Comparisons of a Constrained Least Squares Model versus Human-in-the-Loop for Spectral Unmixing to Determine Material Type of GEO Debris

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Sixth European Space Debris Conference, Darmstadt, Germany, April 2013

The Problem

- **Spectral data collected in the lab are usually single material samples at one orientation**

- **Spectral data collected from remote observations are usually multiple material at various orientations**

- **Problem: How to unmix the multiple materials into specific single materials?**

Current Method and Proposed Method

- **Previously, "human-in-the-loop" method determined material type by examining absorption feature locations and strengths seen in remote spectra**
  - Time consuming
  - Limited to those with a priori knowledge of the materials and feature locations

- **Program written to use a constrained linear least squares method to determine the materials in the remote sample**

Constrained Least Squares Unmixing Model

- **Combined spectra can be added linearly**

$$\mathrm{S}_{combined} = \sum_{i=1}^{n} p_i B_i S_i + \mathrm{N}$$

where p_i is material proportion of the full spectrum, and S_i is the spectrum of that material, and B_i, is the orientation coefficient plus some noise, N

- **Using Vector Math, the above becomes:**

$$\mathrm{S}_{combined} = \mathrm{SA}$$

- **But S is not square so you need psuedo-inverse to solve for A**

Constrained Least Squares Unmixing Model

- **Psuedo-Inverse yields:**

$$(S^T S)^{-1} S^T S_c = \mathrm{A}$$

where S is the spectrum, S_c is the combined spectrum, S^T is the transpose

- **This can lead to negative proportions which is impossible: used a modified Lagrange multipler method to constrain the problem**

- **Error calculations (for both this method and human-in-the-loop) is:**

$$Error = \frac{\sqrt{S_{diff}^T S_{diff}}}{\sqrt{S_c^T S_c}}$$

Remote Data Collection

- Las Campanas Observatory, Chile
- Imaging Spectrograph on 'Landon Clay' (one of the twin 6.5m Magellan telescopes
- 1-2 May 2012 observations with the LDSS3 (Low Dispersion Survey Spectrograph 3)

Photo credit: http://obs.carnegiescience.edu/Magellan

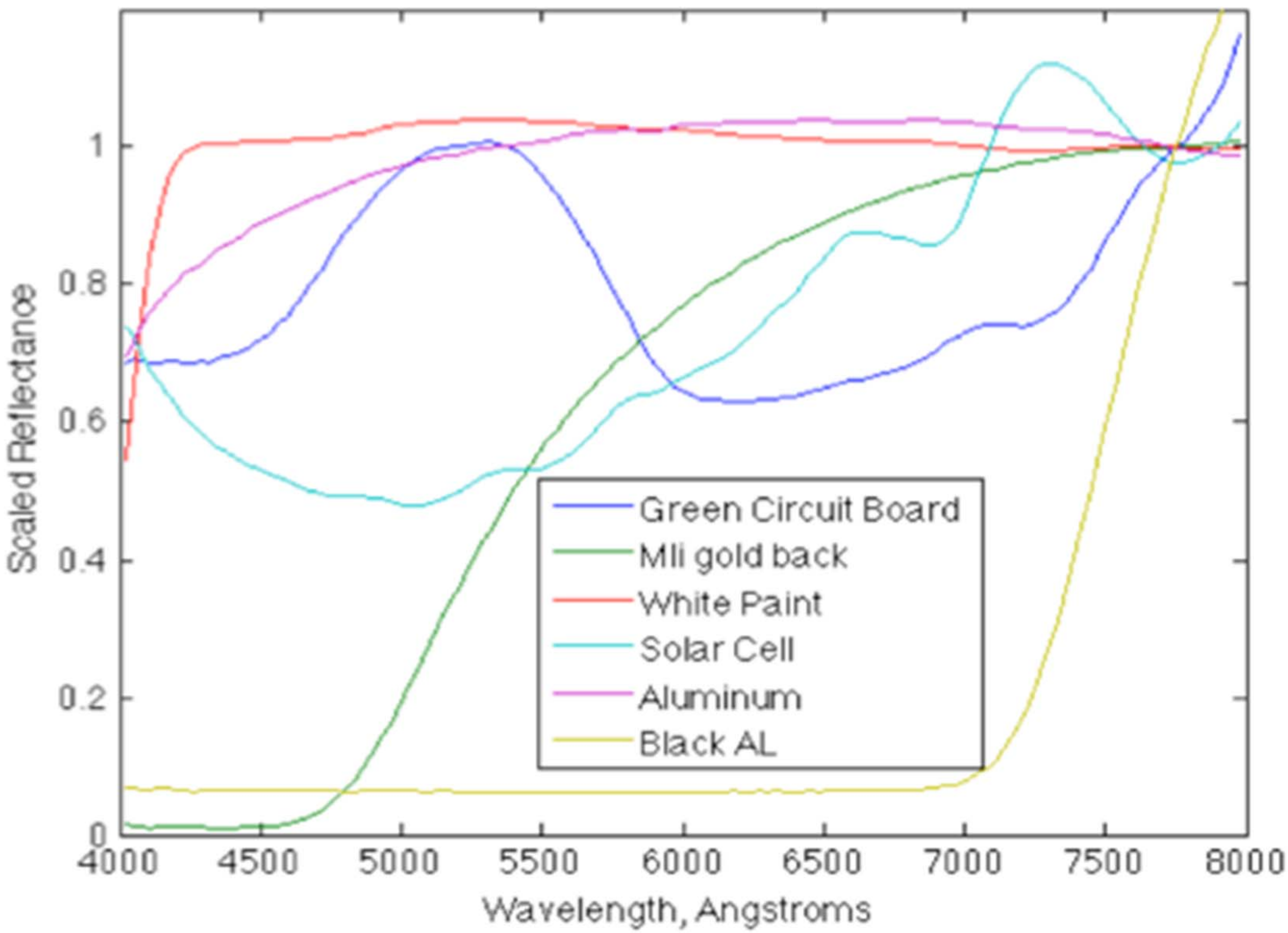
Remote Observation Collection

- **LDSS3**
  - 5 arc-second wide slit
  - VPH-ALL grism
  - 3800-9000 Å (only reporting 4500 to 8000 Å due to atmospheric refraction effects and no order-separating filter)
  - Spectral Sampling: 1.9 Å /CCD pixel
  - Airmass < 1.7
  - Normally, five 30-second exposures per object

Laboratory Data Collection

- **Collected with an Analytical Spectral Device (ASD) field spectrometer**
  - Resolving power of 10 nanometers at 2 microns
- **Data collected on three cubesats, Inertial Upper Stage (IUS) rocket body, and various solar cell types**
- **Data was collected at orientations to limit specular reflections while ensuring the highest signal to noise**

Sample Laboratory Data

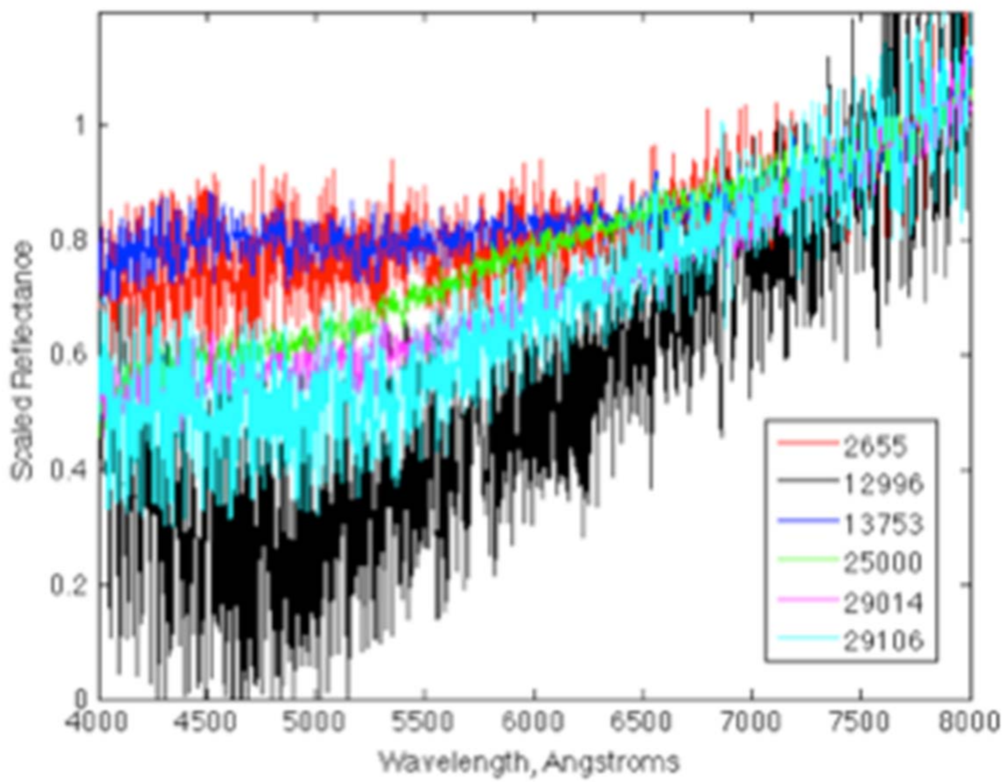


Objects Acquired

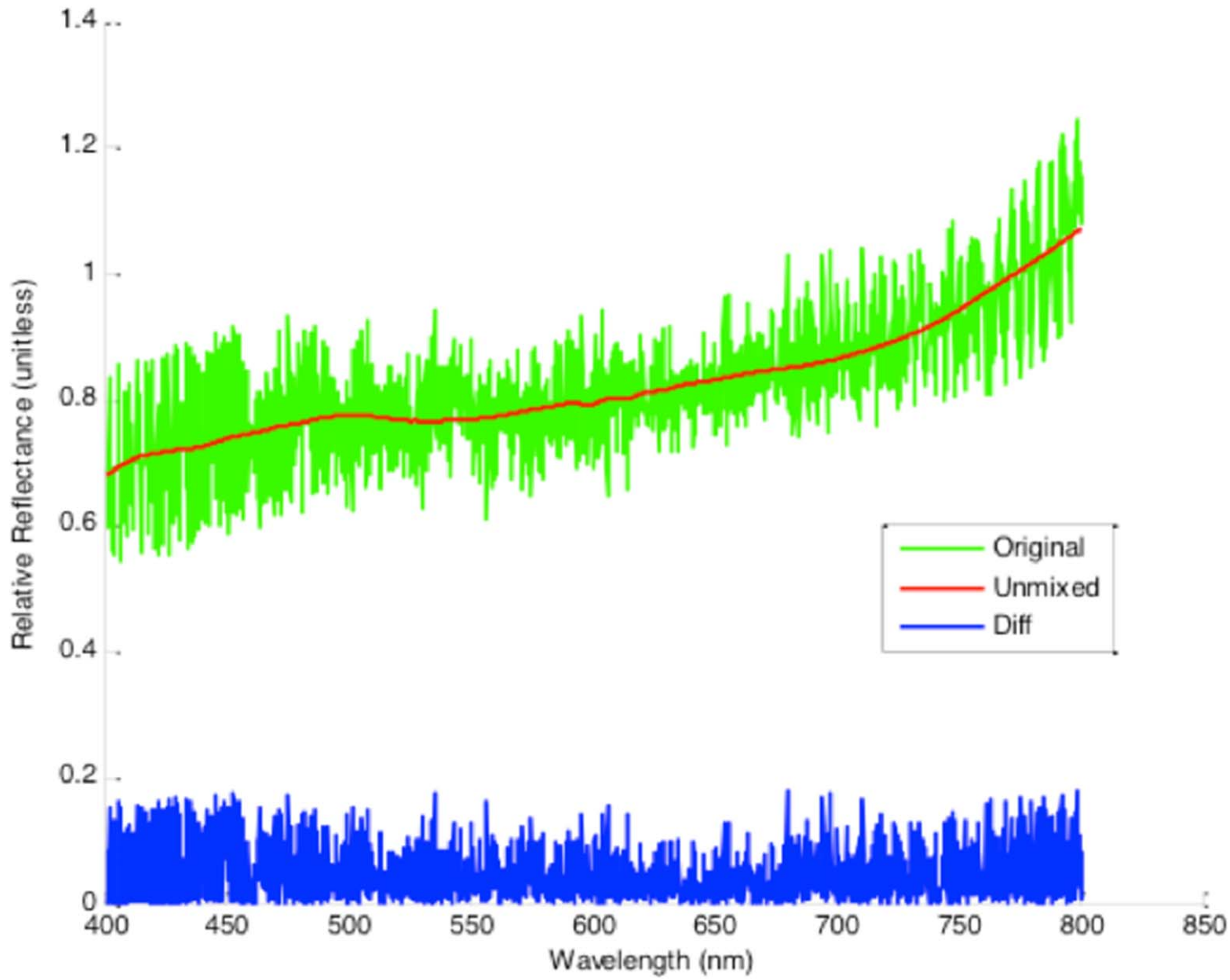
SSN	Launch Date	Description
2655	1967	IDSCP
12996	1977	EKRAN 2 DEB
13753	1976	LES 8,9/SOL 11A,B DEB
25000	1968	TITAN TRANSTAGE DEB
29014	1977	EKRAN 2 DEB
29106	2005	MSG 2 DEB (COOLER COVER)

Initial Impressions of the remote data

- **Shape examination only**
- **2655 and 13753 are similar (IDCSP and LES)**
- **29104, 29106, 12996 (Ekran 2, Cooler cover, Ekran 2) similar**
- **25000 (Titan) different from those two sets**
- **Only one from each set shown here; see paper for all results**



Results: IDCSP (SSN 2655)
Model Match to actual data plus difference



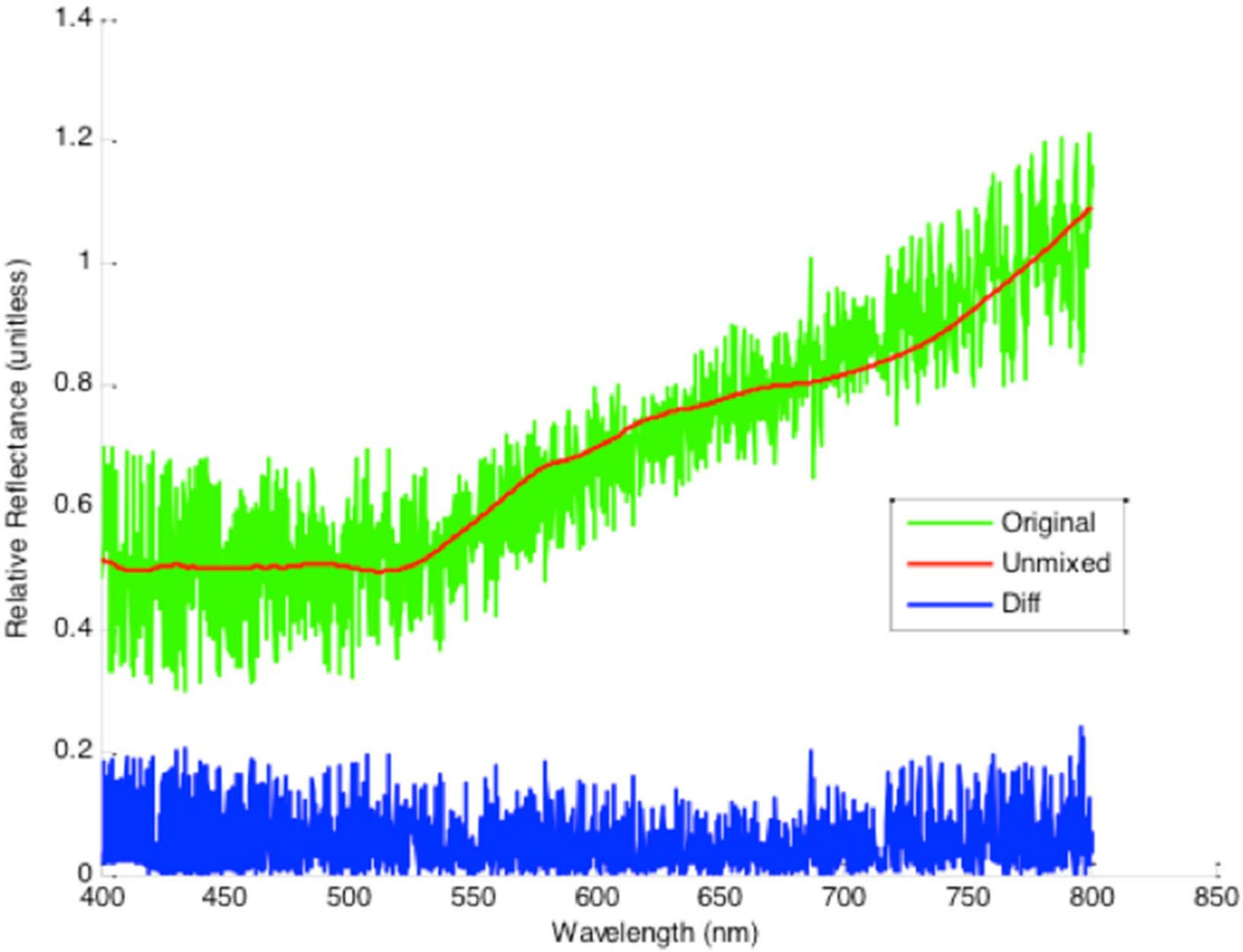
Results: IDCSP (2655): Materials found by the model & traditional method

Constrained Linear Least Squares Materials Used in the Combined Spectrum (7.4% error)	Traditional method materials used in the combined spectrum and percentages (11% error)
White paint from IUS	Yes (30%)
Blue cable	No
MLI gold	No
Solar Cell TRMM	No
Solar Cell MT	Yes (50%)
Green circuit board	No
Black circuit board	No
AL-Kapton	No
AL Unanodized	Yes (20%)
Germanium	No

Photocredit: http://sortingoutscience.net/2012/10/22/the-scientific-tourist-245-idcsp/

- Object known to have solar panels
- Both methods found majority solar panels

Results for Object 29106
(Kapton Covered Cooler Cover)



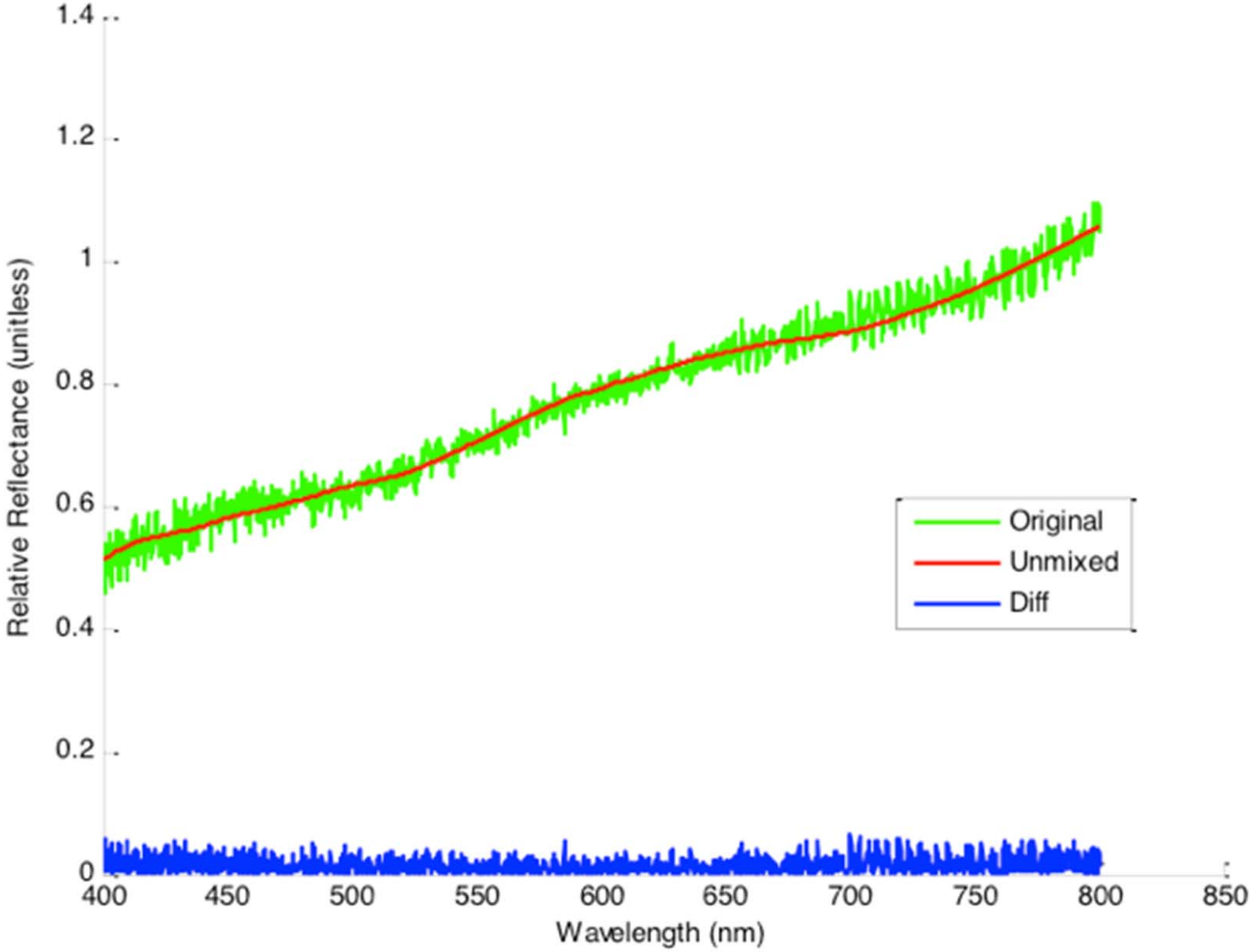
Results for Object 29106 (Kapton Covered Cooler Cover)

Constrained Linear Least Squares Materials Used in the Combined Spectrum (9.5% error)	Traditional method materials used in the combined spectrum and percentages (11% error)
Blue cable	No
MLI gold backing	Yes (30%)
Solar Cell TRMM	Yes (20%)
Solar Cell MT	Yes (40%)
Green circuit board	No
ITO Kapton	No

Photo credit: Mark Skinner, et al, Further analysis of infrared spectrophotometric observations of high area to mass ratio (HAMR) objects in GEO

- **Both methods found solar panel, which is definitely not correct**
- **Both methods did find MLI, which is likely**
- **One possible future avenue would be to remove materials from the possible list that are unlikely to be on a specific object prior to running the model**

Results from SSN 25000 (Titan 3C Transtage Debris)



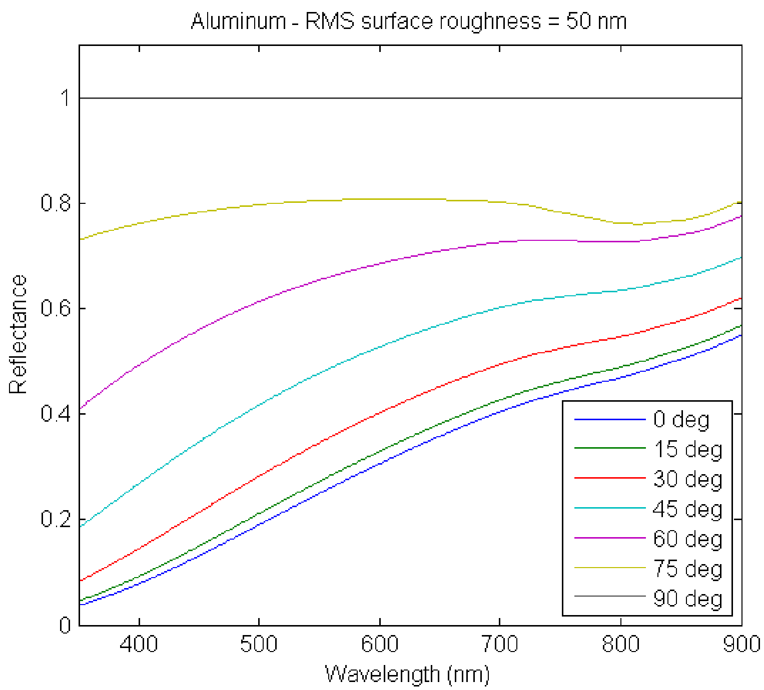
Results from SSN 25000 (Titan 3C Transtage Debris)

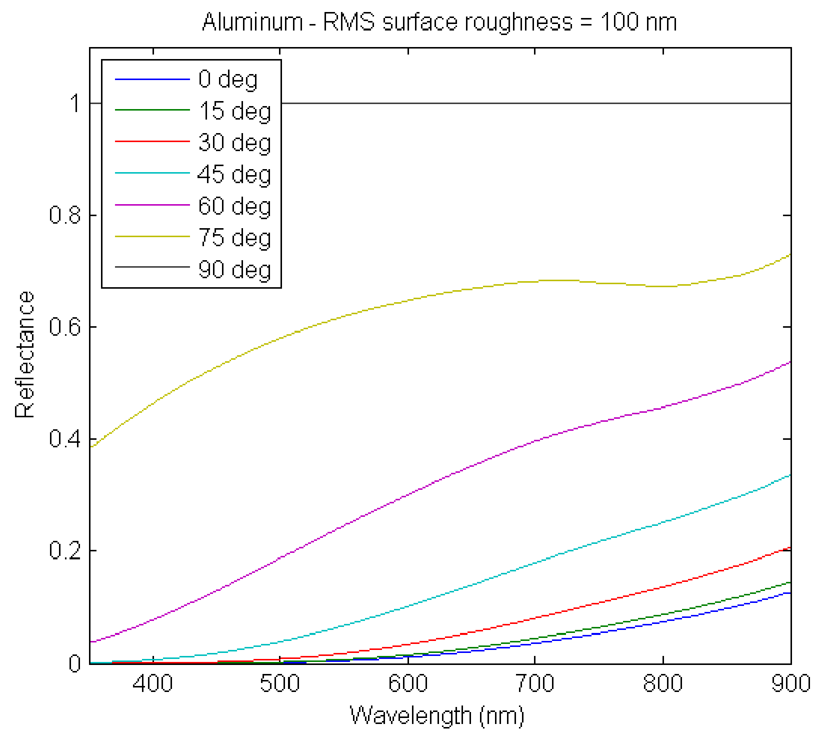
Constrained Linear Least Squares Materials Used in the Combined Spectrum (2.5% error)	Traditional method materials used in the combined spectrum and percentages (14% error)
Aluminum	Yes (15%)
Blue cable	Yes (15%)
MLI gold front and back	Yes (25%)
Green circuit board	Yes (15%)
Black board	Yes (10%)
ITO Kapton	Yes (20%)

- **No solar panels (good thing!)**
- **Lots of materials**
- **Need longer spectrum to see Aluminum feature near 8500 Å**

Future Additions to the Model

- **Continuum Division to remove reddening of spectrum**
- **Surface Roughness and Orientation, B_i**
  - Possibly responsible for 'reddening effect'
  - Orientation not taken into account yet
  - Surface Roughness models needs to be incorporated





Conclusion

- **Constrained Linear Least Squares model is generally more accurate than the "human-in-the-loop"**

- **However, "human-in-the-loop" can remove materials that make no sense**

- **The speed of the model in determining a "first cut" at the material ID makes it a viable option for spectral unmixing of debris objects**