RESEARCH AND DEVELOPMENT TOPIC

Mapping Atmospheric Effect Grayscales with Scene Statistics

Note

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Summary

- *The Closed-Form Method for Atmospheric Correction (CMAC) algorithm is applied within the RESOLV™ commercial service. We refer to the algorithm here as CMAC as in our journal papers.*
- *The workflow for development of a unique, new atmospheric index, Atm-I, is described.*
- *The basis for Atm-I is an intrinsic property of healthy vegetation: stable blue surface reflectance.*
- *Atm-I development employed reflectance properties of plants approached through field measurements and statistical modeling.*
- *The Atm-I model produces a grayscale representation of the atmospheric effect recorded in top-of-atmosphere images. The brightness of this grayscale is used to spatially adjust mathematical reversal of atmospheric effect to retrieve surface reflectance from top-of-atmosphere reflectance (TOAR) differentially for each pixel across the image.*
- *Because the Atm-I model is derived entirely from scene statistics, CMAC processing to estimate surface reflectance can occur without delay upon image download from the satellite.*

Introduction

Virtually all smallsats have at least four bands: three visible bands (blue, green and red) and one near infrared band (NIR). This combination is commonly referred to as VNIR, though this abbreviation for visible and near infrared could be applied to any visible/near infrared band groupings. For example, include a yellow band, or a set of the “red edge” bands (as found in Sentinel-2), and an added NIR band and this could also be referred to as VNIR band combinations. Specifically, we will use the term VNIR here to refer to the basic suite of four spectral bands because they are standard on smallsats. These four bands can support a wide variety of applications including mapping an index of atmospheric effects across images and these bands are the initial focus for CMAC development and application. The term “atmospheric effect” is used as a general term for how light is changed through its interaction with Earth’s atmosphere.

Existing atmospheric correction software, for example LaSRC for correction of Landsat, apply ancillary data generated by another satellite, MODIS (Moderate Resolution Imaging Spectroradiometer). This requirement for ancillary data is a significant impediment for smallsat applications because MODIS data have coarse spatial resolution; ancillary data need to be processed before becoming available, thereby delaying processing the data of interest and may be obtained at a time differing by up to hours from the image capture by the smallsat. The third impediment, temporal mismatch, increases uncertainty, especially due to rapidly changing cirrus effects that cannot be measured by VNIR smallsats. From the outset, we strove to develop a method that applies scene statistics from the image, itself, that conveys a series of benefits: (1) removing uncertainty due to temporal mismatch; (2) providing higher resolution assessment of atmospheric effect; (3) enabling processing upon download; and (4) reducing uncertainty by applying the same data to estimate, then reverse, the atmospheric effect individually for each pixel.

At the start of CMAC R&D, we evaluated online spectral libraries and decided to apply the visible portion of plant reflectance spectra for atmospheric correction. The low visible band reflectance of plants was an obvious basis for estimation of the degrading effects upon reflectance from the atmosphere. Our research and development effort disclosed that blue reflectance was sufficiently stable to support estimation of atmospheric effects as a residual. We also knew that development of an atmospheric index model based upon scene statistics would be a game changer for smallsats because ancillary data would no longer be needed.

The completed CMAC workflow has three parts: (1) new sensor calibration customizing the CMAC algorithm for sensor responses in orbit, rendering it applicable to all subsequent images; then for each image to be corrected, (2) mapping the atmospheric effect from the top-of-atmosphere reflectance (TOAR) observed by the sensor as a grayscale; and finally (3) guided by the grayscale, reversing the effect for each individual pixel across the image. Once a smallsat is calibrated, CMAC works from then on for all environments, but is subject to periodic recalibration to accommodate episodic sensor degradation known to occur in orbit. In this paper, we describe how an index from scene statistics is generated, and how it can be used as a scalar for sensitive reversal of the atmospheric effect spatially across the image.

A convenient and easily understood term for atmospheric effect is "haze ." We see haze in imagery as brightening, muddling, and shifting the color balance toward blue. CMAC principally corrects the effects of aerosols that are atmospherically suspended particles such as dust, smoke, salt, pollen, etc., also including water droplets and ice crystals. CMAC corrects each of these effects. Atmospheric effect within CMAC is determined as a lump sum, and this simplifies atmospheric correction by ignoring the potential individual contributions from aerosols or gases. Trying to account for these and other effects separately is likely a wasted effort in most applications because their interactive effects are unknown. Judging from statistical analysis of CMAC output versus far more complex radiative transfer-based applications that do try to account for these separate influences, CMAC's simplification provides accuracy, utility and reliability.

Analysis and Methods

Atmospheric effect is measured in CMAC as an index value assessed by a model that applies spatially discrete statistics of VNIR bands. The index is based on the blue reflectance of continuous canopies of healthy vegetation. Figure 1 shows a spectrum for lawn grass and the spectrometer setup that measured it. Both the Landsat and the S2 programs use vegetation for assessing atmospheric effect, calling it dense dark vegetation (DDV). Another appropriate descriptor could be "continuous healthy and active plant canopies." The spectrometer setup as shown in Figure 1b was used to measure the surface reflectance of a number of crops and types of continuous plant cover, all from relatively short statured canopies.

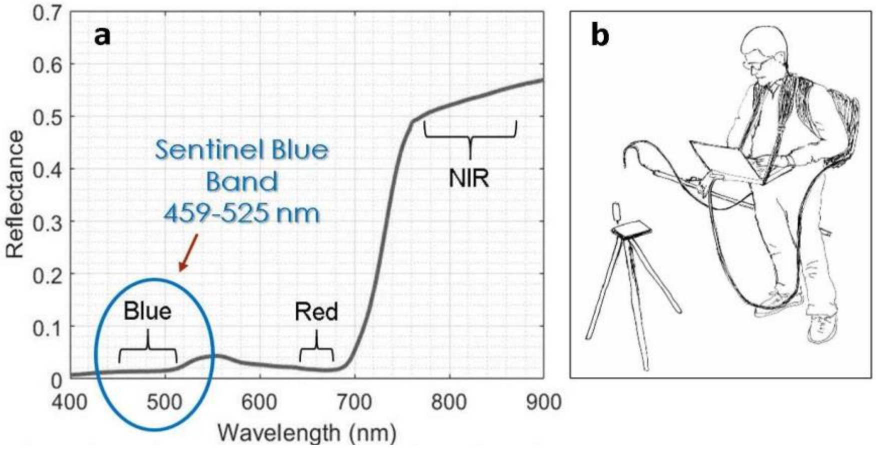


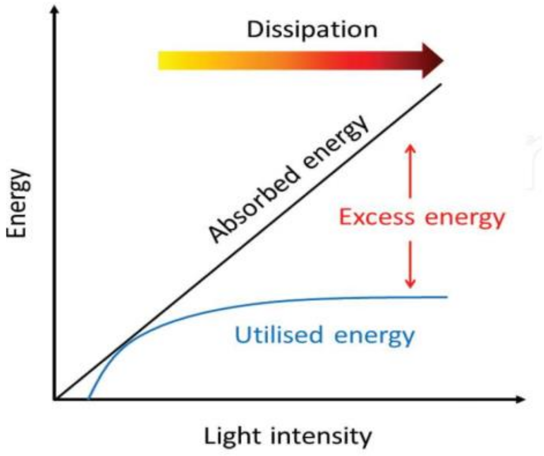
Figure 1 .Reflectance of lawn grass (a) obtained by field spectrometer (b). The spectrum shows the position of three bands of Sentinel-2 (green is the small hump between blue and red). 700 nm is the approximate upper limit of visible light. Sentinel-2 data were the testbed for initial CMAC development.

In Figure 1, the extremely low reflectance of the visible bands is notable: it can easily be seen why healthy and continuous vegetation canopies are described as dark. The blue and red bands are employed in photosynthesis to supply the energy to split water molecules that are then combined with carbon dioxide to form sugars. The cascade of carbohydrates, starting with photosynthetic sugar, forms the building blocks for plant tissue and the basis for global biodiversity.

To generate the statistical model to assess atmospheric effect, we chose the Sentinel-2 blue band 2, as our indicator rather than blue band 1 that we observed saturates at relatively low levels of atmospheric effect. Spectrometer measurements disclosed remarkably consistent blue reflectance of plants growing under the open sky. To answer why, we turned to the plant physiology literature. Near complete light absorption in blue and red bands for photosynthesis optimizes for conditions that include cloudy days or partial shade. Photosynthesis saturates on clear sunny days at a fraction of the absorbed solar radiation and the excess light energy could damage the leaf tissue were it not dissipated (Figure 2). This presents an existential dilemma. When of short stature and shaded by surrounding plants, a seedling or sapling needs to freely absorb all available sunlight, thus, protective reflectant coatings would be maladaptive. Therefore, another more common but intrinsic physiologic method must be in play.

Figure 2 *Nearly all sunlight is absorbed on bright sunny days. Photosynthesis saturates during peak insolation of clear sunny days leaving a large excess of the absorbed energy that could potentially damage the plant. This excess energy must be dissipated.*

[Figure from Guidi L, Tattini M, and Landi M. 2017. How does chloroplast protect chlorophyll against excessive light? Intech Open Science. 21-36]



The mechanism to deal with the photosynthesis dilemma is for plants to shunt away the excess solar energy using beta carotene pigments that absorb the energy and dissipate it as heat. The energy of light is inversely proportional to its wavelength, and the position for energy absorbance by beta carotene covers a large portion of the excess blue light energy, as shown in Figure 3 *(below)*. Plant canopies are well coupled with the atmosphere, so the process of heat dissipation is highly efficient. In addition, photosynthesizing plants transpire water that absorbs large amounts of heat when evaporated from internal structures in the leaf.

Figure 3 *Comparison of excess energy (Es) and beta-carotene absorbance (from Kume, 2017). The spectral win-dow for the Sentinel-2 blue band 2 was added by the author.*

[Original figure from Kume, A. 2017. Importance of the green color, absorption gradient, and spectral absorption of chloroplasts for the radiative energy balance of leaves. Journal of Plant Research. 130:501-514]

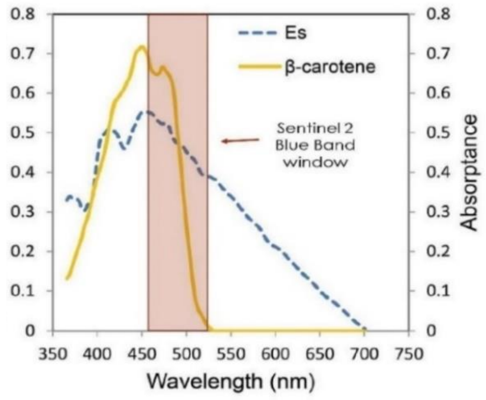


Figure 3 shows that while the Sentinel-2 blue band 2 is not perfectly positioned to capture the beta carotene response, its spectral position represents an optimization between sufficient sensitivity and the ability to record the range of backscattered light without saturating. The reflected blue light of DDV is a low and stable residual and, accordingly, is consistent because it is actively controlled by plants to be the residual light that was not absorbed. Ubiquitous to high light plant canopies, such reflectance control is likely a very early evolutionary adaptation that enabled terrestrial plants to flourish, perhaps earlier than 470 million years ago. Its existence set the stage for the later Carboniferous Era resulting in coal and oil deposits exploited for energy contributing to climate change that now enhances wildfires and smoke challenging atmospheric correction of satellite images today.

The potential to use DDV as a stable surface reflectance yardstick for assessing atmospheric effect was tested early in our R&D process using locations dominated by such vegetation; for example the rain forest in the Amazon Basin (Figure 4). A grid of multiple pixels was used to assess the variable degree of the atmospheric effect across the image in non-overlapping gridcells. The potentially confounding effects from water were removed by imposing an NIR threshold to eliminate any pixel not dominated by DDV. This early testing confirmed that the lowest non-water blue reflectance, alone, could be a sufficiently sensitive indicator of atmospheric effect. This result was expected simply because we could trust that the lowest non-water blue reflectance was a stable yardstick for estimation of the atmospheric effect.

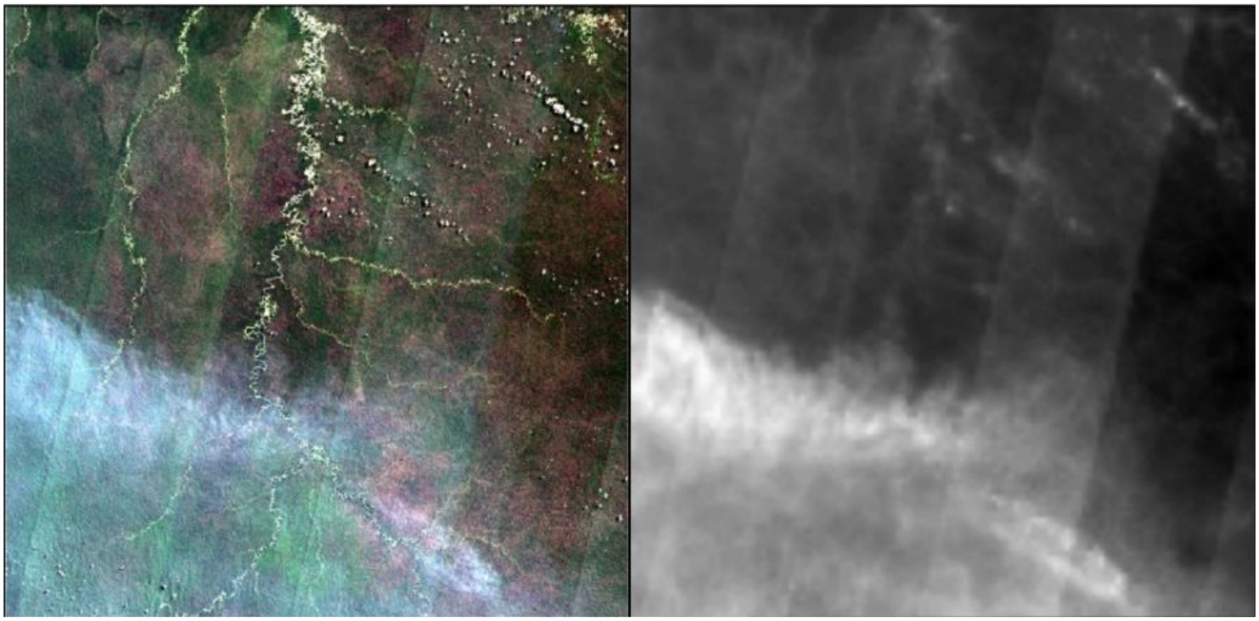


Figure 4 *A Sentinel-2 image of the Amazon basin was used to confirm a blue band reflectance index to assess atmospheric effect based upon plant reflectance. This demonstrated a grayscale that was more sensitive than the eye can perceive judging from the TOAR image. This image contained detector striping that was also corrected after application of the CMAC equation described in another RESOLV Development topic paper.*

The way this simple approach for mapping atmospheric effect was structured meant that DDV would need to be present in every gridcell across the image, thus posing an obvious problem for environments where DDV is not present. This impediment was bypassed through assembly of a model using VNIR band statistics as input. The first step in model assembly was to select a vegetation type to serve as a surrogate surface reflectance reference to be predicted by bandwise spectral statistics. An average reflectance spectrum of alfalfa generated as in Figure 1, was chosen to serve as the surrogate groundtruth. Alfalfa is a cultivated crop that reaches maximal canopy expression under a wide range of conditions, whether through irrigation in low plant-cover arid climates or watered by rainfall in humid climates. For modeling atmospheric effect, a range of environmental conditions for alfalfa culture sup-ported sampling many types of adjacent plant cover across the potential range of from barren desert to continuous healthy canopies.

Alfalfa is often grown in groups of multiple fields to supply nearby dairies and livestock feeding operations. Normalized index vegetation index (NDVI) is commonly used for agricultural applications and the highest-NDVI alfalfa fields in such groups were assumed to have the known spectral statistics of verdant sampled plots, so were used as a surrogate ground truth to estimate blue band surface reflectance. This approach was made with the assumption that such alfalfa fields would exhibit the stable surface reflectance found during field work. Peak NDVI alfalfa fields were identified on numerous mid-summer images under clear to hazy conditions across a range of arid to humid climates; these cultivated fields were selected for treatment as index plots after measurements to assure that they represented maximal NDVI within groupings of multiple fields. Adjacent plots were identified as subsamples in ranges of cover from none to continuous canopies of whatever vegetation was present, not necessarily alfalfa, nor cultivated. The spectral band values of the index plots and their subsamples were extracted, pooled and modeled for prediction of the assumed blue band values of the index samples.

The resulting model was tested and found to be accurate, so was applied as a scalar to predict blue-band DDV response, thus constituting an index of atmospheric effect for the surrogate surface reflectance of alfalfa plus the backscatter from atmospheric aerosol. This index, “Atm-I,” was found to work for all environments whether vegetation was present or not, including water bodies as described in another RESOLV Development topic paper dealing with the phenomenon of forward scatter. Atm-I is estimated by the statistical model from extracted TOAR spectral data by applying the same sampling method from the image test of Figure 4: non-overlapping sampling gridcells arrayed across the image. The resulting workflow outputs spatially discrete Atm-I values representing the lumped-sum atmospheric effect as a grayscale. The brightness of this grayscale is the driving variable for atmospheric correction, scaling the degree of correction necessary to reverse the lumped-sum atmospheric effect to retrieve surface reflectance from TOAR. In this TOAR-to-surface-reflectance reversal, two parameters described in a subsequent RESOLV Development topic paper, are calibrated to Atm-I for each sensor of each satellite.

Results

Figure 5 shows a Sentinel-2 image, its correction and its Atm-I grayscale. The image views also contain portions of extreme Atm-I where insufficient ground signal precludes atmospheric correction, and a comparison of the Atm-I results with the MODIS ancillary data (aerosol optical thickness) used for LaSRC. While images such as in Figure 5c can be cleared of haze with the results much closer to true surface reflectance than TOAR, such extreme effects may not provide accuracy sufficient for some uses above a certain level of Atm-I, as was found for precision agriculture applications of NDVI and described in the RESOLV Applications topic paper dealing with NDVI. The Atm-I in the well-defined smoke plume of Figure 5c exceeded 2500. For the uncorrected portions of the smoke plume in Figure 5c, the Atm-I was much higher than can be corrected because no ground signal remained.

A preliminary scale provides estimates of CMAC utility relative to Atm-I in Figure 6. Radiative transfer can retrieve surface reflectance for a more restricted range than CMAC. For example, examination of atmospherically corrected values in the NDVI Application topic paper found that Sen2Cor was inaccurate above an Atm-I of about 1060 while CMAC NDVI was accurate to above 1240 (Atm-I > 1255 were removed). This preliminary scale is conservative since most of the high Atm-I images excluded from that study were compromised due to nearby clouds. The limit also depends upon the application. For example in the RESOLV Verification topic paper examining atmospheric correction of Landsat 8 and 9, the accuracy of three normalized difference indices from atmospherically corrected data was maintained by CMAC at a much higher level of Atm-I (1428) compared to LaSRC that contained from 3x to 9x of CMAC error at Atm-I = 1002.

Clearing haze from images is a by-product of surface reflectance conversion. We've applied the Atm-I model to map grayscales for hundreds of images and multiple sensors and have confirmed haze was correctly removed from the images. Accuracy of the surface reflectance estimates has also been corroborated in two journal papers examining CMAC correction through extensive statistical analyses for Sentinel-2 and Landsat 8 and 9 (summarized in RESOLV two Verification topic papers). The CMAC work-flow has proven correct, and therefore by extension, the Atm-I model must also be correct. In the CMAC workflow, there is abundant confirmation that Atm-I correctly portrays the atmospheric effect in images for Sentinel-2 and when migrated to new satellite sensors, this includes smallsats through a series of adjustments. Figure 7 is an example of visible haze, its portrayal in an Atm-I grayscale, and Sen2Cor and CMAC corrections.

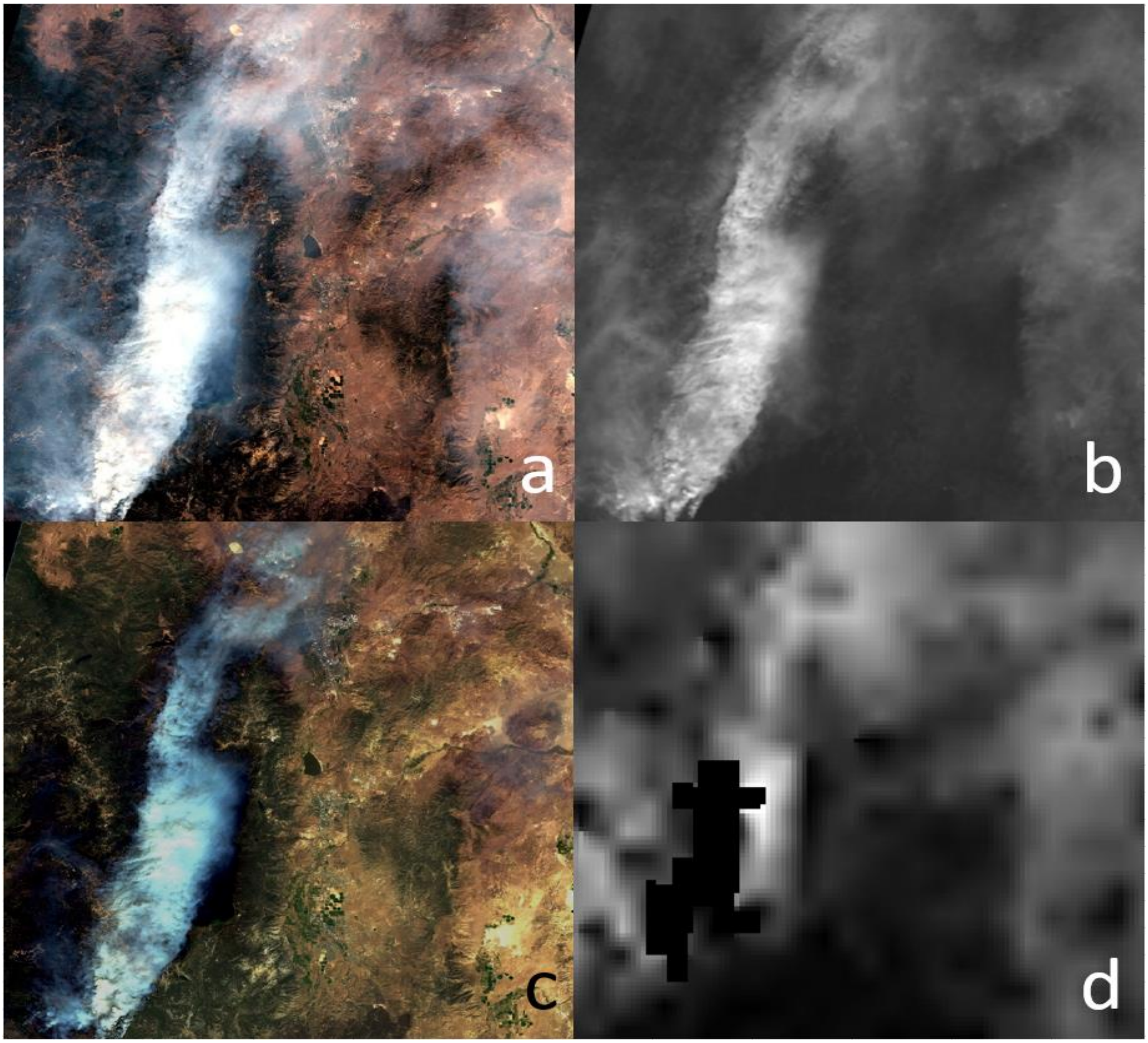


Figure 5 *Sentinel-2 full tile (T11SKD_20210824) over Lake Tahoe, California and Nevada: (a) TOAR; (b) Atm-I grayscale (0.1 km2 spatial resolution); and (c) the resulting CMAC correction from it. The yellow-red color shift in (a) and (c) result from selective spectral effect that will be the subject of a future paper. Image (d) is the MODIS AOT ancil-lary data (1.0 km2 spatial resolution) for LaSRC processing on the same day with black pixels indicating no data.*

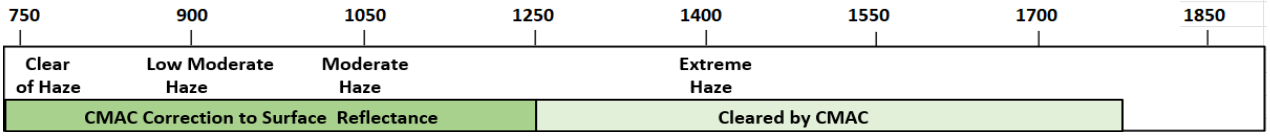


Figure 6 *A rough quantitative scale for Atm-I corrections based upon observation of repeated correction of images and noting the results. Note that the cutoff for surface reflectance corrections may vary.*

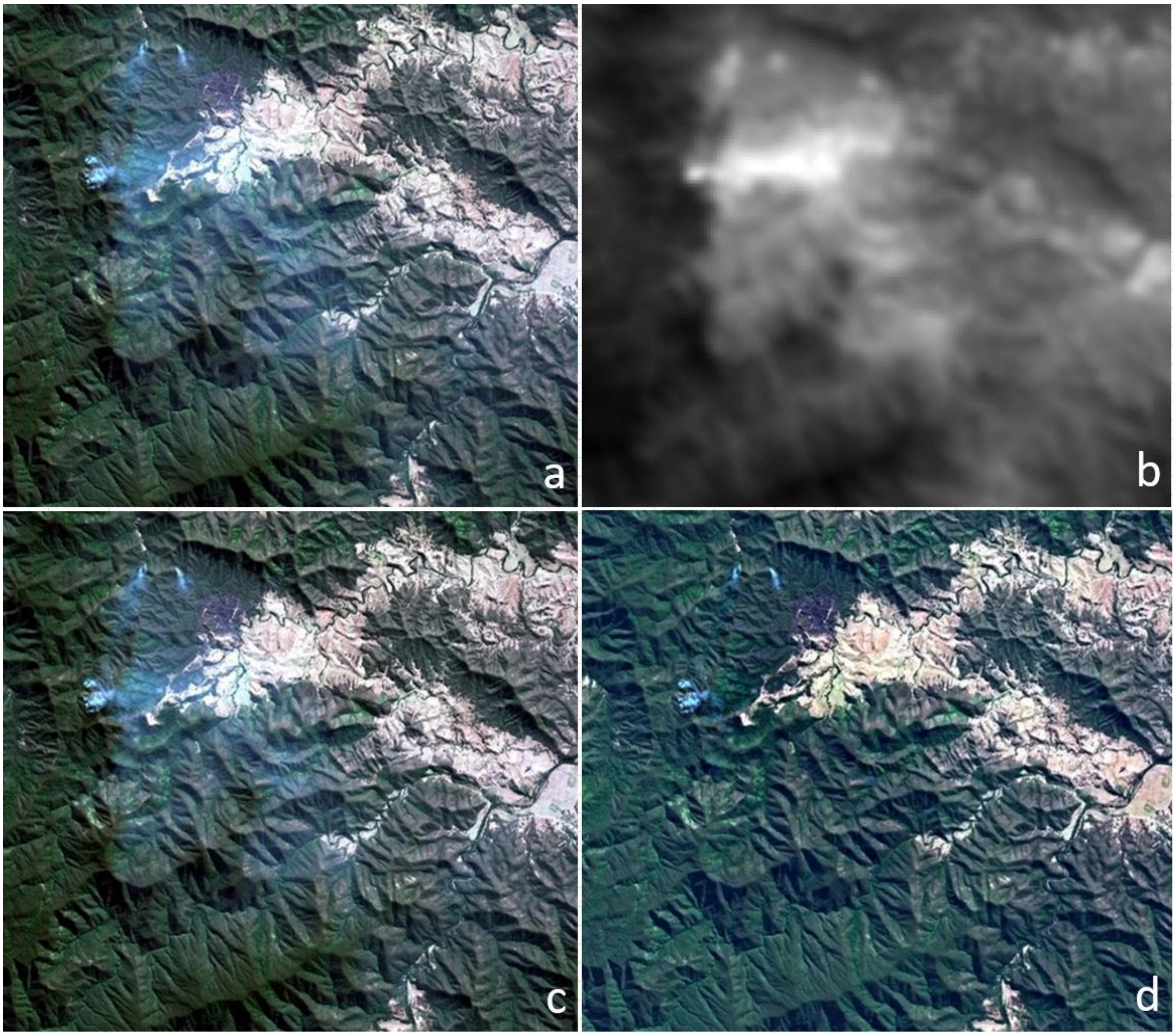


Figure 7 *Sentinel-2 (T56JML_08/04/2019) screenshot of a wildfire in Australia: (a) TOAR, (b) Atm-I, (c) Sen2Cor, and (d) CMAC. The Atm-I view (b) illustrates both the effect from the smoke aerosol and forward scatter from highly reflectant exposed rock that backlights and accentuates the haze of the aerosol particles. Sen2Cor is presented for comparison of CMAC to the state of the art in atmospheric correction.*

Next Generation Atm-I Model Improvement

As can be seen from statistical testing of the CMAC workflow, output for very different satellite platforms is more accurate over a greater degree of atmospheric effect than the software that was designed specifically for those data (e.g., Sen2Cor for Sentinel 2 and LaSRC for Landsat 8/9). By reference, CMAC's constituent Atm-I model is also working more accurately than other methods. Since the Atm-I model was generated using assumed values, the model is undergoing further refinements using real, not assumed groundtruth through a program that applies extensive surface reflectance groundtruth. Acquiring surface reflectance groundtruth at the correct scale is the major challenge for developing accurate surface reflectance correction but can be solved through methods pioneered by our team.

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.

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