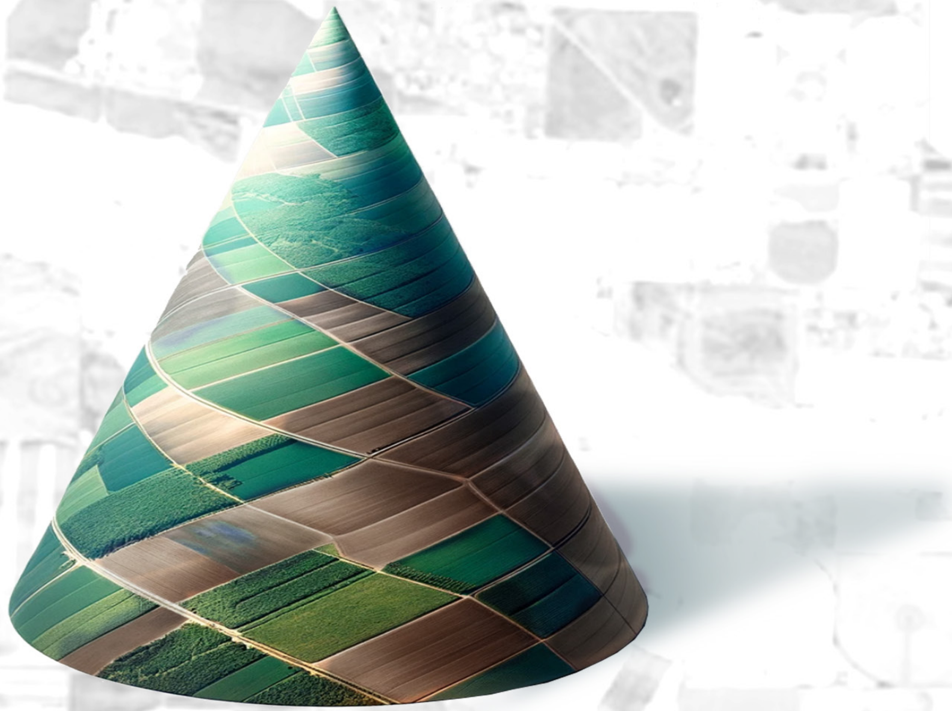
RESOLV



APPLICATION

Tools for Assessing Atmospheric Correction Quality

Note

CMAC is patented technology developed by Advanced Remote Sensing, Inc., commercialized as RESOLV™

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Summary

- » *CMAC technology is applied in RESOLV as a SaaS (software as a service) provided on annual subscription to the smallsat company for unlimited use per satellite, each smallsat to be meticulously calibrated. We use the name "CMAC" here for continuity with our other technical papers.*

- » *CMAC was invented specifically to work with smallsats and provide processing immediately upon image download for any band or band combination. CMAC is verified to be accurate and reliable.*

- » *Two applications are described: (1) a standard Atm-I grayscale raster that accompanies corrected images can be applied as a quality raster to eliminate data unsuitable for the intended application – especially needed by precision ag application over thousands of square miles; and (2) A GIS-based application for rapid evaluation of atmospheric correction quality through visual inspection.*

- » *Please read our other RESOLV topic papers for further background.*

Introduction

CMAC was developed for smallsats in a two-part process that first maps the atmospheric effect in each image and then reverses it to deliver surface reflectance. Through our work developing CMAC, we have learned useful methods and applications. Two robust and simple applications are described here:

1. CMAC Atm-I grayscale estimation of atmospheric effect can be used to eliminate clouds and levels of haze that may cause the output to be insufficiently accurate for the application. CMAC has been verified to correct images with the highest levels of haze and will salvage more useful images. However, the Atm-I grayscale allows user-defined classification of thresholds for automatic removal of unsuitable data, wherever it exists on the image. This application is based upon the direct relationship of Atm-I level to image correctability and the reliability for the surface reflectance estimates.

2. When an image contains some minimum count of 'nodata' fill (i.e., zero reflectance pixels), QGIS scales the display that can be standardized by zero-value pixels. Standardization permits comparison with imagery treated in like manner. Starting the scale at zero causes any unresolved atmospheric correction to become visible as haze in the image. Many images come with sufficient black pixels that fill corners or missing slices and these suffice for the desired display. However, if there are insufficient black pixels, they can be added for the same effect by a downloadable widget we developed that prepares Sentinel-2 images for display in QGIS and is adaptable for other satellites. This application overcomes the fact that zero reflectance is theoretically impossible in daytime imagery.

Atm-I Output Applied as a Quality Raster

Atm-I is the atmospheric index mapped by CMAC in the first of two steps for surface reflectance conversion. An Atm-I statistical model cues on the top-of-atmosphere reflectance (TOAR) using an image's spectral-band responses to assess the degree of atmospheric effect. Atm-I is a lump-sum index for the collective effect upon blue-band TOAR reflectance as described in the first RESOLV Development topic paper. Atm-I is assessed spatially across the image, resulting in a grayscale whose brightness then scales the potential reversal of the atmospheric effect for the digital data over thousands of square kilometers.

The Atm-I grayscale output from CMAC processing is provided as a separate raster to aid interpretation of the corrected image. This grayscale is useful for eliminating areas of the image from consideration where the level of atmospheric effect, whether cloud or extreme haze, prevents sufficient accuracy for reliable interpretation. The grayscale can be used to both identify and remove data of unacceptable quality. A strongly promotional consideration for grayscale application is that smallsats have sufficient resolution to permit identifying clouds that are vexingly small (down to ~100-m diameter).

As a tool, the Atm-I raster is a potential game changer, particularly for application to precision agriculture and intelligence gathering because it can provide interpretations and allow evaluation of their reliability immediately upon data download from the satellite with no delay. For example, precision agriculture requires data updates at least every week to assure early detection of crop problems to be solved before potential yield loss. However, precision agriculture imagery for much of American farmland has been problematic due to clouds and smoke from distant wildfires that have severely limited growing season applications.

Figure 1 illustrates the problem before and after CMAC correction where very little of the scene contains data appropriate for analysis; however, such scenes may be all that are available for a month at a time, so reliable data as scattered bits and pieces may be particularly valuable. The Atm-I raster can be classified so that the reliable data can be put to use wherever it happens to coincide with fields of interest. Two versions of the grayscale are shown in Figure 1, both with minimal filtering (3x3 median filter), where the granularity from the Atm-I model calculations is visible but more sensitively portrays the fine details that are removed in the second grayscale through an additional Gaussian smoothing step. Although Figure 1 grayscales are displayed in few brightness steps, these Landsat 8 data are output as 16-bit (65,536 separate steps), offering Atm-I classification and application in finer mathematical detail.

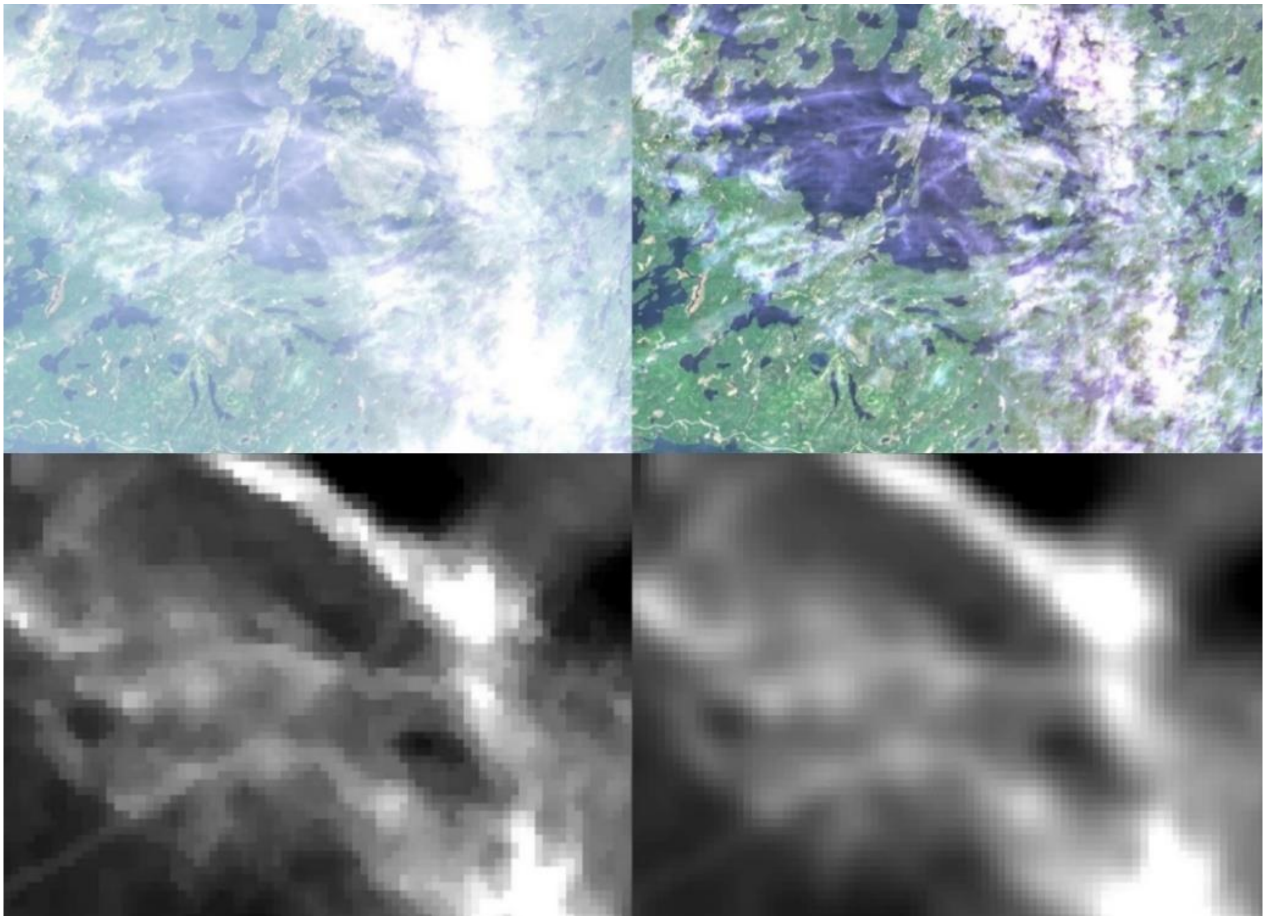

Figure 1 *Part of a Landsat 8 image acquired June 15, 2023, of Canada near Dryden, ON (P028R026) that shows views of the TOAR, CMAC correction and two versions of the Atm-I output. Much finer detail through application of the higher resolution data of smallsats will enhance the spatial granularity 100x compared to Landsat 8/9 (evaluated arealy).*

Precision agriculture applications of imagery must be automated for delivery at a price point that attracts and maintains farmers while making no missteps (e.g., growing field + small cloud = farmer mistrust). The Atm-I grayscale provides a robust automated solution to identify where data are application-appropriate in corrected imagery. Atm-I is a single raster whose brightness can be calibrated directly to the quality of the surface reflectance estimates using thresholds to separate reliable from unreliable data. An example of an Atm-I threshold was applied to four analyses of NDVI described in the initial RESOLV Application topic paper: images that precluded accurate application were removed using an Atm-I threshold.

Atm-I grayscales simplify data proofing for precision ag application by flipping the problem to one of identifying only the data that are of potential quality, rather than mapping/removing clouds. Cloud re-oval is a notoriously difficult operation: the spectral information used to identify a "cloud" can change based upon imaging and much of that information cannot be collected through for 4-band VNIR smallsat data, alone. Atm-I scaling allows the use of a simple threshold value to map the applicable data.

Two grayscales are provided with Figure 1 to make an additional point. Extremely bright targets in the Atm-I grayscale are virtually always clouds. Bright clouds enhance the reflectance in the region surrounding a cloud from light scattered off of the cloud that can extend laterally to over 5 km distance. As mentioned above, the "fuzzier" appearing of the two grayscales has had additional Gaussian smoothing applied that can be engineered to smear cloud areas sufficiently so the adjacent areas can also be identified and eliminated using a threshold, even if their Atm-I level would have included them. A threshold for gray-scale brightness can be used as input for application of GIS tools to buffer outward a set distance from the bright features to affect the same result. Note that the "fuzzier" Atm-I representation is more desirable if the image is being prepared solely for viewing, as otherwise, borders between areas of highly contrasting reflectance will tend to appear castellated due to bright/dark pixelation.

GIS-Applied Display Tool for Rapidly Proofing Atmospheric Correction Quality

Repeated correction and examination of many images has taught that GIS image display provides rapid feedback as to the quality of the conversion from TOAR to surface reflectance. Image appearance on GIS display is a qualitative means to assess whether atmospheric correction is actually correct. Another lesson is that how the image brightness is mapped by the GIS largely determines that visual interpretation. Our image interpretations are made using the open-source QGIS software for image display. We avoid adjusting such image mapping for small areas of images, instead, preferring mappings based on the entire tile.

Changing image appearance relative to dark and bright ends of the reflectance distribution is often called stretching; it is not the same as the "stretching" that adjusts the size of an image, a more general application. Atmospheric correction, in essence, is a form of reflectance stretching in each spectral band; however, the results correct the underlying digital representation of the bands, not just their display. How a consistent area of interest changes from surface reflectance to various TOAR distributions at increasing levels of Atm-I is illustrated in Figure 2. Note how the TOAR increases for low (dark) reflectance and decreases for bright reflectance. This observation is the "pinwheel effect" noted in other topic papers that motivated investigation and development of CMAC.

Four of the 2021 images whose blue reflectance curves are displayed in Figure 2 are reproduced as QGIS screenshots in Figures 3 through 5. Sen2Cor results for Sentinel-2 are added for comparison.

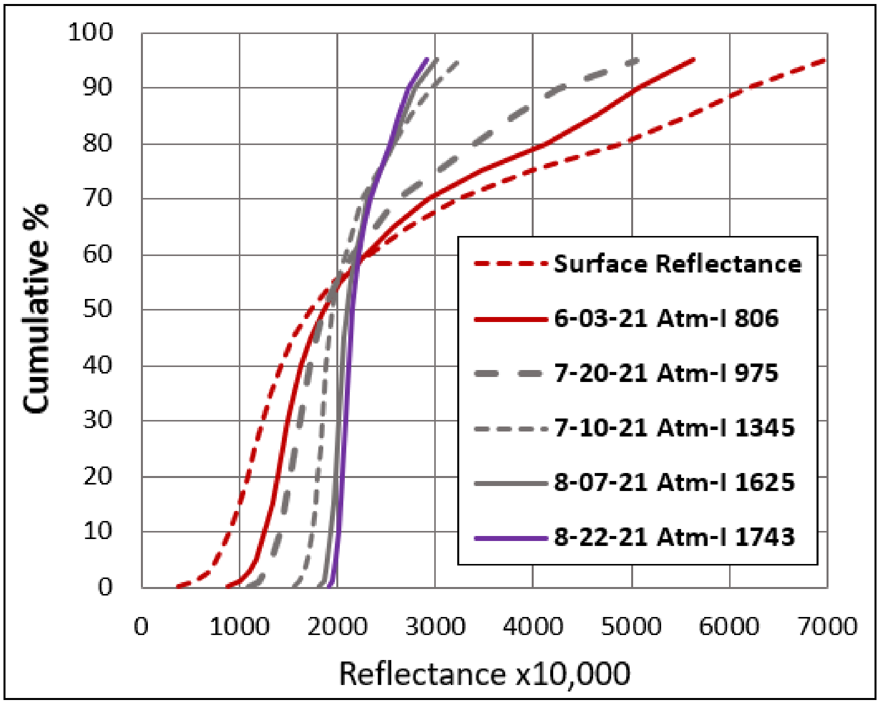

Figure 2 *Sentinel-2 blue band surface reflectance and five TOAR curves were generated from the image data acquired over a quasi-invariant area (QIA) in Reno, Nevada. The median Atm-I for each image is given. Surface reflectance was estimated using CMAC for the lowest Atm-I image (6-03-2021). The data shown here were extracted from the Reno outline shown on Figure 3. QIAs are areas whose reflectance remains consistent through periods of measurement.*

The challenge for atmospheric correction is to stretch the TOAR images back to surface reflectance (dashed red). This becomes increasingly more difficult as Atm-I increases.

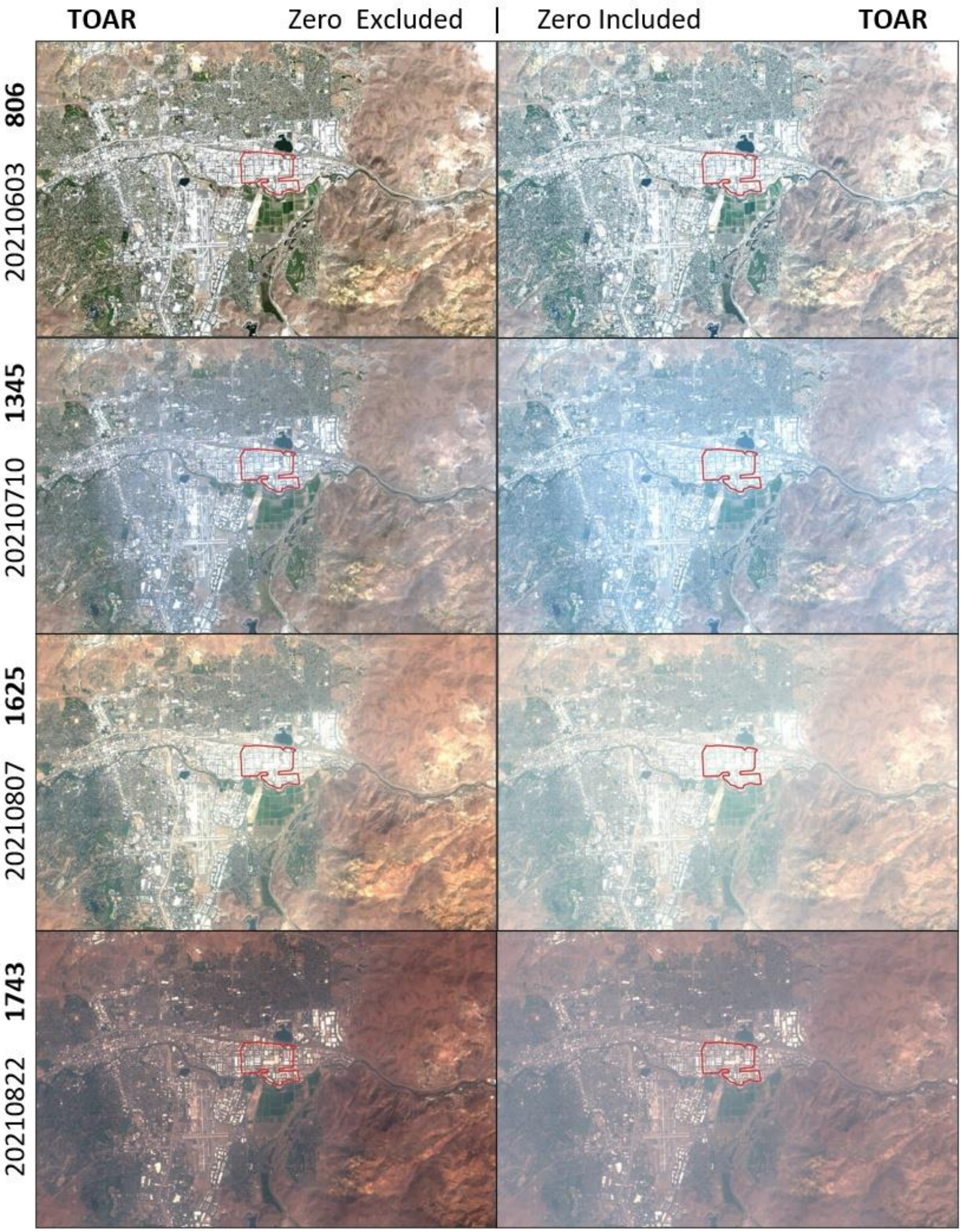

Figure 3 *Four Sentinel-2 TOAR images under increasing Atm-I from top to bottom (listed on the left margin with the date). Those on the left are not zeroed while those on the right have had zero values added as a black border. Zeroing standardizes GIS display to reveal the truer magnitude of the atmospheric effect as haze.*

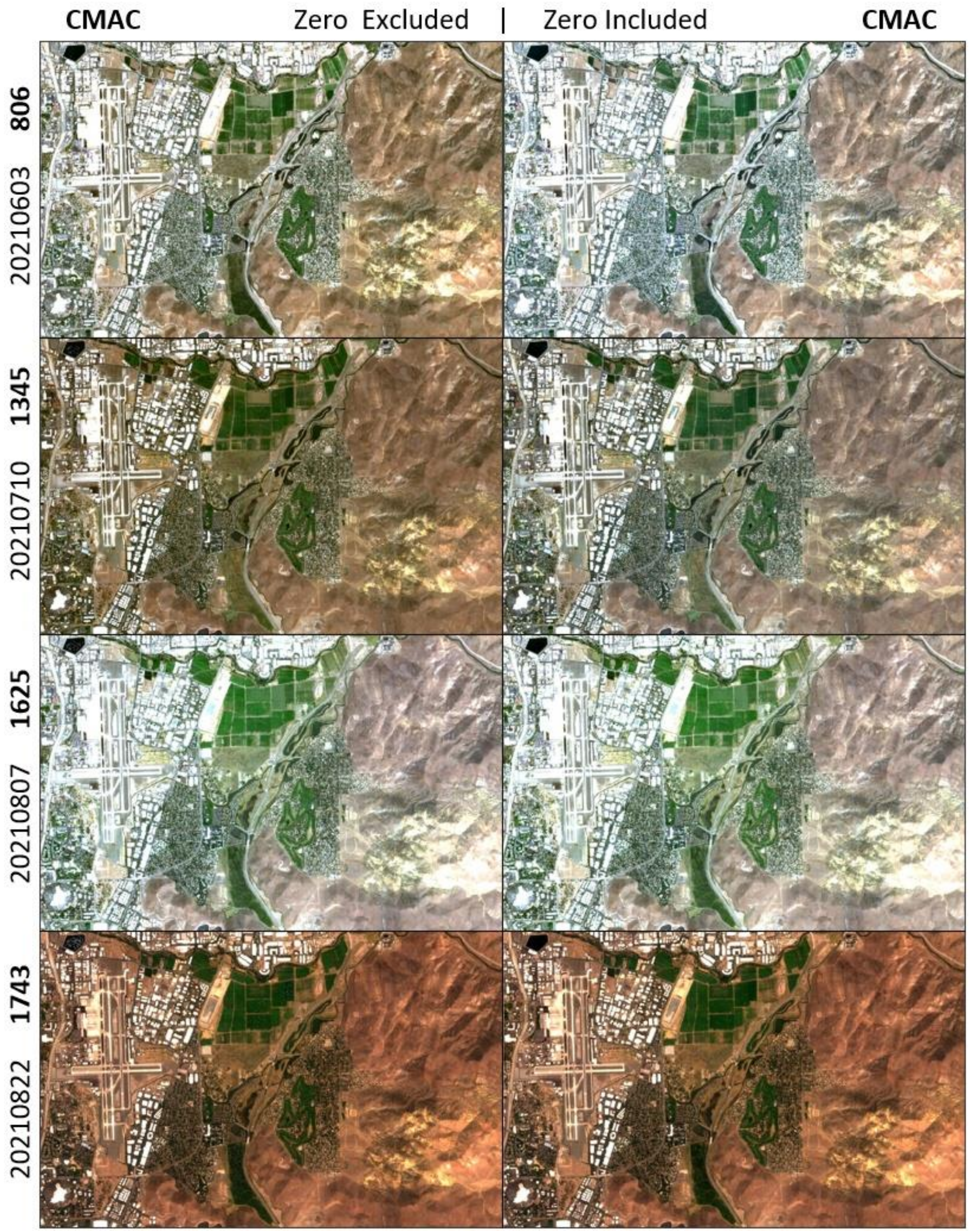

Figure 4 *CMAC corrections of the same four Sentinel-2 images of Figure 3. No black border was added to the image on the left. A black border was added for the image on the right. If the image correction results are very close to the true surface reflectance, there should be no difference in image appearance, with and without the black border.*

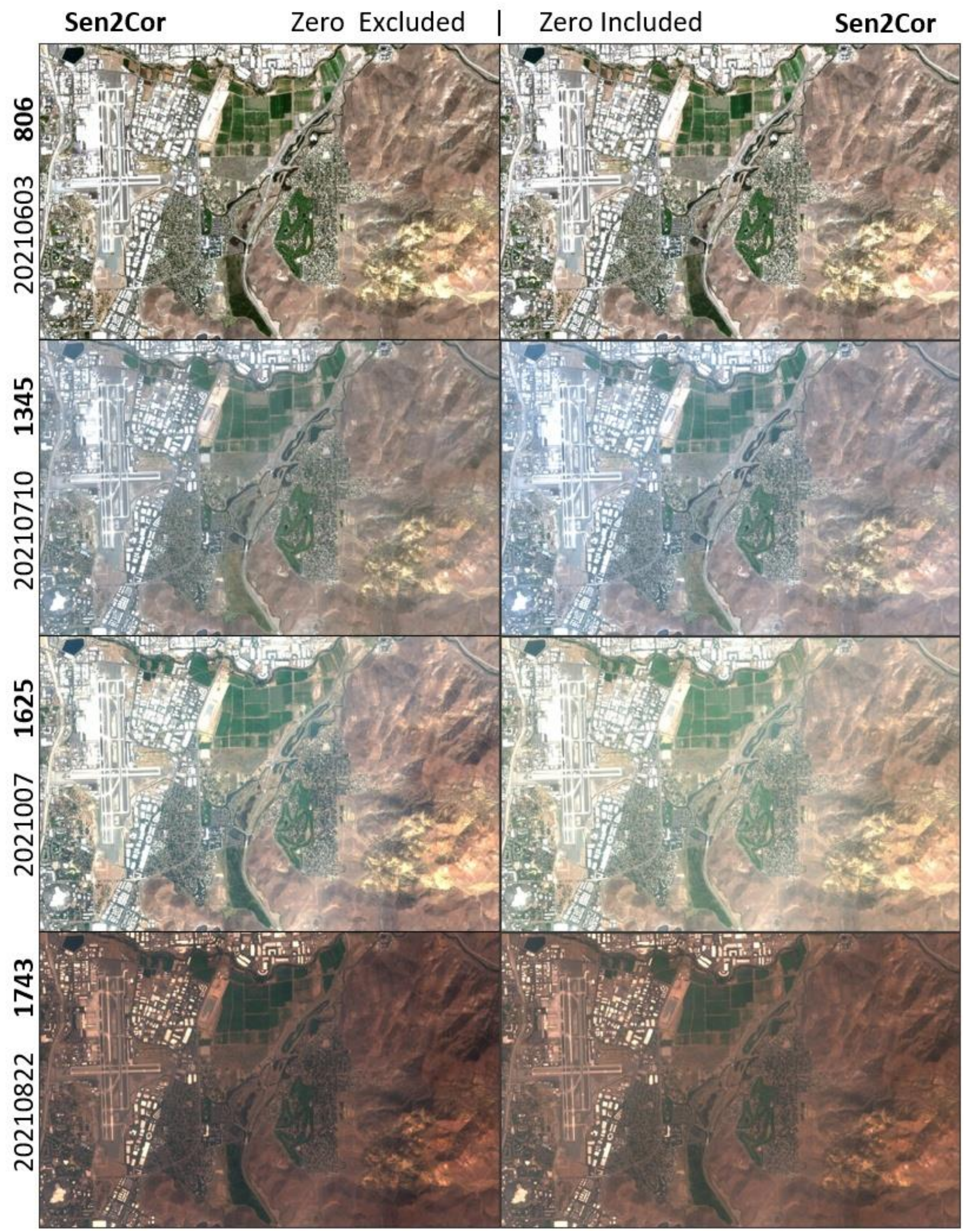

Figure 5 *Sen2Cor corrections of the same four Sentinel-2 images, without black border on the left and with the border on the right. Although Sen2Cor partially cleared the images, residual haze is clearly visible and to a greater extent with the black border added. This method confirms that the clean Atm-I = 806 image, Sen2Cor is correct.*

DISCUSSION

Atm-I and Image Display Zeroing

Application of Atm-I grayscales as a quality raster requires threshold values; ideally these thresholds are user-defined. Thresholding is simple, but care must be taken to ensure that the threshold is applicable across all cases and if not, to identify when and where the threshold can be applied accurately. The sim-lest statistical test arises from applying reflectance distributions through ranking. A highly promotional aspect of this application for remote sensing data is that the CDF percentile position from before and after processing does not change. An example application of this fact was used to test whether CMAC or LaSRC atmospheric correction is reliable for two environments of disparate spectral diversity: a high spectral diversity environment where CMAC and LaSRC outputs agreed and low spectral diversity where they did not. The results are provided in the third RESOLV Verification topic paper: CMAC was accurate for low spectral diversity AOI; LaSRC was not. Those results call into question LaSRC application for precision agriculture since low spectral diversity is typical of cultivated fields at all crop growth stages.

The displays in Figures 3 through 5 represent a rapid qualitative test for image correction not achievable through any other means than including zero reflectance to scale the image appearance. Displaying images that are scaled with black as the minimum is a form of standardization for image appearance. Some minimal percentage of black pixels is needed for the GIS display to respond by scaling the image appearance relative to the zero value. Many images already contain a sufficient number of 'nodata fill' pixels to rep-resent zero reflectance in QGIS displays, examples being Landsat 8 and 9 images that, while geometrically corrected, are aligned NE to SW to their orbital path. This creates corner areas of 'nodata fill' (Figure 6). Likewise, many Sentinel-2 and smallsat images may not be square or rectangular and so, have significant areas of zero fill values. Tile areas may be completely imaged (i.e., lacking 'nodata fill') and for such images, we recommend adding a border of zero reflectance pixels to enhance interpretation: a border of 5 pixels on all sides of the full Sentinel-2 tile has been found to be sufficient for correct image scaling by QGIS. A ***widget*** was developed for that application and is modifiable for application to other satellites as well.

Focusing on the TOAR and CMAC results underscores the sensitivity and value for applying image scaling with inclusion of zero reflectance. For example, in Figure 3 the cleanest image we found for Reno 8-06-2021 over 4 years, appears clear when viewed without zeroing: adding a black border discloses the presence of haze. This simple application provides instant confirmation of the quality of atmospheric corrections for digital application – otherwise, there is no digital means to assess accuracy for surface reflectance output other than spectrometer ground truth acquired during the overpass. CMAC has been verified to be robust and reliable: delivering the same digital values from the same values of digital input for environments with very different spectral diversity, as reported in the third RESOLV Verification topic paper.

Notable in the images of Figures 3 through 5 is a marked reddening taken through an extremely high Atm-I (median of 1743 on the August 22, 2021 image). Such reddening is a common feature of extremely high Atm-I images as described in a subsequent RESOLV Application topic paper. This color shift is hypothesized to result from the disconnect between the industry standard image processing step that uses top-of-atmosphere solar irradiance to normalize the radiance (amount of light) to reflectance (ratio of radiance/irradiance). The actual irradiance on the ground surface has been affected by the atmospheric transmission and must pass through atmosphere again on its way to satellite sensors. Because blue and green light are more highly scattered than red, a color shift towards red occurs due to a hypothesized selective scatter effect. The same disconnect between the projected top-of-atmosphere irradiance and the reflected light is also hypothesized to cause darkening of images at high levels of Atm-I from an aerosol shading effect.

There can be a bit of confusion when preparing Landsat images for visual check in QGIS, the selection of the software settings for the desired display are apparently reversed for Landsat 8 and 9 relative to Sentinel-2. No matter how the GIS display is configured, this problem is made simpler through a quick visual rule that is intuitive and logical no matter how the display options of the GIS software are configured. Figure 6 shows the same Landsat-8 image, TOAR and CMAC-corrected, viewed in two display scenarios. One display is “natural, ” i.e., an expected appearance were it possible to observe the ground from space without an intervening atmosphere. This hypothetical appearance is scaled from the least reflectance of zero (black). The other is a display where the color mapping excludes the zero ‘nodata fill’ pixels from consideration and the GIS image display maps the lowest nonzero reflectance levels as effectively zero (black), since zero surface reflectance cannot be measured in daytime imaging of the Earth. The low reflectance verdant crops are then portrayed as nearly black rather than green. This causes the visual appearance of the two displays to be significantly different and the image pair not scaled from zero reflectance to appear unnatural.

An overarching fact must be kept in mind that, while displays can be used as tools for checking the quality of atmospheric correction, the underlying data values are not changed through manipulation of the GIS display.

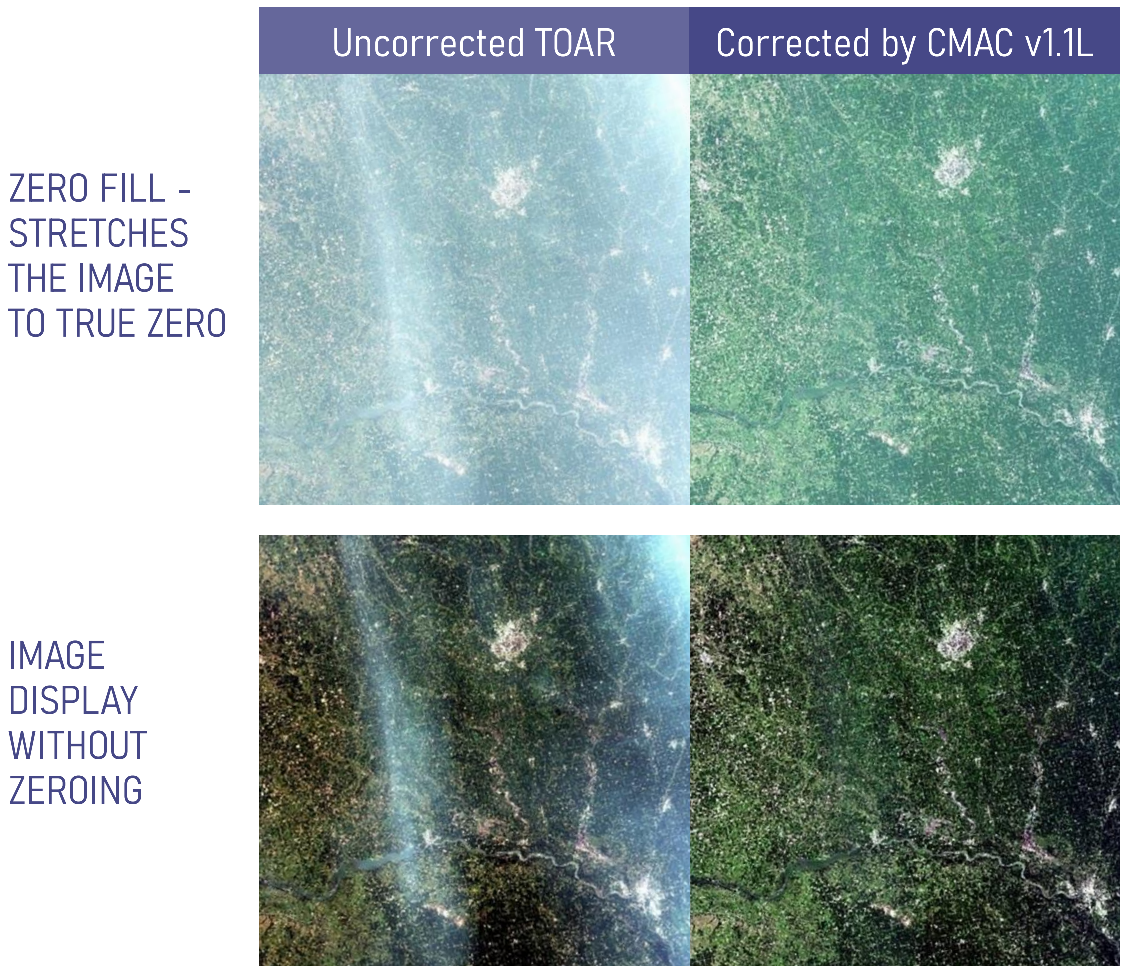

Figure 6 *A severely hazy, wildfire smoke-affected Landsat 8 image of Sioux Falls, South Dakota (acquired 8-11-2018) in four QGIS displays. The top two images are TOAR and the CMAC output displayed with the zero fill that stretches the image to true zero producing a natural image appearance. The two lower images are the stretches applied for image display without zeroing where the GIS software maps the low reflectance green vegetation as nearly black and scaling all bands from there. The left-hand pair is the uncorrected TOAR. The right hand pair were corrected by CMAC v1.1L for Landsat 8 and 9.*

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.