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Title:

Recipes for writing algorithms to retrieve columnar water vapor for 3-band multi-spectral data

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ABSTRACT

Many papers have considered the theory of retrieving columnar water vapor using the continuum interpolated band ratio (CIBR) and a few the atmospherically pre-corrected differential absorption (APDA) methods. In this paper we aim at giving recipes to actually implement CIBR and APDA for the Multi-spectral Thermal Imager (MTI) with the hope that they can be easily adapted to other sensors such as MODIS, AVIRIS and HYDICE. The algorithms have the four following steps in common: (1) running a radiative transfer (RT) algorithm for a range of water vapor values and a particular observation geometry, (2) computation of sensor band-averaged radiances, (3) computation of a non-linear fit of channel ratios (CIBR or APDA) as a function of water vapor, (4) application of the inverse fit to retrieve columnar water vapor as a function of channel ratio.

Keywords: MTI, Multi-spectral Imaging, Water Vapor Algorithms, CIBR, APDA

1. Introduction

The Multi-spectral thermal imager (MTI) launched in March of 2000 has three water vapor sensing channels at 20 m ground sampling distance centerd on the 940 nm water absorption feature. Details on MTI can be found in Bell and Weber, 2001 and its references. Characterizing the atmosphere is needed to retrieve earth surface reflectances and temperatures from satellite imagery. Since one of the main goals for Multi-spectral Thermal Imager (MTI) is to measure surface temperatures accurately, we have implemented two methods for determining the columnar water (CW) vapor amount. Knowing the columnar water vapor amount allows us to improve water surface temperature estimates for the robust and physics based water temperature retrieval algorithms which are found in Borel et al, (1999) and Borel and Clodius, (2001). These methods have been implemented into the MTI processing pipeline: the Atmospheric Pre-corrected Differential Absorption (APDA) method and the Continuum Interpolated Band Ration (CIBR).

In this paper we describe three algorithm recipes to retrieve water vapor from the three water vapor bands of MTI. Two recipes are for the CIBR method which were independently developed by the first two authors and one of an APDA implementation implemented by the second author with support from Peter McLachlan.

2. Transmission based CIBR recipe

To save computation time it is quicker to run MODTRAN in the transmission mode for two situations (1) the path from the sun to the ground and (2) from the ground to the sensor. The total spectral attenuation due to water vapor alone is given by:

$$T_{H2O}(\nu, CW) = T_{\text{H2O,sun}\rightarrow\text{ground}}(\nu, CW) \;\; T_{\text{H2O,ground}\rightarrow\text{sensor}}(\nu, CW), \tag{1}$$

where ν is the wavenumber in cm^{-1} and CW is the columnar water vapor in g/cm^2 where we assume for now that the water vapor profile to be the same on both paths.

The steps for this retrieval are:

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1. The default *TAPE5* for MODTRAN4 was:

```
T    a    2    0    0    0    0    0    0    0    0    0    0    0   0.001   0.00
F   0T    2   355.000  Gb.bb
    1    0    0    0    0    0     0.000     0.000     0.000     0.000     0.000
   ccc.ccc     d.ddd   eee.eee   0.000     0.000     0.000     0.000    0
    0.8000    1.1000    0.0100    0.0200          M  A
    0
```

As listed we choose MODEL : a = 1 tropical atmosphere but in our implementation we can chose between all 6 model atmospheres: 1=Tropical Atmosphere, 2=Midlatitude Summer, 3=Midlatitude Winter, 4=Sub-arctic Summer, 5=Subarctic Winter, 6=1976 US Standard. To scale the water vapor profiles we used the method described in Borel and Clodius (2001) for up to 18 water vapor amounts. The spacings for CW we are (The letter "G" sets the units to $/g/cm^2$): $\mathrm{H2O_STR}$: CW = b.bb=0.05, 0.1, 0.2, 0.3, .5, 0.75, 1., 1.25, 1.5, 1.75, 2., 2.5, 3., 3.5, 4., 4.5, 5., 6., 6.5, 7. and 8. g/cm^2.

The viewing geometry is read from a database which stores this information for each image taken with MTI. The sensor altitude is set to $H1$: *ccc.ccc* = 100.00 km, the target altitude to the mean ground altitude in the database $H2$ = *d.ddd*. The phase angle is ANGLEi : eee.eee = $180^o - \theta$, where θ is either the sun or view zenith angle. The computation is performed between 0.8 and 1.1 μm with 10 nm sampling and 20 nm resolution. The aerosol model is fixed to a 23 km visibility rural atmosphere ($IHAZE = 1$).

2. The `TAPE7` output file contains a table of the wavenumber ν in cm^-1 where the wavelength $\lambda = 10000/\nu$ in column 1, the total transmission T_{total} in column 2 and the transmission due to water vapor in column 3. The spectral transmissions were used to compute the band-average transmission for bands E, F and G which are plotted in Figure 1. The filter functions $R_i(\nu)$ were derived from nadir measurements at room temperature by Barr Associates and using a model from Sandia National Laboratories (SNL) converted to 75 K temperature and light cones equivalent to a $f = 3.5$ telescope impinging on 3 different locations on the focal plane which we denote with sub-chip assembly (SCA). The band-averaged transmission due to water vapor is defined as:

$$T_{i,H2O}(CW) = \frac{\int_{\nu(i)_a}^{\nu(i)_b} R_i(\nu) T_{H2O}(\nu, CW) d\nu}{\int_{\nu(i)_a}^{\nu(i)_b} R_i(\nu) d\nu}, \quad (2)$$

where $R_i(\nu)$ is the spectral response of the i-th channel, $i = \{E,\ F,\ G\}$. For use in the CIBR equation 6 we compute the center wavelengths $\lambda_{c,i}$ with:

$$\lambda_{c,i} = \frac{10000}{\nu_{c,i}}, \quad \text{where} \quad \nu_{\mathrm{c,i}} = \frac{\int_{\lambda(\mathrm{i})_\mathrm{a}}^{\lambda(\mathrm{i})_\mathrm{b}} \lambda \mathrm{R_i}(\lambda) \mathrm{d}\lambda}{\int_{\lambda(\mathrm{i})_\mathrm{a}}^{\lambda(\mathrm{i})_\mathrm{b}} \mathrm{R_i}(\lambda) \mathrm{d}\lambda}. \quad (3)$$

The center wavelengths for the Barr/SNL filter functions are: $\lambda_{c,E} = 0.874 \mu m$, $\lambda_{c,F} = 0.938 \mu m$ and $\lambda_{c,G} = 1.016 \mu m$. The bandwidths for the Barr/SNL filter functions are $BW_E = 0.0160 \mu m$, $BW_F = 0.0428 \mu m$ and $BW_G = 0.0340 \mu m$.

Now we can construct a look-up-table of columnar water vapor amounts CW_{RT} and the corresponding two-path transmission $CIBR_{RT}(CW_{RT})$ computed with a radiative transfer (RT) program such as MODTRAN:

$$CIBR_{RT} = \frac{T_{F,H2O}(CW_{RT})}{w_1 T_{E,H2O}(CW_{RT}) + w_2 T_{G,H2O}(CW_{RT})}, \quad (4)$$

where the weighting coefficients w_1 and w_2 are defined in eq (6). We find a quasi-linear interpolation scheme to fit this table for arbitrary CW's using the ordinate y and abscissa x transforms:

$$x = \sqrt{CW_{RT}} \quad \text{and} \quad \mathrm{y} = \log_{10}[\mathrm{CIBR_{RT}}(\mathrm{CW_{RT}})]. \quad (5)$$

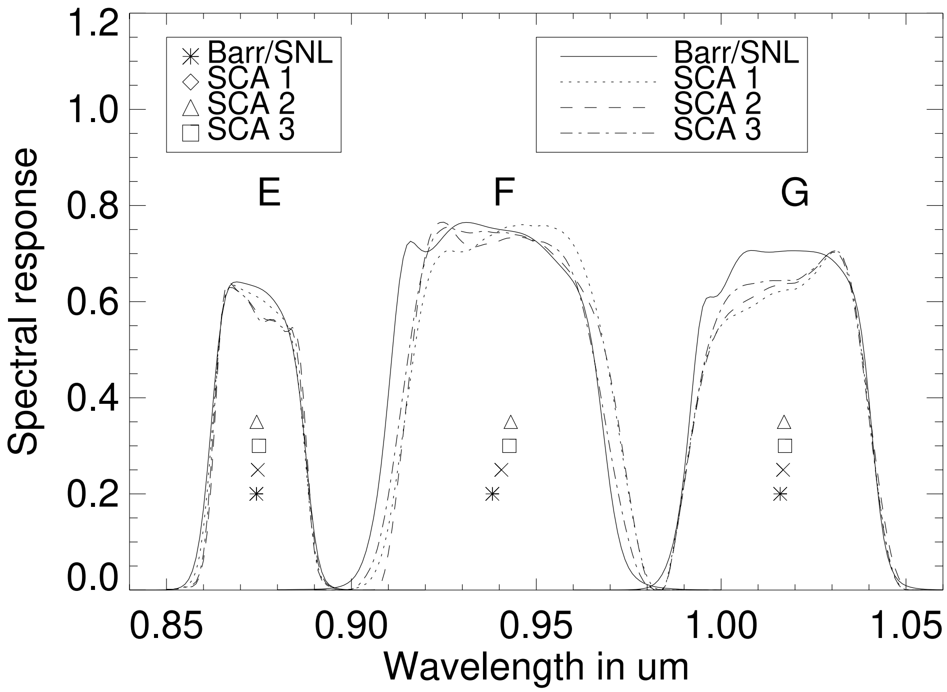

Figure 1. MTI spectral responses for water vapor channels E, F and G and location of bandcenters (y-axis position is arbitrary). The Barr/SNL function is averaged over 3 SCA's and the functions labeled SCA 1, SCA 2 and SCA3 are averages over a SCA measured by LANL. Note, that only the Barr/SNL filter responses were used in this paper.

The advantage is that eq (5) can be used in cases where the measured $CIBR_{data}$ which is equivalent to $CIBR_{RT}$ exceeds the maximum allowed water vapor amount which can occur if a drier winter atmosphere is chosen instead of a US standard or mid-latitude summer case.

Using a linear fit $Q(z) = a_0 + a_1 z$ to the pair (x, y) we can now generate a continuous LUT with $CW_{RT} = x^2$ and $CIBR_{RT} = 10^{Q(CW_{RT})}$.

3. To compute the CIBR from MTI data we use band-averaged radiance values L_i in the following expression (for detailed derivations see Schläpfer et al, (1996)):

$$CIBR_{data} = \frac{L_F}{w_1 L_E + w_2 L_G}, \quad \text{where} \tag{6}$$

where:

$$w_1 = \frac{\lambda_{c,G} - \lambda_{c,F}}{\lambda_G - \lambda_E} \quad \text{and} \quad \mathrm{w}_2 = \frac{\lambda_{\mathrm{c,F}} - \lambda_{\mathrm{c,E}}}{\lambda_{\mathrm{G}} - \lambda_{\mathrm{E}}}.$$

For MTI using the Barr/SNL filter functions we have $w_1 = 0.5495$ and $w_2 = 0.4505$. In Figure 2 we show a typical example of the band-averaged transmissions due to water vapor for channels E, F and G.

4. Assuming that the $CIBR$ using RT calculations is equivalent to the $CIBR$ from data we can compute the columnar water vapor CW_{data} from $CIBR_{data}$ the following inverse function is used:

$$CW_{data} = [P(\log_{10}(CIBR_{data}))]^2, \tag{7}$$

where $P(z) = b_0 + b_1 z$ is a linear fit to $x = \log_{10}[CIBR_{RT}(CW_{RT})]$ and $y = \sqrt{CW_{RT}}$.

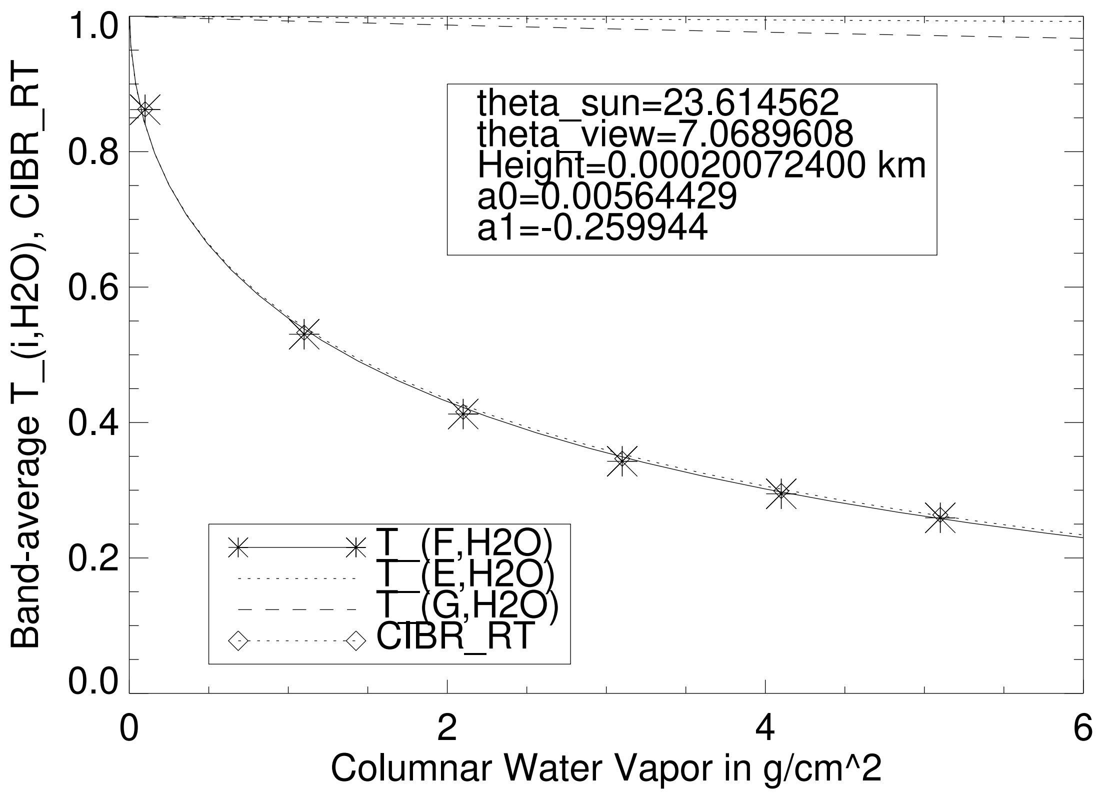

Figure 2. Example of fitting the band-averaged water vapor transmissions $T_{i,H2O}(CW_{RT})$ for a MTI data set.

Note that the assumption that $CIBR_{RT} = CIBR_{data}$ is only valid when the surface reflectance is greater than about 0.3 as was shown in Schläpfer et al, (1998). Other methods to correct the CIBR for reflectance effects are discussed in Hirsch et al, (2001).

The advantages of the reflectance based $CIBR$ method are:

1. Simpler to implement and much faster to run than radiance based CIBR or APDA.
2. Other potential applications using separate transmission path calculations, see Figure 3, are:
   (a) The surface receives direct sunlight and light scattered from the side of a cloud.
   (b) The surface is in a cloud shadow and we receive light scattered through the cloud.
   (c) The atmosphere is not horizontally homogeneous, e.g. devise a retrieval where the water vapor profiles are iteratively adjusted for both paths.

This general method has been used with AVIRIS, ATSR, MODIS and other hyper-spectral and multi-spectral sensors Note, however, that CIBR is a very simple and quick method. It works best over bright and dry surfaces. It underestimates CW over dark surfaces, like water and water soaked surfaces where the atmospheric pre-corrected differential absorption (APDA) technique performs better.

3. Radiance based CIBR recipe

This algorithm is very similar to the one in the previous section with the main difference that it involves running MODTRAN in radiance mode. The radiance based CIBR fit follows the following steps:

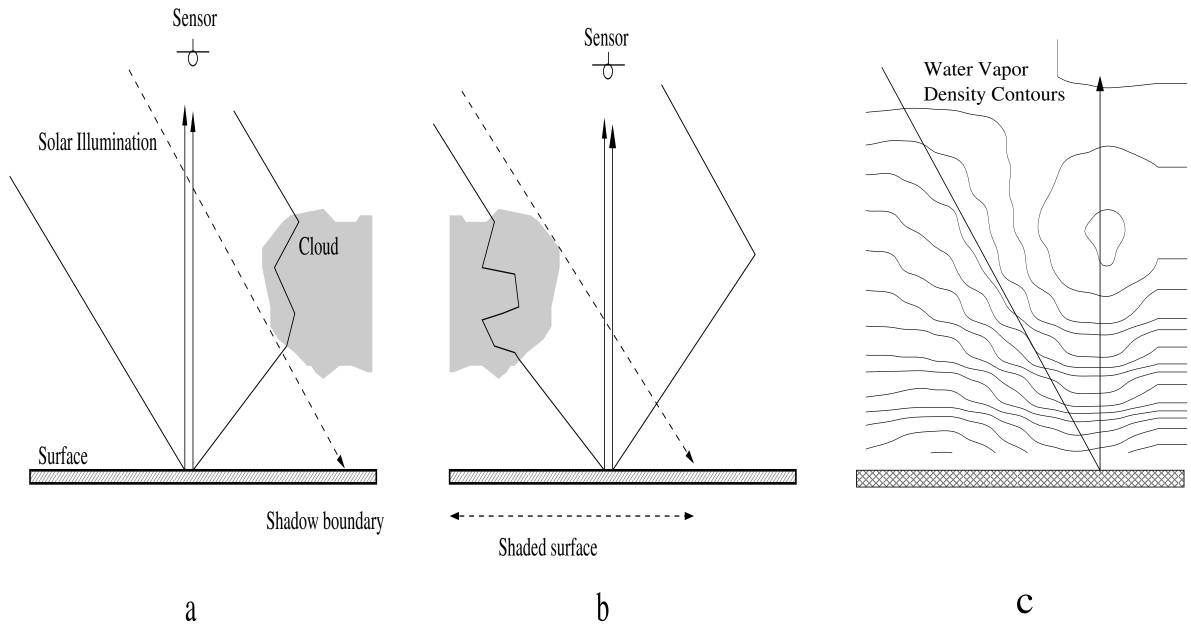

Figure 3. Cases which could be handled by a modified transmission based CIBR.

1. Run MODTRAN4 in radiance mode for a specific CW_{RT}, atmosphere (tropical, mid-latitude summer, mid-latitude winter, sub-arctic summer, sub-arctic winter) and aerosol model (rural, maritime or urban). The visibility was set to 23 km and the surface reflectance to 0.45. The multiple scattering code used is the two-stream Isaacs method.

   Calculate $CIBR_{RT}(CW_{RT})$ using the instrument specific response functions $R_i(\nu)$:

$$CIBR_{RT}(CW_{RT}) = \frac{L_F}{w_1 L_E + w_2 L_G}, \quad \text{where} \quad \mathrm{L_i} = \frac{\int_{\nu(\mathrm{i})_\mathrm{a}}^{\nu(\mathrm{i})_\mathrm{b}} \mathrm{R}(\nu)\mathrm{L}(\nu)\mathrm{d}\nu}{\int_{\nu(\mathrm{i})_\mathrm{a}}^{\nu(\mathrm{i})_\mathrm{b}} \mathrm{R_i}(\nu)\mathrm{d}\nu}, \tag{8}$$

   where $L(\nu)$ is obtained from MODTRAN TAPE7.

2. Repeat 1 for 10 times to create a look-up table of equally spaced $[CW_{RT}, CIBR(CW_{RT})]$ from a minimum to a maximum value of CW_{RT}.

3. For each pixel calculate $CIBR_{data}$ ratio from sensor data using eq (8) where the measured radiances are used in L_F, L_E and L_G.

4. For each pixel interpolate $CIBR_{data}$ to determine the appropriate CW for that pixel from the look-up-table $[CW_{RT}, CIBR_{RT}(CW_{RT})]$.

The advantage of this method is that MODTRAN needs to be run only once and that we compute the $CIBR_{RT}$ using radiance data very similar to when sensor data is used.

4. APDA recipe

APDA is an enhanced CIBR (Schläpfer et al, (1998)). In contrast to CIBR, APDA corrects for path radiance in the absorption band by using MODTRAN4 determined path radiance as a function of water vapor column amount. Neglecting the path radiance in CIBR causes the retrieved water vapor amounts to be more than 10% in error at low reflectances which is not acceptable when the water vapor is used to atmospherically correct thermal data or enhance the robust water temperature retrieval, Borel et al, (1999). Theoretically we have shown that APDA's error is about 5%, Borel et al, (1996). Thus the method can be described by iterating between a two coupled equations, one based on a 3-channel ratio and the other on a function $f_{RT}()$ to convert the ratio into columnar water vapor:

$$APDA_{data} = \frac{L_{F,data} - L_{F,Path,RT}(CW_{data})}{w_1(L_{E,data} - L_{E,Path,RT}) + w_2(L_{G,data} - L_{G,Path,RT})} \quad \text{and} \quad \mathrm{CW_{data}} = \mathrm{f_{RT}}(\mathrm{APDA_{data}}) \qquad (9)$$

where $L_{F,Path}(CW_{data}) = c_0 + c_1 CW_{data} + c_2 CW_{data}^2$ is a second order polynomial fit to the values of $L_{F,Path}$ as a function of CW_{RT} calculated from MODTRAN4. $L_{E,Path}$ and $L_{G,Path}$ are assumed to be water vapor independent, due to their position outside the water vapor feature at 940nm. A similar relationship is derived for $APDA_{RT}$ using band averaged radiance values derived from MODTRAN4 run at a surface reflectance of 0.45 as a function of CW_{RT}. This $APDA_{RT}(CW_{RT})$ is interpolated so that a CW_{data} value is returned for each value of $APDA_{data}$.

To create an APDA determined CW_{data} image an iterative procedure is used:

1. Run MODTRAN4 for a value of CW_{RT}.
2. Compute L_i and $L_{i,Path}(\nu)$ by convolving the top of atmosphere radiance $L(\nu)$ and path radiance $L_{Path}(\nu)$ values with response functions $R_i(\nu)$ for $i = \{E, F, G\}$.
3. Repeat 1 and 2 to create $L_E(CW)$, $L_F(CW)$, $L_G(CW)$, $L_{E,Path}$, $L_{F,Path}(CW)$, and $L_{G,Path}$ for a set of spaced CW's.
4. Create a lookup table $[CW_{RT}, APDA_{RT}(CW_{RT})]$.
5. Create a quadratic fit to the look-up table $[CW_{RT}, L_{F,Path}(CW_{RT})]$.
6. Using eq (9) calculate $APDA_{data}$ for an initial value of CW_{data}, e.g. the neighbor pixel.
7. Find CW_{data} value from $f_{RT}(APDA_{RT}(CW_{data})$
8. Convergence is achieved when the previous estimated CW_{data} value is within 1×10^{-3} of the current value. Otherwise, iterate, so that the new CW_{data} becomes the previous estimated CW_{data} value.

Not many iterations are necessary to converge, typically three iterations, often faster if the adjacent pixel CW is used as an initial guess.

This automated implementation of APDA is not yet optimal. While it is possible for APDA to do much better than CIBR over dark pixels (like water), this requires a good knowledge of the aerosol type and the aerosol optical depth. For MTI we observe that a pixel on the boundary between water and land can be in error due to registration errors (Henderson et al, (1996)). If the aerosol parameters are well chosen (e.g. from an independent aerosol retrieval based on other MTI channels) the water appears to have the same amount of CW as the land (approximately, and using lake scenes).

5. Comparison of results

Since the filter functions and radiometric calibrations were improved several times during MTI's first year in orbit, the following results should be regarded as preliminary and not indicative of MTI's ultimate performance. In a separate paper in this conference results of four of the five water vapor algorithms are compared in detail (Hirsch et al, (2001)). In this section we will compare the transmission based CIBR to the radiance based CIBR and APDA for a scene where we had ground truth - Ivanpah Playa in Nevada for September 15, 2000. The results are shown in Figure 4. Notice that small spectral variations between SCA's and even within a SCA (e.g. middle) appear. We attribute these variations to pixel dependent interference effects in the filters.

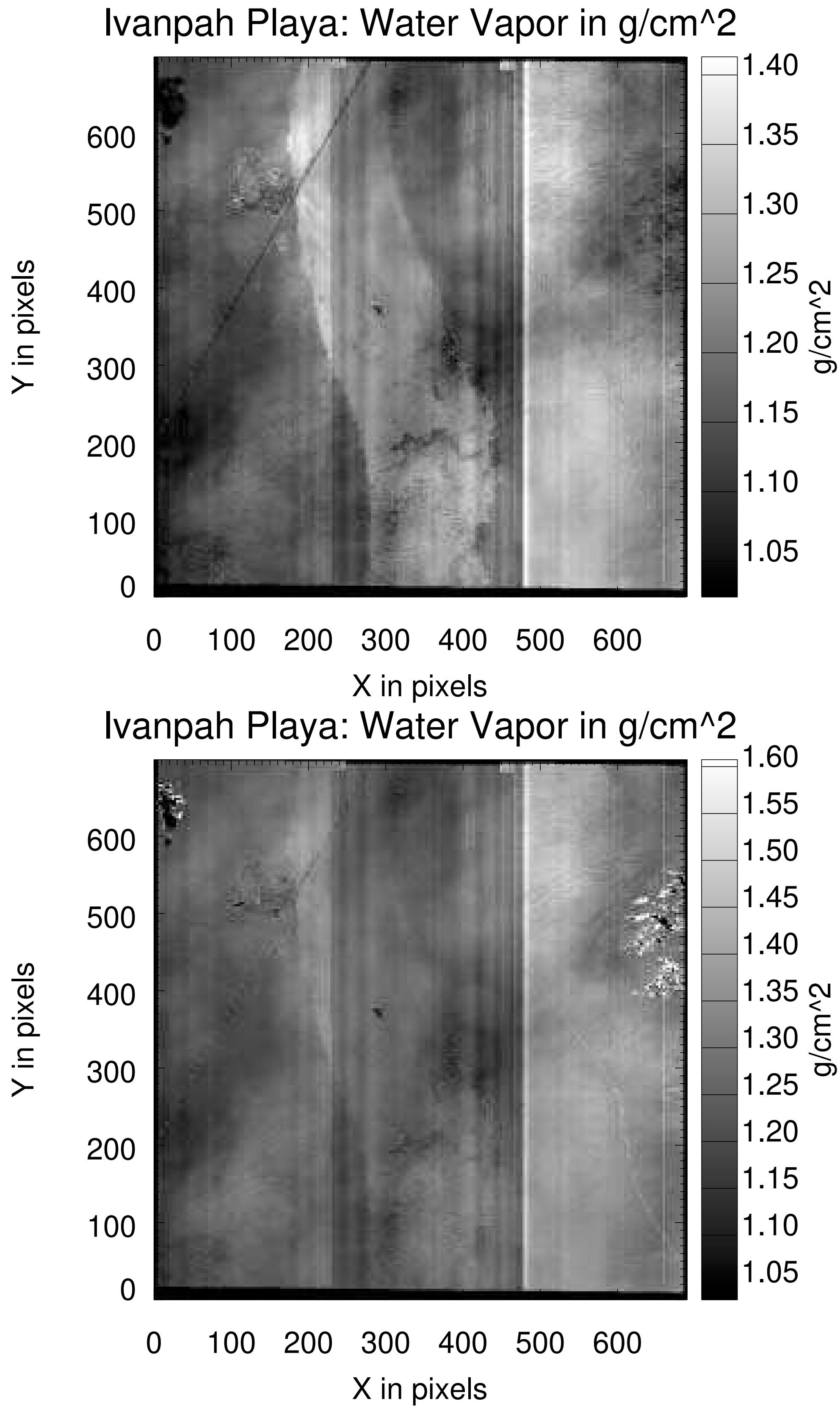

Figure 4. CIBR (top) and APDA (bottom) radiance based retrieved water vapor image for Ivanpah Playa. The measured water vapor amount was 1.35 g/cm^2. Notice that the boundary of the bright playa is less visible in the APDA retrieval.

6. Conclusions

For the MTI level2 pipeline codes, our goal was to create routines that were mostly automated, requiring little interaction from an analyst, yet robust and reliable enough to provide consistent, useful products for users who need them. We described the motivation for using these two methods, their implementation, validation and caveats. On off-nadir images, APDA sometimes fails to converge. The transmission based CIBR reports higher values than the radiance based algorithm but also seems to underestimate the water vapor for humid atmospheres as well as when compared to ground truth.

To our knowledge this is the first automated implementation of APDA. In practice neither of these methods achieves reliable automated results over dark targets, although, given better atmospheric information, APDA performs much better over dark targets.

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