Sensitivity analysis of atmospheric compensation algorithms for multispectral systems configuration

Eric Webber
Sensitivity Analysis of Atmospheric compensation Algorithms for Multispectral Systems Configuration

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Abstract

This study evaluates a series of atmospheric correction techniques developed at RIT called Total Inversion. The ability to convert remotely sensed image data to physically meaningful scientific units, such as surface reflectance, has been demonstrated for hyperspectral systems. This capability, however, has not been proven with the use of multispectral satellite-based remote sensing systems. The goal of this study is to determine the feasibility of adapting the Total Inversion techniques for multispectral sensors by understanding the capabilities and limitations of these techniques for operational use. This means that the algorithmic process being used must be image based, have practical run times, require little or no user intervention and produce consistent results within acceptable error tolerances. Three tasks were performed to study the feasibility of using Total Inversion for multispectral sensors.

Task one evaluated the potential for using a pre-built set of lookup tables (LUTs) for use with the radiative transfer based spectral atmospheric correction methods. Task two is a sensitivity analysis for using independent ancillary estimates for elevation and water vapor inputs. Task three of this study focused on the comparison of two algorithms for the estimation of aerosol visibility. These included the regression intersection method (RIM) for spectral fitting and the non-linear least squares spectral fit method (NLLSSF). For all these tasks the study used existing image data and ground truth to enable evaluation and demonstration of quantitative performance of various approaches. Specifics and rationales of these tasks are covered in the Project details section.
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Title: Sensitivity Analysis of Atmospheric compensation Algorithms for Multispectral Systems Configuration

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Sensitivity Analysis of Atmospheric compensation Algorithms for Multispectral Systems Configuration

Eric Webber

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Sensitivity Analysis of Atmospheric compensation Algorithms for multispectral Systems Configuration

1. Introduction and Executive Summary

The purpose of this study is to determine the feasibility of adapting the Total Inversion techniques, (Sanders et al., 1999) for multispectral sensors and understanding the capabilities and limitations of these techniques for operational use. To study this feasibility, three tasks were outlined to be researched. Task one of the research involved a study exploring the possibility of constructing a set family of look up tables. This study addressed the sensitivity of the inversion process regarding the look up table size and the type of atmosphere used. Task two of the research studied the Total Inversion sensitivity to atmospheric estimates, water vapor and elevation. This study addressed the practicality of using ancillary estimates of these atmospheric parameters. Task three of this research involved a study to find the optimal method for estimating aerosol visibility. The latter compared two algorithms, Non-Linear Least Squares Spectral fit (NLLSSF) as suggested by (Green, 1993) and the Regression Intersection Method for Aerosol Correction (RIMAC) suggested by (Crippen, 1986) in finding the aerosol visibility.

The results from this research were positive, pointing to the feasibility of using Total Inversion for the correction of the atmosphere for multispectral sensors. From the results in task one, it appears that the inversion process is not overly sensitive to the resolution of the LUT being used. The results show that there is not a large difference in the inversion of multispectral data sets between the use of a high resolution LUT and a lower resolution LUT. Task one also shows that it may be possible to use standard atmospheres. The results indicate that there is little difference when using the atmosphere of Mid-latitude Summer versus a scene specific radiosonde atmosphere, yet this conclusion is being drawn on a very limited data set.

The results in task two of this research show that it is possible to use ancillary sources of water vapor and elevation estimates. Retrieved image reflectances varied little when large errors in elevation and water vapor estimates were introduced into the inversion process. To further test the possibility of using ancillary estimates, we used a water vapor estimate retrieved from the Buffalo International Airport 65 miles west of the imaged scene and an elevation estimate retrieved from the Rochester Airport. The results of using these ancillary estimates of water vapor and elevation were encouraging, producing relatively small reflectance errors.

Task three of this research compared the use of NLLSSF and RIMAC in the estimation of Aerosol Visibility. The results from Task three show that using RIMAC on multispectral data sets is comparable to the results using NLLSSF on the same data sets. The results from this section imply that it is more practical to use RIMAC in the estimation of aerosol visibility. RIMAC makes a single estimate of aerosol visibility for the entire image as opposed to doing pixel by pixel processing. As a result of the single estimate, its run
significantly reduced from that of NLLSSF. The results show that RIMAC requires less time to process the data and is comparable to the results of using NLLSSF.

The results of this research involved some issues requiring further investigation. The multispectral imagery from the inversion process using NLLSSF contained spatial artifacts, which may be a result of the pixel by pixel processing of aerosol visibility values. To make sure that the results being studied were not influenced by these anomalies, we introduced a default value to be applied to the whole image that was calculated from average of the non-anomalous values in each of the multispectral images. We also noticed that when comparing RIMAC to NLLSSF in the estimation of aerosol visibility, RIMAC was estimating the maximum aerosol visibility in the look up table. The NLLSSF algorithm also estimated the aerosol visibility values near the maximum, but fluctuated on a pixel by pixel basis. The ramifications of this are not yet known, further study will try to determine the cause of this.

Results

2. Background

The objective of atmospheric correction is to retrieve surface reflectance of a target by removing the effects the atmosphere has made on the radiation propagation from the solar source to the target and from the target to the sensor. Reflectance from the target undergoes significant interaction with the atmosphere before it reaches an aerial or satellite sensor. This interaction with the atmosphere occurs through scattering or absorption of the radiation in a spectrally dependent fashion. This relation can often be severe in reducing the ability of remotely sensed imagery to be used for developing and validating various studies regarding land cover dynamics, (Fallah-Adl, 1995). It is important when analyzing remotely sensed data to understand the effect the atmosphere has made to the radiance responses at the aerial or satellite sensor.

Early sensor designs, however, did not have the resolution or calibration to definitively infer the effect atmosphere. It was not until the advent of radiometrically calibrated multi/hyperspectral sensors that information about the atmosphere became quantifiable. Today it is possible for aerial/satellite radiometrically calibrated remote sensing systems to extract information about the surface properties of a given target provided the effects of the atmosphere are compensated. The imagery coming from these systems also contains information about the atmospheric layers between the surface target and the sensor. These atmospheric layers contain well-mixed molecular gases, as well as, aerosol particles and water vapor. Specially designed algorithms can be used to retrieve information about these atmospheric constituents from aerial or satellite remotely sensed imagery. This research studies the possibility of using such specially designed model algorithms in a sensor radiance to ground reflectance inversion program for hyper-spectral imagery multi-spectral remote sensing imagery, (Sanders, 1999).

It has been shown that the best methodology for extracting information about atmospheric constituent elements has relied a great deal on a combination of ground truth measurements of targets and ground based atmospheric measurements for aerosol and water vapor determinations. This method of extracting at information is not always feasible. Obtaining ground truth is a time-consuming, expensive task that requires extensive labor, (Sanders, 1999).

A more feasible method for attaining the atmospheric information is through the use of algorithms that have been developed to extract atmospheric data directly from the spectra of individual pixels in the image. This can be accomplished using some sort of radiative transfer model of the atmosphere. Many of these atmospheric correction techniques are targeted at specific spectral regions, sensor configuration or operational constraints,
Total Inversion implements these concepts as a means to measure these atmospheric parameters, gaining information about aerosol and water vapor determinations, for example.

The Total Inversion routine is a modular package allowing the user to select optimal techniques based on specific images or sensors. It allows for the use of state of the art information extraction; NLLSSF, a method for surface-pressure depth at the 760nm band, columnar water vapor at the 940nm band and the atmospheric visibility from the 400nm to 700nm band, (Green, 1989); APDA, a method for columnar water vapor, (Schlaepfer & Borel, 1996) and a modified version of the regression intersection (RIM) for atmospheric visibility from 550nm to 700nm, (Sanders et al., 1999). The baseline total inversion algorithm design for extraction of ground reflectance did multi-spectral based configurations.

This research studies the application of Total Inversion for multispectral satellite based remote sensing systems. This research documents the performance of the algorithm in a multispectral mode. One of the problems with using these algorithms on multi-spectral imagery is that the ability to estimate information of water vapor and surface-pressure depth for the 940 nm and 760 nm bands, respectively is compromised by coarseness of multispectral bandwidth. This research investigates the use of alternate sources of water vapor and surface-pressure depth data and explores methods of optimizing the atmospheric correction algorithm.

### 3. Experimental Design and methods

Various aspects of the Total Inversion algorithm were studied. Specifically these aspects included the optimization of atmospheric compensation LUTs, the sensitivity analysis of using independent ancillary estimates for water vapor and elevation (surface pressure depth), and a study to find the optimum method for correcting for aerosol visibility. As part of this research, sensitivity analyses of the inversion process for multi-spectral satellite based imagery is targeted at transitioning the inversion technique from proof of concept to an operational state. These analyses are focused on the optimization of the algorithm sequence defining optimum set of algorithmic techniques and configurations that have acceptable errors and processing times. This research studied the strategy of modeling the atmosphere and its effect on the fundamental inversion techniques that were applied. Analysis was applied to the AVIRIS imagery of Rochester, NY in its hyper-spectral configurations and in convolved multi-spectral states, where the following tasks were performed.

**Task 1:** Evaluation of the potential to use pre-built atmospheric compensation look up tables.

**Task 2:** Sensitivity analysis of using ancillary independent estimates of elevation and water vapor as inputs to the inversion process.

**Task 3:** The comparison of the performance of atmospheric correction algorithms used for correction of aerosol effects.

These tasks are elaborated upon in the project details.

### 3.1 Project Details
3.1.1 Task 1

Task one of the research evaluated the potential to use a pre-built set of look up tables used with the radi transfer based spectral matching correction methods. The findings of this task are important because they indicate if generating a handful of representative atmospheric look up tables is sufficient. This would facilitate operational processing. Total Inversion makes use of model matching techniques in the form of Linear Least squares Spectral Fit (NLLSSF) for the calculation of Aerosol visibility, water vapor and elevation (surface pressure depth), Atmospheric Pre-corrected Differential Absorption (APDA) for calculation of water vapor, and Regression Intersection Method (RIM) for the calculation of aerosol visibility. In all cases development focused on the use of look up tables made specifically for the atmospheric conditions of the specific scenes in interest. The generation of this LUT account for the major computational burden and expense in the inversion process. The traditional computational strategy is a brute force approach that iteratively executes MODTRAN spanning a wide range, and fine increments of atmospheric parameters. An ideal situation would include the ability to use a pre-built family of look up tables that cover the expected range of atmospheric conditions used for the bulk of operational imagery, rather than generating a LUT for each specific scene. This study will address the sensitivity of the inversion process to the specificity of the look up table and the size of the look up table needed. A reference set of hyper-spectral cases was established as a baseline. These hyper-spectral cases include processing using NLLSSF to extract atmospheric information needed for the inversion process. The hyperspectral baseline then could be applied to the understanding of LUT size needed for optimal correction of multi-spectral data sets. The effort is to attempt to define the size of the database needed in terms of numbers of atmospheres and the granularity within each LUT, and did so with the use existing ground truth to provide knowledge of accuracy, (Raquerño, 1999).

3.1.2 Task 2

The second task will evaluate the sensitivity of the impact of decreased spectral information on the multispectral reflectance inversion. This analysis will determine if key spectral bands have significant impact to the reflectance inversion. Specifically, the analysis focuses on the oxygen (760 nm) and water vapor (940 nm) bands that are used to measure physical characteristics of the atmosphere, terrain elevation (surface pressure depth) and total column water vapor, respectively. This task is important because the ability of Inversion to estimate information about water vapor counts and terrain elevation is greatly compran multispectral systems by the prospect of having insufficient spectral resolution to sense the 940 and 760 nm bands. The inability to estimate these atmospheric parameters means that the information will need to come from other sources. As an example, the oxygen pressure depth is an estimate of surface elevation and assuming that most scenes of interest have low elevation variability, estimates of elevation can come from other sources such as a Digital Elevation Model. The same can be done with Total column water vapor estimates where these estimates can be derived from sources like the National Weather services or local airports. These estimates coming from alternate data sources may not be as accurate as the estimates derived by Total Inversion in a hyperspectral baseline case, yet they do provide a starting point that makes multispec atmospheric correction feasible. To understand the accuracy requirements of ancillary estimates of terrain elevation and total column water vapor, a sensitivity analysis of these constituents was performed. This analysis involved using the requisite hyperspectral bands to get baseline estimates of each atmospheric parameter (using NLLSSF) as default inputs into multispectral inversions. The inversion resulting from baseline estimates will represent the multispectral baseline producing the ‘best answer’ given all necessary inputs for the hyperspectral algorithms. Using these baseline estimates errors of ±25% and ±75% were introduced to the best elevation and water vapor estimate derived from the NLLSSF technique (hold parameters constant) and the corresponding inversions were generated. These were then compared with the best possible inversion to measure the errors propagated to the inversion. Once these errors were known example of applying ancillary estimates of water vapor and terrain elevation was performed to see if it is possible to use these alternate data sources.
3.1.3 Task 3

The third task involved a study to find the optimum methodology of correcting for aerosol effects. The study was done to understand which method performs better in an operational situation. It is important to know which algorithms give the best performance with the highest accuracy when using multi-spectral imagery. This analysis will address whether the atmospheric correction algorithms being used can work with operational systems with fewer spectral bands. The algorithms under study for this task are the regression intersection method (RIM) and the nonlinear least squares spectral fit method (NLLSSF). These algorithms were multi-spectral versions of the AVIRIS imagery and utilized existing ground truth as a means of testing accuracy. The issues to be addressed include the relative performance of the algorithms, runtime, implementation concerns and the potential to use multi-spectral vs. hyper-spectral data sets for the aerosol part of the atmospheric correction, (Raqueño, 1999).

3.2 Scene Analysis

The AVIRIS image being used is a data set collected over Rochester, NY (May 20, 1999). This scene is particularly useful because of its accessibility to specific targets and the availability of ground truth. The study was focused around the RIT campus area where grass fields and building tops were analyzed. This AVIRIS imagery is particularly attractive for this analysis because of its high fidelity calibration characteristics and its high altitude geometry closely matches conditions encountered by space-based sensors.

![AVIRIS image of Rochester area. Single pixel spectra will be compared to ASD truth data taken on the target.](image)
The spectra coming from targets within the AVIRIS imagery after being corrected for atmospheric effects were compared against ground truth of the target. The ground truth for each target being analyzed was gathered using an ASD (analytical spectra device) field spectrometer. The data was taken in the grass field region (Grass) and on a rooftop of the R.I.T. gym, (SAU Gym) shown in Figure 1. Figures 3 and 4 are examples of using the ASD to gather spectral information about the targets being used. When using the truth data coming from the ASD spectrometer for comparison convolved down to the same configuration as the image data used. The multispectral configuration being used is modeled after that of Landsat 7 reflective bands. Figure 2 below is an example of the multispectral response file used in this research.

![Figure 2](image)

Figure 2 Response file of Landsat 7 used in this research.

The ASD spectrometer is a valuable tool to gather accurate information about a given target. The spectrometer uses a 512-element photo diode array. It has a spectrum against inverted hyperspectral or multispectral datasets, the truth data will be 1 range from 0.350 to 2.5 μm with a sampling interval of 1.4 nm from 0.350 to 1.0 μm and a sampling interval of 2.0 nm for 1.0 to 2.5 μm. The spectrometer has a spectral resolution of 3.0 nm at 0.7 μm and 10.0 nm at 1.5 μm. We can use the ASD truth data to get an idea of the accuracy of the inversion process by calculating RMS (Root Mean Squared) errors between the spectra predicted by T Inversion and the truth data being used. Figure 5 is a graphical RMS metric example.
**Figure 3**
This is an example of ASD data taken in a grass field with an example of a single grass spectra from the ASD that was used in this research.

**Figure 4**
ASD truth data taken on the roof of the gym at R.I.T. with the corresponding single spectra. This data was used throughout the research process.
The RMS error at a particular pixel was calculated by summing up and squaring the differences between the two spectra dividing by the number of bands in the spectra and then taking the square root. The equation below summarizes this procedure,

$$RMS_{\text{pixel}} = \sqrt{\frac{\sum_{i=1}^{N} (T_i - A_i)^2}{N}}$$

Where $N$ is the number of bands being analyzed, $T_i$ is the truth spectrum and $A_i$ is the inverted reflectance spectrum coming from AVIRIS. When calculating the RMS we do not include the water absorption region where signals are extremely low.

### 4.0 Results of Inversion from Sensor Radiance to Ground Reflectance

The results presented in this section are the reflectance retrievals of the Lake Ontario – Rochester, NY site from the AVIRIS sensor on May 20, 1999. The emphasis will be on the AVIRIS image shown in Figure corresponding RMS error analysis.

### 4.1 RMS of Baseline Total Inversion Performance

A hyperspectral comparison between a ground truth point and the corresponding pixel in Total Inversion processed for the AVIRIS image. In this case a baseline RMS metric was computed for a hyperspectral inversion using a radiosonde-based, rural aerosol, full resolution atmospheric LUT using the NLLSSI algorithm. The baseline RMS errors were computed for the grass field region (Grass) and the building rooftop...
(SAU Gym) of Figure 1. These RMS values were computed by comparing the ground truth spectral reflectance against the spectral reflectance predicted by Total Inversion for a single pixel, these comparisons are shown below in Figures 6 and 7.

The RMS results shown in Figures 6 and 7 theoretically represent the most accurate performance of the Inversion algorithm as it has been implemented. Further analysis of the results in the later sections will allow us to compare these hyperspectral RMS errors with errors from the inversion of the corresponding multispectral imagery.

**Figure 6** Comparison of inverted hyperspectral AVIRIS data against truth for the Grass region, with the RMS value for the hyperspectral bands and the RMS of just the Landsat-7 bands.
4.2 Results from Task 1

4.2.1 Atmospheric look-up table resolution analysis

A look-up table, (LUT), resolution analysis for the above AVIRIS scene was performed. The goal of this study is to address the sensitivity of the inversion process to the size of the LUT. Knowledge about the optimum necessary to provide an acceptable reflectance inversion will help in understanding its operational feasibility.

Figure 8 Number of Water Vapor (WV) runs, Elevation (EL), and aerosol visibility (VS) runs for high and low resolution LUTs.

Figure 8 above is a graphic comparing a full resolution LUT block to a down sampled low resolution LUT block. The difference in the two LUTs is the amount of information for the number of water vapor, elevation and visibility levels. Currently the generation of this LUT accounts for a major part of the computational burden and time expense in preparation of the inversion process. By using a smaller size LUT like the one shown to the right in Figure 8 with 2 runs each for water vapor, elevation and visibility the computational burden and processing time would be greatly reduced. To understand if it is possible to use lower resolution LUTs in the inversion process, a sensitivity analysis was performed. This analysis involved down sampling the atmospheric LUT for ranges of water vapor, aerosol (Visibility), and elevation (pressure depth) to 8 different levels, as illustrated below in Table 1.

Table 1 Individual water vapor, elevation, and Aerosol runs for each LUT size.
Each case in Table 1 represents an individual size LUT block used for the inversion process. RMS errors were then calculated for the reflectance images corresponding to each spectral block.

The results indicate that there are only small increases in the RMS errors as the LUT resolution is decreased. This is illustrated below in Figure 9, showing inverted hyperspectral AVIRIS data of Grass for the high resolution LUT and the lowest resolution LUT in comparison to ground truth.
The difference in RMS between the full resolution and lowest resolution LUT for the hyperspectral case is 0.230 reflectance units. The average RMS over all resolution LUTs is 4.18 reflectance units. This is encouraging because for the hyperspectral case we have comparable atmospheric compensation performance for a small number of MODTRAN runs as well as the cases with a large number of MODTRAN runs.

A similar resolution comparison was applied to the same scene, this time however, using the AVIRIS image that was convolved down to a multispectral configuration. In this inversion process scene wide water vapor and elevation estimates came from those that were calculated from the hyperspectral baseline inversion. We are interested in the results of the inversion to reflectance from the different resolution LUTs used for the inversion to reflectance for multispectral imagery. These results change when the Water vapor and Elevation part of the LUT is varied in size, for example, from 7 to 2 entries for water vapor and 10 to 2 entries for elevation. The resulting image reflectance changes even though the default values for each are applied to the whole image. Though we may use a fixed water vapor and elevation value, the resulting radiometry will differ depending on existing values in the LUT used in the interpolation process. This is better illustrated in Figure 10 where a comparison of interpolation results is depicted between a low resolution and high resolution LUT. The variation in the calculated up-welled radiance from the two LUTs results in slightly different reflectance inversions. The remaining variable that gets calculated is then the Aerosol visibility, which dependent on the size LUT used.
Figure 10 An illustration of the interpolation process used to find radiometric parameters and its dependency on LUT size.

It should be noted that the multispectral imagery resulting from the inversion process using Non Linear Squares Spectral Fit (NLLSSF) contained spatial artifacts which seem to be attributed to the pixel by pixel multispectral processing of aerosol visibility values. For about 1/5 of the pixels in the image Total Inversion was unable to converge in on a visibility value. To bypass these non-convergent cases we applied a scene wide default visibility value that was calculated from the average of the convergent case values in the multi-spectral image. These visibility values can be seen in Table 2.

The corresponding multispectral analysis shows similar encouraging results to the hyperspectral results, increases in RMS error for significant reduction of LUT resolution. We can see in Figure 11 that there is only a small change in the spectrum between inversions from the high and low resolution LUTs.
The increase in RMS for Grass from the full resolution LUT to the lowest resolution LUT for Figure 11 was 1.108 reflectance units with an average RMS over all resolution LUT of 1.887 reflectance units. The same analysis was applied to the multispectral image by looking at the roof of a gym building (SAU Gym). Figure 12 below shows the relationship between the two different resolution LUTs and their truth data for SAU Gym.

The increase in RMS from the high resolution LUT and the lowest resolution LUT for Figure 12 was reflectance units with an average RMS over all resolution LUTs of 1.905. These results imply that it may be possible to get accurate surface reflectance values from radiances at the sensor using low resolution LUTs. Table 2 below shows the corresponding RMS values for the multispectral inversions of Grass and SAU Gym.
for each LUT combination.

**Table 2** RMS values of multispectral versions of Grass and SAU Gym with each LUT resolution.

<table>
<thead>
<tr>
<th>Radiosonde</th>
<th>LUT Resolution</th>
<th>Visibility</th>
<th>Grass RMS</th>
<th>SAU Gym</th>
<th>Gym RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(7,10,12)</td>
<td>50.511</td>
<td>1.302</td>
<td>1.728</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(2,10,12)</td>
<td>52.622</td>
<td>2.52</td>
<td>1.68</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(7,2,12)</td>
<td>52.74</td>
<td>1.368</td>
<td>2.25</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(7,10,2)</td>
<td>52.517</td>
<td>1.314</td>
<td>2.06</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(2,2,12)</td>
<td>54.82</td>
<td>2.22</td>
<td>1.74</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(2,10,2)</td>
<td>54.127</td>
<td>1.34</td>
<td>2.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(7,2,2)</td>
<td>51.87</td>
<td>2.627</td>
<td>1.702</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(2,2,2)</td>
<td>53.186</td>
<td>2.41</td>
<td>1.734</td>
<td></td>
</tr>
</tbody>
</table>
Figure 13 Multispectral RMS for Grass and SAU Gym for each LUT size.

From Table 2 the RMS values for both grass and SAU Gym reveal small variations in value between the LUT resolutions. This can also be seen with Figure 13 below. The standard deviation of the RMS values from Table 2 for Grass is 0.606 reflectance units. The standard deviation for the RMS values for SAU Gym is 0.241 reflectance units. This implies that regardless of the size LUT used, the resulting accuracy does not vary a great deal.

4.2.2 Comparison of radiosonde-based vs. Mid-latitude summer (MLS)

This part of the research was designed to determine if the use of standard atmospheres included in MODTRAN can sufficiently characterize most of the atmospheres encountered. In this analysis the atmosphere of Mid-latitude Summer was compared against a scene specific radiosonde atmosphere. The current version of Total Inversion requires scene specific radiosonde to characterize the atmosphere. It would be ideal to relax this requirement because the availability of scene specific radiosonde data is very limited. If generating LUTs based on a standard set of atmospheres is sufficient to produce reasonable results, it would be feasible to create a family of pre-built LUTs for all possible inversions. This ability to generate a handful of representative atmospheres will greatly facilitate operational processing.

An analysis was done for the multispectral version of the AVIRIS image looking at SAU Gym. Figure 14 below shows inverted AVIRIS data of SAU Gym with the corresponding ground truth, comparing a Radiosonde. As it can be seen there is a very small difference between the MLS case and the Radiosonde case.
The RMS for the Radiosonde case in Figure 14 is 1.728 reflectance units and the corresponding RMS value for the MLS case is 2.091 reflectance units. This is an increase in value of 0.363 reflectance units. A similar analysis was done by looking at the Grass spectrum. Figure 15 below shows inverted AVIRIS data of SAU Gym with the corresponding ground truth, comparing MLS with Radiosonde.
The RMS for the Radiosonde case in Figure 15 is 1.302 reflectance units and the corresponding RMS value for the MLS case is 1.368 reflectance units. This is an increase in value of 0.066 reflectance units. This reinforced by Figure 16 below showing a comparison of the two atmospheric cases over LUT resolution AVIRIS multispectral data.

![Figure 16](https://www.cis.rit.edu/research/thesis/bs/2001/webber/report_for_web.png)

**Figure 16** Comparison of MLS vs. Radiosonde for each LUT resolution.

The average RMS value over all LUT resolutions for the Radiosonde case is 1.887 reflectance units corresponding MLS case shows an improvement to 1.768 reflectance units. This is a reduction in RMS error of 0.118 reflectance units. These results are encouraging because they do not show a large variation in RMS error from the radiosonde atmospheres to the MLS atmosphere. This supports the proposition of creating a pre-family of LUTs based on MLS atmosphere.

### 4.3 Results from Task 2 of this research

#### 4.3.1 Total Inversion Sensitivity to Atmospheric Estimates.

For the Total Inversion algorithm to be applied to multispectral imagery it is essential to have an understanding of Total Inversion’s performance with respect to errors in estimating water vapor and εp (pressure depth) values. This is important because multispectral bands do not have sufficient resolution to probe the characteristic absorption features normally used to estimate water vapor and elevation parameter using hyperspectral instruments. The process will require that these parameters be estimated through ancillary data from other sources such as the National Weather Service. Because of possible time and spatial differences between the acquisition of ancillary and image data, discrepancies between the two measurements are expected. Since it is conceivable that these external measurements may contain significant errors when compared to model derived estimates it is important to study Total Inversion’s robustness to these default inputs. For this analysis default values of water vapor and elevation were set to a "best estimate" derived from a hyperspectral Total Inversion run of the AVIRIS scene. Different levels of over and under estimation errors up to 75% of estimation value determined by the hyperspectral mode, were then applied to a corresponding multispectral Total Inversion process. The resulting increases in RMS when compared to the baseline case
shown in Figure 17.

**Figure 17** RMS resulting from over and under estimation of water vapor.

**Figure 18** RMS resulting from under and over estimation of elevation.
For Figure 17 data was taken for under and over estimation of 25% and 75% from the baseline 2.0 g/cm². The 0% in the figure represents the RMS resulting from the best estimate of water vapor. The resulting increase in RMS when compared to the baseline case in figure 16 for an over estimation of 75% was 0.297 reflectance units. The corresponding increase in RMS for the 75% under estimation of water vapor was 0.061 reflectance units. Figure 18 below shows the same analysis done for the under and over estimation of the elevation baseline of 0.4 km.

![RMS as a function of Percent difference in both water vapor and elevation for Grass region](image)

**Figure 19**

RMS resulting from over and under estimation interactions for both water vapor and elevation. The left estimation is for water vapor, while the right estimation is for elevation, and the 0,0 case is the "best estimate", Aerosol was calculated NLLSSF.

The corresponding increases in RMS for the elevation case were 0.03 and 0.016 reflectance units for under and over estimation by 75%, respectively. An interaction study was also performed. In this analysis, interactions in estimation errors between the water vapor and elevation factors were studied, producing the plot in Figure 19. These would represent the most extreme cases. The differences in reflectance RMS value from Figure 19 when compared to the baseline case produced the following results:

<table>
<thead>
<tr>
<th>Water vapor</th>
<th>Elevation</th>
<th>RMS increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>75%</td>
<td>75%</td>
<td>0.31</td>
</tr>
<tr>
<td>-75%</td>
<td>75%</td>
<td>0.026</td>
</tr>
</tbody>
</table>
These results are encouraging because they indicate that Total Inversion does not exhibit significant sensitivity to errors in estimation of water vapor and elevation. This means it may possible to get accurate surface reflectances by applying ancillary data for defaults of elevation and water vapor values for the Total Inversion process.

To realistically test the multispectral inversion cases, we took estimates of elevation and water vapor independent sources. Using the water vapor value extracted from May 20th, 1999 for the Buffalo International Airport, about 65 miles southwest of Rochester, and a known elevation of the Rochester Airport we were able to test how well the inversion process performs. The water vapor value used in this test was calculated using the formula below for \( u \), defined as total precipitable water.

\[
\frac{AC \cdot T_d}{\left(\frac{T_d + K - BC + 0.1133}{P(Lat, Season) + 1}\right)}
\]

Where \( AC \) is the vapor pressure constant 17.269°C, \( K \) is the constant of 273.15°C, \( BC \) is another vapor pressure constant 35.86°C, and \( P(Lat, Season) \) is the moisture profile exponent dependent upon latitude and season. The remaining variable in the equation that needs to be extracted for a particular scene is the dew point temperature, \( T_d \), found to be 20°C, (DCS Corporation, 1991). The dew point temperature can be found for a particular airport using the website: [http://www.nws.noaa.gov/](http://www.nws.noaa.gov/), in this case the Buffalo Airport was used to estimate the dew point for Rochester. Using the above equation the water vapor value calculated was 1.40 g/cm². Figures 20 and 21 below are examples of Inverted AVIRIS data using a water vapor value of 1.40 gm/cm², a 30% difference from the baseline water vapor value of 2.0 g/cm².
Figure 20  
Example of inverted data using ancillary data for elevation and water vapor, aerosol was calculated using NLLSSF.

Figure 21  
Example of inverted data using ancillary data for elevation and water vapor.

The RMS errors for the highest and lowest resolution LUT for Grass is 1.14 reflectance units and 2.1 reflectance units respectively. The corresponding RMS values for the SAU Gym case are 2.13 and 1. reflectance units. The results from figures 19 and 20 show that the reflectance inversion resulting from t external estimates are comparable to the hyperspectral derived results previously discussed.
4.4 Results from task 3 of the research

4.4.1 RIMAC Algorithm Vs. NLLSSF results

When inverting multispectral imagery estimates from ancillary data sources of water vapor and elevation need to be used as default inputs to the program. After these estimates are inserted into the program, Total Inversion still must calculate the Aerosol visibility. There are two methods Total Inversion uses to estimate the Visibility for a particular scene, they are the Regression Intersection Method for Aerosol Correction (RIMAC) and the Non-Linear Least Squares Spectral Fit (NLLSSF).

The RIMAC technique assumes that the majority of the up-welled radiance is a function of aerosol scattering in the 550 nm – 700 nm wavelength range. An advantage of using the RIMAC method is that it prov statistically derived results from the actual image data with no atmospheric or other scene information needed. The NLLSSF technique, on the other hand, relies on a close starting estimate to the truth in order to obtain realistic atmospheric parameters. This method solves for these atmospheric parameters by using a multi-solution to a non-linear least squares spectral fit (NLLSSF) between the spectral radiance measured by the sensor and the spectral radiance calculated by the radiative transfer code, such as MODTRAN 4. It makes this fit by using a constructed LUT where the visibility is varied in predetermined increments until a best fit is found. This algorithm is run on a pixel by pixel basis where the visibility is found for each pixel.

The RIMAC technique depends on an automated scene segmentation that can identify homogeneous areas varying spectral contrasts in the terrain. As implemented, an unsupervised ISODATA classification is done by a non-interactive ENVI call. Starting from the first band and going band pair by band pair, the DC’s for each class are regressed to extrapolate toward the origin and the intersections of all the class regressions are calculated from the combinations of the first band with the others (c.f. Figure 22). Once a cluster of acceptable intersections are found for the band pair, the mean value is determined and the transformed DC counts become the upwelling radiance estimate for the first band of the comparison. This process is then repeated for all subsequent bands. Total Inversion then finds the aerosol-specific visibility that corresponds to the best model based match to the scene derived total upwelled radiance values. This aerosol-specific visibility is then assigned to the entire image.
The RIMAC algorithm for calculating the Aerosol visibility was applied to the multispectral imagery cases and gave results that were comparable to the NLLSSF algorithm. This algorithm can be very useful if accurate results are produced because the algorithm makes a single estimate of aerosol visibility for the entire image. As a result, its run time is significantly reduced (almost an order of magnitude) from that of NLLSSF, making it attractive for operational use.

When comparing the two algorithms in their ability to extract the aerosol visibility estimate, it became apparent that RIMAC was estimating the maximum aerosol visibility in the LUT. The NLLSSF algorithm estimates were also near the maximum in the LUT, but fluctuated on a pixel by pixel basis. The RIMAC results show, however, that the retrieved reflectance results do not vary greatly from the results given by the NLLSSF algorithm. Figures 23 and 24 show inverted AVIRIS data for Grass, comparing results from RIMA and NLLSSF for both the Radiosonde case and the MLS case.

**Figure 22** Example of In-Class distributions in two bands.
The RMS error value from the above Figure 23 was 1.227 reflectance units. The corresponding RMS value for the NLLSSF case is 1.302 reflectance units, a difference of 0.075 reflectance units. The same analysis was done for the MLS atmosphere case, this is shown below in Figure 24.

The RMS error value from the above Figure 24 was 1.301 reflectance units. The corresponding RMS value for the NLLSSF case is 1.368 reflectance units, a difference of 0.067 reflectance units. These results for the RIMAC algorithm show that the AVIRIS imagery for this simulation represents a condition that does adequately stress the algorithm in retrieving aerosol visibility. The results from RIMAC are not much different from that of the NLLSSF results.
5.0 Conclusion

The results from this research show that it is feasible to use Total Inversion for atmospheric correction of multispectral sensor images. From the results in task one, it appears that the inversion process is not overly sensitive to the LUT size. The results show that there is not a large difference in the inversion of multispectral data sets between the use of a large LUT and a small LUT. The RMS value using the full resolution LUT for the grass spectrum is 1.302 reflectance units and the corresponding RMS error for the lowest resolution LUT is 2.410, an increase of 1.108 reflectance units. Looking at the SAU-gym rooftop we see that the RMS resulting from the use of the high resolution LUT is 1.728 reflectance units. The corresponding RMS resulting from the use of the lowest resolution LUT is 1.734 reflectance units. These results may indicate that it is feasible to use sub-sampled LUTs for the correction of the atmosphere on multispectral data sets. Further analysis will need to be done to see if it is possible to strengthen this premise. To see if Total Inversion is consistent with its inversion process for other multispectral sensor imagery, we will be testing the process over the bands of Earth Observing-1 (EO-1), Advanced Land Imager (ALI).

Task one also shows that it may be possible to use standard atmospheres. The research indicates that there is little difference when using the atmosphere of Mid-latitude Summer versus a scene specific radiosonde atmosphere. The inversion process using an MLS atmosphere yielded an RMS value of 1.368 reflectance units for the Grass spectrum. The RMS error for the coresponding Grass spectrum using a radiosonde atmosphere was 1.302 reflectance units. This is a difference of 0.066 reflectance units for the two atmospheres. Further study will be performed to see if this is the case when correcting for the atmosphere using other standard atmospheres, until then it is recommended that radiosonde specific atmospheres be used.

The results in task two of this research show that it is possible to use ancillary sources of water vapor and elevation estimates. Retrieved image reflectances varied little when elevation and water vapor estimates were widely varied in the inversion process. Underestimation of the water vapor value by 75% of the baseline value resulted in an increase in RMS error of 0.061 reflectance units. Overestimating the water vapor value by 25% resulted in an increase in RMS error of 0.297 reflectance units. The corresponding increase in RMS error for the elevation cases are 0.03 and 0.016 reflectance units for under and over estimation by 75% of the baseline value respectively. When actual ancillary estimates of water vapor and elevation were used the inversion to reflectance yielded reasonable results. It is recommended that ancillary estimates of water vapor and elevation be used whenever necessary.

Task three of this research compared the use of NLLSSF and RIMAC in the estimation of Aerosol Visibility. The results from Task three show that using RIMAC on multispectral data sets is comparable to the results using NLLSSF on the same data sets. The RMS for the grass spectra using RIMAC to estimate the aerosol visibility is 1.227 reflectance units. The corresponding case using NLLSSF to calculate the aerosol visibility results in a RMS error of 1.302 reflectance units. This is difference of 0.075 reflectance units. The same analysis for the SAU-gym rooftop yields RMS errors of 1.227 reflectance units for the RIMAC algorithm and 1.368 reflectance units for the NLLSSF algorithm. This is a difference of 0.067 reflectance units. The results from this section imply that it is more practical to use RIMAC in the calculation of aerosol visibility. RIMAC makes a single estimate of aerosol visibility for the entire image as opposed to doing pixel by pixel processing. As a result of the single estimate its run time is significantly reduced from that of NLLSSF. The results show that RIMAC requires less time to process the data and may also be slightly more accurate in the inversion from radiance to reflectance. It is recommended that RIMAC be used for the estimation of the aerosol visibility.

Results
6.0 Further Research

A.
Further work in this area will involve a sensitivity analysis of the inversion process to Aerosol type. This involves a comparison between a rural type aerosol and an urban type aerosol. The understanding of aerosol type is important because the atmospheres over an assorted set of scenes will have a diverse set of scene properties. Rural aerosols typical in atmospheres over non-urban areas tend to have very small particles and very large water droplets. The small particles tend to be much smaller than the wavelength of the incident flux; this is known as Rayleigh scattering. The large water droplets are particles that are much larger than the wavelength of the incident energy, this type of scattering is called Nonselective scattering. Urban type aerosols are those existing over urban-city areas and usually contain small dust particles and fossil fuel combustion products along with water droplets. Urban area aerosols create both Rayleigh and Nonselective scattering similar to that of rural aerosols. In addition to creating these two types of scattering, urban aerosols create scattering associated with particles that are approximately equal to the wavelength of the energy. This scattering. Various combinations of these three kinds of scattering produce dissimilar types of visibility, (Schott, 1997). This study will address whether it is important to use specific aerosol types for individual scenes or if the inversion process is robust enough to use one type of aerosol over a large variety of scenes.

B.
Future work will also involve testing the inversion process over Earth Observing-1 (EO-1), Advanced Land Imager (ALI) bands. This will allow us to see if Total Inversion produces consistent results for different combinations of multispectral bands. In this analysis we will test to see how well Total Inversion estimates aerosol visibility and whether it is still robust enough to use subsampled LUTs.

C.
A comparison between one-pass and two-pass multispectral reflectance inversions will be made. The inversion methodology is a two-pass process in which the second pass compensates for adjacency effect through a convolution kernel. In this analysis we will study the accuracy of the retrieved reflectance images for each pass. This examination will tell us if there is a significant difference between the reflectance in resulting from the first pass of the inversion process and those resulting from the second pass of the inversion process. We will perform this test using different algorithms to estimate Aerosol visibility and will do so with subsampled LUTs.

D.
Further study will also include implementation and testing of the baseline MODIS aerosol estimation algorithm. This is a method of estimating atmospheric aerosol characteristics using in scene-derived measurements. The premise behind this algorithm is that there is a strong correlation in reflectance values of "dark targets" between the short wave infrared region (SWIR) and the red and blue regions of the visible bands. These low reflectance targets provide estimates of the upwelled radiance, which is then correlated to estimated aerosol number density. The MODIS algorithm will provide a comparison against currently existing routines in the inversion package. This study will incorporate a sensitivity analysis of the algorithm to differences in aerosol characteristics such as urban and rural aerosols. The algorithm will be run using high and low resolution LUTs of different atmospheric types.

E.
The research will then conclude with the evaluation of the potential advantages of adjacency effect. The current approach in the Total Inversion package is a two-pass method through the model matching atmospheric correction process. This correction to compensate for the environment and adjacency effect is a pixel-by-pixel determination of the spatial convolution kernel. This kernel is derived from scattering phase function defined by the modeled atmosphere. A study will be done to see if it is possible to decrease the dependency of "pixel by pixel" processing by creating an image wide estimate of this kernel applying it to the entire image. This investigation will identify whether or not a simpler approach of an ima
A wide convolution kernel can be used. If the image wide convolution kernel proves to bring acceptable results, then a strategy will be applied to include it as a single pass method through the model matching atmosphere correction.

Table of Contents

7.0 References


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