EPSC Abstracts
Vol. 9, EPSC2014-261, 2014
European Planetary Science Congress 2014

Surface temperature determination of small bodies

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Abstract

We illustrate a Bayesian approach to nonlinear inversion which allows, upon selection of initial guesses for the unknown parameters, i.e. surface temperature and spectral emissivity, constrained by their expected range of variability, to simultaneously compute them from the measured spectral radiance.
We show spatially-resolved temperature maps of asteroids 2678 Steins and 21 Lutetia obtained by using this approach on infrared data acquired by the VIRTIS imaging spectrometers onboard the ESA Rosetta spacecraft in 2008 and 2010 respectively, and temperature maps of asteroid Vesta obtained from infrared data acquired by the VIR mapping spectrometer onboard the NASA Dawn spacecraft in 2011-2012.

1. Introduction

Consider an ideal, noise-free, infrared (IR) spectrum sampled in *N* channels. The retrieval of surface temperature 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 measurements (*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 the solution.
A variety of approaches have been adopted in the past to cope with this condition [1,2]. In most cases, emissivity and surface temperature are not retrieved simultaneously. Rather, an extrapolation of the apparent reflectance of the spectral continuum in the thermal region is first performed, then the emissivity is set equal to 1, and a temperature is estimated at a given wavelength along with a reflectance. At this point, Kirchhoff's law 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] deals with the search of a constrained local minimum by iteratively searching the pair of unknown parameters ($T_{\rm surf}$ and ε_i) that *simultaneously* provide a best fit with the measured data. Unlike other approaches, it does not require any extrapolation of the spectral reflectance in the thermal region and offers a clear way to include an *a priori* hypothesis (i.e., is our best estimate of the unknown parameters prior to their measure) in the solution. This numerical method achieves convergence in a broad range of *a priori* guessed values of spectral emissivity and temperature, within the instrumental noise.
We compute a synthetic radiance spectrum by summing the solar contribution (solar spectrum scaled to the heliocentric distance and modeled by a photometric function in such a way that the surface topography and/or the photometric characteristics of the surface can be taken into account) and the thermal contribution, with emissivity and temperature defined by their respective first guesses based either on theoretical considerations (models) or independent measurements (e.g., spectral libraries).
A covariance matrix of the emissivity is built, which describes the likely range of variability of the solution in the neighborhood of the first guess. This matrix is a new element compared to other approaches used in the past, and is used to constrain the search of a local minimum.
Spectral emissivity and temperature providing the best fit between the synthetic spectrum and the measured spectrum within the instrumental error are iteratively and simultaneously computed in a cycle, until convergence around stable values is achieved. No spatial relation in surface temperatures among adjacent pixels is assumed, meaning that each pixel is treated separately.
Formal errors on the unknown quantities, related to random variations of the signal, are also a standard output of the Bayesian algorithm.
The VIRTIS instrument onboard Rosetta and the VIR instrument onboard Dawn are not sensitive to physical temperatures on the nightside of their targets, where the signal is considerably low. Typically, 170-180 K is the minimum temperature that allows one to derive surface temperatures while preserving small formal errors (<1 K on retrieved temperatures). On the other hand, for a given local solar time (LST), the maximum temperature depends on the solar incidence angle and on surface properties such as thermal inertia and albedo.

2. Results

The application of a Bayesian approach to data acquired by Rosetta/VIRTIS [4] provides a range of temperatures between 170 K and 245 K for Lutetia, and between 170 K and 230 K for Steins (**Fig. 1**); in both 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 [5,6]. In anticipation of the arrival of Rosetta at the comet 67P/Churyumov-Gerasimenko in the second half of 2014, we plan to re-apply this method to spatially-resolved data of the nucleus that will be obtained by VIRTIS.

In the case of asteroid Vesta as observed by Dawn/VIR [7], we derived spatially-resolved thermal images of a significant percentage of the asteroid at spatial scales ranging from 0.17 to 1.3 km/px. Valuable results were also obtained for local scale features, such as concentrations of unusual brightness i.e. high-albedo (bright) and low-albedo (dark) material units [8] (**Fig. 2**), pitted terrains [9], and olivine-rich sites [10]. The size of Vesta, far larger than that of other asteroids explored by spacecrafts, also makes this work the first of its kind for the amount of data and the overall surface area covered. A similar analysis will be carried out when spatially-resolved data will be obtained by VIR at the dwarf planet Ceres.

The availability of spatially-resolved, accurate temperature observations, significantly spaced out in local solar time, provides clues to the physical structure of such peculiar sites, which complements the mineralogical investigation based on imaging spectroscopy data collected at shorter wavelengths.

3. Figures

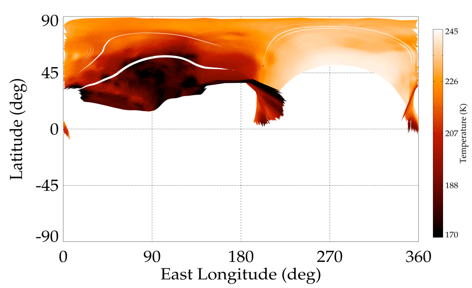

Figure 1. Map of Lutetia's temperatures as determined by VIRTIS, shown in simple cylindrical projection. Due to the obliquity of Lutetia and the pole-on configuration of the fly-by in the closest approach phase, only northern latitudes were explored by VIRTIS. The maximum spatial resolution achieved by VIRTIS during the fly-by was ~0.8 km/px.

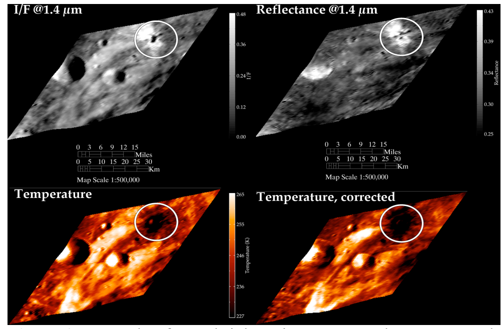

Figure 2. Example of very bright unit on Vesta. The upper panels show the unit as observed by Dawn/VIR at a wavelength of 1.4 µm, before (left) and after (right) applying the photometric correction. The lower panels show temperature maps of the same area, derived from VIR infrared spectra at wavelengths > 4.5 µm, respectively without (left) and with correction (right) for the cosine of the solar incidence angle. A horizontal scale baraccounts for the size of the features observed in the scene. The average pixel resolution is 0.17 km/px.

Acknowledgements

This work is supported by the Italian Space Agency (ASI), ASI-INAF Contracts n. I/024/12/0 and I/004/12/0. Support of the Rosetta Science, Instrument, Operations Teams as well as of the Dawn Science, Instrument, Operations Teams, is gratefully acknowledged.

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