APPLICATION

NDVI from Atmospherically Corrected Satellite Data

Note

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

Summary

» *The CMAC algorithm powering RESOLV software is tested here for agriculture applications.*

» *NDVI is the most widely used index for monitoring crop development but is highly affected by haze due to climate change-induced wildfires that are increasing in frequency, extent and duration.*

» *Two software packages for atmospheric correction were compared: Sen2Cor v2.11, European Space Agency's software for Sentinel-2 data; and Closed Form Method for Atmospheric Correction (CMAC) v.1.1 developed for smallsat application and calibrated for Sentinel-2.*

» *NDVI was calculated for 44 Sentinel-2 images of 3 irrigated Idaho corn fields through growing-season 2021 that experienced episodic haze from wildfires. The analysis tested four questions:*

1. Why not use uncorrected top-of-atmosphere reflectance (TOAR) to generate NDVI?

Result: TOAR data adds unacceptable uncertainty for NDVI. Without atmospheric correction, TOAR offers little practical benefit for agricultural application except as a snapshot for crop vigor across a limited spatial extent (e.g., an 80-acre field). CMAC correction enables comparison of any field for the majority of growing season images, across thousands of square miles. These results also demonstrated that Sentinel-2 imagery was provided at a cadence sufficient for all but one of the weekly updates needed for precision agriculture, even with images removed, because haze level precluded accurate surface reflectance retrieval. That result will vary with climate due to climate change.

2. Which method of atmospheric correction is more reliable, CMAC or Sen2Cor?

Result: Below Atm-I of 1060, Sen2Cor and CMAC provided virtually the same NDVI output. Atm-I is the atmospheric index developed for CMAC. Sen2Cor output was unreliable above Atm-I of 1060. CMAC NDVI was competent up to 1240, almost twice the level of atmospheric effect (clearest images start around Atm-I of 800). Elevated Atm-I over large regions which occurs due to growing season wildfires are increasing in number and extent.

3. Can broad band NIR Band 8 that is sensitive to water vapor yield acceptably accurate NDVI?

Result: NIR Band 8 was as accurate as narrow Band 8A, but scaled slightly lower, therefore, Band 8 is usable at least for conditions of low atmospheric water vapor – how low remains to be determined.

4. So what - why is atmospherically corrected NDVI better?

Result: Enhancing NDVI accuracy through atmospheric correction adds significant utility for precision agriculture and can be expected to increase the demand for smallsat images. An example is provided for automated NDVI indexing of crop start dates that can time crop treatments and harvest for each of thousands of fields under management.

» *Beyond better performance, there is a major difference between CMAC and Sen2Cor-CMAC can process images immediately upon download. Sen2Cor is highly complex, never real-time and likely not improvable. In contrast, version 1.1 of CMAC was the first iteration and the path for its upgrade is well understood and eminently achievable.*

Introduction

NDVI (normalized difference vegetation index) and similar indices represent plant activity mathematically to express vigor that directly translates to photosynthetic production , carbon uptake, yield, etc. For agriculture, NDVI is the most commonly used of many indices because it is both simple and reliable: NDVI = (NIR − Red) / (NIR + Red). Nearly all vegetation indices apply red and near infrared (NIR) bands to evaluate plant vigor. The red band experiences the least atmospheric scatter in the visible wavelengths, and NIR even less. Vigorous plants absorb nearly all red light to support photosynthesis; down to about 2-3% reflectance, while NIR is highly reflected from healthy plants. Atmospheric effects in imagery reduce the plant signal because plant canopy red reflectance is increased due to backscatter of light from airborne particles, while NIR reflectance is reduced. Atmospheric aerosols such as smoke particles from wildfires are a chief factor impacting image use for North American agriculture, a problem that is steadily increasing. The goal for atmospheric correction is to return each spectral band to its original surface reflectance, thereby forming a natural standard for quantitative analyses.

Methods

To test CMAC correction, 44 Sentinel-2 images in the vicinity of Burley, Idaho, acquired between May 3 and September 30, 2021, were selected and downloaded from the Copernicus website. These growing-season images were affected by significant periodic smoke haze from regional wildfires. Three center-pivot-irrigated fields cropped in corn, confirmed on the USDA Cropland Data Layer, were selected for this analysis in the area west of Burley. Shapefiles defining areas of interest (AOI's) were drawn within visibly homogeneous cover in the fields. The data were processed by CMAC and Sen2Cor and pixel values were extracted from each field.

Figure 1 shows a Sentinel-2 image of the AOI with mapped locations of the shapefiles that defined the data extraction. The reflectance data and Atm-I are reported in reflectance x 10,000.

Atm-I is an atmospheric index developed for CMAC application typically ranging from about 800 to about 900 for clear images to above 1700 for "dirty" images that CMAC can still correct to clarity. For this analysis, all images above 1240 Atm-I were discarded; seven to eight images exceeded this threshold for each of the three fields. An Atm-I of 1240 or higher is uncommon and generally within 50 miles of wildfire.

Figure 1 *Sentinel-2 image of Burley, ID and the Snake River on June 15, 2021. Shapefiles indicate analyzed portions of the 3 fields: yellow for Field 1; cyan for Field 2; and red for Field 3. The crop development for the three fields here was after germination but before the crop was visible. Field 2 was receiving irrigation at time of image capture.*

ANALYSIS 1

Why not use uncorrected TOAR to generate NDVI?

To answer this question, NDVI generated from CMAC correction was compared to TOAR NDVI using Band 8A. Band 8A is a narrow band very close to the sensor responses for Landsat Band 5 (Figure 2). Sentinel-2 also contains a broader NIR band 8, and using this band would simplify application for agriculture, so NDVI calculated from band 8 is compared to band 8a in Analysis 3.

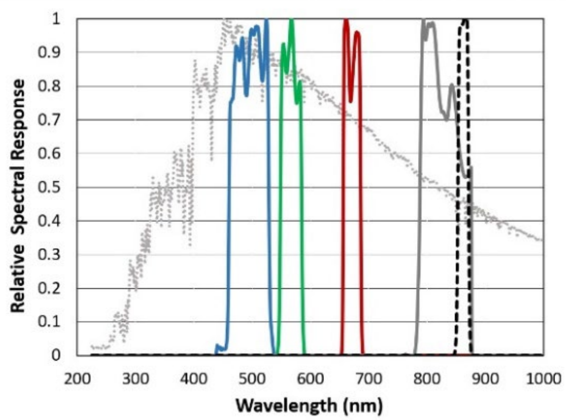

Figure 2 *Sentinel-2 spectral bands displayed in appropriate colors for the visible bands. The 10-m NIR band 8 (gray solid line) is a broader band than the 20-m band 8A (black dashed line). The light gray trace is the top-of-atmosphere solar irradiance as an indicator of the energy available for measuring reflected light.*

Figure 3 provides NDVI graphs for band 8A plotted according to the day of year. This illustrated that the uncorrected atmospheric effect in TOAR caused NDVI to be highly variable and therefore unusable for automated analyses. The discrepancies were caused by elevated aerosol from wildfire smoke that is known to cause TOAR reflectance of red to increase (backscatter) and NIR to decrease (attenuation). The CMAC NDVI results for all three example corn fields reached a stable plateau with minor fluctuation due to residual uncertainty thereafter. These fluctuations represent minor uncertainty and are only a few percent of the NDVI distribution, so are sufficient to support automated precision analytics from Sentinel-2 images. A peak NDVI of 1240 was imposed to remove uncertainty in CMAC. Climate-change-induced wildfire smoke over North America during the summer crop season often precludes the use of satellite data for precision agriculture unless atmospherically corrected. NDVI values generated from TOAR are unreliable.

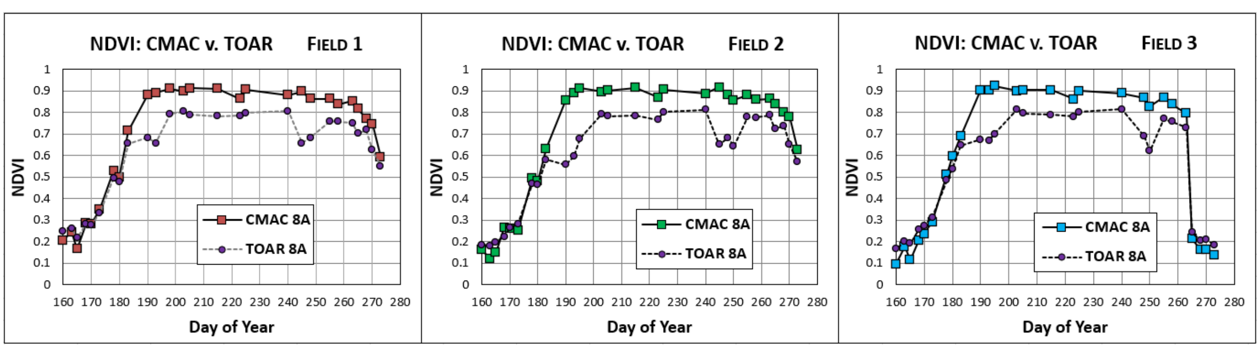

Figure 3 *Comparison of CMAC and TOAR calculated NDVI calculated for images with Atm-I less than 1240 for three irrigated corn fields in Burley, Idaho.*

The imposed CMAC Atm-I limit of 1240 provided (1) acceptable atmospheric correction accuracy for precision agriculture applications, (2) proof that CMAC NDVI is stable for elevated aerosol conditions, and (3) even after removing high Atm-I images from consideration, sufficient data remained for all but one of the weekly updates generally needed for precision agriculture analytics. Further calibration upgrades can push the 1240 Atm-I limit significantly higher.

ANALYSIS 2

Which method of atmospheric correction is more reliable, CMAC or Sen2Cor?

Reliability infers consistently accurate measurements. The red-to-NIR ratio built into NDVI provides a rigorous test for comparison of method reliability because NIR and red reflectances from vegetation are affected in an opposite manner: under increasing Atm-I the red band reflectance increases while the reflectance of the NIR band slightly decreases. This phenomenon is discussed in the second RESOLV Development topic paper and given the name “pinwheel effect”. Time series comparisons of NDVI are a robust test because growth curves of cultivated and irrigated crops are smooth, so any changes to NDVI should be gradual since it takes time for plants to respond to environmental cues. Hence, NDVI is an excellent means to compare utility for CMAC and Sen2Cor. NDVI was calculated from the results of these two methods and are plotted according to the acquisition date of year for each image as day of year in Figure 4. A deviation lower than expected is due to the pinwheel effect.

The results in Figure 4 show that Sen2Cor suffers significant points of under estimation for NDVI. These failures were traced to images affected by smoke haze as indicated by higher Atm-I levels starting around Atm-I = 1060 as described earlier. CMAC performed as expected with only slight digressions from the expected smooth curves.

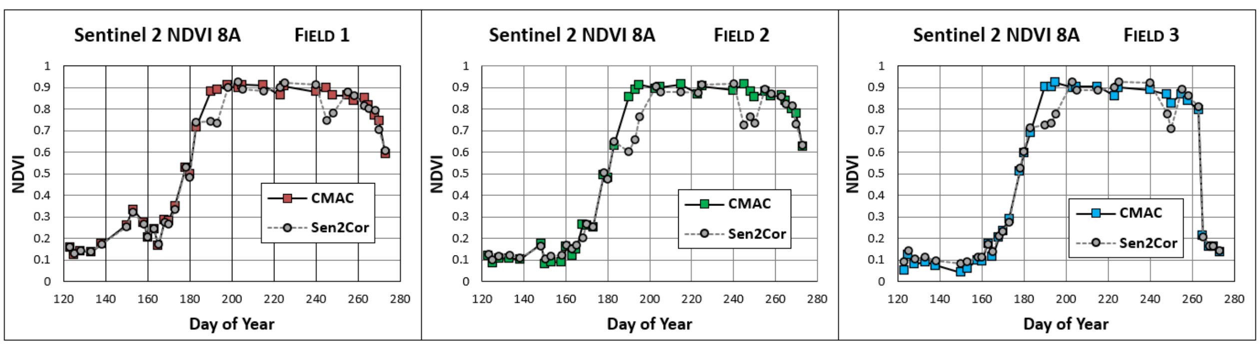

Figure 4 *A comparison of CMAC and Sen2Cor NDVI for the three corn fields. High spatial variability of Atm-I resulted in the differences among these fields. Sen2Cor errors, judged by divergence from the expected curve are due to inaccurate atmospheric correction above for Atm-I = 1060. All values from Atm-I exceeding 1240 were not considered.*

For Field 1, the initial increase, then decrease of NDVI from both methods captures weed growth followed by herbicide application on or around DOY 153. This would account for the initial very early increase followed by decline in the pre-emergence corn crop. Such initial herbicide application is a common practice referred to as a “burn down” to eliminate weeds prior to planting the main crop. Field 2 suggests this as well but not as pronounced. The results in Figure 4 show that Sen2Cor is limited to clear conditions not impacted by wildfire haze. Judging from observed smoke effects of the 2023 growing season, these conditions can occur anywhere in the northern half of the United States for months at a time.

ANALYSIS 3

Can NIR Band 8 yield acceptably accurate NDVI?

NIR is important for many analytical applications in agriculture, an obvious example being NDVI; however, the NIR spectral region is a challenge that presents a tradeoff for smallsat engineering. The highest level of energy from sunlight occurs in the shorter wavelength ultraviolet into the blue spectrum (Figure 2). For this reason, NIR bands most often cover comparatively broad windows to gather sufficient energy to excite the sensor detectors to preserve appropriate levels of signal to noise. For agriculture or other precision uses, this can impact portions of the spectrum where atmospheric water vapor absorbs the light energy, thus decreasing the NIR response. This factor prompted the development of narrow bands that are employed on both Sentinel-2 and Landsat 8 and 9 satellites. The narrow NIR bands are almost identical between these two sensor platforms. To compensate for the reduction in reflected energy, the Sentinel-2, NIR band 8A (20-m pixels) samples an area four times that of the broader Band 8 that has 10-m pixels for the visible bands. The Sentinel-2 narrow Band 8 is shown next to the broad Band 8 in Figure 2. The v1.1 CMAC software used here was calibrated for Band 8A and applied without alteration to Band 8.

The important point of Analysis 3 is that the width of the NIR band for high resolution smallsats may well be limited to larger spectral windows in order to gather sufficient energy to achieve appropriate signal to noise ratios. What then is the effect on NDVI for a wider band that may be affected by water vapor absorption? This was tested by comparing the CMAC NDVI calculated from Bands 8 and 8A from the same Sentinel-2 data collection processed using CMAC v1.1 and presented in Figure 5.

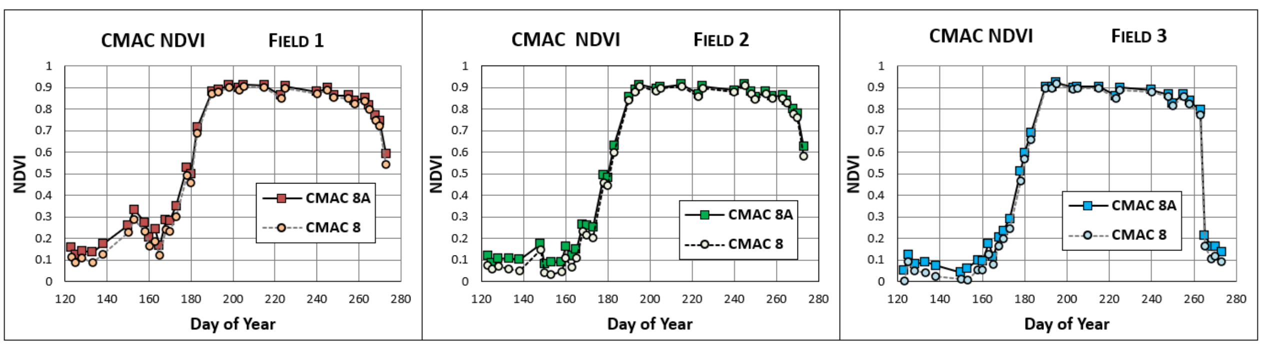

Figure 5 *Plots of CMAC NDVI calculated from Bands 8 or 8A. As shown here, Band 8 was lower than Band 8 for all three Idaho fields. This divergence was systematic and greater for lower NDVI levels.*

While Figure 5 results for Band 8 are slightly lower than Band 8A, they show about the same level of precision. Thus, in semi-arid Burley, Idaho (25 cm rainfall/yr) where high concentrations of water vapor are unlikely, errors caused by water vapor absorption would not be expected and either band can be used. From the plots, a simple linear scaling factor could make Band 8 results robustly equivalent to Band 8A. Further analysis will determine the tradeoff between pixel size, and the impact due to water vapor and where on the globe the broader band windows of NIR can be applied with reliable accuracy. From these results, however, it is a safe conclusion that no meaningful loss of accuracy would occur from use of Band 8 for summertime climates similar to Burley, Idaho. This is a significant finding that is promotional for smallsat application and that can be tested through comparison of NDVI results for row crops in more humid locations such as Mississippi, Louisiana, etc. during the summer growing season. The degree of effect from water vapor can be summarized mathematically through expression of the variability of Band 8 versus 8A and linear scaling that is needed to make the adjusted reflectance values equivalent.

ANALYSIS 4

So what – why is atmospherically correct NDVI better?

NDVI has been the index of choice for many applications because it is simple, well known, and widely used. The only drawback for NDVI is its sensitivity to atmospheric degradation that synergistically incorporates the opposing changes of the red and NIR band reflectances used to calculate it. CMAC removes this impediment for NDVI so can be highly promotional for agriculture applications. Figure 6 presents an example application of potential interest to manage crops such as vegetables and cotton that require precise estimation of growth stages to enable scheduling treatments, harvest, canning, etc. CMAC-corrected NDVI can be used under automation for crop start indexing that is highly accurate because individual fields can be independently tracked, and the measured NDVI represents actual plant growth. After planting and the impeding cool temperature early-season weather are past, crop growth follows a linear growth rate when tracked by NDVI. The crop's NDVI reaches a plateau when the crop canopy becomes continuous (Figure 6).

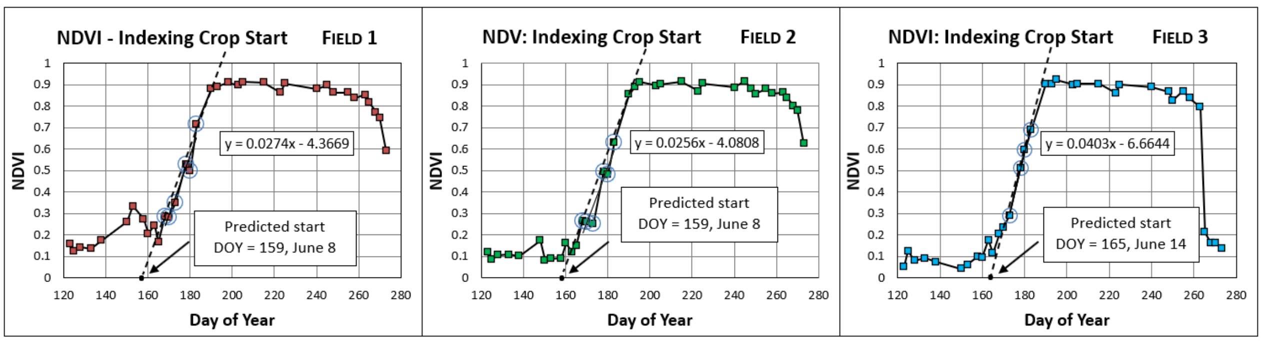

Figure 6 *Demonstration of indexing crop start dates using NDVI. A line fitted to the linear growth phase and solved for y=0 provides an index for when the plant was released from the cool spring temperatures to begin development and growth. The resulting index can forecast treatments and harvest across thousands of fields under automation.*

The accepted alternative and long-used method for such indexing charts growing degree days through temperature measurements for calculation of the approximate day when the crop actually started. Such indexing of multiple cropped fields is needed because in some areas, crops could be planted at any time within a several-month window, but the treatments and harvest need to be applied at certain times based upon growth stage. While the growing degree day concept finds wide application, it is inconvenient and may suffer accuracy issues when a weather station is not located in the immediate vicinity of the field.

For the three example fields, CMAC atmospheric correction and the automated application of rules-based decision trees could select all field median NDVI values above 0.25 that follow a consistent increasing trend. When placed into a buffer, these data can be called up for calculations after each new image is acquired. For each date, a single datum represents the crop status as an x-axis value for the day of year and a median NDVI y-axis value. When the NDVI reaches or exceeds 0.65 (or so), a regression line is calculated and solved for NDVI = 0 to represent the start date for the field. Treatments and harvest dates for the crop can then be automatically scheduled months in advance. The use of accurate surface reflectance enhances the certainty for when vegetables can be harvested and canned, for when cotton growth inhibitors can be applied, when thereafter seed corn can be de-tasseled, and when many other applications can proceed. This is one of many numerous applications for surface reflectance data in precision agriculture.

CMAC and Sen2Cor Image Comparison

The foregoing comparisons document that CMAC correction provides sufficiently accurate output for automated precision agriculture application. Accurate numerical applications from digital satellite data are crucial for adoption because farmers are cost conscious-extremely so regarding high tech programs. The accuracy demonstrated in the analyses here prove that automated analysis is possible over thousands of farms on each Sentinel-2 image because CMAC correction works over such scales. Another metric, purely qualitative, is image appearance that is demonstrated by display in a GIS. Figure 7 provides visual comparison for TOAR, CMAC and Sen2Cor of the Idaho fields for two images from hazy and clear conditions. These images show that CMAC provides image clarity in addition to accurate numerical results. Image clarity provides simple, rapid confirmation of the statistical validity of atmospheric correction. Sen2Cor cannot reliably correct hazy images.

Figure 7 *The two rows are portions of a Sentinel-2 tile T11QH: DOY 193 (top) 7-12-2021, that was hazy (average Atm-I=1209) and DOY 203 (bottom) 7-22-21 that was clear (average Atm-I=874). From left to right, the columns are TOAR, CMAC corrected and Sen2Cor corrected. CMAC processing improved both clear and hazy images.*

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.