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Speed and accuracy improvements in FLAASH atmospheric correction of hyperspectral imagery

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Timothy Perkins Steven Adler-Golden Michael W. Matthew Alexander Berk Lawrence S. Bernstein Jamine Lee Marsha Fox Spectral Sciences, Inc. 4 Fourth Avenue Burlington, Massachusetts 01803-3304 E-mail: adlergolden@spectral.com Abstract. Remotely sensed spectral imagery of the earth's surface can be used to fullest advantage when the influence of the atmosphere has been removed and the measurements are reduced to units of reflectance. Here, we provide a comprehensive summary of the latest version of the Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes atmospheric correction algorithm. We also report some new code improvements for speed and accuracy. These include the re-working of the original algorithm in C-language code parallelized with message passing interface and containing a new radiative transfer look-up table option, which replaces executions of the MODTRAN® model. With computation times now as low as 10 s per image per computer processor, automated, real-time, on-board atmospheric correction of hyper- and multi-spectral imagery is within reach. @ 2012 Society of Photo-Optical Instrumentation Engineers (SPIE). [DOI: 10.1117/1.OE.51.11.111707]

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1 Introduction

Remotely sensed spectral imagery of the earth's surface can be used to fullest advantage when the influence of the atmosphere has been removed and the measurements are reduced to units of reflectance. Elimination of molecular and particulate scattering and absorption from the data 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. Firstprinciples atmospheric correction of visible-near-infraredshortwave infrared (VNIR-SWIR) hyperspectral imagery (HSI) typically consists of two steps. The first is the retrieval of atmospheric parameters, including an aerosol description (most importantly, the visibility or optical depth) and the column water vapor amount. The second step is the solution of the radiative transfer (RT) equation for the retrieved aerosol and water vapor and transformation from radiance to reflectance.

A number of first-principles atmospheric correction algorithms have been developed over the years for both hyperspectral and multispectral imagery.^{1–8} This paper provides a comprehensive summary of the latest version of the fast line-of-sight atmospheric analysis of spectral hypercubes (FLAASH) algorithm, which has been previously described piecemeal in conference papers^{8–14} and in a 2005 journal article.¹⁵ We also report some new code improvements for speed and accuracy. These include the re-working of the original Interactive Data Language (IDL) code in C-language code parallelized with message passing interface (MPI) and containing a new radiative transfer look-up table (LUT) option, which replaces executions of the MODTRAN® model.^{16,17} FLAASH-IDL and FLAASH-C have been developed by Spectral Sciences, Inc. working in close collaboration with, and with support from, the US Air Force, NASA, and other US Government agencies. FLAASH-IDL is commercially available as an add-on to the well-known Environment for Visualizing Images (ENVI) software package sold by ITT Exelis Visual Information Solutions.

2 Algorithm Description

2.1 Radiative Transfer Equation and Solution Overview

FLAASH solves for the pixel surface reflectance ρ using a standard at-sensor radiance equation which may be written as^{1,6,8,18}

$$L^{*} = \frac{a\rho}{1 - \rho_{e}S} + \frac{b\rho_{e}}{1 - \rho_{e}S} + L^{*}{}_{a}.$$
 (1)

Here, ρ_e is a spatially averaged surface reflectance, *S* is the spherical albedo of the atmosphere from the ground, L^*_a is the radiance backscattered by the atmosphere, and *a* and *b* are coefficients that solely depend on atmospheric and geometric conditions. Wavelength dependence of these quantities is omitted for notational convenience. The second term in Eq. (1) corresponds to the radiance from the surface that is diffusely transmitted into the sensor, giving rise to the "adjacency effect".

The values of *a*, *b*, *S*, and L^*_a are determined from MOD-TRAN simulations of total and direct-from-the-ground spectral radiances computed at three different surface reflectance values, such as 0, 0.5, and 1. The latest versions of FLAASH use MODTRAN5¹⁶ with defaults of 5 cm⁻¹ spectral resolution for hyperspectral images and 15 cm⁻¹ resolution for multispectral images. The model atmosphere is based on user selections of one of the six standard MODTRAN

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atmosphere types (Tropical, Mid-latitude Summer, Midlatitude Winter, Sub-artic Summer, Sub-arctic Winter, and U.S. Standard) and one of the four standard aerosol types (rural, urban, maritime, and tropospheric). The viewing and solar angles of the measurement and nominal values for the surface elevation, aerosol type, and visible range (visibility) for the scene are initially specified, as well as the sensor wavelength band centers and instrument response functions.

The variable atmospheric quantities that have the greatest impact on VNIR-SWIR wavelengths are the column water vapor and the aerosol amount. Strong water absorption bands are located around 0.82, 0.94, 1.13, 1.4, and $1.9\,\mu\text{m}$. The centers of the stronger bands are usually too opaque for retrieving useful surface information. However, elsewhere the atmospheric correction processing can compensate for this absorption using a water amount derived from hyperspectral measurements at one of the near-IR bands. Here, the MODTRAN calculations are iterated over a series of varying column water vapor amounts, and the water vapor is retrieved with the algorithm described below. In the next step, a visibility estimate for the scene is retrieved using "dark" pixels, as described below. A refined water vapor retrieval with the updated visibility is then performed to establish the final atmospheric description.

The averaging implied in ρ_e is a convolution with a spatial point spread function (PSF). Strictly speaking, different PSFs apply when ρ_e appears in the numerator and denominator of Eq. (1). However, since $\rho_e S$ is generally very small, we approximate the denominator PSF with the numerator PSF, which describes the upward diffuse transmittance. ρ_e is estimated from an approximate form of Eq. (1)

$$L^*_{\ e} = \frac{(a+b)\rho_e}{1-\rho_e S} + L^*_{\ a}.$$
 (2)

Here, L^*_{e} is the radiance image convolved with the PSF. Equation (1) is then solved for ρ .

The most time-consuming part of the MODTRAN atmospheric simulation is the calculation of multiple scattering, which is needed to accurately represent heavy aerosol loadings and Rayleigh scattering. The best balance of speed and accuracy is provided by MODTRAN's "DISORT scaling" method.¹⁴ This method works by first running fast twostream scattering calculations over the full wavelength range, then spectrally rescaling the results by interpolating from a handful of more time-consuming, but more accurate, discrete ordinates (DISORT)¹⁹ calculations performed at atmospheric window wavelengths.

2.2 Point Spread Function Computation

We use the term "kernel" for FLAASH's representation of the upward diffuse transmittance PSF. The transmittance is governed by the path atmospheric extinction, the scattering albedo for each scattering event and the value of the scattering phase function. For a stratified atmosphere, the phase function depends on the relative contributions of scatterers as a function of altitude. For a cloud-free atmosphere, the relative strengths of aerosol and Rayleigh scattering dictate the shape of the PSF. The kernel calculation in FLAASH accounts for both of these sources, and models the radial asymmetry that occurs in off-nadir viewing geometries. The sensor-to-ground vertical extinction optical depth consists of four components, the aerosol absorption (t_{aa}) and scatter (t_{as}) , the Rayleigh scatter (t_{ms}) , and atmospheric molecular absorption (t_{ma}) , which are implicitly altitude and wavelength dependent:

$$t = t_{\rm aa} + t_{\rm as} + t_{\rm ms} + t_{\rm ma}.$$
(3)

The PSF derives its angular and wavelength dependence from the two scattering terms, t_{as} and t_{ms} . Expressions for Rayleigh and aerosol scattering optical depth are well known.²⁰ The phase function for aerosol scattering is approximated by a two-term Henyey-Greenstein analytical function. We assume an inverse exponential altitude dependence of scatterers for both aerosol and Rayleigh terms. Then the single-scatter aerosol and Rayleigh adjacency kernels, $< t_{as} >$ and $< t_{ms} >$, respectively, are defined as products of the line-of-sight scattering optical depth and a densityweighted average phase function. The total adjacency kernel is then expressed by the normalized sum of $< t_{as} >$ and $< t_{ms} >$.

Since convolution of the full PSF with the radiance image in Eq. (2) can be computationally intensive, we employ a few timesaving approximations. The outer tail region is removed from the kernel, leaving a square array, and the kernel and radiance arrays are reduced in size by resampling to larger pixels. The arrays are then convolved using a Fourier transform method, and finally the convolved array representing L_{e}^{*} is inflated to the original image size.

2.3 Water Vapor Retrieval

As in other HSI atmospheric correction codes, atmospheric column water vapor is retrieved on a pixel-by-pixel basis. This not only accounts for potential variations in actual atmospheric water vapor across the image but also compensates for apparent variations due to surface elevation differences, which FLAASH does not directly model. The water vapor retrieval is performed using radiance averages for two sets of spectral channels: an "absorption" channel or set of channels centered at a water band (typically the 1.13 μ m band) and a set of "reference" channels taken from the edges of the band. The default band and channel selections may be overridden by the user. The water retrieval is performed rapidly with the aid of a two-dimensional look-up table constructed from the MODTRAN outputs. One dimension of the table is the "reference" to "absorption" ratio and the other is the "reference" radiance. The second dimension accounts for a reflectance-dependent variation in the ratio arising from the different amounts of absorption in the atmospherically-scattered and surface-reflected radiance components; the absorption is generally smaller for the atmospherically scattered photons because they avoid the high concentration of water vapor close to the ground.

2.4 Visibility Retrieval

When appropriate "dark" pixels are present, FLAASH provides the option of retrieving a visibility estimate from the image. Visibility, as defined in MODTRAN, is related to horizontal optical depth at 550 nm via the equation

visibility(km) =
$$\frac{\ln(50)}{E_{550} + 0.01159 \text{ km}^{-1}}$$
. (4)

Horizontal and vertical optical depths are related via the thickness of the aerosol layer in the model atmosphere. The visibility retrieval algorithm in FLAASH is based on the assumption that a particular type of dark terrain has a characteristic, known reflectance ratio in a specific pair of bandpasses. Different bandpasses and ratios define methods based on dark land or dark water. The land pixel method is based on the work of Kaufman and coworkers^{21,22} with Landsat and MODIS data, and assumes that the dark pixels are dominated by green vegetation and soil with a characteristic reflectance ratio of 0.5 at ~0.66 μ m versus ~2.1 μ m. We have developed an analogous two-bandpass method for deep water, where the reflectance ratio for a water surface at 2.1 μ m versus 0.8 μ m is assumed to be 0.8 for off-nadir angles of up to 30 deg. The dark pixels are selected by means of a reflectance upper limit, or cutoff, imposed on the denominator bandpass; defaults are 0.08 and 0.03 for the land and water methods, respectively. The default bandpass selections, ratios, and cutoffs in FLAASH may be replaced by the user. The current default values in FLAASH-C and in the most recent version of FLAASH-IDL are based on Ref. 13. A comparison of visibilities retrieved using the land and water pixels methods shows good consistency (Fig. 1) and reasonable agreement with the available ground radiometer measurements.¹³

The retrieval procedure involves solving the RT equation for the aerosol bandpass reflectances over a series of trial visibility values that are evenly spaced in optical depth. Pixels fulfilling the cutoff criterion are selected as described in Adler-Golden et al., 2007;¹² with the land pixel method, water and shadow pixels are removed using a radiance ratio test. Then the average difference between the calculated and assumed reflectances in the numerator bandpass is computed for the selected pixels. Finally, the scene visibility is calculated by interpolating between the trial values to yield a difference of zero. Our work to date suggests that the



Fig. 1 Comparison of FLAASH land- and water-based visibility retrievals for six different images; see Adler-Golden et al., 2008.¹³ The straight line corresponds to exact agreement between the retrievals.

reciprocal of the visibility can be derived with an accuracy of approximately 0.01 km⁻¹ when using appropriate dark pixels and aerosol models.

In addition to the basic land and water pixel methods, Adler-Golden et al., 2008^{13} evaluated a "red-blue" method that showed promise for visibility retrieval from data that lacked SWIR wavelengths. We have subsequently found that variants of this method work well with hard shadow pixels that are often found in imagery with high spatial resolution (pixel sizes of a few meters or less). In particular, we have recently applied the method to multispectral data from the DigitalGlobe WorldView-2 sensor using the combination of band 1 (extreme blue) and band 5 (red). A band 1 to band 5 ratio of 0.5 and band 5 cut-off ratio of 0.02 have been found to yield reasonable visibility values and generate atmospherically corrected imagery with excellent visual contrast and true color.²³

2.5 Wavelength Recalibration

FLAASH provides the option of recalibrating hyperspectral sensor wavelengths using sharp molecular absorption features in the atmosphere, such as water vapor, oxygen, and carbon dioxide bands. The feature matching is based on a transformed spectrum called the normalized optical depth derivative (NODD),²⁴ which minimizes sensitivity to both the shape of the surface reflectance spectrum and the molecular column density. The implementation in FLAASH uses an average spectrum of 10 to 20 fairly bright pixels chosen at random. The recalibration technique essentially consists of matching MODTRAN-calculated spectral shapes with the average spectrum by shifting the channel center wavelengths until the best NODD fit is obtained. Since most hyperspectral sensors contain more than one spectrometer, a wavelength shift is determined separately for each spectrometer and then applied to all of its channels.

2.6 Spectral Smile Correction

While hyperspectral sensors are designed to provide nominally uniform spectral and radiometric calibration across the image; in practice, the data may exhibit significant wavelength and slit function dependences on the image column. Contributors may include uncorrected spectral "smile" and misalignment between the detector array and the spectrometer. We refer to all of these dependences as smile effects.

Both FLAASH-IDL and FLAASH-C can accept columndependent calibration information as optional inputs and adjust the atmospheric compensation accordingly. FLAASH-IDL divides the image into narrow strips, each of which is processed with its own spectral calibration. FLAASH-C applies a similar procedure to selected individual columns and interpolates the correction in between those columns. This smile compensation may be combined with the wavelength recalibration option; here, a separate recalibration is performed on each selected column. Smile compensation is currently not implemented in the ENVI version of FLAASH. A smile compensation implementation for FLAASH-C has been developed for NASA's EO-1 Hyperion sensor.¹⁴

2.7 Spectral Polishing

"Spectral polishing"²⁵ describes a renormalization method for removing artifacts from hyperspectral reflectance retrievals using only the data itself. When properly applied, it dramatically reduces spurious, systematic spectral structure due to wavelength registration errors and molecular absorption residuals while leaving true spectral features of the surface intact. The renormalization is taken as a linear transformation, defined by a gain spectrum and (optionally) an offset spectrum. These are derived from spectrally smoothed "reference" pixels in the scene, such as soil or pavement, which are assumed to be spectrally smooth in reality.

Boardman's original polishing method²⁵ used a Legendre polynomial fit for smoothing and linear regression fitting to derive the gain and offset. Gao et al., 1998^{26} used cubic spline fitting for smoothing and ignored the offset. In FLAASH, smoothing is performed by considering a running average over *n* adjacent spectral channels, where *n* is a userselectable odd number (default is 9). To select the reference pixels, the normalized variance between the smoothed and unsmoothed pixels is calculated and histogrammed, and pixels whose values lie below the peak of the histogram are selected. Then a band ratio test is applied to exclude vegetation from the smooth pixel set. Assuming the offset is negligible, the gain factor is taken as the ratio of the RMS smoothed to RMS unsmoothed spectra of those pixels.

An illustration of the benefit of spectral polishing is shown in Fig. 2, from Ref. 9. Here, FLAASH reflectance spectra for vegetation and soil are compared with ground truth reflectance spectra via the spectral angle. The smaller the angle, the closer is the agreement in spectral shape. In general, spectral polishing improves agreement with ground truth by an amount comparable to, or greater than, wavelength calibration optimization, with the best results usually obtained by combining the two. The results depend somewhat on the spectral resolution of the MODTRAN calculations, the 15 cm⁻¹ results being slightly inferior to those performed at 1 cm⁻¹ or 5 cm⁻¹ resolution.



Fig. 2 Spectral angle comparisons of ground truth spectra with FLAASH-corrected results from an AVIRIS hyperspectral image, from Matthew et al., 2003⁹ (angle in radians). "Pol" = polished, "Shift" = recalibrated wavelengths, "ACORN" = results from atmospheric correction now.



Fig. 3 Hyperion spectral radiance measurement from the 2011 Los Alamos forest fire, before (dots) and after (dashes) atmospheric correction. The estimate of thermal radiance emitted by the ground, gases, and smoke in the fire pixel (solid) was produced by subtracting a nearby background pixel.

2.8 Ground-Leaving Radiance Output

Many hyperspectral sensors cover the atmospheric window region between 2.0–2.4 μ m, where thermal emission from hot materials can be observed. To characterize the emission in terms of surface temperature and emissivity, it is necessary to remove atmospheric and solar dependences from the measured spectrum. Accordingly, a new output, atmospherically corrected ground-leaving spectral radiance, has been added to FLAASH-C. This is the spectral radiance with atmospheric absorption and scattering removed-i.e., the product of the FLAASH-retrieved reflectance and the solar function. This quantity contains both solar reflected and emitted components. Figure 3 shows an example of ground leaving radiance for a Hyperion image of a forest fire. The solar reflected component can be estimated using cooler pixels in the scene and removed, leaving the emitted component. A map of elevated surface temperature can be derived from this emission spectrum given reasonable surface emissivity assumptions.² Besides the emission from the surface, the estimated thermal signature depicted here also exhibits molecular emission at wavelengths around 2000 nm from the hot CO₂ released by the fire, and elevated radiance in the visible wavelengths due to scatting by the optically thick smoke plume. The results of such analysis should facilitate identification and characterization of forest fires as well as geothermal phenomena such as lava flows and hot springs.

3 Calculation Speedups

With increases in computer speed over the years, FLAASH computation times have been reduced to less than a minute on a single PC processor, making the goal of on-board, real-time atmospheric correction within reach. Here, we describe some recent work toward achieving this goal.

For hyperspectral imagery, the two most time-consuming parts of the FLAASH atmospheric correction are the MODTRAN computations and the solution of the radiative transfer (RT) Eq. (1) for each spectral channel of each pixel. A timesaving strategy for the latter, devised early in the FLAASH code development, is based on spatially resampling the pixels into "superpixels" that are assigned common water vapor amounts and ρ_e values.¹⁰ We estimate that with 4×4 superpixels the procedure speeds the solution by a factor of four.

Typically half or more of the remaining computation time is associated with performing custom MODTRAN calculations of the Eq. (1) RT quantities. These computations can in principle be eliminated by constructing a large LUT of these quantities, which may be interpolated to match the conditions of the observation. However, it is very challenging to build a general set of tables for all sensors, given the need to cover not only a wide range of atmospheric parameters and surface elevations but also a wide range of sensor altitudes for both airborne and spaceborne platforms and off-nadir as well as nadir viewing geometries.

In an initial study of LUT feasibility, we addressed the simpler problem of constructing a LUT for the JPL AVIRIS sensor viewing nadir from 20 km AGL. This allowed us to develop appropriate parameter grid spacings and evaluate interpolation errors. We have recently extended the LUT approach to satellite platforms with nadir and moderately off-nadir views. The view-independent atmospheric variables in the LUT are the solar zenith angle (sza), visibility (in km) or aerosol optical depth (AOD), surface elevation, and column water vapor amount. The viewing geometry is expressed in terms of two angles, an elevation angle relative to nadir and an azimuth angle relative to the solar azimuth. Since the viewing geometries of the intended missions are likely to be no more than ~20- deg off-nadir, two offnadir geometries were selected to span this 20-deg space with each geometry sampled at four solar azimuth angles. A finer gridding of the other four parameters mentioned above was selected, producing a total of approximately 435,000 simulations. For some variables, such as the solar zenith angle and aerosol optical depth, the grid parameters were sampled on a nonlinear scale to produce a more uniform separation between the model calculations. The column water vapor amount represents the largest of the grid dimensions, with 20 linearly-spaced values to account for the diversity of climates and seasons. The base model atmosphere was taken as the MODTRAN Tropical model to enable coverage of a very wide range of water amounts without saturation. Since VNIR-SWIR spectra are rather insensitive to atmospheric temperature and pressure, the Tropical model turns out to be a satisfactory choice for most, if not all, atmospheric conditions. The aerosol model was the MODTRAN rural aerosol, which works well over most land scenes. The calculations performed over the 350 to 2500 nm wavelength range at 5 cm⁻¹ resolution required roughly one week on a

single computer, and produced around 16 GB of data containing the FLAASH RT parameters.

The RT database was then reduced to a manageable size for on-board processing using a principal component analysis (PCA) transformation. In this representation, the data are expressed as linear combinations of orthogonal basis vectors, and, by restricting the combination to a subset of the most significant basis vectors, constitutes a reduced-dimensional, compressed database. The standard method for PCA using singular value decomposition (SVD) analysis derives the basis vectors as eigenvectors of the data covariance matrix. However, the calculation of the covariance matrix and subsequent diagonalization requires far too much computer memory to efficiently apply to the LUT data due to its very high dimensionality, equaling the number of wavelength values. Therefore, an alternative method based on the nonlinear iterative partial least squares (NIPALS) algorithm²⁰ was adopted. This iterative approach requires much less computer memory and permits the successive calculation of basis vectors until an acceptable level of accuracy has been obtained. By retaining 24 to 32 eigenvectors, sufficient for sub-percent-level residual for the entire LUT, the database was reduced to ~100 MB for a compression ratio of 160:1. Interpolation from the LUT is performed linearly on all dimensions except for the solar azimuth angle, where the interpolation is linear in angle cosine to provide better accuracy.

An illustration of the new LUT-based FLAASH-C atmospheric correction with data from the NASA EO-1 Hyperion sensor is given in Fig. 4. Agreement with the corresponding MODTRAN-based correction is excellent (generally at the sub-percent level); the LUT-based and MODTRAN-based results overlay almost perfectly at nearly all wavelengths, the exceptions being at the edges of the water absorption bands.

A timing test was performed running FLAASH-C on a single PC processor with both Hyperion hyperspectral data and advanced land imager (ALI) multispectral data. Operation with the LUT saved nearly half the computation time with ALI data and 2/3 of the computation time with Hyperion data. The computational saving is smaller with the ALI data because water vapor retrievals, and the associated MODTRAN calculations, are not performed with those data. Total FLAASH-C execution time was 14 s



Fig. 4 FLAASH-C reflectance retrievals from Hyperion data using the original MODTRAN-based method (solid) and the LUT ("GLUT") method (dots).

with a typical ALI image ($\sim 2000 \times 3500$ pixels) and 12 s with a typical Hyperion image ($\sim 256 \times 3500$ pixels).

The remaining envisioned speedup for FLAASH, which will dramatically shorten both the atmospheric retrieval and correction times, will be operation with parallel processors. FLAASH-C is currently parallelized with MPI (Message Passive Interface) routines. We anticipate providing multithreading parallelization for FLAASH-C in the near future. With either of the methods, the PSF spatial convolution step is parallelized by band, while the other processing steps are parallelized spatially, i.e., by image line or pixel.

4 Summary and Conclusions

The FLAASH atmospheric correction code has been developed by Spectral Sciences, Inc. and the US Government over the past 15 years to provide accurate and fast first-principles atmospheric correction of VNIR-SWIR hyperspectral and multispectral imagery. This paper describes the latest version of the algorithm, as implemented in both IDL and C languages, including the recent development of a MODTRAN LUT for improved speed and portability. FLAASH-C with a LUT for satellite sensors is currently operational on NASA's Sensor Web, where it provides automated processing of imagery from the EO-1 Hyperion and ALI sensors. FLAASH-IDL is in widespread use throughout the remote sensing community as an ENVI add-on. The latest upgrades to that code, which offer more accurate visibility retrieval¹³ and easier access to the water surface method, are being provided with ENVI 5.0.

Validation of FLAASH has been ongoing. Our studies include comparisons of retrieved reflectances with "ground truth" spectra,⁹ comparisons of visibility retrievals using different FLAASH methods,¹³ and comparisons of derived aerosol atmospheric properties with results from field radiometers.¹⁵ Comparisons of FLAASH with other atmospheric correction codes have also been reported.^{9,28,29} More recent FLAASH upgrades¹³ use a higher-fidelity adjacency PSF and robust visibility retrievals from water bodies for increased accuracy.

Using the LUT, FLAASH-C computation times are now around 12-14 s with a single 3 GHz processor for a typical spectral image (e.g., EO-1 ALI or Hyperion). Comparable computation times are found with other first-principles atmospheric correction algorithms written in efficient computer languages such as C or FORTRAN. A C-language version of the empirical QUAC algorithm³⁰ runs an EO-1 image in around 1/3 the time of FLAASH-C with the LUT, but is less accurate. FLAASH-C is currently being evaluated for operation on NASA's Intelligent Payload Module, the data processing platform for the planned HyspIRI mission,³¹ where it would perform atmospheric correction in real or near-real time for direct broadcast of data products to the ground.

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