ATMOSPHERIC CORRECTION OF SPECTRAL IMAGERY: EVALUATION OF THE FLAASH ALGORITHM WITH AVIRIS DATA

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1. INTRODUCTION

Visible to near infrared (NIR) hyperspectral imaging from aircraft or spacecraft is a highly valuable technology for remote sensing of the earth's surface because of its combination of good spatial and spectral resolution. Elimination of atmospheric effects caused by molecular and particulate scattering and absorption from the measurements is desired for many applications, such as when comparisons are to be made with data taken in the laboratory or under different atmospheric or viewing conditions. This process, which transforms the data from spectral radiance to spectral reflectance, is known as atmospheric correction, compensation, or removal.

A variety of methods and algorithms for atmospheric correction are available. The "empirical line method," consisting of a linear transformation derived from ground-truth spectra, remains a popular and accurate method where truth data exist. In other situations, a first-principles method is needed. ATREM, developed by Gao *et al.* (1996) using the 5S and, later, 6S radiation transport (RT) models (Vermote *et al*., 1994), was for many years the industry-standard algorithm. Recently, more sophisticated algorithms have been developed, focusing primarily on land imagery. These algorithms, which incorporate more accurate RT models and improved methods for retrieving the atmospheric properties needed for the correction, include ATCOR (Richter, 1997), ACORN (Green, 2001), FLAASH (Matthew *et al*., 2000; Adler-Golden *et al.,* 1998, 1999) and HATCH (Qu *et al*., 2001).

In this paper we review the basic first-principles atmospheric correction methodology and present results from the latest version of FLAASH (Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes). FLAASH is an efficient correction code based on MODTRAN4 (Berk *et al*., 1998) that has been developed collaboratively by Spectral Sciences, Inc. and the Air Force Research Laboratory; with assistance from the Spectral Information Technical Applications Center (SITAC); FLAASH is available in the Research Systems Inc. ENVI software package. We show some comparisons of ground truth spectra with FLAASH-processed AVIRIS data, including results obtained using different processing options, and with results from ACORN that derive from an older MODTRAN4 spectral database.

2. ATMOSPHERIC CORRECTION METHOD

2.1 Overview

First-principles atmospheric correction typically consists of three steps. The first is the retrieval of atmospheric parameters, most notably an aerosol description (the visibility or optical depth, and, if possible, an aerosol "type") and the column water amount. Since current methods allow aerosol retrieval over a very limited set of surface types (water and dark land pixels), typically only an average visibility is obtained for a scene. On the other hand, the spectral signature of water vapor is sufficiently distinct that the column amount may be retrieved on a pixel-by-pixel basis. The second step in the correction is the solution of the RT equation for the given aerosol and column water vapor and transformation to reflectance. Finally, an optional post-processing step called spectral polishing has been shown to remove many artifacts remaining from the correction process.

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2.2 Radiance Equation

FLAASH uses the standard equation for spectral radiance at a sensor pixel, L*, in the solar wavelength range (neglecting thermal emission) from a flat Lambertian surface or its equivalent (Vermote *et al.*, 1994). Collecting constants reduces the equation to the form

$$L^* = A\rho/(1-\rho_e S) + B\rho_e/(1-\rho_e S) + L^*_a \qquad \textbf{(1)}$$

Here ρ is the pixel surface reflectance, ρ_e is a surface reflectance averaged over the pixel and a surrounding region, S is the spherical albedo of the atmosphere, L^*_a is the radiance backscattered by the atmosphere, and A and B are coefficients that depend on atmospheric and geometric conditions but not on the surface. Each of these variables depends on the spectral channel; the wavelength index has been omitted for simplicity. The first term in Eq. (1) corresponds to radiance that is reflected from the surface and travels directly into the sensor. The second term corresponds to radiance from the surface that scattered by the atmosphere into the sensor, resulting in a spatial blending, or adjacency, effect.

In most other atmospheric correction codes (e.g., ACORN, HATCH, ATREM), ρ and ρ_e are replaced by a single variable, resulting in neglect of the adjacency effect. This approximation, which is a user option in FLAASH, is satisfactory for homogeneous surface areas and under high-visibility conditions, but is less successful under hazy conditions. The importance of the adjacency effect in a forested scene with a visibility of around 25 km is illustrated in Figure 5 of Adler-Golden *et al*. (1999), which shows FLAASH reflectance spectra of calibration panels retrieved with and without the adjacency correction. As another example, Figure 1 shows some spectra retrieved from an extremely hazy (~7 km visibility) AVIRIS image of rural N. Carolina taken on 7/22/93 as part of the Smoke, Clouds And Radiation (SCAR) experiment. Note that correction for the adjacency effect eliminates a chlorophyll residual in the soil spectra caused by strong scattering from the surrounding vegetation.

2.3 Radiation Transport Calculations

The atmospheric constants in Eq. (1) are calculated from an RT model, such as MODTRAN. These calculations usually represent the single most computationally intensive part of the atmospheric correction. For greatest efficiency, a look-up table (LUT) of these constants may be pre-calculated and interpolated as needed for the specific viewing geometry, atmospheric condition, and sensor channels of interest. A LUT for nadir viewing geometries is incorporated in ACORN. Other codes, including FLAASH, perform a custom RT calculation for the image at hand to permit coverage of a wider range of conditions (e.g., off-nadir viewing, all MODTRAN standard aerosol models).

When using MODTRAN, for the most accurate short-wave correction (which is needed over water, for example) the DISORT (Stamnes *et al*., 1988) discrete ordinate multiple scattering option is superior to the computationally much faster Isaacs 2-stream method. Another option that can be selected in MODTRAN is the band model spectral resolution. Results at different resolutions are compared in Section 3.

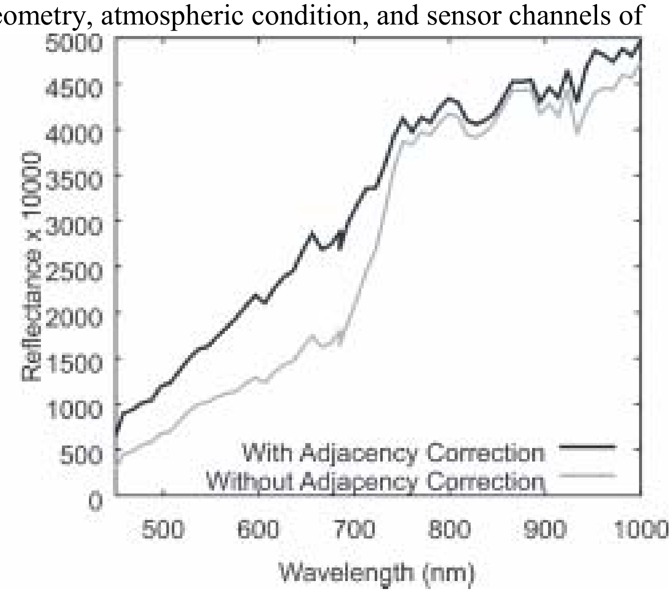

Figure 1. Comparison of light soil spectra retrieved by FLAASH from a very hazy 7/22/93 AVIRIS image of N. Carolina. The MODTRAN rural haze model was assumed.

2.4 Atmospheric Parameter Retrieval

The values of A, B, S and L^*_a in Eq. (1) depend on the viewing and solar angles and surface and sensor elevations, as well as on the atmospheric parameters of column water vapor, aerosol type, and visibility. A number of methods are available for retrieval of column water vapor and visibility. Perhaps the most accurate, but also the most computationally intensive, method for water vapor retrieval is a smoothness optimization approach, used in HATCH (Qu *et al*., 2001). Other correction codes perform the retrieval from one or more water absorption features using a small number of in-band and out-of-band radiance values. FLAASH uses the combination of a radiance ratio and an out-of-band radiance to interrogate a MODTRAN4-generated 2-dimensional LUT for the column water vapor in each pixel. The water band typically used is at 1.13 µm, with the LUT for this spectral region generated on-the-fly. Several correction codes also provide a means to retrieve an approximate scene-average visibility (i.e., aerosol optical depth). In FLAASH this is done with a fast, adjacency-corrected implementation (Matthew *et al*., 2000) of the 660 nm to 2200 nm reflectance ratio constraint for dark land pixels (2200 nm reflectance < ~0.1) found by Kaufman *et al.* (1997). Shadow and water are excluded from the dark pixel set by requiring that the ratio of 400-450 nm to 750-865 nm radiance is less than 1 (D. Miller and S. Sarlin, private communication).

2.5 Solution of the Radiance Equation

Once the atmosphere is adequately characterized and the Eq. (1) constants are derived, calculation of the image reflectance is straightforward using a method described in several papers (Richter, 1996; Vermote *et al*., 1997). The method involves computing a spatially averaged radiance image L^*_e, from which the spatially averaged reflectance ρ_e is estimated using the relationship

$$L^*_e \approx (A+B)\rho_e/(1-\rho_e S) + L^*_a \quad \textbf{(2)}$$

The spatial averaging is performed using a point-spread function that describes the relative contributions to the pixel radiance from points on the ground at different distances from the direct line of sight. FLAASH approximates this function as a nearly exponential function of radial distance. Since clouds can be a severe contaminant in the spatial averaging process for the L^*_e calculation, FLAASH automatically identifies cloudy pixels (Matthew *et al*., 2000) and replaces them with an average radiance.

As discussed elsewhere, up to an order of magnitude improvement in speed can be obtained by using an approximation in which the convolved reflectance and water vapor are averaged within pixel groups ("superpixels") and Eq. (1) is reduced to a simple linear form (Matthew *et al*., 2000). This method, implemented with 4x4 superpixels, is the default in FLAASH, and is suitable for sensors that have a spatial resolution finer than the typical ~100 m distance of the adjacency point spread function.

2.6 Spectral Polishing

Spectral polishing refers to a spectral smoothing process that removes consistent artifacts in an atmospherically corrected hyperspectral image using only information from the image itself. The original, stand-alone algorithm, called EFFORT, was developed by Boardman (1998); others have been developed for particular atmospheric correction codes, including FLAASH (Adler-Golden *et al*., 1999). The basic assumption behind polishing is that the scene contains some spectrally smooth pixels, such as road surfaces or bare soil that can be identified by a variance or similar measure. By comparing their raw reflectance spectra with a smoothed (low-pass filtered) spectrum, these pixels are used to develop a linear correction for the entire scene. The correction typically consists of a spectral gain or transmittance factor, and (in EFFORT) may also include a spectral offset. In FLAASH the smoothing is accomplished by taking a running average of N adjacent channels, where N is typically an odd number between 7 and 11.

The key to successful polishing is the selection of appropriate spectrally smooth pixels. They must not only be free of consistent, true spectral features, but also must be bright enough for derivation of a meaningful gain factor for all wavelengths. Vegetation pixels, although quite smooth overall, are unsuitable because of their sharp chlorophyll edge and darkness in the visible. As shown in the FLAASH results of Figure 2, using a ratio test to exclude vegetation from the smooth pixel set eliminates a chlorophyll edge artifact in the polished spectra.

3. FLAASH RESULTS WITH AVIRIS DATA

In October 1998, a set of images were taken by the JPL AVIRIS instrument at the NASA Stennis Space Center in conjunction with a set of "ground truth" surface reflectance measurements. The sensor was at 3 km altitude, the sun was reasonably high (zenith angle of 48 deg), water vapor was moderate (1560 atm-cm according to a radiosonde measurement), and visibility was high. This data collection provides an excellent opportunity to evaluate the accuracy of FLAASH with a well-calibrated sensor covering the 0.4 – 2.5 μm range.

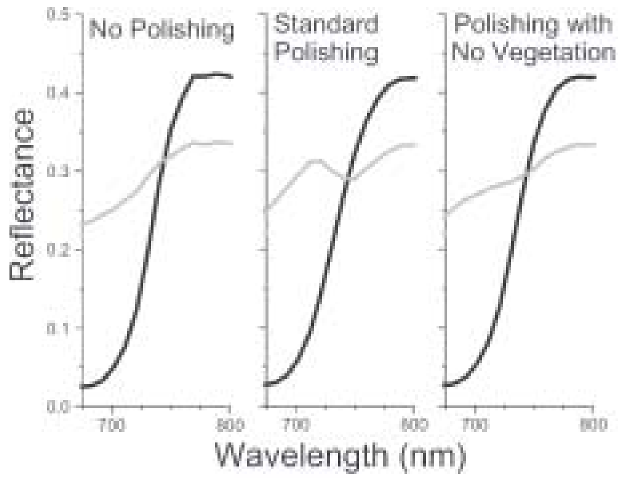

Figure 2. FLAASH retrieved spectra for soil (black curve) and vegetation (gray curve) in the chlorophyll edge region. At left, unpolished results; at center, with vegetation pixels included in the smooth set used to generate the polishing correction; and, at right, with vegetation pixels excluded from the smooth set.

Figure 3 compares near-"best" FLAASH results (1 cm^{-1} resolution with Isaacs multiple scattering and polishing) with ground truth spectra for four materials: a black panel, white panel, grass and soil. The wavelengths have been shifted by a few nm from the original spectrograph calibrations in order to optimize the results. The MODTRAN rural haze model was assumed; the retrieved visibility was around 70 km. Agreement between the two sets of spectra is good; the differences may reflect some combination of radiometric calibration error, atmospheric correction error, and effects caused by material non-uniformity and/or non-Lambertian reflectance. The FLAASH retrieved average water vapor of 1570 atm-cm (derived from the 1.13 μm band) is remarkably (perhaps fortuitously) close to the radiosonde measurement.

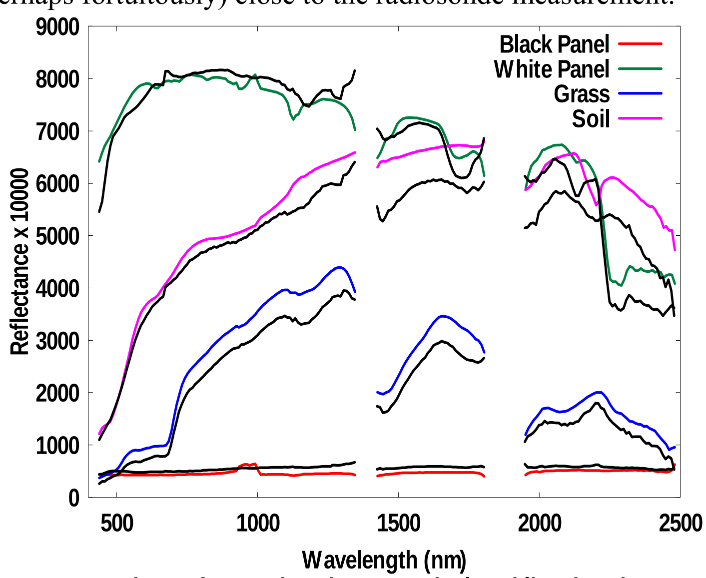

Figure 3. Comparison of ground truth spectra (colored lines) and FLAASH retrievals from AVIRIS data (black lines) at Stennis Space Center using 1 cm^{-1} band model parameters, shifted wavelengths and spectral polishing (*N* = 9).

Figure 4 compares unpolished spectra retrieved by FLAASH with different MODTRAN band model resolutions and with both the original and shifted wavelength sets. The shifted wavelengths yield a dramatic improvement in the unpolished spectra. The MODTRAN band model resolution has a smaller effect. The 5 cm^{-1} results are very close to the 1 cm^{-1} results at all wavelengths. The 15 cm^{-1} results are close to the others at short wavelengths but are inferior at long wavelengths, where the resolution approaches the width of the instrument function. At all resolutions the polished results are similar to the 1 cm^{-1} spectra shown in Figure 3.

Figure 5 quantitatively compares the FLAASH results with the ground truth reflectance spectra via the Spectral Angle Mapper. The smaller the spectral angle, the closer is the agreement in spectral shape. In general, spectral polishing and wavelength optimization yield comparable and substantial improvements in accuracy, with the best results usually obtained by combining the two. The 1 cm^{-1} and 5 cm^{-1} results are very close and are virtually identical when polishing is used.

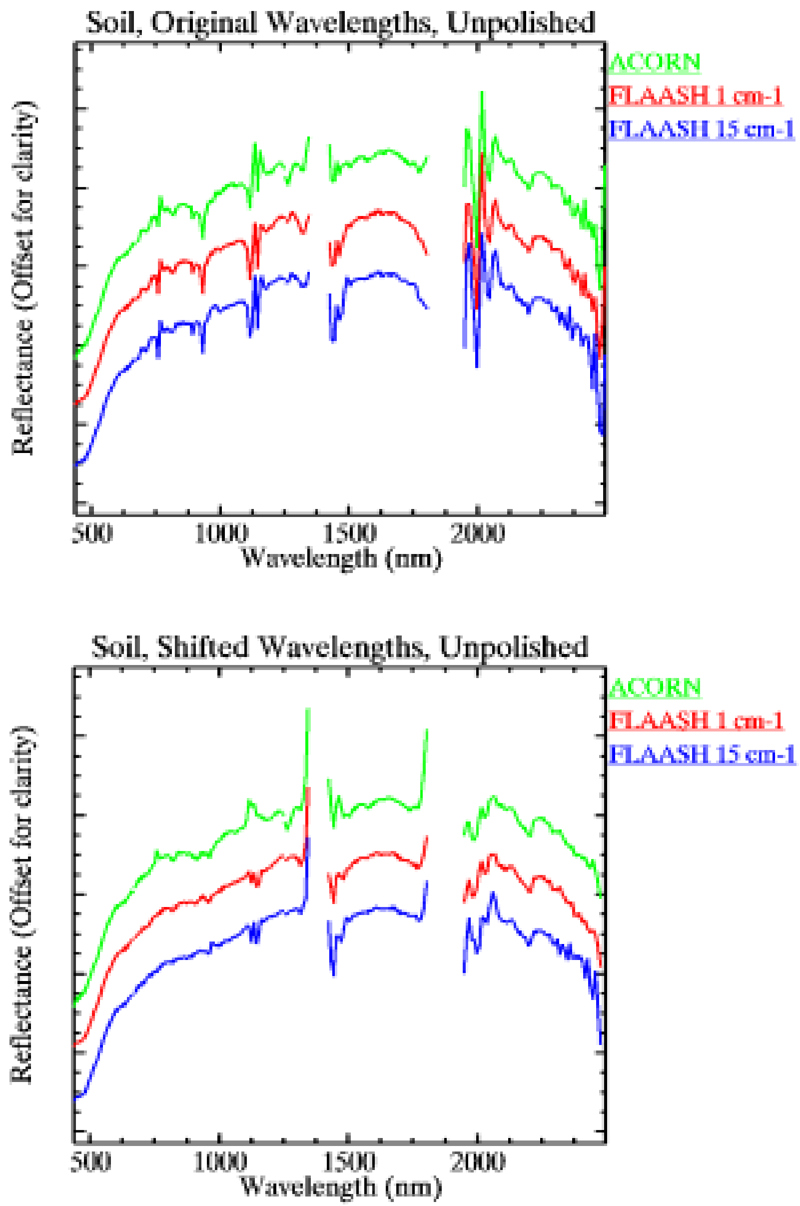

Figure 4. Comparisons of FLAASH retrieved spectra with different MODTRAN band model resolutions and wavelength calibrations. The ACORN calculations are from Version 3.12.

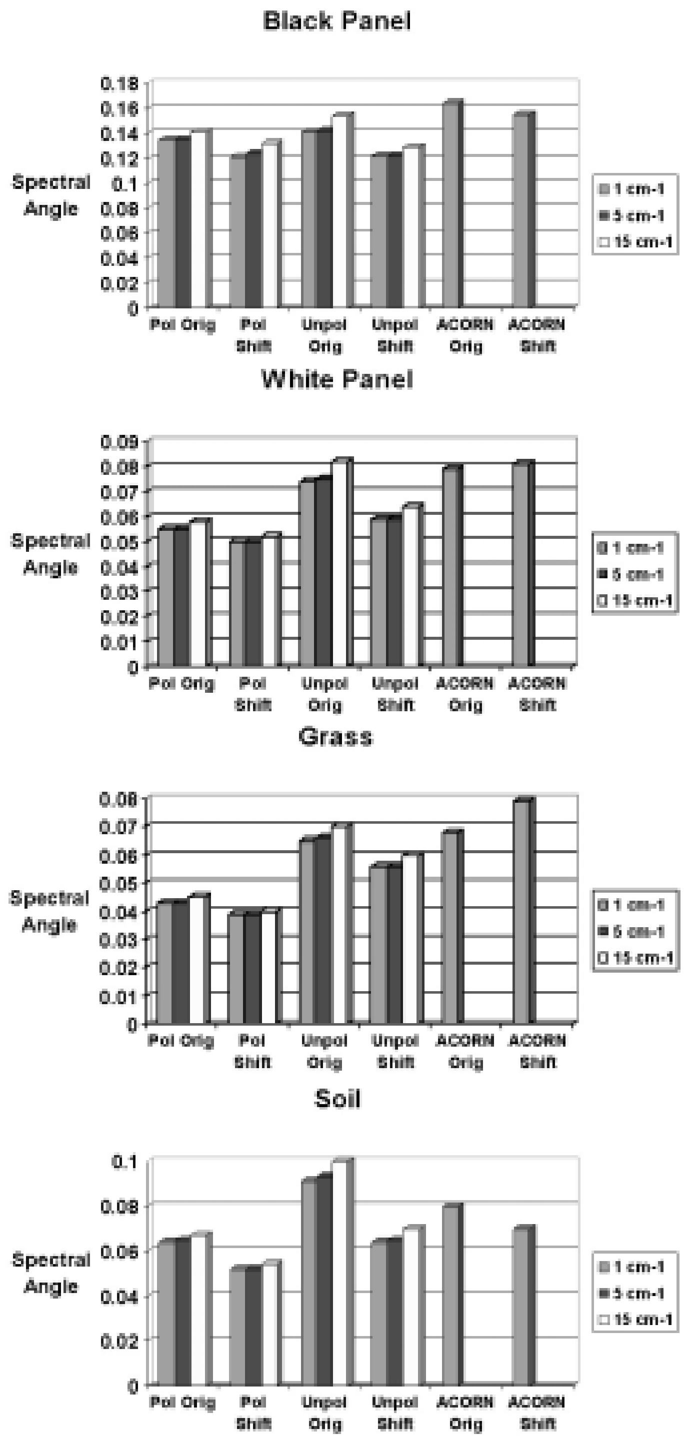

Figure 5. Spectral Angle Mapper comparison of ground truth spectra with atmospherically corrected spectra from the AVIRIS Stennis scene (angle in radians).

Also appearing in these comparisons are unpolished calculations from ACORN Version 3.12. Its LUT derives from older MODTRAN4 band model parameters that omitted collisional bands of O_2 and contained a 940 nm water band strength from HITRAN 1996 (Rothman *et al*., 1998) that is around 12% too weak (Giver *et al*., 2000). At long wavelengths the ACORN and FLAASH results are similar, but at short wavelengths the effect of the improved spectral parameters in FLAASH's newer version of MODTRAN4 can be seen. Interestingly, the shifted wavelengths do not consistently improve the ACORN results, perhaps because they may exaggerate the water vapor overestimation that would result from the incorrect 940 nm band strength. We also tried ACORN's artifact removal algorithms, but the results turned out to be much less accurate and are not shown.

4. CONCLUSIONS

The FLAASH results presented here, together with previous work by a variety of investigators, confirm that a state-of-the-art atmospheric correction algorithm is capable of generating accurate surface reflectance spectra from hyperspectral imagery, at least under conditions of clear to moderate aerosol/haze, low to moderate water vapor, and nadir viewing from any altitude between the ground and the top of the atmosphere.

Many challenges remain, including developing real-time processing capability and achieving high accuracy under more stressing atmospheric and viewing conditions. In addition to the surface visibility, detailed aerosol/haze properties need to be retrieved for heavy aerosol conditions, for viewing at far off-nadir angles, and for achieving the accuracy needed for remote sensing of water bodies, including bathymetry and measurement of water composition and bottom properties. Knowledge of both the surface visibility and the single-scattering albedo is required for the simultaneous accurate correction of dark surfaces, which are sensitive to the backscatter term L^*_a, and of bright surfaces, which are sensitive to the transmittance factors in A and B. Possible uncertainty in the scattering phase function, which controls the ratio of forward to backward scattering, further complicates the analysis. A key test of aerosol and haze models is their ability to predict downwelling radiance. There have been reports of lower-than-expected diffuse downwelling radiance in clear skies (Kato *et al*., 1999), which has been ascribed to aerosol "anomalous absorption;" however, both the observations and explanation remain controversial (Charlock *et al*., 2001). Model refinements that address this issue should enable further improvements in atmospheric correction accuracy.

5. ACKNOWLEDGEMENTS

The work at Spectral Sciences, Inc. was supported by the U.S. Air Force Research Laboratory through the SBIR program under contract no. F19628-00-3010. The authors also acknowledge with thanks the contributions from many individuals, including David Miller and Paul Lewis (currently at NIMA) for FLAASH development and validation provided by SITAC, as well as P. K. Acharya, L. S. Bernstein and J. Gruninger (SSI), T. Cooley, M. L. Hoke, A. J. Ratkowski, J. H. Chetwynd, and J. A. Gardner (AFRL).

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