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New insights into Europa's surface using Galileo/NIMS data and MCMC modeling

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Introduction : Europa's surface is one of the youngest surfaces in the solar system. The great diversity of morphologies observed quickly raised the question of the processes responsible for this active resurfacing. The Jovian moon is believed to hide a global liquid water ocean under its ice crust [1] which led to the assumptions of exchange between the surface and the putative subsurface ocean [1]. In addition, Europa is exposed to intense space weathering due to the continuous bombardment by electrons and ions from Jupiter's magnetosphere [2]. The surface therefore appears as the key witness of these internal and external processes.

To finely characterize the microphysics of the ice it is necessary to use radiative transfer (RT) modeling. Such modeling allows to estimate these parameters integrating the highly nonlinear effects of the light path within the icy regolith due to scattering. A recent work has been proposed to determine surface properties using Bayesian Monte Carlo Markov Chain (MCMC) [3]. This approach is based on RT models [4,5] using the optical properties of the considered chemical species and physical properties of the regolith. Here we report the use of a RT model [5] in a Bayesian MCMC inference framework to retrieve microphysical properties of Europa's surface using the Galileo Near-Infrared Mapping Spectrometer (NIMS) hyperspectral data [6].

Data: We use data acquired by NIMS collected during the Galileo mission. Here we present the analysis of calibrated data from the hyperspectral cube "e6007ci" (available from the PDS archive) from the trailing Anti-jovian hemisphere (Fig. 1). The estimated signal-to-noise ratio (SNR) is between 5 and 50, we mainly focus on the 1.0-2.5 µm region for which the SNR is higher. Within this spectral range the uncertainty on the absolute calibration is up to 10% [7].

Radiative transfer model requires the optical constants of the pure chemical species considered. Here we consider 15 different compounds: crystalline and amorphous water ice [7,8], sulfuric acid octahydrate (SAO; [2]), hydrated sulfates [9,10], hydrated chlorine salts [11], and minerals such as magnetite [12], sodium chloride [13] and ammonium sulfate [14].

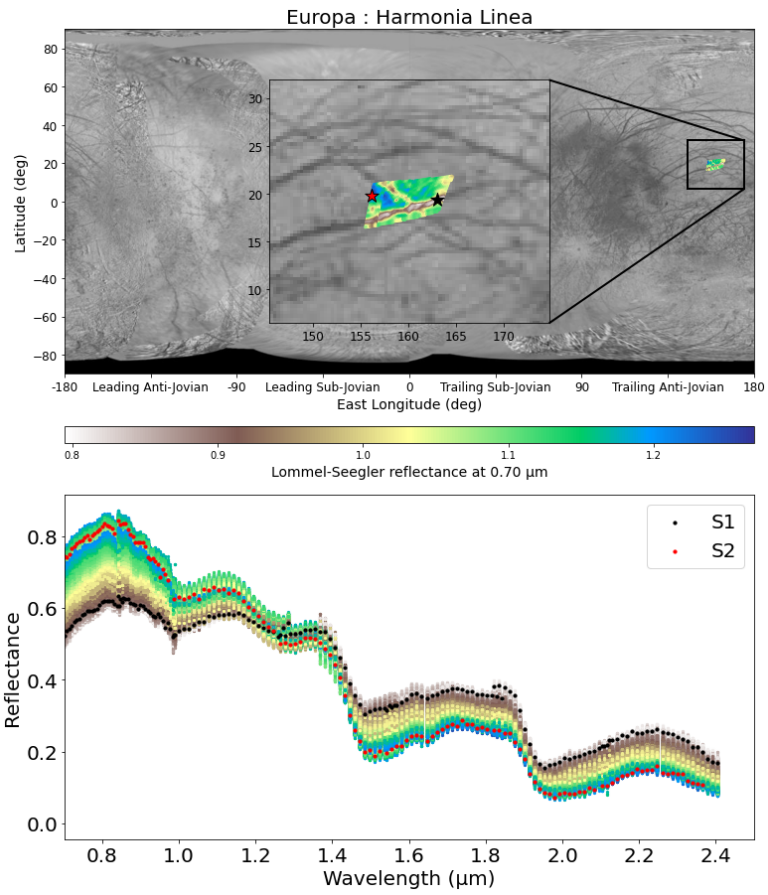

Figure 1 - (top): Map of Europa with a zoom on Harmonia Linea observation. The color represents the reflectance at 0.7 µm normalized using the Lommel-Seegler law. (bottom): all spectra from the corresponding cube and the selected spectra (S1 and S2) used in this study.

Method: We use a MCMC Bayesian inference approach [15,16] to analyze NIMS spectra because it has the advantage of allowing the exploration of a large parameter space and looking for non-unique solutions while statistically constraining the model parameters [17,18]. We compute the bidirectional reflectance of the regolith using a RT model [5]. Then, the algorithm is used to sample the parameter space following the Bayesian Posterior distribution. The parameters we are adjusting are: abundances, grain size of each chemical species and macroscopic roughness of the regolith. For the abundances we use a Dirichlet prior to ensure that they are sum up to 1, while we use a uniform distribution prior for the other parameters.

A first study was done to test all combination of 3, 4 and 5 chemical species among the 15 compounds on the S1 spectrum to select the most appropriate chemical species to consider for the surface characterization. For each of this combination (4823 in total), we perform the MCMC inversion.

Results: We first discuss the chemical species selection (called here endmember) by looking at all best-fit from all combination of 3, 4 and 5 endmembers and their associated RMS. We first show that going from 3 to 4 endmembers significantly improves the quality of the fit while using 5 endmembers only slightly improve it. In addition, some compounds appear necessary to reproduce the observation, such as water ice and SAO. We show that adding either hydrated sulfates or chlorine salts produces results substantially similar. Fig. 2 illustrates such results when considering 4 endmembers. Finally we perform MCMC inversion with 5 endmembers including both crystalline and amorphous water ice. The best fit from the 5 endmembers model and their associated posterior pairwise distribution are shown fig. 3 and 4 for the S1 and S2 spectra.

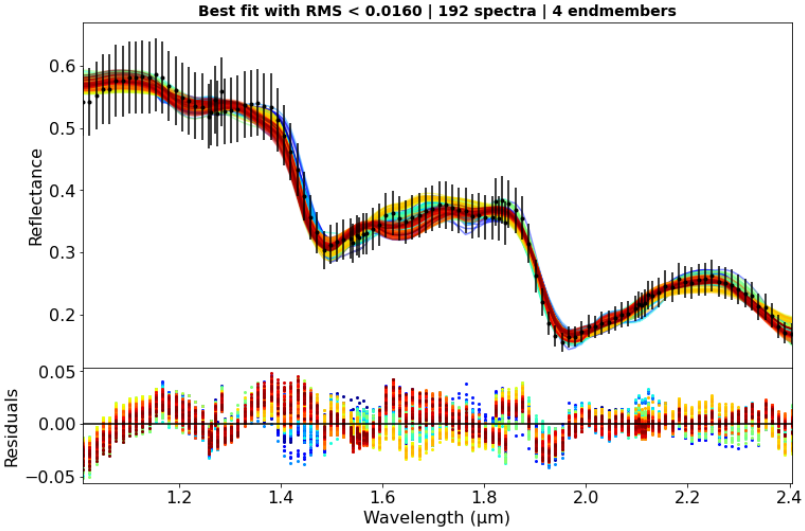

Figure 2 - Results of all combination for the 4 endmembers case: only the best-fit with RMS below 0.016 are showed.

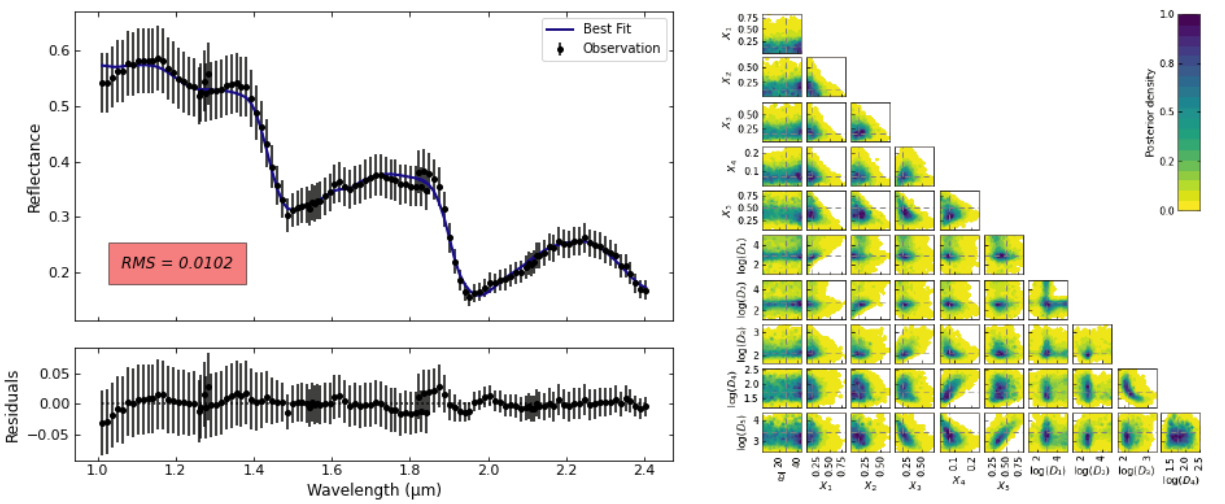

Figure 3 - results for S1: best fit (left) and pairwise posterior distribution (right) using 5 endmembers.

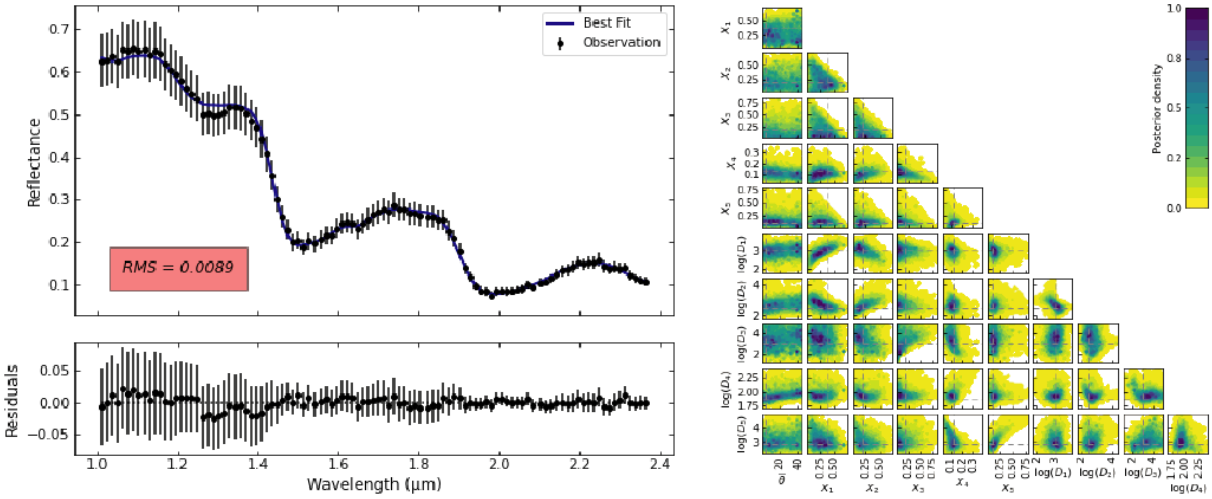

Figure 4 - results for S2: best fit (left) and pairwise posterior distribution (right) using 5 endmembers.

Conclusion: We tested, for the first time and in a systematic way, the inversion of Galileo NIMS infrared spectra using a significant number of 3, 4 and 5 compounds combinations out of a selection of 15 chemical compounds, using a non-linear radiative transfer model**.** We found that there is no unique solution to determine the exact composition of the surface, but a family of endmember are required: water ice, SAO and sulfates. This composition set seems to be coherent for both bright and dark regions of Europa. We will discuss the implication of these results on the Europa's surface processes.

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