Simulation Schiaparelli's Entry and Comparison to Aerothermal Flight Data

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The European Space Agency recently flew an entry, descent, and landing demonstrator module called Schiaparelli that entered the atmosphere of Mars on the 19th of October, 2016. The instrumentation suite included heatshield and backshell pressure transducers and thermocouples (known as AMELIA) and backshell radiation and direct heatflux-sensing sensors (known as COMARS and ICOTOM). Due to the failed landing of Schiaparelli, only a subset of the flight data was transmitted before and after plasma black-out. The goal of this paper is to present comparisons of the flight data with calculations from NASA simulation tools, DPLR/NEQAIR and LAURA/HARA. DPLR and LAURA are used to calculate the flowfield around the vehicle and surface properties, such as pressure and convective heating. The flowfield data are passed to NEQAIR and HARA to calculate the radiative heat flux. Comparisons will be made to the COMARS total heat flux, radiative heat flux and pressure measurements. Results will also be shown against the reconstructed heat flux which was calculated from an inverse analysis of the AMELIA thermocouple data performed by Astrium. Preliminary calculations are presented in this abstract.

I. Introduction

Researchers from the European Space Agency's ExoMars mission recently published flight data from the Schiaparelli descent module's entry into the Martian atmosphere [1, 2]. The data obtained during Schiaparelli's descent are invaluable for validating models used to design thermal protection systems for future Mars missions and can be used to complement the data MEDLI measured during the Mars Science Laboratory entry in 2012. In order to assess the performance of the heat shield, characterize the atmosphere and better understand the trajectory, the Atmospheric Mars Entry and Landing Investigations and Analysis (AMELIA) [3] package led out of the Università degli Studi di Padova in Italy was integrated with Schiaparelli. Reliable flight data are essential for the optimization of thermal protection system design, which in general is carried out with relatively high safety margins. This is particularly true for the backshell where margin factors up to 3x have been used for many past missions [4]. High margins compensate for the large uncertainties associated with simulation tools in expanding and separated flow as experienced on the backshell. Limited ground experimental data are available to validate radiation from CO_2 when the flow is expanded around the

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[¶] Senior Research Scientist, Aerothermodynamics Branch, and Associate Fellow AIAA vehicle shoulder to the backshell [5,6]. This heating mechanism has not been accounted for in most previous Mars mission designs. Separated flow environments also make prediction of convective heat flux difficult. Therefore, DLR, the German Aerospace Center, developed the Combined Aerothermal and Radiation Sensor package, called COMARS+, to measure the total heat flux, pressure and radiative loads at different back-shell positions on Schiaparelli [1,2]. COMARS+ consisted of three combined aerothermal sensors, one broadband radiometer sensor and an electronics box. Due to the failed landing of Schiaparelli it was not possible to retrieve the complete data package. However, communications between the Schiaparelli module and the orbiter during entry allowed data to be transmitted at ten trajectory points.

II. Description of Simulation Tools

This section will provide a brief overview of each software for reference.

II.A. LAURA

The Langley Aerothermodynamic Upwind Relaxation Algorithm (LAURA) is a structured grid flow solver, specialized for hypersonic re-entry physics, utilizing state-of-the-art algorithms for CFD simulations [7,8]. Fluxes are computed using Roe's averaging [9] and Yee's Symmetric Total Variation Diminishing (STVD) [10] formulation in order to obtain higher order accuracy.

II.B. HARA

The High-temperature Aerothermodynamic RAdiation (HARA) model applied in the present study is discussed in detail by Johnston et al.[11,12] A line-by-line approach is used for atoms and a multi-band opacity binning model for molecules [13]. HARA also has the capability of running line-by-line for optically thick molecules, or a smeared band model for optically thin molecules as needed. HARA is based on a set of atomic levels and lines from the National Institute of Standards and Technology (NIST) [14] and Opacity Project databases [15]. The atomic bound-free model is composed of cross sections from the Opacity project's online TOPbase [16], which were curve fit by Johnston [11].

II.C. DPLR

DPLR [17,18] uses a finite-volume discretization to solve the reacting Navier-Stokes equations for fluids in thermochemical non-equilibrium. While the software was originally designed for steady-state aerothermodynamic analysis of planetary entry vehicles, DPLR has evolved over the years to include a broad spectrum of numerical and physical models that enable it to accurately simulate most compressible flows. Additional details on DPLR's capabilities can be found in references [17,18]. The version of DPLR used in this work is v4.04.0.

II.D. NEQAIR

Non-EQuilibrium AIr Radiation (NEQAIR) is a line-by-line radiation code which computes spontaneous emission, absorption and stimulated emission due to transitions between various energy states of chemical species along a line-of-sight [19]. Individual electronic transitions are considered for atoms and molecules, with the molecular band systems being resolved for each rovibronic line. Since the report of Whiting et al. [19], numerous updates have been incorporated into NEQAIR, such as: using the latest version of the NIST atomic database (version 5.0) [20], using the bound-free cross sections from TOPbase [16], parallelization and improvements to the mechanics of the Quasi Steady State (QSS) model. The current release version of NEQAIR is known as v14.0 [21].

III. Preliminary Results

Figure 1 shows the locations of the various COMARS sensors. More detail will be provided in the final paper, however, for the abstract, preliminary results are presented in Figs. 2 and 3. The DPLR/NEQAIR simulations are listed as "Ames" and the flight data are listed as "DLR" in the figures. Simulations from LAURA and HARA will be added to the final version of the paper. A comparison of the total heat flux calculated by DPLR and NEQAIR with the COMARS 1, 2 and 3 flight measurements is shown in Figs. 2(a), 2(b), and 2(c), respectively. The preliminary unmargined simulation results shown in Fig. 2 generally over-predict the flight data and are within expected uncertainties and show similar trends to COMARS. The only data point to be under-predicted is for COMARS2 at 135 s, see Fig. 2(b). Given the low heat flux signal at this time point, this might just be within the noise of the measurement accuracy.

The results presented in Fig. 2(d) show the approximately co-located COMARS3 total heat flux and radiative heat flux as measured by the radiometer. With co-located measurements of total and radiative heat flux, the convective heat flux can be inferred. The radiometer data are significantly over-predicted by preliminary DPLR/NEQAIR solutions. Further calculations and attempts to improve understanding of the radiometer data are on-going. Even though there is good agreement with convective heat flux at 125 and 135 s, this may be fortuitous due to an incorrect prediction of the radiative heat flux. Furthermore, as pressure is not well matched, a good match to the convective heat flux cannot be expected.

The simulations shown in Fig. 2 were performed axi-symmetric. However, due to not matching the pressure measurements on the backshell, these calculations will be repeated in 3-D and at various angles of attack. The pressure measured at three back cover locations showed almost no gradient based on measurement location. This result suggests completely separated aftbody flow at the measurement locations, which is not what is predicted by the axi-symmetric CFD.

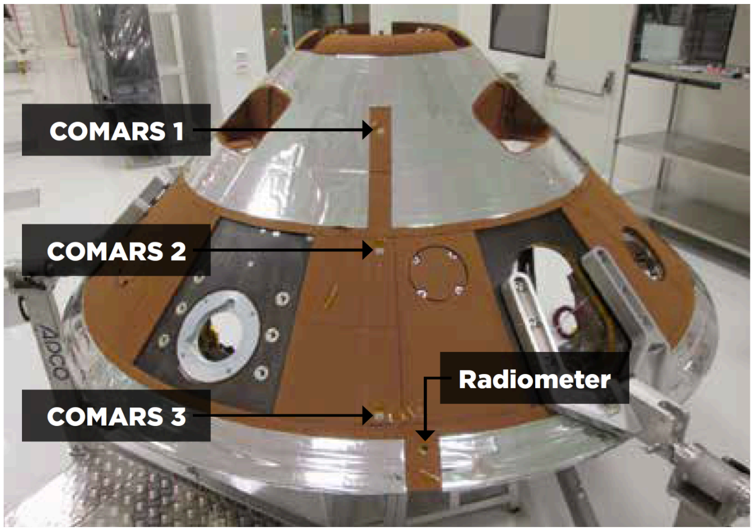
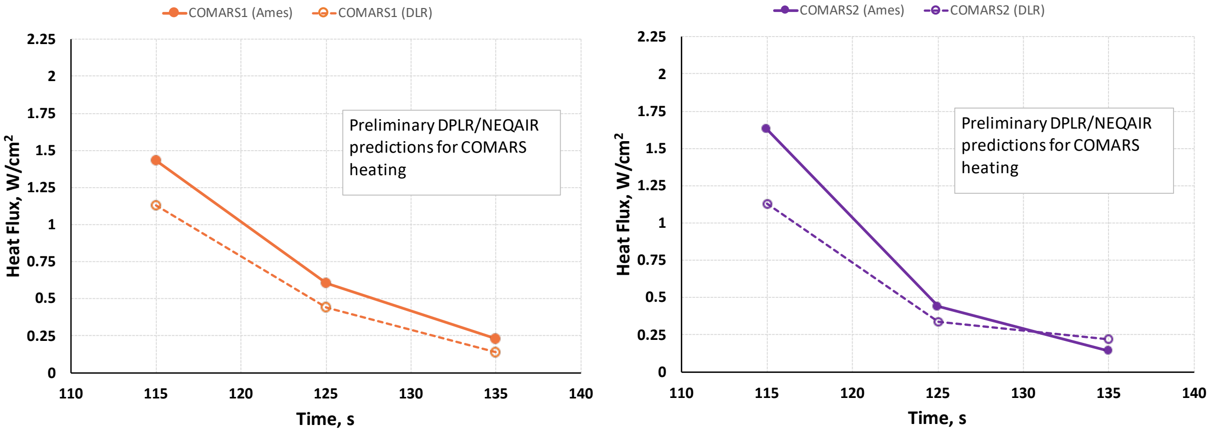
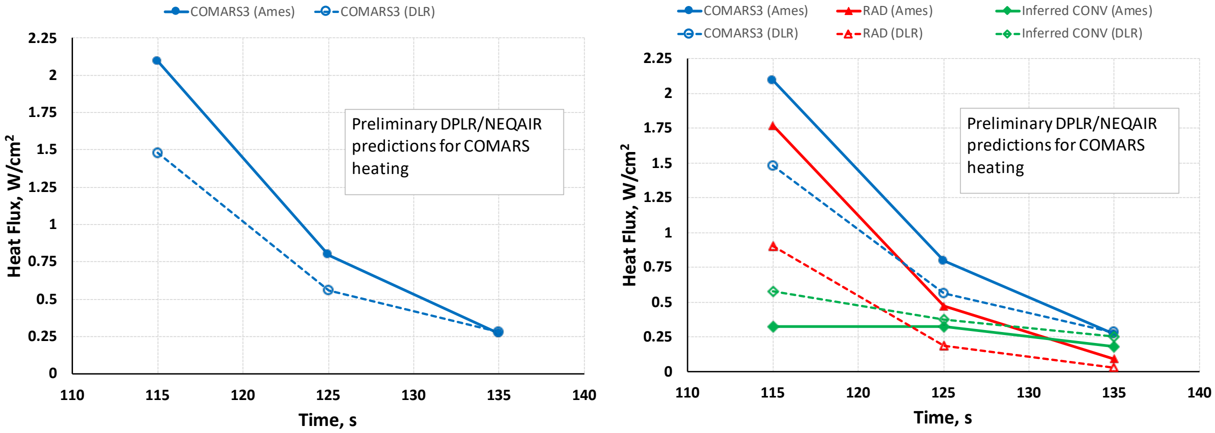


Figure 1. Overview of COMARS sensor locations on the backshell of Schiaparelli.



(a) COMARS1: Total Heat Flux

(b) COMARS2: Total Heat Flux



(c) COMARS3: Total Heat Flux

(d) COMARS3 & Radiometer: Total Heat Flux, Radiative Heat Flux and Inferred Convective Heat Flux

Figure 2. Comparisons of Heat Flux measurements made by COMARS to DPLR/NEQAIR simulations.

A thermocouple-based heating reconstruction was performed to estimate the heat flux with inverse methods [3]. A preliminary comparison to the reconstructed heat flux is shown in Fig. 3. The data of interest in Fig. 3 are the DPLR/NEQAIR simulations which are shown in green triangles, the COMARS3 data shown in red circles and the inverse analysis net total heat flux shown in the solid black line. The figure shows excellent agreement between the current Ames simulations and the reconstructed heat flux for the two earlier trajectory times simulated. For the last time point, the Ames result under-predicts the reconstructed heat flux. The COMARS3 data also agree well with the reconstructed heat flux at the first time point. Even though there is a discrepancy between COMARS3 and the Ames simulations, due to the high gradient in the data around these times, both appear to agree well with the reconstructed heat flux. For the two later times, the COMARS3 data show a lower heat flux than the reconstructed results.

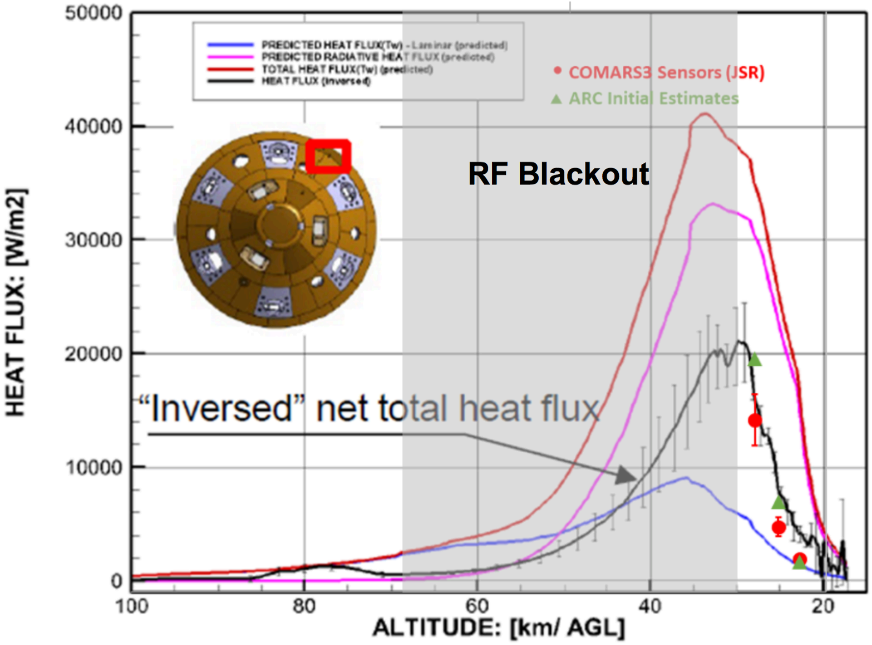


Figure 3. Comparison of DPLR/NEQAIR results with heat flux estimated from TC inverse analysis.

IV. Conclusion and Future Work

Preliminary comparisons of the Schiaparelli aerothermal data with DPLR and NEQAIR are shown. Generally, the simulations provide an over-prediction compared to the flight data. Further work for the final version of the paper includes simulating results from the ICOTOM sensors, 3-D angle of attack simulations to improve the agreement with pressure on the backshell, improving understanding of the radiometer data and interpretation of the results, simulating earlier times to compare against more of the inverse heat flux from thermocouple data, and attempting to estimate the effect of ablation on the aerothermal measurements. From these initial comparisons, it is clear that valuable flight data were gathered by both COMARS and AMELIA, even though some of the heat pulse was obscured by black-out.

Acknowledgments

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