CALCULATING A DISTRIBUTION OF SURFACE TEMPERATURES FROM THERMAL EMISSION IN NEAR-INFRARED SPECTRA: APPLICATION TO COMET 67P/C-G AND (1) CERES. J.-Ph. Combe[1] and T. B. McCord[2], [1]Bear Fight Institute (22 Fiddler's Road, Winthrop WA 98862, United States of America; jean-philippe_combe @ bearfightinstitute.com).

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 with near-infrared spectra at wavelengths where thermal emission becomes non-negligible with respect to the local reflectance. At 5 µm, the longest wavelength for VIRTIS-M [1] on the Rosetta mission [2] which observed comet 67P/CG, and VIR [3] on the Dawn mission [4] which is currently in orbit around Ceres, the minimum brightness temperature that can be measured is ~150K. The usual technique is to fit a Planck function to each spectrum, providing one temperature per pixel (e.g. [5], [6]).

However, the calculation of a distribution of temperatures per pixel is justified by the fact that the topography at all scales results in variable illumination conditions (variable incidence angle and shadow casting) within the surface covered by one pixel, which produces a distribution of temperatures – and thus a distribution of thermal emission contributions [7].

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.

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 two techniques that are based on different assumptions: they are expected to have different levels of performance and relevance to our objectives, depending on the circumstances. First, we have to test them in order to characterize their behavior for each case.

Multiple-Endmember Linear Spectral Unmixing model (MELSUM)

MELSUM [8] has been developed to fit reflectance spectra of planetary 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 [8] with the OMEGA imaging spectrometer on Mars Express, Vesta [9] and Ceres [10] with the VIR mapping spectrometer on the Dawn spacecraft.

In order to retrieve a distribution of temperatures with MESLUM, 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 zero if the corresponding temperature is not represented in the surface observed)
- The temperatures that can be tested are limited by a range (minimum and maximum values) and a resolution (typically 1 K or less).
- 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.

Truncated-Newton non-linear optimizationt (IDL TNMIN.pro)

TNMIN is based on the Truncated-Newton method [11], and is designed to fit any type of one-dimension function to a dataset. Unlike MELSUM, TNMIN converges iteratively to the best fit, which is more time-efficient. The assumptions in using TNMIN are:

- The temperatures that can be tested are limited by a range (minimum and maximum values) and a resolution (typically a fraction of a pixel, much smaller than with MELSUM).

- Values for the weighing coefficients for each Planck curve can be constrained to the interval 0 to 1.
- The maximum number of Planck functions that can be used to fit a spectrum is fixed, however it does not have to be as small as in MELSUM.
- The sum of weighing coefficients cannot be constrained to be <1: this is the main drawback of this technique, because it may lead to values that are not physically possible.

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 by using the two inversion techniques. 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 with MELSUM as well as with TNMIN,both excuted 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).

Perspectives: Comparisons between techniques

The current efforts consist in improving the performance and computer efficiency of the different techniques that we have developed to fit a combination of multiple Planck curves to any spectrum. Once it becomes practical to process entire hyperspectral cubes, then we will start comparing results.

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.

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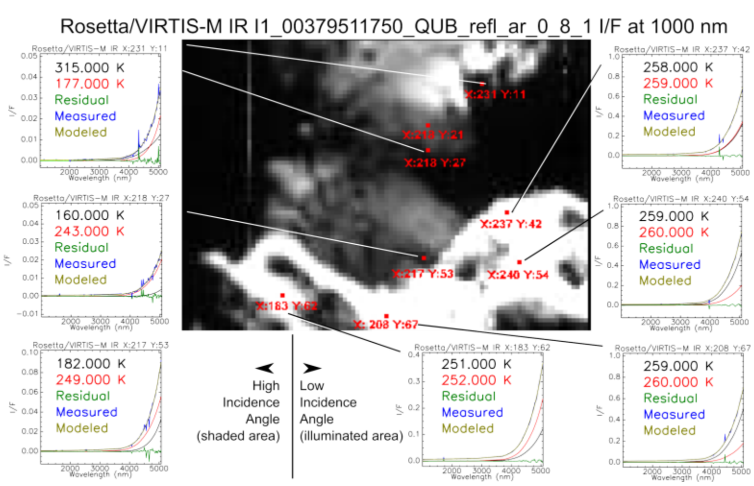

Figure 1: Example of spectral modeling of thermal emission contributions in Rosetta/VIRTIS-M IR spectra of comet 67P/Churyumov-Gerasimenko using MELSUM with two Planck curves (two surface temperatures) for each pixel. Spectra of shaded areas are systematically modeled by two temperatures separated by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