Using Space Weathering Models to Match Observed Spectra to Predicted Spectra

Michael Guyote and Jennifer Okada
Boeing LTS, Inc.
5555 Tech Center Dr, Suite 400
Colo Spgs, CO 80919-2374

Kira J. Abercromby[1]
ESCG/Jacobs Sverdrup
P.O. Box 58447
Houston, TX 77258-8447
Attn: Kira Abercromby, MC: JE 104

ABSTRACT

Observations of spacecraft obtained by the Spica spectrometer on the AMOS 1.6 meter telescope have shown spectral alterations between observed spectra and that obtained by ground measurements prior to launch. These spectral changes (sometimes referred to as reddening) appear to be an effect of the space environment. A similar effect has been described by B. Hapke for asteroids and the lunar surface. We have explored the possibility of utilizing Hapke models to analyze the degree to which these models can be applied to spacecraft weathering, with promising results. This paper details the continuing research into linking the reddening phenomenon with theory, and covers the methods by which the Hapke relationships will be used to match actual ground spectra to that obtained by the FORMOSAT and ANDE satellites.

1. Introduction

The SPICA spectrometer (located on the AMOS 1.6 meter telescope) has obtained data from orbital objects that is used to classify object types and identify materials. Comparison of these observations with ground data showed an increase in reflectance as wavelength increased (hereafter termed reddening). This reddening is not seen with spacecraft that have returned to earth, which enforces the belief that the root cause of the reddening is an effect of the space environment. One possible explanation is that oxygen vacates the surface, thus allowing particulate contamination to attach to the space object's surface, thereby changing the reflectance properties of the surface material. Recent data indicates that satellites in low earth orbit (LEO) may have surface contamination consisting primarily of silicon – which appears to come from silica-based paints used on satellites [7]. B. Hapke has developed a model for asteroid spectral reddening that we have modified and combined it with multi-variable search techniques [2]. This is done with the goal of demonstrating the concept of obtaining information on space weathering by comparing ground and space spectra. Current research is directed towards refining the process of closing the loop between ground and space-based observations such that additional information on space weathering effects can be gained and exploited. The current thrust of this research is to link recently obtained ground spectra FORMOSAT and ANDE satellites with observations obtained by the Spica Spectrometer once they are placed into orbit. This paper covers the process by which ground-based and space observational spectral data will be utilized to gain knowledge of space weathering effects. Actual results will be compiled as soon as space observation data is obtained.

2. Hapke Reflectance and Emittance Analysis Technique

Spectral reddening is modeled using modified Gaussian Hapke equations [2,4,5] defining the reflectance (R) of an object.

$$\log R(\lambda) \cong C(\lambda) + \sum_i s_i * \exp\left(-\frac{(\lambda-\mu_i)^2}{(2\sigma_i^{\;2})}\right)$$

The basic spectral equation, consists of a wavelength-dependent continuum function C(λ) to which absorption features are manually added. The weighting of each feature is controlled by the internal scattering coefficient (s_i), while the spectral location and width of each absorption feature is controlled by μ_i and σ_i .

The continuum function, C(λ) consists of a continuum constant (c_0) – essentially a dc-like offset to the spectra, to which the wavelength-dependent absorption coefficient (α_ω) is added.

$$C(\lambda) = c_0 + \alpha_w$$

The absorption coefficient α_w, (which handles the reddening of the spectra), is broken into contributions by the host (α_h) and the coating particles (α_{part})as follows.

$$\alpha_w = \alpha_h + \alpha_{part} = \frac{4\pi k_h}{\lambda} + \frac{36\pi\phi z}{\lambda}$$

The first portion of the absorption coefficient depends only upon the complex portion of the host (h), whilst the second portion depends upon factors possessed by both the host and the coating particles.

Z is a variable based on the index of refraction:

$$z = \frac{n_h{}^3 n_p k_p}{(n_p{}^2 - k_p{}^2 + 2n_h{}^2)^2 + (2n_p k_p)^2},$$

where n_h, k_h, n_p, k_p are the real and imaginary refractive index coefficients of host (h) and particle (p). Depending on the location of the particle, φ is defined by either distributed by,

$$\phi = \frac{\rho_p f}{\rho_h},$$

for a particle distributed throughout the host medium or by,

$$\phi = \frac{\rho_h fD}{2t\rho_p},$$

for particles coating the surface. ρ_{part} represents particle density, ρ_h represents host density, f is the mass fraction of the particle over the entire medium, t is the coating thickness of the particle, and D is the path length.

Note that ϕ and z are essentially "weighting" factors that control the amount of reddening. These equations have been shown to provide reasonable reddening spectra for asteroids [2, 4, 5], and are the basis for spacecraft spectral reddening analysis shown in this paper.

3. Closing the Loop

The Hapke spectral reddening equations as implemented in current research contain 11 variables. In addition, many of these variables are complimentary, that is, an increase in one variable can be accompanied by a commensurate decrease in one of the companion variables, resulting in an identical solution. Many multi-variable search techniques exist to aid in find solutions. The particle swarm technique was chosen primarily because of readily available software capable of implementing the algorithm. In this technique, the particles navigate through the multi-dimensional problem space. Each variable is given an initial value and a random velocity. Following each iteration, particle positions and velocities are altered such that they tend to those values producing the best "fit" to the target function. In evaluating the swarm technique, a series of test runs were conducted to explore algorithm performance and ascertain the accuracy of the results [2]. For these tests, a reference spectral curve was generated utilizing set values for all variables in the Hapke equations. Limits to search space were programmed into the swarm algorithm, and the variable values recorded after the search was judged to be stabilized (by utilizing a preset error threshold). Although individual results showed wide variations between set and resultant values, average values obtained multiple runs showed that the system appeared capable of overcoming the complimentary function problem.

The technique has been further refined, and will be utilized to analyze any spectral reddening observed in the FORMOSAT and ANDE observations. Reddening will be analyzed by computing a difference between ground-based spectral data with observational data. This will be the reddening spectrum. The swarm technique will then be utilized in an attempt to alter a "flat" spectrum such that it will match the reddened spectrum. The process is shown in fig 3.1. Ground- and space-based spectra will be gathered, combined, and normalized such that a reddened spectrum can be calculated. The Hapke diffusion equations will then be utilized to alter a "flat" spectrum such that the difference between the altered spectra and the reddened spectra can be minimized. Existing knowledge of particle types and sizes expected to be encountered during each object's orbit will aid in setting search variable parameters, and will hopefully aid in minimizing the complimentary function problems described previously.

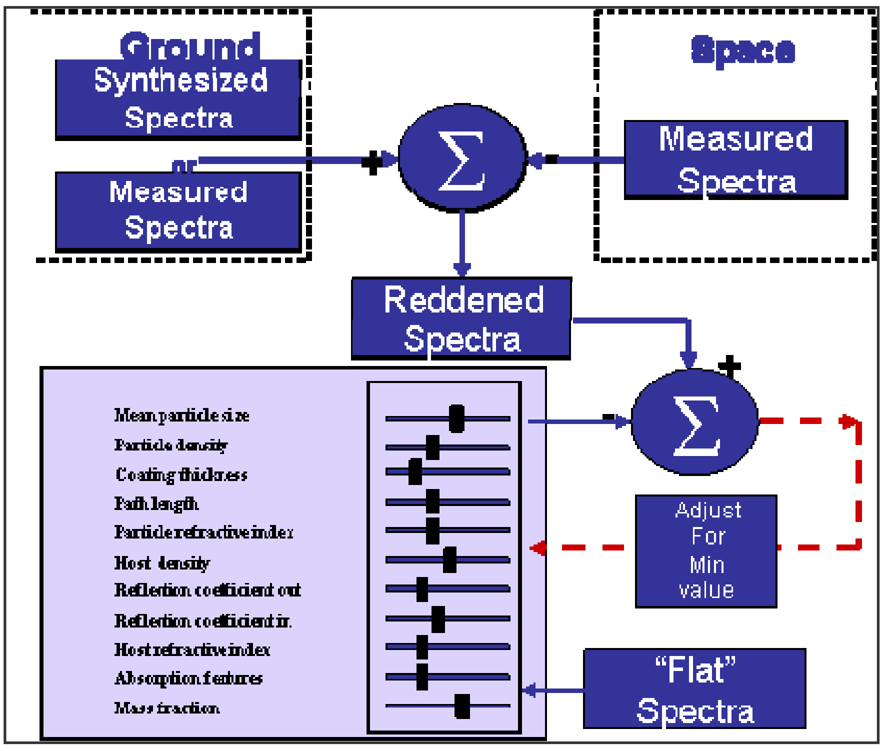

Figure 3.1: Space Weathering Closed-Loop Analysis Technique

4. Data Preparation

Preparation of the data processing algorithms necessary for use was done prior to the availability of actual ground- and space-based FORMOSAT and ANDE data. However, since the data formats were known, preliminary work was done utilizing Inertial Upper Stage (IUS) data which was readily available. This allowed functional checks of data truncation and normalization.

This section first describes the generic data preparation procedures, and then provides a short summary of the recently obtained direct observation ground data that will be utilized for spectral reddening comparisons. The data format for both the direct measurement and GUI-based synthesis is identical, thus allowing the existing conversion and normalization algorithm to be utilized when processing FORMOSAT and ANDE inputs.

4.1. Data Preparation Techniques – IUS Ground Data

The methodology underlying the GUI-based spectral synthesis technique has been detailed in previous papers. [2,3] The GUI system was utilized to generate IUS ground data. The following material proportions were utilized: IUS mli with a kapton outer layer: 25%, carbon for the nozzle: 17%, and IUS upper section: 58%.

The resulting spectrum was normalized to 0.6 µm. Fig 4.1 diagrams the steps performed by the GUI-based synthesis technique. The GUI synthesis was utilized in lieu of actual ground measurements because this was the fastest means of obtaining preliminary measurements for test purposes. Actual ground measurement data will be used for FORMOSAT III and ANDE spectral reddening research. The GUI technique will be utilized for comparison purposes, if the materials are available in the spectral database.

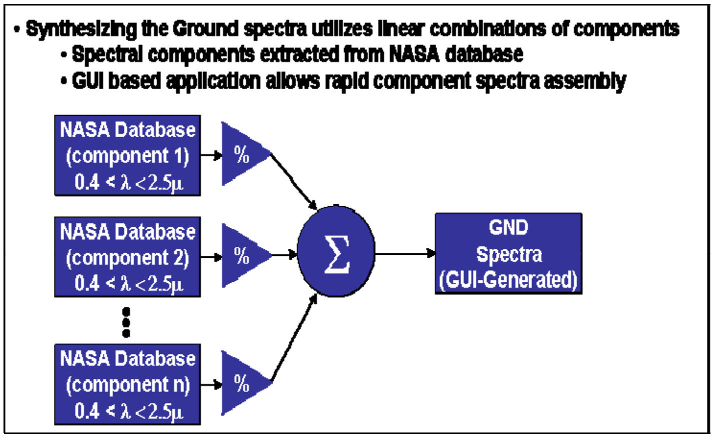

Figure 4.1: GUI-Based Spectral Technique Utilized for IUS Ground Data

4.2. Data Preparation Techniques – IUS Observational data

IUS observational data taken with SPICA are provided in two wavelength bands: 0.37 to 0.72 microns (µm) and 0.6 to 0.89 µm. Obtaining a spectrum requires two separate observations, which are normally obtained one night after the other. The spectral bandwidths also overlap. The data sets are combined by normalizing the reflectance and joining them at 0.6 µm.

A typical result of the processing described above is shown in fig 4.2, where the GUI synthesis spectrum is represented by the blue line. Also included in this plot is one of the space-based spectra as obtained from SPICA. The GUI-based and SPICA spectra match closely at wavelengths greater than 0.6 mm, thus reinforcing the belief that the GUI synthesis technique provides useful data for cases where an actual ground measurement is not available.

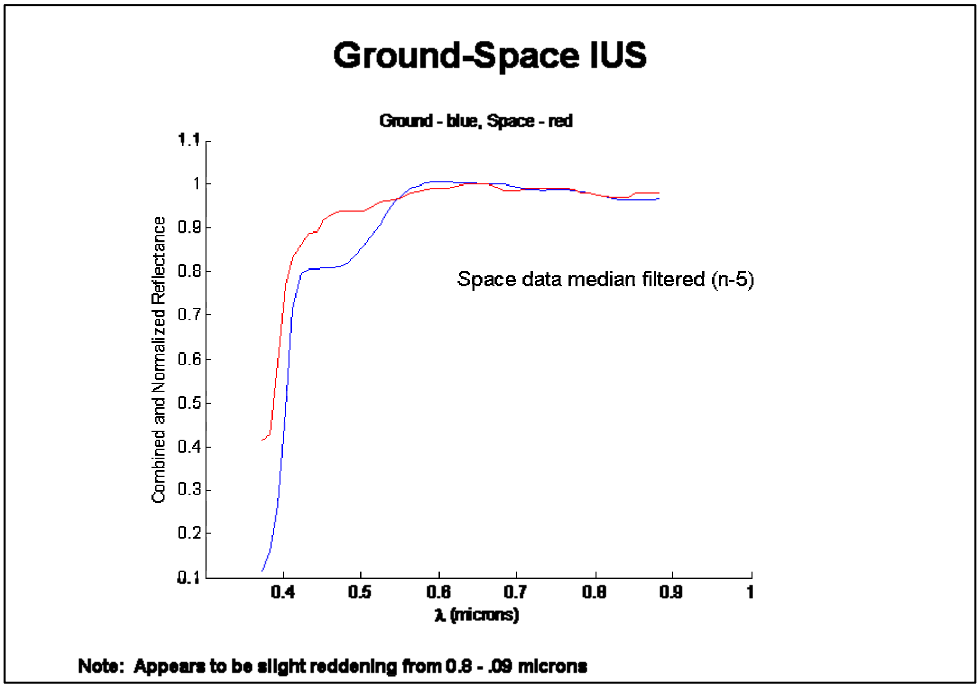

Figure 4.2: Comparison of Normalized Ground and Space IUS Spectra

4.3. Obtaining the Spectral Difference

The reddened spectrum is obtained by computing the spectral difference between the normalized and joined observational spectrum and the ground-based spectrum. The process is diagrammed in fig 4.3

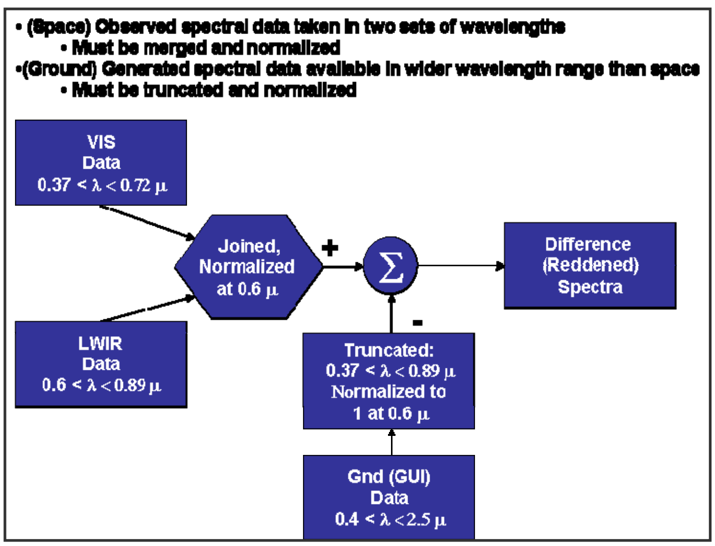

Figure 4.3: Methodology for Computing the Difference (Reddening) Spectrum

A typical difference spectrum is provided in fig 4.4. The difference spectrum appears to show some reddening. It has been noted prior that the IUS shows much less reddening then is seen with other space objects [9]. These results are considered to demonstrate proof of concept of the data normalization, combination, and differencing techniques.

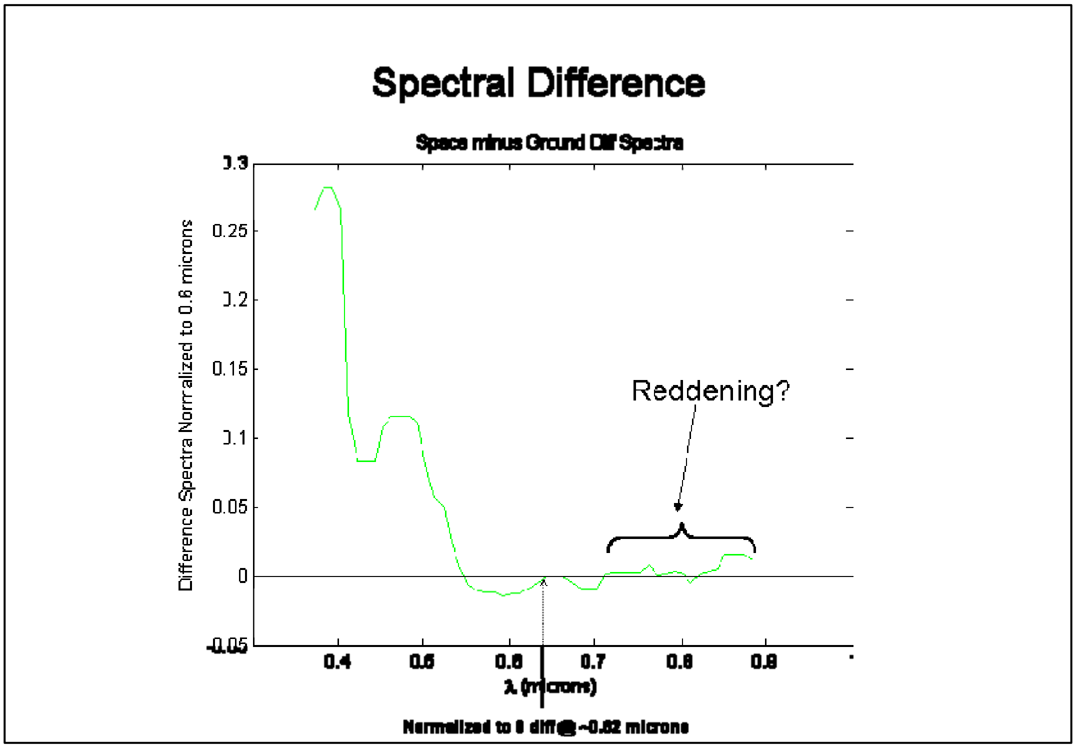

Figure 4.4: IUS Ground and Observation Spectral Difference

4.4. Direct Measurement FORMOSAT and ANDE Data

Data to be utilized for space weathering research will be obtained from two sets of satellites: FORMOSAT III, and ANDE Spheres. FORMOSAT III is a constellation of six Taiwanese satellites that were launched in April 2006. Two ANDE satellites (Atmospheric Neutral Density experiment) have been produced for the Naval Research Laboratory and are scheduled to launch in November or December of 2006. Ground data is obtained either by direct measurement, or by a GUI-based spectral synthesis algorithm. Direct measurement ground data has been obtained on both sets of satellites. A detailed explanation of data acquisition techniques, along with results, can be found in [1]. The GUI-based spectral synthesis algorithm has been detailed in [2, 3].

Figure 4.5 shows one direct measurement FORMOSAT spectra. More detailed information along with additional spectra on both FORMOSAT and ANDE can be found in [1]. This data is currently being incorporated into the processes described above in preparation for combination with SPICA observational data.

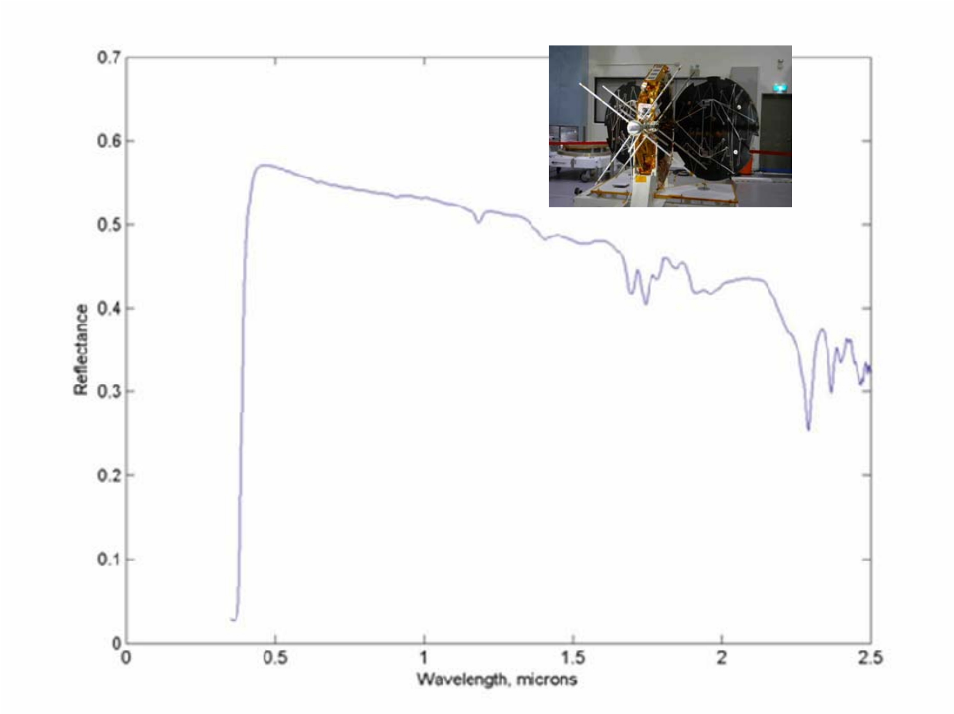

Figure 4.5: Example of FORMOSAT Ground Spectral Data [1]

5. CONCLUSIONS

The Hapke spectral reddening equations have demonstrated potential in evaluating the reddening effects which have been observed in spacecraft. These multi-variable mathematical relationships have been combined with the particle swarm search techniques such that the effects of space weathering on observed spectra (reddening) can be analyzed with the goal of remotely determining various aspects of surface contamination, to include particle size, thickness of contamination, etc. The research is being further refined with the goal of comparing ground data and observational data obtained from FORMOSAT III and ANDE satellites, and utilizing the Hapke diffusion equations and swarm techniques to obtain space weathering information.

6. ACKNOWLEDGEMENTS

The authors would like to the Dr. Kent Miller and the Air Force Office of Scientific Research (AFOSR) for their continual support financially of this project. The authors would also like to thank Brian Birge for his assistance with the particle swarm theory. Also, thanks goes to Dr. Bruce Hapke who kindly explained his program in great detail. In addition, many people assisted with this paper but are not authors: John Africano, Kris Hamada, Paul Kervin, Ed Barker, Dennis Liang, and all of the observers and operators at MSSS.

REFERENCES

1. Jorgensen Abercromby, K., Guyote, M., Okada, J. Hamada, K., and Barker, E., Comparison of Ground Truth and Remote Spectral Measurements of the FORMOSAT and ANDE Spacecrafts, *2006 AMOS Technical Conference*, Wailea, Maui, Hawaii, 10-14 September, 2006.

2. Abercromby, K., Guyote, M., Okada, J., Barker, E., Applying Space Weathering Models to Common Spacecraft Materials to Predict Spectral Signatures, *2005 AMOS Technical Conference*, Wilea, Maui, Hawaii. 5-9 September, 2005.

3. Jorgensen, K., Okada, J., Guyote, M., Africano, J., Hall, D., Hamada, K., Barker, E., Stansbery, G., and Kervin, P., Reflectance Spectra of Human-made Objects, *2004 AMOS Technical Conference*, Wailea, Maui, Hawaii, 8 – 12 September 2004.

4. Hapke, B, Space Weathering from Mercury to the asteroid belt, *Journal of Geophysical Research*, **Vol. 106**, No E5, Pages 10,039-10,073, May 25, 2001.

5. Hapke, B, Theory of reflectance and Emittance Spectroscopy, Cambridge University Press, 2005.

6. Nishimoto, D.L. Kervin, P., Sydney, P., Hamada, K., and Africano, J., Spectroscopic Observations of Space Objects and Phenomena using Spica and Kala at AMOS, *Proceedings of SPIE*, **Vol. 4490B**, San Diego, California, 29 July - 3 August 2001.

7. Abercromby Jorgensen, K., personal telecon, July 7, 2006.

8. Abercromby, K.J., Jorgensen, K., Rivkin, A., Binzel, R., Whitely, R., Hergenrother, C., Chodas, P., Chesley, S., and Vilas, F, Observations of J002E3: Discovery of a possible Apollo 12 rocket body, *35th DPS Conference Poster Session*, September 2003.