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Blackout Analysis of Reentry Vehicles for Martian Missions

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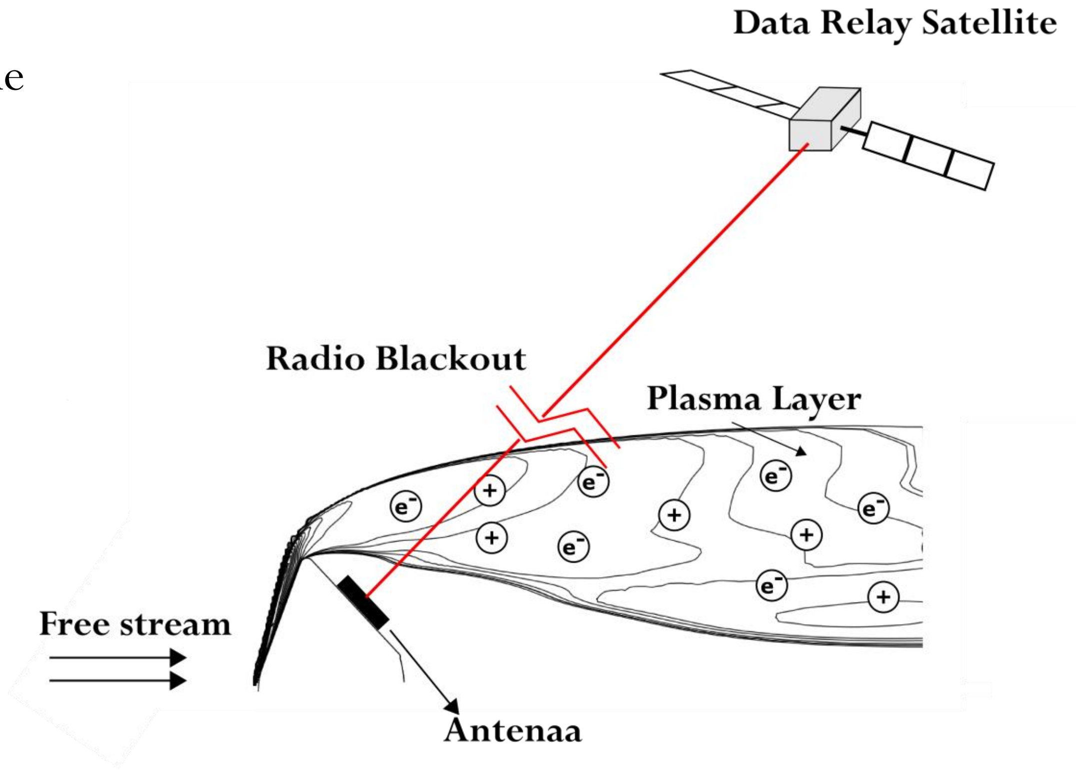
Problem Description & Motivation

- Blackout Phenomena
  - Freestream is rapidly disassociated by aerodynamic heating in the shock layer
  - Electromagnetic interference caused by highly dense plasma
  - Blackout due to refractive index [1]
- Missions
  - Mars Pathfinder at 7.5km/s -30 second blackout at x-band [2]
  - MSL suffered a period of ~70s of brownout and blackout at UHF [3] and ExoMars 2016 had a ~60s blackout at UHF
  - Future missions require increased landing performance [4] [5]



Novelty of Research

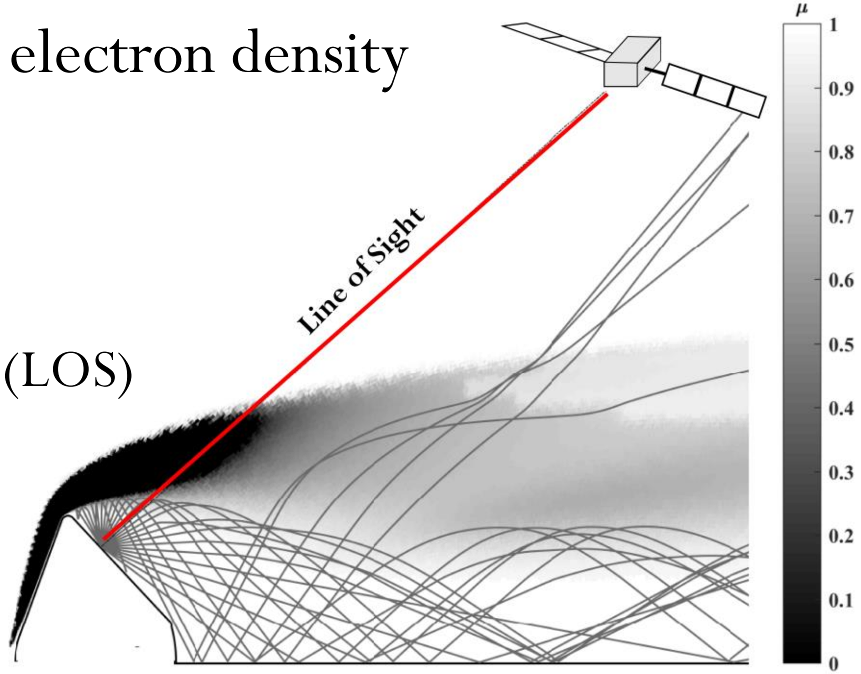
In literature, typically use CFD to characterize the reentry plasma [1-3]

- Multi-temperature models & extensive chemical mechanisms add to computational cost
- 3D simulations including two temperature model, 20 chemical species at 10 trajectory points of MSL [1]

❖ Apply a computationally inexpensive approach to extract electron density fields

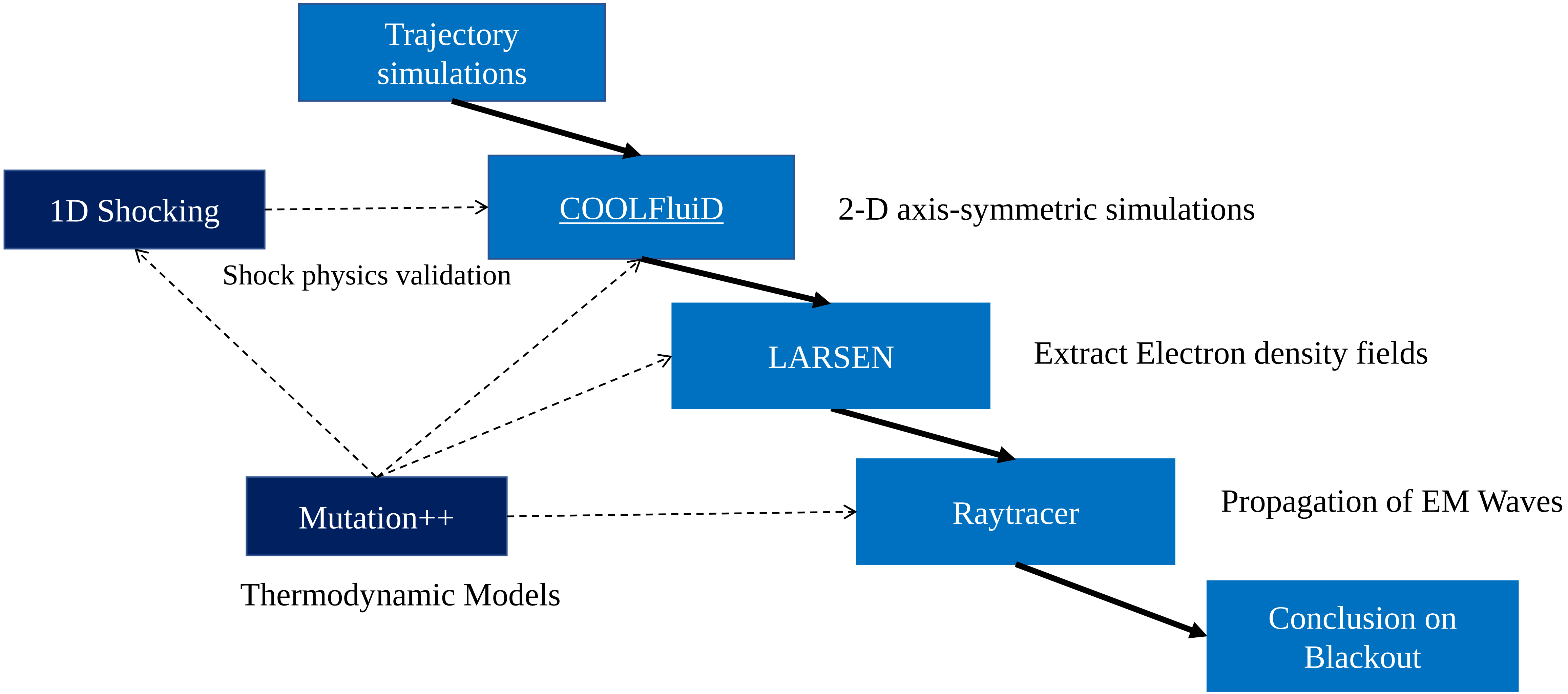
❖ Ray tracing [1],[5]

- A method to estimate the most likely signal path
- In literature, consider transmission of signal along Line of Sight (LOS)



Implement and Apply Tools for Predicting CO_2 Blackout
Introduce improved physics modeling
Validate these tools on literature data from previous missions

Methodology & Approach

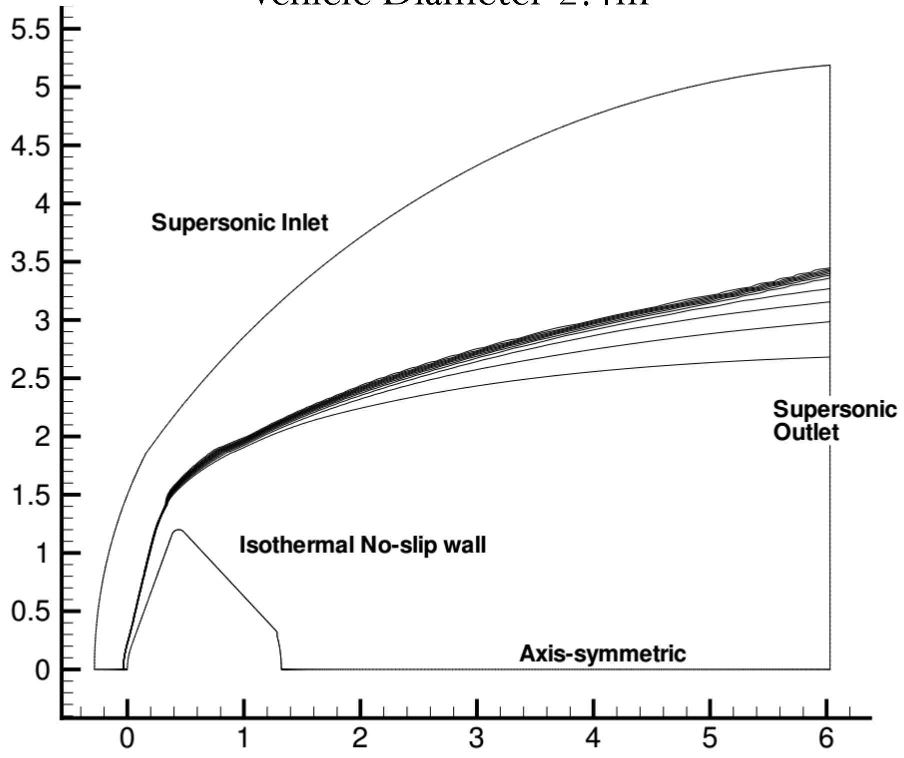


COOLFluiD

- Parallel, structured/unstructured 2D/3D finite-volume
  CFD code that has the capability to simulate hypersonic reacting flows [8]
- Implicit time stepping
- Viscous Navier-Stokes Equations in chemical non-equilibrium and
thermal equilibrium
    - **[CO_2 O_2 C O C_2 CO]- Mars6**
    - (Continuity equations for 6 species, 2 momentum equations,
      and 1 energy equation solved)
- Finite volume formulation where numerical convective fluxes
 are computed using AUSM+ scheme
- **Boundary Conditions (100% CO2)**
    - Supersonic Inlet and Outlet
    - 2-D axis-symmetric
    - Isothermal no-slip wall 1500 K

ExoMars Schiaparelli

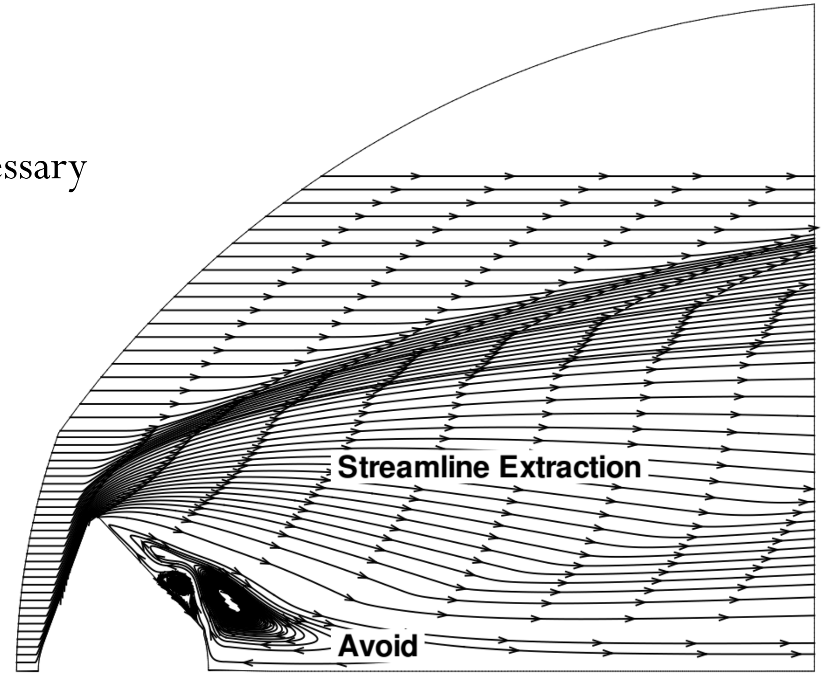
70^0 sphere cone frontshield
47^0 conical backshield
Nose radius 0.6 m
Vehicle Diameter 2.4m



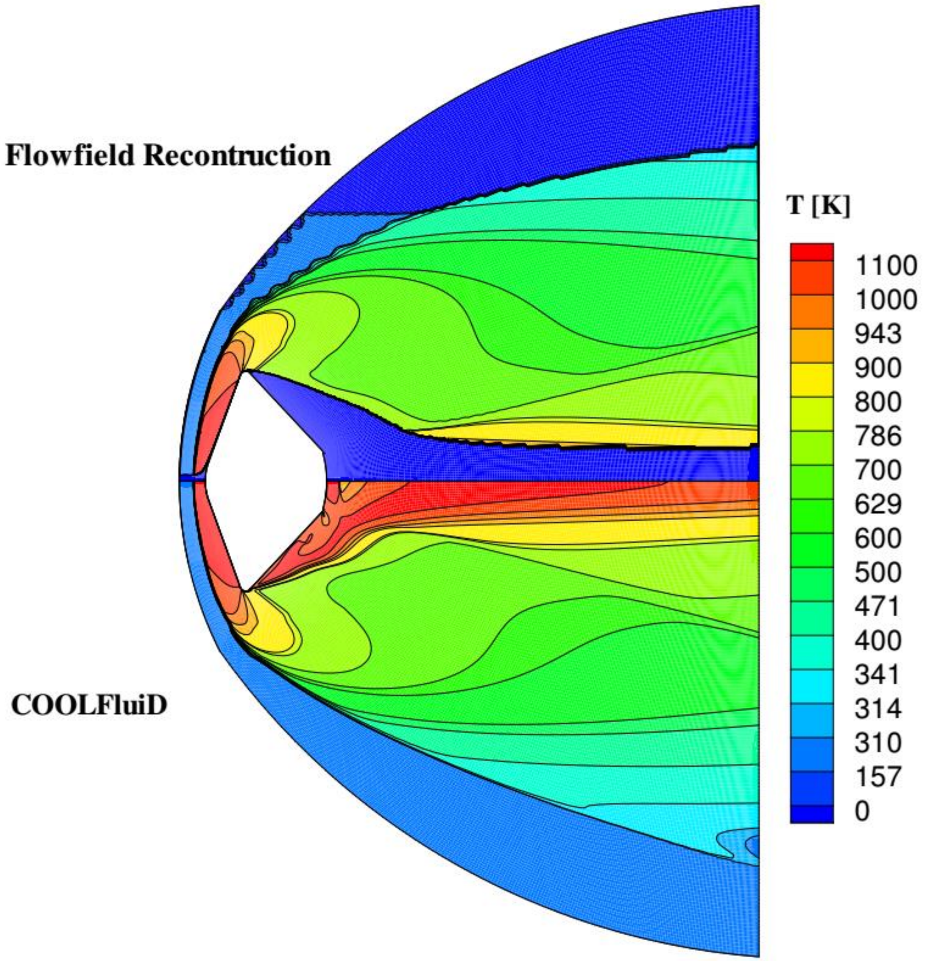
https://github.com/andrealani/COOLFluiD/wiki

LARSEN

- A solver that is able to refine a baseline solution along a streamline by introducing new chemical species and internal temperatures [9]
- Assumptions
  - Velocity and density field are taken from the baseline simulation
  - The mass and momentum equations for the whole mixture are no longer necessary
- Governing Equations
  - Mass Conservation equation for each chemical species
    - $\frac{Dy_i}{Dt} = \frac{1}{\rho}(\dot{\omega}_i - \nabla \cdot \mathbf{J}_i)$
  - Total energy conservation equation (thermal equilibrium)
    - $\rho \frac{DH}{Dt} = \phi = \nabla \cdot \mathbf{q} + \nabla \cdot (\mathbf{u} \cdot \boldsymbol{\tau})$
    - $\phi = \left(\rho \frac{DH}{Dt}\right)_{ref}$ Energy Flux is taken from reference simulation
    - $\frac{DT}{Dt} = \left[\phi - \frac{Du^2/2}{Dt} - \sum_{i \epsilon s} \frac{h_i \dot{\omega}_i}{\rho}\right] / \left[\sum_{i \epsilon s} y_i c_{p,i}\right]$ Give T, ρ, u, y_i along streamline from neutral simulation



Flowfield Reconstruction



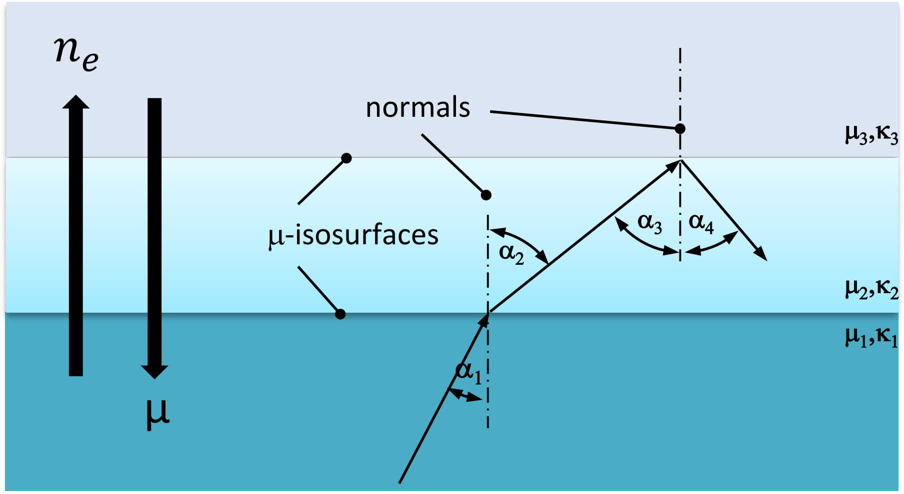
- ❖ Create contour plots from streamline data
- ❖ ExoMars t=123s [Safely after blackout]

  u =1441 m/s, T=205 K, $\rho_{CO_2} = 2.606x10^{-3}\, {}^{kg}/_{m^3}$
- ❖ Vortex region and stagnation region avoided
- ❖ Temperature in wake will not create a sufficient electron density to cause blackout

  400 Mhz ➡ $2x10^{15}$ e^{-}/m^3

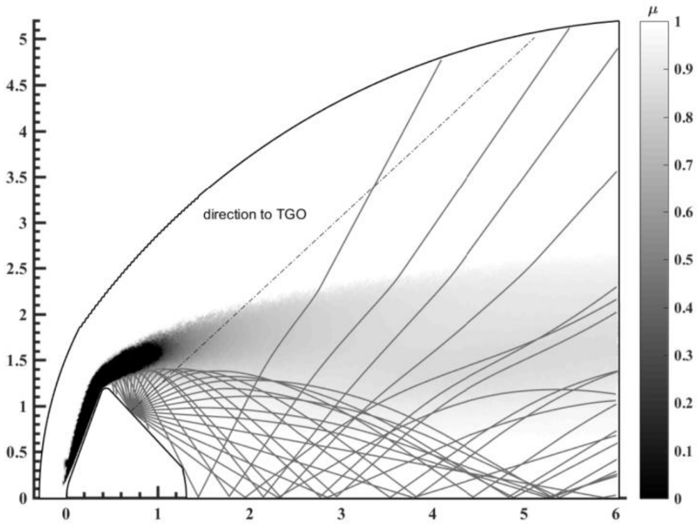
BlackOut RAyTracer [BORAT]

- Iterative marching application of Snell's Law
  - $\mu \, sin\alpha_1 = \mu_2 \, sin\alpha_2$
- In typical reentry application rays from antenna move from a relatively cold region to a hot region
- Step size chosen as to resolve the gradients in the refractive index accurately [0.02 m]
- Assume antenna is omni-directional with equally strong signals in all directions [400 MHz]

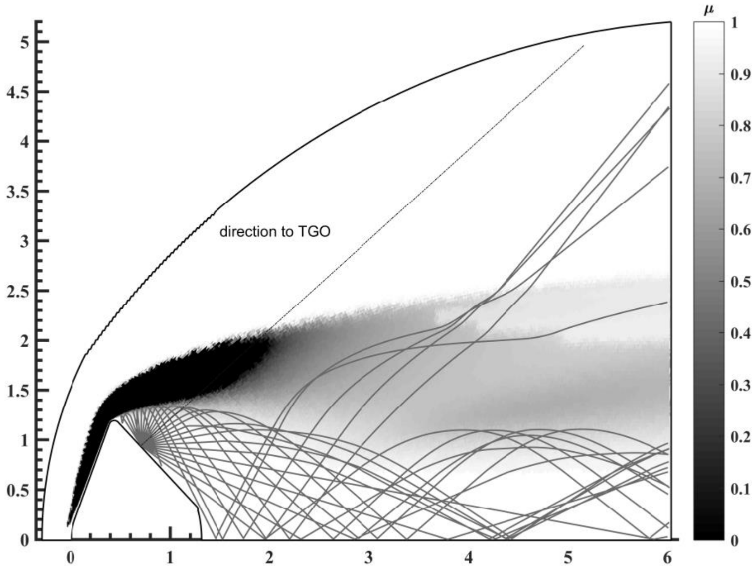


Results

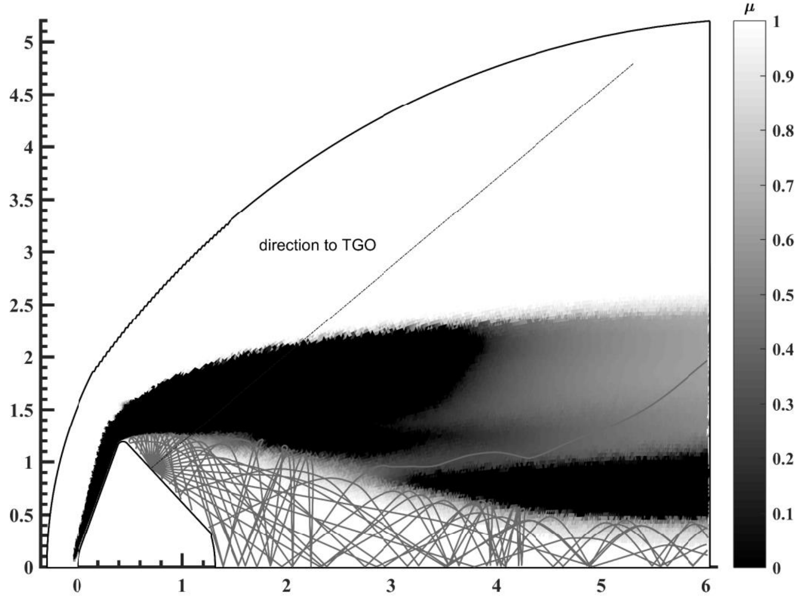
t= 17s



t= 22s



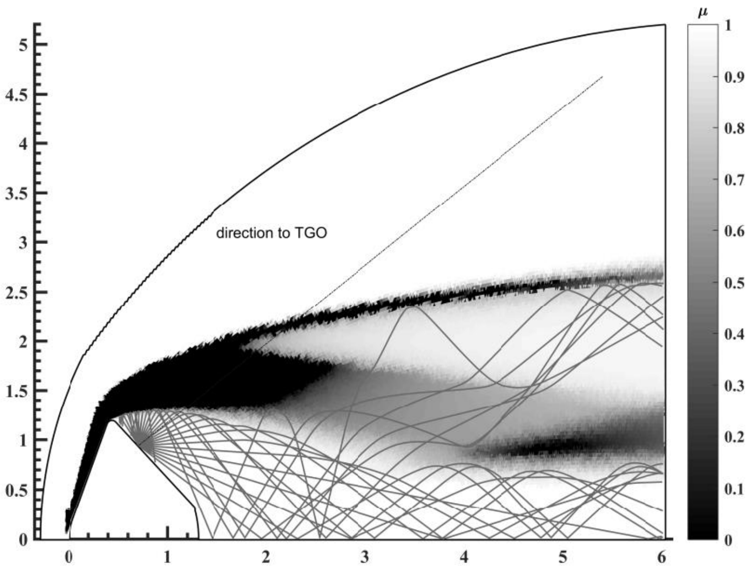
t= 38s



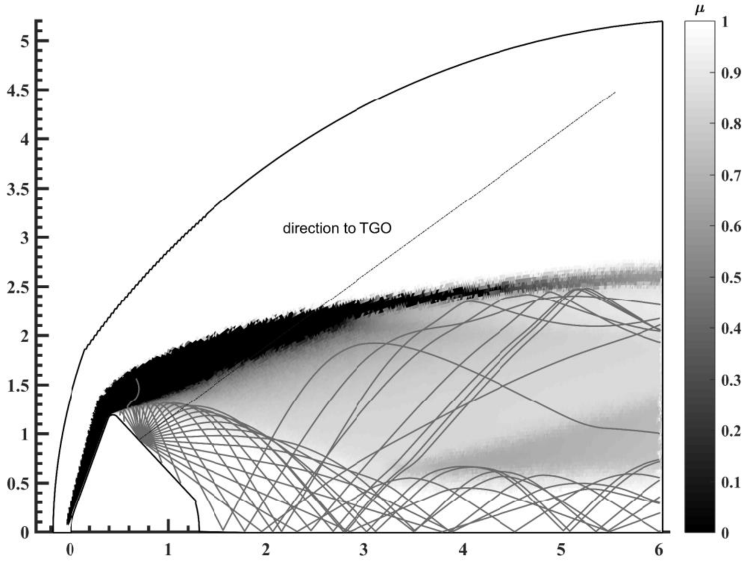
- Brownout to eventually blackout where rays are confined to the axis

Results

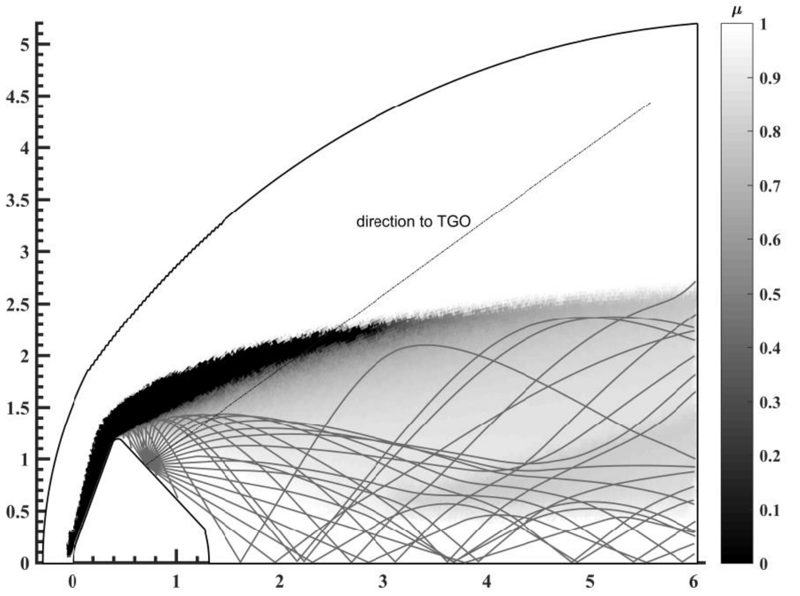
t= 50s



t= 73s

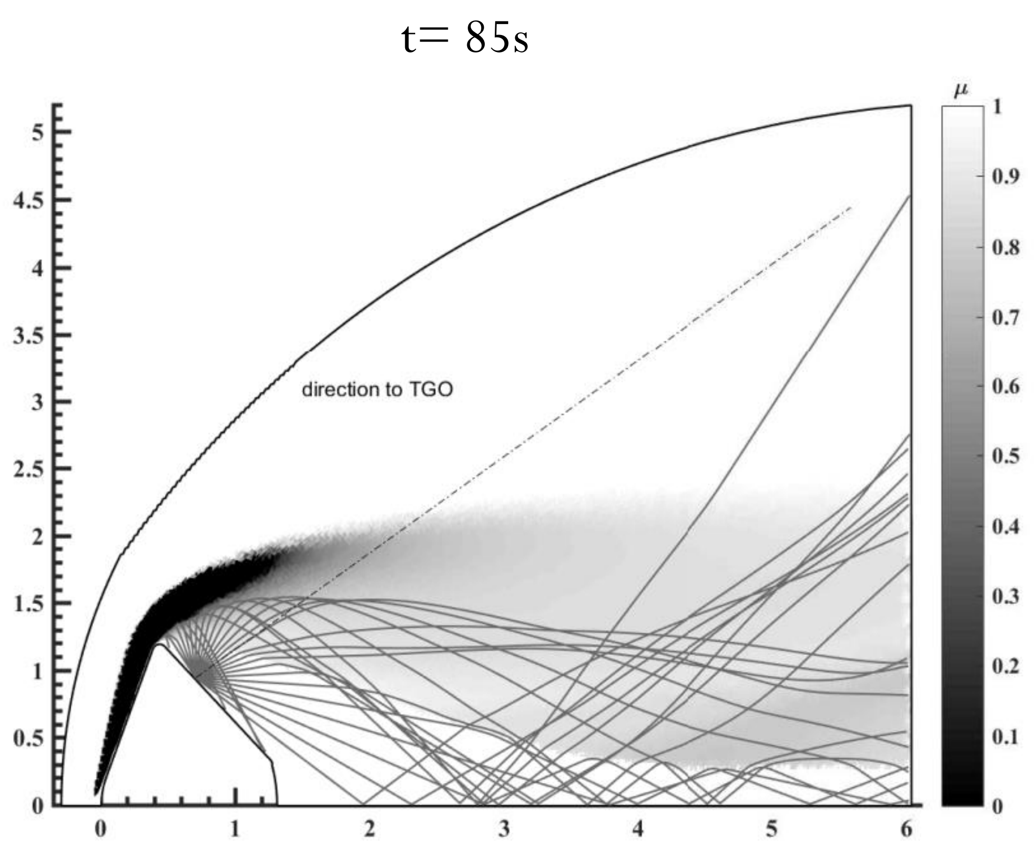


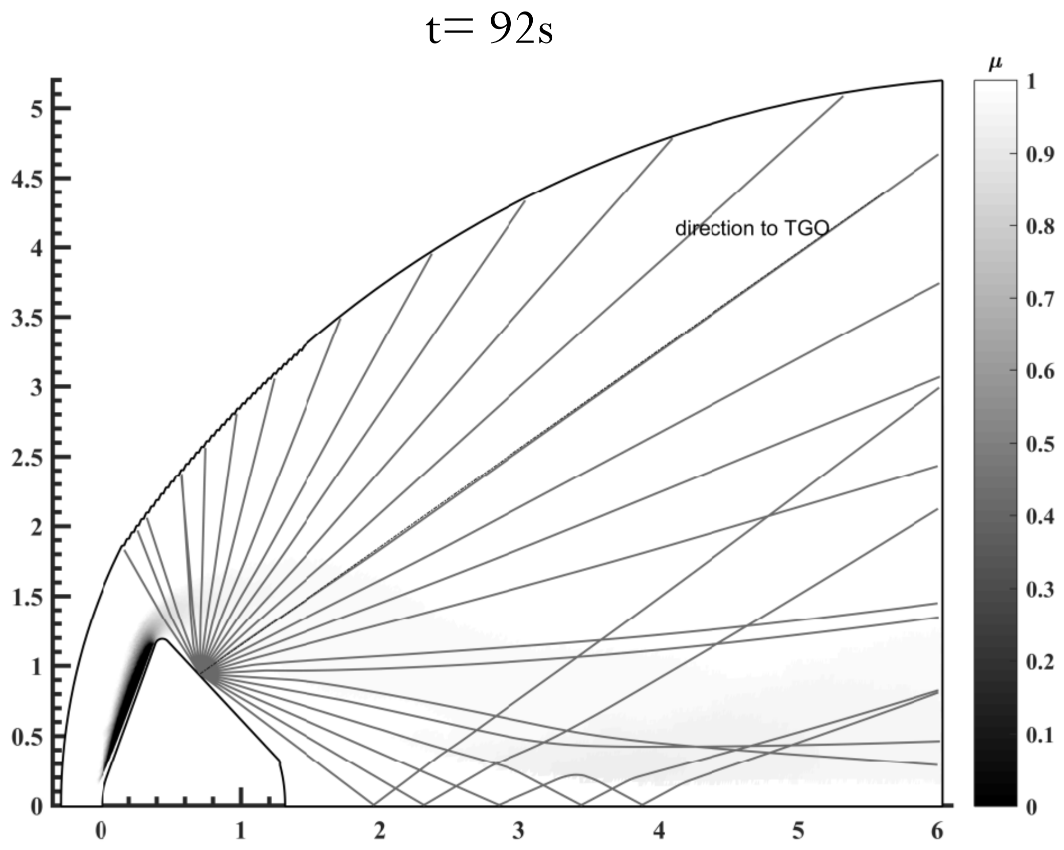
t= 80s



- Blackout to brownout as rays are initially confined to the axis and gradually move away

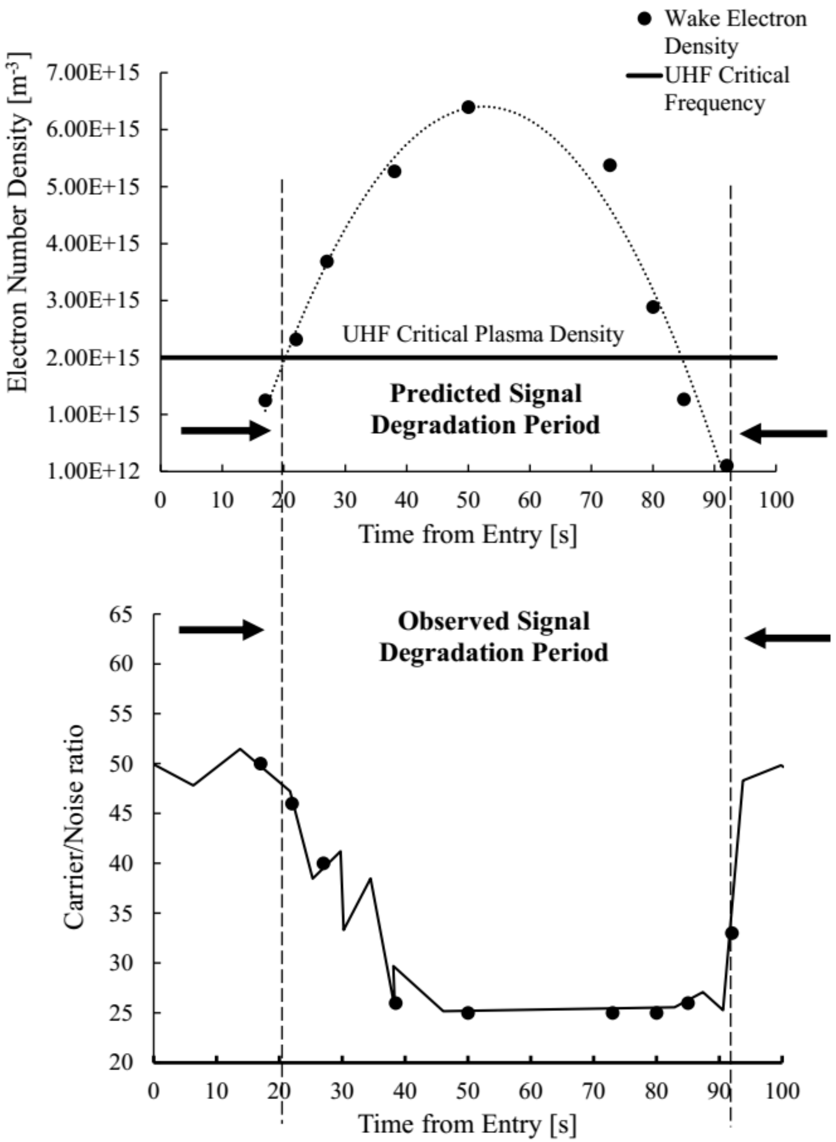
Results





- Brownout to no blackout
- Improved physics modeling

Comparing with Flight Data



Conclusions

- Implemented and validated blackout analysis tools
  - Lagrangian approach applied to retrieve electron density [LARSEN]
  - Raytracing applied to CO_2 flows [BORAT]
    - -Apply more accurate modeling of the physics
    - -LOS method is not accurate [signal is bent by electron density gradients in plasma]
  - Results are in good agreement with flight data
- Developed a computationally inexpensive way to examine blackout
  - Run CFD with 6 species, use LARSEN to reconstruct the electron density, then BORAT

Acknowledgments

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References

- [1] G. Vecchi, M. Sabbadini, R. Maggiora and A. Siciliano, "Modelling of Antenna Radiation Pattern of a Reentry Vehicle in Presence of Plasma," in Antennas and Propagation Society International Symposium, IEEE, Monterey, CA, 2004.
- [2] D. Morabito, "The Spacecraft Communications Blackout Problem Encountered During Passage or Entry of Planetary Atmospheres," Jet Propulsion Laboratory, IPN Progress Report 42-150, Pasadena, 2002.
- [3] D. Morabito, B. Schratz, K. Bruvold, P. IIlott, K. Edquist and D. Cianciolo, "The Mars Science Laboratory EDL Communications Brownout and Blackout at UHF," IPN Progress Report 42-197, 2014.
- [4] M. J. Wright, C. Y. Tang, K. T. Edquist, B. R. Hollis, P. Krasa and C. A. Campbell, "A Review of Aerothermal Modeling for Mars Entry Missions," in 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, 2010.
- [5] R. D. Braun and R. M. Manning, "Mars Exploration Entry, Descent, and Landing Challenges," Journal of Spacecraft and Rockets, vol. 44, no. 2, pp. 310-323, 2007
- [6] A. Delfino, MODELING OF THE ANTENNA RADIATION PATTERN OF A RE-ENTRY SPACE, Chicago: University of Illinois, 2004.
- [7] S. C. Aune, "COMPARISON OF RAY TRACING THROUGH IONOSPHERIC MODELS," DEPARTMENT OF THE AIR FORCE , Wright-Patterson Air Force Base, Ohio , 2006.
- [8] A. Lani, T. Quintino, T. Kimpe, H. Deconinck, S. Vanderwalle and S. Poedts, "COOLFluiD framework: design solutions for high-performance object oriented scientific computing software," in Computational Science ICCS 2005, 2005. https://github.com/andrealani/COOLFluiD/wiki

References

- [9] S. Boccelli, "Development of a Lagrangian Solver for Thermochemical Nonequilibrium Flows," Politechnico Di Milano, Italy, 2015-2016.
- [10] K. Davies, Ionospheric Radio Propagation, Washington D.C.: US Government Printing Office, 1965
- [11] B. Esser, A. Gulhan, “Test Plan for Experiments,” SACOMARS DLR, SPA.2010.3.2-04, 2011
- [12] Camac, M., “CO, Relaxation Processes in Shock Waves,” Fundamental Phenomena in Hypersonic Flow, edited by J. G. Hall, Cornell Univ. Press, Ithaca, NY, 1966, pp. 195-215.
- [13] GRAHAM CANDLER. "Computation of thermo-chemical nonequilibrium Martian atmospheric entry flows", 5th Joint Thermophysics and Heat Transfer Conference, Fluid Dynamics and Co-located Conferences
- [14] M. Technologies, "CFD++ User Manual," [Online]. [Accessed 5 December 2013].
- [15] M. Fertig, "Report and Library on Gas Phase Chemistry," SACOMAR DLR, SPA.2010.3.2-04, 2012.
- [16] Scoggins, James, Magin. T. Development of Mutation++: Multicomponent Thermodynamics And Transport Properties for Ionized Gases Library in C++, 11th AIAA/ASME Joint Thermophysics and Heat Transfer Conference, 16-20 June 2014 https://www.mutationpp.org/

Backup Slides

Plasma Cut-off Frequency

- $f_p = \frac{1}{2\pi}\sqrt{\frac{n_e e^2}{m_e \epsilon_0}}$

f_p plasma cutoff frequency, Hz
n_e electron density, m^{-3}
e electron charge, 1.6x10-19 C
m_e electron mass, 9.1x10-31 kg
ϵ_0 permittivity in free space

Electromagnetic Wave Propagation

- Refractive index (μ) and absorption coefficient (χ) are described by the Appleton Equation [8]
  - $n^2 = (\mu - i\chi)^2 = 1 - \frac{X}{1-Zi}$
  - $X = \frac{{n_e}^2}{\epsilon_0 m \omega^2}$, $Z = \frac{\nu}{\omega}$
- Neglecting collision frequency
  - $n = \mu = \sqrt{1-X} = \sqrt{1-\left(\frac{f_p}{f}\right)^2}$
  - f_p is measure of the oscillatory movement of electrons in plasma
- Consider collision frequency
  - $\mu = 1 - \frac{X}{1-Zi}$, $\kappa = \frac{\omega}{c}\chi = \frac{e^2 n_e \nu}{2\epsilon_0 m c \mu(\omega^2+\nu^2)}$
  - the collision frequency reduces the effect of the electron density

[Can predict a weaker signal if you neglect collisions]

n complex refractive index
n_e electron density, m^{-3}
ν collision frequency, s^{-1}
μ real part of refractive index
χ imaginary part of refractive index

f_p plasma cutoff frequency, Hz
f frequency band, Hz

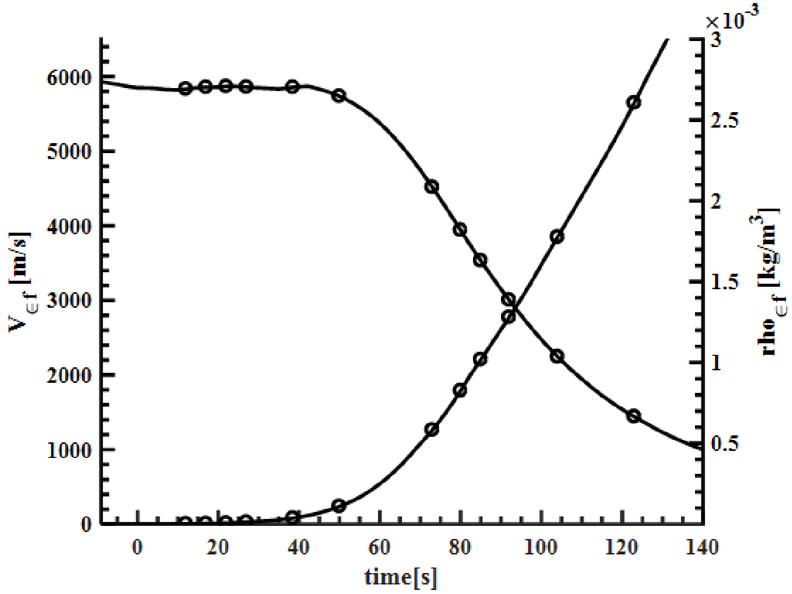
κ absorption factor, Np/m
m electron mass, 9.1x10-31 kg
e electron charge, 1.6x10-19 C
ω radio angular frequency, rad/s

Computational Matrix

TABLE I. Freestream conditions for ExoMars Schiaparelli trajectory.

	t (s)	Alt. (km)	u_∞ (m/s)	ρ_∞ (kg/m^3)	T_∞ (K)	$K_n \times 10^3$	$R_e \times 10^{-3}$
2[a]	17	101	5856	3.83×10^{-6}	169	30.0	4.75
3	22	96	5867	6.97×10^{-6}	165	17.0	8.77
4	27	91	5859	1.29×10^{-5}	155	9.0[d]	16.76
5	38	80	5856	3.72×10^{-5}	175	3.0	45.37
6	50	71	5736	1.10×10^{-4}	169	1.0	134.00
7[b]	73	56	4516	5.82×10^{-4}	174	0.19	548.00
8	80	52	3941	8.25×10^{-4}	180	0.13	668.00
9	85	50	3532	1.01×10^{-3}	184	0.11	725.00
10[c]	92	48	3006	1.27×10^{-3}	189	0.08	770.22
11	104	44	2245	1.77×10^{-3}	196	0.06	784.00
12	123	39	1441	2.60×10^{-3}	205	0.04	722.17

[a] Brownout.
[b] Maximum blackout.
[c] After blackout.
[d] Traditional limit for accurate CFD simulations



Blackout occurs between [30s-80s]

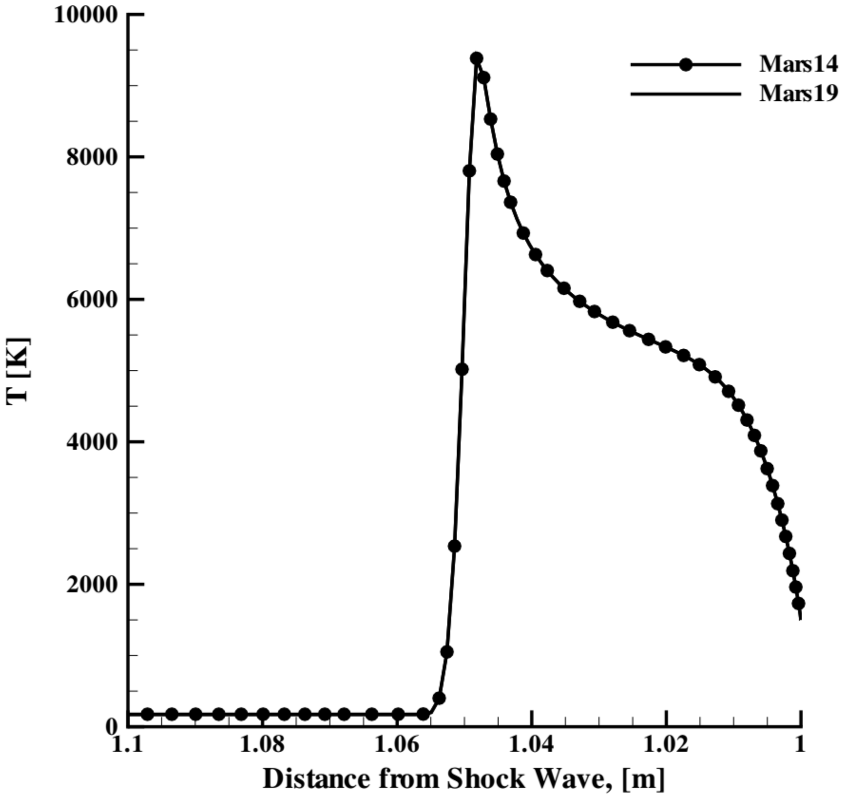
Chemical NEQ Model

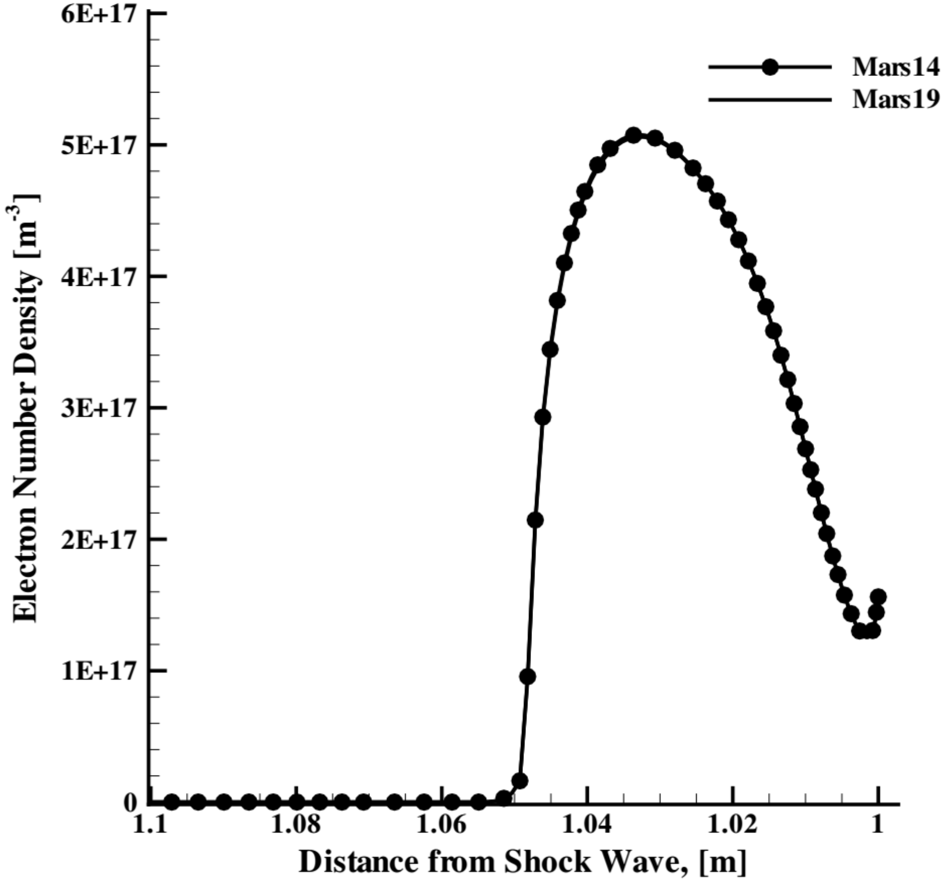
- 1-D Stagnation Line Code [R=1m sphere] [5]
- ExoMars ⟶ t=38seconds
- T=175.5, T_w=1500K, u=5856.2 m/s

  - $\rho_{CO_2} = 3.6258x10^{-5}\ {}^{kg}/_{m^3}$
  - $\rho_{N_2} = 9.6027x10^{-7}\ {}^{kg}/_{m^3}$

- **Mars19** [Park]
  - [e- CO_2 N_2 C N O O_2 CO NO C_2 CN]
  - Ions: [CO+ NO+ C+ O+ O_2+ N+ N_2+ CN+]
- **Mars14** [Park]
  - [e- CO_2 N_2 C N O O_2 CO NO]
  - Ions [CO+ NO+ C+ O+ O_2+]

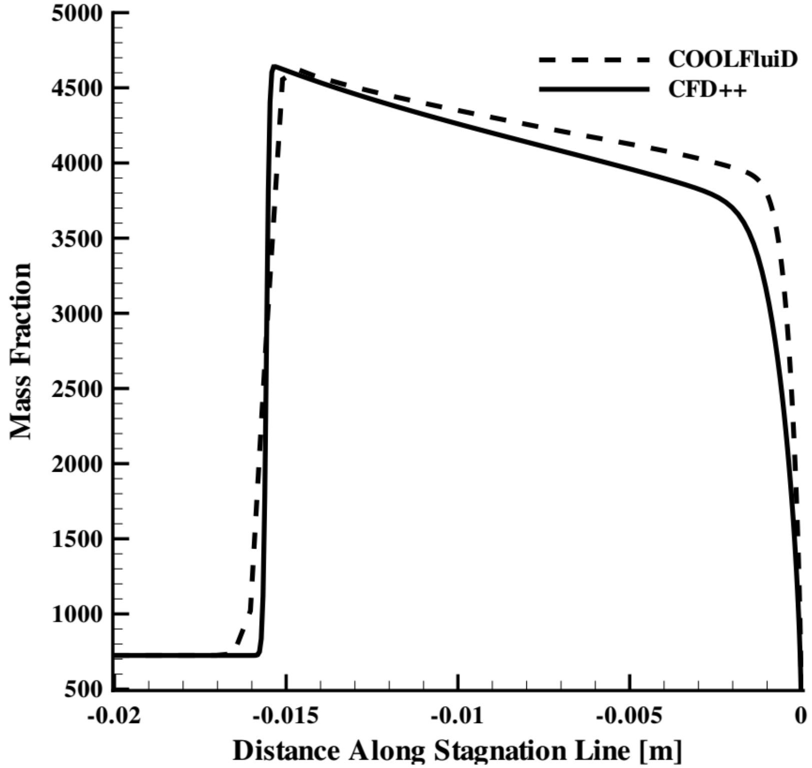
Electron Density

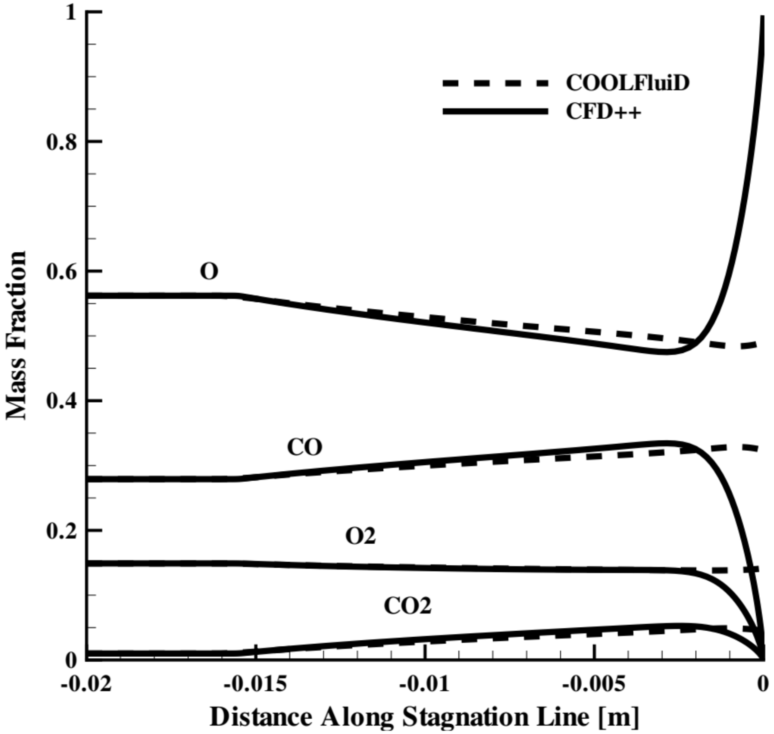


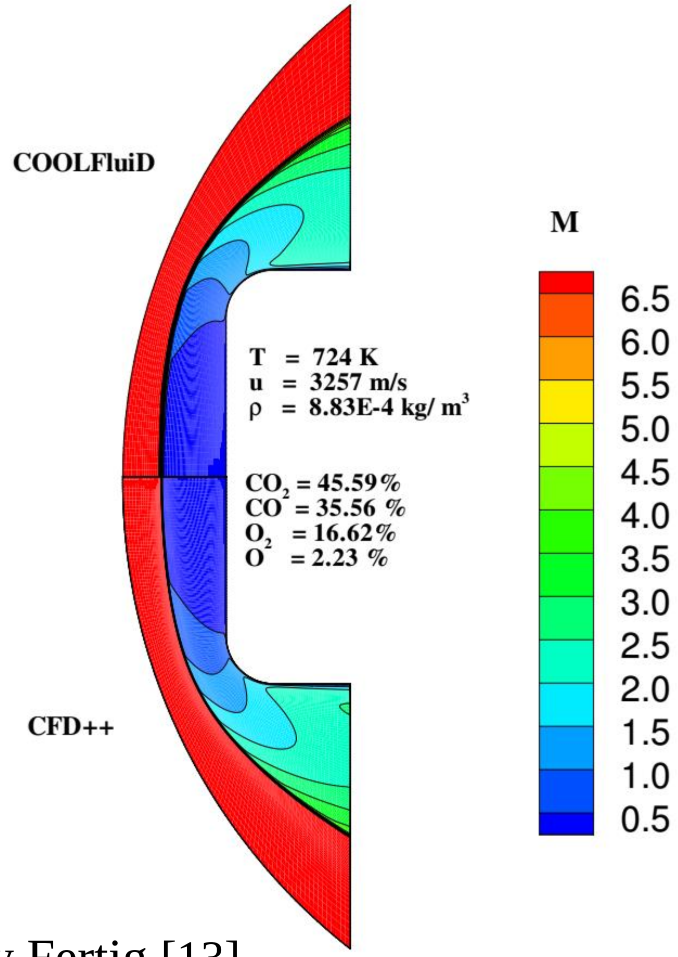


- Maximum reentry velocity of ExoMars Schiaparelli ~5900 m/s
- The Mars14 chemical NEQ model will be sufficient in predicting the electron density

CO_2 Modeling Validation







- Numerical results in good agreement with CFD++ [12] and the DLR TAU Code by Fertig [13]
- Supercatalytic Boundary used in CFD++