Bayesian-based method with metamodels for rebuilding freestream conditions in atmospheric entry flows

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Abstract. *The paper investigates a new methodology to rebuild freestream conditions for the trajectory of a re-entry vehicle from measurements of stagnation-point pressure and heat flux. Uncertainties due to measurements and model parameters are taken into account and a Bayesian setting supplied with metamodels is used to solve the associated stochastic inverse problem.*

Keywords: Uncertainty Quantification ; stochastic inverse problems ; bayesian inference methods ; stochastic metamodels.

Simulation of atmospheric entries of spacecraft is a challenging problem involving many complex physical phenomena, including rarefied gas effects, aerothermochemistry, radiation, and the response of thermal protection materials to extreme conditions. The availability of powerful computational resources and general-purpose numerical algorithms creates increasing opportunities to perform multiphysics simulations of complex systems, in particular in aerospace science. Reliable predictions require sophisticated physico-chemical models as well as a systematic and comprehensive treatment of model calibration and validation, including the quantification of inherent model uncertainties.

Conventionally, engineers resort to safety factors to avoid space-mission failure. At the interface of physics, mathematics, and computer science, Uncertainty Quantification (UQ) aims at developing a more rigorous framework and more reliable methods to characterize the impact of uncertainties on the prediction of Quantities Of Interest (QOI). Some uncertainties arise from the physical simplifications made to obtain a mathematical model representative of the complex phenomena studied; others come from the numerical approximations due to the finite discretization used in the numerical solver for approximating the solution of the mathematical model. In the sequel, we will not account for modeling and numerical uncertainties. Our interest lies in uncertainties associated to a limited knowledge or an intrinsic variability of the input quantities required for performing the analysis. For instance, numerical simulations need the precise specification of boundary conditions and model parameters, such as reaction rate coefficients, and typically only limited information is available from corresponding experiments and observations.

The post-flight analysis of a space mission requires accurate determination of the freestream conditions for the trajectory, that is, temperature and pressure conditions and the Mach number in front of the shock. These quantities can be rebuilt from the pressure and heat flux measured on the spacecraft by means of a Flush Air Data System (FADS) [6]. This instrumentation comprises a set of sensors flush mounted in the thermal protection system to measure the static pressure (pressure taps) and heat flux (calorimeters) (see Figure 1). As shown by zur Nieden and Olivier [10], state of the art techniques for freestream characterization rely on several approximations, such as the equivalent specific heat ratio approximation, which means that one replaces a complex high temperature effect possibly including thermo-chemical non-equilibrium by an “equivalent” calorically perfect gas. This approximation is

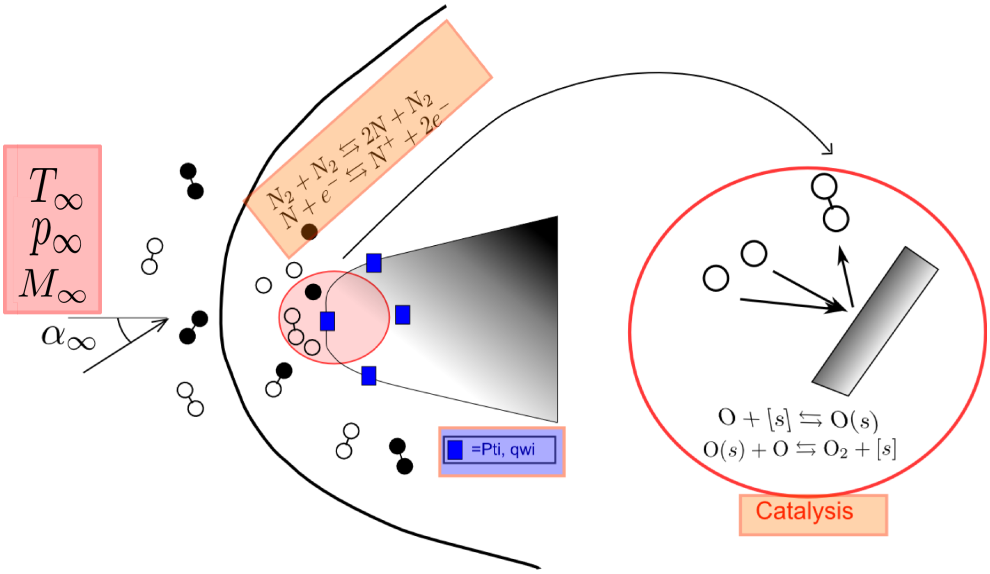

Figure 1: RAFLEX Flush Air Data System (FADS), sensors indicated in blue are flush mounted in the thermal protection system to measure the static pressure (pressure taps) and heat flux (calorimeters).

then used, starting from sensors measurements, to reconstruct freestream conditions and prescribe error intervals on these quantities. These techniques do not yet integrate measurement errors nor the heat flux contribution, for which a correct knowledge drives more complex models such as gas surface interaction. In this context, Computational Fluid Dynamics (CFD) supplied with UQ tools permits to take into account chemical effects and to include both measurement errors and epistemic uncertainties on the chemical model parameters in the bulk and at the wall (surface catalysis). Rebuilding the freestream conditions from the FADS data therefore amounts to solving a stochastic inverse problem.

The forward problem, which consists in predicting stagnation-point pressure and heat flux from freestream conditions, is described by a physico-chemical model and solved by suitable numerical methods proposed by Barbante [1]. We investigate one point of the trajectory of the European EXPerimental Reentry Test-bed (EXPERT) vehicle, which has been developed by the European Space Agency as part of its General Technological Research Program [9]. The trajectory point corresponds roughly to the chemical non-equilibrium flow conditions of Table 1. The inverse prob-

Flow conditions	Altitude [km]	T_∞ [K]	p_∞ [Pa]	M_∞ [-]
Chemical non-equilibrium	60	245.5	20.3	15.5

Table 1: Freestream conditions for one trajectory point of the EXPERT vehicle.

lem is then reduced to determine for instance only freestream pressure and Mach number. The purpose of this paper is to propose a new methodology for solving the inverse problem based on a Bayesian setting, that is, probability densities of possible values of freestream conditions are rebuilt from stagnation-point pressure and heat flux measurements. A Bayesian setting offers a rigorous foundation for inferring input parameters from noisy data and uncertain forward models, a natural mechanism for incorporating prior information, and a quantitative assessment of uncertainty on the inferred results [5]. It has already been used in the context of atmospheric entry for turbulence modeling calibration [2] and atomic nitrogen ionization modeling calibration [8].

Prior uniform distributions are first assumed for (p_∞, M_∞) and some chemistry parameters are considered uncertain, with known distribution functions. The impact of the different uncertain inputs on the forward problem simulated by the in-house code COSMIC is studied owing to a non-intrusive stochastic spectral method [4, 7, 3]. Uncertainties on (p_∞, M_∞) are observed to have a large impact on $p_{\rm st}$, whereas the chemistry uncertainties are observed to have a negligible impact on it. On the contrary, all the input parameters are observed to have a considerable impact on $q_{\rm st}$. Then, a backward uncertainty propagation method is proposed to solve the inverse problem by taking into account uncertainties due to measurements and model parameters. To this end, we rely on a Bayesian framework supplied with MCMC algorithms to sample the posterior distribution of (p_∞, M_∞). A major difficulty lies in the fact that one needs to compute the forward problem for each iteration in the Markov chain. A metamodel for $p_{\rm st}$ is computed owing to the non-intrusive spectral method, unfortunately such a metamodel can not be obtained for $q_{\rm st}$ because of the large interactions between the different parameters and the strong dependence of $q_{\rm st}$ on all the parameters. It was therefore decided to solve the stochastic problem only relying on the stagnation pressure measurements and the metamodel for $p_{\rm st}$. The methodology exhibits a reduced set of credible couples (p_∞, M_∞); however a neighborhood around a Maximum A Posteriori credible couple has not been brought out, meaning that only stagnation point pressure measurements are not sufficient to determine freestream conditions. Ongoing efforts consists in building a new metamodel for $q_{\rm st}$, based on adaptive local representations, so as to add stagnation point heat flux measurements in the bayesian algorithm in an effective way.

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