Initial Estimates from AVIRIS of the Temperature and Fractional Areas of Fires at the World Trade Center Disaster

Robert O. Green,[1] Roger N. Clark,[2] Joseph Boardman,[3] Betina Pavri,[1] Chuck Sarture[1]
[1]Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California 91109
[2]U.S. Geological Survey
[3]Applied Imaging and Geophysics LLC

1.0 INTRODUCTION

On the 14th of September 2001, in the wake of the destruction of the World Trade Center, the question of using AVIRIS (Vane et al., 1993; Green et al., 1998) to detect possible asbestos contamination was raised. AVRIS measures the spectral range from 370 to 2510 nm, with 10 nm sampling and high precision. This spectral range, spectral resolution, and precision, supported the use of AVIRIS to measure the 2300-nm absorption features of the principal asbestos minerals. Based on this potential contribution, approval was given for AVIRIS to acquire data over the disaster site.

At the time, AVIRIS was installed on the Twin Otter aircraft and grounded at the Atlanta, Georgia, airport. With careful and persistent effort in the challenging environment following September 11th, permission was given to fly AVIRIS at low altitude over the disaster site. AVIRIS data were acquired of the site and surrounding area on the 16th of September 2001. Rapid examination of these data in the following 24 hours unexpectedly revealed the presence of multiple hot fires still burning in the debris. Subsequently, rapid characterization and reporting of the hot-fire properties in the debris area were added to the analysis objective for the AVIRIS data.

A Planck-function-based spectral-fitting fire temperature and fractional area algorithm (Green, 1996; Green, 2001) was applied to the AVIRIS-measured hot-fire spectra. A precise georectification of these AVIRIS data was performed to locate the geographic position of the hot fires (Boardman, 1999). The locations and derived fire temperatures and fractional areas were reported to the rescue teams on the ground on the 17th of September. Based on these initial results additional AVIRIS overflights of the disaster site were made on the 18th, 22nd, and 23rd. This paper reports the measurements, algorithms, analyses, and results of the fire temperature and fractional area determinations with AVIRIS calibrated spectra at the World Trade Center site in September 2001. Additional results relating to the detection of asbestos and other materials are reported elsewhere (Clark et al., 2002).

2.0 MEASUREMENTS

AVIRIS spectral image measurements were acquired over the World Trade Center disaster site in the period from 14:51 to 17:07 UTC on the 16th of September 2001. They were returned to JPL early in the morning of the 17th for analysis. Figure 1 shows an AVIRIS image cube rendition of a portion of one of the AVIRIS flight lines, with the disaster site in the left center of the image. The edge panels of the image cube rendition depict the spectral dimension of the AVIRIS data.

These data were acquired from an altitude of 1500 m, which gives a corresponding spatial resolution of 1.5 m, based on the 1 milliradian instantaneous field-of-view of the AVIRIS instrument. Early examination of the AVIRIS image data at 2300 nm on the morning of the 17th revealed a number of high-intensity radiance targets. Figure 2 shows the AVIRIS image from the 2300-nm spectral region, with numerous bright targets evident in the area of the World Trade Center. Additional bright targets at this wavelength are also evident towards the right of the image at some distance from the disaster site. Detailed examination of the spectra from high-intensity targets at the World Trade Center disaster site revealed spectral signatures of hot fires. The bright spectra to the right of the image in Figure 2 were shown to be the result of sun glint from reflective roof surfaces. AVIRIS spectra from surface background material, a burning fire at the disaster site, and sun glint from a building roof are shown in Figure 3. The background material spectrum has the form of solar-reflected radiance from a surface, of moderate uniform spectral reflectance across the AVIRIS range. The hot-fire spectrum exhibits the reflectance of a dark material in the range from 400 to 1000 nm. At wavelengths longer than 1000 nm, the hot fire spectrum radiance intensity increases until reaching the AVIRIS instrument saturation level in the 2000–2500-nm spectral range. This increase in radiance to longer wavelengths is consistent with surface sourced radiance emitted by a hot fire. In contrast, the sun glint spectrum shows a high spectral radiance that conforms to the shape of the solar spectral irradiance source convolved with the two-way transmittance of the atmosphere. In this spectrum, minor AVIRIS instrument saturation occurs near the 1000 nm wavelength region. AVIRIS instrument radiance saturation levels are set to preserve measurement precision for materials in the range from 0 to that of a 1.0 reflectance Lambertian surface with the sun directly overhead. Both the burning fire and sun glint spectra exceed this saturation level in limited portions of the spectrum. However, measurement of the spectral shape by AVIRIS in the nonsaturated portions of the spectrum provides a basis to identify the properties of these targets. In the case of the burning fire, the spectral shape and intensity may be used to derive estimates of both the temperature and fractional area of the hot source.

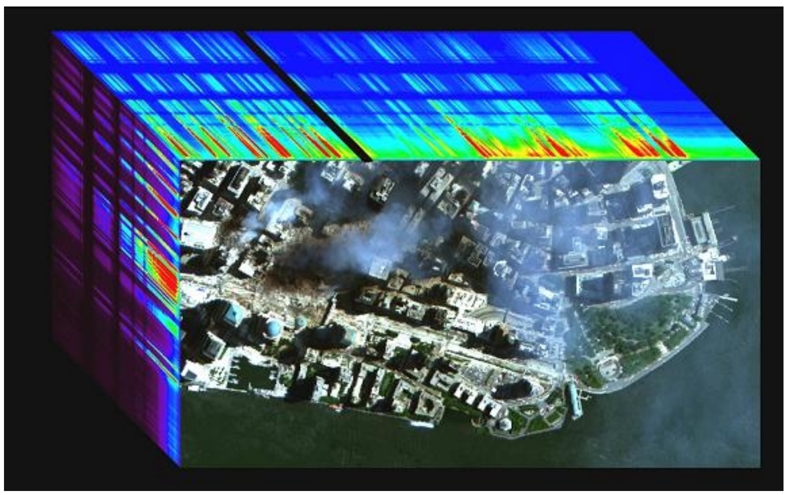

Figure 1. AIRIS image cube of World Trade Center disaster site acquired on the 16th of September 2001.

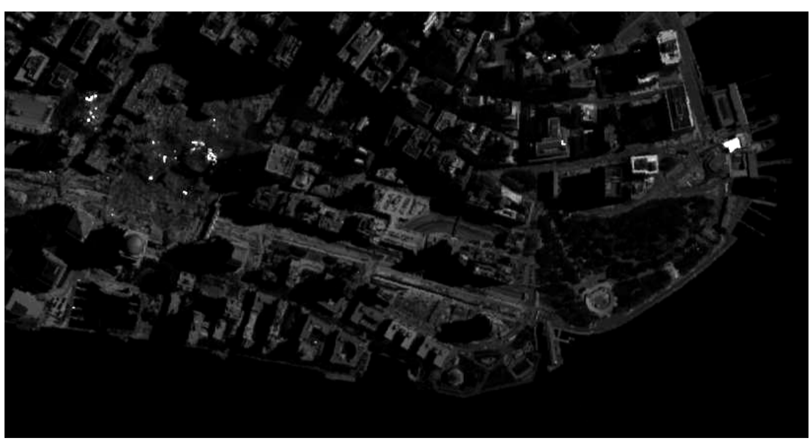

Figure 2. AVIRIS 2300-nm wavelength image of the World Trade Center disaster site. The bright signal to right side of the image is sun glint from a reflective roof surface.

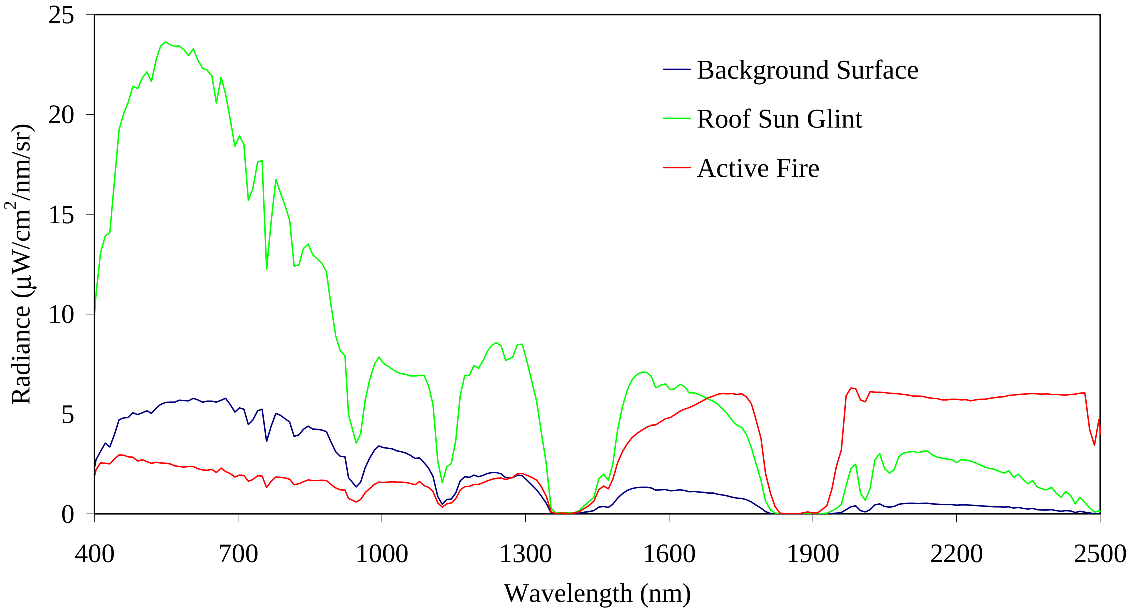

Figure 3. AVIRIS spectra for the World Trade Center disaster site. Background, active fire, and roof sun glint spectra are shown. The active fire exhibits exceptionally high radiance in the 2000–2500-nm wavelengths emitted from the fire and comparatively low radiance in the 400 –1000-nm spectral region.

3.0 PHYSICAL MODEL AND ALGORITHM APPROACH

The electromagnetic energy emitted by matter is a function of spectral emissivity that is related to composition and of the material temperature. The well-known Plank function (Liou, 1980) describes the radiance emitted by a target with emissivity of 1.0 as a function of temperature. Figure 4 shows the calculated Planck-function curves for a series of targets of temperature 600, 800, 1000, and 1200 Kelvin. In addition, the solar-reflected radiance for a 1.0 reflectance Lambertian target is also shown. For the Planck-function-modeled spectra, the radiance emitted increases as a strong function of temperature. Just as importantly, the slope and position of the Planck-function spectrum increases and shifts to shorter wavelengths as the temperature increases. This change in slope and wavelength position provides a basis for use of spectral measurement to determine the temperature of hot fires.

Because hot fires almost never uniformly fill the field of view of a spectral measurement, the fractional area of the hot source must be accounted for as well as the temperature. Equation 1 gives a simple relationship between the measured radiance at a given wavelength ($L\lambda$) and a Planck function ($B\lambda$) at a given temperature (T) and fractional area (A) for a 1.0 emissivity target.

$$L\lambda = A^* B\lambda(T) \qquad (1)$$

For daytime measurements by AVIRIS in regions of the spectrum where the atmospheric transmittance in approximately 1.0, an additional term is needed to account for the solar-reflected radiance ($L\lambda s$) and is included in Equation 2. This equation provides a simple model of the radiance measured by AVIRIS over a hot target in the highly transparent regions of the atmosphere

$$L\lambda = A^* B\lambda(T) +L\lambda s \qquad (2)$$

With this equation, a spectral-fitting algorithm has been implemented, where the fractional area and temperature parameters of the model are adjusted until optimal agreement is reached with the AVIRIS-measured radiance for the hot-target spectrum. The best fit resulting temperature and fractional area are then reported for each analyzed spectrum. For this approach, the solar-reflected radiance may be estimated from adjacent measured spectra that are not hot, or with a radiative transfer model such as MODTRAN (Berk et al., 1989; Anderson et al., 1995; Anderson et al., 2000). Planck-function spectral-fitting algorithms have been previously used with AVIRIS measurement of hot volcanic lava and hot burning fires (Oppenheimer et al., 1993; Green, 1996; Green; 2001).

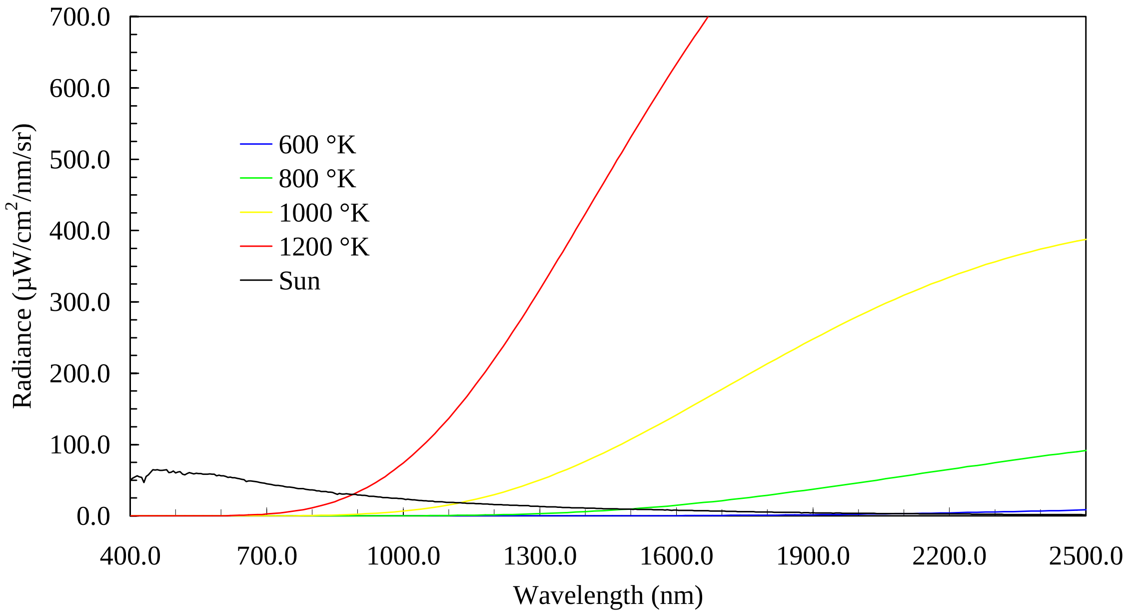

Figure 4. Planck-function calculated radiance for targets at different temperatures. The radiance of a 1.0 Lambertian target illuminated with the Sun at the zenith is also shown.

4.0 ANALYSIS

Hot-fire AVIRIS spectra from the World Trade Center data set were analyzed with this Planck-function spectral-fitting algorithm for derivation of temperature and fractional area. Areas with active fires were identified in the AVIRIS image from the 2300-nm wavelength region of the spectrum. For the 16^{th} of September AVIRIS data set, the brightest spectra from eight different areas with active fires in the World Trade Center site were analyzed. These spectra were labeled A to H. Figure 5 shows a hot-fire spectrum and an adjacent solar-reflected spectrum as well as the difference spectrum. Apart from the regions of strong atmospheric absorption near 1400, 1900, and 2500 nm, the spectral shape of the difference spectrum is dominated by the fire-emitted radiance.

The fire temperature and fractional area estimation analysis proceeds by determining the best fit between the AVIRIS spectrum with solar reflected component subtracted and the Planck function model. Figure 6 shows the best spectral fit between the hot fire spectrum and the Plank function model for the spectrum from area G in the 16^{th} of September AVIRIS data set. No portion of this spectrum is saturated in the AVIRIS measurement. The fit was optimized in the spectral regions with minimal atmospheric absorption. A temperature of 984 K and fractional area of 1.48% was derived for this spectrum. This is expected to be a low estimate for the temperature because the emissivity of the hot target was assumed to be 1.0. If the emissivity were lower than 1.0 the temperature would be higher to generate the intensity of measured radiance.

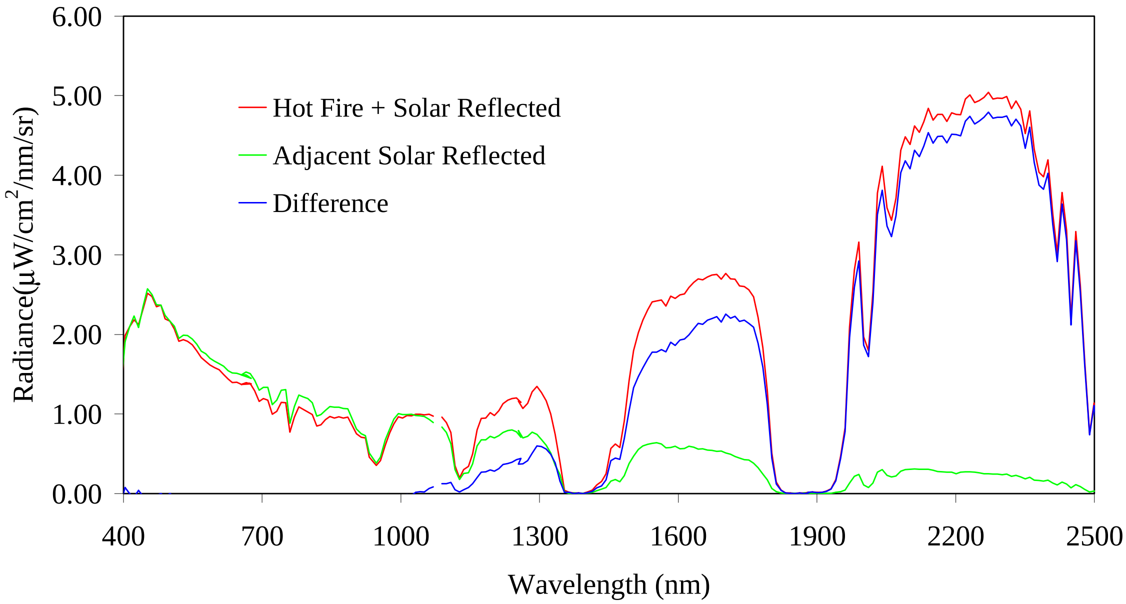

Figure 5. Hot-fire spectrum, adjacent solar-reflected spectrum, and difference spectrum for area G in the World Trade Center AVIRIS data set.

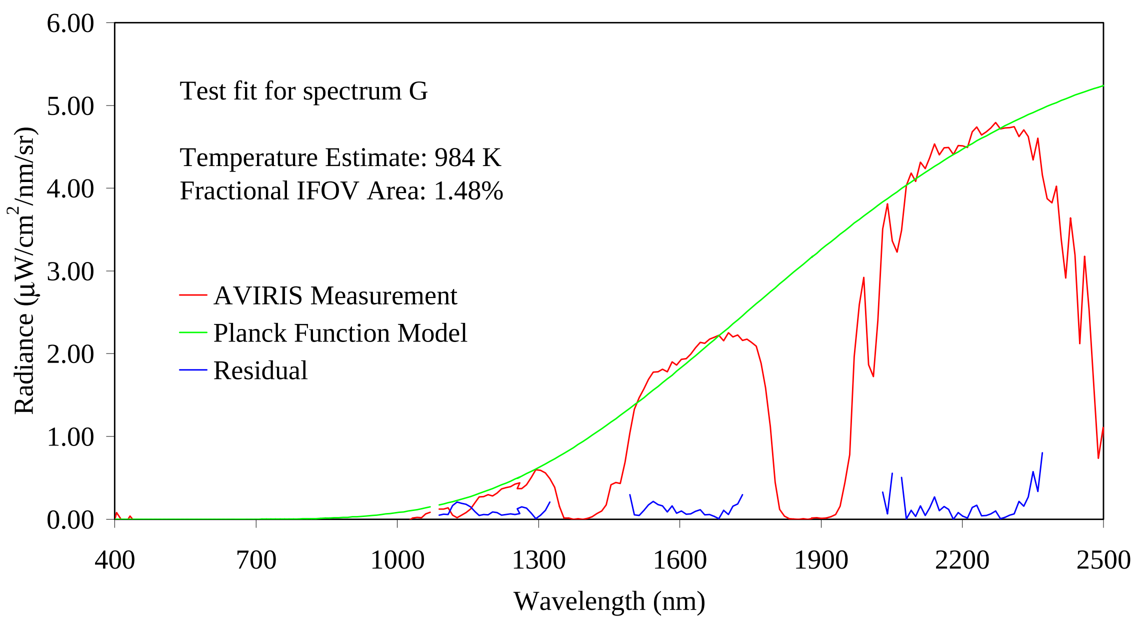

Figure 6. Spectral fit result in continuum regions between AVIRIS spectrum with solar-reflected background radiance subtracted and Planck-function model.

An additional example of the temperature and fractional area estimation algorithm for the highest intensity spectrum from area A of the 16^{th} of September data set is shown in Figure 7. For this spectrum a temperature of 928 K with a fractional area of 6% was derived. As with all analyses, the solar-reflected component of the radiance was estimated and subtracted using an adjacent solar-reflected dominated spectrum. For this spectrum from area A, the temperature and fractional area of the fire measured were sufficient to cause instrument saturation in the 2000- to 2500-nm region of the AVIRIS spectral range.

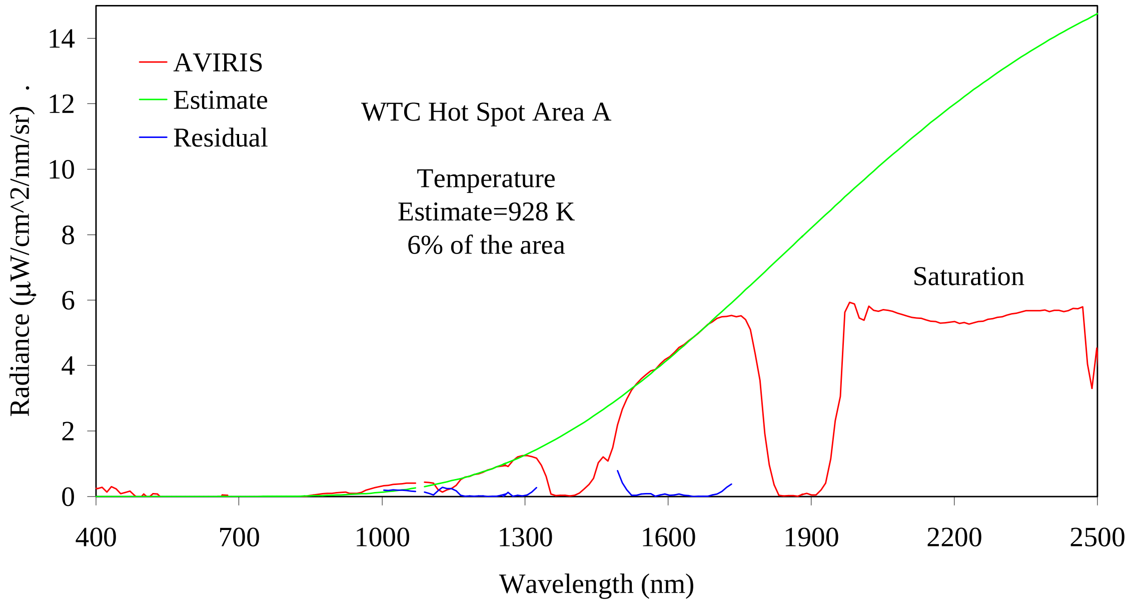

Figure 7. Temperature and area estimate for spectrum A acquired on the 16th of September 2001.

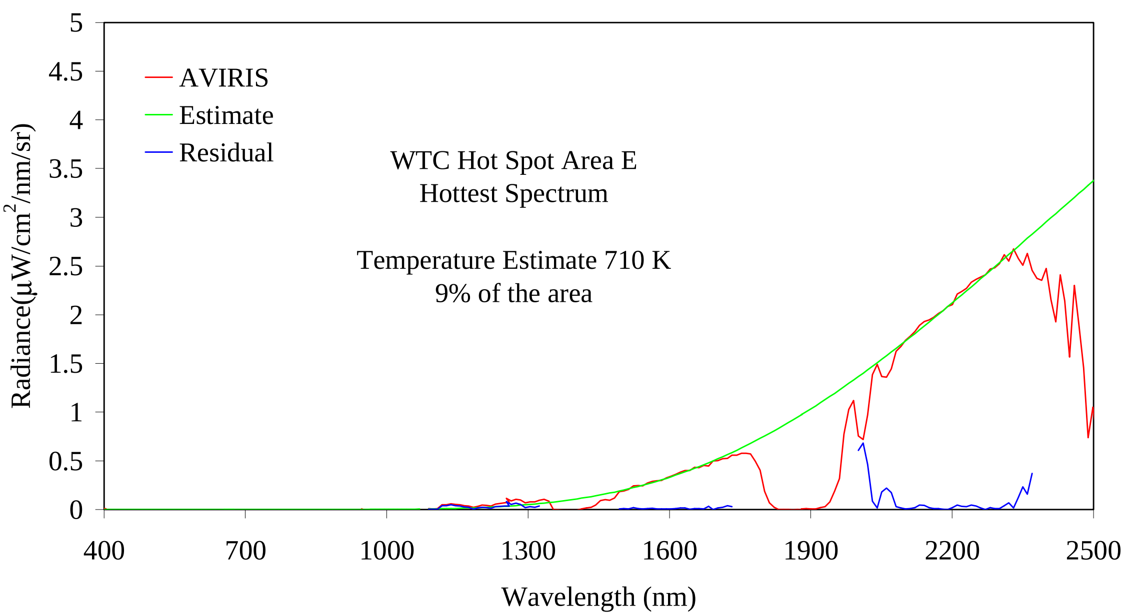

Figure 8. Spectral fit result for World Trade Center spectrum E.

However, even with saturation over part of the AVIRIS spectral range, the measured spectral shape and intensity in the 1000- to 1800-nm spectral range provide sufficient the leverage for the algorithm to derive a temperature and fractional area for this spectrum.

A further example of the temperature and fractional area analyses is shown in Figure 8 for the spectrum from area E of the 16th of September AVIRIS World Trade Center data set. The AVIRIS-measured spectrum with solar-reflected component subtracted, the Planck-function model fit, and residual difference are shown. For this spectrum, a temperature of 710 K and fractional area of 9% was derived. This spectrum was best modeled with a lower derived temperature and higher fractional area than the previous examples. This result is consistent with the shallower spectral slope of this spectrum and the shift of intensity rise to longer wavelengths.

To present and demonstrate the algorithm and analyses for estimation of fire temperature and fractional area from the 16th of September AVIRIS World Trade Center data set, selected examples have been shown. Temperature and fractional area parameters were derived even in the presence of AVIRIS instrument saturation over a portion of the spectrum. As expected, a range of temperatures and fractional areas were derived from spectra with distinctly different spectral forms. For these examples, the spectral fits between AVIRIS measured spectra and the Planck-function-based modeled spectra were in good agreement in the regions of high atmospheric transmittance. These spectrally derived values of temperature and fraction area are consistent with the expected emitted radiance from the hot fires burning an extended period in the surface debris of the World Trade Center disaster site.

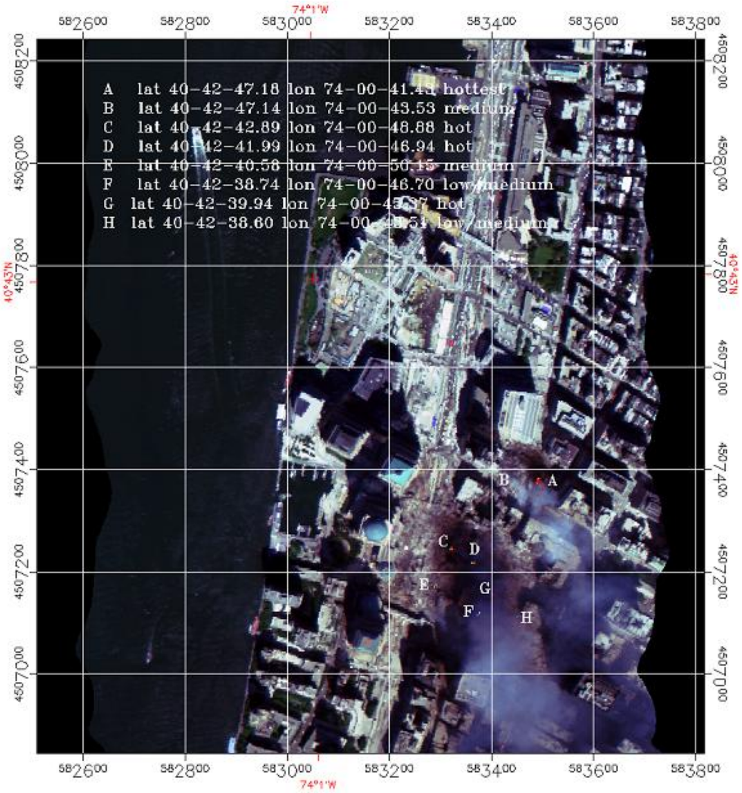

Figure 9. AVIRIS image acquired on the 16th of September 2001 with hot spots labeled.

5.0 RESULTS

The algorithm was applied to the highest intensity spectrum from each of the eight hot-fire areas identified. Figure 9 shows a portion of an AVIRIS image of the World Trade Center disaster site acquired on the 16th of September. The eight hot-fire areas identified are labeled A to H. Table 1 shows the corresponding locations of the hot-fire areas and the derived temperature and fractional area for the analyzed spectra. Temperatures range from 700 to 984 K, and fractional areas range from 1.5 to 18 % for the 16th of September data sets. These results were reported to the teams on the ground at the disaster site.

Table 1. Location, temperature, and fractional area determined for the highest intensity spectrum in the eight hot target areas identified.

Spectrum	Latitude	Longitude	Temp (K)	Area (%)
A	40 42 47.18	74 00-41.43	928	6
B	40 42 47.14	74 00-43.53	827	2
C	40 42 42.89	74 00-48.88	921	3.3
D	40 42 41.99	74 00-46.94	791	18
E	40 42 40.58	74 00-50.15	710	9
F	40 42 38.74	74 00-46.70	700	8
G	40 42 39.94	74 00-45.37	984	1.5
H	40 42 38.60	74 00-43.51	817	1.8

Based on the results with the data measured on the 16th of September 2001, AVIRIS was requested to over fly the World Trade Center disaster site on the 18th of September. A subset of an image from that overflight is shown in Figure 10. In this data set acquired on the 18th, hot-fire areas were identified and labeled from A to L. The A to H designations were selected to match the areas of the 16th of September data set. The additional hot areas—J to L—were not identified in the data set from the 16th September overflight. This increase in hot-fire areas on the 18th may be due to increased sophistication in identifying hot areas or to the occurrence of new hot areas. Table 2 gives the locations, temperatures and fractional areas derived for the highest intensity spectra in the hot-fire areas of the 18th of September AVIRIS data set. Derived temperatures range from 471 to 952 K and areas from 0.5 to 36 %. In the case of area E identified in the 16th of September data set no hot spectra were found on the 18th. For area J the spectral fit algorithm did not converge successfully.

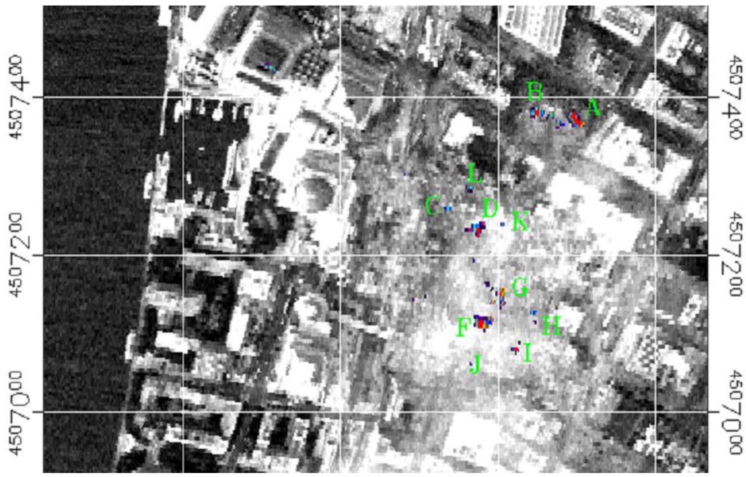

Figure 10. AVIRIS image from the 18th of September 2001 with identified hot zones labeled.

Table 2. Location, temperature, and fractional area determined for the 18th of September data set.

Hot Spectrum	Latitude	Longitude	Temp (K)	Area (%)
A	40-42-46.96	74-00-41.21	952	2.2
B	40-42-47.31	74-00-43.31	790	36
C	40-42-43.38	74-00-48.15	500	22
D	40-42-42.48	74-00-46.64	700	5
E			not seen	
F	40-42-38.62	74-00-46.41	725	7
G	40-42-39.77	74-00-45.45	932	2
H	40-42-39.04	74-00-43.65	471	4
I	40-42-36.97	74-00-44.54	762	35
J	40-42-36.97	74-00-47.01	no fit	
K	40-42-42.69	74-00-45.26	538	7
L	40-42-44.14	74-00-46.98	805	0.5

These results from the 16th and 18th September AVIRIS World Trade Center measurements show the estimation of fire temperatures and fractional areas for the highest intensity spectra in each of the hot areas identified. The spectral-fitting algorithm used is based on the physics of the Planck function and a simple model of the effects of solar-reflected energy and fractional filling of the spectral measurement spatial sample. Temperatures and fractional area were derived from the AVIRIS calibrated spectra that were consistent with the conditions at the World Trade Center disaster site in this period of September 2001.

6.0 TEST OF THE FRACTIONAL AREA COMPONENT OF THE MODEL

Following initial analysis and reporting of hot-fire location, temperature, and fractional area results from the AVIRIS World Trade Center data sets, a test of the fractional area component of the Planck-function model was performed. The high-intensity spectrum from site G on the 16th of September was used. This spectrum was averaged with an adjacent spectrum that did not exhibit a hot-fire signature. Spectrum G, the adjacent spectrum, and the average are shown in Figure 11. Based on the simple temperature and fractional area model, the effect of the averaging should be to reduce the fractional area by a factor of 2. However, the derived temperature should remain unchanged because the spectral shape of the emitted energy is preserved across the spectrum.

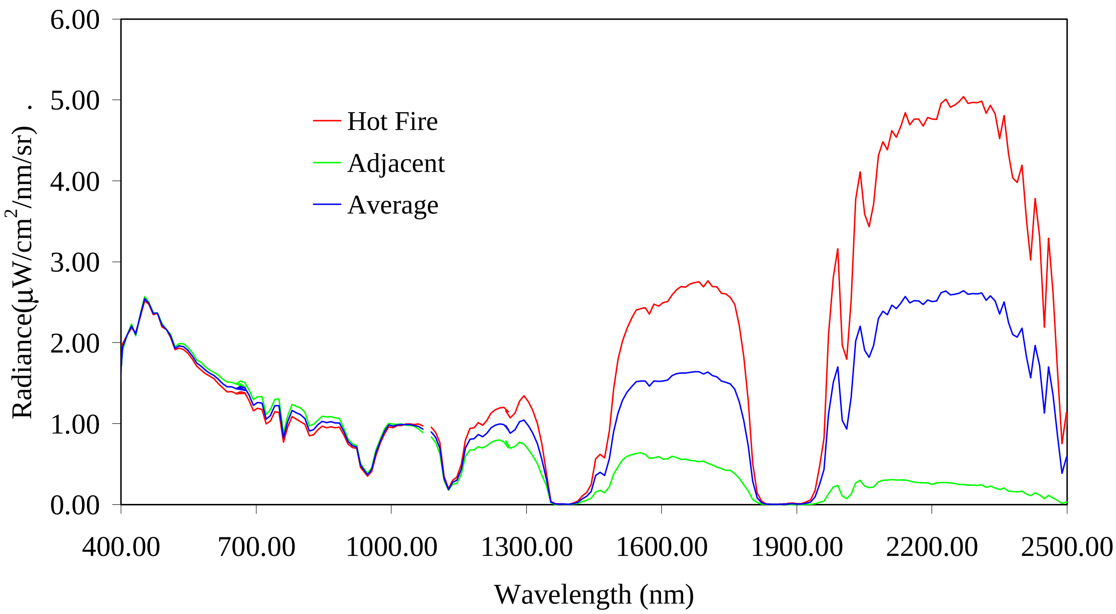

Figure 11. Dilution of the hot-fire component of spectrum G from the AVIRIS measurements on the 16th of September 2001 at the World Trade Center disaster site.

To test the validity of the fractional area component of the model, the diluted spectrum was analyzed with the full Planck-function algorithm. Figure 12 shows the spectral-fitting results from this test. As expected, the derived fractional area was half that derived for the undiluted spectrum G shown in Figure 6, and the derived temperature was the same. An additional test was performed with dilution of spectrum G by 3 adjacent nonburning spectra. A similar conservation of temperature estimate was achieved with a reduction of fraction area to one fourth of the original. These simple tests support the validity of the fractional area estimation component of the Planck-function-based hot-target model used in these analyses of the AVIRIS World Trade Center data.

7.0 CONCLUSION

On the 14th of September 2001, a request was made for AVIRIS to acquire spectral measurements over the World Trade Center disaster site for detection of asbestos contamination in the debris. AVIRIS measurements were acquired on the 16th of September. Rapid examination of the data showed spectral expression of hot fires in the World Trade Center debris. A simple Planck-function-based spectral-fitting algorithm was applied to the AVIRIS-calibrated radiance spectra to estimate the temperature and fractional area of the highest-intensity AVIRIS spectrum in each identified area of hot fires. The location, temperature, and fractional area derived for the eight zones identified in the 16th of September data set were delivered to the teams on the ground. Based on these rapid results, AVIRIS was requested to acquire additional data on the 18th of September. A similar analysis was performed estimating the temperature and fractional areas of the highest intensity spectra of the identified area of hot fires for this data set. Overall, the derived temperatures of the analyzed spectra from each of the hot zones decreased from the 16th to the 18th. In one case, no hot spectrum was identified on the second date. As with the results from the 16th, the hot-fire location, temperature, and fractional area derivations were provided to the ground teams to help understand and mitigate risk.

AVIRIS measurements in the solar-reflected spectrum offer an important approach to estimate the temperature and fractional area of hot targets. The estimation of temperature and area is based on the spectral slope, position, and intensity of the emitted radiation. This approach may be extended to a range of applications such as disaster response, controlled burn and wild fire research as well as volcanic lava flow temperature investigation. Additional research is needed to further validate the derived temperatures from this approach and to understand the sensitivity of the results to the assumption in the inversion model.

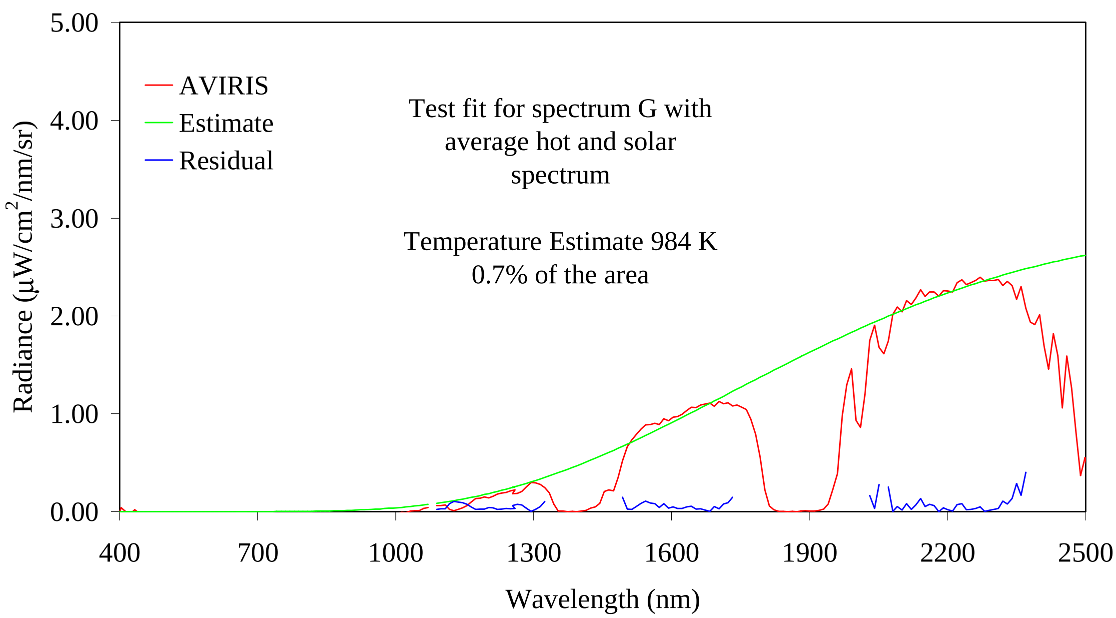

Figure 12. Derived temperature and fractional area from the diluted spectrum G. The derived temperature was unaffected by dilution of the original spectrum from an adjacent non burning spectrum.

8.0 REFERENCES

Anderson, G.P. et al., "MODTRAN3: An update and recent validations against airborne high resolution interferometer measurements," *Summaries of the Fifth Annual JPL Airborne Earth Science Workshop*, JPL Publication 95-1, Vol. 1, pp. 5-8, Jet Propulsion Laboratory, Pasadena, California, 1995.

Anderson, G.P., M. L. Hoke, J. H. Chetwynd, Jr., A. J. Ratkowski, L. S. Jeong, A. Berk, L. S. Bernstein, S. M. Adler-Golden, et al., "MODTRAN4 Radiative Transfer modeling for remote sensing," *SPIE*, *4049*, pp. 176–183, 2000.

Berk, A., et al., "MODTRAN: A moderate resolution model for LOWTRAN 7," Final Report, GL-TR-0122, Air Force Geophys. Laboratory, Hanscom AFB, Massachusetts, 42 pp., 1989.

Boardman, J. W., "Precision Geocoding of Low-Altitude AVIRIS Data: Lessons Learned in 1998," *Proc. Eighth Airborne Earth Science Workshop*, JPL Publication 99-17, Vol. 1, Jet Propulsion Laboratory, Pasadena, California, 1999.

Clark, R. N., R. O. Green, G. A. Swayze, G. Meeker, S. Sutley, T. M. Hoefen, K. E. Livo, G. Plumlee, B. Pavri, C. Sarture, S. Wilson, P. Hageman, P. Lamothe, J. S. Vance, J. Boardman I. Brownfield, C. Gent, L. C. Morath,

J. Taggart, P. M. Theodorakos, and M. Adams, "Environmental studies of the World Trade Center area after the September 11, 2001 attack," U. S. Geological Survey, Open File Report OFR-01-0429, http://speclab.cr.usgs.gov/wtc/, 2002.

Green, R. O., "Estimation of Biomass Fire Temperature and Areal Extent from Calibrated AVIRIS Spectra," *Proc. Sixth Annual Airborne Earth Science Workshop*, JPL Publication 96-4, Vol. 1, Jet Propulsion Laboratory, Pasadena, California, March 3–5, 1996.

Green, R. O., M. L. Eastwood, and C. M. Sarture, "Imaging spectroscopy and the Airborne Visible Infrared Imaging Spectrometer (AVIRIS)," *Remote Sens. Environ.* 65: (3) 227–248, September 1998.

Green, R. O., "Estimating the Expressed Temperature and Fractional Area of Hot Lava at the Kilauea Vent with AVIRIS Spectral Measurements," *Proc. Tenth JPL Airborne Earth Science Workshop*, JPL Publication 02-1, Jet Propulsion Laboratory, Pasadena, California, 2001.

Liou, K. N., *An Introduction to Atmospheric Radiation*, Academic Press, Inc., New York, 392 pp., 1980.

Oppenheimer, C., D. A. Rothery, D. C. Pieri, M. J. Abrams, V. Carrere, "Analysis Of Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) Data of Volcanic Hot-Spots," Open Univ., Dept. Earth Sci./Milton Keynes/MK7 6AA/Bucks./England/*International Journal of Remote Sensing*, 14, (16), 2919–2934, 1993.

Vane, G., R. O. Green, T. G. Chrien, H. T. Enmark, E. G. Hansen, and W. M. Porter, "The Airborne Visible Infrared Imaging Spectrometer (AVIRIS)," *Remote Sens. Environ.*, *44* (2-3), 127–143, 1993.

9.0 ACKNOWLEDGMENTS

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, under contract with the National Aeronautics and Space Administration.