Communications Blackout Predictions for Atmospheric Entry of Mars Science Laboratory

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Plasma Blackout Problem

- When a supersonic spacecraft enters a planetary atmosphere with $v >> v_{sound}$, a shock layer forms in the front of the body.
- An ionized sheath of plasma develops around the spacecraft, which results from the ionization of the atmospheric constituents as they are compressed and heated by the shock or heated within the boundary layer next to the surface.
- When the electron density surrounding the spacecraft becomes sufficiently high, communications can be disrupted (attenuation/blackout)
- In the 1960s, during planning for the Apollo mission, NASA conducted several experiments involving Earth atmospheric reentry.
- For Apollo, the interaction of the high speed capsule with the Earth's atmosphere caused a communications blackouts of 4 to 10 minutes durations at S-band.
- The main cause of blackout is reflection or absorption of electromagnetic energy at frequencies, f, which lie below the plasma frequency, f_p (Hz),

$$f_p \equiv \frac{1}{2\pi}\sqrt{\frac{q^2 n_e}{\varepsilon_0 m_e}} = 8.98\sqrt{n_e}$$

where n_e is electron concentration in m^{-3}.

- For $f < f_p$ the plasma behaves like a conductor, the result is a BLACKOUT
- For $f > f_p$ the plasma is transparent, the result is NO BLACKOUT

Previous Work

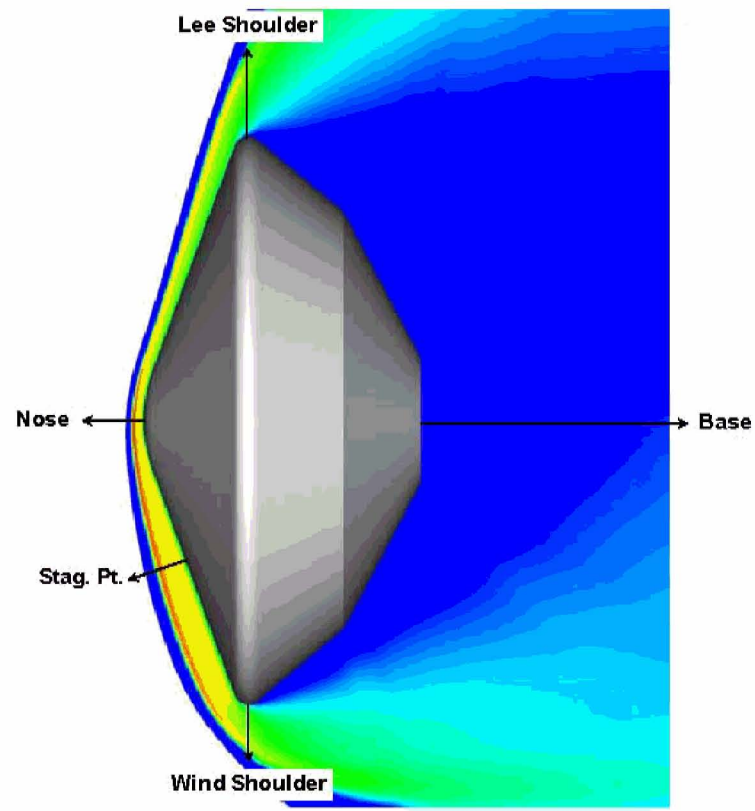
- Mars Pathfinder underwent a 30 second communications blackout at X-band
  - Previous analysis found that at least the first 20 seconds of the blackout period was consistent with the presence of a sheath of charged particles generated by heating and compression that exceeded critical electron number density
- Mars Exploration Rovers did not experience any blackout during the period centered around peak heating
  - Consistent with analysis that predicted levels of charged particle density well below X-band threshold

LAURA

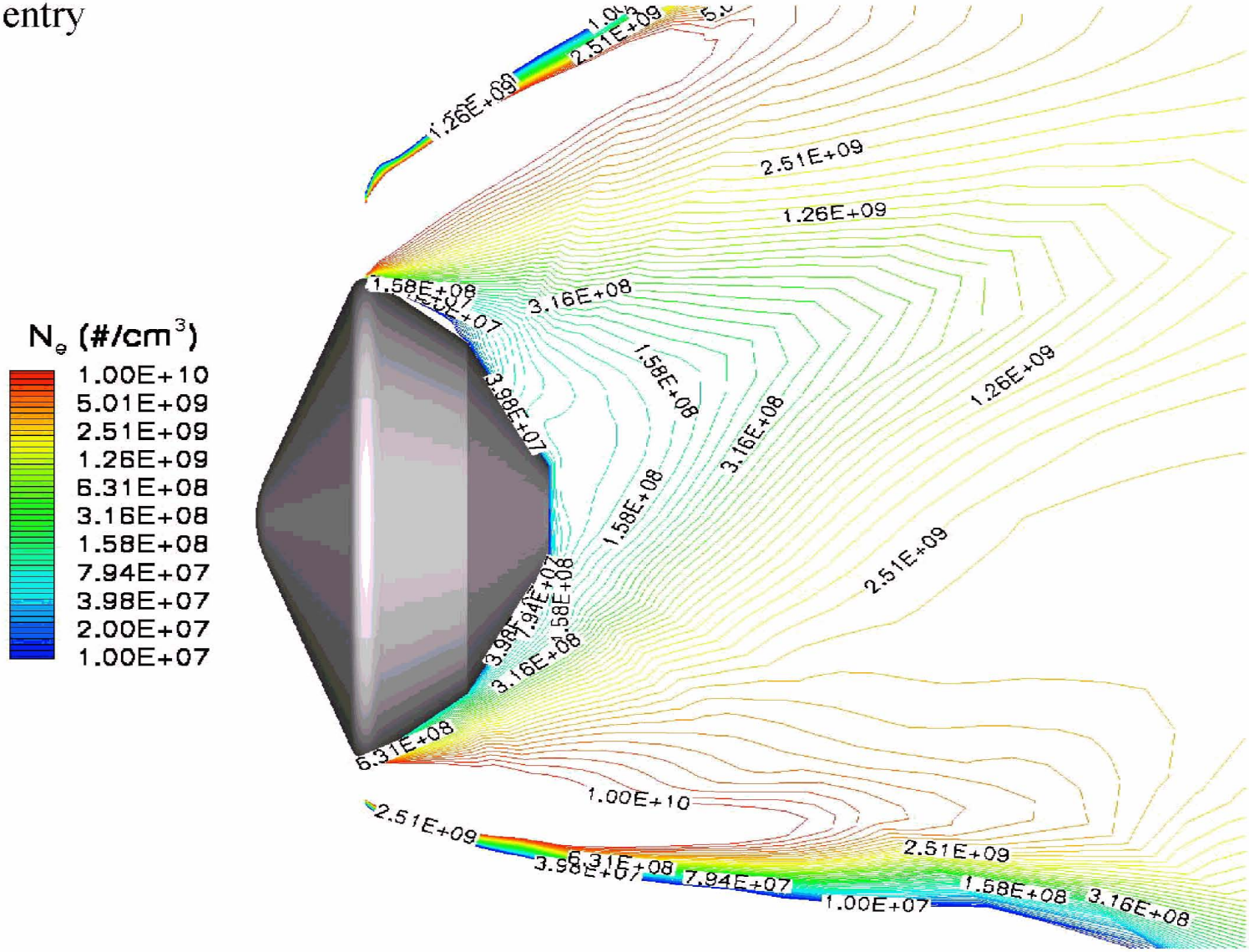
- The Langley Aero-thermodynamic Upwind Relaxation Algorithm (LAURA) was run to provide estimates of electron number density around the period centered around peak heating.
- LAURA is a finite-volume computational fluid dynamics (CFD) code that solves the viscous Navier-Stokes equations using models for chemical non-equilibrium (including ionization), thermal non-equilibrium (two-temperature) and Park-94 reaction rates
- LAURA uses a 20-species constituent set for Mars to estimate electron number density levels and assumes a free-stream composition for the atmosphere of 97% carbon dioxide, and 3% molecular nitrogen by mass.
  - Species considered: C, C^+, CN, CN^+, CO, CO_2, C_2, C_3, CO^+, N, N^+, NO, NO^+, N_2, N_2^+, O, O^+, O_2, O_2^+, e^-
- Reactions may occur in both forward and backward (recombination) directions.
- Detailed descriptions of conservation equations and physical models used by the LAURA program are provided in the cited literature.
- Comparisons of LAURA estimated aero-thermodynamic parameters to experimental data are well documented in the literature
- The LAURA predictions of electron number density are estimated to have an uncertainty of about an order of magnitude.
- The calculation of a chemically-reacting hypersonic flowfield remains a difficult problem that requires a combination of several physical models.
- The problem becomes even more challenging in the wake region of a blunt body, where the flowfield is often unsteady and is characterized by complex flow features that are difficult to capture computationally.

MSL EDL Plasma-Induced Communication Outage Modeling Approach

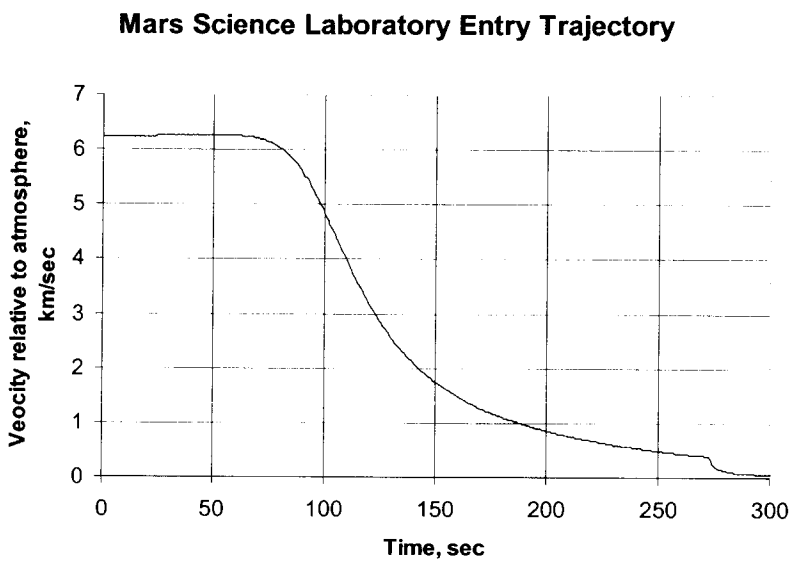
- Obtained entry trajectories which include profiles of time-tagged atmospheric density and atmospheric relative velocity for two cases
  - Stressful case (0306) (83° latitude, entry velocity of 6.26 km/sec)
  - Nominal case (0301) (-41° latitude, entry velocity of 5.7 km/sec)
- Performed a series of LAURA runs centered about the period of peak heating for the entry vehicle
  - Contour plots of electron number density were obtained for each selected time point in the trajectory
  - Peak electron number densities for each of the following signal path directions looking out of the vehicle were obtained and plotted
    - Stagnation point
    - Nose
    - Wake shoulder wind-side
    - Wake shoulder lee-side
    - Wake base region (looking out the rear of the vehicle)
- Since wake region is where communications antennas would be located, the wake region electron number density profiles were compared against critical electron number densities for possible communications frequencies
  - UHF used to communicate with orbiters
  - X-band possible direct-to-earth link
- If electron number density exceeds critical number density, then a blackout is likely for a given frequency
- If electron number density lies below the critical number density, then a blackout is unlikely for a given frequency

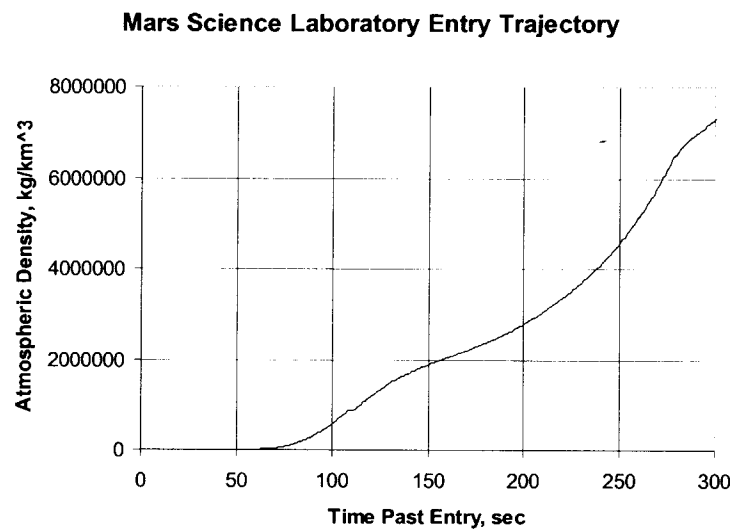


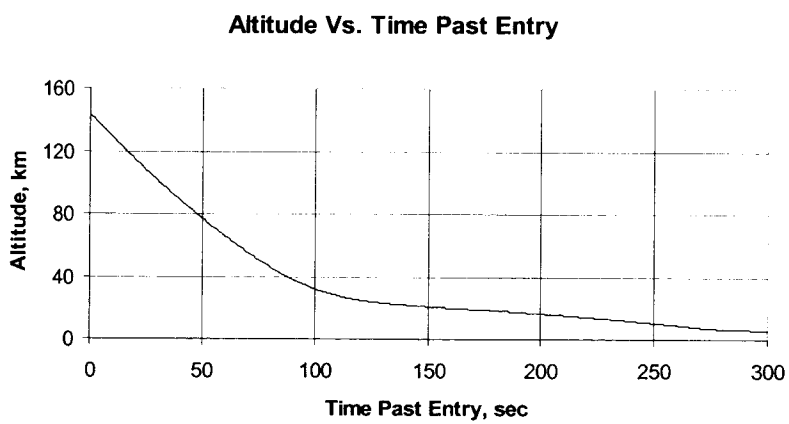
Example of Langley LAURA contour plot of electron density in wake region for 60-sec past entry



MSL Entry Profiles: Case 0306







Key Events:

Maximum heat rate 91.64 sec

Maximum deceleration local 105.065 sec

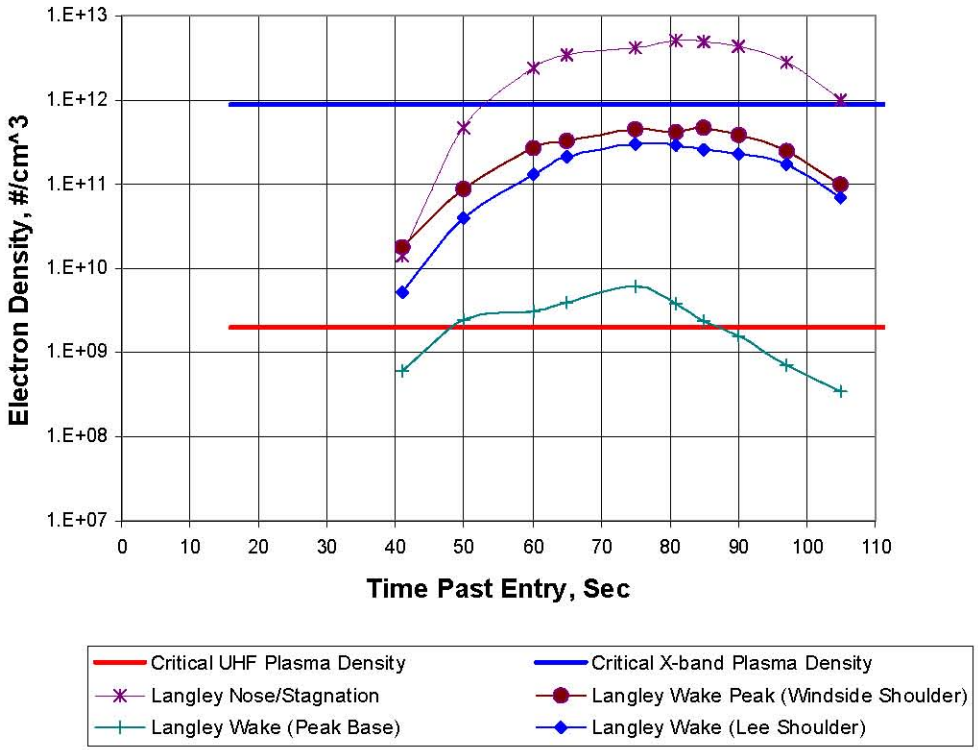
Stagnation Pmax local 105.436 sec

Dynamic Pmax local 105.436 sec

Active guidance maneuver – (switch in bank angles from 68 deg to 20 deg) 196 sec

Chute deploy 272.99 sec

MSL Stressed Entry Trajectory Case 0306: 83 Deg North, Ventry = 6.26 km/sec



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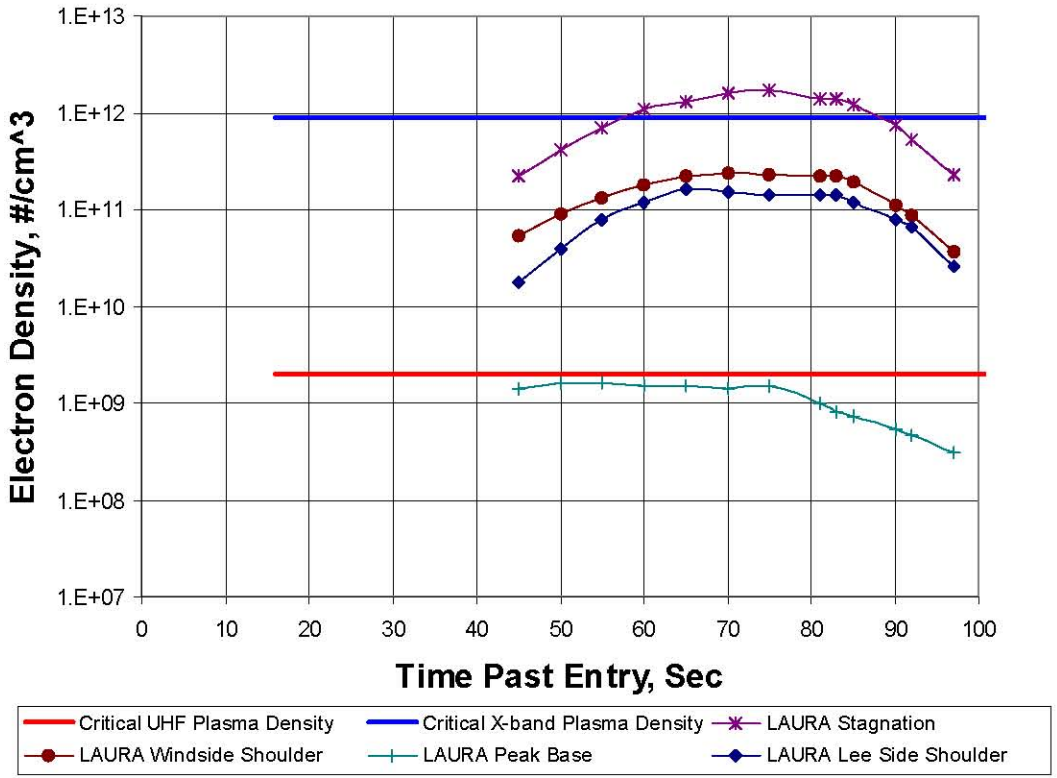
MSL Nominal Trajectory Case 0301, –41.45° latitude, Ventry = 5.7 km/sec



Conclusion

- During MSL's atmospheric entry there will likely be a communication outage due to charged particles on the order of 60 to 100 seconds using a UHF link frequency looking out the shoulders of the wake region to orbiting relay asset
- A UHF link looking out the base region would experience a shorter duration blackout, about 35 seconds for the stressed trajectory and possibly no blackout for the nominal trajectory
- There is very little likelihood of a communications outage using X-band (however, X-band is not currently planned to be used during peak electron density phase of EDL)

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