SENSITIVITY OF ATMOSPHERIC COMPENSATION MODEL RETRIEVALS TO INPUT PARAMETER SPECIFICATION

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1. INTRODUCTION

Hyperspectral imaging sensors have been used for more than a decade to aid in the detection and identification of diverse surface targets, topographical and geological features. It is clear to the user, however, that hyperspectral data are not immune to the effects of the intervening atmosphere. The term "atmospheric compensation" refers to the removal of unwanted atmospheric components of the measured radiance. For hyperspectral data analysis, the general objective for atmospheric compensation algorithms is to remove solar illumination and atmospheric effects (predominantly aerosol scattering and water vapor absorption) from the measured spectral data so that an accurate estimate of the surface reflectance can be obtained. The retrieved surface reflectance spectra can then be compared with library spectra of a collection of materials for background or target identification.

Models have been developed to isolate the surface reflectance signal and remove unwanted atmospheric and illumination affects. These models all require some knowledge of the scene characteristics, which are used in the compensation process. Incomplete knowledge or inaccurate estimation of certain input parameters adds a degree of error to the retrieval of the surface reflectance. The extent of this error and the sensitivity of the model to specific input parameter accuracy form the basis for this study. The following sections provide a brief description of the hyperspectral data source (AVIRIS), the atmospheric compensation models and sensitivity analyses performed.

2. AVIRIS HYPERSPECTRAL SENSOR

Through measurements of the solar and near-infrared reflected spectrum, hyperspectral data satisfies a host of scientific research applications including: atmospheric water vapor, cloud properties and aerosols, agriculture and forest properties, mineralogy, soil type, snow and ice hydrology, biomass burning, environmental hazards, calibration of aircraft and satellite sensors, sensor simulation and validation, radiative transfer modeling and atmospheric correction. To meet the requirements for these applications, airborne imaging spectrometers were designed to provide enhanced capabilities in the areas of spatial resolution, sensitivity, and accuracy of absolute calibration. The Airborne Visible-InfraRed Imaging Spectrometer (AVIRIS) sensor has been used extensively to provide measurements in the visible and near-infrared spectrum. AVIRIS contains 224 different detectors, each with a spectral bandwidth of approximately 10 nanometers (nm), allowing it to cover the entire range between 380 nm and 2500 nm. AVIRIS uses a scanning mirror to sweep back and forth in a whisk broom fashion, producing 614 pixels for each scan. Each pixel produced by the instrument covers a 20 meter square area on the ground (with some overlap between pixels), yielding a ground swath width of 10 kilometers for an ER-2 flight altitude of 20 km (see Vane, 1987 and Vane, et al., 1984 for more information on AVIRIS).

3. ATMOSPHERIC COMPENSATION MODELS

Imaging spectrometers acquire images in an array of contiguous spectral bands such that for each pixel in the image, a complete set of reflectance or emittance spectra is measured. The two-dimensional spatial image (elements and lines) combined with a third spectral dimension produces the hyperspectral image "cube." Typical reflectance measurements from hyperspectral sensors contain information not only about the spectral characteristics of the surface but of the intervening atmosphere as well. Since these sensors are primarily used as a tool to derive spectral reflectance information for the surface (including vegetation, targets, geology, etc.), it is advantageous to be able to remove or "compensate" for the effects of the intervening atmosphere. Many atmospheric compensation models that process AVIRIS data exist, two of the physics-based models are utilized in this study: the Atmospheric REMoval (ATREM) and the Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) codes. While each model uses a different method for atmospheric compensation (described below), both use similar 3-band ratio techniques to account for the effects of water vapor on the hyperspectral measurements (Gao and Goetz, 1990).

ATREM uses the Malkmus (1967) narrow band spectral model to derive the gaseous transmittance and the 6S (Vermote, et. al., 1996) code to compute the necessary scattering terms using a user selected aerosol model. The individual gas concentrations are assumed to be uniform across the scene except for water which the algorithm treats separately. In this manner only a single transmittance spectrum is calculated for each uniform gas. Water vapor transmittances, however, are calculated on a pixel-by-pixel basis (see Figure 1 for a schematic of the ATREM program).

FLAASH (Adler-Golden, et al., 1998) utilizes the full MODTRAN-4 (Berk, et al., 1996) functionality drawing on its complete package of transmittance and scattering methods including a new correlated-k radiative transfer algorithm and full accounting for adjacency effects associated with atmospheric scattering. However, the technique used by FLAASH to derive the surface spectral reflectance follows similar steps to those used in ATREM. Figure 2 provides a schematic diagram of the FLAASH algorithm including program output products. As shown in the Figures 1 & 2, both codes require a number of input parameters at program initiation. The primary input is the measured spectral radiance. Supplementary inputs include the solar and viewing geometries, estimates of the atmospheric visibility, aerosol model type and atmospheric model. The sensitivity of the models to deviations of the input parameters from the true scene characteristics is analyzed in the following section. It should be noted that FLAASH has the capability to compute an estimate of the scene visibility using the "dark pixel" technique (Kaufman and Sendra, 1988). The visibility routine is still undergoing testing and was not used in this study.

4. SENSITIVITY ANALYSES

To illustrate the degree as to what the effect of mis-specification of the input parameters could have on the retrieved surface reflectance ρ_s, FLAASH was executed using known or estimated input parameters depicting the atmospheric state for an AVIRIS data cube collected near Moffet Field, CA on June 20, 1997. The retrieved spectral reflectance at three specific locations in the image was compared to retrieved reflectance values from a FLAASH run using two sets of physically reasonable input specifications. Figure 3a is a false-color image of the AVIRIS scene and Fig. 3b displays the comparison. The input specifications for both runs are shown in the figure. It is apparent that under these circumstances, differences in the retrieved ρ_s values can range up to 0.11 (absolute difference) depending on the surface feature and the wavelength. For many remote sensing operations, these errors would be unacceptable. Accurate specification of the input parameters to the extent that the characteristics of the atmosphere are known is clearly an important part of the remote sensing process.

To investigate this further, simulated AVIRIS data were generated from MODTRAN-4 calculations for clear-sky, uniform surface reflectance scenes under three different moisture and visibility conditions from a relatively clear and dry atmosphere to one with hazy, wet conditions (see Table 1 for a description of the AVIRIS test data characteristics). Using these test data cubes it is possible to vary specific input parameters and determine the effect they have on the retrieved surface reflectance. Comparison to the known ρ_s provides an absolute measure of the sensitivity to the varied input parameter. The following subsections will attempt to isolate the degree as to which each of the following atmospheric compensation model input parameters can affect the final retrieved ρ_s.

Table 1. Characteristics of the simulated AVIRIS test cases. All cases were modeled with a rural aerosol model and solar zenith angle of 30 degrees. Values were computed for surface reflectances of 0.2 and 0.4.

Model Atmosphere	Conditions	Visibility (km)	Column Water Vapor (cm)
Tropical	Hazy & Humid	5	4.11
Mid-latitude Summer	Moderate	10	2.93
Subarctic Winter	Clear & Dry	23	0.42

4.1 Visibility

Atmospheric visibility is inversely proportional to the optical depth. The optical depth varies as a function of the aerosol and moisture content of the lower 2-3 km of the atmosphere. Water vapor absorbs and aerosols scatter the radiance in proportion to their concentration. The higher the aerosol concentration (or optical depth), the lower the visibility. Hence, visibility is an indicator of the amount of attenuation in the lower atmosphere and therefore an important component of the atmospheric compensation process. In this effort, the sensitivity of the models (FLAASH and ATREM) to variations in the input visibility were studied. Figure 4 displays the surface reflectivity absolute difference (shown as the retrieved reflectivity error) for FLAASH runs using three different input visibilities at the two ρ_s values. The error is computed by subtracting the test cube ρ_s values (0.2 and 0.4) from the retrieved ρ_s values for the three different visibility runs. All runs utilized a mid-latitude summer atmosphere with a rural aerosol model. The "truth" run was for a 10 km visibility. Since the test cases were computed using MODTRAN-4 it would be expected that FLAASH would accurately retrieve the test cube reflectances provided the correct input parameters since its radiative transfer code is also based upon MODTRAN-4. Such was the case as denoted by the dotted line in Figure 4.

The reflectivity errors for both the 5 and 23 km visibility runs are within $\pm$ 0.03 of the true values except near the 0.94 and 1.14 water vapor absorption bands. The sloping error lines in the shortwave are most likely a result of using the Isaacs two-stream multiple scattering code in our FLAASH computations and the increased effect of Rayleigh scattering. Experience has shown that the Isaacs model can produce erroneous results in the SW especially under optically thick conditions. Using the DISORT 8-stream option generally removes this effect but at the price of greatly increased computation time.

In Figure 5, the retrieved reflectance errors for ATREM runs are given. ATREM does not reproduce the surface reflectivity values as accurately as FLAASH for a number of reasons. ATREM model parameterizations are based on older HITRAN line-by-line coefficients and different aerosol models than those used in MODTRAN-4. Also, ATREM decouples the absorption from the scattering processes in the radiative transfer model calculations. This can be seen in Figure 5a where the "truth" ρ_s values are subtracted from the retrieved ρ_s values for the three visibility runs (5, 10, 23 km). Here the water vapor absorption line structure is still quite apparent in the spectral reflectance curves. To remove the absorption and other model effects from the reflectance, the ATREM retrieved ρ_s values for the 10 km visibility run are subtracted from the retrieved ρ_s values for the other visibility runs with results shown in Figure 5b. These error curves are much more similar to what FLAASH produces after compensating for the model-induced differences.

As a rule of thumb, if the value for the visibility input to the model is greater (clearer) than the true visibility of the scene, the retrieved reflectance will be under-estimated. The converse is also true, an input visibility less (more opaque) than the true visibility will result in an overestimate of the reflectance values.

4.2 Aerosol model type

There are a variety of aerosol models that are available for use in the ATREM and FLAASH models. The models typically represent the characteristics of aerosols found in the lowest 2 km (within the boundary layer) for a set of basic topographic types: desert, maritime, rural and urban. Each model consists of a weighted mixture of four basic components: dust, oceanic, water-soluble and soot. Urban, for example, has more soot and water-soluble particles than maritime which consists of predominantly oceanic particles such as salt and sea foam. The rural (or continental) aerosol model consists of a large percentage of dust particles. It's clear that with such a diversity of scatterers, the choice of the aerosol model for a particular scene could have a significant effect on the radiative transfer in the lower atmosphere and on the retrieved surface reflectance.

Figure 6 displays the sensitivity of the FLAASH retrieved reflectance to various aerosol models for two highly different atmospheres. For the dry and relatively clear rural aerosol case in Figure 6a, the effect of varying the aerosol model produces errors less than $\pm$ 0.02 except at short wavelengths where the effect gradually increases for the urban model only. The urban aerosol model seems to be most sensitive to the atmospheric composition as can be seen in Figure 6b for the tropical, hazy test case. While the other model errors are generally less than 0.04, the errors for the Urban model are within 0.10 at wavelengths greater than 1 μm but increase rapidly in the shortwave. This seems to indicate a strong sensitivity of the Urban model to moisture and visibility. The significant degree of soot in the model, can have a strong scattering effect under low visibility (high aerosol density) conditions masking the signal from the surface and producing erroneous results from the model.

4.3 Atmospheric model

In MODTRAN, there are six types of model atmospheres. Each model atmosphere includes a set of profiles defining the pressure, temperature, density, water vapor and ozone characteristics representative of the seasonal conditions for a geographic region. Surface temperatures for these atmospheres vary from 257 K for a subarctic wintertime atmosphere to 300 K for a tropical atmosphere. From Table 1, it is observed that the amount of moisture an atmosphere can support varies greatly over the range of standard atmospheres used in MODTRAN. This is a function of the temperature profile, i.e., colder temperatures saturate at lower levels of moisture than do higher temperatures. This limits to some extent the choices of model atmospheres for a specific scene. Errors could result if a model atmosphere incapable of supporting the moisture content of the scene were used. Keeping this limitation in mind, a set of model atmospheres was used as input to FLAASH to study the sensitivity of the model retrievals to changes in the atmospheric profiles.

Results of varying the atmospheric model type (and associated moisture and temperature profile) seem to have little effect on the retrieved reflectance values as long as the input model temperature profile can support the total column water vapor of the scene. In Figure 7, retrieved reflectance errors are generally less than $\pm$ 0.01 except near the water vapor absorption bands. FLAASH does a good job of defining the true water vapor content using virtually any moderately moist atmospheric profile. This applies to relatively dry scenes as well since FLAASH can internally adjust the moisture content of the model to provide the closest approximation to the scene moisture amount. However, the converse does not always apply, using a dry atmospheric model on input to process a moist scene can provide erroneous results.

4.4 Solar Zenith Angle

For a typical AVIRIS scene, the date and time are known quite accurately and therefore the solar zenith angle can be computed with precision. On occasion, a series of scenes or an entire flight lasting many minutes or several hours may need processing. The plots in Figure 8 show the errors incurred by using a constant solar zenith angle (SZA) assumption for scenes taken at different times during the flight. For a forty minute flight the SZA varies by approximately 2 degrees (from a mid-flight value of 30 degrees) and the retrieved reflectance errors are within $\pm$ 0.04. As would be expected these errors increase for a two hour flight exceeding 0.10 at shorter wavelengths. Specifying input of a larger SZA than the "true" value results in an overestimate of the retrieved reflectance value; the converse is true as well. It is also useful to note that errors tend to be less at low SZAs (high sun) than for high SZAs (low sun elevation).

5. SUMMARY

Using results from two physics-based atmospheric compensation models, FLAASH and ATREM, an attempt was made to quantify the sensitivity of the retrieved surface reflectance to incorrectly specifying the input parameters to the models. These errors varied spectrally for a specific parameter. Sensitivity to input visibility generally varied between $\pm$0.03 for both FLAASH and ATREM runs. Higher errors were generally present in the SW where scattering processes were most significant. Varying the input aerosol model under relatively clear and dry conditions produced errors between 0.04 and -0.01. For the moist and hazy case the errors increased dramatically, especially for the urban aerosol model. A strong sensitivity to moisture and optical depth (or visibility) exists for this model, which can produce large errors (> 0.10) in the retrieved surface reflectivity. The sensitivity to the input atmospheric model was less than $\pm$0.01 for all cases where the specified input model temperature profile could support the ambient scene moisture. For those cases where the input model atmosphere could not support the total column water content of the scene (i.e., using a dry, cool atmosphere on input for a moist scene), large errors would result especially near the water vapor absorption bands. While information as to the date/time of a specific scene and hence the solar illumination geometry is generally known, estimates of the errors incurred by using a constant SZA for a series of scenes or an entire flight were found to vary from $\pm$0.02 for a 40 minute flight to $\pm$0.10 for a 2-hour flight.

In general, if the surface reflectance retrieval error is constant in magnitude throughout the spectrum, it has less effect on background or target identification. A simple "bias" correction to a known spectrum can be applied. However, if the error varies with wavelength, a typical example being the stronger aerosol effect in the shorter wavelengths, correct background and target identification is more difficult. For these cases, to obtain accurate retrievals of the surface reflectance, precise input parameters corresponding to the ambient scene characteristics are essential.

6. REFERENCES

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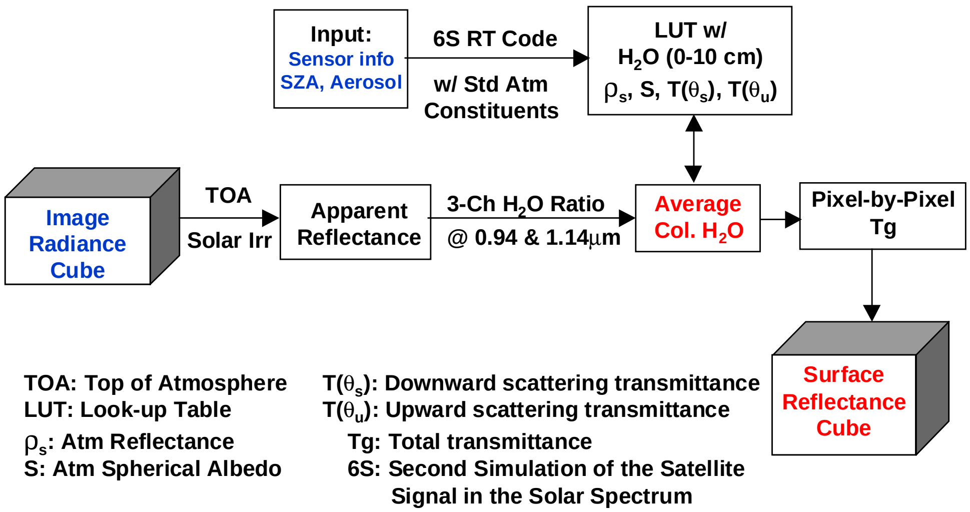


Figure 1. Schematic Flow of the ATREM program.

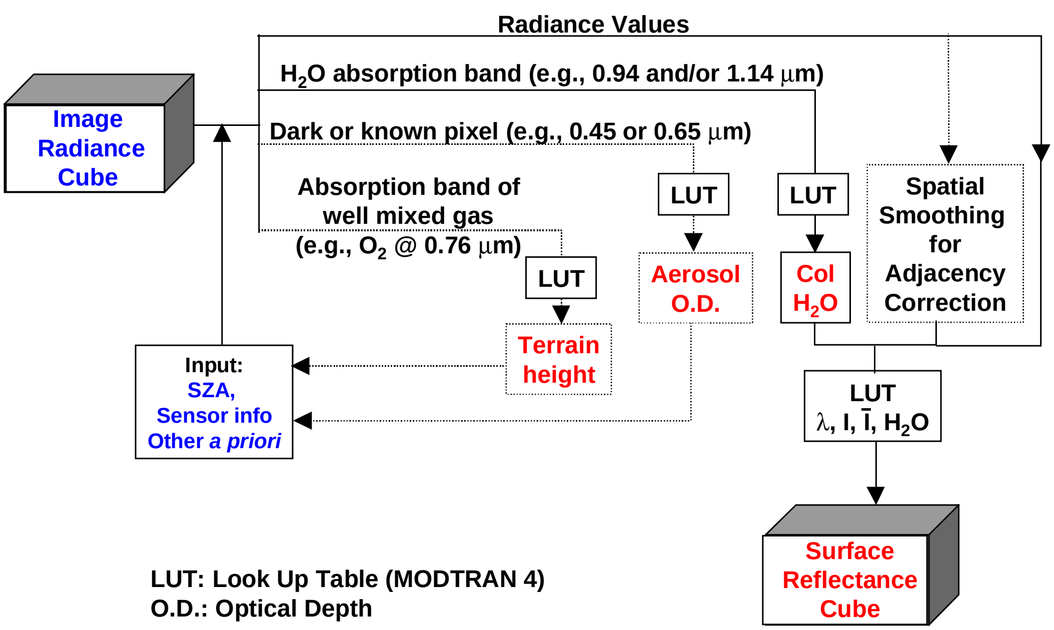
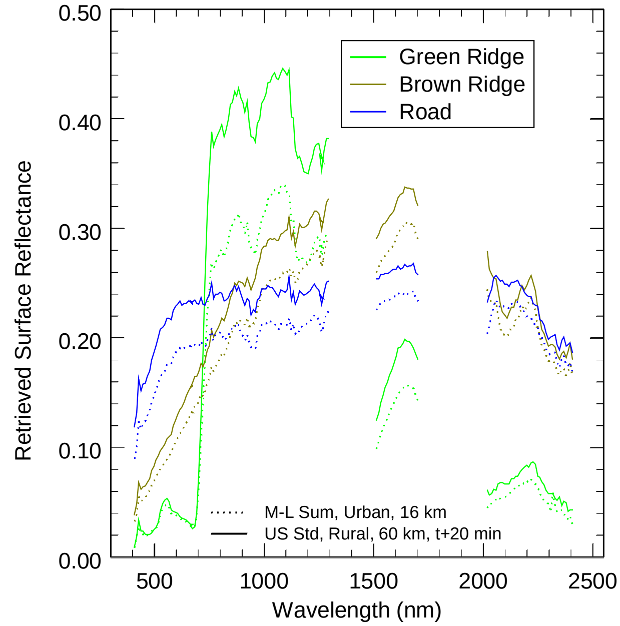


Figure 2. Schematic Flow of the FLAASH code.



(a) (b)

Figure 3. Depicted are a) an AVIRIS scene collected near Moffett Field, CA and b) the retrieved spectral reflectance at three locations denoted by "+" in the image for two different runs of FLAASH. The input specifications for the two runs are 1) mid-latitude summer atmosphere, urban aerosol model and 16 km visibility, and 2) US Standard atmosphere, rural aerosol model, 60 km visibility and a time offset error of 20 minutes (equivalent to a 2 degree error in the solar zenith angle).

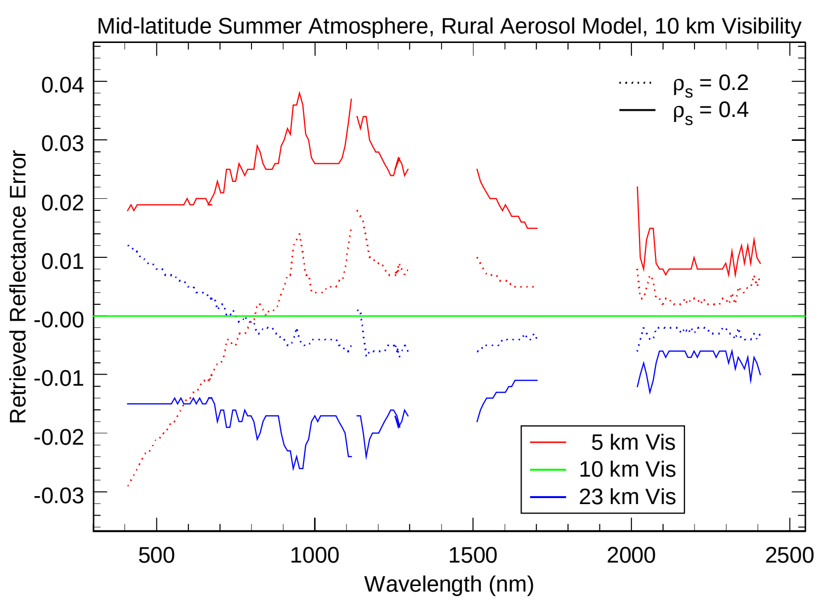
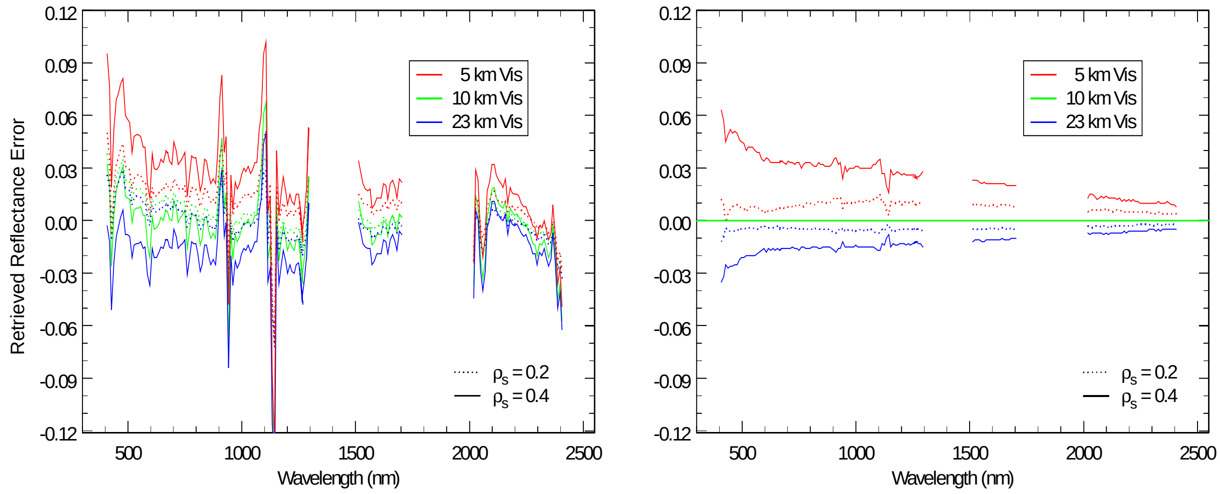
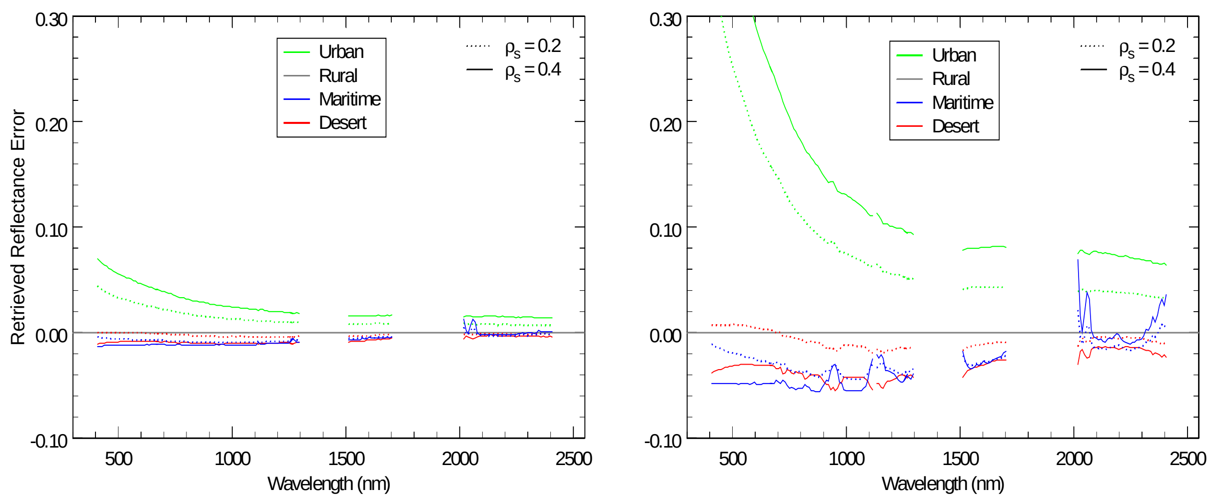


Figure 4. FLAASH retrieved reflectances with "true surface reflectance" subtracted for three input visibilities. Truth scene values are given in the figure.



(a) (b)

Figure 5. ATREM retrieved reflectances with a) "true surface reflectance" subtracted and b) the ATREM retrieved reflectance using the true visibility as input subtracted, for three input visibilities. Truth scene values are mid-latitude summer atmosphere with a rural aerosol model and 10 km visibility.



(a) (b)

Figure 6. FLAASH retrieved reflectance errors for four aerosol model types. Values are shown for two atmospheric scenes, a) dry and relatively clear (subarctic winter atmosphere, rural aerosol model, 23 km visibility) and b) humid and hazy (tropical atmosphere, rural aerosol model and 5 km visibility).

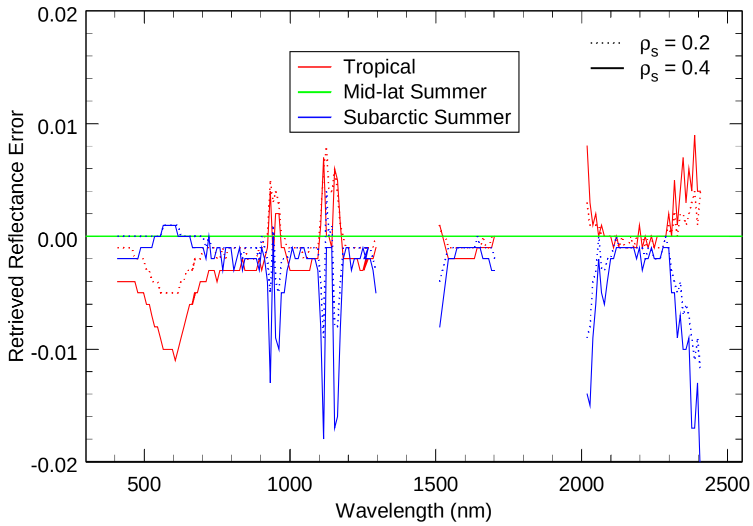


Figure 7. FLAASH retrieved reflectance errors for runs made with three atmospheric models (truth atmosphere is Mid-latitude summer).

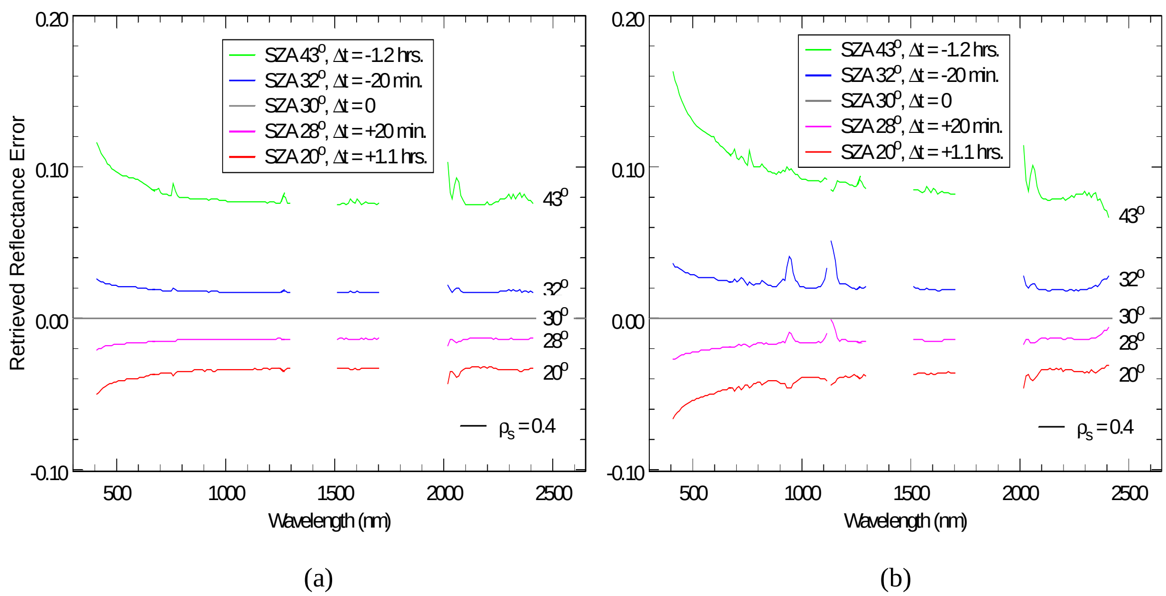


Figure 8. FLAASH retrieved reflectance errors for using a constant SZA in the model calculations for two flight lengths (40 minutes and 2 hours). Values are shown for two atmospheric scenes, a) dry and relatively clear (subarctic winter atmosphere, rural aerosol model, 23 km visibility) and b) humid and hazy (tropical atmosphere, rural aerosol model and 5 km visibility) both with a truth SZA value of 30 degrees.