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A Bayesian approach to retrieve surface temperatures

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Abstract

The inference of surface temperature of planetary targets has been a major scientific objective of infrared instrumentation since its first usage in the spaceborn platforms. Nonetheless, this study requires a number of assumptions, for the complexity of radiative transfer involved. We have developed a Bayesian approach to nonlinear inversion for mapping surface temperature of Vesta by using the Dawn Visual and Infrared Mapping Spectrometer (VIR). A Bayesian approach relies on the knowledge of the general properties of the physical system before it is measured: in our case, this translates into knowledge of the target body in terms of composition and expected range of temperatures. Upon selection of initial guesses for the temperature and the spectral emissivity, combined with the standard deviation of these unknown parameters, the method iteratively and simultaneously computes surface temperature and spectral emissivity from the measured radiance.

We successfully implemented this method to data of asteroid 2867 Steins and 21 Lutetia returned by the Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) onboard Rosetta. Knowledge of the surface temperature allows one to retrieve information on surface properties such as thermal conductivity, porosity, and thermal inertia.

1. Introduction

The radiance emerging from the surface of an airless body is given by:

$$I(\lambda) = r(\lambda)F(\lambda) + \varepsilon(\lambda)B(\lambda,T_{surf}) \qquad (1)$$

where $r(\lambda)$ is the surface spectral reflectance, $\varepsilon(\lambda)$ is the surface spectral emissivity, $F(\lambda)$ the solar reflected radiance (scaled for the heliocentric distance), and $B(\lambda,T_{surf})$ is the Planck function where T_{surf} is the surface temperature.

This equation holds true as long as the variation of temperature with depth in the surface material can be neglected within the vertical range where opacity becomes >>1. For the fine granular regolith expected on the Moon or asteroids, the latter condition is satisfied for depths in the order of radiation wavelenght, and eq. (1) is therefore adequate in the spectral range of imaging spectrometers (1-6 μm) currently operating in planetary missions (e.g., Rosetta/VIRTIS, Chandrayaan-1/M3, Dawn/VIR).

Let us consider an ideal, noise-free, IR spectrum sampled in *N* channels. The retrieval of surface temperature through eq. (1) represents an ill-posed problem since the number of unknowns (*N*+1, i.e. *N* emissivities of as many spectral channels, plus the surface temperature) is greater than the number of measures (*N* radiances at the *N* sampling channels). Furthermore, possible complications may come from sub-pixel slopes or roughness. Consequently, inference of surface temperature from IR spectra is not possible without imposing some *a priori* constraints on the expected values of soultion.

A variety of approaches has been adopted in the past to cope with this condition [1,2]. In most cases, the emissivity and the surface temperature are not retrieved simultaneously: rather, an extrapolation of the apparent reflectance of the spectral continuum is first performed, then the emissivity is set to 1 and a temperature is estimated at a given wavelength along with a reflectance. At this point, the Kirchhoff's law: $r(\lambda) = 1 - \varepsilon(\lambda)$ is used to retrieve the emissivity, hence a second estimate of the temperature can be done. In the context of our interest, a Bayesian approach [3] offers a clear way to include the a priori hypothesis in the solution.

2. Implementation

For the purpose of analysis of asteroids surface, the following assumptions have been adopted:

1. Surface spectral reflectance is modeled by the most common photometric functions (e.g., Lambert, Lommel-Seeliger, Minnaert, etc). This requires knowledge of the observational geometry (illumination angles for each pixel) computed by means of a shape model in the case of irregular bodies.

2. Spectral reflectance and spectral emissivity are related by the Kirckhhoff law. This is a reasonable assumption as long as we consider small surface thickness like those typically sounded by IR spectrometers (a few to some tens of microns).

A best guess on the unknown parameters (spectral emissivity ε(λ) and surface temperature T_{surf}) is made, based on theoretical considerations or independent measurements (e.g., public spectral libraries). A lower limit for surface temperature can be derived from the evaluation of average brightness temperature in a region where r(λ) can be neglected.

A covariance matrix of the emissivity is build, which describes the likely range of variability for solution in the neightborhood of the first guess. Elements along the diagonal describe the variances of the N+1 elements; off-diagonal elements describe the covariances of different elements of state vectors, i.e. the statistical correlation of the two elements multiplied by the corresponding standard deviations.

A priori constraints are also put on the standard deviation of the unknwon quantities.

Spectral emissivity and temperature providing the best fit with the measured spectral radiance within the instrumental error are iteratively and simultaneously computed in a cycle, until convergence around stable values is achieved. Spectral reflectance is finally obtained as: $r_\lambda = 1 - \varepsilon_\lambda$.

3. Results

The nonlinear inversion applied to Rosetta/VIRTIS data provides a range of temperature between 170 K and 245 K for Lutetia, and between 170 K and 230 K for Steins; in both the cases, direct correlation with topographic features is observed. Accuracies down to a few K are achieved for Steins and <1 K for Lutetia, in regions of the dayside (high SNR) unaffected by limb proximity. The minimum retrievable temperature (170÷180 K) is set by the instrument's characteristics (cutoff sensitivity and temperature of the optics), while the maximum temperature depends on some surface properties: density, thermal conductivity, and specific heat. These three quantities give the surface thermal inertia.

This method is numerically robust, i.e. the algorithm achieves convergence in a broad range of guessed values of spectral emissivity and temperature, and within the instrumental noise.

We plan to test this method on VIR calibrated cubes of Vesta and to compare its results with other methods. As in the case of VIRTIS, we expect to be able to map only day side temperatures above 180 K. However, caution should be put in interpreting the first results, both because the method requires a good knowledge of the observational geometry in order to properly model the spectral reflectance (shape model of Vesta is subject to change in time), and because the calibration of the instrument may also change quite rapidly as new data are acquired and analysed.

References

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