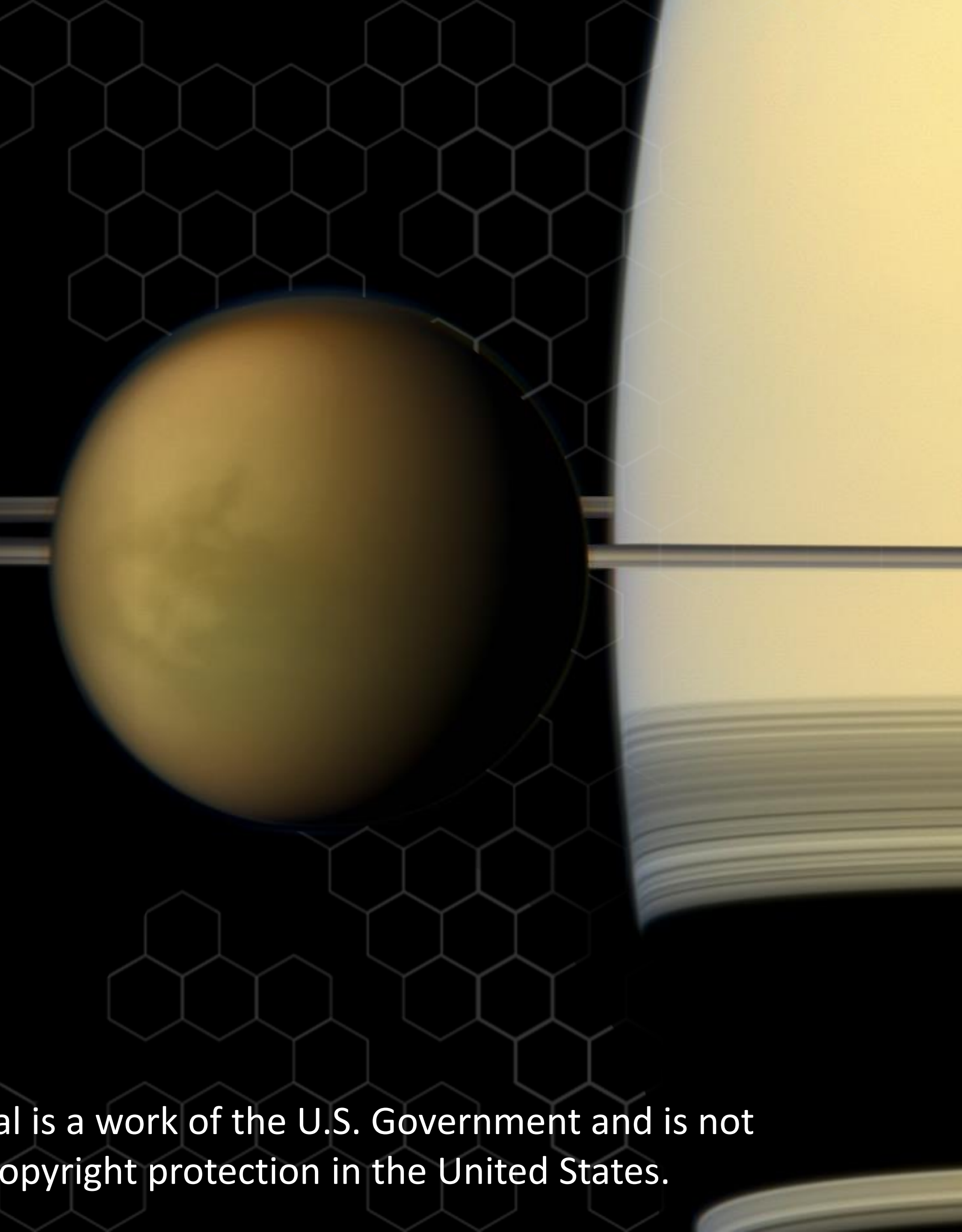
DRAGONFLY

A relocatable lander to explore Titan's prebiotic chemistry and habitability



Simulated Trajectory Reconstruction of the Genesis Aeroballistic Testing for Dragonfly

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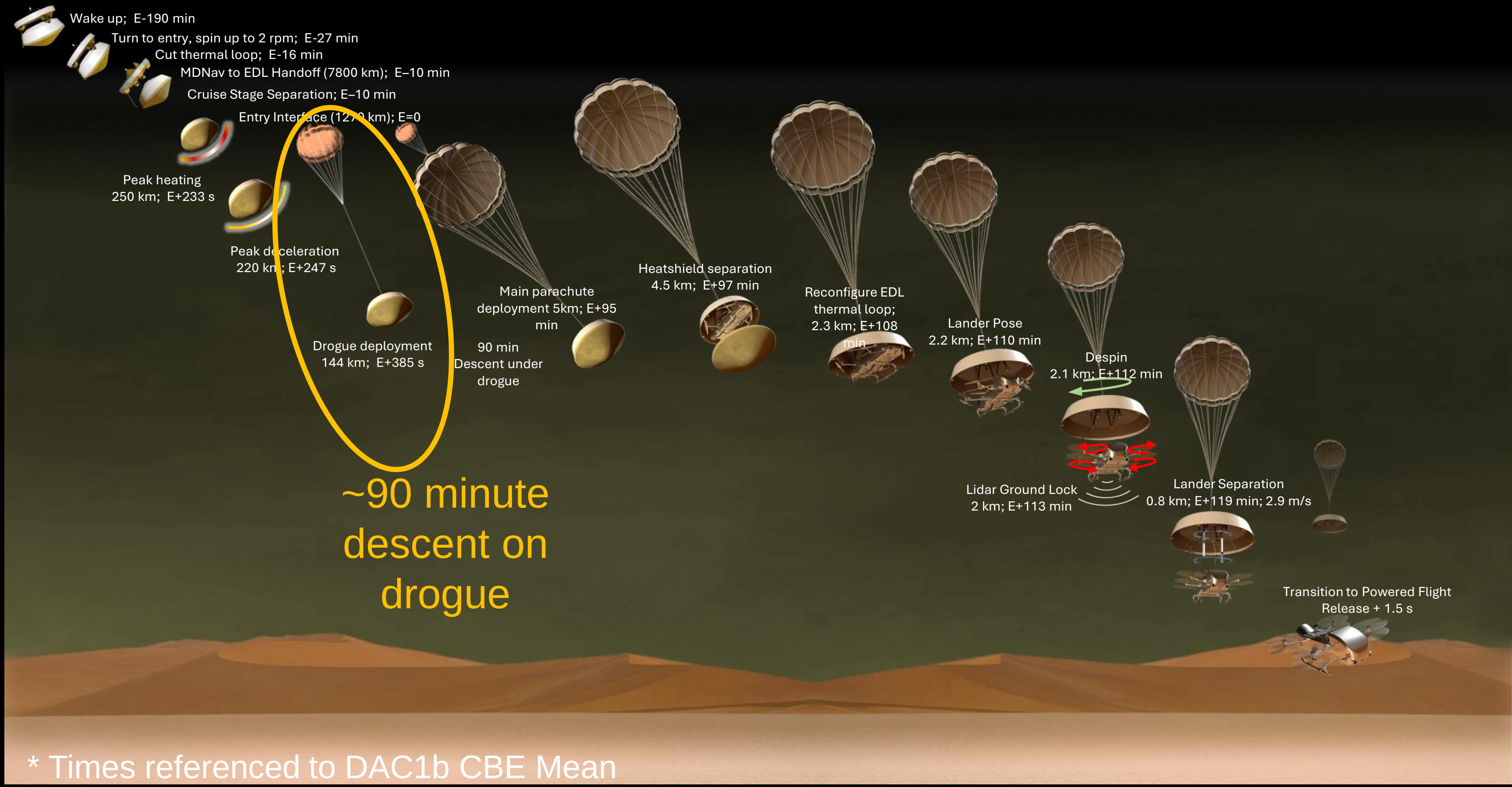
AMA/NASA Langley

Dragonfly Overview

- Dragonfly is a New Frontiers Program mission that will deliver a rotorcraft lander to Saturn's moon, Titan.
- This mission is designed to explore diverse locations to characterize the habitability of Titan's environment.
- This presentation gives an overview of Dragonfly's entry aerodynamic model substantiation efforts for the Genesis SRC ballistic range data



- Dragonfly uses the same shape as the Genesis SRC
- *Genesis SRC = Sample Return Capsule

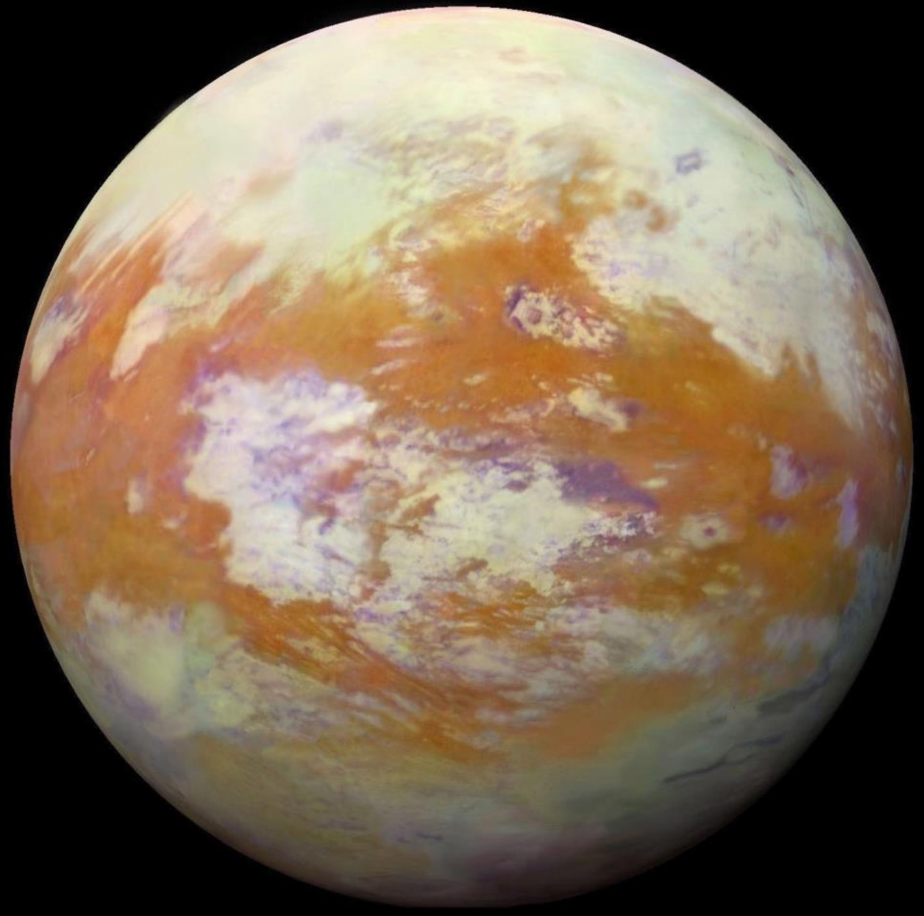
A Rotorcraft Lander to Explore Saturn's Moon Titan

What makes a world habitable?

What chemical processes led to the development of life?

Titan is an ideal destination to answer fundamental astrobiology questions because it has the key ingredients for life:

- Energy: sunlight drives organic photochemistry
- Complex organic material is abundant on the surface
- Liquid water on the surface in the past at impact craters (and potential cryovolcanism) and in the interior ocean
- A liquid methane cycle similar to Earth's water cycle



Titan's dense atmosphere and low gravity make it easier to fly there than on Earth. By flying, Dragonfly can explore and sample materials in different areas, including organic sand dunes and impact crater deposits where organics may have mixed with water.

Titan EDL Compared to Mars EDL

- Titan: Taller/denser atmosphere and lower gravity leads to much longer descent time under parachute(s), > 2 hours versus ~2 minutes for Mars
  - Results in thermal and power challenges
- Dragonfly: supersonic (drogue) parachute diameter is slightly larger than capsule diameter, unlike Mars (4-5X)
  - Dragonfly EV 4.5 m, drogue chute 6 m
  - M2020 EV 4.5 m, chute 21.5 m
  - Blunt entry vehicles tend to have low angle of attack dynamic instabilities leading to limit cycle motions
  - Results in descent system dynamics challenges over a long duration

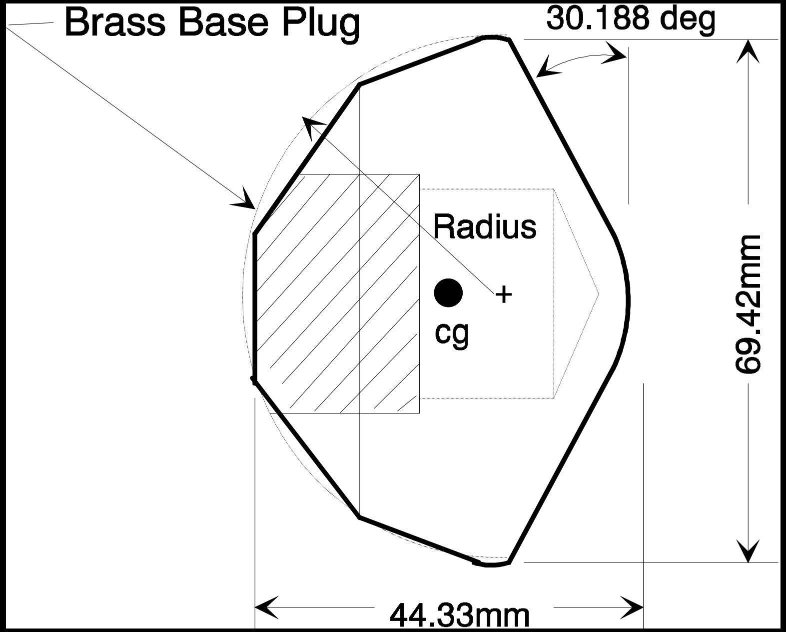
	Titan	Mars
Height of Atmosphere (km)	~1270	~125
Density at surface (compared to Earth)	4X	<0.02X
Temperature at surface (K)	~94	~200
Scale Height (km)	~40	~7
Surface gravity (Earth g)	0.14	0.38
Atmosphere (by mass)	98% N_2 + 2% CH_4	96% CO_2 + 2% N_2 + 2% Ar
Avg. distance to Earth (millions of mi)	800	140

Titan environment leads to EDL challenges due to atmosphere height/density/composition and lower gravity compared to Mars

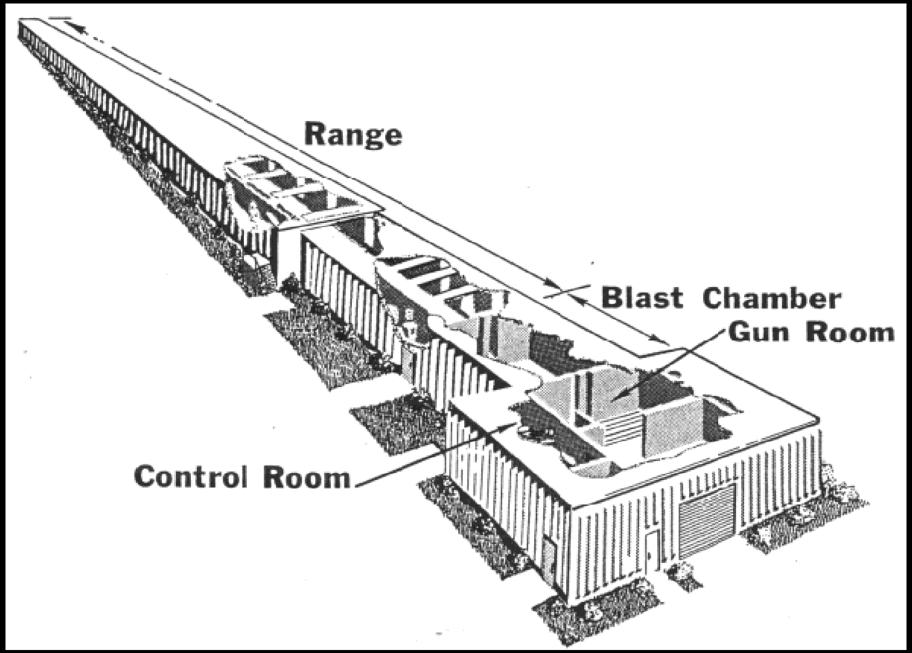
Genesis SRC Ballistic Range Testing

- Ballistic range (BR) free-flight testing allows determination of vehicle dynamic stability characteristics

- 12 tests were conducted in the Aeroballistic Research Facility (ARF), located at Eglin AFB, FL, during April 1999
  - Shots varied from Mach 1 to 4.5



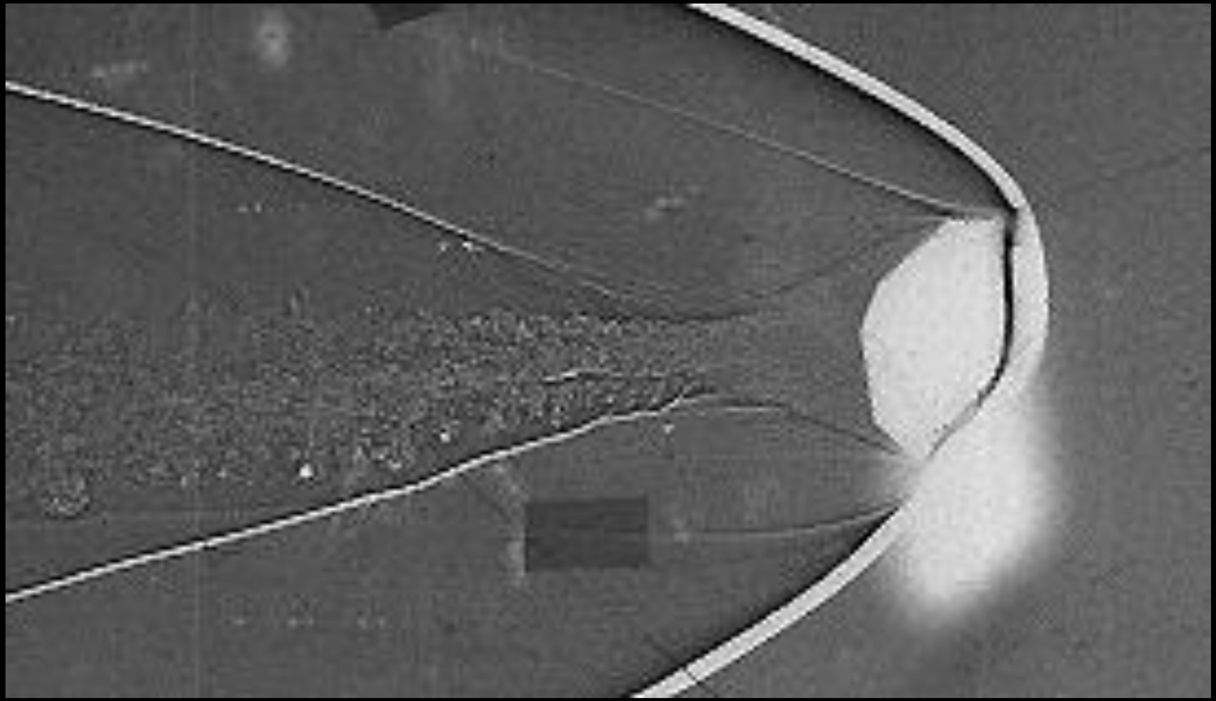
0.047 Scale Model of the Genesis SRC



Eglin AFB Aeroballistic Research Facility

Genesis SRC Ballistic Range Testing

- The resulting images provide a spatial position and angular orientation history
- These times, positions, and orientations are used to determine aerodynamic forces and moments acting on the model during the observed flight
- For the Genesis SRC BR testing, initial conditions were less precisely controlled than more recent testing and not published (attitude & attitude rates)
- Results: Static and dynamic aero from Mach 3.5-1, AoA 0-25°



Genesis M = 3.7

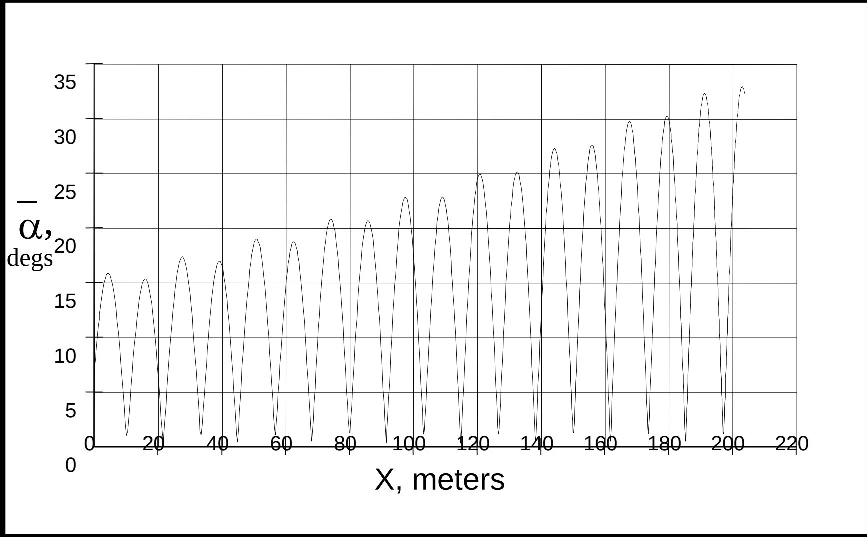
Typical In-flight Shadowgraph

Credit: Cheatwood NASA Langley

Genesis SRC Ballistic Range Testing Observations

- What was observed?

- “No limit cycle below 40 degrees was observed for these conditions”
  - Limit cycle is where the angular oscillation amplitude builds up to a maximum value and then continues to oscillate at that amplitude



Mach 1.9 Average - (M = 2.68 to 1.10)
Credit: Cheatwood NASA Langley

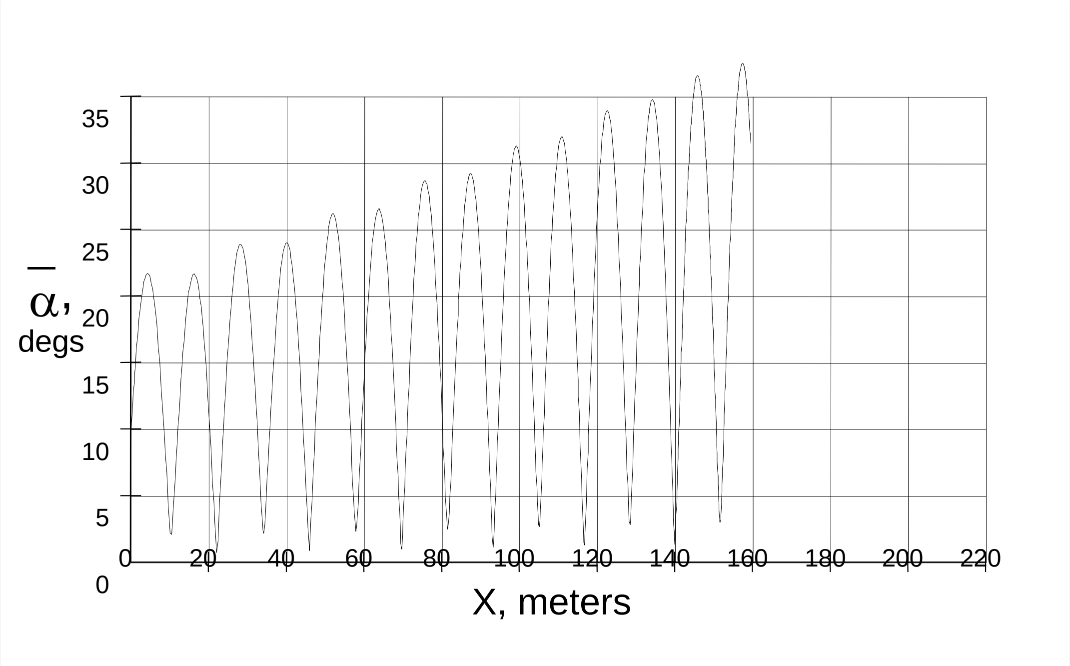
- “The results for this configuration indicate that the models were dynamically unstable at low angles of attack for all Mach numbers tested. At Mach numbers below 2.5, the models were also unstable at the higher angles of attack (above 15 deg), and motion amplitudes of up to 40 deg were experienced. Above Mach 2.5, the models were dynamically stable at the higher angles of attack.”
  - Source: “Dynamic Stability Testing of the Genesis Sample Return Capsule” AIAA 2000-1009, Cheatwood, et al.

How does the Genesis SRC relate to Dragonfly?

- The Dragonfly entry vehicle (EV) uses the same shape as the Genesis SRC and uses the Genesis ballistic range data directly in the aerodynamic database
- The Dragonfly EV spends a large amount of time at the conditions that the Genesis BR data covers, it is very important to ensure that the project is not using overly conservative aerodynamic coefficients that introduced undue dynamics
  - Unstable dynamic behavior has been predicted in the POST2 simulation of the full scale entry vehicle
  - EV AoA grew as the EV approached drogue chute deployment and did not damp easily under drogue chute
  - Large AoA swings can impact the Dragonfly lander and navigated states necessary for lander separation and flight

What is Dragonfly doing with the Genesis BR data?

- The Dragonfly project is attempting to perform an independent reconstruction of the Genesis BR tests using the aerodynamic database to confirm unstable dynamic behavior seen in the POST2 simulation of the full scale entry vehicle



Mach 1.4 Average - (M = 1.88 to 0.99)
Credit: Cheatwood NASA Langley

- EV AoA grew as the EV approached drogue chute deployment and did not damp easily under drogue chute
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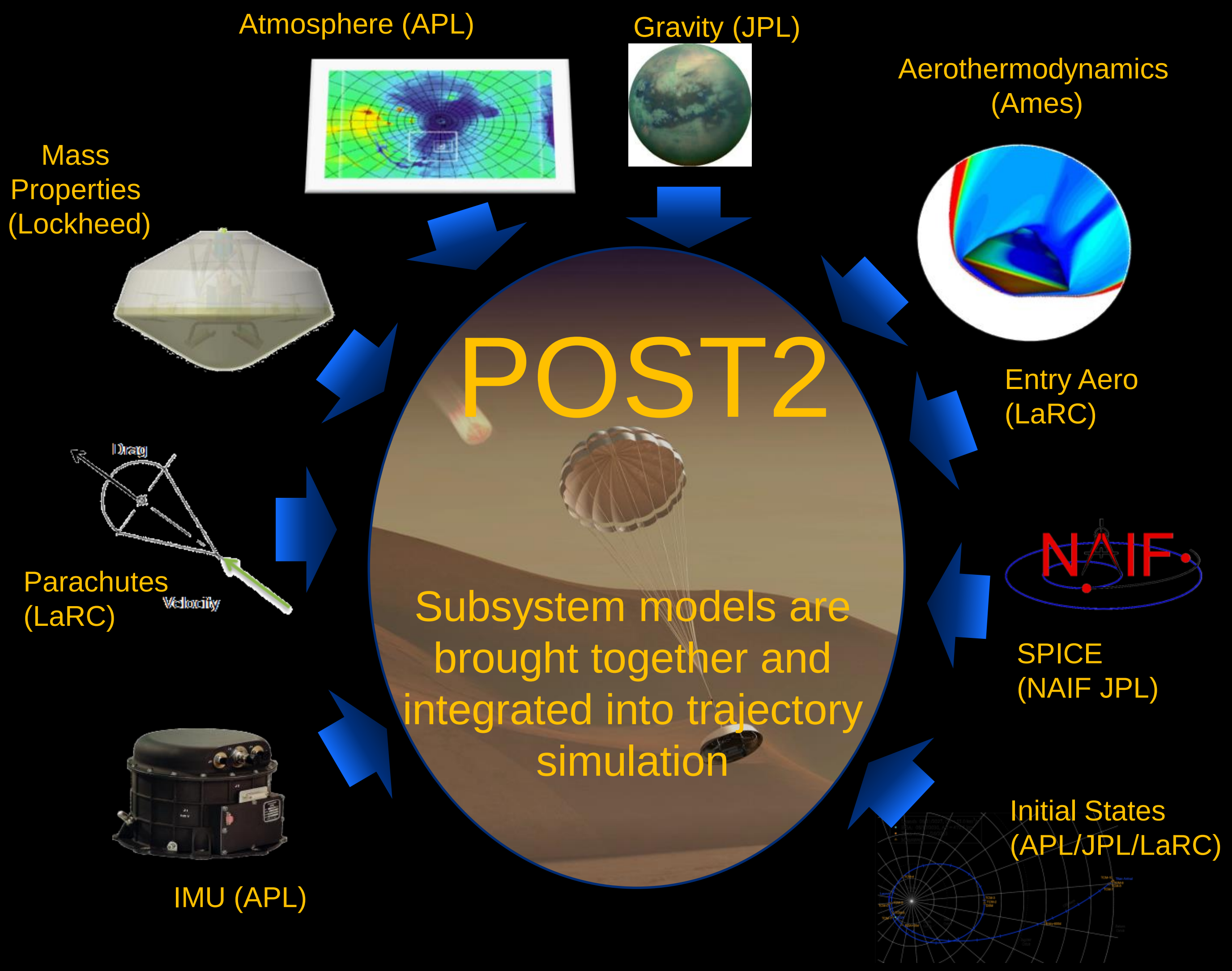
POST2 Entry & Descent Simulation

LaRC – NASA Langley Research Center
APL – Applied Physics Laboratory
JPL – Jet Propulsion Laboratory
Ames – NASA Ames Research Center
Lockheed – Lockheed Martin Space Company



System performance is assessed through augmented cluster computing scripts that enable Monte Carlo and sensitivity analyses

POST2 Input File

Param Input File

Monte Carlo Input Files

POST2 – Program to Optimize Simulated Trajectories II, developed at NASA Langley
“Enabling Thread Safety and Parallelism in the Program to Optimize Simulated Trajectories II” Williams, et al., AIAA SciTech 2023

Reconstruction Process

- External optimizer used to minimize the residuals compared to Genesis (published) SRC BR data
- Investigated multiple parameterizations of BR data and initial conditions
- Investigated multiple residual options (AoA, θ, single shots, multiple shots, etc.)

DAKOTA
Explore and predict with confidence
Optimizer

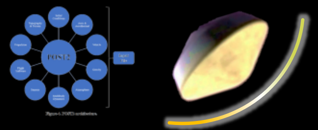
No

Converged ?

Yes

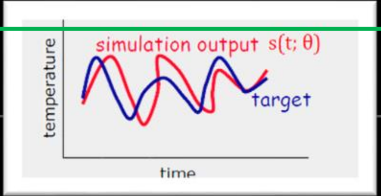
Inputs:
- Initial conditions:
  - Velocity
  - Angle
  - Angular Rates

POST2



$$SSE(\boldsymbol{\theta}) = \sum_{i=1}^{n} [(s_i(\boldsymbol{\theta}) - y_i]^2 = \sum_{i=1}^{n} [r_i(\boldsymbol{\theta})]^2$$

Calculate residuals compared to Genesis SRC Eglin ballistic range data



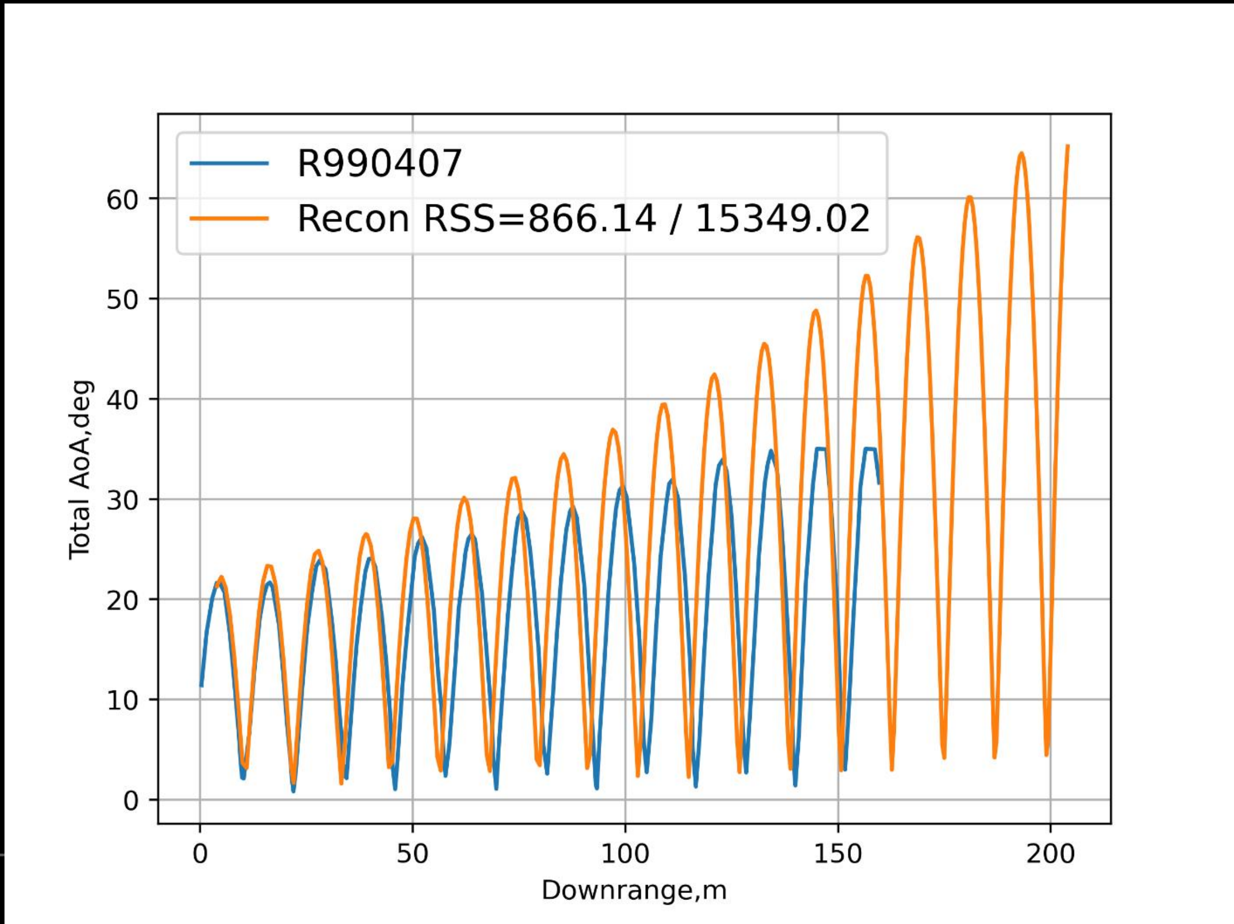
Outputs:
- Residuals

Best matching resulting Cmq and ICs

Shot R990407

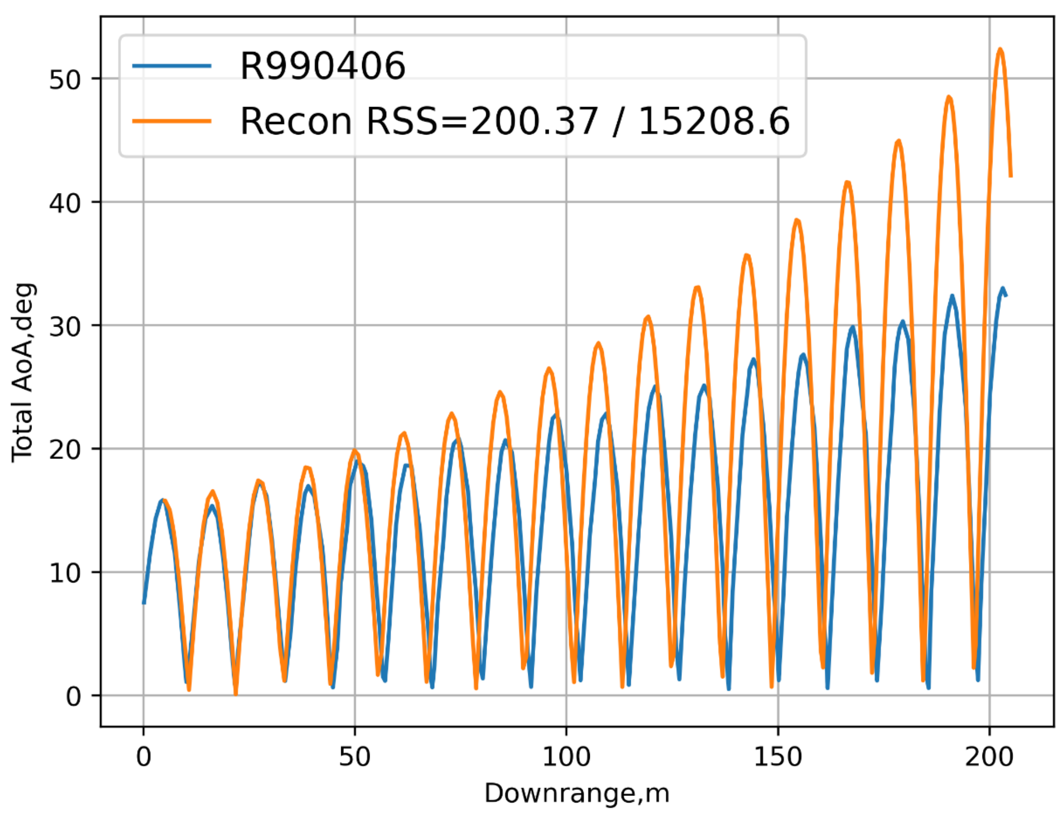
- Representative results using the Genesis aerodatabase and adjusting initial conditions only (show all shots starting at first peak)
  - Blue is the Genesis SRC reconstructed motion
  - Orange is the POST2 simulation result
- Generally, does not match the amplitude growth while matching the initial oscillation

- Average Mach 1.4 (1.88 to 0.99)

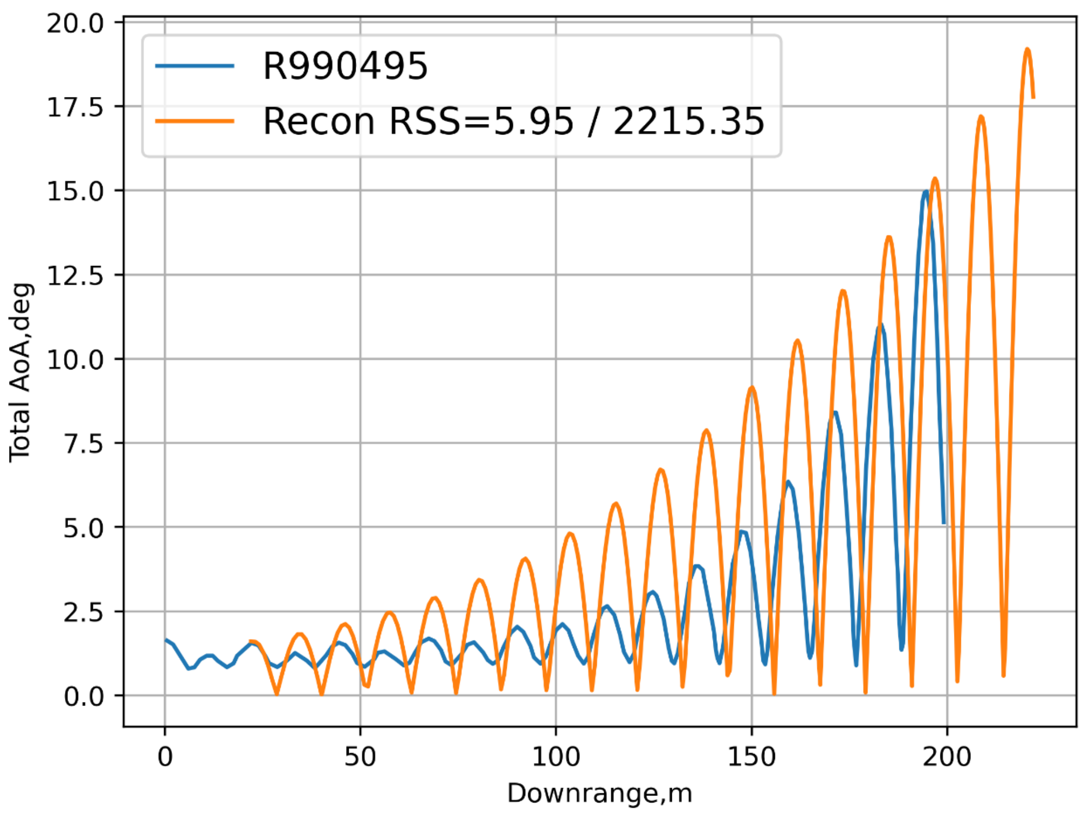


Other BR Shots

- Shot R990406
- Average Mach 1.9 (2.68 to 1.10)

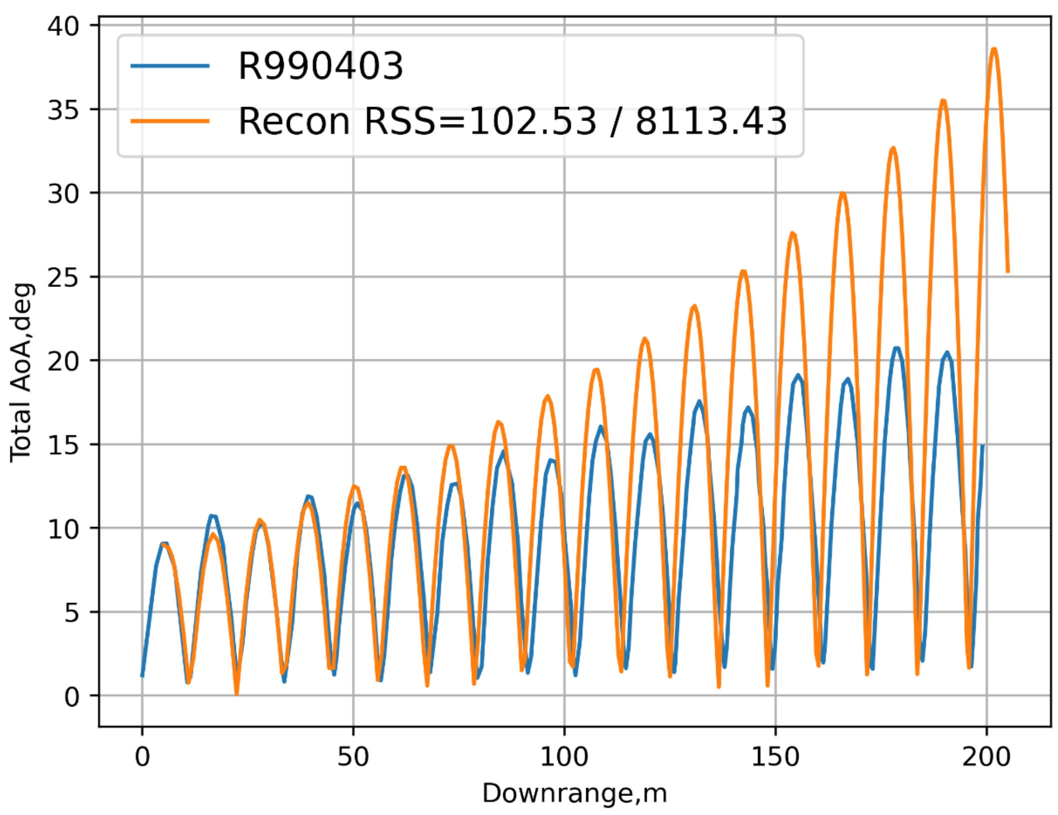


- Shot R990495
- Average Mach 2.6 (3.65 to 1.44)

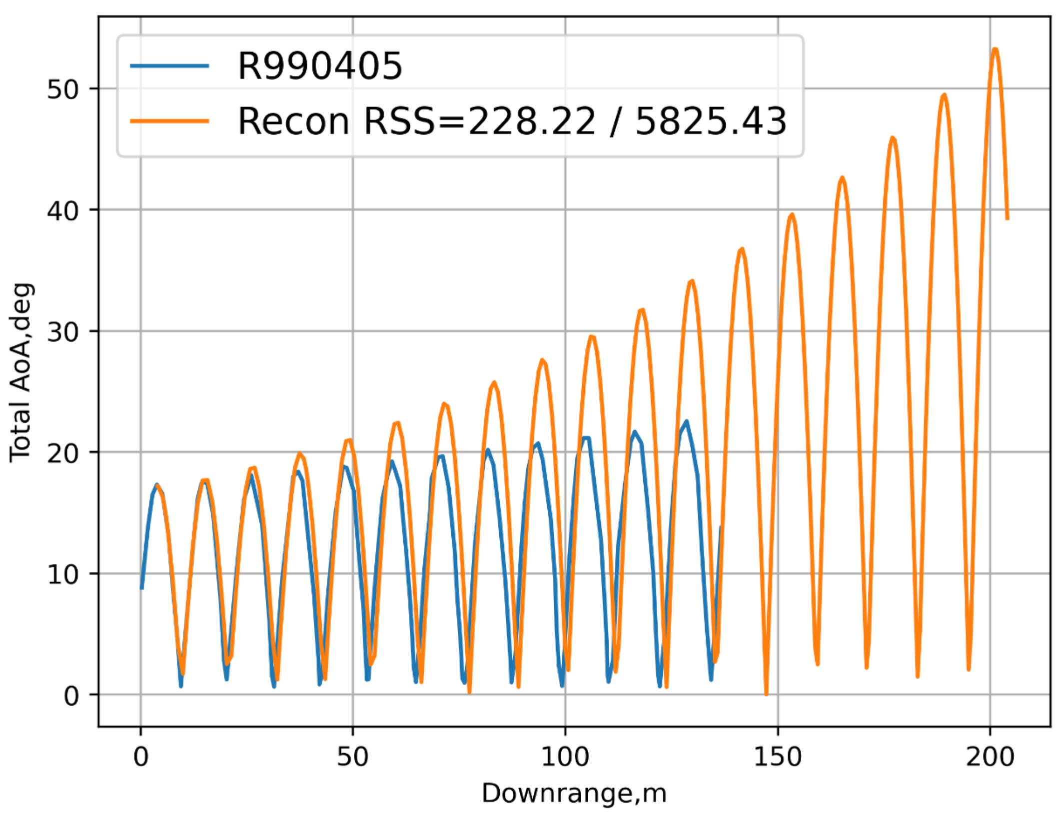


Other BR Shots

- Shot R990403
- Average Mach 2.6 (3.63 to 1.48)



- Shot R990405
- Average Mach 2.9 (3.61 to 2.10)



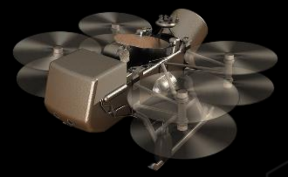
Summary & Future Work

- The Genesis aeroshell shape was known to have instability – Genesis CONOPS used a parachute to eliminate
- Based on POST2 BR simulation results, we believe there is conservatism in the Dragonfly aerodynamic model
  - Genesis also accepted the conservatism
- Multiple design mitigations exist to allow the baseline Dragonfly mission to overcome stability issues observed

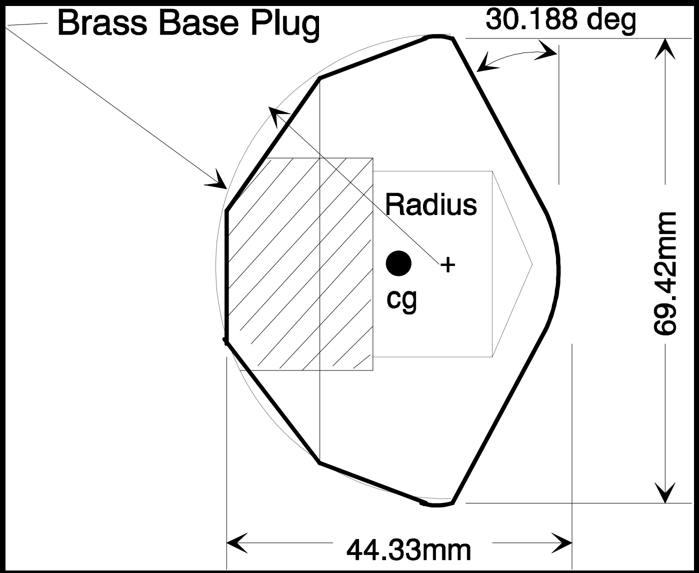
- Future work:
  - Additional ballistic range testing is an option being investigated now
  - Investigation of additional aerodynamic models to better match BR test data
  - Incorporation of unpublished data from the original testing which may have relevance

DRAGONFLY

Genesis Ballistic Range Testing



- 12 ballistic range (BR) shots were performed at Eglin AFB to determine the dynamic stability characteristics of the Genesis entry vehicle
  - Shots varied from Mach 1 to 4.5



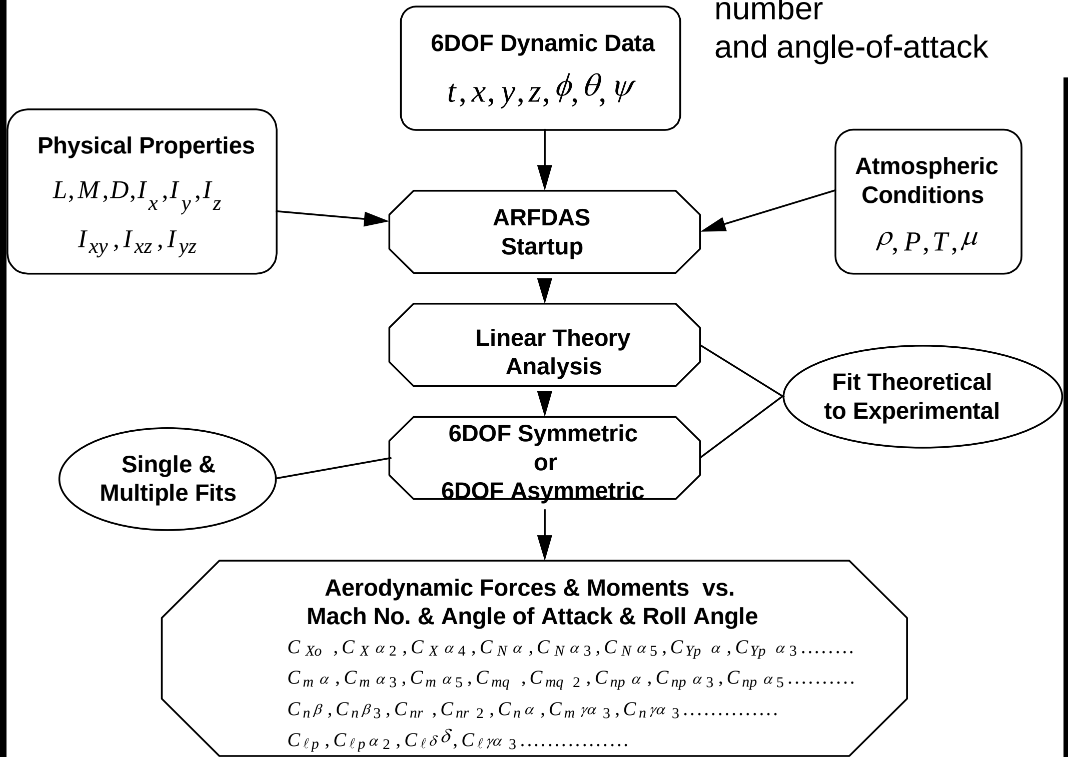
0.047 Scale Model of the Genesis SRC

Shot Number	No. of Stations	Observed Distance [m]	Pressure [mbar]	Temperature [deg C]	Relative Humidity [%]	Density [kg/m3]	Speed of Sound [m/s]
R990407	31	137.2	1019.98	19.79	56	1.213	343.11
R990406	42	181.4	1019.98	19.79	56	1.213	343.11
R990495	45	199.7	1021.68	20.21	55	1.2133	343.36
R990403	37	175.4	1019.98	19.79	56	1.213	343.11
R990496	48	199.7	1022.01	20.21	54	1.2136	343.36
R990405	28	112.8	1019.98	19.79	56	1.213	343.11
R990497	46	199.7	1014.56	19.66	55	1.2071	343.04
R990498	46	199.7	1006.44	19.66	60	1.1974	343.04
R990499	41	198.1	1018.97	19.66	54	1.2123	343.04
R990404	37	180.3	1019.98	19.79	56	1.213	343.11
R990401	27	141.7	1021.34	19.72	56	1.2149	343.08
R990402	26	111.3	1019.98	19.79	56	1.213	343.11

ARFDAS

- ARFDAS uses a 6DOF dynamics simulation to fit against measurements derived from the free flight images

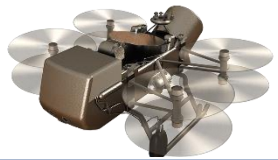
Note:
Mathematical expansion
for Cmq was modified
to account for the complex
variation with Mach
number
and angle-of-attack



Aeroballistic Research Facility Data Analysis

Aerodynamic Configurations

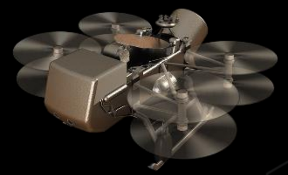
* EI = entry interface
* Scales and times are approximate



Capsule	Capsule on Drogue	Capsule on Main	Heatshield Separation	Stowed Lander in Backshell	Posed Lander in Backshell
Entry to Mach 1.5	Mach 1.5 to 7 m/s	Mach < 0.04	3.6 km		2.7 m/s
EI – 10 min to EI + 6 min	90 min	2 min	Main + 2 min	12 min	11 min

- Entry Vehicle:
  - Current Best Estimate (CBE) Mass: 2255 kg
  - Maximum Possible Value (MPV) Mass: 2500 kg
  - Diameter: 4.5 m
  - Sphere Cone Angle: 60°
  - Based on Genesis Sample Return Capsule
  - Aerodatabase uses computational fluid dynamics (CFD), the Langley 12' low speed wind tunnel, and the Langley Transonic Dynamic Tunnel (TDT).
- Drogue Parachute
  - 6 m Disk Gap Band (DGB)
  - Deployed via mortar fire using a smart trigger to minimize the total angle off attack
- Main Parachute
  - 16.55 m Ringslot
  - Deployed using Drogue parachute at a specified altitude

How does the Genesis SRC relate to Dragonfly?



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- The Dragonfly EV spends a large amount of time at the conditions that the Genesis BR data covers, it became very important to ensure that the project was not using overly conservative aerodynamic coefficients that introduced dynamics
  - Dynamic behavior has been predicted in the POST2 simulation of the full scale entry vehicle
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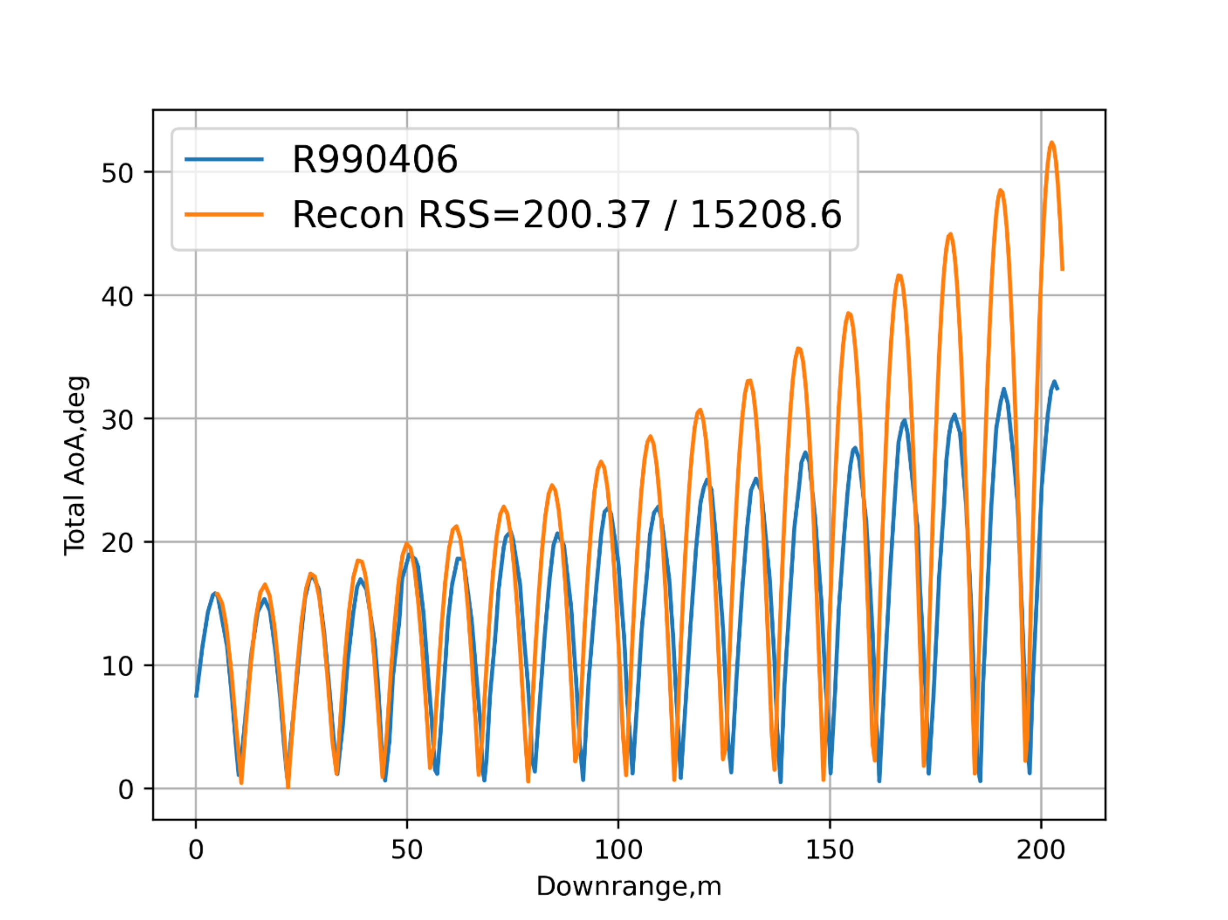
  - Large AoA swings can impact the Dragonfly lander and navigated states necessary for lander separation and flight

Shot R990406

- Representative results using the Genesis aerodatabase and adjusting initial conditions only (show all shots starting at first peak)

- Generally, does not match the initial oscillations while matching the amplitude growth

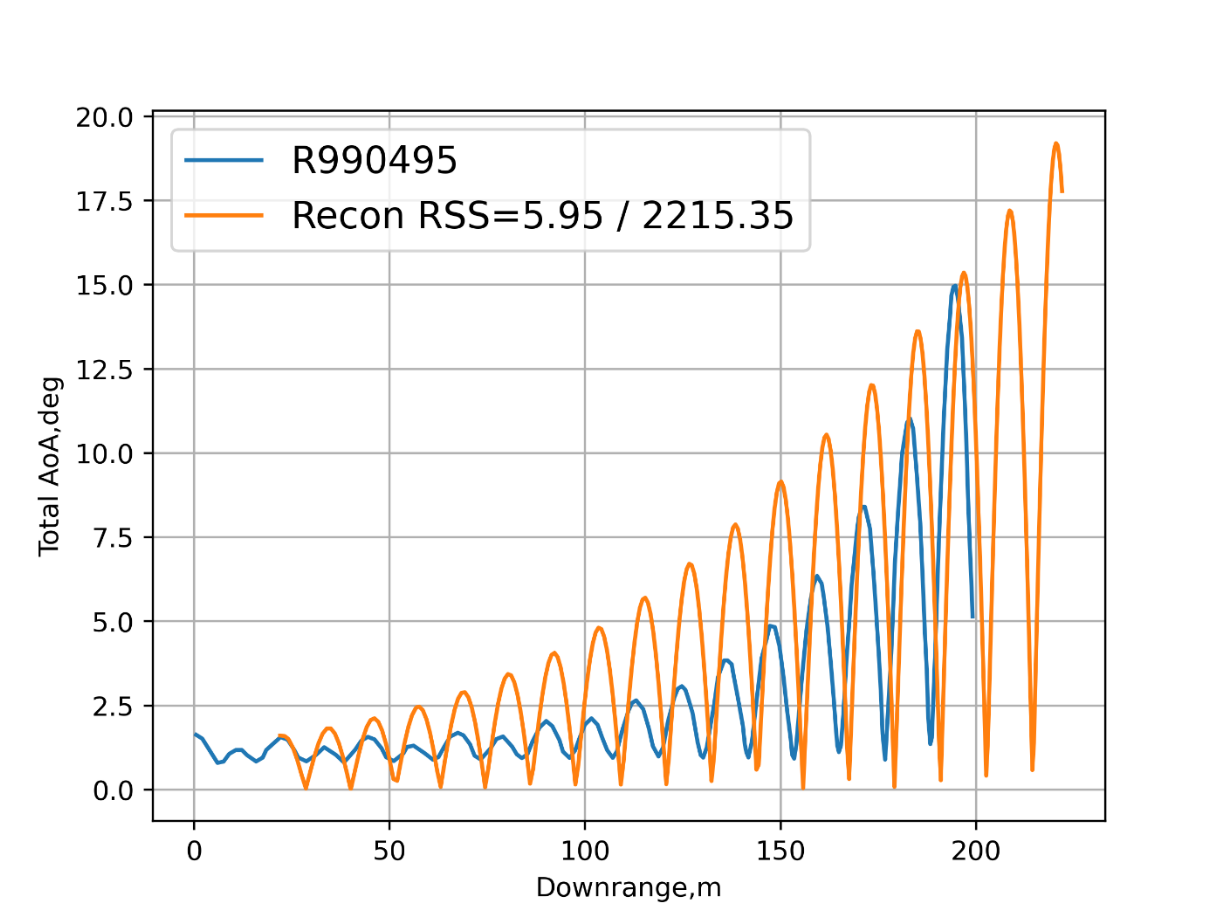


Shot R990495

- Representative results using the Genesis aerodatabase and adjusting initial conditions only (show all shots starting at first peak)

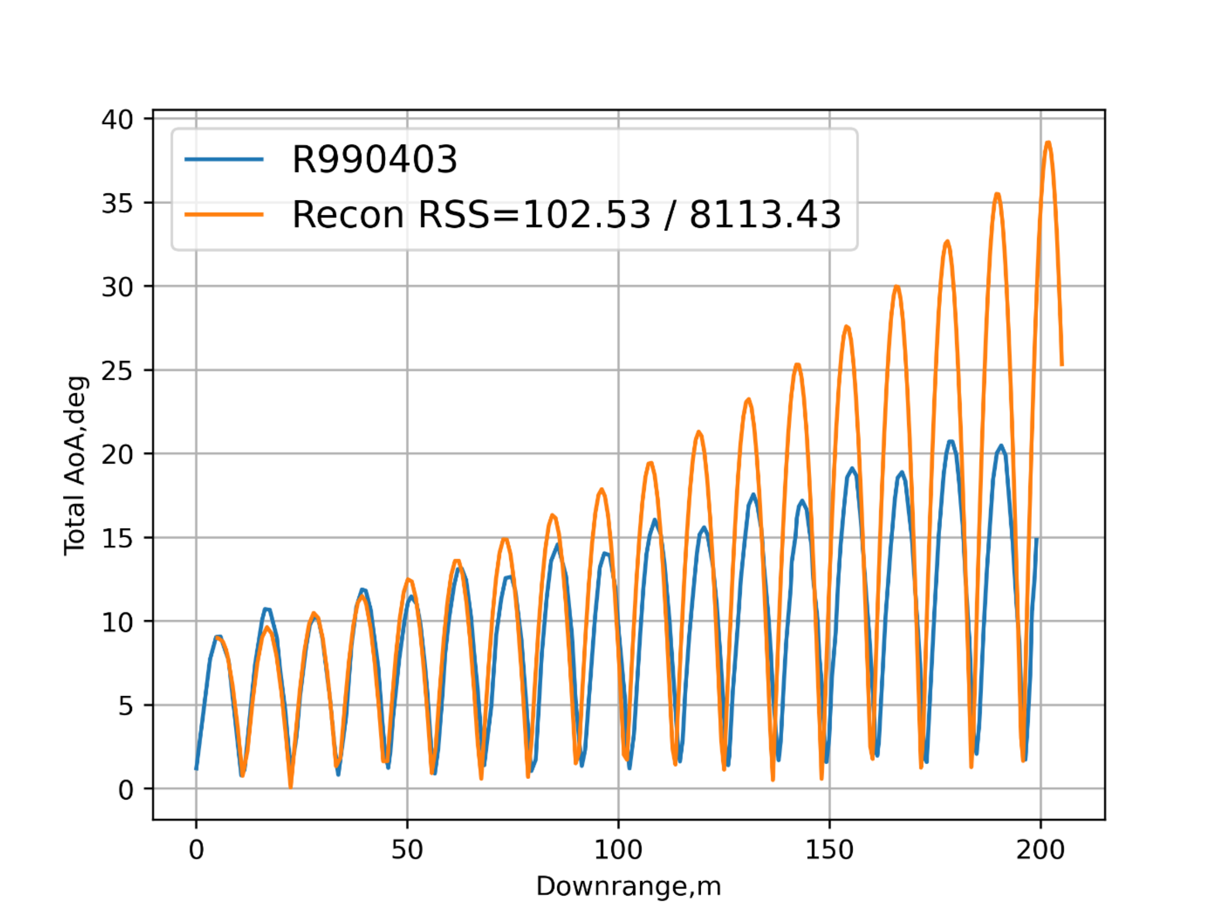
- Generally, does not match the initial oscillations while matching the amplitude growth

- This particular case also missed the total AoA minimums at the oscillations



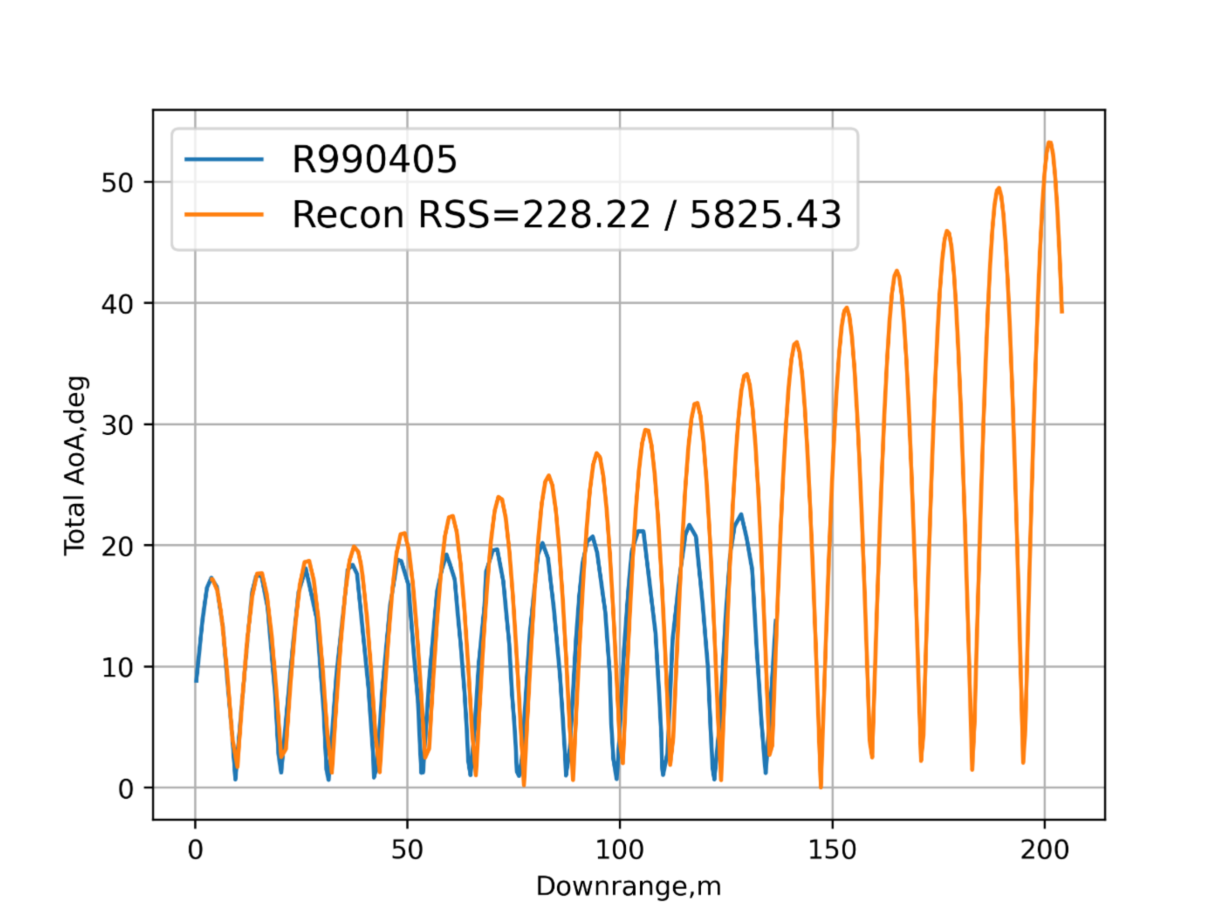
Shot R990403

- Representative results using the Genesis aerodatabase and adjusting initial conditions only (show all shots starting at first peak)
- Generally, does not match the initial oscillations while matching the amplitude growth



Shot R990405

- Representative results using the Genesis aerodatabase and adjusting initial conditions only (show all shots starting at first peak)
- Generally, does not match the initial oscillations while matching the amplitude growth



Shot R990404

- Representative results using the Genesis aerodatabase and adjusting initial conditions only (show all shots starting at first peak)
- Generally, does not match the initial oscillations while matching the amplitude growth
- Average Mach 3.1 (4.46 to 1.77)