Federal Aviation Administration

Unified 4D Trajectory Approach for Integrated Traffic Management

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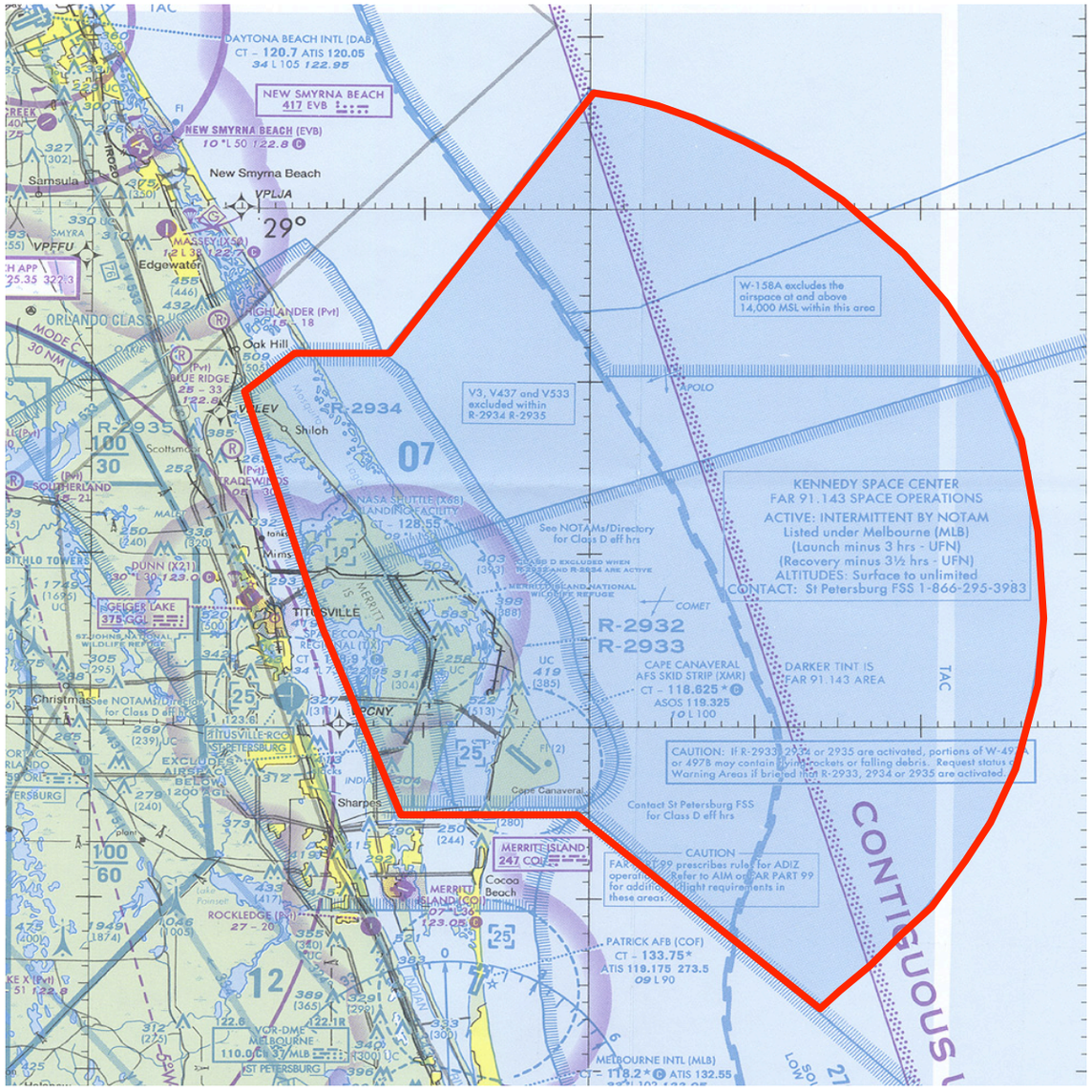
Outline

- **Brief overview of the aviation/space transportation conflict**
- **Research: Propose architectures for aircraft safety during launch and re-entry and analyze them using compact 4D envelopes**
- **Analysis Environment / Methodology**
  - **Propagate Uncertain Trajectories and Debris**
  - **Generate probabilistic compact 4D envelopes**
  - **Measure impact on NAS with FACET**
- **Example Scenario**
- **Concluding thoughts and directions**

What's The Problem?

- **Safely and fairly sharing the NAS**
  - **Need launch architectures to ensure NAS users are safe**
  - **Current method uses SUAs, NOTAMs, etc and cannot respond dynamically**
  - **No robust quantitative framework for creating SUAs, thus they are overly conservative**
  - **Commercial space traffic in rising volume and launching from new ranges requires new ATM architectures**



Source: 45 SW Eastern Range: Special Use Airspace, PPT Presentation by Art Ladd

What's Needed?

- **Airspace Management Architectures For Launch / Re-entry**
  - **Procedures governing how the airspace will be handled / partitioned to keep planes and rockets safe**
  - **Specific to each vehicle's mission and quantifiably safe**
- **Examples**
  - **Proactive: No-fly zone is established encompassing entire potential danger area for launch until successful staging**
  - **Reactive: No-fly zone bounds nominal trajectory only. In the event of off-nominal event, SUA is dynamically created and enforced**

Purpose of Task 185

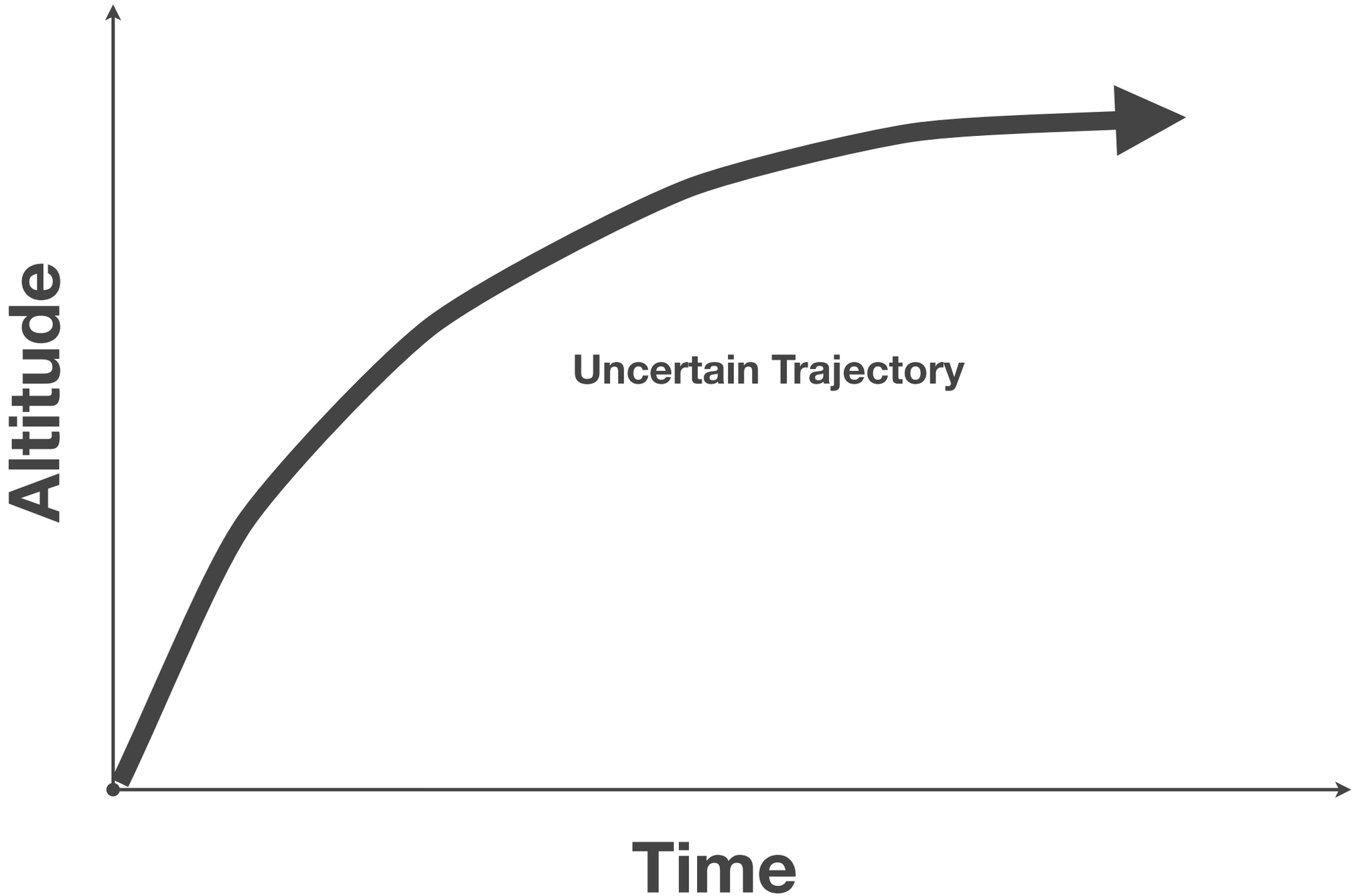
- **Development of requirements, architecture and prototype implementations of simultaneous air/space traffic management procedures for commercial space transportation. Leverage projected improvements derived from NextGen.**

Photo Credit: (NASA/Robert Markowitz)

- **Research, develop, analyze and optimize plausible architectures for an Integrated Airspace Management System based on 4D, time-space probabilistic trajectories and safety assessments**

Compact Envelope Concept

Compact Envelope Concept



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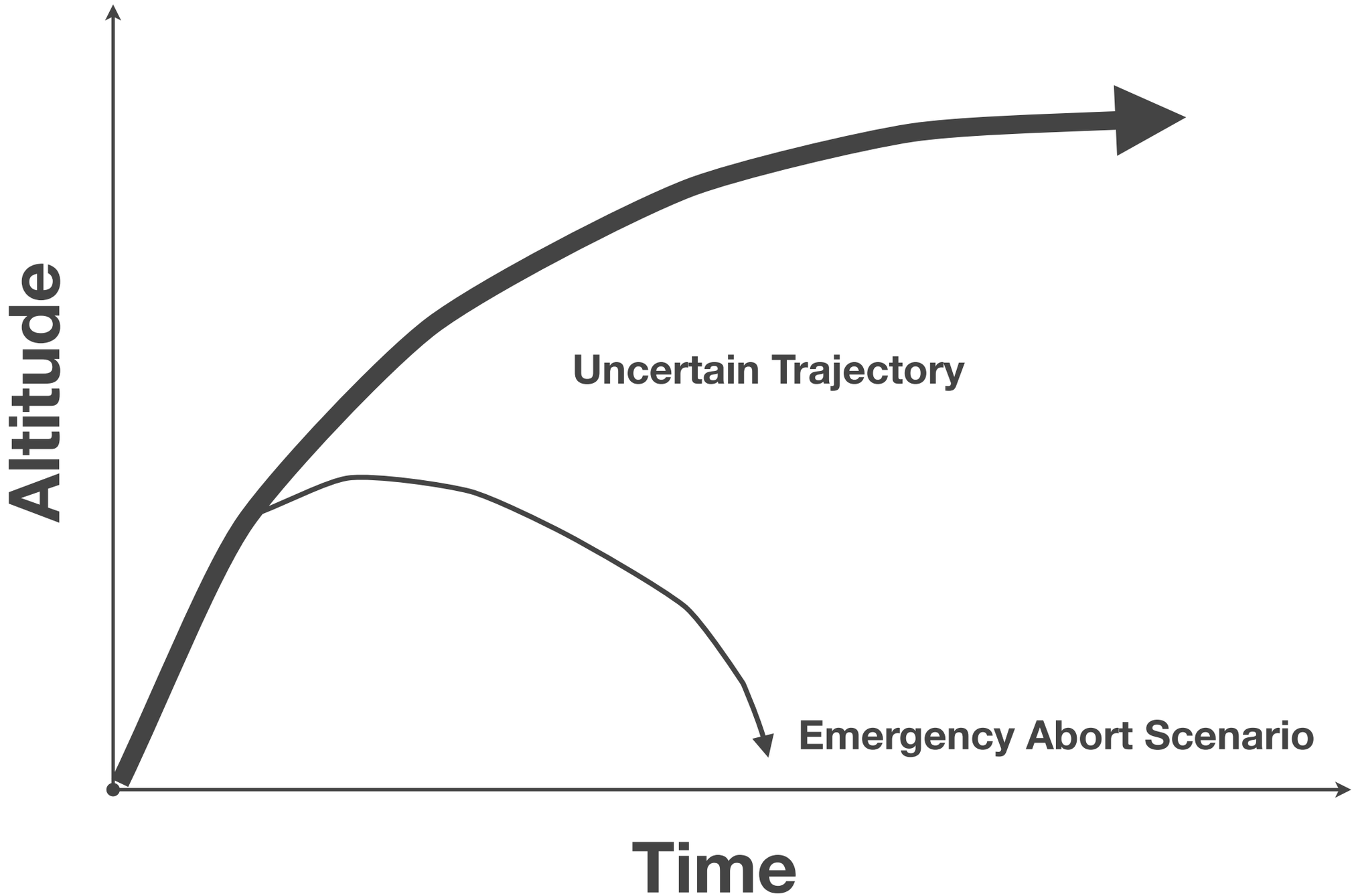

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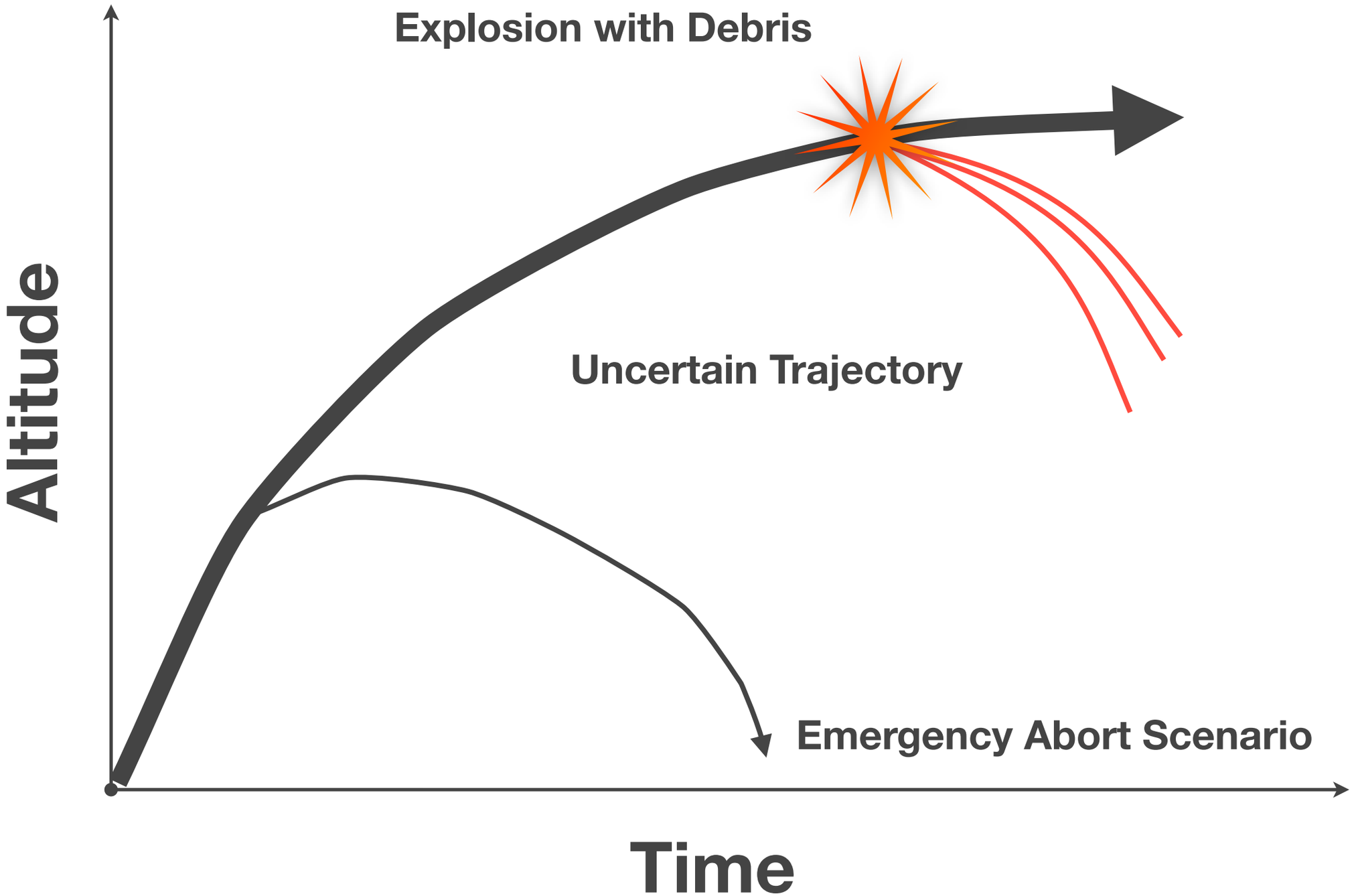

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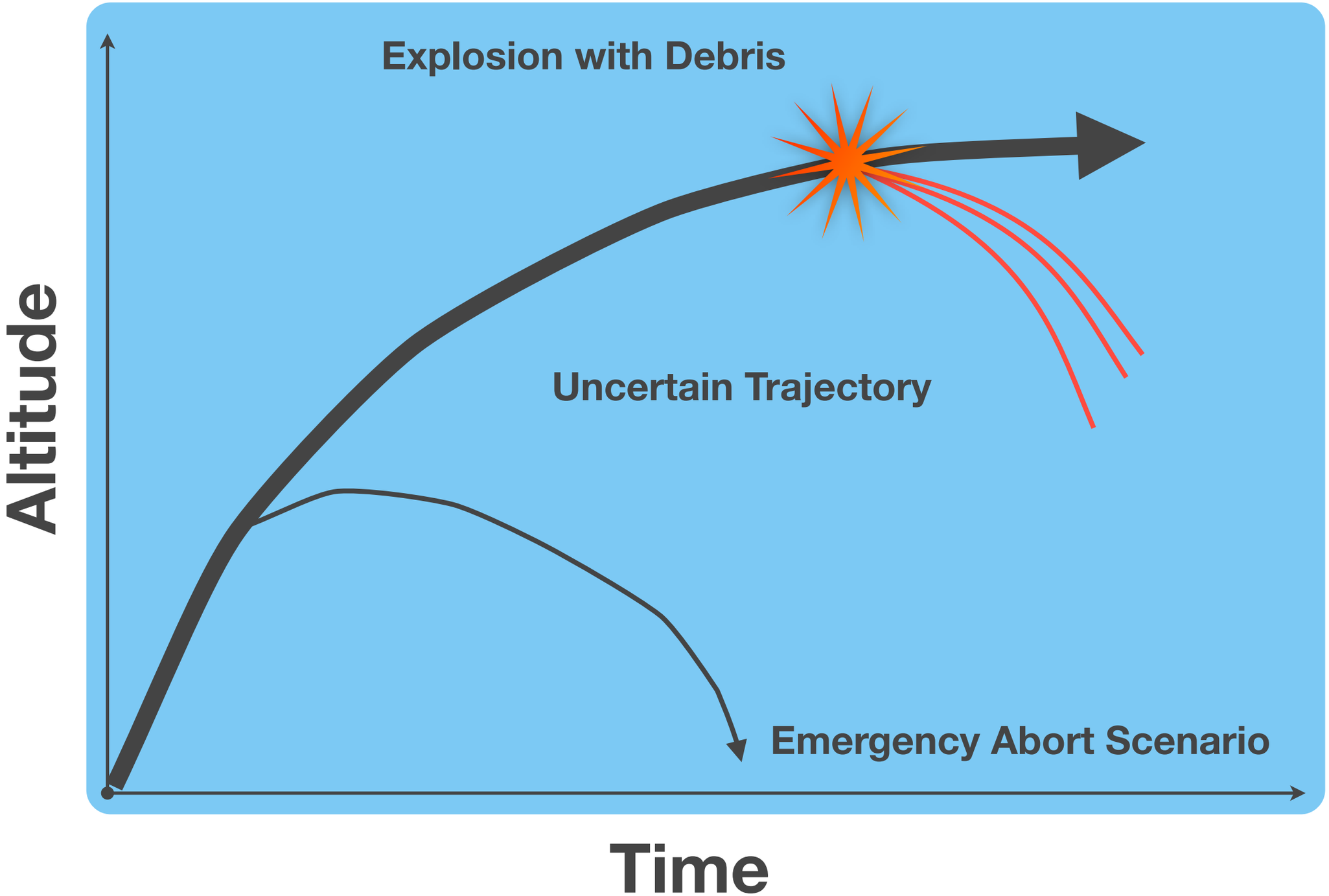

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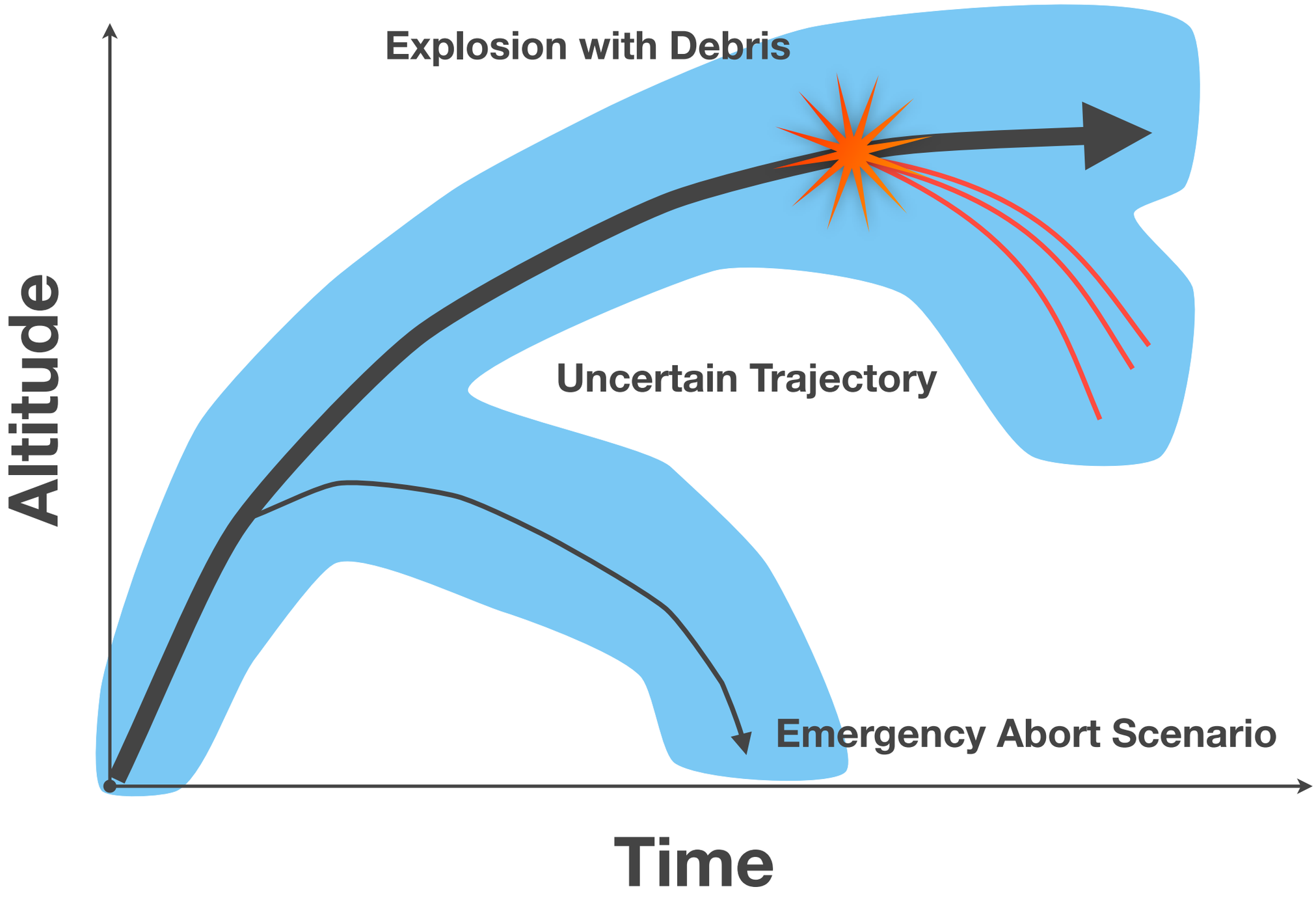
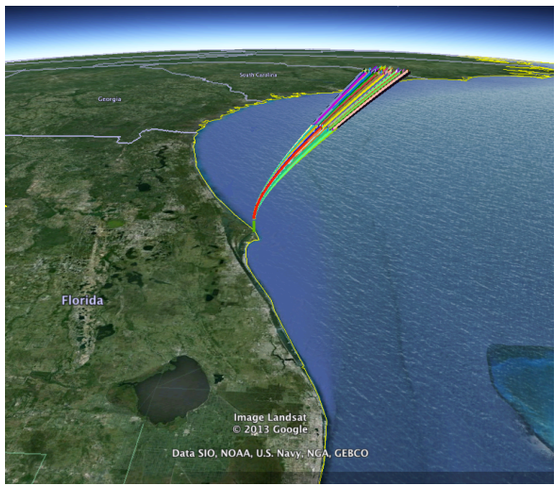
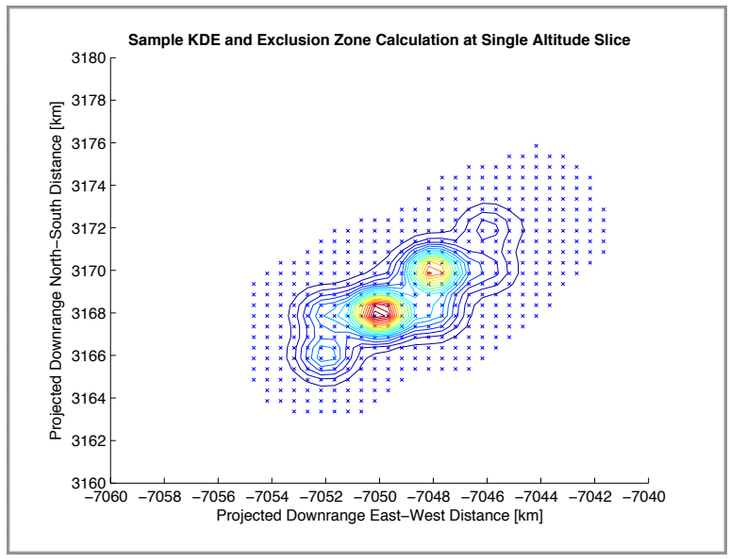


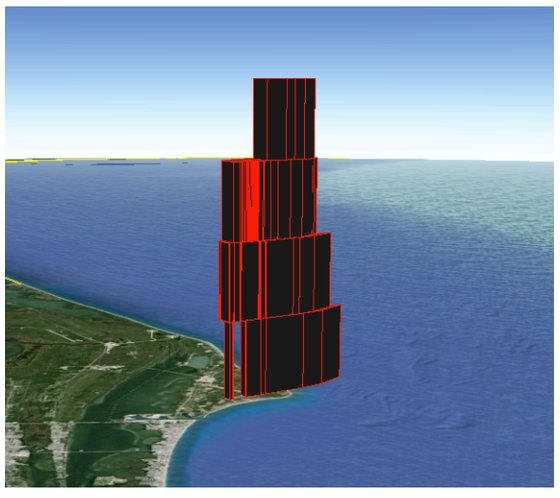
Methodology - Individual Scenario



Run a Monte Carlo simulation that accounts for variation in thrust profiles, weather and time-of-launch uncertainties, and distributions for time of failure.

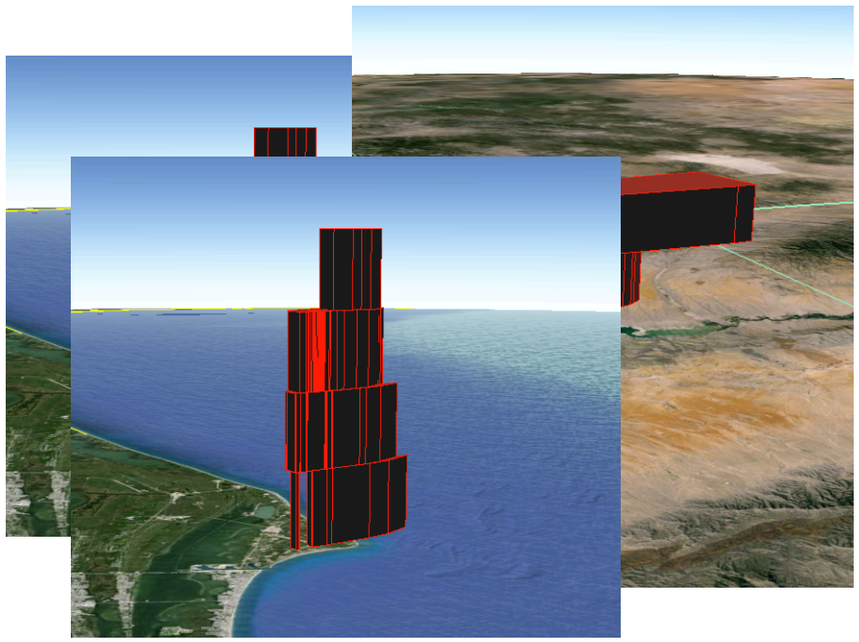
Bin the results of the simulation. Estimate the pdf of the debris / rocket locations via Kernel Density Estimation and find exclusion zone based on probability of aircraft strike prescribed from regulation or user-input.



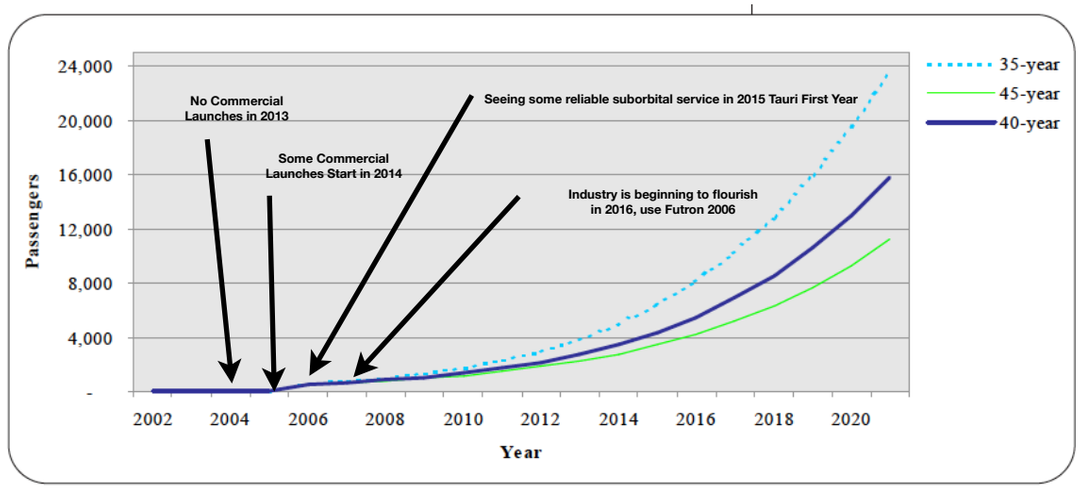


Create compact envelope around the exclusion points using the Swinging Arm Algorithm. Visualize the envelopes in Google Earth or analyze their impact on the National Airspace with FACET.

Methodology - System Level Scenario



Store envelopes from single scenario analysis and collect them into a compact envelope library.



	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Baseline (40-year)	503	642	820	1,045	1,330	1,692	2,150	2,726	3,448	4,350	5,468	6,842	8,517	10,532	12,923	15,712
35-year	611	798	1,042	1,358	1,768	2,298	2,980	3,853	4,962	6,359	8,100	10,241	12,829	15,895	19,443	23,437
45-year	489	608	756	939	1,166	1,447	1,794	2,222	2,747	3,390	4,174	5,125	6,273	7,646	9,277	11,192

Figure 45: Suborbital forecast ranges using a Fisher-Pry model

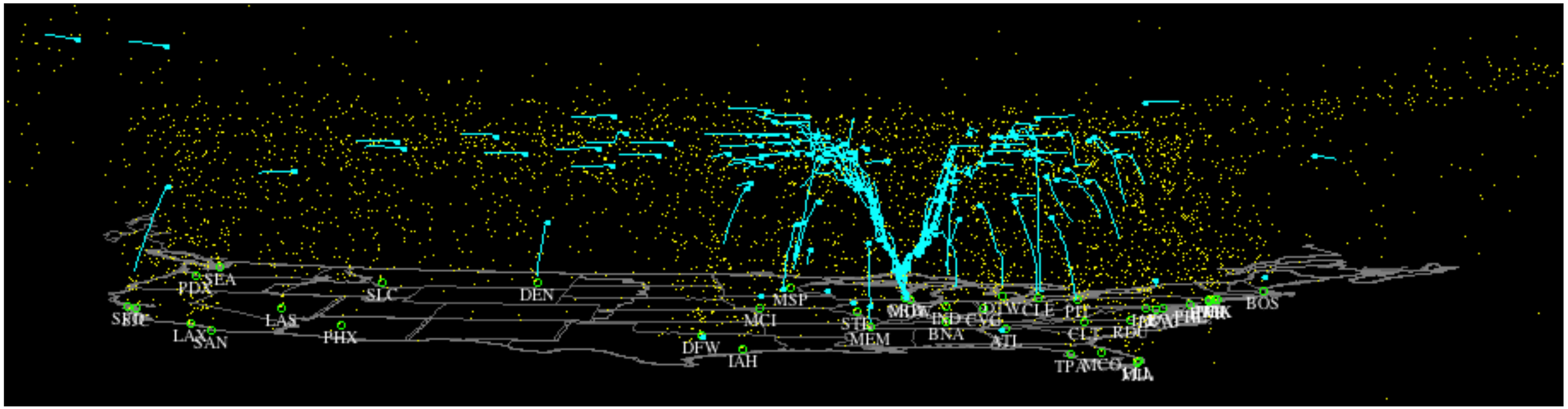
Estimate the volume of orbital and suborbital launch and reentry traffic in the future. Collaborated with FAA (SVO and Advanced Op Concepts) to produce estimates for years 2018 and 2025.

Approximate new missions within estimated space traffic scenarios by using previously calculated envelopes. Rotate and translate as needed then analyze in FACET.

Measure NAS Impact With FACET

- **Future ATM Concepts Evaluation Tool**
- **Simulation environment for preliminary testing of advanced ATM concepts over continental United States**
- **Award Winning**
  - **NASA's Software of the Year Award 2006**
  - **AIAA Software Engineering Award 2009**
- **Examples of advanced ATC concepts already implemented**
  - **Aircraft self-separation, prediction of aircraft demand and sector congestion, system-wide impact assessment of traffic flow management constraints, wind-optimal routing, etc.**
- **<u>Massive</u> amount of multi-threaded code in C and Java**

How It Works (Bird's-Eye View)

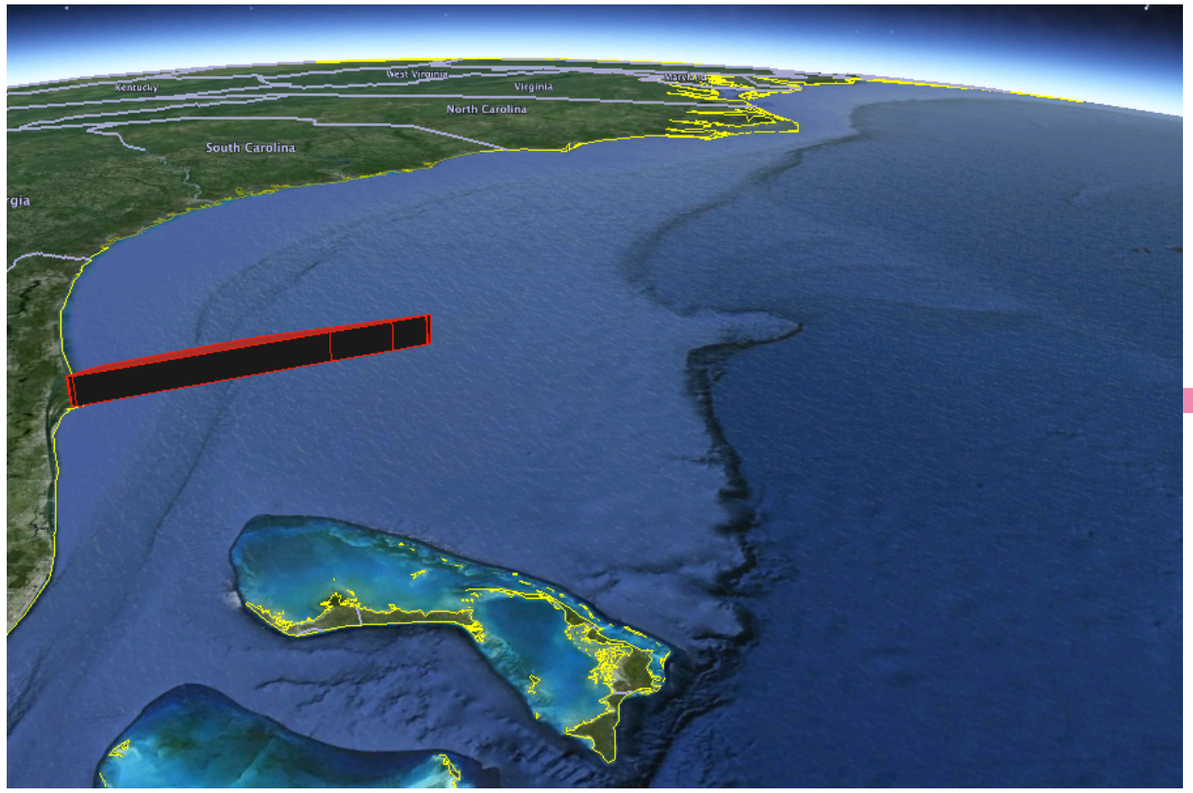


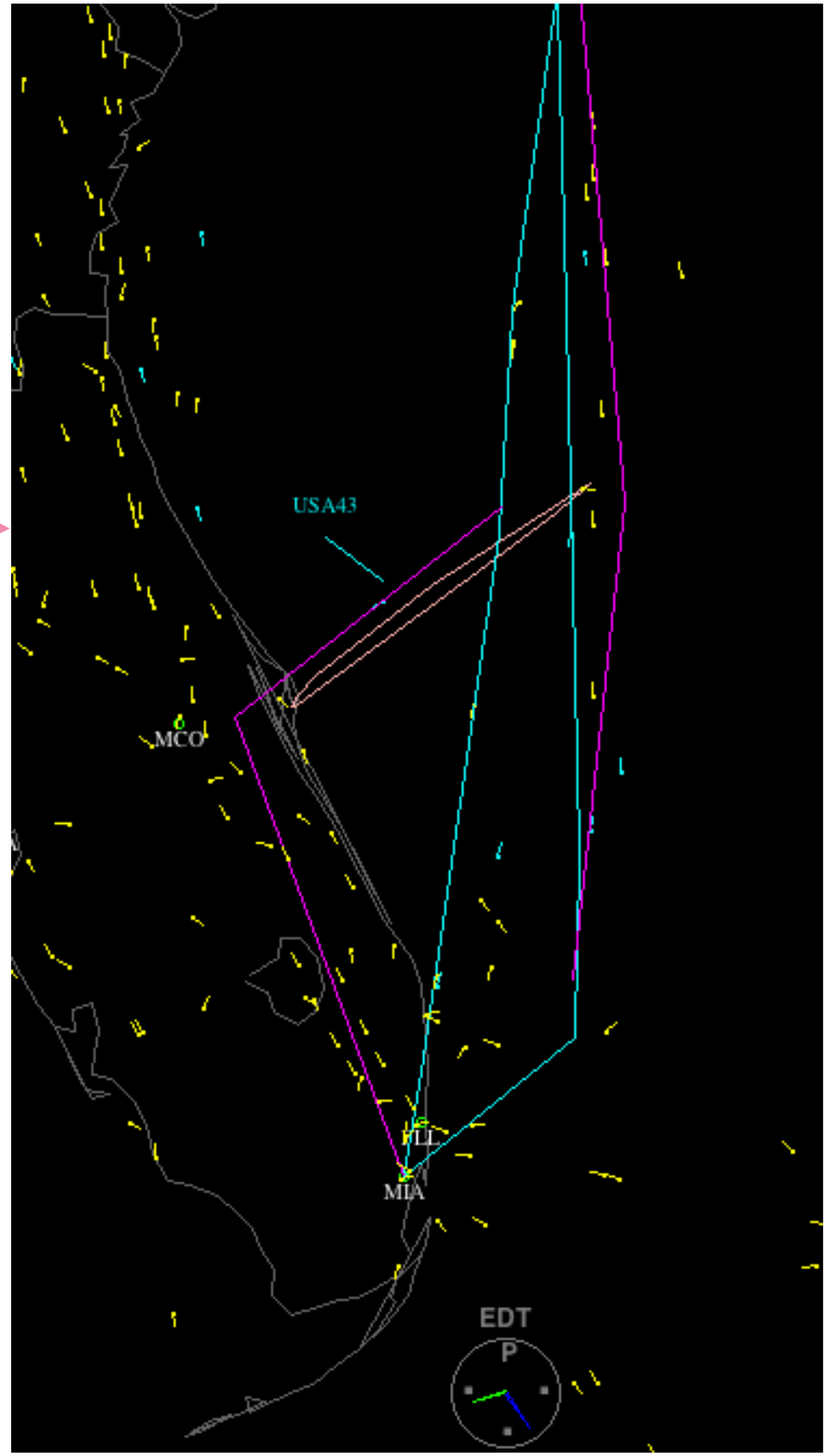
- **FACET uses aircraft performance profiles, airspace models, weather data, and flight schedules, etc.**

- **Models trajectories for the climb, cruise, and descent phases of flight for each type of aircraft.**

- **Graphical interface displays the traffic patterns in two and three dimensions, under various current and projected conditions.**

Example Scenarios

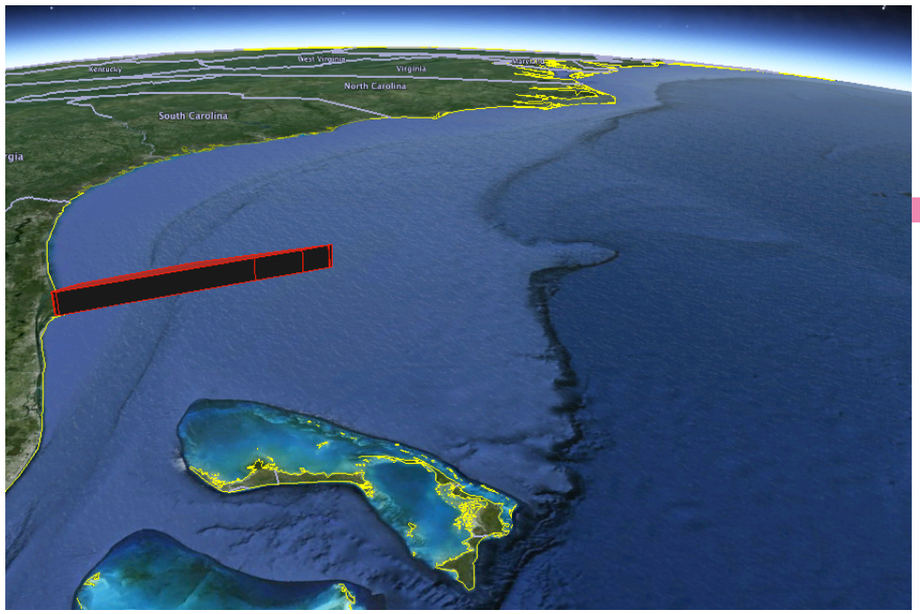


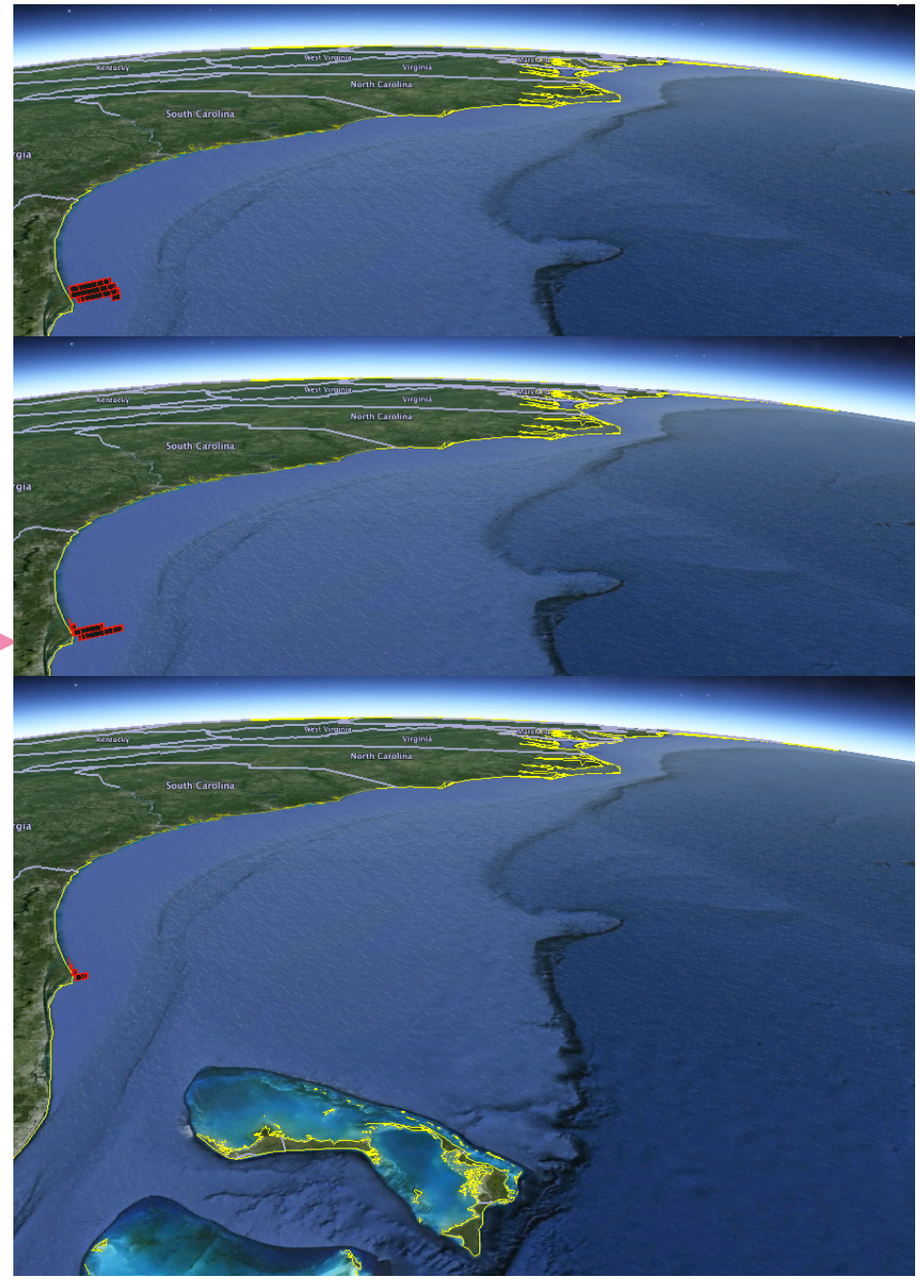


<u>Falcon9-style launch from Cape Canaveral:</u> Using a reactive architecture, we assume that the airspace needs five minutes to react to an off-nominal event; we create an envelope around the potential debris cloud to which the NAS would not have adequate time to react. In event of nominal operations, airspace is only blocked off for two minutes post-launch.

Example Scenarios

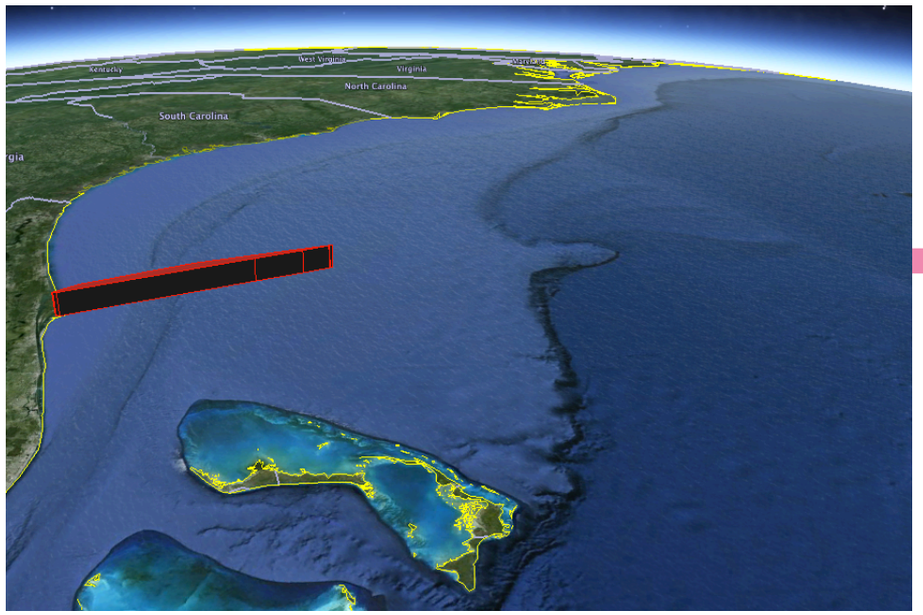
<u>Failure at Maximum Q:</u> The debris footprint from this type of failure is dramatically smaller than compact envelope that is already on. If this event occurs, switch to smaller envelope.

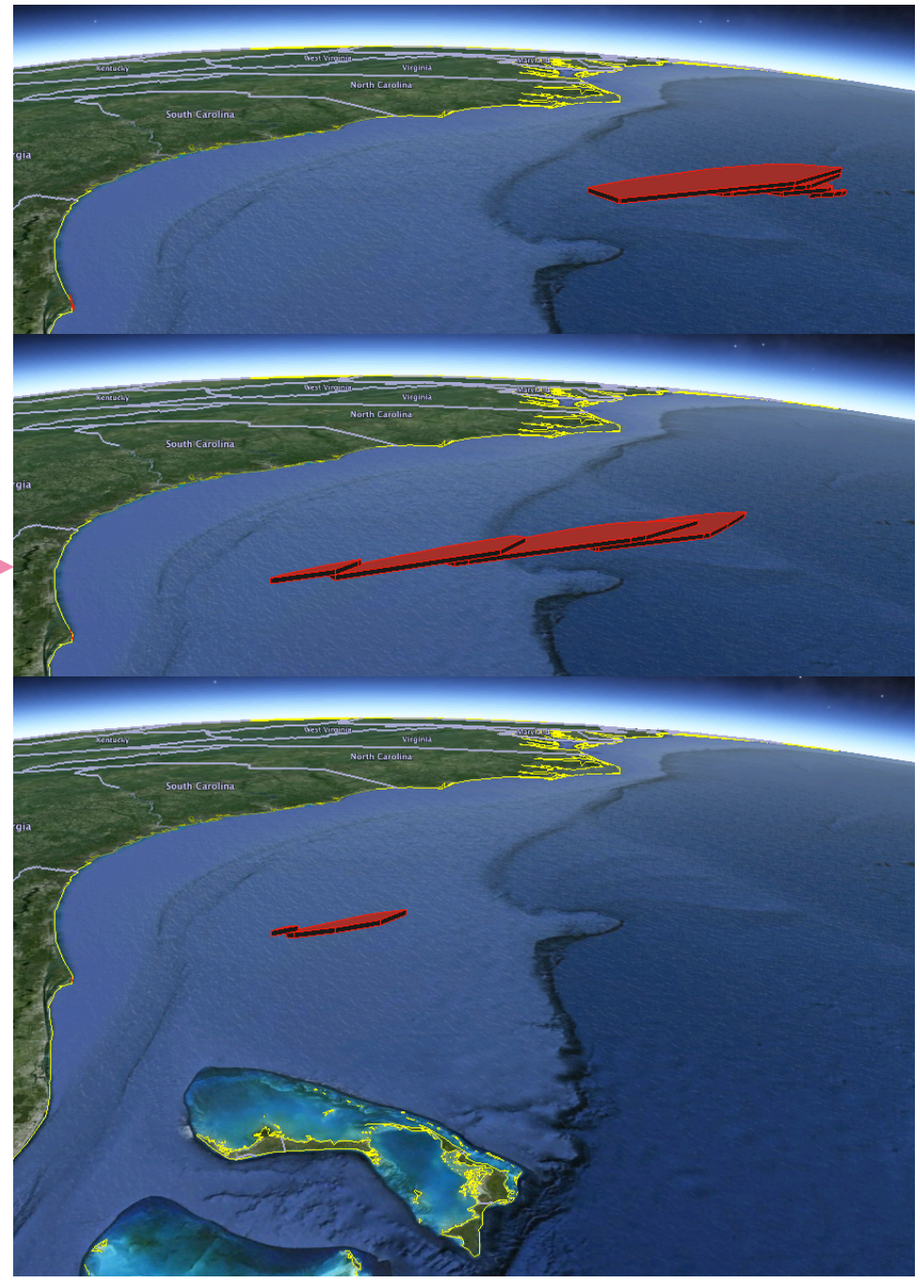




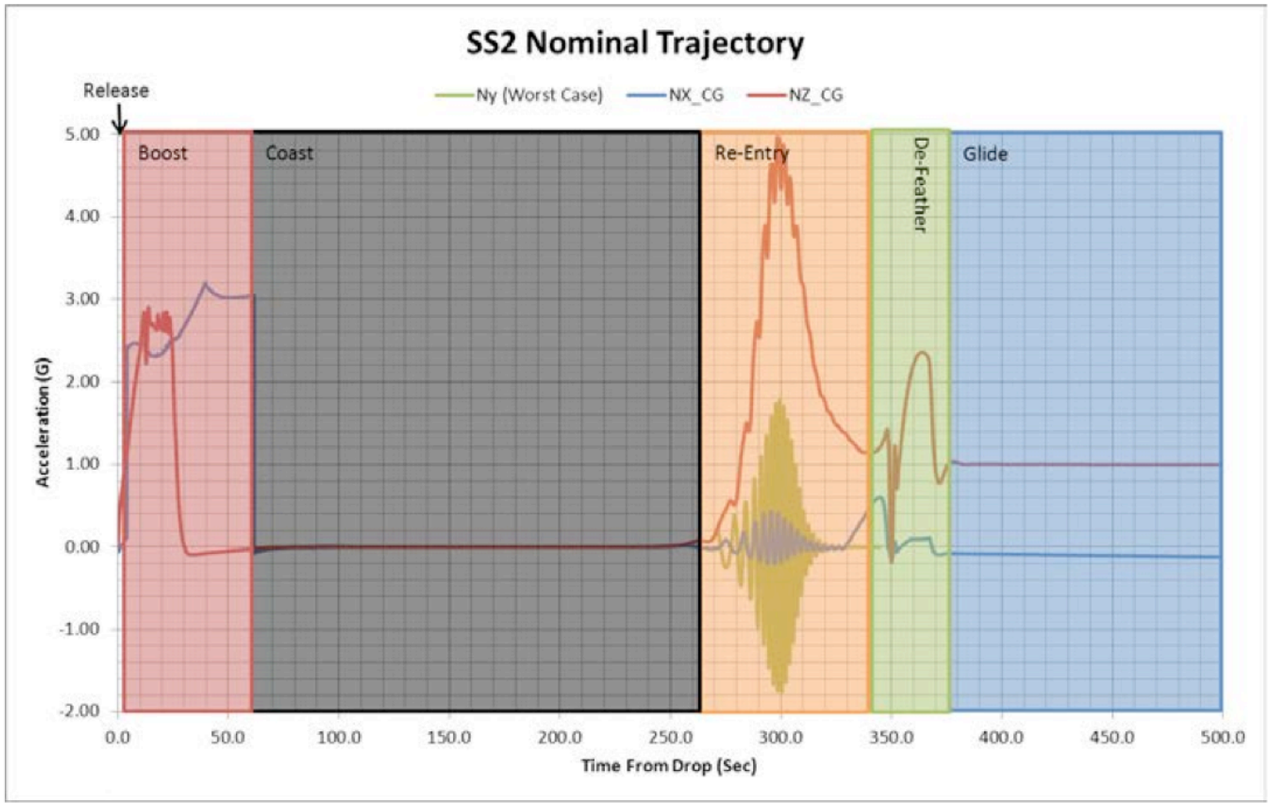
Example Scenarios

<u>Failure at staging event:</u> When this happens, it will be more than 5 minutes until debris reaches the NAS, so can be reactive.





Not Just Orbital: SpaceShipTwo



Source: Virgin Galactic SpaceShipTwo User Guide

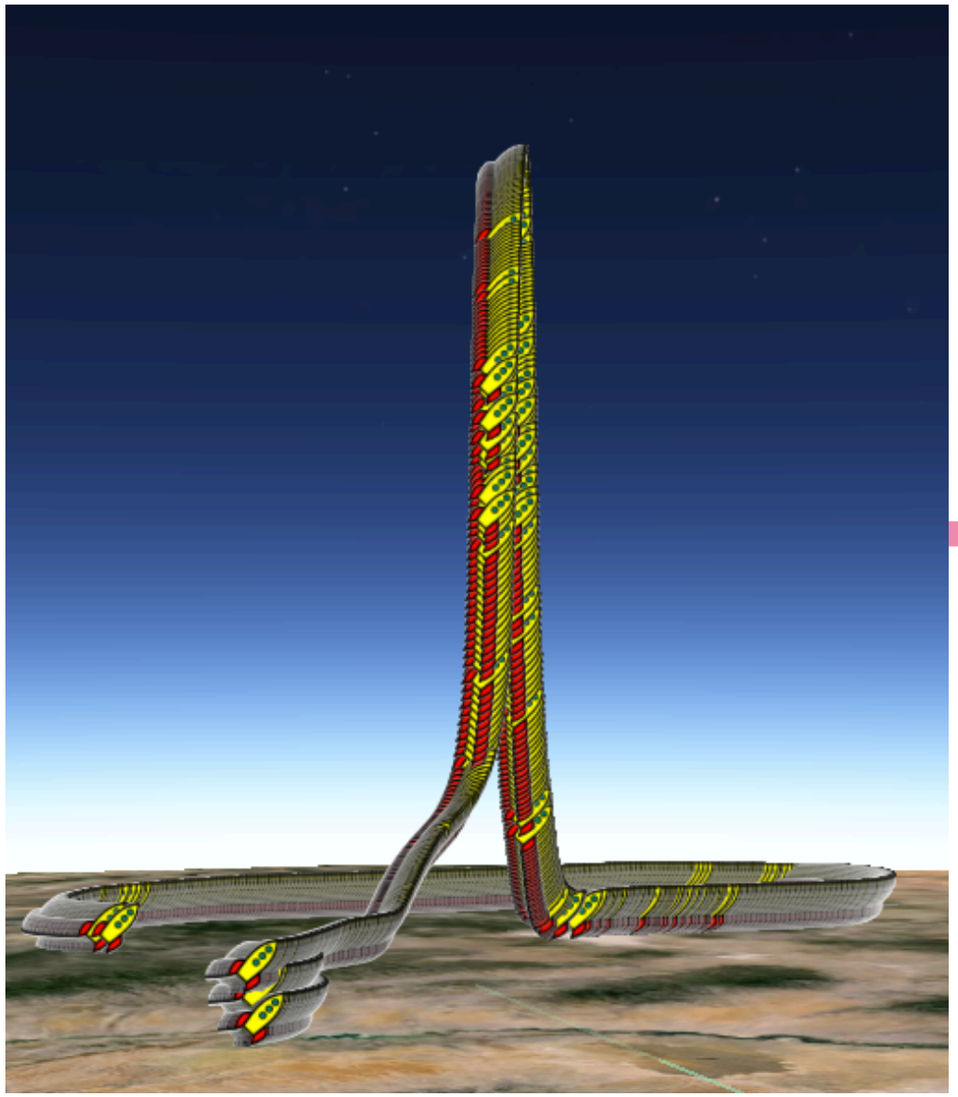
Table 2: Expected g-Loads for Flight and Crash Conditions

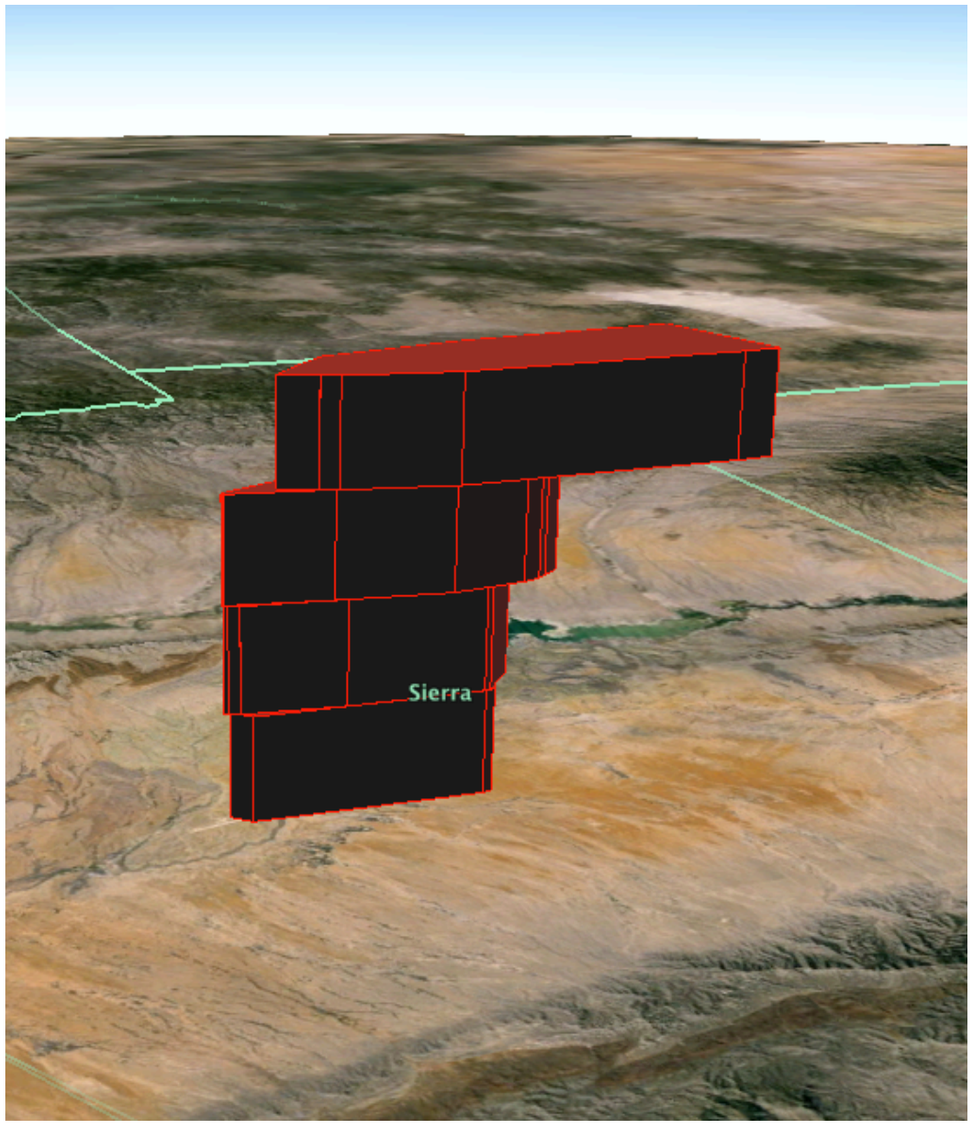
Direction	Maximum Boost Loads	Maximum Re-Entry Loads	Crash Loads
Front/Back (N_x)	+0.1 / -3.4	+ 1.4 / -1.5	+15.8 / -0.0
Left/Right (N_y)	+0.0 / -0.0	+1.8 / -1.8	+2.8 / -2.8
Down/Up (N_z)	+3.7 / -1.0	+8.4 / -0.1	+4.5 / -4.5

Source: Virgin Galactic SpaceShipTwo User Guide

- **Used acceleration profile graph to back out thrust profile in body frame**
- **Estimated weight between 21k-30k lbs**
- **Made assumptions about pitching angle**
- **Propagated realistic suborbital trajectory for SS2**

Suborbital Example





SpaceshipTwo-style Launch: **We have the ability to create compact envelopes for multiple suborbital architectures (aircraft first stage, Lynx-style HTHL, VTHL, etc). This is an example trajectory and compact envelope for a vehicle modeled after SS2, dropped from a plane at 50kft, and climbs to 100km above the surface of the earth and explodes a few moments after launch.**

Results

- **We have an environment ready to begin analyzing ATM architectures for launching commercial space missions**
  - **Propagate Uncertain Trajectories and Debris**
  - **Probabilistically generate compact 4D envelopes**
  - **Automated interface with FACET**
  - **Counting aircraft / launch vehicle conflicts with FACET**
  - **Can simulate arbitrary day in the NAS, rerouting aircraft around compact envelopes**
  - **Outputs new flight plans, times, and difference in distance**

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Conclusion

- **Have suite of interfacing software environments that can simulate missions with uncertainty, bound the results probabilistically, and analyze their effect on the airspace.**

- **Have been collaborating closely with FAA to estimate launch / reentry traffic volumes for 2018 and 2025 in preparation for NAS-wide study.**

- **Beginning to validate FACET's results with FAA's AirTOp. Both have some odd rerouting behaviors which must first be investigated. Working with FAA's Kevin Hatton (SVO) to ensure rerouting algorithms produce realistic results for our scenarios.**

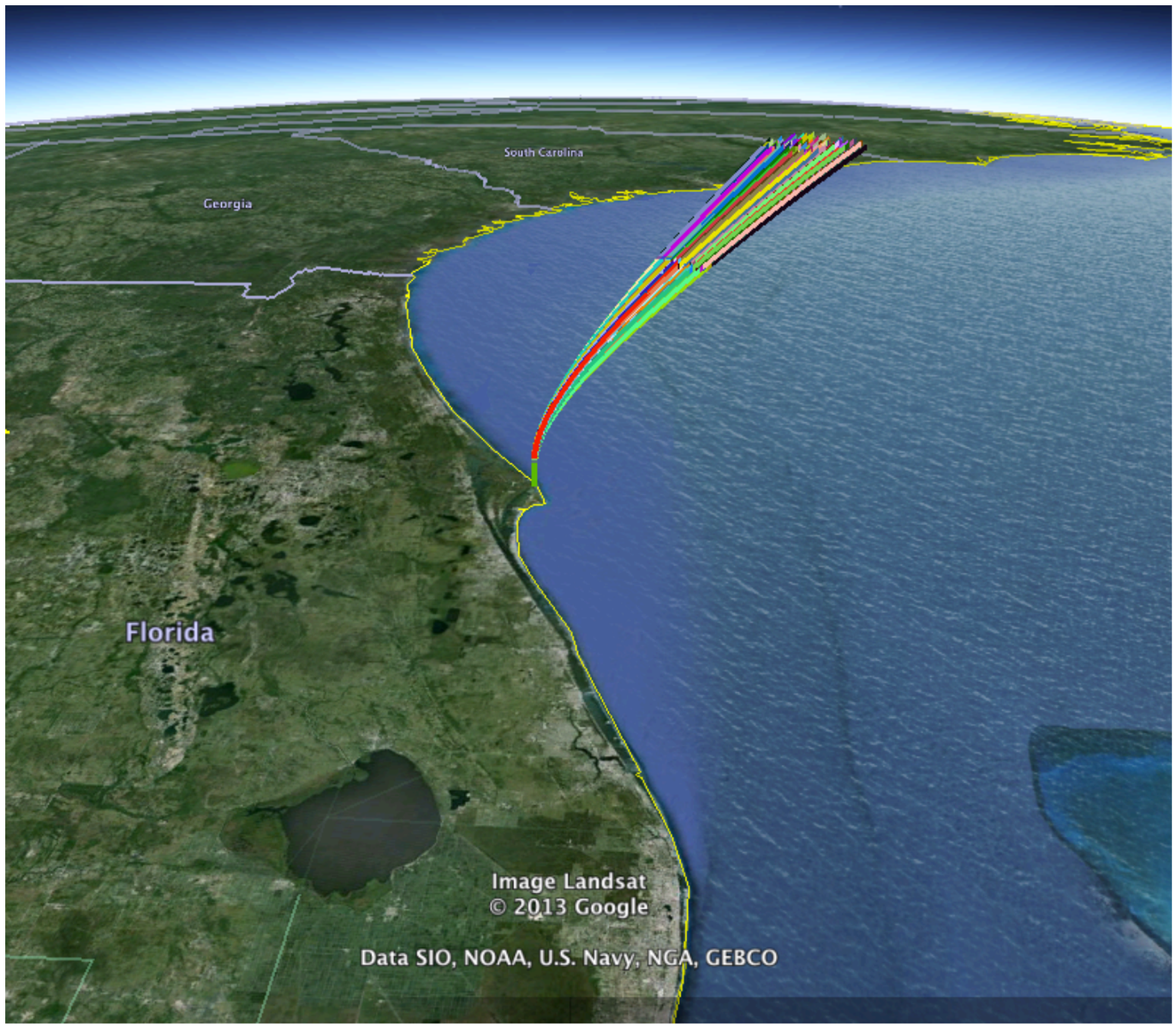
- **Will use FACET as part of an optimization to research launch architectures and air traffic routes that are optimal for the integrated space-and-air-traffic system.**

The End

- **return 0; }**

Propagation Code

- **Monte Carlo software framework that accepts arbitrary:**
  - **Thrust profiles (TVC, etc)**
  - **Weather profiles for wind and temperature, with uncertainty parameters for each**
  - **Failure parameters and distributions**
  - **Debris model**
- **Outputs:**
  - **Collection of (x,y,z,t) points which represent all places a vehicle or its debris may be found from a MC simulation**



Kernel Density Estimation

Currently

- **Create a histogram for debris locations at each altitude level**
- **Use bivariate gaussian kernel with naive bandwidth parameters**
- **Make assumptions about aircraft density**
- **Find exclusion points based on probability of aircraft strike**

Coming Soon

- **Improved aircraft density model**
- **More appropriate bandwidth matrix (e.g. UCV)**