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Retrieving the distribution of comet 67P/Churyumov-Gerasimenko surface temperatures for individual Rosetta/VIRTIS-M spectra (pixel) by linear spectral unmixing – Method and first results –

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1. Introduction

Knowledge of surface temperature and its variations as function of illumination conditions is key for understanding the thermodynamical properties, the chemical properties and the physical structure of the regolith (porosity, roughness) of planets and small bodies in the solar system. The surface temperature can be retrieved from near-infrared spectra at wavelengths where thermal emission becomes non-negligible with respect to the reflected components. At 5 µm, the longest wavelength measured by VIRTIS-M [1] on the Rosetta mission [2] which observed comet 67P/Churyumov-Gerasimenko (67P/C-G), the minimum brightness temperature that can be measured is ~150K [3] (instrumental noise equivalent temperature). The usual technique is to fit a Planck function to each spectrum, providing one temperature per pixel (e.g. [3], [4], [5]).

However, the calculation of a distribution of temperatures per pixel is justified by the fact that the local topography changes at all scales resulting in variable illumination conditions (variable incidence angle and shadow casting) within the area covered by each pixel. This causes a distribution of temperatures which turns out in a distribution of thermal emission contributions [6].

Furthermore, the combination of different thermal emission contributions (the linear combination of several Planck curves) is not a Planck function. Consequently, fitting one Planck function to a spectrum results in retrieving a value for the brightness temperature that is not representative of thermophysical properties of the regolith, because it is not the average of all temperatures in the area covered by that pixel.

2. Method: Inversion of multiple Planck curves

Our approach is to perform a linear spectral unmixing of thermal functions, because the spectral thermal emission in each spectrum is the sum of all the thermal contributions that correspond to each facet of the surface, weighted by their areal proportion. We are developing a technique that is based on the Multiple-Endmember Linear Spectral Unmixing model (MELSUM) [7], which has been developed to fit reflectance spectra of particulate surfaces (or laboratory samples) by a linear combination of spectral endmembers (spectra of pure minerals, or spectra collected from relevant locations in the database). With this technique, a spectrum is considered as a vector, and the spectral library of endmembers as a matrix. The inversion relies on the covariance vector and covariance matrix. Its main feature is to be able to test one by one each linear combination of N spectral endmembers among a total of M available in order to retrieve the best one, and to ensure that all spectral endmembers selected contribute positively. Typically, N is 2 to 5, and M is ~10 to 20. This technique has been applied successfully to map the surface composition of Mars [7] with the OMEGA imaging spectrometer on Mars Express, Vesta [8] and Ceres [9] with the VIR mapping spectrometer on the Dawn spacecraft.

In order to retrieve a distribution of temperatures with MELSUM, each spectral endmember is a Planck curve that corresponds to one value of surface temperature. The assumptions in MELSUM are:
- The sum of all weighing coefficient must not exceed 1 (the sum of all illuminated parts within the surface covered by one pixel must not exceed the total surface covered by that pixel).

- The weighing coefficients must not be negative (they can be 0 if the corresponding temperature is absent in the surface observed)
- The temperatures that can be tested are limited by a range and a resolution (typically ≤1 K).
- The maximum number of spectral endmembers (the maximum number of Planck curves) that can be used to fit a spectrum must be small (<5). This is necessary because the total number of combinations to be tested equals $M!/(N! \times (M-N)!)$, which increases rapidly as function of N. As a consequence, the number of representative temperature values within a given pixel cannot exceed 5: this is the main limitation of this technique.

3. Results: First evaluation of our inversion model

We have already tested with some success the spectral fitting approach for the retrieval of temperature values and their areal proportions within the area covered by one pixel. 1) We have demonstrated that we can fit the spectra with a sum of Planck curves. 2) MELSUM is a tool that is already functional for processing hyperspectral datasets. 3) Using MELSUM, we have observed that with a model constrained to use a maximum of two or three spectral endmembers (two or three values of temperatures), areas illuminated with a low incidence angle resulted in a selection of only one temperature (or two temperatures separated by the resolution interval of 1K), whereas areas illuminated with a high incidence angle forced the model to select two or three temperatures separated by an interval of several tens of degrees. Our first analysis (Figure 1) indicates that this behavior may be systematic, which is consistent with our expectations: under high incidence angles, a rough surface presents facets that are fully illuminated by the sun, and facets that are shaded (high contrast and variability in the distribution of temperature), whereas under low incidence angle, most facets appear fully illuminated from the point of view of the instrument, near the zenith position.

These preliminary results are encouraging, and they justify pursuing this approach. The obvious area of improvement is computing performance, since it takes several tens of seconds to process a single spectrum executed with the Interactive Data Language (IDL, Harris Geospatial Solutions) on a 64-bit operating system, with a dual core CPU clocked at 2.50 GHz (Intel i5-3210M).
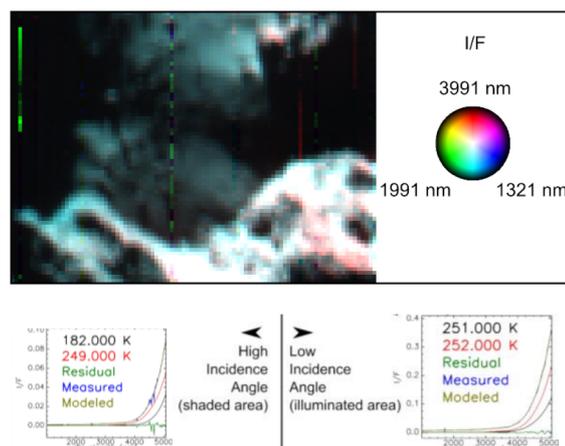

Figure 1: Spectral modeling of thermal emission contributions in Rosetta/VIRTIS-M IR spectra of comet 67P/Churyumov-Gerasimenko using MELSUM with two Planck curves (two surface temperatures) for each pixel. Spectra of shaded areas are systematically modeled by two temperatures separated by several tens of degrees, whereas illuminated areas are always modeled by temperatures separated by one degree.

The current efforts consist in improving the performance and computer efficiency. In addition, each approach can be used to correct the spectra for thermal emission contribution, and thus to map absorption bands that are partially masked or distorted, such as the absorption band at 3.2 µm of organics, or carbonate absorption bands at 4. µm and beyond. These maps could also provide some feedback and could help calibrate the thermal emission correction models.

Acknowledgement

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