

Communications Blackout Predictions for Atmospheric Entry of Mars Science Laboratory

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Abstract—The Mars Science Laboratory (MSL)^{1,2} is expected to be a long-range, long-duration science laboratory rover on the Martian surface. MSL will provide a significant milestone that paves the way for future landed missions to Mars. NASA is studying options to launch MSL as early as 2009. There are three elements to the spacecraft; carrier (cruise stage), entry vehicle, and rover. The rover will have a UHF proximity link as the primary path for EDL communications and may have an X-band direct-to-Earth link as a back-up

Given the importance of collecting critical event telemetry data during atmospheric entry, it is important to understand the ability of a signal link to be maintained, especially during the period near peak convective heating. The received telemetry during entry (or played back later) will allow for the performance of the Entry-Descent-Landing technologies to be assessed. These technologies include guided entry for precision landing, a new sky-crane landing system and powered descent.

MSL will undergo an entry profile that may result in a potential communications blackout caused by ionized particles for short periods near peak heating. The vehicle will use UHF and possibly X-band during the entry phase. The purpose of this report is to quantify or bound the

likelihood of any such blackout at UHF frequencies (401 MHz) and X-band frequencies (8.4 GHz). Two entry trajectory scenarios were evaluated: a stressful entry trajectory to quantify an upper-bound for any possible blackout period, and a nominal trajectory to quantify likelihood of blackout for such cases.

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1. INTRODUCTION

Several missions have flown or are being planned in which spacecraft will descend into planetary atmospheres to realize a variety of objectives. Such missions include landers, rovers, and airplanes, as well as orbiting spacecraft, which can use the planetary atmosphere to decelerate into the desired science orbit with reduced fuel usage. Mars Science

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² IEEEAC paper #1163, Version 1, Updated October 20, 2004

Laboratory is a direct entry lander which will use atmospheric drag to slow down sufficiently prior to parachute deployment, and thruster rocket firing to further slow down before landing.

As a spacecraft enters a planetary atmosphere at a velocity that significantly exceeds the speed of sound, a shock layer forms in front of the vehicle. The resulting sheath of charged particles, which develops around the spacecraft, is the result of ionization of the atmospheric gases as they are compressed and heated by the shock, or heated within the boundary layer adjacent to the spacecraft. When the electron number density exceeds the critical plasma number density at the link frequency, communications can be disrupted and result in significant attenuation or even blackout. Blackout is caused by reflection or absorption of electromagnetic energy at frequencies below the critical plasma frequency. At frequencies higher than the plasma frequency, the layer will be effectively transparent to the transmitted signal, and communications can take place.

In order to assess any potential blackout problem, the atmospheric entry profile can be analyzed by using aerothermodynamic tools. Such tools make use of composition, pressure, temperature, and density information of the planetary atmosphere as well as a variety of other parameters [1-2]. Such tools produce as output the estimated number densities of chemical species that may be present including electron number density at the stagnation point or wake region. (Note: The stagnation point is the point near the nose of the vehicle where the flow splits up (or divides) or where the velocity of the fluid decreases and eventually comes to rest effectively without any deflection).

The electron number density is the result of the combined concentrations of the various ionized species, which are generated due to the high temperatures encountered. Since the antennas used for communication during atmospheric passage are mounted on the back-shell of the spacecraft, the electron number density along the signal path in the wake region must be estimated. The wake region electron number density will be significantly less than that at the stagnation point, but still could exceed the critical electron number density required for blackout in some cases. Some early work on the communications blackout problem at Mars such as that of Nordgard [3] and D. Spencer 1964 [4] are summarized in [1].

During the entry phase of the Mars Pathfinder spacecraft into the Martian atmosphere on July 4, 1997, communications with Earth were lost for an approximately 30-second period starting at about 17:03:20 UTC [5] around the time of peak heating. The emitted signal frequency of 8.43 GHz was configured in the one-way tracking mode at the NASA Deep Space Network (DSN) 70-m diameter antenna located in Madrid, Spain. Among the several possible explanations for the outage, was one attributed to

ions generated from the interaction of the heat shield with the Martian atmosphere. To test the likelihood of this possibility, the reconstructed flight profile of Mars Pathfinder during the blackout period was input to an aerothermodynamic program to estimate electron number density [1]. The analysis provided estimates of the electron number densities in the entry vehicle's stagnation and wake regions. For the wake region, where the LGA antenna mounted on the back-shell used to communicate with Earth is located, the estimated electron number density exceeded the critical 8.4 GHz (X-band) electron number density at least during the first 20-seconds of the 30-second blackout period. Other factors may have contributed to the blackout during the last 10-seconds [1]. Thus, at least most of the Mars Pathfinder communications 30-s blackout period was likely caused by the sheath of charged particles that were generated by the heating behind the shock during atmospheric entry.

The Mars Exploration Rovers (MERs), Spirit and Opportunity, made their entries of the Martian atmosphere on January 4, 2004 and January 25, 2004, respectively (UTC times). The MERs entered the Martian atmosphere at a sufficiently lower atmospheric relative velocity (~5.5 km/sec) than Mars Pathfinder (~7.4 km/sec). The MERs were predicted to not experience a communications blackout, as estimated levels of electron number density were orders of magnitude below the critical X-band electron number density required for blackout [1]. The DSN maintained lock on the 8.4 GHz signal transmitted by each vehicle during descent, including the intense periods centered around peak heating (P. Estabrook, private communication), when the charged particle number densities were at their peak. The DSN only lost the signals transmitted from each vehicle after landing and bouncing as expected, well after the period of peak heating.

This report will detail predictions of blackout for the upcoming Mars Science Laboratory entry into the Martian atmosphere in 2010. Both the JPL Horton program, and the Langley Aero-thermodynamic Uppwind Relaxation Algorithm (LAURA) program were run using a time series of input velocity and altitude (atmospheric density) pairs derived from predicted entry profiles for both a stressful entry case and a nominal entry case. The first case was chosen in order to quantify any upper bound on blackout for either, the baseline UHF link (401 MHz) or for a possible X-band (8.4 GHz) link currently being considered for the design. The Horton program is documented in [1-2].

The Langley Aero-thermodynamic Uppwind Relaxation Algorithm (LAURA) was run to provide independent estimates over 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 [6]. LAURA uses a 20-species

constituent set for Mars to estimate electron number density levels and assumes a freestream composition for the atmosphere of 97% carbon dioxide, and 3% molecular nitrogen by mass. 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 [7]. Comparisons of LAURA estimated aero-thermodynamic parameters to experimental data are well documented in the literature [8, references therein]. 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.

2. EFFECTS OF CHARGED-PARTICLES ON COMMUNICATIONS

The surrounding plasma on a spacecraft entering a planetary atmosphere, if sufficiently dense, will attenuate any emitted signal by absorption and reflection. Electrons are the principle contributors to reflection of waves in a plasma gas. The ability for a signal to propagate will depend on the transmission frequency, the electron collision frequency and the plasma frequency of the charged particle sheath. Since the collision frequency is usually much smaller than the critical plasma frequency, collision effects are not considered important. The effect of charged particles generated by the heating of atmospheric gases or by an ablating heat shield as a spacecraft enters an atmosphere will be to blackout the signal if the resulting charged particle number density exceeds the plasma density at that frequency. The signal will be attenuated for frequencies which fall below the plasma frequency, and will be unaffected for frequencies which lie above it. The critical plasma densities for a few common telecommunications link frequencies are provided in Table 1 [1]. The critical density is expressed in particles/cm³, a commonly used number density unit.

Table 1 - Critical Electron Number Densities

<u>Link Frequency</u>	<u>Designation</u>	<u>Critical Electron Number Density</u>
(GHz)		(particles/cm ³)
0.4	UHF	2.0 x 10 ⁹
2.3	S-band	6.6 x 10 ¹⁰
8.4	X-band	8.8 x 10 ¹¹
32.0	Ka-band	1.3 x 10 ¹³

The typical telecommunications strategy during atmospheric entry is to maintain carrier visibility for as long as possible. For MER, Multiple Frequency Shift Keying (MFSK) modulation was chosen to relay spacecraft conditions, using a very low data rate with one "tone" or frequency transmitted every ten seconds to Earth reporting on the status of the vehicle's state. An open-loop receiver system was developed by the DSN to increase the probability of detection of the carrier and the tone. In addition, vehicle telemetry is recorded on-board during any expected blackout period and transmitted when communications are later restored. The use of higher frequencies can reduce the blackout period or eliminate the blackout condition entirely. Thus, as an example, MSL using an X-band direct-to-earth link may not suffer blackout during EDL while the proximity UHF link may be blacked out, depending on the entry trajectory.

3. THE USE OF AERO-THERMODYNAMIC MODELING TO PREDICT ELECTRON DENSITY

Aero-thermodynamic tools have been used in a wide variety of applications for several different atmospheric flight applications and scenarios, including entry vehicles and spacecraft as they fly through a gaseous environment such as a planetary atmosphere. One such program, the JPL Normal Shock and Chemical Equilibrium Program (here-to-fore referred to as the Horton program) developed and first used in the 1960's [2], calculates chemical equilibrium properties associated with traveling, standing and reflected normal shocks. This program determines thermodynamic properties and chemical composition of high-temperature multi-species real gas mixtures under conditions of chemical equilibrium. A detailed discussion of the Horton program and its input and output quantities are provided in [1]. The results of a set of Mars atmosphere and Earth atmosphere entry cases is also detailed in [1].

The Horton program evaluates the various quantities approximating free flight conditions for the case when the gas is in chemical equilibrium. The effect of wall shear and heat transfer are considered negligible in this treatment. The shape of the vehicle is not modeled in the calculations. The use of this method will start to break down at higher altitudes or under conditions such that the gas is in a state of non-equilibrium. It is in these cases, that the use of the LAURA program is expected to provide more reliable results.

Alternate predictions were generated using the LAURA CFD code, which models the entire chemical non-equilibrium flowfield, including the ionization of component species at high temperatures. Figure 1 provides a pictorial perspective of the atmosphere entry during peak heating when a shock forms about the vehicle, using the specifications of MSL. The heat shield is on the left side and

the backshell is on the right side. In this figure, the X-band antenna would normally be designated 'BLGA' as the backshell low gain antenna used to communicate with Earth. The relative locations of two of the three UHF antennas are also displayed. The LAURA program was used to generate this image where the different colors denote different levels of electron number density about the MSL vehicle.

The nominal Martian atmosphere model assumes a surface pressure of about 6.1 mb and compositional proportions of CO₂ 95.3%, N₂ 2.7% and Argon of 1.6%. An Argon-free simplification Martian atmosphere model was actually used as input to the Horton program to facilitate comparisons with the Langley Research Center LAURA program results, which neglects Argon, since it does not contribute appreciably to the production of free electrons during atmospheric entry.

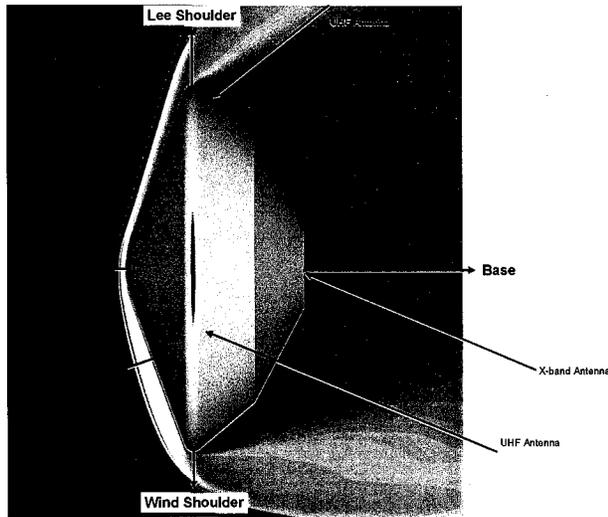


Figure 1 – A pictorial representation of MSL with the LAURA flowfield, depicting the various points for which electron number density estimates are referred to. The location for two of the three UHF antennas (spaced 120 deg apart) are displayed, as well as that of the X-band antenna. The different colors depict different levels of charged particle number density.

In order to estimate the number density of electrons in the region around a spacecraft entering a planetary atmosphere using the Horton program, a flight profile consisting of a series of atmosphere-relative velocity and altitude time-tagged points is required. When actual reconstructed atmospheric density as a function of flight altitude are available, such as was the case for Mars Pathfinder [9] these are input directly into the program (after appropriate normalization).

A series of normal shock cases using the Horton program at a given input pressure are run for several different

“expected” shock temperatures. The program output will include values of shock velocity and electron number density for each case. The electron number density estimated by the Horton program is referenced to the stagnation point, defined to be a point near the nose on the fore-body of the vehicle encountering the shock as the vehicle transits the atmosphere (see Figure 1). This estimate is obtained from the normal shock solution for the temperature, which produces the shock (or free-flight) velocity closest in agreement with flight path profile velocity for that point. Non-linear interpolation is performed over several solution pairs of electron density and shock velocity, to allow for an optimal estimate of the electron number density at the predicted flight profile velocity.

The antenna used for communications with Earth lies in the rear of the vehicle partly due to the difficulty of placing an antenna on the vehicle’s heat shield, and largely due to the direction towards Earth lying behind the vehicle during descent. It is thus necessary to estimate the electron number density in the wake region. The ratio of electron number density in the wake region to that at the stagnation point can be estimated using:

$$\frac{n_{e,w}}{n_{e,s}} = \left[\frac{\kappa P_{\infty}}{P_G} \right]^{\frac{1}{\gamma}} \quad (1)$$

where $\frac{P_{\infty}}{P_G}$ is the pressure ratio across the shock region, (an output of the program for the given flight profile point), γ (1.33) is the isentropic expansion coefficient (or ratio of specific heats), and κ (3.5) is the free-stream to wake region pressure correction factor [1]. The approximation of (1) can produce different results as the coefficient, γ , is not constant as the gases expand, and the wake region pressure can be significantly higher than the free-stream pressure P_{∞} during certain periods during atmospheric entry.

Using the frozen flow approximation with $\kappa = 1$ in (1), the electron number density in the stagnation region is assumed to remain constant as the gases flow around the spacecraft into the wake region. This approximation does not account for any recombination of the chemical species, as the change in number density is assumed due entirely to the expansion of the gases. This method is thus considered conservative [4] and serves as an upper bound on the wake region electron density. A refinement to (1) using $\kappa = 3.5$, was estimated from an independent set of stagnation and wake region peak number densities output from the LAURA program [1]. The Horton program estimates of wake region electron number density using (1) were found to be in agreement with independently determined peak wake-region values estimated by Langley’s LAURA program to the 50% level [1] for high velocities. The inclusion of the factor κ in (1),

thus allows for a better approximation of the wake region peak electron number concentration during the period around peak heating. Given that the uncertainty is expected to grow for periods away from the peak heating regime, and that the uncertainty in the LAURA estimates are of comparable magnitude, the uncertainty of the electron number density estimates from the Horton program is taken to be about an order of magnitude for entry velocities above ~5.7 km/sec and deteriorates rapidly for velocities that lie below it.

The wake region electron number density using equation (1) is compared against the critical electron number density at the link frequency (Table 1) to determine if a communications blackout condition is likely. This assumes that the communication antenna is located in the wake region. The basic "rule of thumb" for testing for a blackout condition is (1) if the calculated electron number density lies below the critical plasma number density by more than an order of magnitude, blackout is termed unlikely, (2) if the calculated electron density lies above the critical electron number density by more than an order of magnitude, blackout is termed likely, and (3) if the calculated electron number density is within an order of magnitude of the critical number density, blackout is deemed uncertain, but possible.

4. MARS SCIENCE LABORATORY: ATMOSPHERIC ENTRY

The Mars Science Laboratory is expected to be launched between July 2009 and December, 2009 and will enter the atmosphere of Mars between July 2010 and December 2010. The aero-shell consists of a fore-body heatshield and an aft-body backshell. The fore-body material may consist of SLA-561V with a thickness of ~19 mm. The backshell may be thermally protected using a spray-on version of the SLA-561 material.

The Mars Science Laboratory will have three antennas separated 120° apart on the backshell transmitting telemetry data at UHF to an orbiting relay and possibly one back-shell Low Gain Antenna (BLGA) transmitting carrier and MFSK signals to Earth at X-band during the atmospheric entry. It is during this phase that communications are most susceptible to charged particle build-up. The antennas used for UHF communications will be switched and are of patch design. Based on preliminary MSL design considerations, the X-band BLGA is assumed to be a circular waveguide three-ring choke³, with an on-axis gain of 6.5 dB on axis and an omni-directional antenna pattern (HPBW of ±45°). The BLGA is assumed to be composed of Beryllium copper to be placed on the back shell of the spacecraft if the use of an X-band link during entry is implemented.

MSL Entry Case 0306 (entry velocity of 6.3 km/sec)

The profile designated 0306 is one of the most stressful MSL entry cases identified so far. Case 0306, applies for an 83° N latitude entry, with an atmospheric relative entry velocity of 6.26 km/sec. For this case, MSL will be entering the Martian atmosphere with a Flight Path Angle of -14°. The spacecraft reaches maximum stagnation point heating and peak dynamic pressure within the first 110 seconds of the entry phase. The maximum stagnation point heating rate occurs at 91.6 sec past entry and maximum dynamic pressure occurs near 105 sec past entry where the acceleration was 9.2 g's. An active guidance maneuver employs a switch in bank angles from 68° to 20° that occurs at 196 seconds past entry, and a chute deploy that occurs at about 273 seconds past entry. Prior to the cruise stage separating, MSL is expected to execute a turn in preparation for entry, where X-band may be used for communications to a 70 m diameter DSN subnet antenna. After the cruise stage separates, X-band may also be used to transmit carrier and MFSK signals to a 70 m DSN antenna or subnet array. During the atmospheric entry to landing phase, the UHF link will be used with 2 to 8 kbps telemetry to an orbiting relay⁴. Figure 2 displays a depiction of an MSL entry profile along with possible communications scenarios. For MSL entry trajectories, the period when a significant number of charged-particles are generated is expected to lie between 20 and 110 seconds past atmospheric entry. Atmospheric entry is defined as the point for which the probe is at a distance of 3522.2 km from the center of the planet.

The predicted MSL entry trajectory of velocity versus time past atmospheric entry for the 83N case is shown in Figure 3. The altitude versus time past atmospheric entry plot is shown in Figure 4. The atmospheric density versus altitude plot is shown in Figure 5. Atmospheric entry ($t=0$) corresponds to an altitude of about 144 km above the surface for the 0306 case. For reference, the maximum heating rate occurs at 91.6 seconds past entry, and peak dynamic pressure occurs at 105 seconds past entry.

³ S. Valas, private communication, February 2004.

⁴ S. Valas, "Mars Science Laboratory Baseline Telecom Description Document", December 10, 2003.

EDL Communications

(Nominal Timeline; ■ indicates possible blackout)

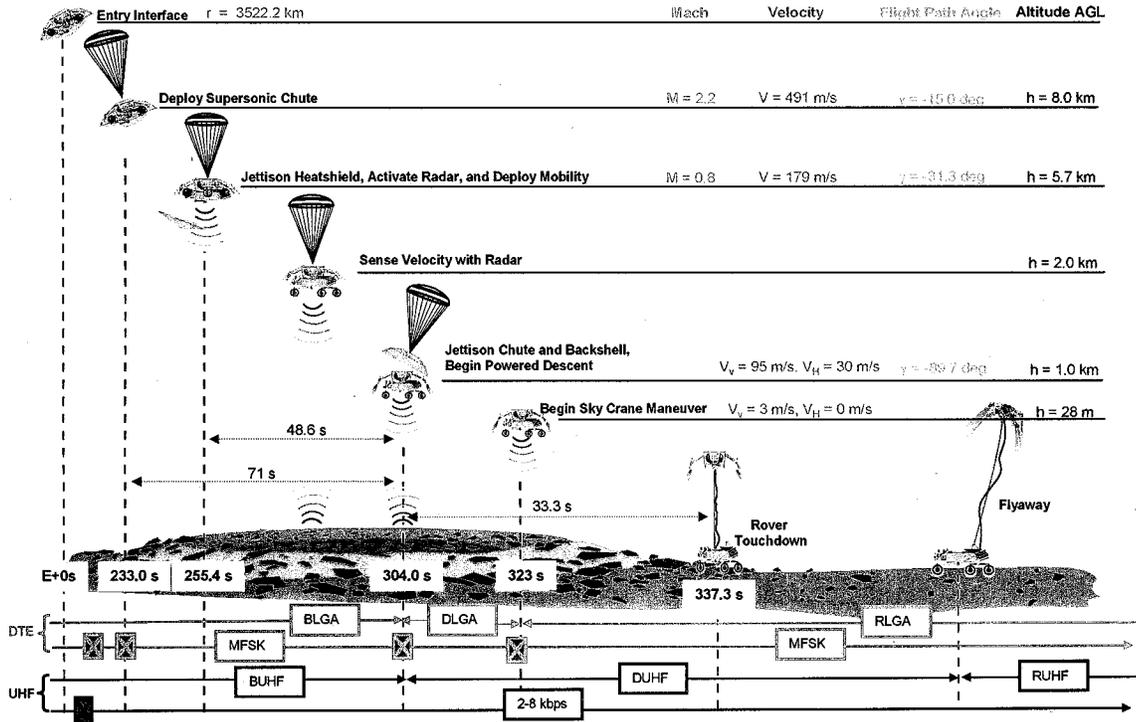


Figure 2 – Possible MSL Entry Profile and Telecom Strategy (Courtesy of Sam Valas)

The Horton Program was run for several entry flight path trajectory points. The wake region peak electron number density was approximated from the stagnation point number densities and pressure ratios output from the Horton program, using values of $\gamma = 1.33$ and $\kappa = 3.5$ in equation (1). The resulting Horton program electron number density profiles for both stagnation and wake regions of the spacecraft are displayed in Figure 6 along with the critical electron number densities for UHF and X-band (solid curves with connected data points). This analysis is based on 19 entry points of altitude, velocity pairs, performing 19 independent program runs using the Horton program. Note that in Figure 6, the wake region electron number density curve lies above the critical electron number density for UHF between 23-s and 90-s after entry. Thus about 67-s of communications blackout is possible at UHF assuming the Horton wake region profile. As the uncertainty of the curves is of order of magnitude, this period could be larger or smaller depending on atmospheric conditions, and this also will depend upon the entry trajectory that is actually used for MSL entry, as well as antenna aspect angles towards any receiving asset.

The Horton wake-region electron number density profiles in Figure 6 however lie below the critical X-band electron number density by about an order of magnitude. Given that the expected uncertainty is about an order of magnitude at

these velocities, a blackout condition is considered unlikely at X-band, especially for any meaningful time duration.

Mars Science Laboratory Entry Trajectory

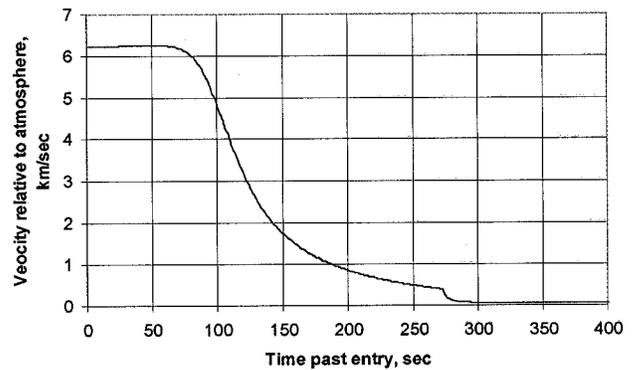


Figure 3 – Case 0306 - Atmosphere relative velocity versus time in seconds past entry

In addition to the peak electron number densities using the JPL Horton program, the corresponding stagnation point and wake region electron number densities extracted from Langley LAURA plots are also plotted in Figure 6.

At 60-sec past entry (Shock velocity of 6.25 km/s, and altitude of 65 km), the Horton program estimated a stagnation electron number density of $n_e = 2.1 \times 10^{12}/\text{cm}^3$ versus the LAURA estimate of $2.4 \times 10^{12}/\text{cm}^3$. At 65-sec past entry (Shock velocity of 6.24 km/s and altitude of 61 km), the Horton program estimated a stagnation electron number density of $n_e = 3.5 \times 10^{12}/\text{cm}^3$ versus the LAURA estimate of $3.4 \times 10^{12}/\text{cm}^3$. At 75-sec past entry (Shock velocity of 6.14 km/s and altitude of 50.85 km), reasonable agreement upon inspection of Figure 6 is again evident between the two programs.

The Horton program estimates for the stagnation point electron number densities are in reasonably good agreement with the LAURA stagnation estimates at least for these data points. For times greater than 80 seconds past entry, the LAURA program stagnation point electron number densities appear to start to significantly exceed the Horton program estimates, suggesting that the realm of validity of the Horton program may be exceeded here. The agreement breaks down away from the period around the peak electron number density curves. The algorithm used in the Horton program assumes equilibrium conditions while the LAURA program was run in a non-equilibrium mode, which allows for recombination (factoring in the transit time considerations).

The LAURA estimates serve as a better estimate of the electron number density environment over all atmospheric realms (equilibrium and non-equilibrium) as well as taking the vehicle shape and size into account. In addition the LAURA contour plots allow for quantifying electron number densities for specific antenna aspect angles. The LAURA program also accounts for more chemical reactions, and provides distribution of electron density about the vehicle (contour plots), a feature the Horton program does not have.

The agreement of the Horton data points near peak heating has been previously quantified to the 50% level with Langley Research Center's LAURA program over a limited set of data points [1]. An order of magnitude uncertainty on the Horton data points is believed to be a reasonable estimate at least in the realm of the highest velocities.

The peak wake region densities previously used to compare with the Horton wake region densities were extracted from the Langley LAURA contour plots usually near the shoulder of the vehicle or nearly 90 degrees off the vehicle axis on the wake region side [1]. These values usually agree between the two programs near peak heating which is not surprising given that the Horton program stagnation values

were converted to wake region densities using equation (1) using a value of κ determined from an independent set of LAURA program estimates of stagnation point density and peak wake region density. The peak wake region values between the two programs also start to deviate significantly at 90 seconds past entry. The electron number density estimates from Horton and LAURA agree to the 50% level over much of the peak wake region profile but discrepancies grow over the last 20 seconds of the peak profile, and is large at the first common point at 41 sec past entry in Figure 6.

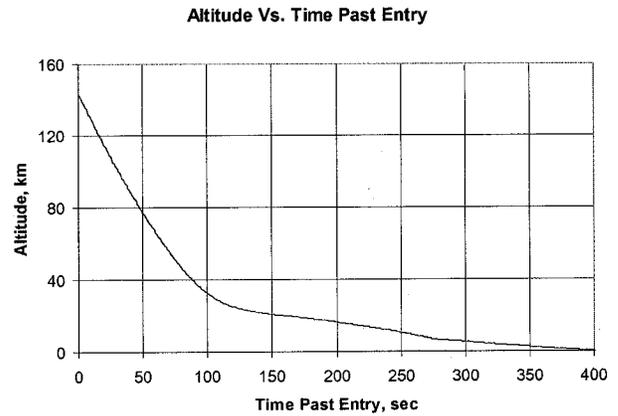


Figure 4 – Case 0306 - Altitude versus time in seconds past entry

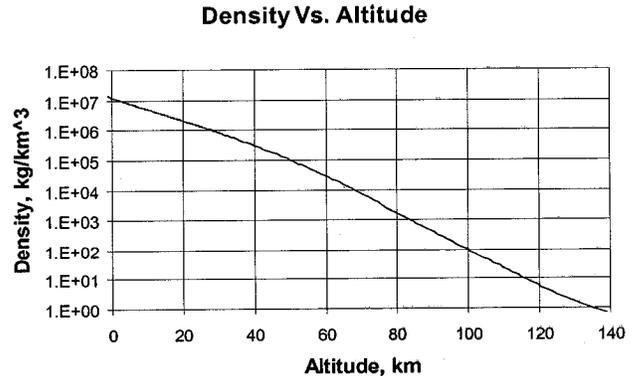


Figure 5 – Case 0306 - Atmospheric density versus altitude

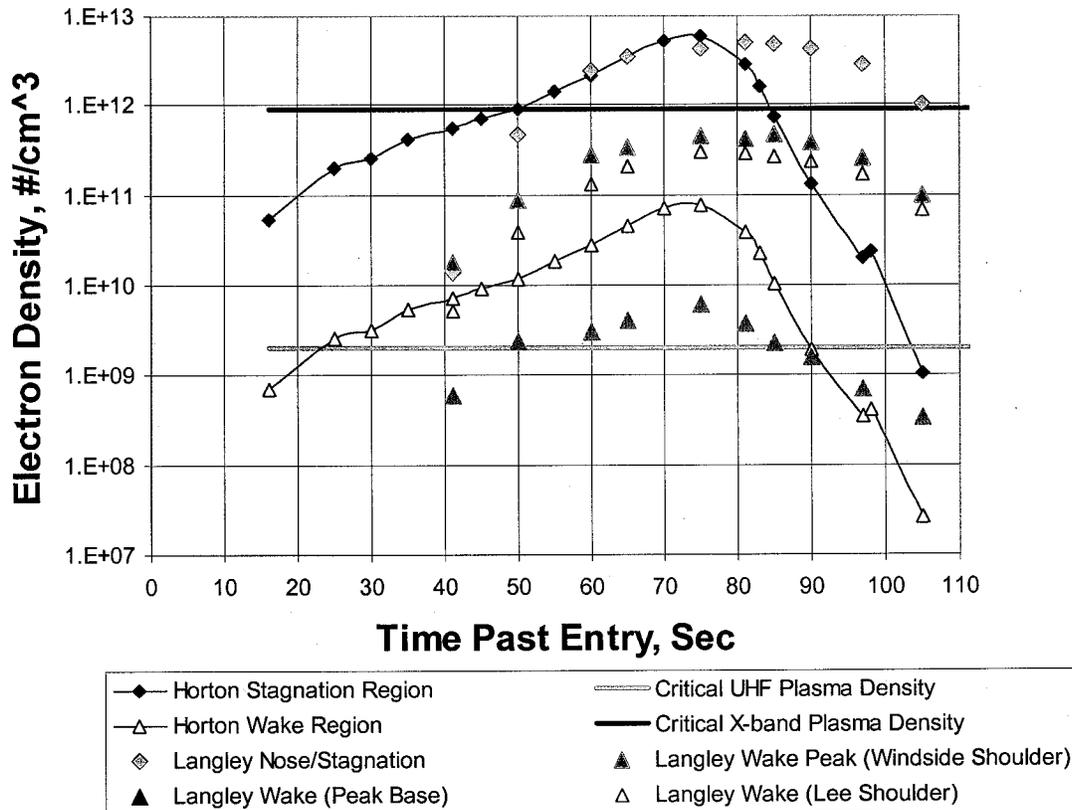


Figure 6 – Mars Science Laboratory atmospheric entry electron number density profiles for wake and stagnation region along with critical UHF and X-band densities for Case 0306

For this study, a different approach was taken. The LAURA peak base wake region number densities were extracted from the maximum contour value lying on the symmetry axis looking directly out into the wake region from the rear of the spacecraft. Both windside and lee side shoulder electron number densities are also plotted. In this treatment, the Horton curve lies somewhere in between the maximum and minimum LAURA wake region estimates during the period about peak heating, and starts to deviate from LAURA away from this region. If one uses the LAURA curves to infer blackout in the wake region, then by simple extrapolation of the data, the outage period can be as long as ~95 seconds using the shoulder curve values and as short as ~35 seconds using the peak base values. This result quantifies worst case communication outage conditions. The actual blackout period duration will depend on the actual entry trajectory used, the location of the Earth relative to the vehicle axis (the antenna aspect angle out of the wake region), the peak electron number density along that path, and any uncertainties such as due to atmospheric variability.

Laboratory atmospheric entry at 60-s, 65-s and 75-s past entry are presented in Figures 7, 8 and 9, respectively. The LAURA program factors the shape of the spacecraft vehicle, but does not consider ablation products from the vehicle itself, which are assumed negligible.

Both JPL Horton and Langley Research Center LAURA programs estimate wake region electron densities, which exceed the critical electron density for a UHF-band communications blackout with durations anywhere from ~35-sec to ~95-sec depending upon antenna aspect angles.

Wake region electron number density contour plots generated by Langley's LAURA program for Mars Science

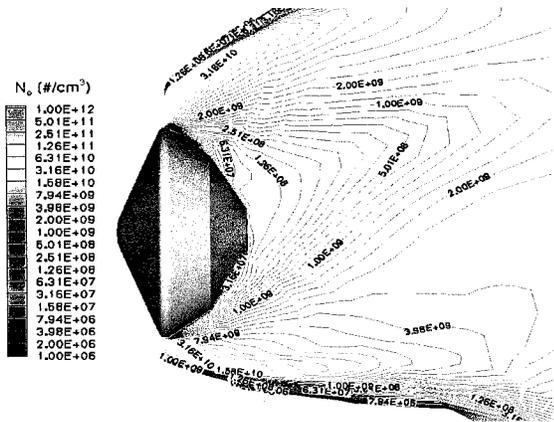


Figure 7 – Case 0306 - LAURA Electron Number Density contour plot for 60-seconds past entry

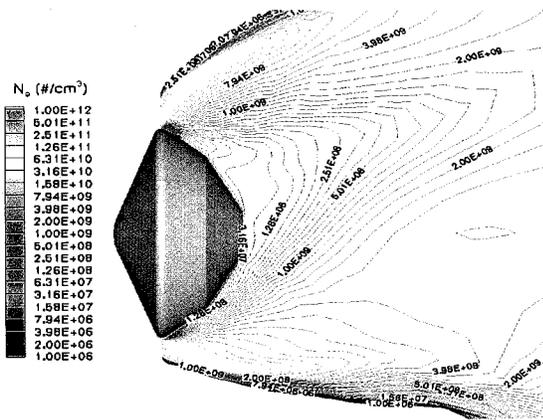


Figure 8 – Case 0306 - LAURA Electron Number Density contour plot for 65-seconds past entry

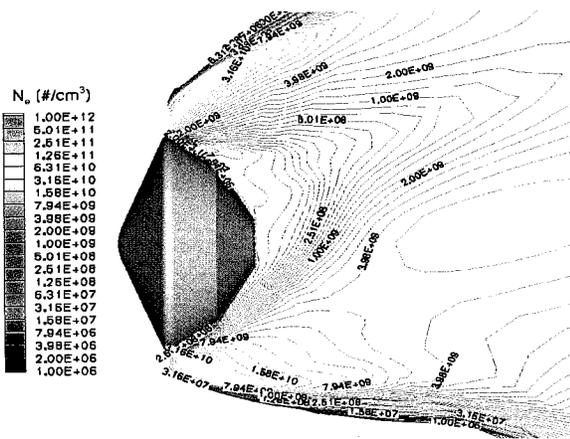


Figure 9 – Case 0306 - LAURA Electron Number Density contour plot for 75-seconds past entry.

For this worse-case trajectory, the LAURA program results support the likelihood of a possible communications

blackout during atmospheric entry using a UHF link frequency (401 MHz), and that there is less likelihood of a blackout using X-band (8.4 GHz).

The spacecraft may have an X-band link to Earth that may transmit carrier and MFSK tones indicating status of the spacecraft during the Entry-Descent-Landing (EDL) phase (see Figure 2). It is expected that this X-band link could be maintained for the entire critical period of EDL atmospheric entry, as the predicted worst-case wake region peak electron number density entry curve in Figure 6 lies below the critical X-band electron number density required for blackout. Compared to MSL’s entry velocity of 6.3 km/sec considered here, the two MER spacecraft (no plasma-induced X-band blackout) entered the Martian atmosphere at much lower velocities (~5.5 km/sec) and the Mars Pathfinder spacecraft (20 to 30 sec induced X-band plasma blackout) entered at a much higher velocity (~7.5 km/sec).

The predicted level of charged particles has an order of magnitude uncertainty associated with it, and thus only bounds on blackout conditions can be provided, but are therefore expected to be significantly lower than those of Mars Pathfinder at X-band. The UHF signal received by an orbiter will likely experience a significant blackout period on the order of a minute during the period around peak heating, assuming this worse-case entry trajectory.

MSL Entry Case 0301 (entry velocity of 5.7 km/sec)

The profile considered here is for a nominal more likely MSL entry case. Case 0301, applies to a -41.45° latitude entry, with an atmospheric relative entry velocity of 5.7 km/sec. For this case, MSL will be entering the Martian atmosphere with a Flight Path Angle of -15°. The supersonic parachute deploys at about 242 seconds past entry (first) and the subsonic at 265 seconds past entry. A possible MSL redesign may use a single parachute. The heat shield is jettisoned at 276 seconds past entry.

The predicted MSL entry trajectory of velocity versus time past entry for Case 0301 is shown in Figure 10. The altitude versus time past atmospheric entry plot is shown in Figure 11. The atmospheric density versus altitude profile is shown in Figure 12. For reference, the maximum heating rate occurs at 84.7 seconds past entry, and peak dynamic pressure occurs at 97.3 seconds past entry.

The LAURA electron number density profiles for both stagnation and wake regions of the spacecraft are presented in Figure 13 along with the critical electron number densities for UHF and X-band. The Horton curves lie significantly below the LAURA curves, and therefore are not plotted here as their realm of validity is apparently exceeded. Note that in Figure 13, the wake region peak base electron number density curve lies entirely below the critical electron number density required for blackout at UHF for all points, but only marginally as the difference is significantly less than an

order of magnitude. However, if the signal path to any relay orbiter from the UHF antennas is looking out in the direction of the shoulders, the densities can exceed the critical electron density at select times. Thus, the likelihood of UHF blackout or duration of blackout is expected to be smaller for this nominal entry trajectory (Case 0301) than for the higher velocity entry trajectory (Case 0306), but still possible. The prospect of a blackout at X-band using the nominal entry trajectory is less likely.

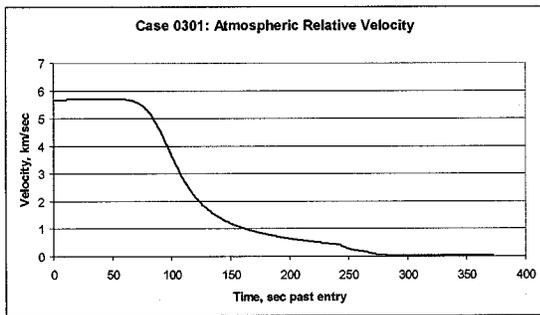


Figure 10 – Case 0301 - Atmosphere relative velocity versus time in seconds past entry

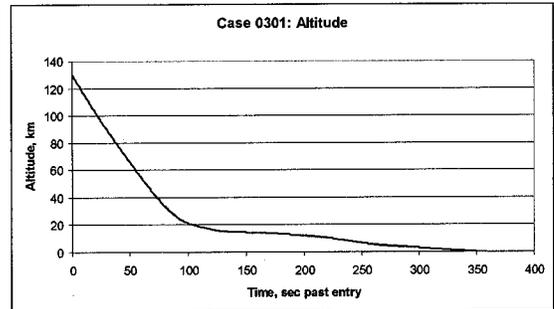


Figure 11 – Case 0301 - Altitude versus time in seconds past entry

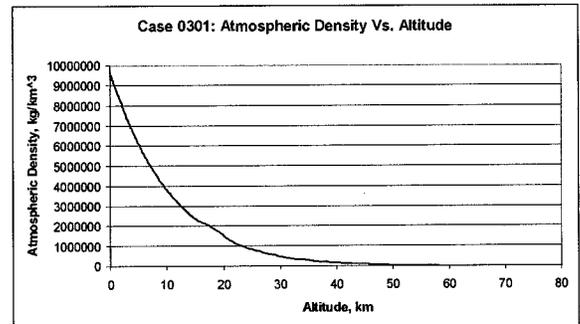


Figure 12 – Case 0301 - Atmospheric density versus altitude

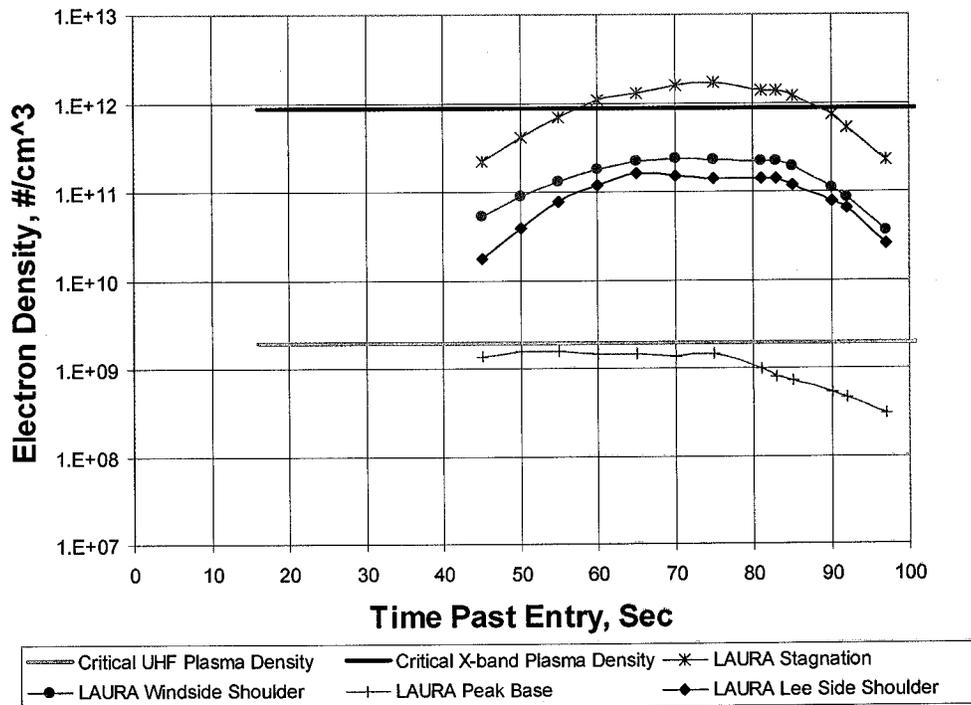


Figure 13 – Case 0301, Mars Science Laboratory atmospheric entry electron number density profiles from LAURA for wake and stagnation regions along with critical UHF and X-band densities

5. CONCLUSION

Based on wake-region electron density estimates produced by the Horton program and the Langley LAURA program, the Mars Science Laboratory is likely to experience a communications blackout at UHF, of up to ~95 seconds in duration assuming the 83°N latitude, 6.2 km/sec atmospheric entry case. This case is close to being the most stressful entry case identified so far. The actual conditions during entry for blackout will depend on the actual trajectory used, the conditions of the Martian atmosphere at the time of entry, antenna aspect angles with respect to Earth, signal-to-noise ratio, and dynamic effects on the received signal such as due to Doppler. However, a communications blackout is deemed less likely if X-band is used as a link frequency during atmospheric entry for this case.

A more likely entry trajectory for MSL suggests that a communications blackout is not as likely for antenna aspect angles out through the back of the wake region at UHF but more probable for signal paths along the shoulders, and virtually non-existent at X-band. Future work includes performing this analysis on any entry trajectory that may become seriously considered, and running the LAURA program over a much larger set of entry times centered about peak heating. This will allow for a full set of data points for both stagnation and wake regions with both upper and lower bounds on the electron number density curves (and confidence limits) to be available for planning a telecommunications link strategy. Once actual antenna aspect angles to any orbiting asset and the Earth are known, refined estimates of the electron number density profile will be realized, and can be compared against threshold number densities required for blackout.

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BIOGRAPHY

David D. Morabito was born in Los Angeles, California. Since 1973, he has worked at Caltech's Jet Propulsion Laboratory in Pasadena, California, on several engineering and scientific research projects. Among the areas he has worked on are spacecraft navigation, Very Long Baseline Interferometry (VLBI), Radio Science experiments on the Voyager 2, Ulysses, and Galileo spacecraft, performance characterization of beam-waveguide antennas, media propagation effects on spacecraft telecommunication links, and telecommunications systems design for proposed future space missions. His most recent project is studying the use of Ka-band (32 GHz) as a telecommunications link frequency for spacecraft communications. He has over ninety publications in several professional journals, and conference proceedings. He is a member of the IEEE, the American Astronomical Society, and the American Geophysical Union.



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