RESEARCH AND DEVELOPMENT TOPIC

Reversing the Atmospheric Effect Mapped by the Atm-I Grayscale

Note

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Summary

- *Closed-Form Method for Atmospheric Correction (CMAC) is the algorithm in RESOLV™. This solution is based upon the mathematical structure of changes to light from atmospheric transmission.*
- *The CMAC conceptual model reverses atmospheric effect in images based upon an observed phenomenon readily apparent in extracted satellite reflectance statistics: atmospheric aerosol causes dark reflectance to increase and bright reflectance to decrease as a linear continuum between dark and bright.*
- *The well-known empirical line method was inverted and adjusted to represent the pinwheel effect as a line. Precedence exists in the remote sensing literature.*
- *The conceptual model was translated into a closed form solution to reverse atmospheric effect spatially mapped by the Atm-I grayscale to deliver surface reflectance from the top-of-atmosphere reflectance of each image.*
- *The CMAC workflow can be applied to smallsat image data upon download to reverse atmospheric effect within seconds through the closed form equation scaled by Atm-I, the atmospheric index.*

Introduction

CMAC development began with a unique discovery: the changes in cumulative distribution functions (CDFs) from top-of-atmosphere reflectance (TOAR) occur in a structured pattern when comparing clear and hazy images for an area of interest (AOI) across short time spans. Increasing haze causes reflectance CDFs to rotate counterclockwise, and for decreasing haze, rotate clockwise. We called this the “pinwheel effect” due to the rotation of the CDF from the changing atmospheric effects (Figure 1). Dark reflectance becomes brighter due to aerosol backscatter and bright reflectance is darkened due to attenuation from diffuse aerosol shading and absorption. The pinwheel effect forms a linear continuum from dark to bright reflectance in each band. Therefore, a point exists between bright and dark reflectance that does not change between uncorrected and corrected CDFs that we are calling the axis point.

The axis point was observed to migrate depending on the Atm-I level: Atm-I is the atmospheric index described in an earlier RESOLV Development topic paper. We discovered the reason the axis point migrates is due to forward scatter from aerosols that are backlit by brightly reflecting targets from forward scatter. The degree of pinwheel effect illumination varies according to target brightness; close to zero effect over darker targets, and with significant effect over brighter targets due to the greater reflected energy. There are important feedback mechanisms from forward scatter that are explored in a later RESOLV Development topic paper, notably how it affects calibration, the use of calibration targets, and how its identification and elimination may enable CMAC application for robust atmospheric correction over water.

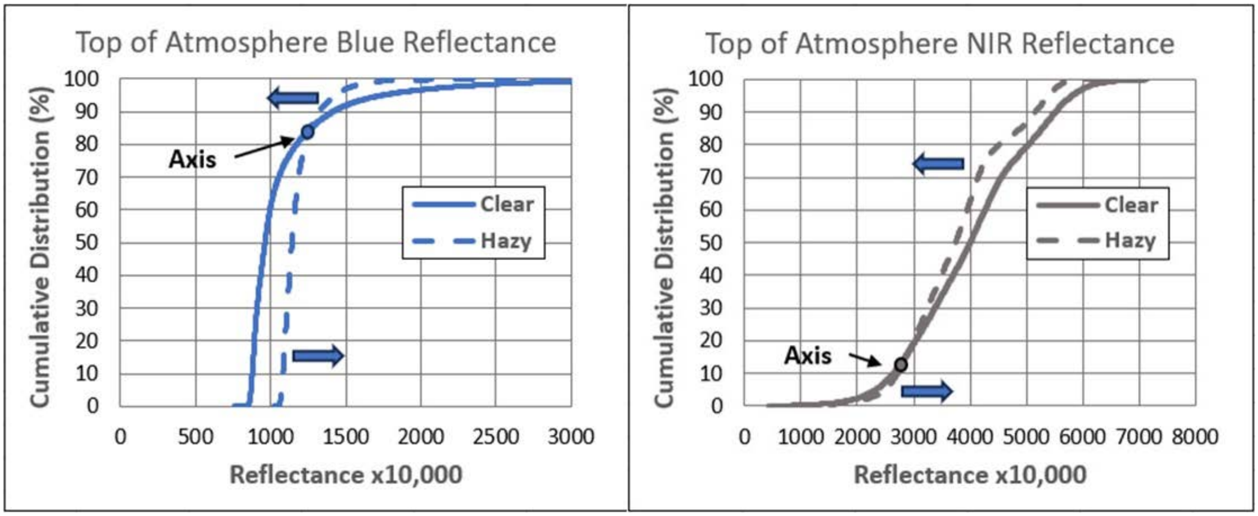


Figure 1 *TOAR CDFs of two Sentinel-2 spectral bands extracted from an AOI with consistent reflectance across both measurements, illustrating the pinwheel effect for the blue and NIR bands. Arrows show the direction of CDF rotation from increasing haze.*

The pinwheel effect was the starting concept in our quest for a new atmospheric correction method. Though it can be readily observed through extraction and display of CDFs, the effect is apparently not described in remote sensing literature. Because this underlying structure is the basis upon which surface reflectance can be accurately retrieved in near real-time, its importance cannot be overstated. How could such an important concept have been overlooked? Figure 1 provides a clue: the expression of rotation is masked in the visible bands because the axis point is barely apparent when found so far to the right in the reflectance distribution. The data for Figure 1 was extracted from a portion of a Sentinel-2 image of Sioux Falls, SD and even though the AOI contained highly reflectant roofs and concrete buildings, the pinwheel expression is hidden for the blue band wavelengths. The pinwheel effect occurs in all four VNIR bands and including the spectral region of the red edge transition and is only apparent when the band contains very high reflectance, or is of longer wavelength, e.g., NIR. Reversing this structure is the key to CMAC atmospheric correction that mathematically reverses the quantified atmospheric effect, scaled by the Atm-I model grayscale output.

As may be apparent through this series of RESOLV topic papers, accurate reversal of atmospheric effect requires analysis of reflectance distributions that can be conveniently expressed as CDFs, such as shown in Figure 1. Expression of reflectance data as distributions provides context for correcting all levels of reflectance, dark to bright, and is central concept for CMAC because a reflectance datum could be correct, but the data distribution could be incorrect, but not vice versa. Comparative distributions for the typical four bands of VNIR satellites are presented as Figure 2. Atmospheric aerosols enhance dark TOAR through backscatter and diminish the bright TOAR through attenuation. For the VNIR spectral window, these effects are greatest in the blue band and least in the NIR band, moving in progression from shorter to longer wavelengths.

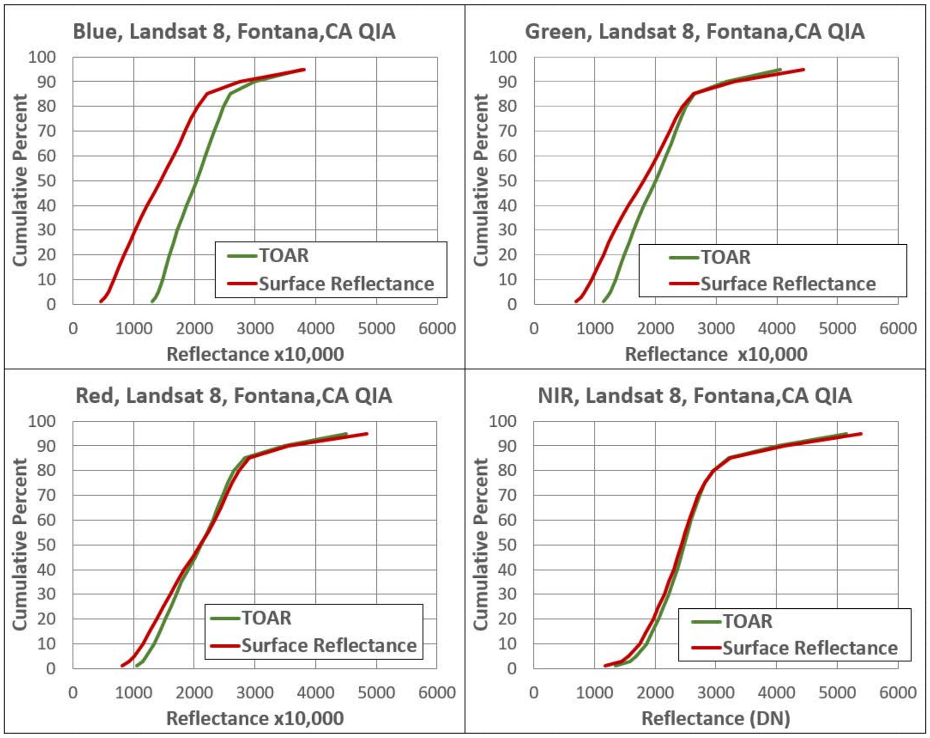


Figure 2 *Data from the four VNIR bands of Landsat 8 extracted from a July 9, 2022 (Atm-I = 919) image of a quasi-invariant AOI located in Fontana, CA. The data are expressed as cumulative distribution functions (CDFs). This image had moderately low Atm-I, 919.*

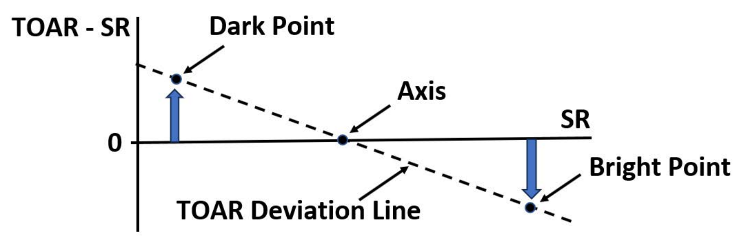
The Empirical Line Method (ELM) is recognized as the most accurate method for atmospheric correction, specifically because it is performed using groundtruth data gathered by spectrometer. ELM has limited application because the necessary groundtruth data are impossible to gather in sufficient time and space for the scale of satellite images; hence, ELM can only be applied within some area near the location of the groundtruth. The size of this area is variable because the atmosphere may or may not be highly diverse spatially at the time of image capture. Groundtruth spectra collected by field spectrometers are hyperspectral, so an intermediate step for comparison to the satellite data is to combine the hyperspectral data into the satellite's spectral bands guided by the published relative spectral responses (RSRs) for the bands. With that done, the ELM can calibrate the bandwise sensors of the satellite in the area of the groundtruth (Figure 3).

Figure 3 *Graphic representation of the ELM developed from paired dark and bright points configured to predict spectrometer-measured surface reflectance (SR) of dark and bright target panels from the satellite measured TOAR. The dashed line represents one overlying atmospheric effect upon any pixel, dark to bright, lying beneath. The slope and offset of the resulting line can be used to estimate bandwise surface reflectance for any nearby pixel. The ELM confirms that the pinwheel effect is linear when expressed as reflectance (CDFs are not linear but express the distribution of the the AOI reflectance).*

A key ELM concept is that any pixel affected by the same atmospheric effect, i.e., near where the ground truth is measured, can be corrected with the resulting linear equation. The limitation with ELM is that the groundtruth measurements are restricted to an immediate area, and certainly of no use for the large areas captured by satellite images because atmospheric effect is highly variable in space, time and wavelength.

The ELM was adapted for CMAC application by inverting the ELM axes and adjusting TOAR by subtracting surface reflectance. The resulting conceptual model captures the rotation due to the pinwheel effect: blue arrows indicate the rotational movement for increasing Atm-I that is expressed by the TOAR deviation line (Figure 4). A TOAR deviation line exists for each spectral band.

Figure 4 *The CMAC conceptual model captures the pinwheel effect. Blue arrows indicate rotation of the TOAR deviation line in response to increasing atmospheric effect (the reverse of CDF rotation). The dashed line represents all pixels, dark to bright, under one atmospheric effect.*



The TOAR deviation line of Figure 4 can be defined by a slope and an offset. The offset is the theoretical upward deviation from backscatter at zero reflectance – i.e., the effect only from the atmosphere. The TOAR deviation line can be fitted by simple linear regression from dark and bright points. Calibration of the sensor packages for a new satellite and repeated recalibration can be made over a target that provides measured surface reflectance of the dark and bright panels. CMAC calibration using a constructed target can be automated, rapid, precise and highly efficient, though special considerations are needed to overcome effects of forward scatter as discussed in the subsequent RESOLV Development topic paper.

A unique TOAR deviation line represents a single atmospheric state with all affected pixels of any surface reflectance lying on this line, dark to bright. To assess surface reflectance, CMAC mathematically transposes values lying on the TOAR deviation line back to their original reflectance on the x-axis, thus reversing the atmospheric effect and delivering an estimate of the surface reflectance for any pixel. TOAR measured for a pixel by the sensor is the atmospheric-transmission-altered input signal from the ground, while slope and offset are the inputs for the atmospheric effect that altered its surface reflectance. The CMAC equation is a simple closed-form mathematical expression translated from the conceptual model:

CMAC Equation: **SR = (TOAR - b) / (m + 1)**

where **m** is the slope and **b** the offset of the TOAR deviation line.

This closed form expression for the CMAC model is promotional in three ways. First, the equation is efficient, and accounts for less than one-third of CMAC processing time; the time otherwise is mostly required for Atm-I model calculations. The equation is simple, so any issues with inputs can be traced back to a root cause: such causes are restricted to potential issues with calibration or the sensors them-selves. Moreover, the equation mimics the natural phenomenon of the pinwheel effect and delivers excellent results in comparison to groundtruth and existing methods. On average, CMAC processing time to adjust each pixel individually on a desktop computer (64 GB RAM) is between one to one and a half minutes for the four VNIR bands of a full-sized Sentinel-2 image tile (~120 million pixels). For the restricted view of most smallsat images, the same process requires seconds.

The conceptual model developed from the pinwheel effect shown in Figure 4, is a useful aid to envision changes due to atmospheric effects and their correction. An example application is dark object subtraction (DOS) for atmospheric correction, in use for over three decades. With reference to Figure 4, imagine a target with quasi-zero reflectance but with some amount of atmospheric scatter. By subtracting that scatter, DOS will shift the TOAR deviation line downward so that the offset would be located at the origin (0, 0), thus causing the entire distribution to shift downward in Cartesian space, deviating below true surface reflectance. Therefore, DOS is not an appropriate atmospheric correction method.

Precedence exists in the literature for CMAC in a paper written by two of the most influential scientists who have worked in optics and remote sensing (Figure 5). This paper (377 citations) underscored that absorption is an important component of changes to reflectance from atmospheric transmission because points of these lines plot below the surface reflectance axis. These authors used the term “absorption” but we use “attenuation” because other factors influence the changes to bright reflectance, for example shading by the aerosol particles that cause backscatter and forward scatter.

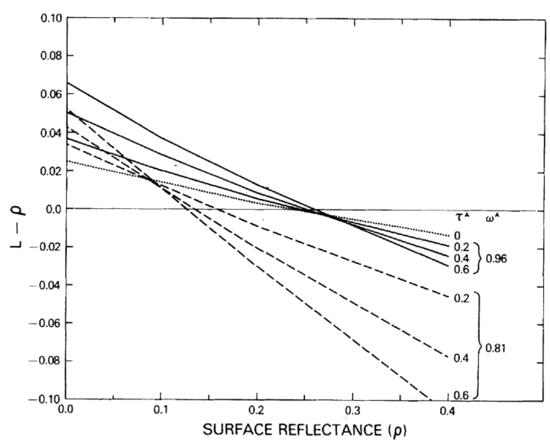


Figure 4 ***A figure from Fraser and Kaufmann, 1985.*** *Fraser, R.S.; Kaufman, Y.J. The relative importance of aerosol scattering and absorption in remote sensing. IEEE Trans. Geosci. Remote Sens.* ***1985****, GE-23, 625–633.*

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Summarization of the CMAC Workflow

Observation of the pinwheel effect began the quest for an alternative solution for atmospheric correction to measure and then reverse the atmospheric effect in TOAR images. The resulting research and development was funded by Phases I and II of the National Science Foundation's SBIR program. The pinwheel effect occurs in each band as determined by the wavelength of the band, the atmospheric aerosol content, and the intrinsic brightness of ground targets, all varying spatially. A combination of the conceptual model based on the pinwheel effect and the Atm-I model gave rise to the CMAC workflow. In a two-step process, CMAC first applies the Atm-I model to assess the spatially discrete atmospheric effects across the image. These effects are then reversed using the CMAC equation based on the pinwheel effect. The CMAC workflow contains only one other major step, calibration, that prepares any band of any optical sensor package to apply the software. Applied now only to the common four-band VNIR configuration. CMAC is appropriate for to any VNIR wavelength band including hyperspectral bands.

In summary, the spatial distribution of atmospheric effect is mapped by the Atm-I model in the CMAC workflow as a blue-band index. Expressed as a grayscale, the brightness serves as the scalar to reverse atmospheric effect to deliver spatial estimates of surface reflectance. The relationship between this scalar and the correction is a linear relationship derived from the initial observation of the pinwheel effect. In comparison to competing methods based on radiative transfer (RadTran), the blue band reflectance predicted by the Atm-I model provides a total, "lumped sum" indicator of atmospheric effect. This approach bypasses the individual focus on aerosol scatter, water vapor and ozone whose interactive effects are unknown. In comparison, CMAC's workflow represents a simplified "see it, correct it" approach. The simplification results in no loss of function but provides convenience, accuracy and reliability over a wider range of atmospheric effect than competing methods.

A quick comparison of RadTran methods and CMAC is instructive. CMAC is based on the structure of the changes to light transmitted through the atmosphere: this can be seen in the CMAC conceptual model and its equivalency with Figure 5. As stated in our topic papers and published journal papers, CMAC:

1. *Agrees with the two automated methods for atmospheric correction, Sen2Cor for Senti-nel-2 data and LaSRC for Landsat 8/9 data when the atmospheric effect is low.*

2. *Delivers accurate surface reflectance in high atmospheric effect where other methods fail.*

3. *Provides clear images free of haze without inducing artifacts where other methods fail.*

4. *Functions in near real time, not delayed by ancillary data.*

5. *Accurately corrects imagery from environments regardless of low spectral diversity.*

Figure 6 provides an analog for CMAC versus RadTran-based methods, such as LaSRC and Sen2Cor.

Figure 4 *While CMAC provides simple and robust mathematical calculations based on the atmospheric structure using a closed-form equation, RadTran methods apply iteration and lookup tables. An analogy of pegs/holes is appropriate: while CMAC provides rapid and certain solutions based on atmospheric structure, RadTran methods must try pegs for each hole to assess whether there is a fit. However, the "holes" are increasingly distorted as the atmospheric effect increases, thereby limiting RadTran solutions to TOAR imagery of relatively low atmospheric effect.*

ABOUT THE AUTHOR

Dr. David Groeneveld

Hello,

I'm Dr. David Groeneveld, founder and leader of RESOLV™. Our software atmospherically corrects smallsat data conveniently, accurately and reliably and does so in near real-time. The benefits of RESOLV™ go beyond its technical capabilities. Better accuracy helps researchers, scientists, and others make smarter choices to monitor and manage our planet.

Curious to learn more about RESOLV™, the science behind it and its potential for correcting smallsat images? Fill out this *short form* and I'll be in touch.

David G.