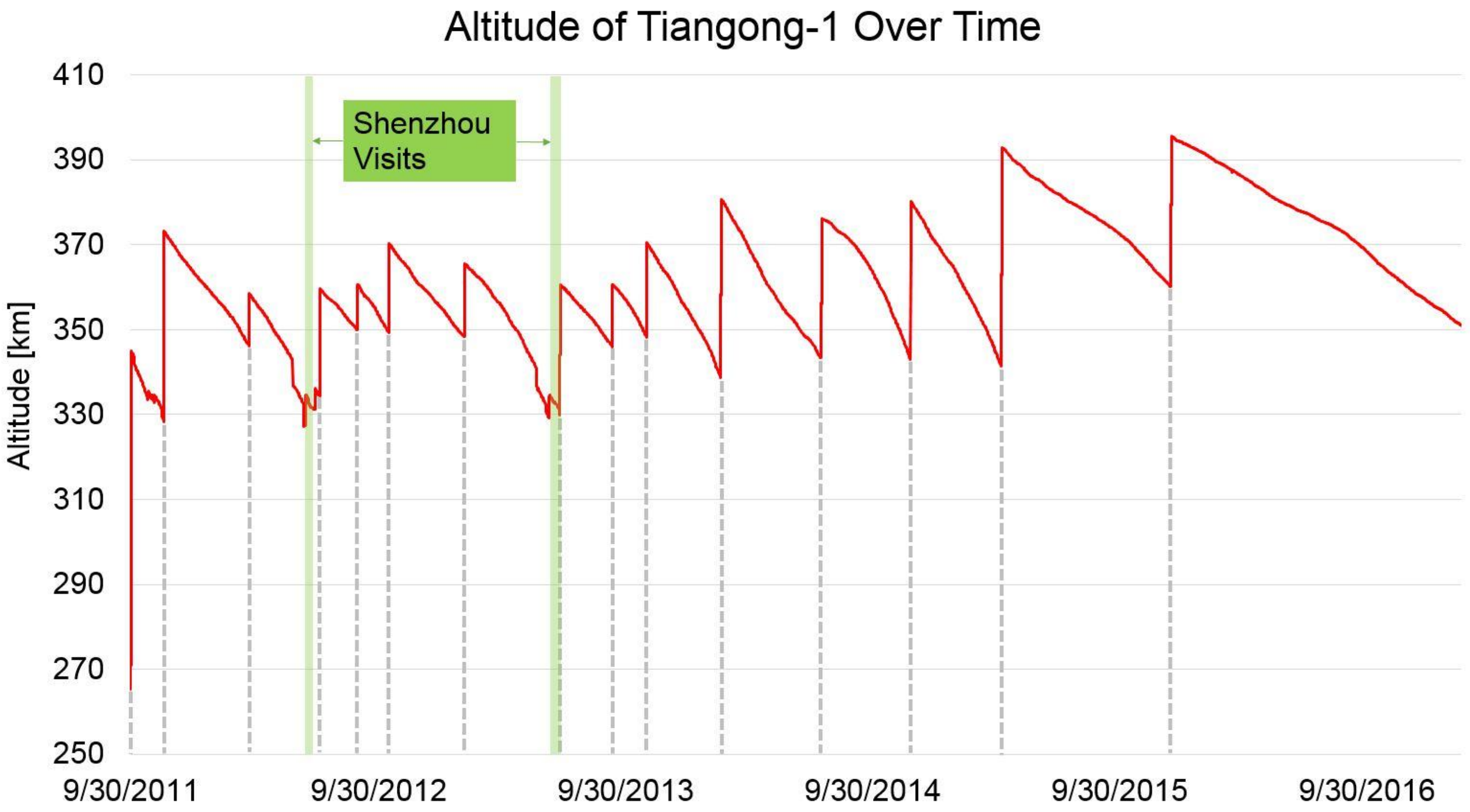


Moe, K. and M. M. Moe, "Gas-Surface Interactions and Satellite Drag Coefficients"

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 ΔV used → approximate Δ fuel mass



Modeling propulsion and orbit maneuvers to raise altitude, estimate propellant mass of 599 – 691 kg

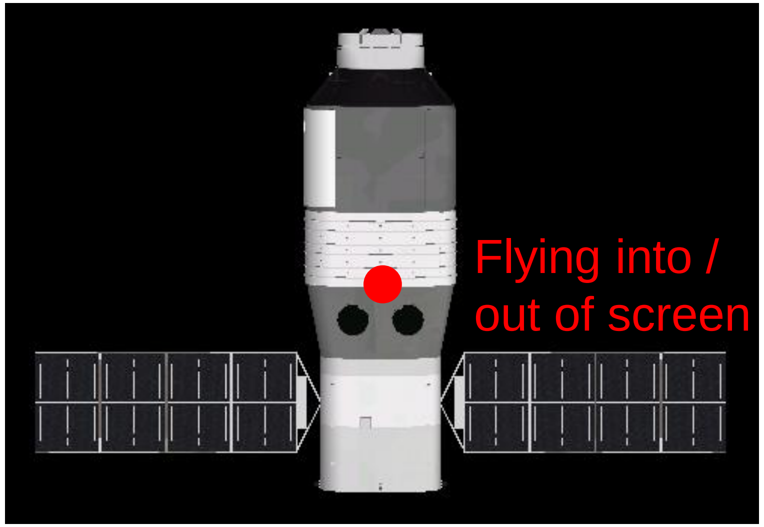
Uncertainty Parameters Breakdown – CSA

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 m^2

"Flat plate" = 77.7 m^2



Uncertainty Parameters Breakdown – Solar Activity

F10.7 and Ap

- NASA MSFC forecasts solar activity values used in orbit propagation

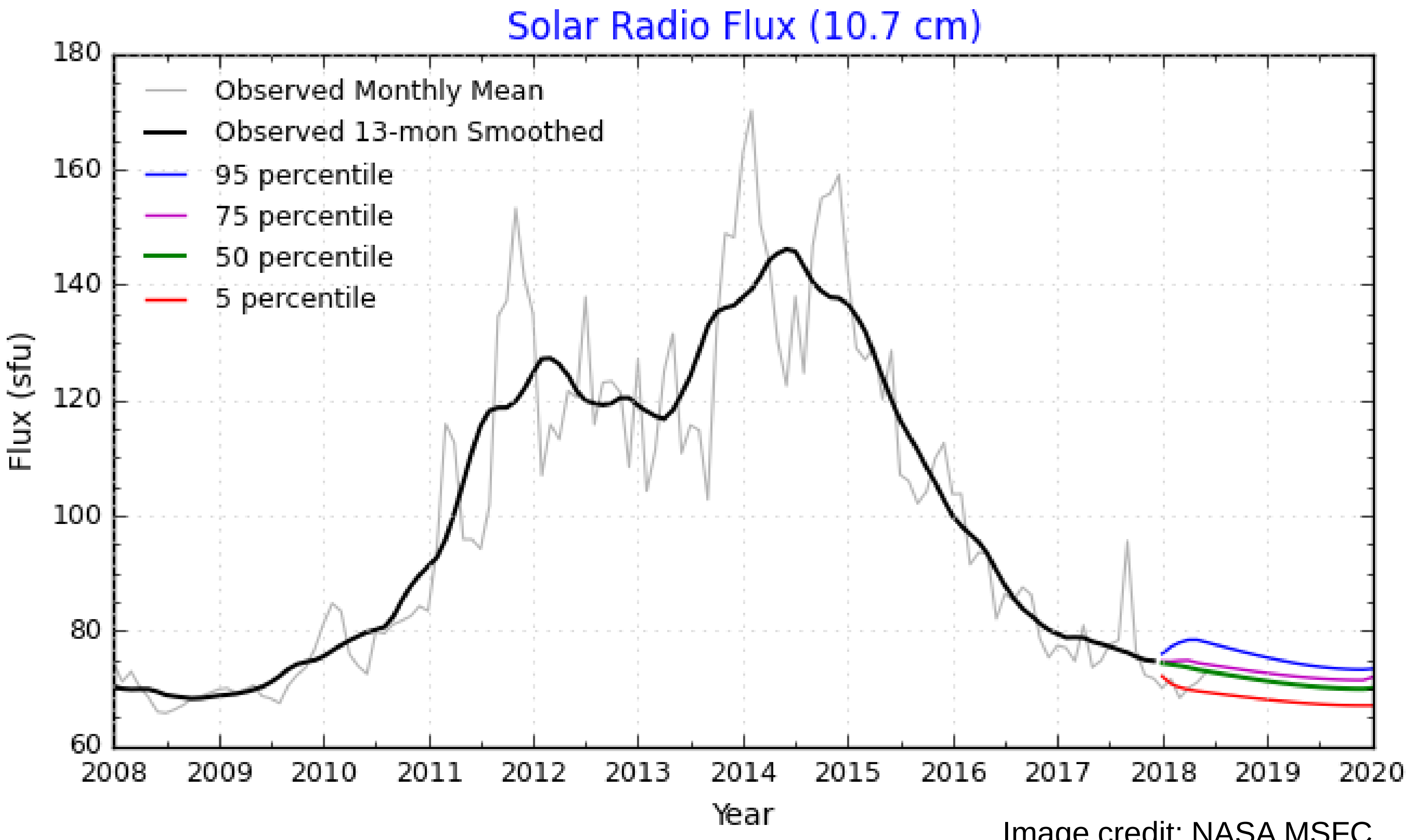


Image credit: NASA MSFC

Reentry Prediction Approach

Parameters characterized – How can they be used?

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

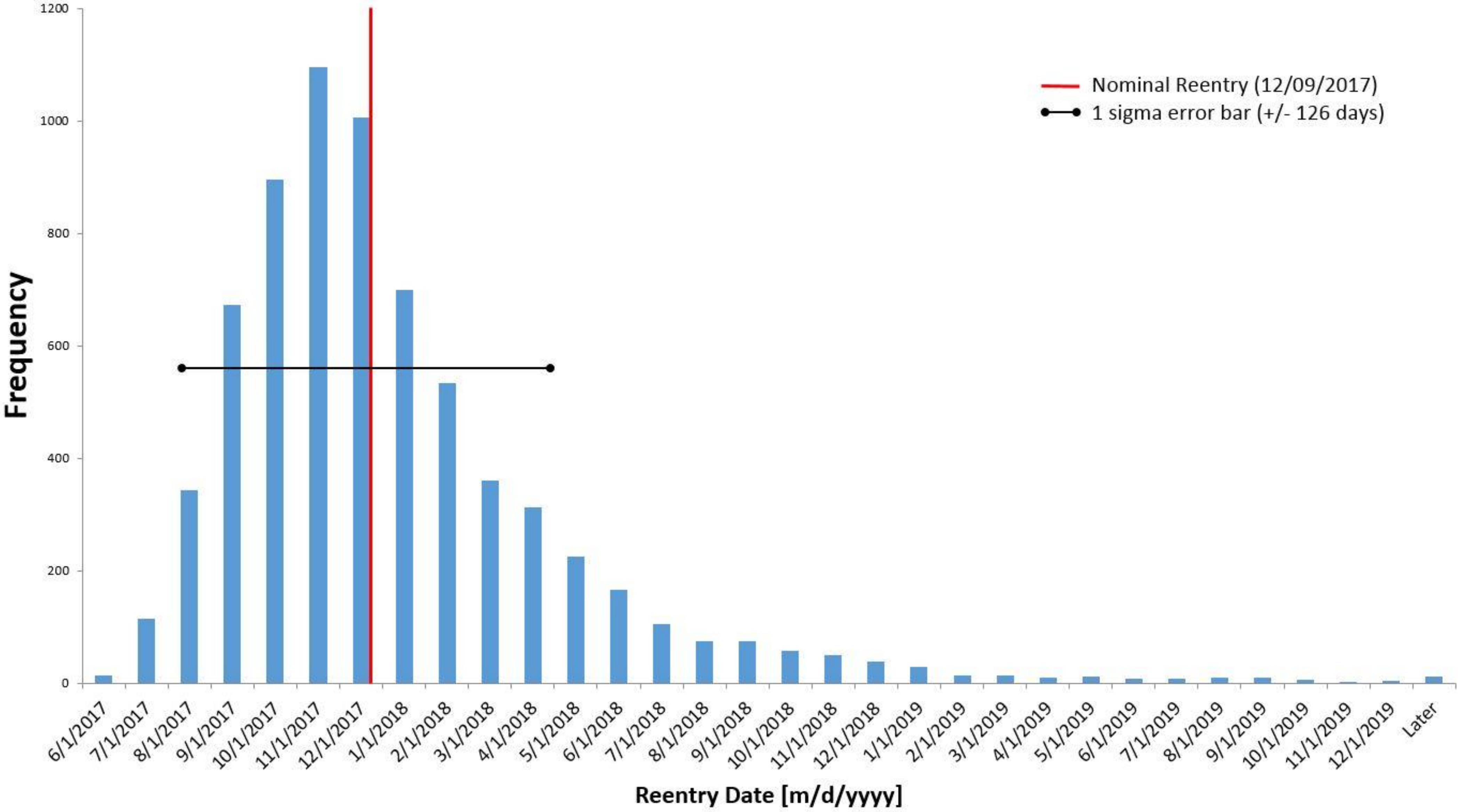
- *Normal distributions* used per parameter to generate input values for the propagator
  - *C_d mean of 2.3, one-sigma of 0.1 (from C_d shape/altitude plot)*
  - *Mass mean of 7855 kg, one-sigma of 46 kg (from ΔV and ISP analysis)*
  - *CSA mean of 43.4 m^2, three-sigma (99.7% of values) of 34.3 m^2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

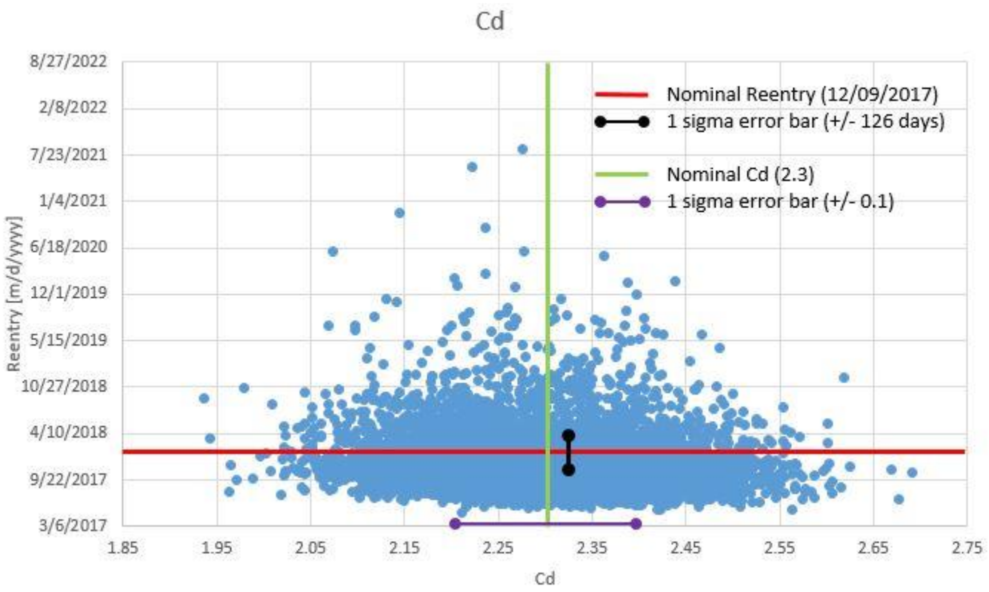
Reentry Prediction Approach Cont.

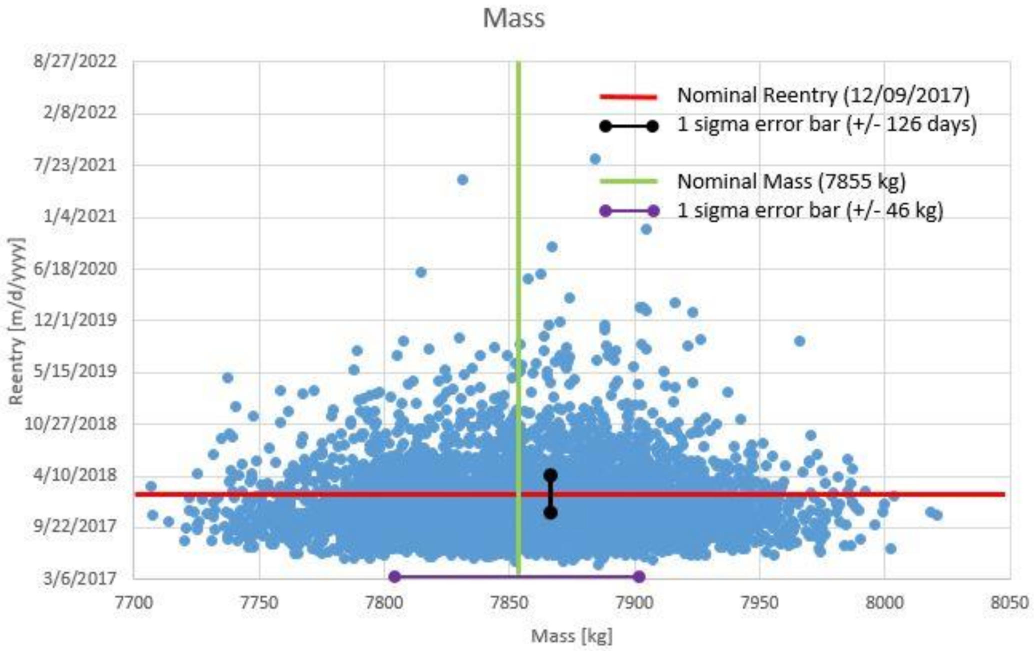
Initial results (March 2017)

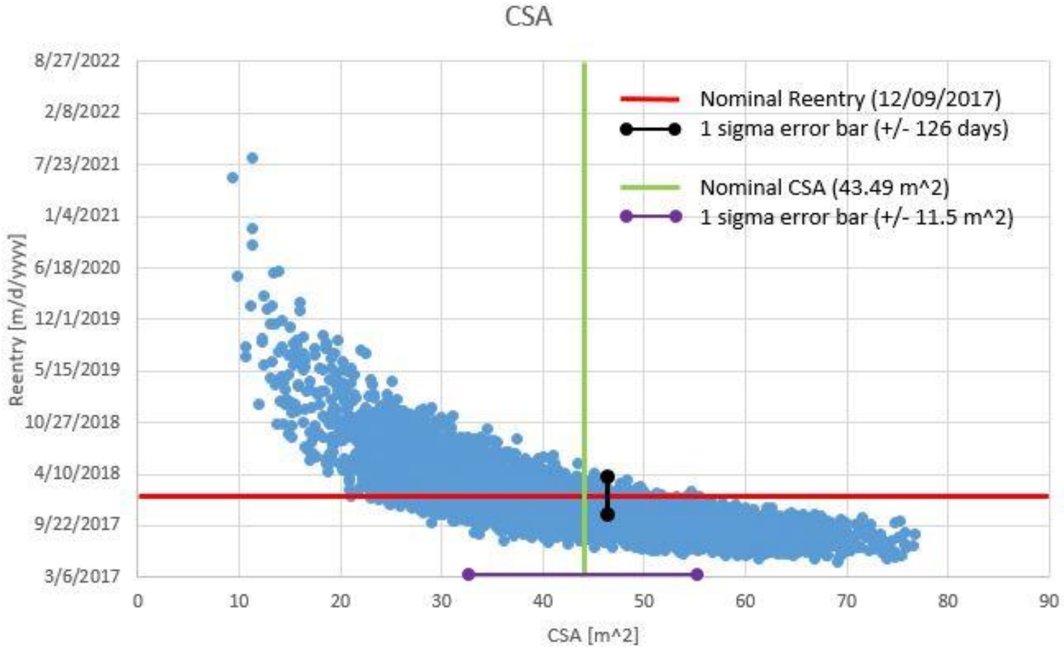


Reentry Prediction Approach Cont.

Initial results



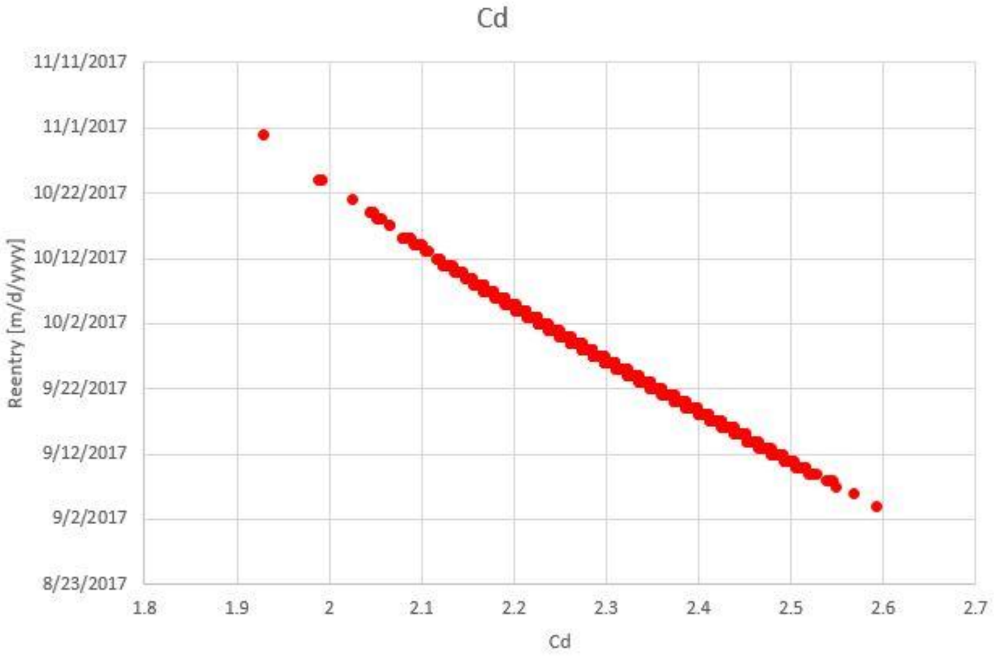


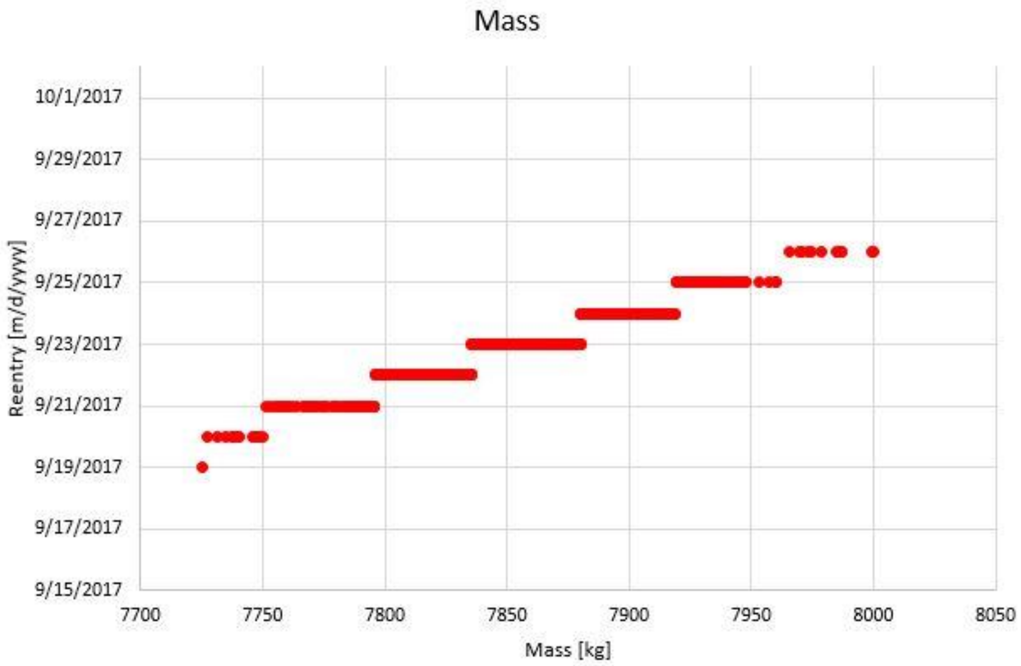


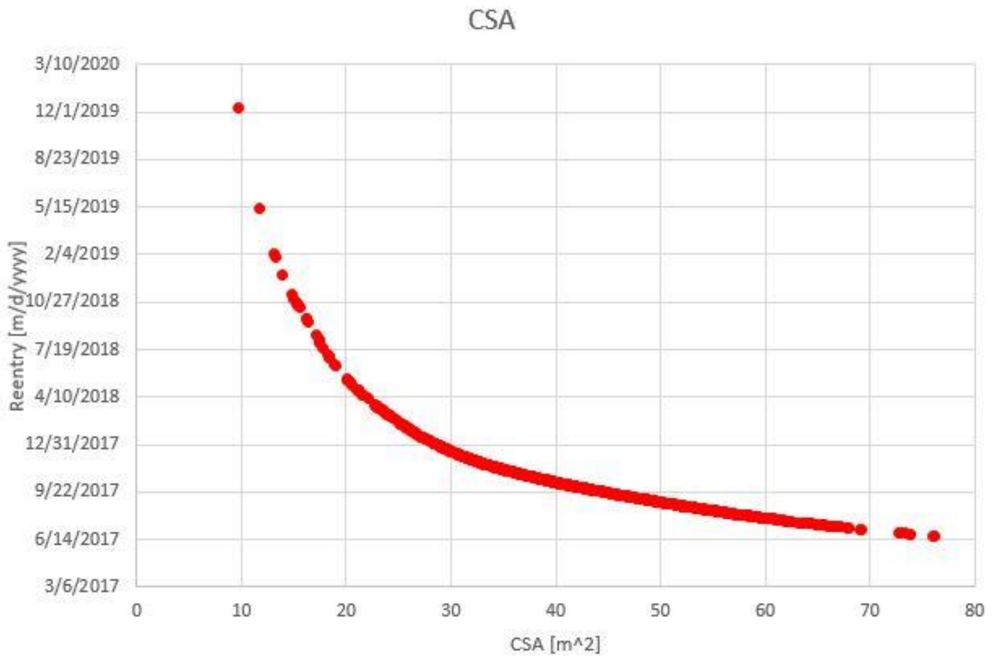
Reentry Prediction Approach Cont.

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



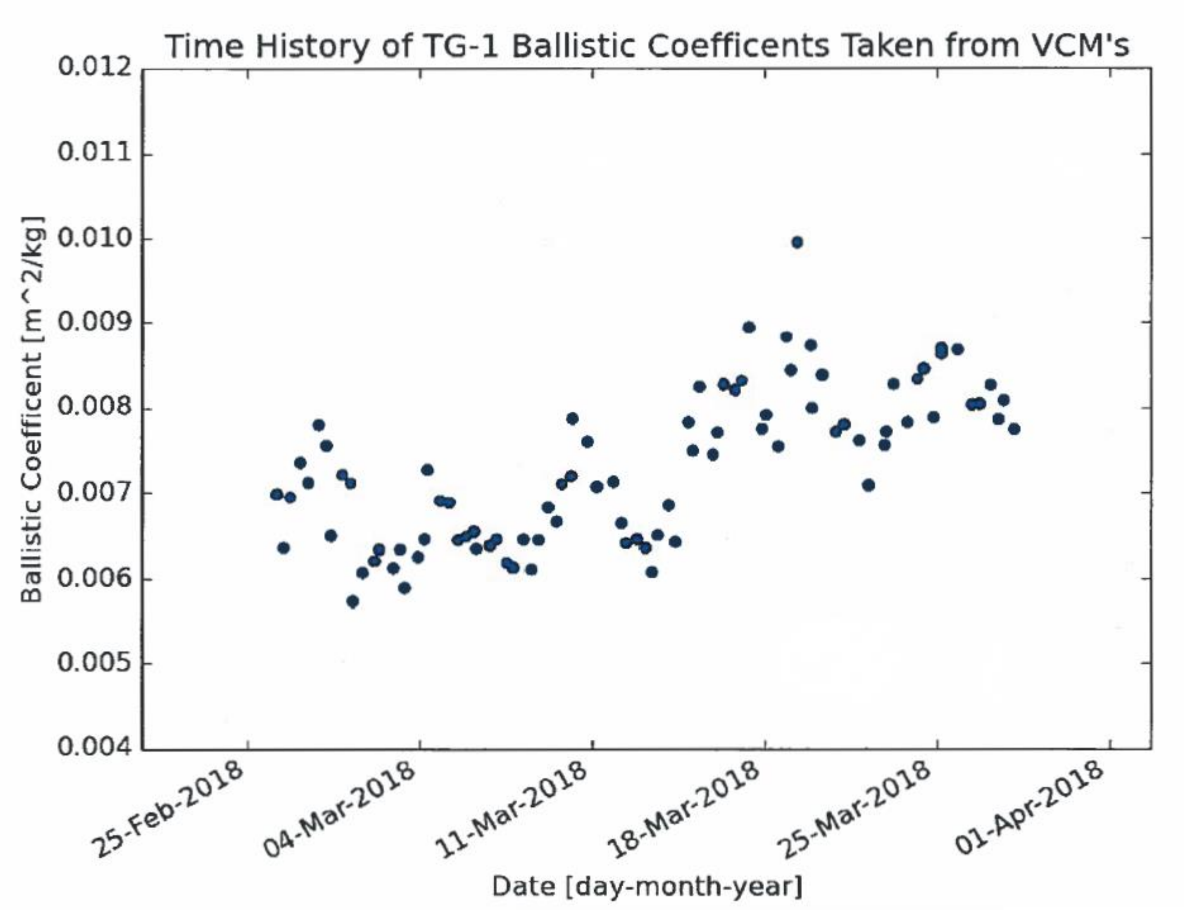


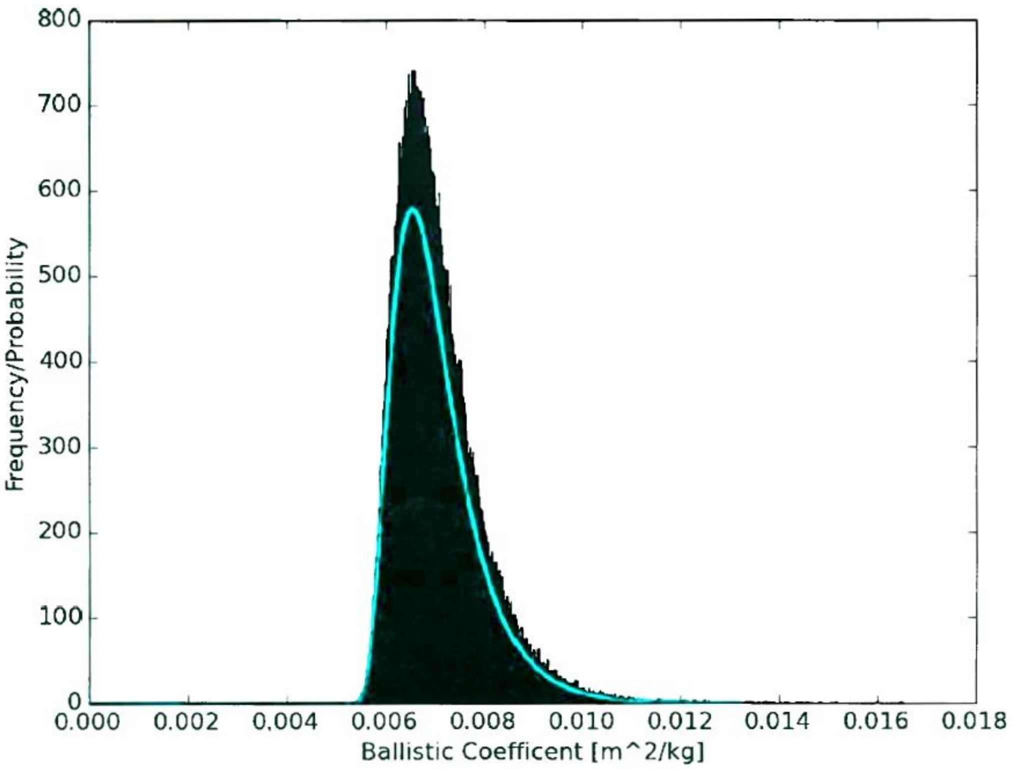


Process Reformulation

Ballistic coefficient must be characterized better

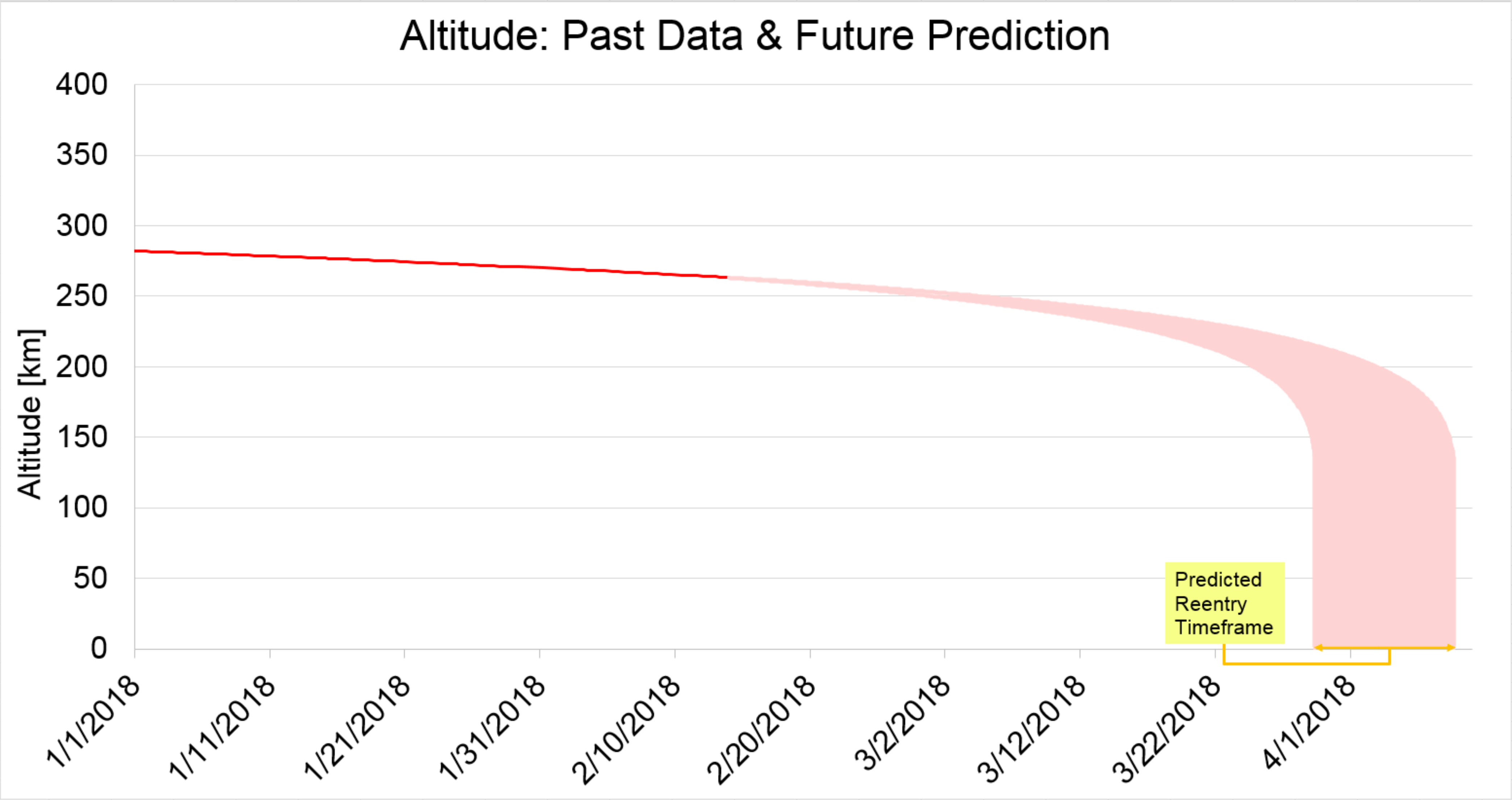
- Calculated ballistic coefficients part of Vector Covariance Messages (VCMs)
- Time history of these ballistic coefficients could provide a more accurate distribution to be used in the Monte Carlo runs





Process Reformulation Cont.

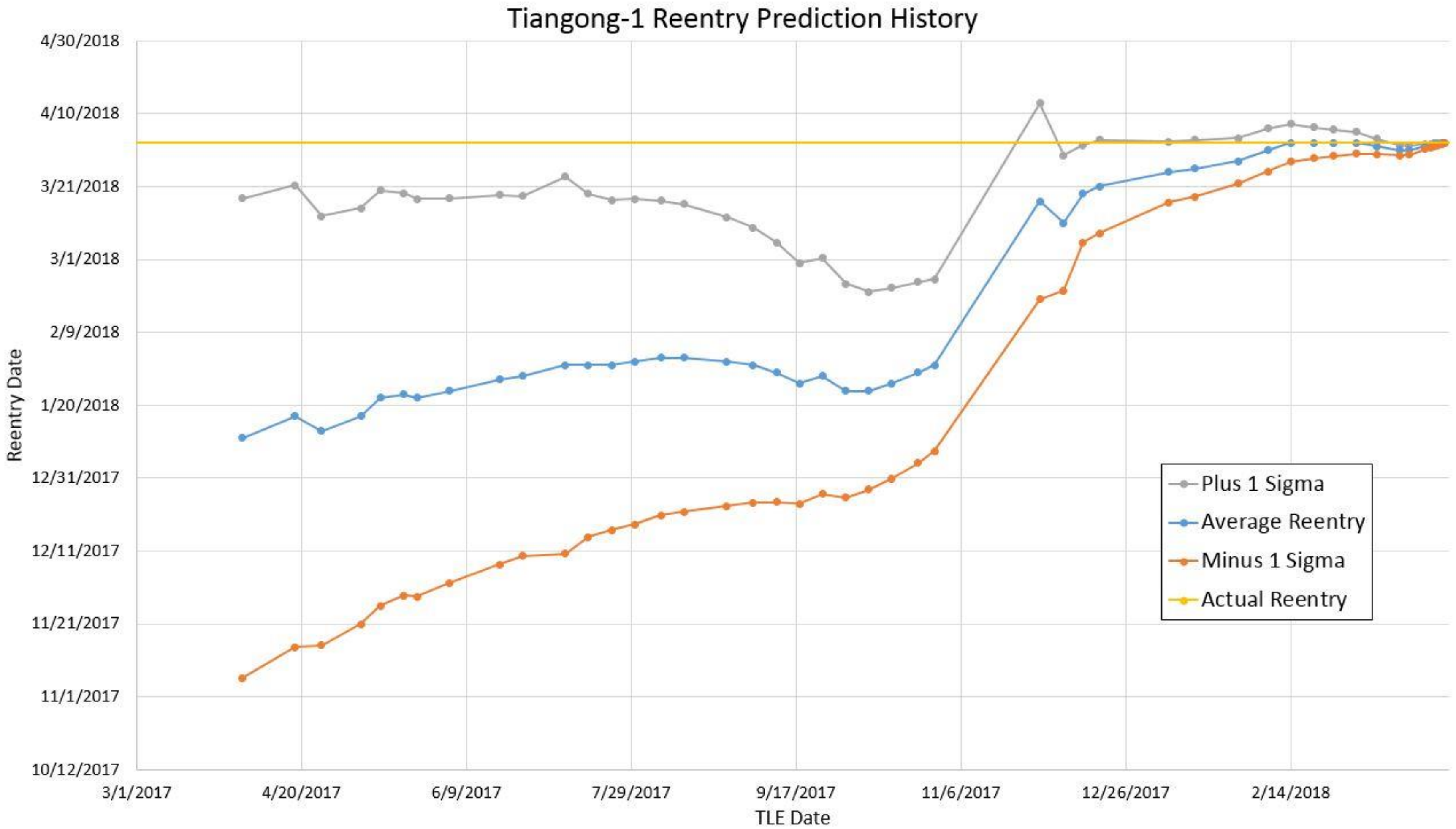
New method used to produce published reentry predictions



Results

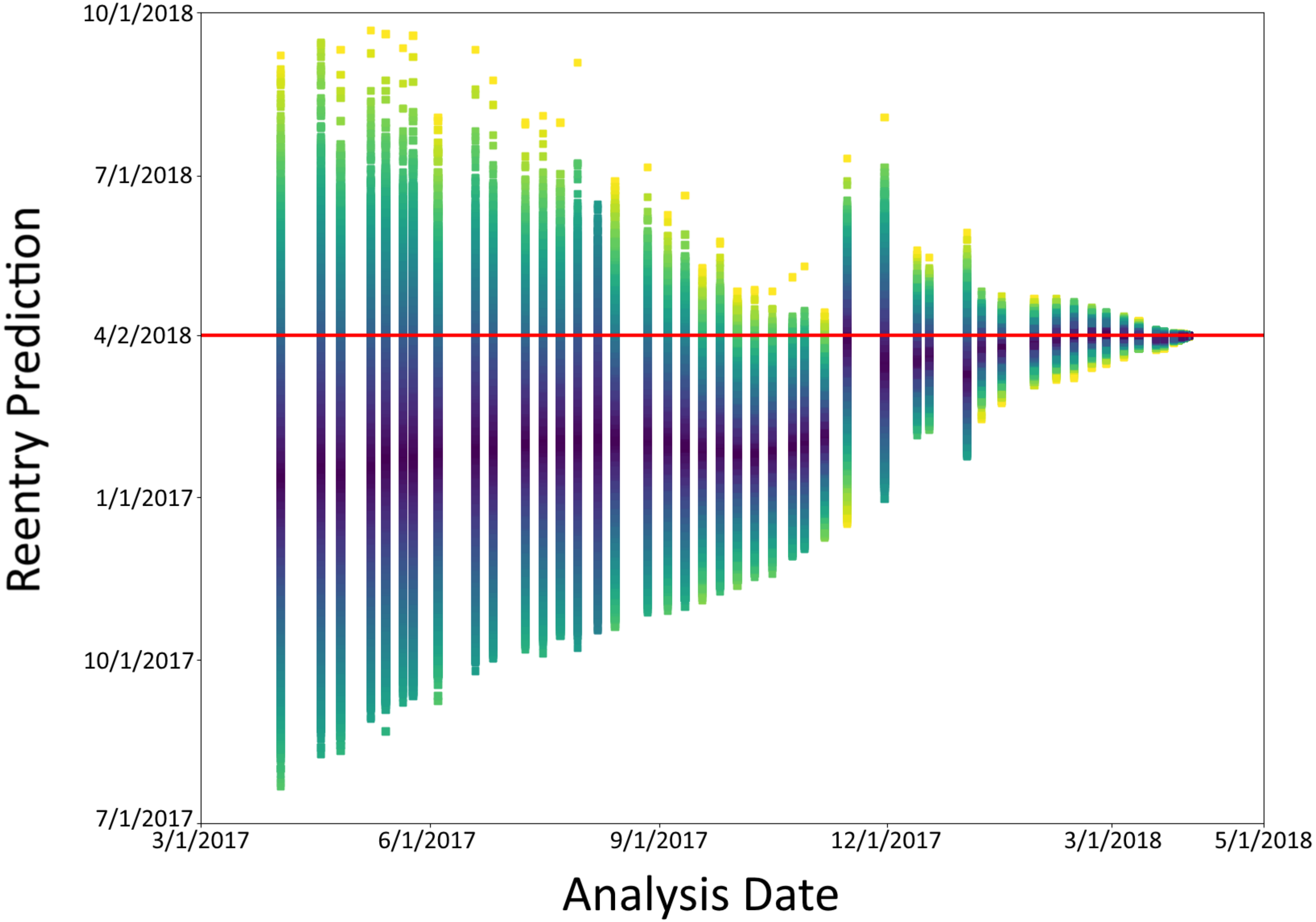
New method led to smaller uncertainties

- 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

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

Date	Std Dev [hr]	20% Rule [hr]	Difference from Truth [sigma]
11/15/2017	759	662	0.11
11/30/2017	644	590	0.57
12/13/2017	320	528	1.00
12/18/2017	307	504	0.88
1/2/2018	430	432	1.26
1/8/2018	200	403	0.84
1/16/2018	187	365	0.90
1/29/2018	149	302	0.71
2/7/2018	142	259	0.21
2/14/2018	124	226	0.08
2/21/2018	103	192	0.07
2/27/2018	85	163	0.20
3/6/2018	71	130	0.10
3/12/2018	51	101	0.20
3/19/2018	34	67	1.01
3/22/2018	31	53	1.22
3/26/2018	18	34	1.36
3/28/2018	12	24	1.49
3/29/2018	9	19	1.34
3/30/2018	7	14	1.30
3/31/2018	3	10	0.79
4/1/2018	1	5	0.06

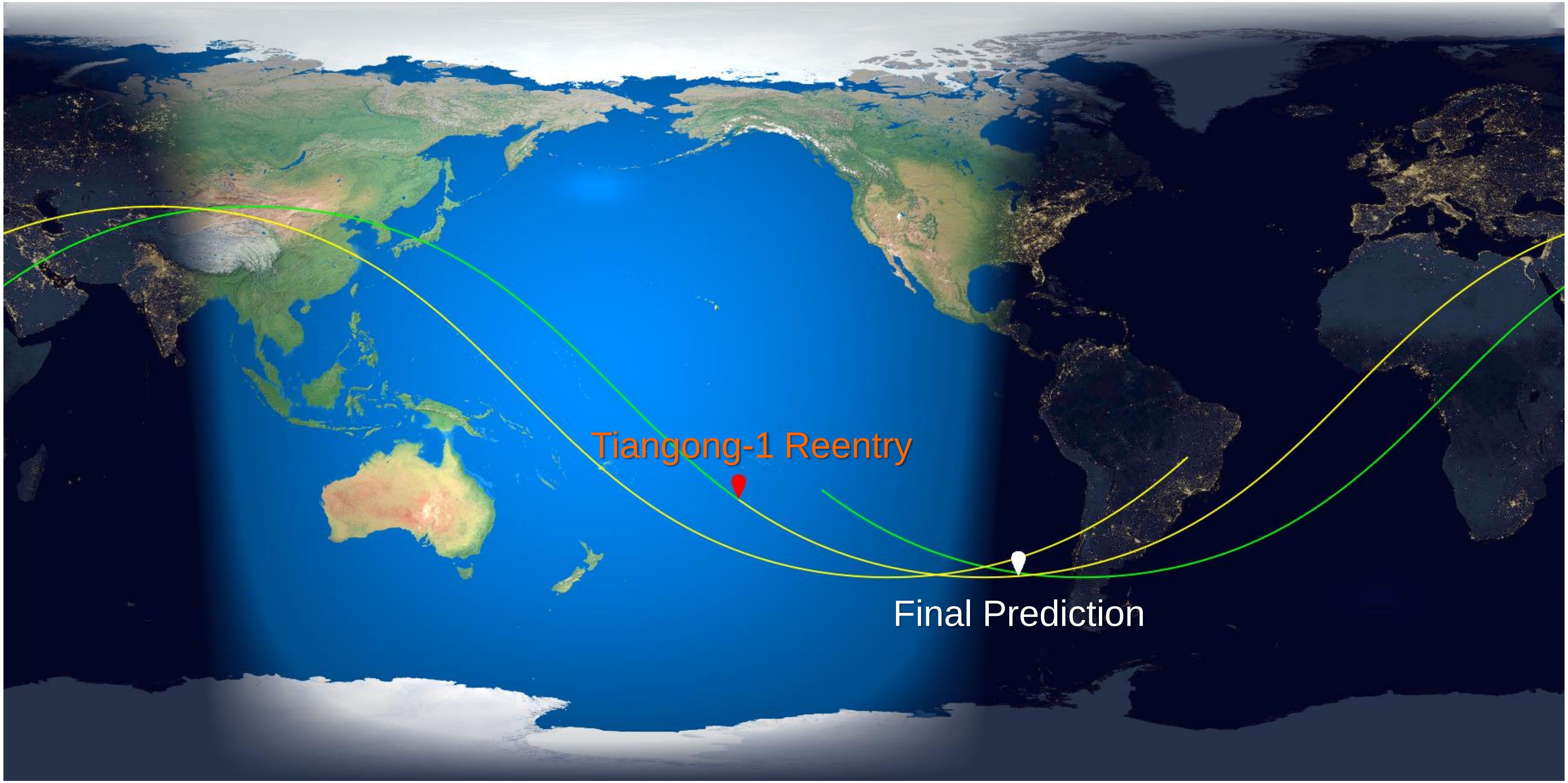
Conclusions

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

- [1] “Tiangong-1 Spacecraft Overview,” Spaceflight 101, 2016, URL: http://spaceflight101.com/spacecraft/tiangong-1/
- [2] “19,000-pound Chinese space station falling "uncontrolled" back to Earth,” CBS News, January 3, 2018, URL: https://www.cbsnews.com/news/19000-pound-space-station-falling-uncontrolled-back-to-earth/
- [3] Eiler, E. A., R. C Thompson, and J. Reiter, “Improved Reentry Predictions with High Fidelity Models,” 2017 AAS/AIAA Astrodynamics Specialist Conference, Stevenson, WA, August 2017.
- [4] Moe, K. and M. M. Moe, “Gas-Surface Interactions and Satellite Drag Coefficients,” *Planetary and Space Science*, Vol. 53, No. 8, 2005, pp. 793 – 801.
- [5] “Tiangong / Shenzhou: China's Human Spaceflight Program / Tianzhou Cargo Spaceship”, eoPortal Directory, 2016, URL: https://directory.eoportal.org/web/eoportal/satellite-missions/t/tiangong
- [6] Herdy, R., “Nitrous Oxide / Hydrocarbon Fuel Advanced Chemical Propulsion: DARPA Contract Overview,” NASA Thermal & Fluids Analysis Workshop, 2006.
- [7] “TABLE 3 ESTIMATES OF 13-MONTH SMOOTH SOLAR ACTIVITY,” NASA Marshall Space Flight Center, URL: https://sail.msfc.nasa.gov/current_solar_report/CurF10.txt