Trajectory Engineering with Modular Patched Conics for Entry Systems and TPS (TEMPEST)

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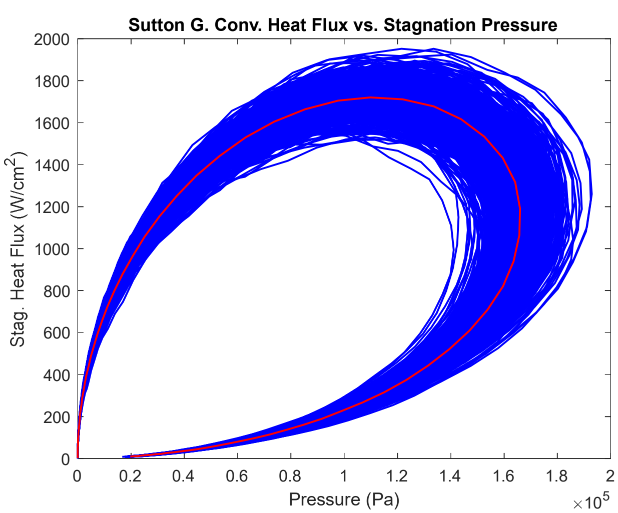
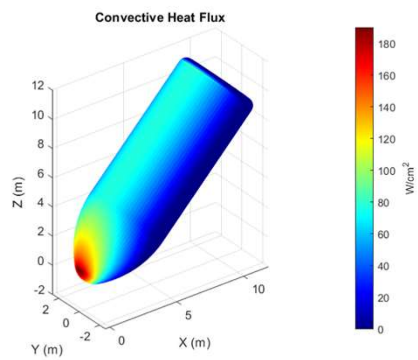
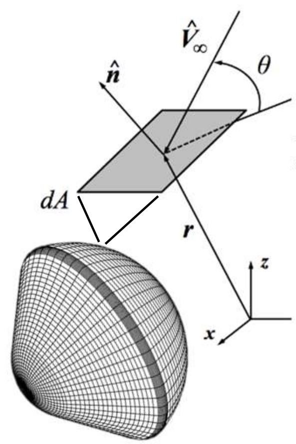
23rd International Planetary Probe Workshop

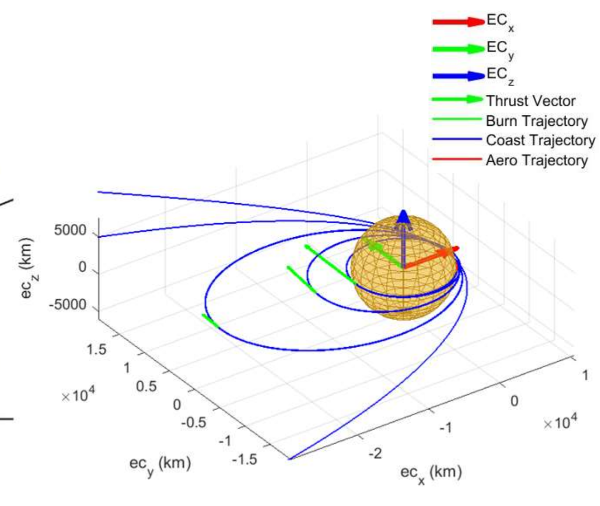
What is TEMPEST?

- TEMPEST is a newly developed trajectory analysis code that is designed from the ground up with aerothermodynamics and TPS (thermal protection systems) design in mind
- TEMPEST is also designed for complex atmospheric entry scenarios such as multi-pass aerocapture or aero-gravity assists
- Project was started as part of my M.S. in Aerospace Engineering



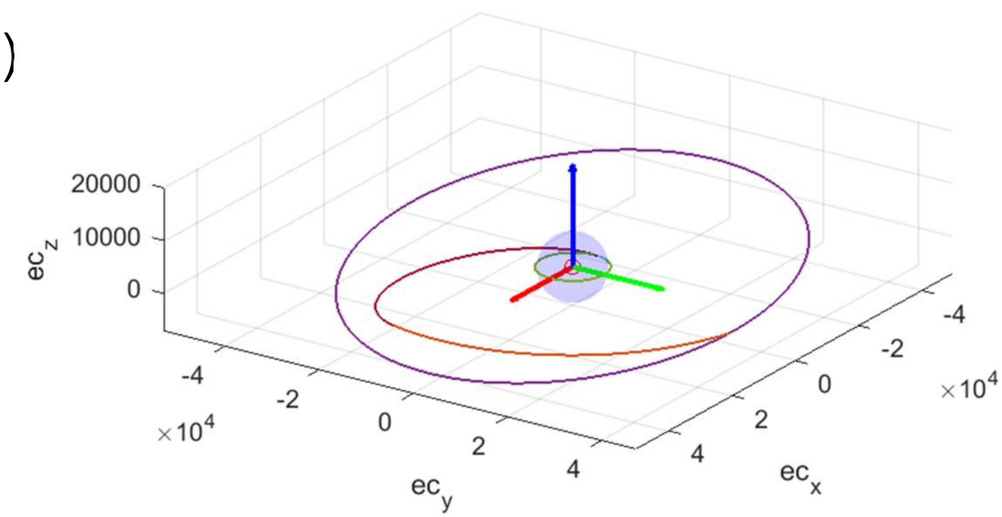






TEMPEST Core Capabilities

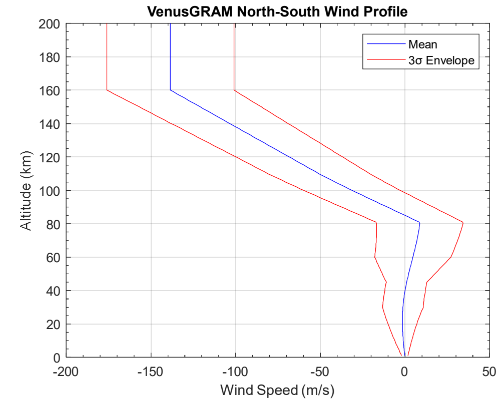
- TEMPEST at its core propagates 3DoF or 6DoF trajectories around a single planetary body
- The primary EOMs (equations of motion) are expressed in modern cartesian coordinates rather than the classic Vinh model, with quaternions for rotations
- Coast, atmospheric flight, or propulsive trajectory segments can be stitched together and optimized as a whole
- Most of the program is implemented in MATLAB using system objects
  - There are several C++ shared libraries for supporting tools like the Global Reference Atmospheric Model (GRAM), and Mutation++

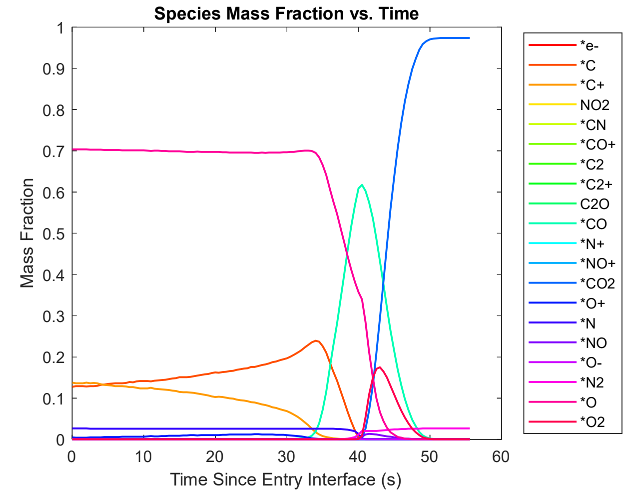


GTO Trajectory and Plane Change Optimization

Atmosphere and Thermodynamics

- TEMPEST utilizes a native GRAM API to seamlessly share atmospheric data live while a trajectory is computed
- All supported GRAM atmospheric properties are used, from composition data for dynamic chemistry modeling to particle number density for rarefied flow aerodynamics
- TEMPEST contains several options for real-gas thermodynamics including CEA, Mutation++, and symbolic math methods
  - Comparison work is on-going, but preliminary results show that all methods provide consistent predictions for most equilibrium conditions
  - Some differences between CEA and mutation++ seen at low temperature edge cases with condensed species
- Lookup tables and external atmospheres like US1976 are also supported

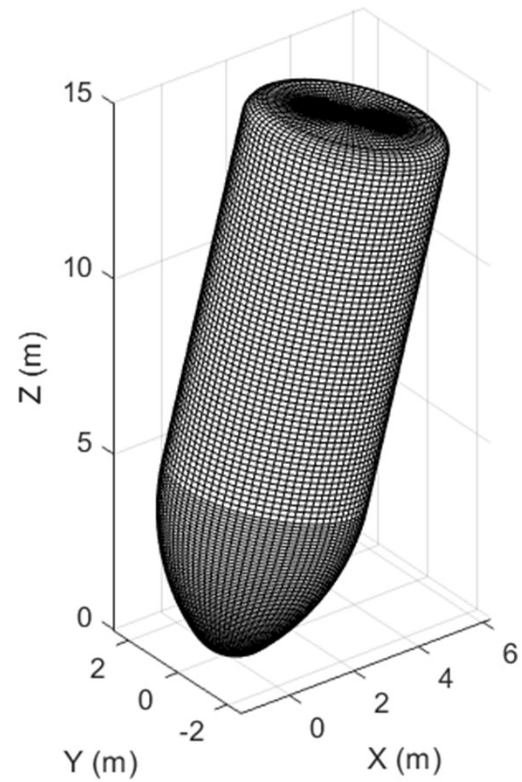




Stagnation streamline shock layer composition along a Venus entry trajectory

Aerodynamics

- TEMPEST contains aerodynamic models for continuum, transitional, and free molecular flight regimes
  - Continuum - MNA (Modified Newtonian Aerodynamics)
  - Free Molecular (FM) - Maxwellian particle collision model [1]
  - Transitional - Sine-squared bridging function
- MNA is widely used for engineering level hypersonic aerodynamics and is utilized by NASA tools such as CBAERO [2]
- Currently, TEMPEST can generate arbitrary axisymmetric bodies on a structured grid
- External aerodynamic databases can also be used to propagate a trajectory



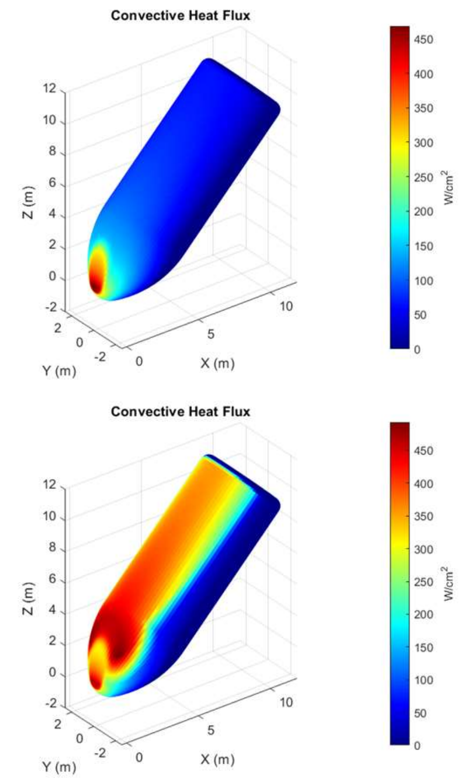
Structured grid for MNA and distributed heating solution

[1] K. A. Hart, S. Dutta, K. Simonis, B. A. Steinfeldt and R. D. Braun. (2014) Analytically derived Aerodynamic Force and Moment Coefficients of Resident Space Objects in Free-Molecular Flow.

[2] D. Kinney. (2004-31) Aero-Thermodynamics for Conceptual Design, 42nd AIAA Aerospace Sciences Meeting and Exhibit.

Aeroheating

- TEMPEST contains a variety of CFD derived correlations for stagnation point convective and radiative heating
  - Includes both legacy correlations (e.g., Sutton-Tauber) and modern ones (e.g., Brandis-West [3])
  - These are used in conjunction with a Rankine-Hugoniot normal shock solution to anchor the thermodynamic state and energy balance at the wall.
- A boundary layer correction model has been implemented for off-stagnation point heating
  - Eckert's reference enthalpy method
- TEMPEST can export a film coefficient and other data necessary for material response tools such as the Fully Implicit Ablation and Thermal Analysis program (FIAT)

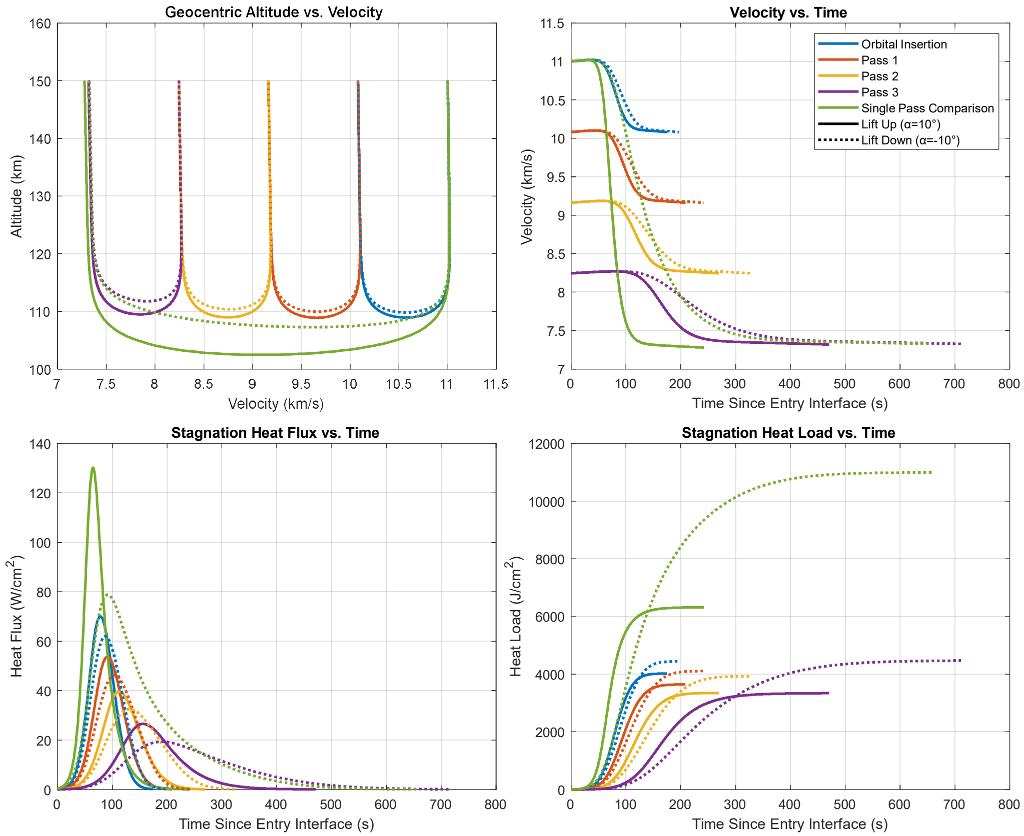


Laminar (top) and turbulent (bottom) solutions for a mid-L/D entry vehicle. Lunar return, α=45°, 8.9 km/s

[3] Aaron M. Brandis and Christopher O. Johnston. "Characterization of Stagnation-Point Heat Flux for Earth Entry," AIAA 2014-2374. 45th AIAA Plasmadynamics and Lasers Conference. June 2014, Atlanta, Georgia, USA. https://doi.org/10.2514/6.2014-2374

Applications

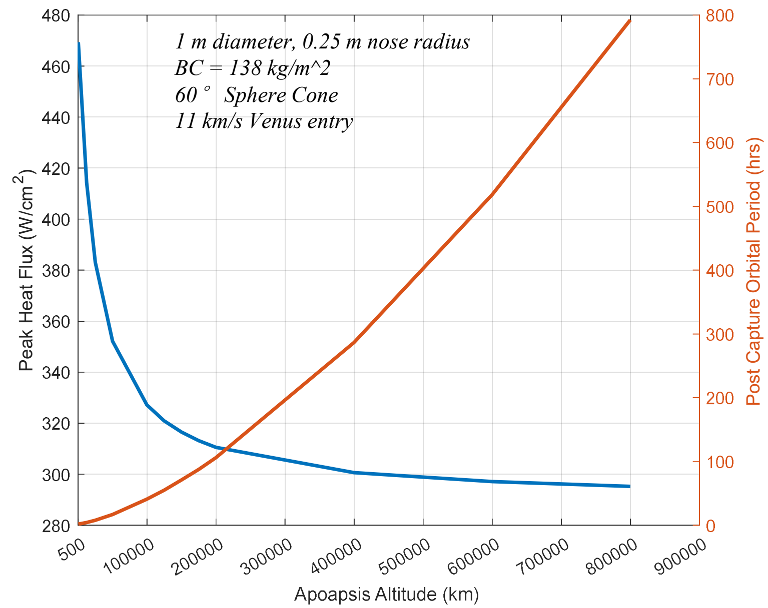
- TEMPEST has been used at a conceptual level to study traditional and multi-pass aerocapture mission scenarios
  - A multi-pass approach can offer reduced aerothermal environments and GN&C demands for certain destinations such as low Venusian orbits
- Large portions of aerocapture/aero assist trajectories are in the rarefied flow regime with high atmospheric uncertainty
- TEMPEST with its aerothermal modeling flexibility is uniquely suited to study these types of missions



Multi-pass aerocapture scenario for a deployable entry vehicle at Venus

Future Work

- Currently in development is a convex optimization scheme that can linearize a trajectory and generate a guided solution to a landing location or exit orbit with cost functions for heating or maximum g-loading [4]
- Another modeling area in development is coupling of TPS ablation and mass loss to the trajectory propagation
  - Shape change, mass loss, and inertial properties would be updated live
  - This capability could support Galileo-like missions with a high TPS mass fraction or even meteoroid ablation and entry predictions
  - Some level of CFD anchoring and validation of the distributed heating model would be necessary



Tradeoffs for aerocapture initial orbital insertion

[4] K. Tracy and Z. Manchester, "CPEG: A Convex Predictor-corrector Entry Guidance Algorithm," 2022 IEEE Aerospace Conference (AERO), Big Sky, MT, USA, 2022, pp. 1-10, doi: 10.1109/AERO53065.2022.9843641.

Acknowledgements

- Paul Wercinski, NASA mentor, NASA ARC, Entry Vehicles and Systems Branch
  - For countless guidance and technical assistance throughout this project.
- Periklis Papadopoulos, Masters Degree Advisor
  - For valuable advice and feedback for this project and throughout my M.S. degree.
- David Hash, Mairead Stackpoole, Ethiraj Venkatapathy, Todd White, Joshua Monk, NASA ARC, Entry Systems Division
  - For valuable feedback and technical insight at various stages of the project.

Questions?

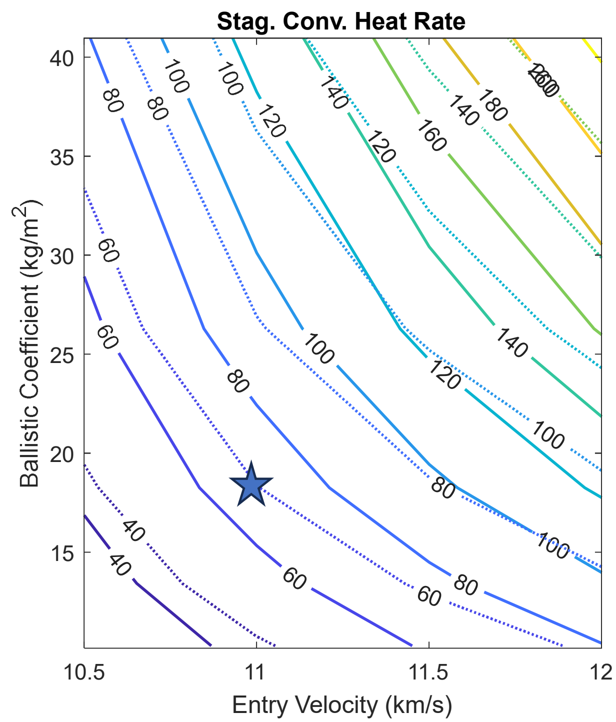
Backup

Current Status of Project

- Current capabilities
  - 3DoF and 6DoF trajectory propagation with events and multiple physics options
  - Continuum, free molecular, and transitional aerodynamics for axisymmetric bodies
  - Mission planning and optimization routines for ballistic entry, traditional, and multi-pass aerocapture
  - GRAM atmosphere model
  - CEA or Mutation++ equilibrium models, direct coupling with GRAM, lookup table generation.
  - Various heritage and modern engineering level heating correlations, FR, Tauber, Sutton, Brandis, etc.
  - Uncertainty analysis through GRAM atmospheric perturbations
  - Rudimentary CBAERO-like distributed heating model
- Development level
  - N-body mechanics
  - SPICE for planetary ephemeris, reference frames, and other computations
  - C++ conversion

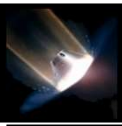
Multi-Pass Aerocapture at Venus

- One of the drawbacks of a multi-pass approach is increased mission duration.
  - Orbital period varies non-linearly with apoapsis altitude.
- Shaving off less ΔV will produce a milder aerothermal environment but also a higher apoapsis and longer orbital period.
  - A "sweet spot" can be found through optimization which for Venus is an apoapsis of ~150000-250000 km.
- Using this data, a conceptual design space can be generated for a low ballistic coefficient aerocapture vehicle at Venus targeting a 500 km science orbit.



- ***Initial orbit apoapsis is 200000 km***
- *Vehicle diameter varied from 2-4 m*
- *Nose radius is ¼ the vehicle diameter*
- *70 ° Sphere Cone*
- *α=10 ° /-10 °*
- *0 ° Lat, 170 ° Long, 150 km*
- *Heating can vary by ~5-7% depending on entry long/lat and JD*
- *Low B_C range chosen to allow for deployable TPS options*

Primary Venus Validation Reference:
Lugo, R. A., Dutta, S., Matz, D., Johnson, B. J., Pensado, A. R., Roelke, E., Aguirre, J. T., and Powell, R., "Performance Analysis of SMALLSAT Aerocapture at Venus," AIAA SCITECH 2023 Forum, Jan. 23–27, 2023, National Harbor, MD. https://doi.org/10.2514/6.2023-0878



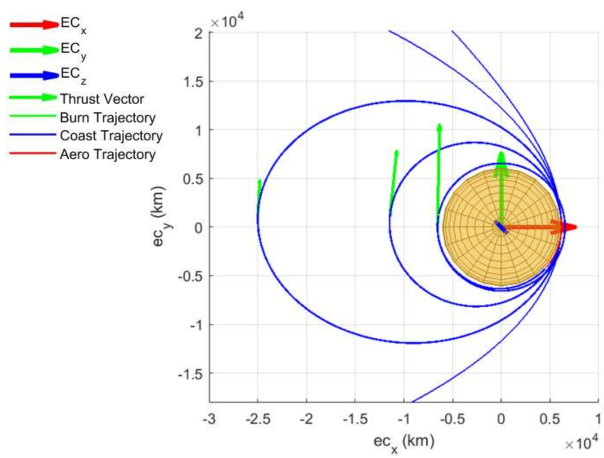
Venus Multi-Pass Additional Results

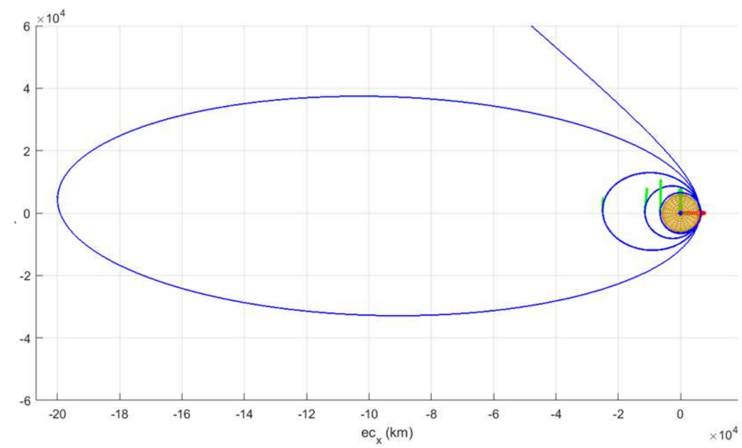
Maneuvers Summary		
Maneuver	**Duration (s)**	**ΔV (m/s)**
Lift Up		
Interplanetary TCM	10.49	0.525
1st Periapsis Adjust	0.128	0.006
2nd Periapsis Adjust	2.000	0.100
3rd Periapsis Adjust	10.15	0.507
Final Periapsis Raise	190.0	116.3
Lift Down		
Interplanetary TCM	12.17	0.610
1st Periapsis Adjust	0.194	0.010
2nd Periapsis Adjust	2.141	0.110
3rd Periapsis Adjust	8.137	0.407
Final Periapsis Raise	177.1	108.2
Totals	**Lift Up**	**Lift Down**
Mission Duration (days)	5.461	5.468
Maneuvers ΔV (m/s)	117.4	109.4
Propellant Usage (kg)	7.832	7.304

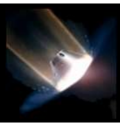
Spacecraft Input Parameters	
Parameter	**Value**
Initial Mass	200 kg
High Thrust System	120 N
Low Thrust System	10 N
ISP (both systems)	300 s
Trim Angle of Attack (α)	10°/-10°
C_D at α=10°/-10°	1.550
C_L at α=10°/-10°	±0.237
Diameter	3 m
Nose Radius	0.75 m
Sphere Cone Angle	70°
B_C at α=0°	17.55 kg/m^2
B_C at α=10°/-10°	18.26 kg/m^2
Final Target Altitude	500 km

Interplanetary Orbital Elements	
Parameter	**Value**
Eccentricity (e)	1.3074
Semi Major Axis (a)	-2.0005e4 km
Inclination (i)	0°
Argument of Periapsis (ω)	0°
Long. of Ascending Node (Ω)	0°
True Anomaly (Θ)	137°
Hyperbolic Excess Velocity	4.0298 km/s
Julian Date	2455504
Initial Target Apoapsis (km)	200000

Aero-Pass Summary			
Pass	q_{max} **(W/cm^2)**	J_s **(J/cm^2)**	**ΔV (km/s)**
Lift Up			
Insertion	70.05	4022	0.916
1st Pass	53.74	3645	0.914
2nd Pass	39.55	3350	0.912
3rd Pass	26.58	3340	0.892
Lift Down			
Insertion	61.66	4416	0.916
1st Pass	46.05	4085	0.915
2nd Pass	32.30	3903	0.914
3rd Pass	19.22	4445	0.912

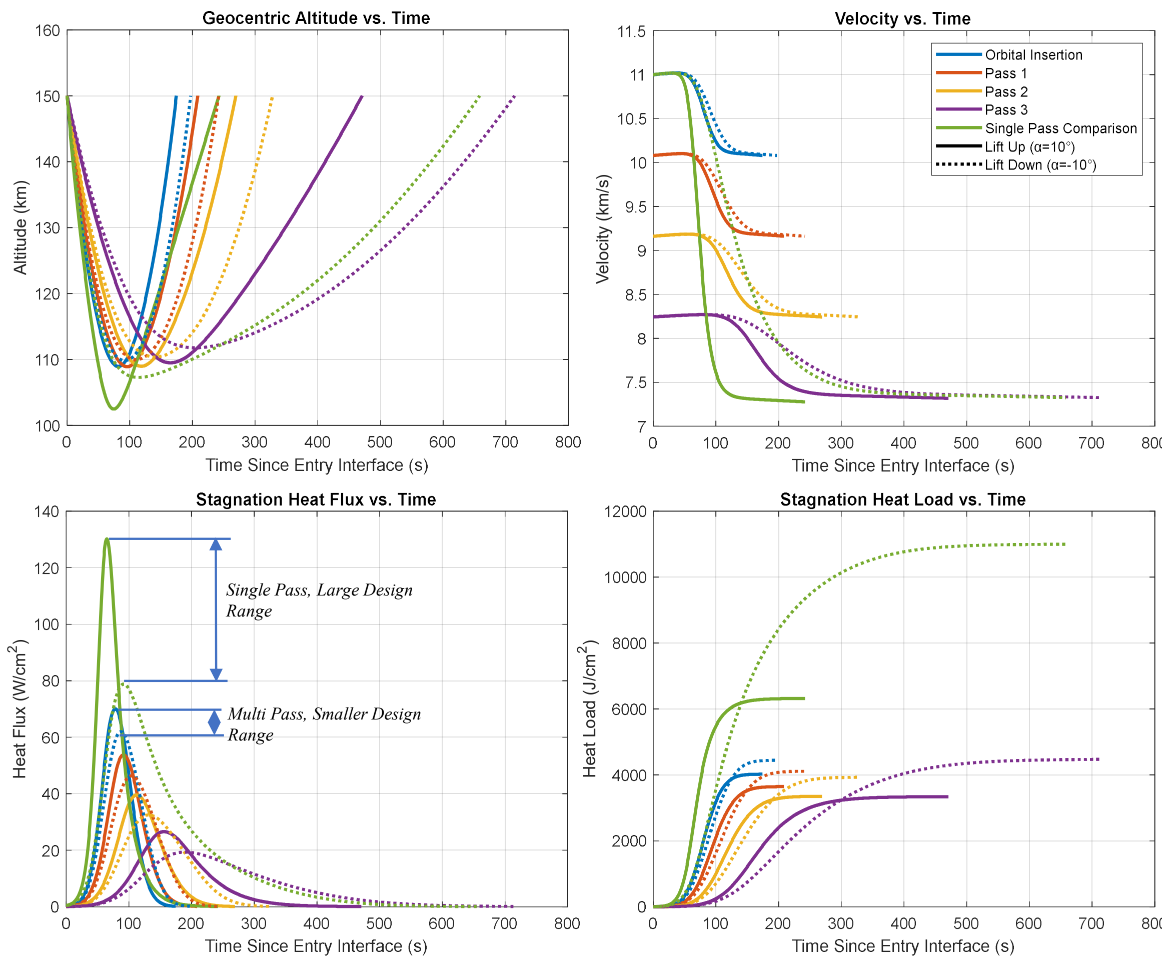




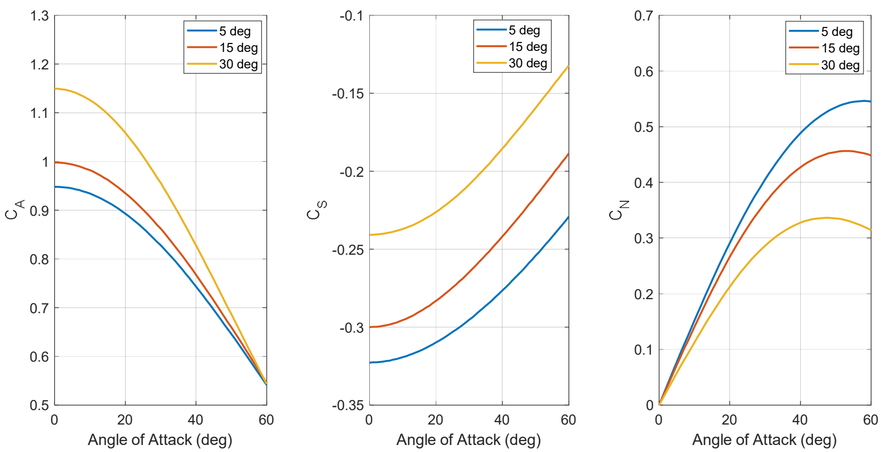


Multi-Pass Aerocapture at Venus

- An adaptive mission planning module was developed for the trajectory program that determines the optimal number of atmospheric passes to reach the final target orbit.
  - The program balances the ΔV of each pass with the bounding initial orbital insertion
  - Periapsis correction maneuvers are optimized and executed after each pass
  - A final periapsis raise maneuver is executed after the final target apoapsis is achieved.



Validations of MNA Panel Method



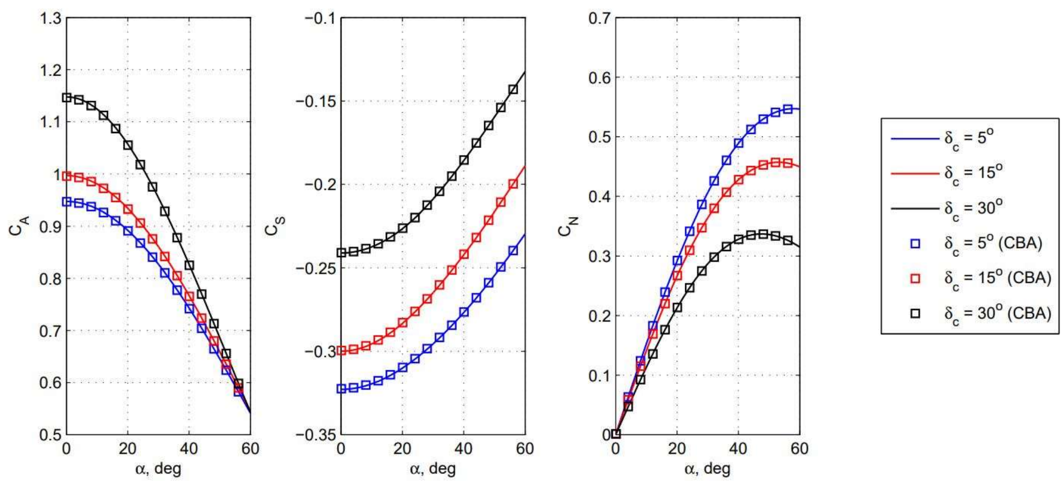


Figure 10. Spherical Segment Force Coefficient Validation, $\beta = 20^o$.

Grant, M., and Braun, R., "Analytic hypersonic aerodynamics for conceptual design of entry vehicles," 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, Jan. 4-7, 2010, Orlando, FL. https://doi.org/10.2514/6.2010-1212

Validations of Free Molecular Panel Method

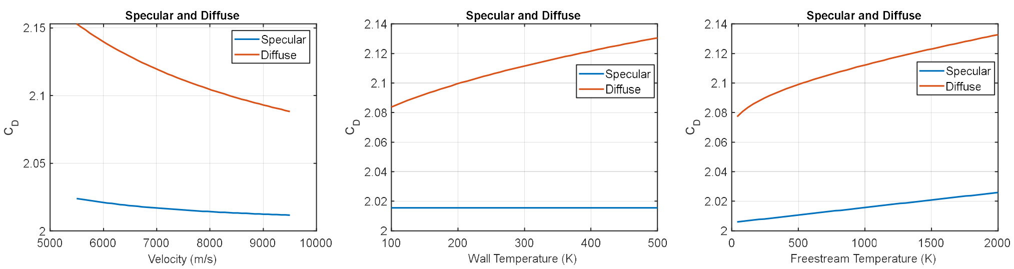


Figure 9.11 Sphere Drag Coefficient Validation Results

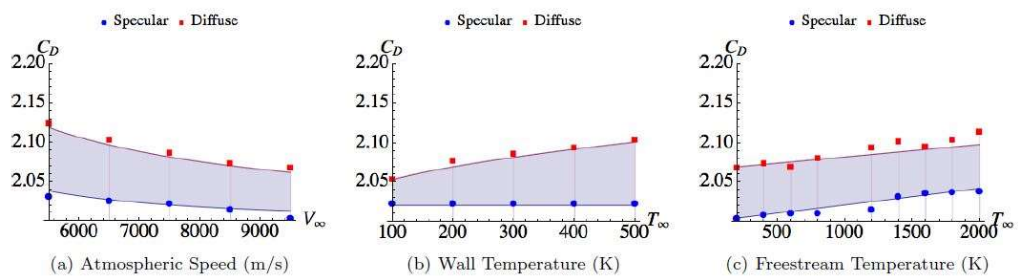
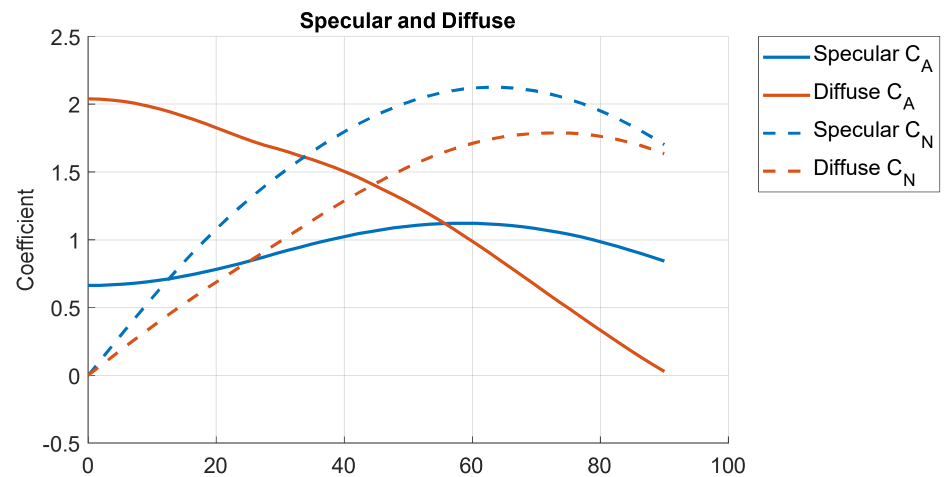


Figure 9.10 Sphere Drag Coefficient Results from [32]

- Kenneth A. Hart, Kyle R. Simonis, Bradley A. Steinfeldt, and Robert D. Braun. “Analytic Free-Molecular Aerodynamics for Rapid Propagation of Resident Space Objects,” Journal of Spacecraft and Rockets 2018 55:1, 27-36 https://doi.org/10.2514/1.A33606
- Kenneth A. Hart, Soumyo Dutta, Kyle Simonis, Bradley A. Steinfeldt and Robert D. Braun. "Analytically-derived Aerodynamic Force and Moment Coefficients of Resident Space Objects in Free-Molecular Flow," AIAA 2014-0728. AIAA Atmospheric Flight Mechanics Conference, January 13-17, National Harbor, Maryland, USA 2014. https://doi.org/10.2514/6.2014-0728



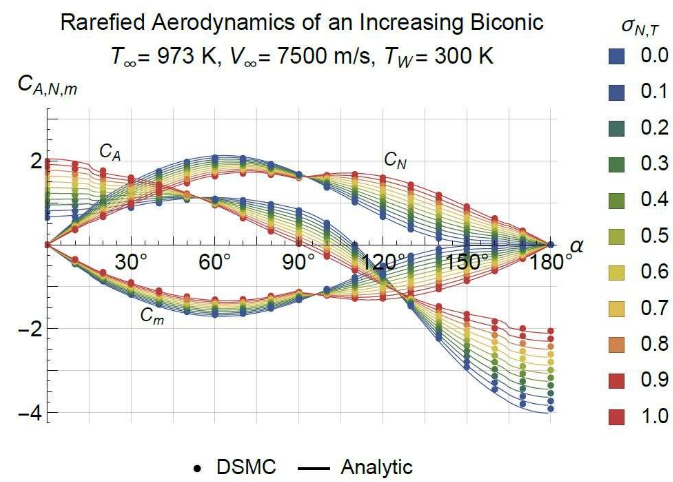
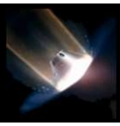
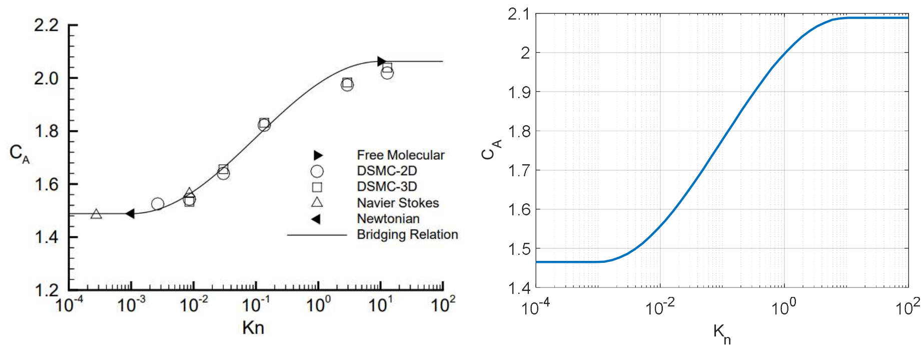


Figure 9.14 Increasing Bi-conic Results from [33]

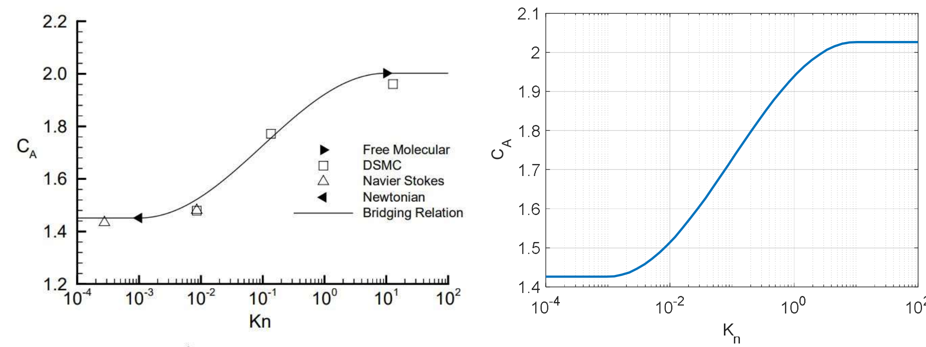


Validations of Free Molecular Panel Method

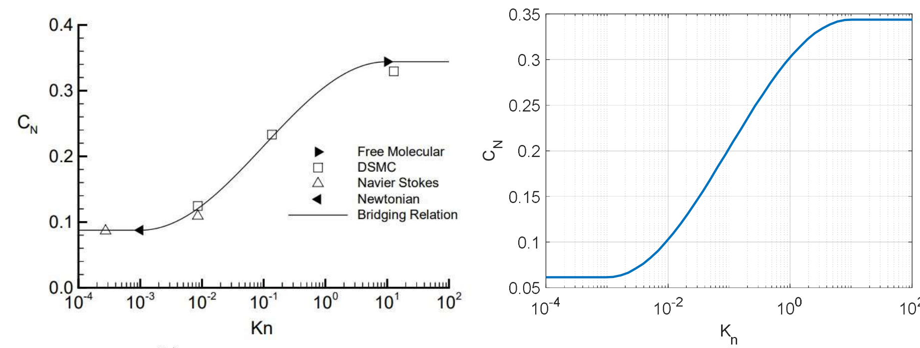


[Figure](#) 9.20 Validation with [36] at α=0°

- Richard G. Wilmoth, Robert A. Mitcheltree, and James N. Moss, “Low-Density Aerodynamics of the Stardust Sample Return Capsule, ” Journal of Spacecraft and Rockets 1999 36:3, 436-44. https://doi.org/10.2514/2.3464



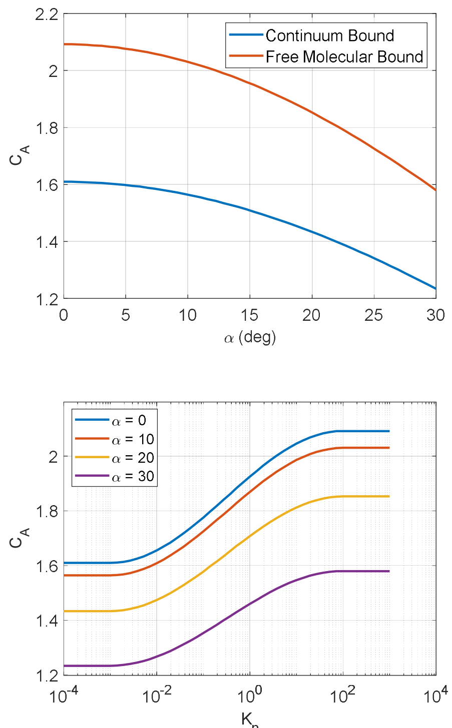
a) Axial force, C_A.

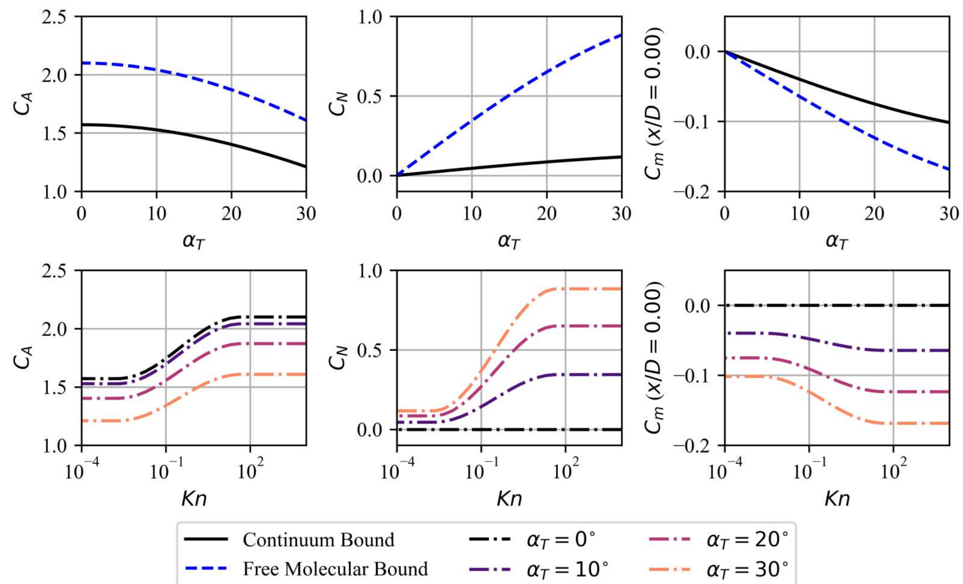


b) Normal force, C_N.

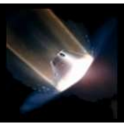
[Figure](#) 9.19 Validation with [36] at α=10°

Validations of Free Molecular Panel Method

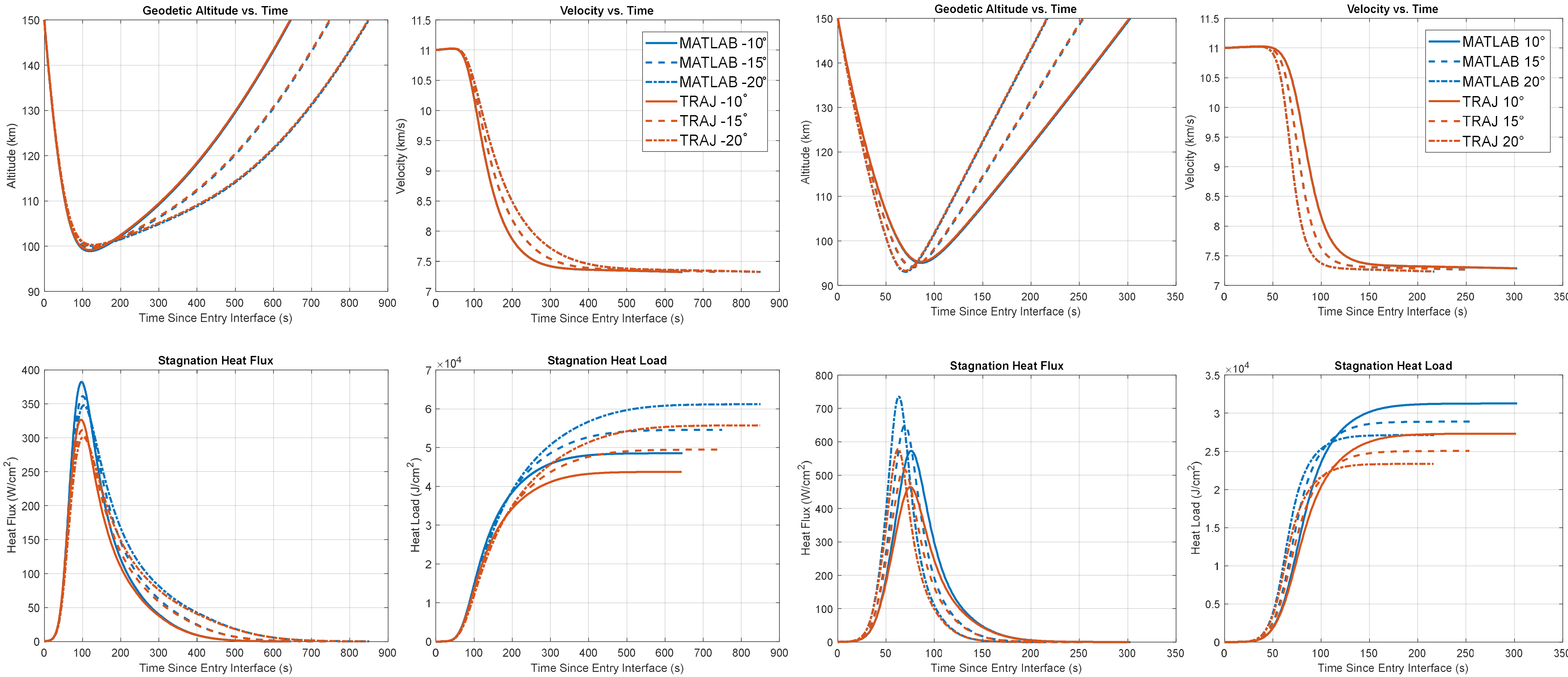




- Shellabarger, E., Scoggins, J. B., Hinkle, A. D., Dutta, S., Deshmukh, R., Patel, M., and Agam, S., "Aerodynamic Implications of Aerocapture Systems for Uranus Orbiters," AIAA SCITECH 2024 Forum, Jan. 8-12, 2024, Orlando, FL. https://doi.org/10.2514/6.2024-0950



Trajectory Validations with TRAJ



Trajectory Validations with TRAJ

Aerocapture Trajectory at Venus	
Velocity	11 km/s
Azimuth/Heading	-90°
Longitude	305.61606°
Latitude	5.170641°
Julian Date	2456755
Mass	150 kg
Cone Half Angle	60°
Diameter	1 m
Nose Radius	0.25 m
Target Apoapsis	500 km

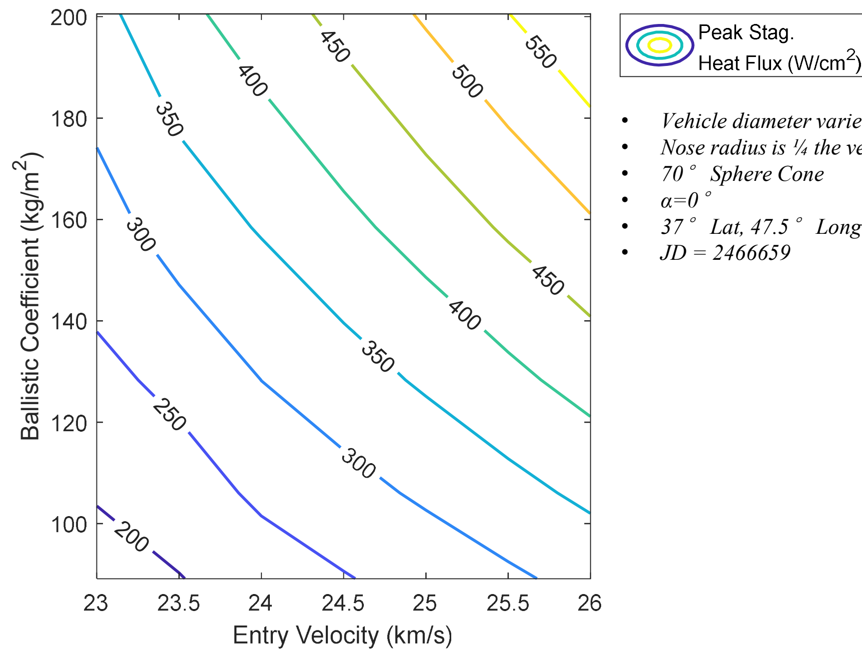
Results				
Lift Down Lift Up	**Resulting EFPA (deg)**	**Peak Convective Heat Flux (W/cm^2)**	**Peak Radiative Heat Flux (W/cm^2)**	**Total Heat Load (Conv. J/cm^2)**
MATLAB (-10°)	-5.424	382.25	-	48521.66
TRAJ (-10°)	-5.410	326.70	11.16	43108.42
MATLAB (-15°)	-5.368	361.27	-	54560.16
TRAJ (-15°)	-5.354	302.84	9.320	48836.38
MATLAB (-20°)	-5.329	347.80	-	61161.99
TRAJ (-20°)	-5.315	301.17	9.590	55053.46
MATLAB (10°)	-5.976	572.89	-	31264.45
TRAJ (10°)	-5.962	464.67	24.49	26578.55
MATLAB (15°)	-6.248	648.38	-	28883.92
TRAJ (15°)	-6.234	518.04	32.14	24242.16
MATLAB (20°)	-6.592	735.47	-	27123.57
TRAJ (20°)	-6.576	578.46	66.14	22462.20

- Shellabarger, E., Scoggins, J. B., Hinkle, A. D., Dutta, S., Deshmukh, R., Patel, M., and Agam, S., “Aerodynamic Implications of Aerocapture Systems for Uranus Orbiters,” AIAA SCITECH 2024 Forum, Jan. 8-12, 2024, Orlando, FL. https://doi.org/10.2514/6.2024-0950

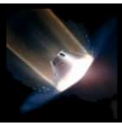
Uranus Aerocapture Analysis

Spacecraft Input Parameters		Entry State	
Initial Mass	4064 kg	Inertial Velocity	24.5 km/s
Trim Angle of Attack (α)	17°/-17°	Lift up EFPA	-23.806°
C_D at α=17°/-17°	1.436	Lift down EFPA	-23.509°
C_L at α=17°/-17°	±0.378	Planetocentric Altitude	4000 km
Diameter	5 m	Longitude (deg)	47.5°
Nose Radius	1.25 m	Azimuth (deg)	-90°
Sphere Cone Angle	70°	Geocentric Latitude	37°
B_C at α=0°	128.4 kg/m^2	Target Apoapsis Altitude	500000 km
B_C at α=17°/-17°	144.1 kg/m^2	Atmosphere Cutoff	4000 km

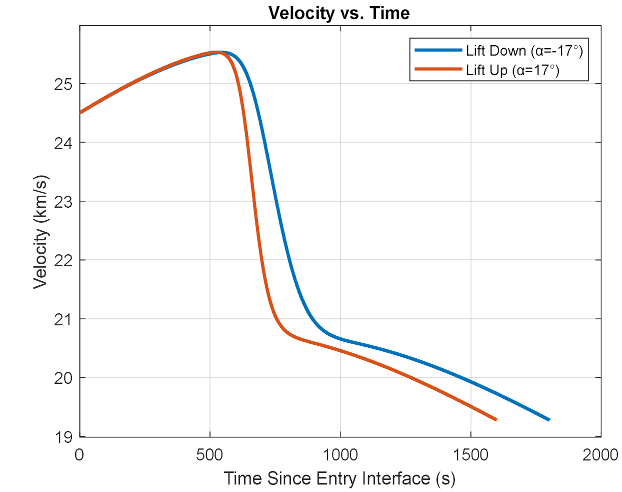
α=17°, alt = 310 km, Mach=26.93	Calorically Perfect (γ=1.45)	Chemical Equilibrium (H_2/He)
C_A	1.4836	1.5840
C_N	0.0587	0.0627
C_D	1.4360	1.5331
C_L	0.3776	0.4032

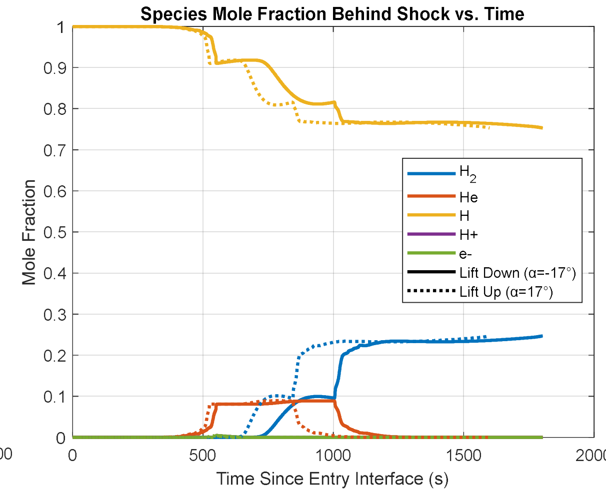


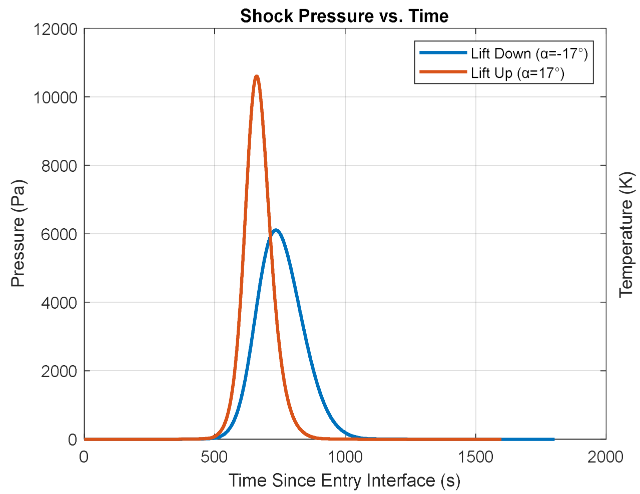
- *Vehicle diameter varied from 4-6 m*
- *Nose radius is ¼ the vehicle diameter*
- *70° Sphere Cone*
- *α=0°*
- *37° Lat, 47.5° Long*
- *JD = 2466659*

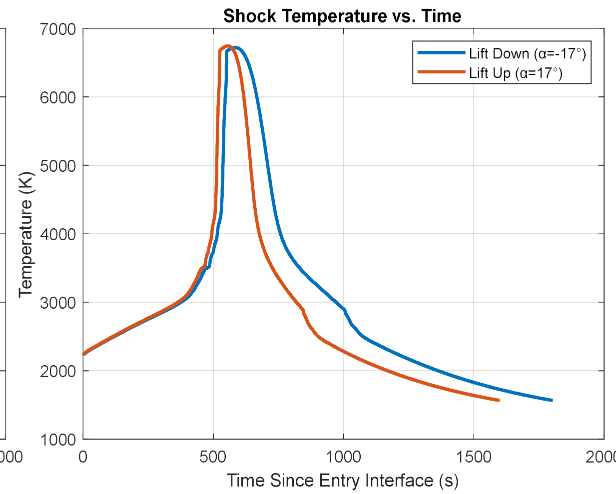


Uranus Aerocapture Analysis

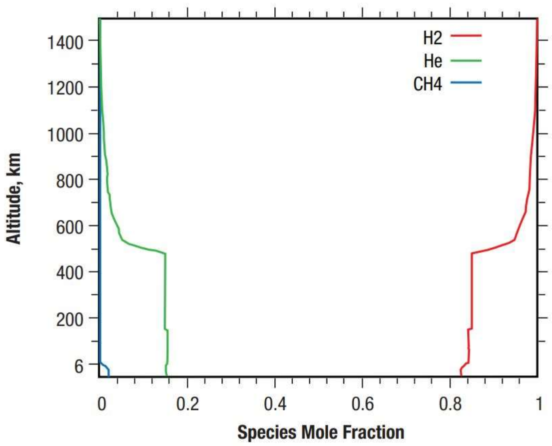


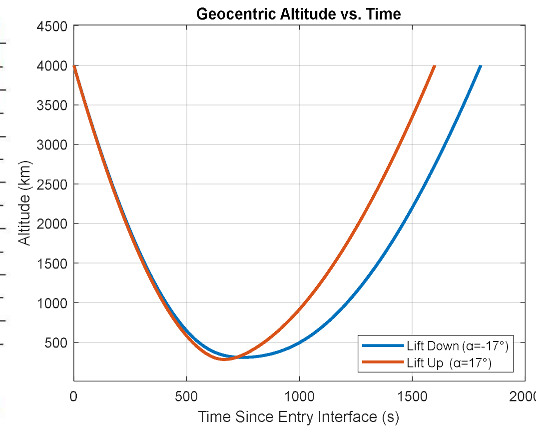


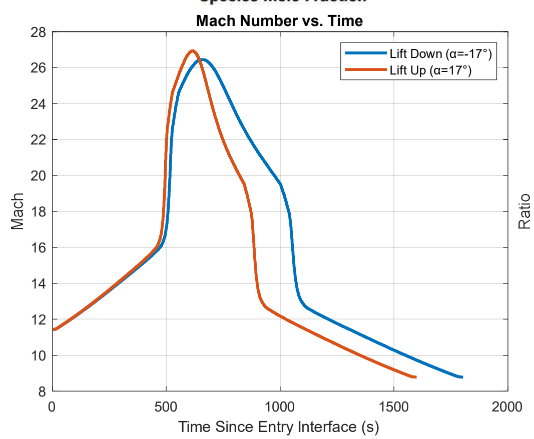


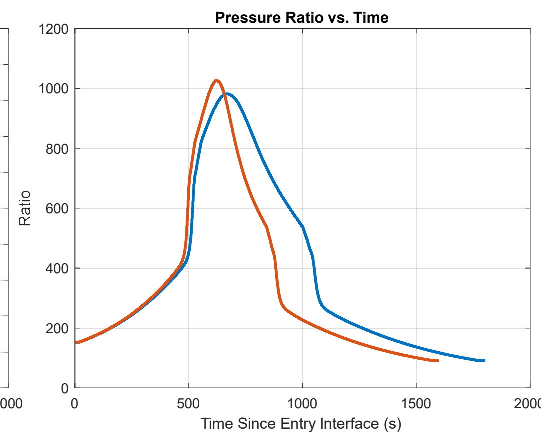


Uranus Aerocapture Analysis

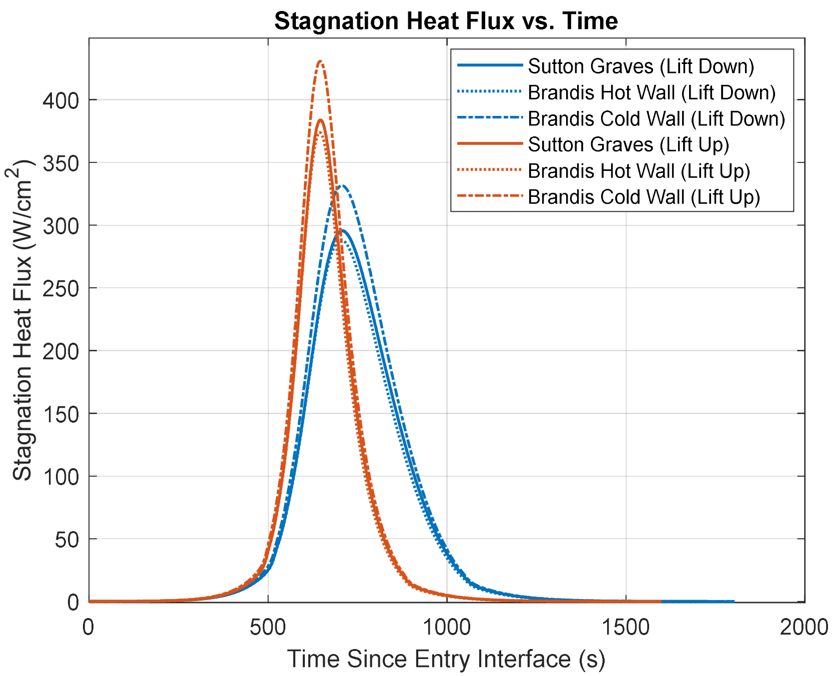


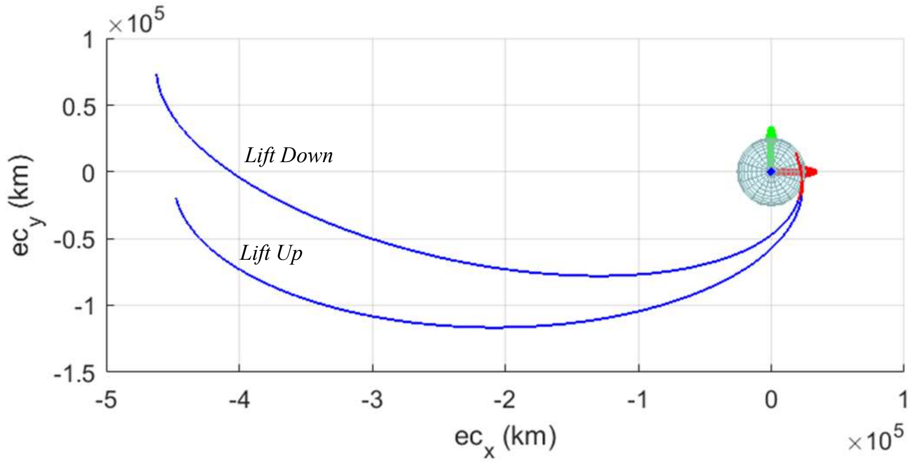






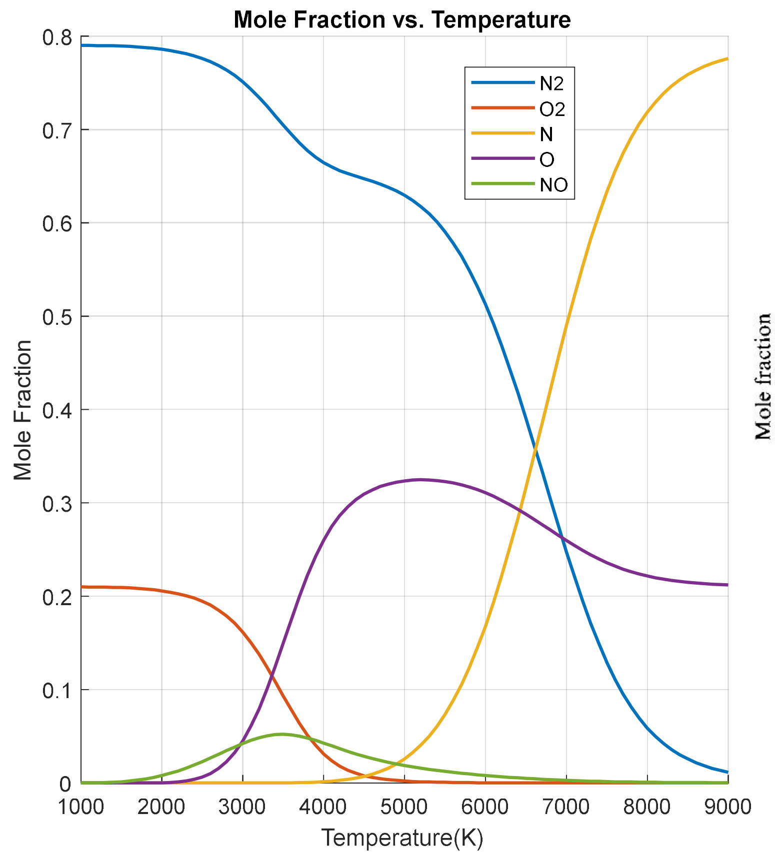
Uranus Aerocapture Analysis

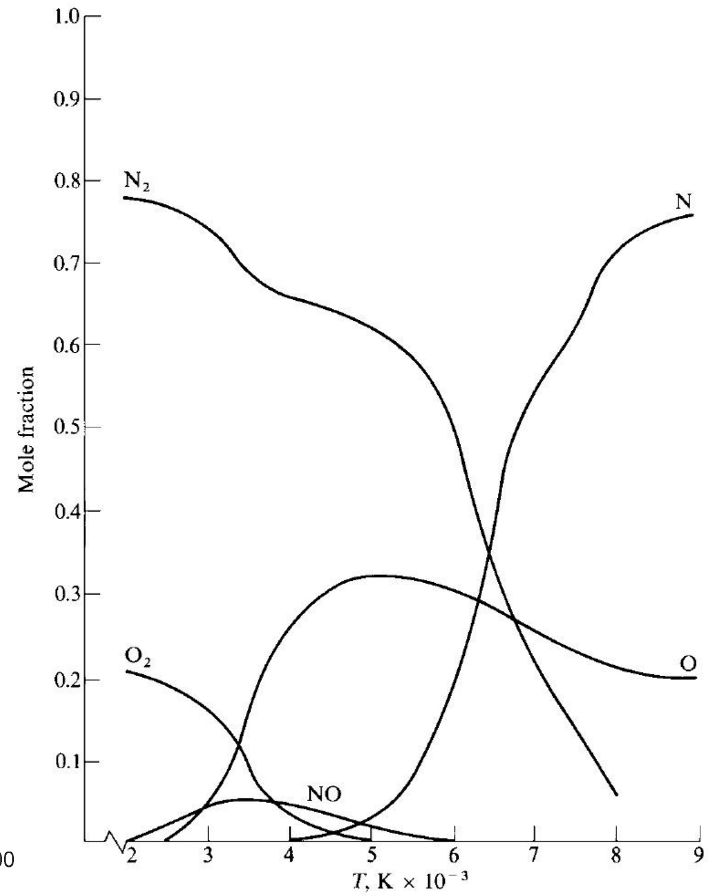




Symbolic Math Chemistry Model Validation (N2/O2)

- Anderson, John D. Hypersonic and High Temperature Gas Dynamics. 2nd ed., American Institute of Aeronautics and Astronautics, 1801 Alexander Bell Drive, Reston, VA. 2006.

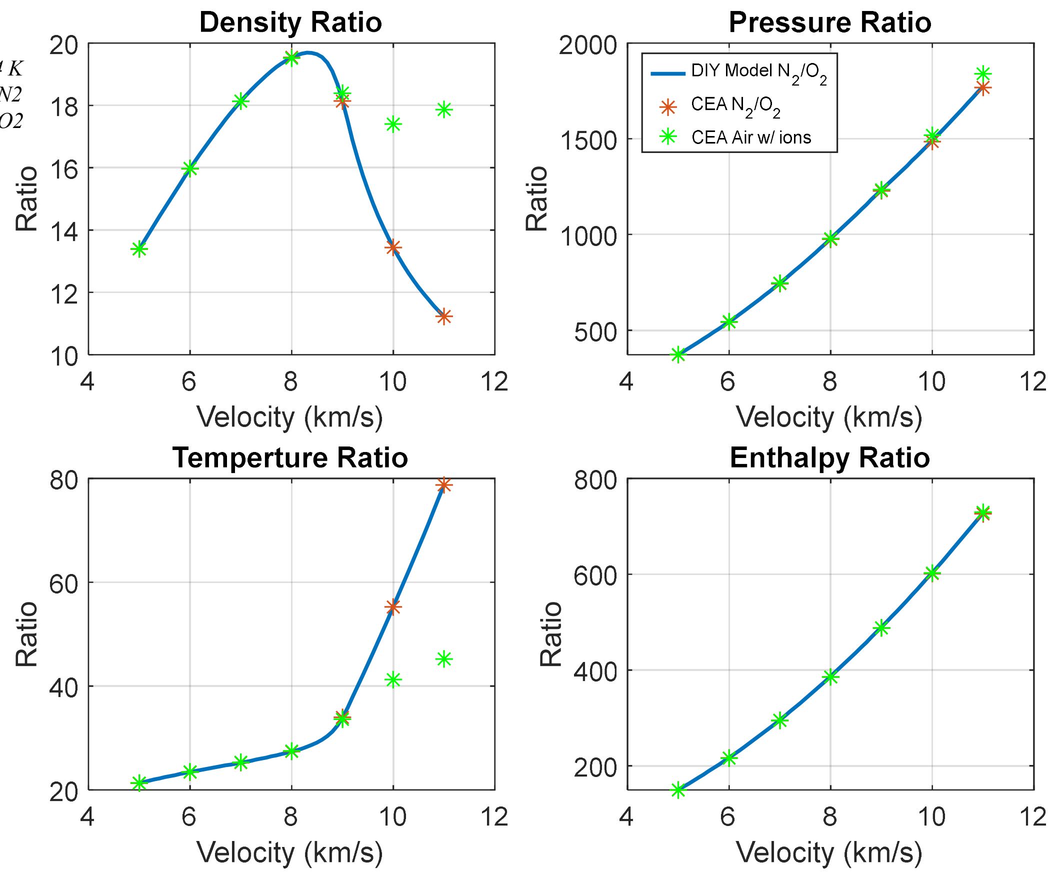




Conditions at 1 atm, Textbook: Fig 11.12, P.541)

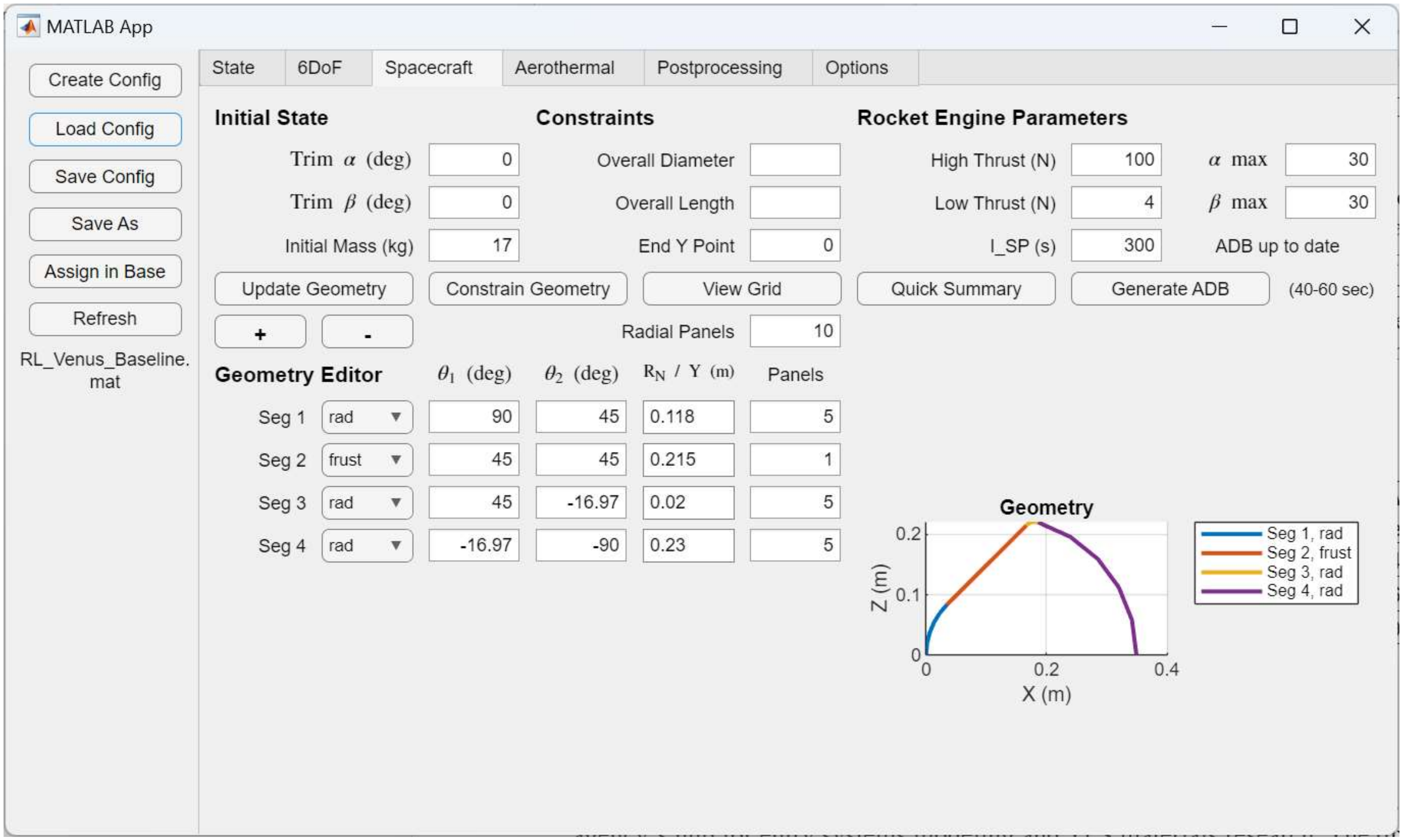
Chemistry Model Validation with CEA

- *P1 = 1 Pa*
- *T1 = 216.4 K*
- *0.79 mole N2*
- *0.21 mole O2*



Conditions at 1 atm, Textbook: Fig 11.12, P.541)

TEMPEST UI


MATLAB App
Create Config
Load Config
Save Config
Save As
Assign in Base
Refresh
RL_Venus_Baseline.mat
State
6DoF
Spacecraft
Aerothermal
Postprocessing
Options
Initial State
Trim α (deg) 0
Trim β (deg) 0
Initial Mass (kg) 17
Constraints
Overall Diameter
Overall Length
End Y Point 0
Rocket Engine Parameters
High Thrust (N) 100
Low Thrust (N) 4
I_SP (s) 300
α max 30
β max 30
ADB up to date
Update Geometry
Constrain Geometry
View Grid
Quick Summary
Generate ADB
(40-60 sec)
+
-
Radial Panels 10
Geometry Editor
θ1 (deg)
θ2 (deg)
RN / Y (m)
Panels
Seg 1 rad 90 45 0.118 5
Seg 2 frust 45 45 0.215 1
Seg 3 rad 45 -16.97 0.02 5
Seg 4 rad -16.97 -90 0.23 5
Geometry
Z (m)
X (m)
0
0.1
0.2
0
0.2
0.4
Seg 1, rad
Seg 2, frust
Seg 3, rad
Seg 4, rad