Generation of GOES-16 True Color Imagery without a Green Band

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Key Points:

- The Advanced Baseline Imager (ABI) is the latest generation Geostationary Operational Environmental Satellite (GOES) imagers operated by the U.S. The ABI is improved in many ways over preceding GOES imagers.
- There are a number of approaches to generating true color images; all approaches that use the GOES-16 ABI need to first generate the visible "green" spectral band.
- Comparisons are shown between different methods for generating true color images from the ABI observations and those from the Earth Polychromatic Imaging Camera (EPIC) on Deep Space Climate Observatory (DSCOVR).

Abstract

A number of approaches have been developed to generate true color images from the Advanced Baseline Imager (ABI) on the Geostationary Operational Environmental Satellite (GOES)-16. GOES-16 is the first of a series of four spacecraft with the ABI onboard. These approaches are complicated since the ABI does not have a “green” (0.55 µm) spectral band. Despite this limitation, representative true color images can be built. A methodology for generating color images from the ABI is discussed, along with corresponding examples from the Earth Polychromatic Imaging Camera (EPIC) on Deep Space Climate Observatory (DSCOVR).

1 Introduction

1.1 Evolution from ATS to GOES-16

Geostationary imagers have greatly evolved since the experimental Applications Technology Satellite (ATS) series in the mid to late 1960s (Suomi and Parent, 1968). ATS-1 had one visible band, with an approximate spatial resolution of 4 km at the satellite sub-point. This can be compared to two visible bands (with spatial resolutions of 0.5 and 1 km), four near-infrared (NIR) and 10 IR (infrared) bands on the Geostationary Operational Environmental Satellite (GOES)-R series Advanced Baseline Imager (ABI) (Schmit et al., 2017; Greenwald et al., 2016; Kalluri et al., 2015; Kalluri et al., 2018). The main ABI scan mode includes a full disk “hemispheric” image every 15 minutes; along with a Contiguous U.S. (CONUS) image every 5 minutes, and two mesoscale images every minute. GOES-16 is the first of the GOES-R series of four spacecraft. GOES-R was launched and became GOES-16 in November of 2016. GOES-16 became the operational East satellite on December 18, 2017. The information from the ABI on the GOES-R series can be used for many applications including severe weather, tropical cyclones and hurricanes, aviation, natural hazards, the atmosphere, oceans, and the cryosphere.

There are other advanced geostationary imagers around the globe, either recently launched or planned. These include Japan’s two Advanced Himawari Imagers (AHI), currently in-orbit on Himawari-8 and -9, China’s Advanced Geosynchronous Radiation Imager (AGRI), Korea’s Advanced Meteorological Imager (AMI) and Europe’s Flexible Combined Imager (FCI) to fly on METEOSAT Third Generation (MTG) (Bessho et al., 2016; Yang et al., 2017; Stuhlmann et al., 2005). These imagers have at least two visible bands. These are the first geostationary imagers to provide true color imagery since the experimental ATS-3 in 1967 (Suomi and Parent, 1968). India and Russia also operate geostationary imagers. Most recently, the AHI, having red, green and blue sensitive spectral bands, has allowed for true color imaging after an adjustment to its 0.51 µm green band (Miller et al., 2016).

As these advanced imagers include additional spectral bands over the previous generation of imagers, there are an increasing number of ways to combine the spectral information. One effective way to communicate multi-spectral information is via Red-Green-Blue (RGB) composite imagery. RGB images fall into two broad categories: false color or true color. False color composites may highlight various features in arbitrary colors, so training is needed to understand what each color means. One such example is the EUMETSAT “Dust RGB” (Lensky and Rosenfeld, 2008). In contrast to false color RGBs, true color RGB approximates more closely normal human color vision and thus requires far less special training to interpret. Images from the Earth Polychromatic Imaging Camera (EPIC) on Deep Space Climate Observatory

(DSCOVR), which view the Earth from Lagrangian Point 1 (L1) orbit, are provided in both "natural" and "enhanced color" options. The "natural" color aims to mimic what the human eye would see if one were looking at earth from a distance. The "enhanced" version aims to boost contrast within the lower end of the signal, which generally correlates to surface features. (https://epic.gsfc.nasa.gov/).

1.2 GOES-16 ABI spectral bands

Unlike previous-generation GOES series imagers, which had only one visible channel, GOES-16 ABI has 16 spectral bands, two of which are within the visible range and four in the NIR range. The two visible bands are known as the Red (0.64 μm) and Blue (0.47 μm) bands. The first of the four NIR bands is often referred to as the "vegetation" band (0.86 μm) due to the strong signal of reflected sunlight from vegetated surfaces. Fig.1 shows GOES-16 ABI spectral response functions for these two visible and one NIR (0.86 μm) band along with their reflectance spectra for asphalt, dirt, grass and snow (Baldridge et al. 2009). It is the differences between these individual channels and how they respond to different surface features that make it possible to combine them to make true color RGB images.

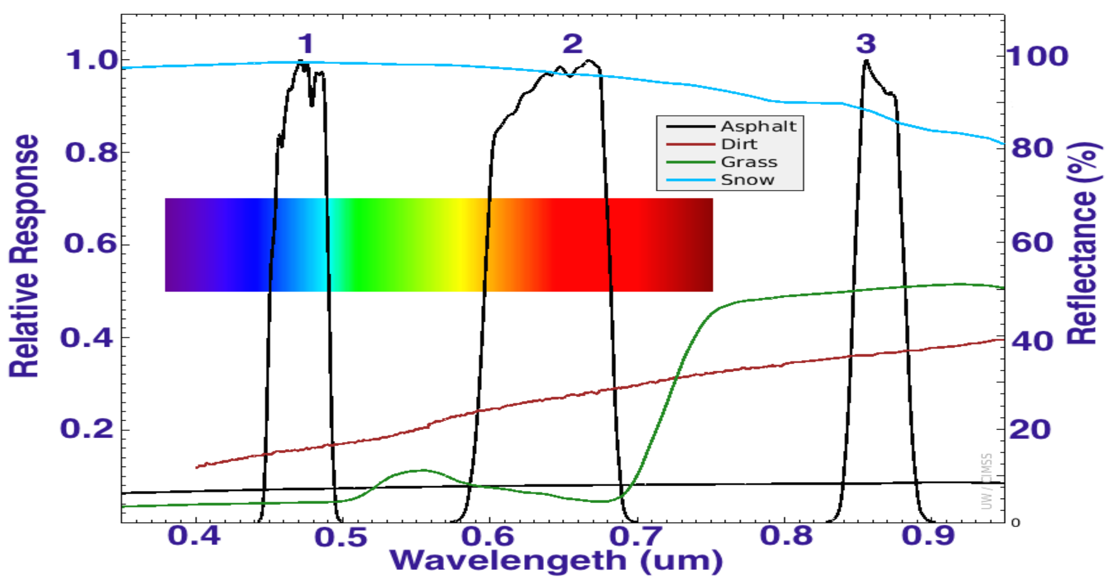

Figure 1. The GOES-16 ABI spectral response functions for bands 1 through 3, along with the visible rainbow spectrum for reference. This plot includes four reflectance (%) spectra from the ASTER spectral library measured signals from "construction asphalt," "reddish brown fine sandy loam," "grass," and "medium granular snow." These spectra, plotted along with ABI spectral response functions, provide some indication of how several surfaces reflect as measured by different spectral bands.

1.3 Construction of true color imagery

Generally, one requires the Red (0.64 μm), Green (0.55 μm), and Blue (0.47 μm) bands to generate true color RGB images, but with ABI on GOES-16 and GOES-17 the next two GOES-series satellites (T/U), the Green (0.55 μm) band is not included. However, GOES-16 does have the vegetation band (0.86 μm) which, when proportionally combined with the existing Red (0.64 μm) and Blue (0.47 μm) bands, can generate a "green-like" band as a first order approximation. This allows for making "enhanced" or "natural" true color RGB images entirely based on the existing GOES-16 bands as shown in Fig. 2, or via a green band Look Up Table (LUT) derived from similar instruments (e.g., Miller et al., 2012). The methodology for generating a green band on the fly to combine with the Red and Blue bands for making GOES-16 true color RGB images is outlined in Section 2.

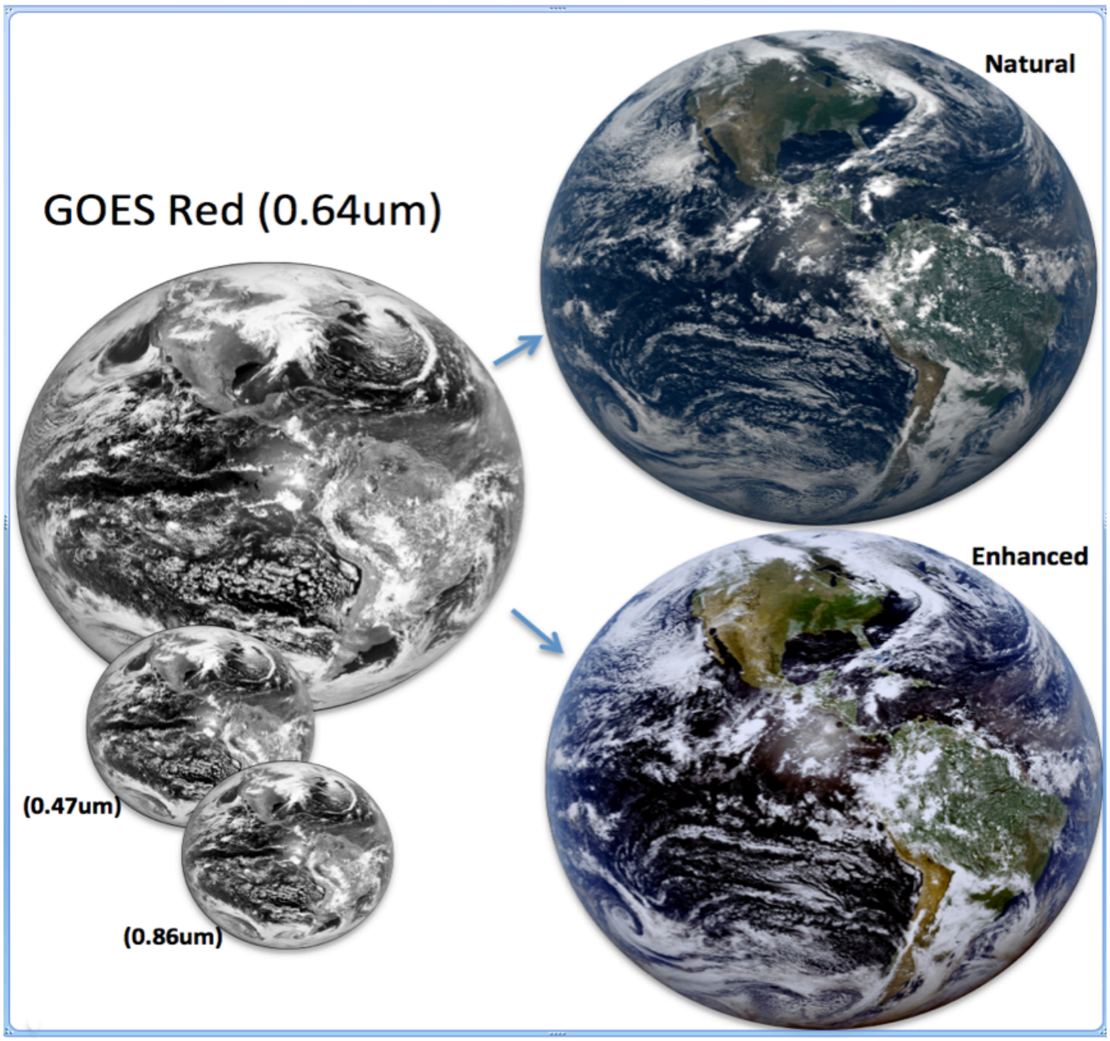

Figure 2. The three GOES-16 bands (0.47 μm, 0.64 μm and 0.86 μm) needed to make true color RGB images shown in black and white on the left along with the generated true color RGB images for the natural (upper right) and enhanced (lower right).

If correctly enhanced and combined for visualization and analysis purposes, these true color RGB images can capture most, if not all, of the information found within the individual channels that were used to generate them as shown in Fig. 2. Due to the nature of the human eye cone's sensitivity to visible light centered near these wavelengths, far less training is needed to interpret "natural' or "enhanced" true color RGB images.

As satellite instruments get more advanced and the number of spectral bands increase, it becomes increasingly important to find simple ways of synthesizing information from multiple bands for simultaneous visualization and rapid analysis purposes instead of parsing through myriad individual bands.

2 Making 'natural' or 'enhanced' true color GOES-16 RGB images

2.1 Overview

For GOES-16 ABI, combining the blue (0.47 μm), red (0.64 μm) and NIR (0.86 μm) bands, true color RGB (natural /enhanced) is a reasonable choice for daytime imagery. This allows for both condensing critical information from three bands into a single image with the added benefit of easily communicating such information. Hence this can be very helpful for both forecasters and the general public.

Making GOES-16 ABI "natural" or "enhanced" true color ABI RGB images requires two main steps. The first step is to generate a green band, and the second is to choose and apply enhancements as required to achieve the desired RGB image. There are multiple ways to approach both steps, with varying degrees of efficacy. In this paper we outline three independent ways of generating a green band, with a principal focus on a straightforward (linear) and readily replicable version. In addition, we describe four enhancement options that can be used either individually or in series with these bands to make GOES-16 true color RGB images (natural or enhanced).

While either radiance or reflectance factor values may be used to generate GOES-16 ABI true color images, only the radiance files were used to generate the RGB images in this paper. This prevents any possible complications that might arise as a result of radiance to reflectance factor conversation and post processing.

2.2 Generating a GOES-16 "green-like" ABI band

2.2.1. Fractional combination: The simplest approach to estimating the needed green-like band (0.55 μm) for GOES-16 ABI is via fractional combination of the existing GOES-16 ABI red (0.64 μm), blue (0.47 μm) and NIR (0.86 μm) bands. Generally, the spectral response functions for the 0.64 μm, 0.55 μm and 0.47 μm behave similarly when remotely sensing bright and dark surfaces such as snow and asphalt or water (Baldridge et al. 2009). Although the 0.47 μm is more sensitive to aerosols, causing the image to be hazier than the 0.64 μm image. However, the bands behave very differently when remotely sensing red, green, and blue objects. Compared to the 0.64 μm and the 0.47 μm bands, the 0.55 μm is more sensitive to vegetation, but the 0.86 μm is even more sensitive to vegetation than the 0.55 μm. Hence by combining fractions of the measured radiances from these three bands, one can construct a "green-like" band that can be used in combination with the already existing red (0.64 μm) and blue (0.47 μm) bands to make a simple GOES-16 RGB image. Through experimentation, the proportion that consistently produced reasonable results was: Green = 0.45*Red + 0.10*NIR

+ 0.45*Blue. Note, this approach is a first-order approximation; it does not replace the information content of the missing green band. However, when enhanced using simple mathematical functions, it can produce very reasonable GOES-16 true color RGB images for both "natural" and "enhanced."

2.2.2. Weighted Nudging with Hybrid Green Adjustment: A second method of generating a green band is by using the "weighted nudge" approach. This approach requires basic preexisting knowledge of the density distribution for the red, green, and blue bands. The logic behind this approach is that independent of time, it is often observed that the data density distribution functions of the red, green, and blue bands correlate in such a way that the green band is located between the red and blue bands. By using an instrument such as the AHI, which already has a green band, one can establish a reference correlation between the density distributions for the red (0.64 μm), green (0.51 μm), and blue (0.47 μm) bands. Next, the red and blue are "nudged" using a weighted function to align with the expected location of the green band, using the normalized distance between the red and green wavelengths to nudge the red, and the normalized distance between the blue and green to nudge the blue. Then average the nudged blue with the nudged red to get a first order approximation of the green-like band. The AHI green at 0.51 μm is not ideal for true color, hence the need for a hybrid green adjustment step: the first order approximated green (green0) is modified using the vegetation band to capture the chlorophyll reflectance response at the first order approximated green (green0) and make a new green (green1) band similar to one centered at 0.55 μm. In this way, without a real green band, one can linearly approximate the normalized distance that the red and blue bands need to be nudged to align with the green band.

2.2.3. Look Up Table (LUT) with Hybrid Green Adjustment: A third method of generating a green band, accounting for the more realistic non-linear relationship between the green, blue and NIR (0.86 μm) information, is to use a LUT approach (e.g., Miller et. al, 2012). This non-linear function is derived from measurements of an existing instrument that has all four bands, and produces a three-dimensional LUT generated at 0.5% reflectance granularity. For GOES-16, the AHI turned out to be a perfect fit for establishing this correlation since it has all the four channels mentioned above. In practice, the pre-generated LUT is interrogated by currently observed pixel values of red, blue and NIR, then the associated green reflectance value from the LUT is used in combination with native red and blue bands to produce the RGB true color image. This approach has been tested successfully using AHI on Himawari-8 as a proxy for GOES-16 ABI and has shown very promising results.

Each of the above-mentioned options for generating a green band with the suggested enhancements for making natural and enhanced true color GOES-16 RGB images will be further explained in more detail under section 4. Sample images made by using the fractional combination approach and weighted nudging with hybrid green adjustment will be shown in Fig. 5 and Fig. 6 respectively.

2.3 Choosing the right enhancements for GOES-16 RGB images

While making a "green-like" band is the first step toward generating a true color RGB for GOES-16, the choices of enhancements needed to apply to those bands are an important second step and have a very significant visual effect on the final image. The choices of enhancements generally depend on the desired RGB features one is looking to enhance. For a simple, general purpose, natural or enhanced true color RGB, one or two options for enhancements applied in series are all that is required to make true color RGB images similar to those shown in Fig. 2. For more detailed and higher quality RGB images, further enhancements and sometimes further corrections might be needed to acquire the desired output. In this paper we will cover four basic but common enhancement examples, namely the: (I) square root, (II) equalized histogram, (III) gamma and (IV) inverse hyperbolic sine functions.

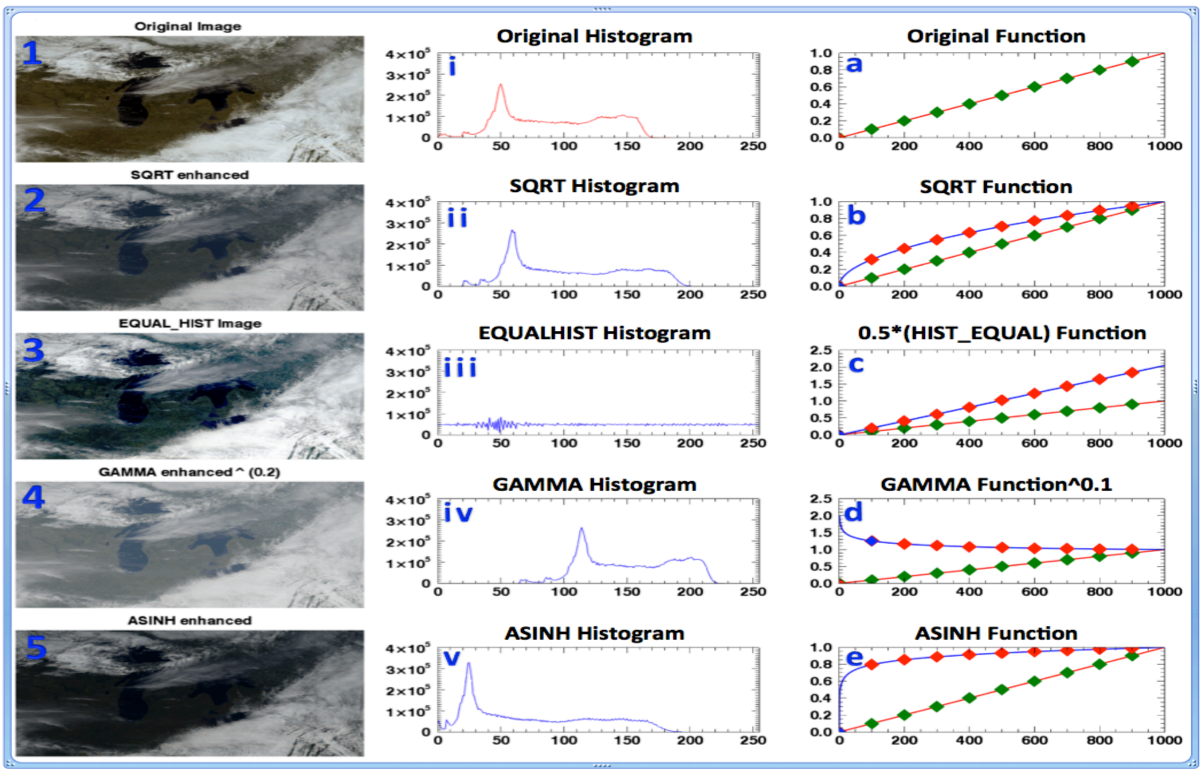

Figure 3. Shows the general effect of applying the square root (SQRT), equalized histogram (EQUAL_HIST), gamma (GAMMA), and inverse hyperbolic sine (ASINH) functions to a sample dataset ranging between 0 and 1. The orange lines with green dots represents the input data. Blue lines with red dots shows the effect of applying the enhancement to the data. (1) shows a sample RGB image with no enhancement and its associated histogram on its right. (2,3,4,5) show the effect of applying, SQRT, EQUAL_HIST, GAMMA and ASINH enhancements to 1 and their associated histograms.

2.3.1 Square root enhancement (SQRT),: $(\sqrt{x}\ x)$, Where “x” represents the L1b radiance scaled between 0.0 to 1.0, “*” represents multiplication and “( )” represents the final product after operations.

The square root enhancement is probably the most commonly used enhancement on GOES visible images. It is so common that some software systems such as the Man-Computer Interactive Data Access System (McIDAS)-X automatically apply it to the legacy GOES series visible band (0.64 µm) when displaying images. An alternative way of accomplishing the same effect without directly interacting with the data is to apply a square root enhanced color bar to the data when displaying it. Generally, a single visible reflectance image when displayed with a linear gray scale color enhancement tends to be very dark on the lower end. Applying a simple square root function to the reflectance helps to boost the overall signal values but more on the darker end than on the brighter end as shown in Fig. 3b. This normally has the desired effect of brightening up the image, particularly the darker values, which tend to be features on the surface. For RGB, when applying an enhancement such as a square root, we tend to apply it to all three bands equally weighted by the input data from each channel. However, there is room to independently adjust them to enhance specific features if desired.

2.3.2 Equalized Histogram (EQUAL_HIST): $(E_{i,j}(x) * x))$ Where: $E_{i,j}$=floor(K-1)$\sum_{n=0}^{Xi,j} \boldsymbol{Fn}$, “*” represents multiplication, $\boldsymbol{Fn}$= (number of pixels with intensity n)/ (total number of pixels), $\mathbf{K = number\ of\ possible\ intensities}$, x= scaled radiance data input.

When applied to data for enhancement purposes, equalized histogram tends to do an excellent job enhancing an image, particularly the darker end of the image as shown in Fig 3c. However, care must be taken not to saturate the already bright parts of the image or to unintentionally enhance some noise within the image.

2.3.3 Gamma enhancement (GAMMA): $(\Gamma(x) * x)$, Where: $\Gamma(x) = (x-1)!$, x=scaled radiance data input.

The gamma is a highly sensitive function that can be used both for general enhancement and contrast adjustment within an image as shown in Fig 3d. When correctly applied to the individual bands, the gamma function can also help alleviate some of the haziness in an image such as those caused by Rayleigh scattering. However, it also has a great tendency to saturate the already bright pixels.

2.3.4 Inverse Hyperbolic Sine enhancement (ASINH): $(SINH^{-1}(x) * x)$

Where: $SINH^{-1}(x) = \ln(x + \sqrt{(1+x^2)})$, x=scaled radiance data input.

The inverse hyperbolic sine enhancements generally tend to enhance the darker pixels of an image and slightly dampen the brighter pixels as shown in Fig 3e. This enhancement tends to maintain the overall nature of the data distribution but is often not enough to provide very vivid true color RGB images. It generally tends to do a great job for natural color when combined with an additional contrast enhancement.

3 Flow diagram to make a GOES-16 true color RGB using the fractionally combining approach

3.1 The steps shown below are mainly meant to make simple natural or enhanced true color RGB images. If you want to make the final image more vivid, further enhancements might be required. For the natural color RGB, the images generally tend to appear a little hazy with less contrast, so applying a contrast enhancement or a gamma function can help to further enhance the image. The histogram equalized on the other end tends to over enhance thereby making the clouds look saturated. To reduce saturation one can linearly dampen the entire image by taking ~ 80% of each channel or apply some other preferred enhancement that will reduce the saturation.

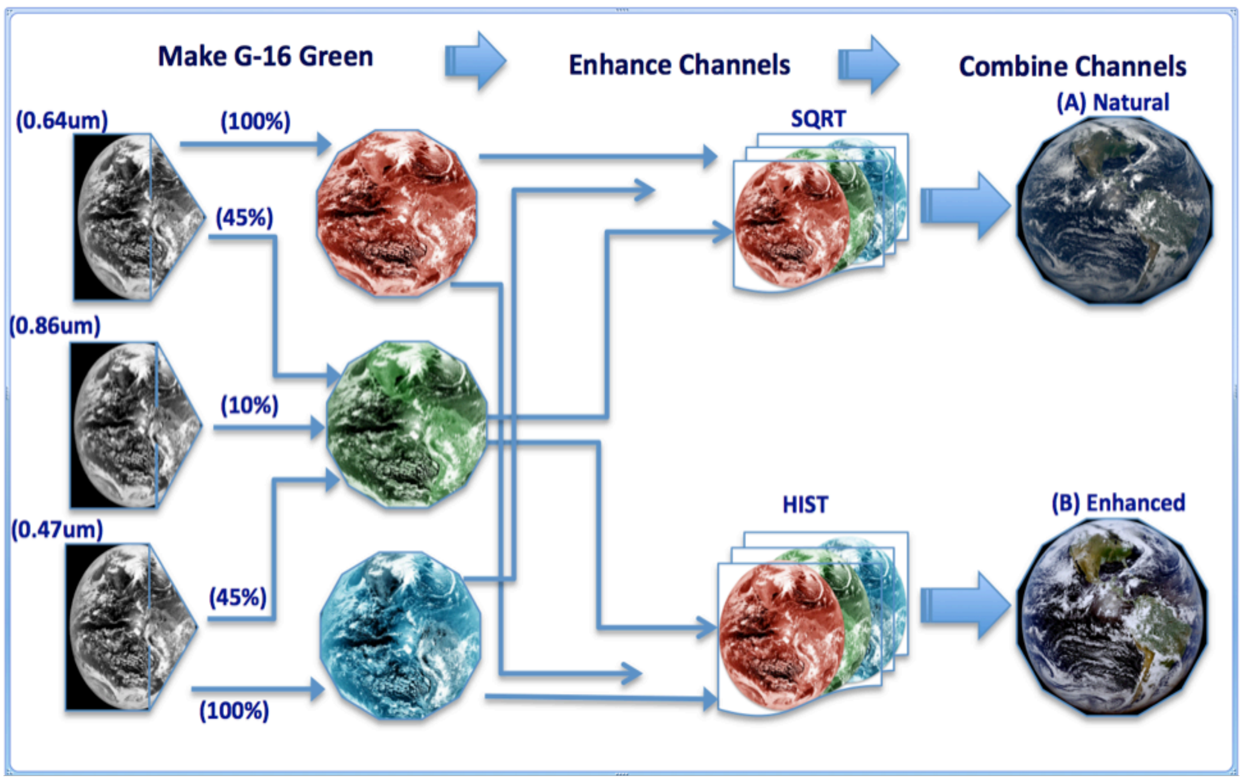

Figure 4. Flow diagram for making GOES-16 true color RGB using the fractionally combining approach for making the green band with square root or histogram equalized enhancements for making a natural or enhanced color respectively

The steps to make a 16 bits per pixel true color RGB image following the fractionally combined approach as shown in the Fig. 4 flow diagram:

1. Read in the Red (0.64 µm), Blue (0.47 µm), NIR (0.86 µm), and scale each band to 16 bits. (Data can be scaled back to 8 bits before making RGB image if desired)

2. Fractionally combine the Red, Blue and NIR to make a “green-like” band.
3. Check for out-of-range values, then set the range to the minimum and maximum possible values.
4. For natural color, make a square root enhancement for each channel (R, G, B) and apply` the enhancement to the associated data (($\sqrt{(x)} * (x)$). Where “x” is the R, G or B input data.
5. For enhanced color, make a histogram equalized enhancement for each channel similar to step (4) above and apply to input data.
6. Combine the new output (R, G, B) to make a natural or enhanced RGB image.

4 Results of using GOES-16 data to make natural and enhanced true color RGB images

4.1 The Earth Polychromatic Imaging Camera (EPIC) on board the Deep Space Climate Observatory (DSCOVR), is a ten channel spectroradiometer orbiting approximately 1 million miles away from earth at the Lagrangian 1 (L1) point. The EPIC team has had success in using three of these channels centered at Red (680 nm), Green (551 nm) and Blue (443 nm) to make Natural and Enhanced Color RGB images as shown at: https://epic.gsfc.nasa.gov/about.

4.2 CIMSS GOES-16 and the EPIC true color RGB for natural and enhanced

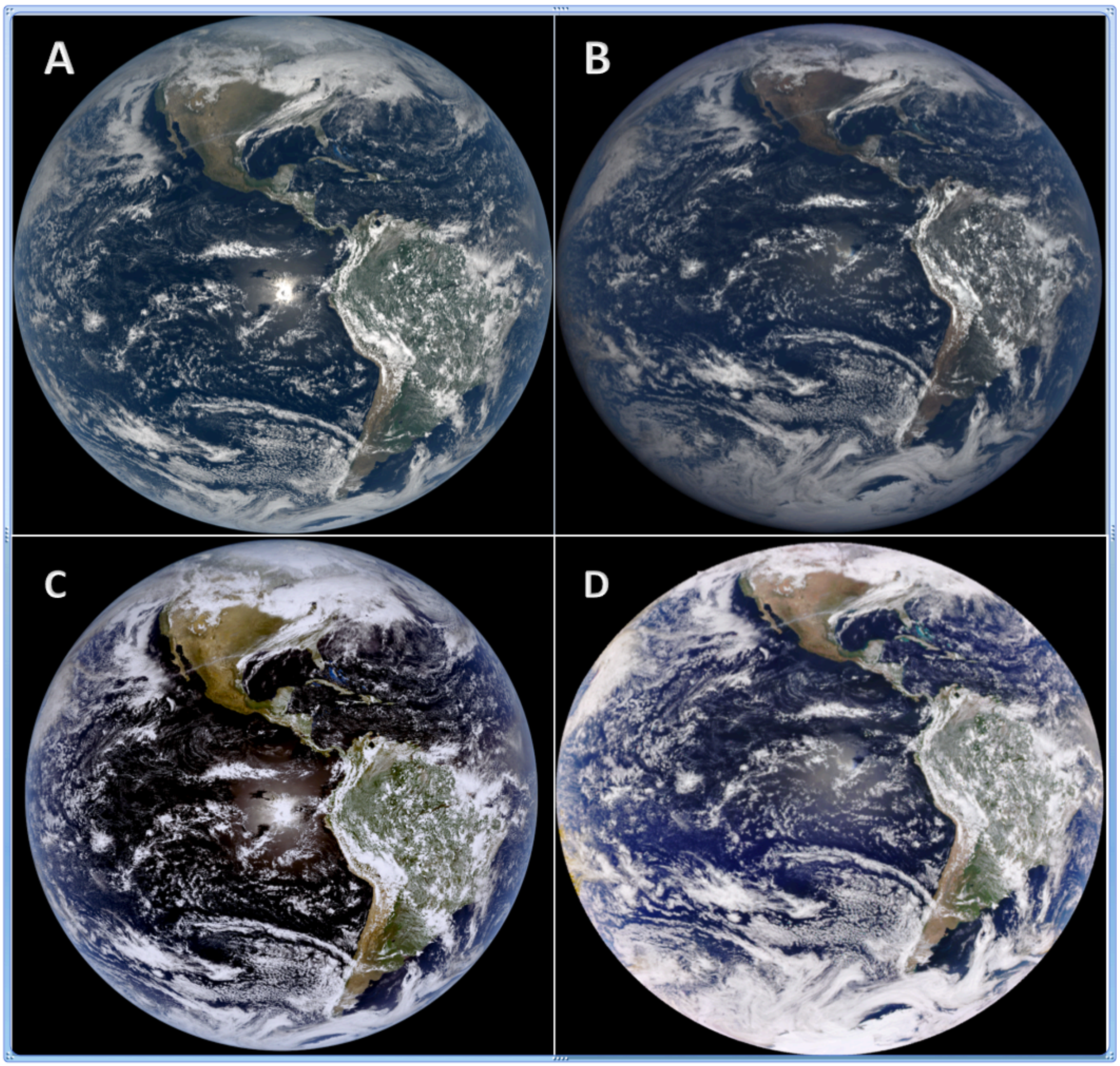

Figure 5. Comparing GOES-16 ABI true color RGB for (March 01^{tst}, 2017, 18:06 UTC) using the fractional combination approach to make the green as compared to EPIC (March 01TH, 2017, 18:27 UTC). (A) CIMSS natural color (with square root enhancement). (B) EPIC natural color. (C) CIMSS enhanced (with equalized histogram). (D) EPIC enhanced color.

Following steps outlined in the flow diagram under section 3, the fractional combination approach for making a "green-like" GOES-16 band along with the right enhancements can lead to very reasonable comparisons to other known natural and enhanced true color RGB images such as EPIC (which has a green band). While GOES-16 and EPIC are comparatively different in both orbital positions and resolutions (spatial, spectral and temporal), in addition to the missing green (0.55 µm) band on GOES-16, the comparisons are shown to be similar. Note that both images remain in their native projections. This is all in addition to using different mathematical functions for enhancement techniques. The GOES-16 green band for these comparisons was created using the fractional combined approach discussed in section 2. The main enhancements used in the GOES-16 RGB are the square root (natural color) and histogram equalized (enhanced color). For details on EPIC enhancements, visit the epic website: https://epic.gsfc.nasa.gov/about

4.3 Weighted Nudging approach to make GOES-16 natural true color RGB

This alternative way of making the green band can also be used to generate both natural and enhanced true color RGB images similar to the fractional combination approach. For this method, we found that applying an inverse hyperbolic sine function enhancement leads to a better natural color image compared to a simple square root as shown in Fig. 6.

Figure 6. GOES-16 True color (natural) RGB image for March 01st, 2017, at 18:06 UTC. The green band in this case was generated using the weighted nudging approach with an inverse hyperbolic sine function enhancement applied.

4.4 Natural features that are easily depicted in “enhanced” or “natural” color RGB images

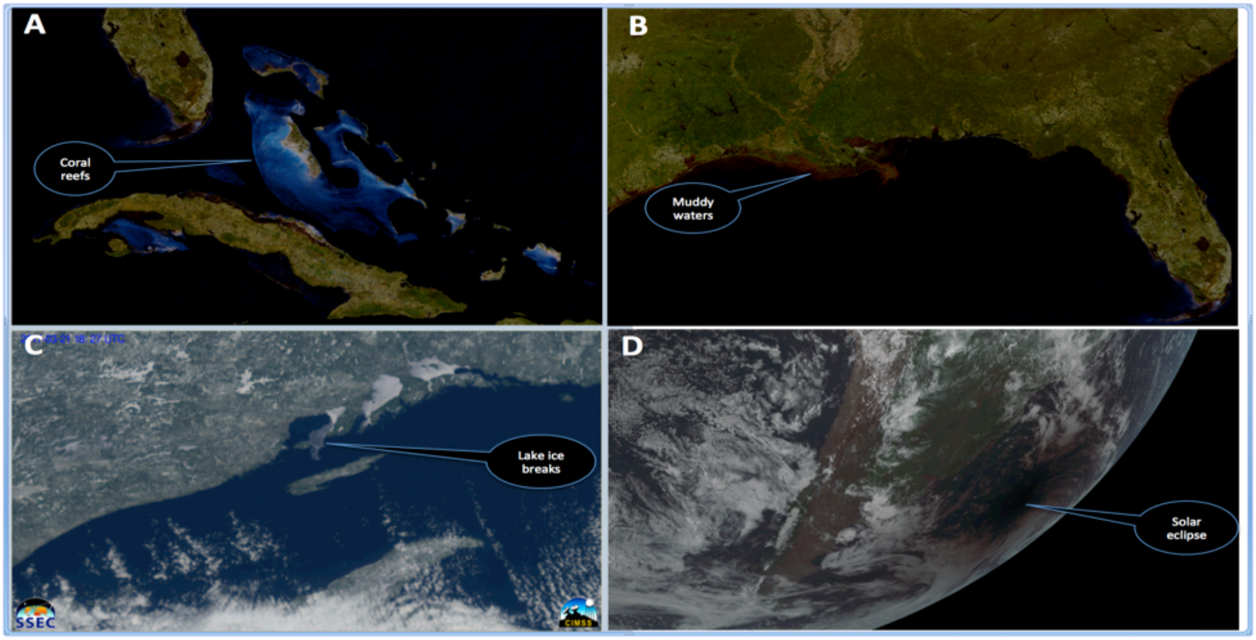

Figure 7. Sample natural features that are easily depicted in true color RGB images without any further required enhancements. (A) Coral reefs over the Caribbean Islands. (B) Muddy shallow waters off the coast of Louisiana. (C) Lake ice breaking in the Great Lakes. (D) Solar eclipse over the Atlantic Ocean. (A) and (B) above use a custom GOES-16 cloud filter algorithm.

One major advantage of enhanced and natural color RGB images over individual visible channels is that of the features within the image become naturally easier to decipher without special training. Fig. 7A shows coral reefs in the Caribbean. Such features are almost impossible to identify in a single visible channel, especially with a standard enhancement. Fig 7B shows muddy shallow waters off the Louisiana coast. Similar to Fig 7A, such features clearly stand out in the RGB images but are more difficult to identify even in a series of visible channels, again using the standard enhancement. Fig 7C shows lake ice breaking over Lake Superior that clearly stood out in the GOES-16 natural color RGB. A loop of this can be found in the following link: http://data.ssec.wisc.edu/abi/true_color_imagery_paper_baetal_2017/ice3x.mp4. Fig 7D shows the February 26th, 2017 solar eclipse over South America. Though this was also seen in the visible channels, it stands out much better in the RGB images. To see a sample loop of this event, visit the following link: http://cimss.ssec.wisc.edu/goes/blog/wp-content/uploads/2017/02/2017_SH_solar_eclipse_shadow_truecolor_anim.gif

4.5 Limitations

While true color RGB images offer great advantages over gray-scale single band images, it also has some limitations that often require non-trivial efforts to correct for visualization effects, some of which are shown in Fig 8.

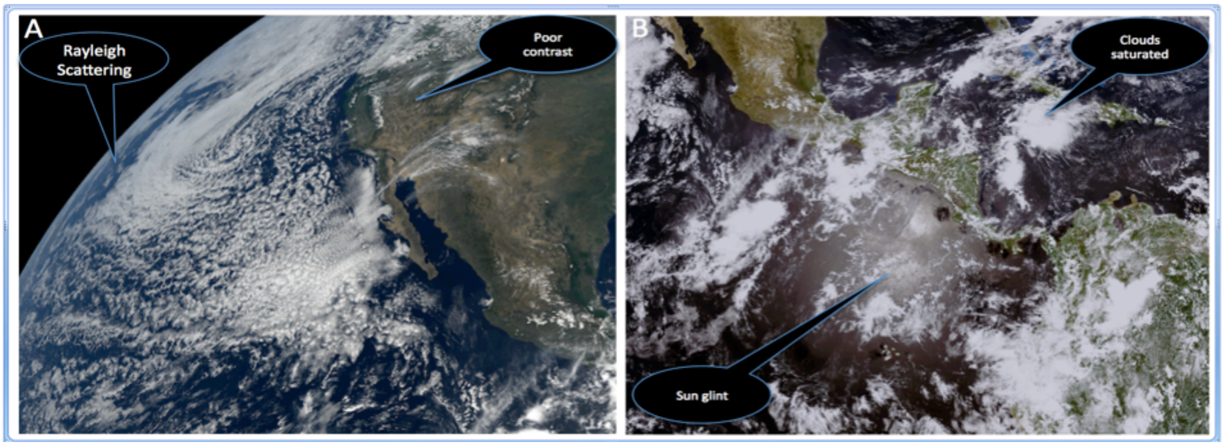

Figure 8. Sample of natural and true color GOES-16 RGB images highlighting some of the limitations that would require further enhancement for corrections. (A) Natural color showing Rayleigh scattering around edges over ocean and poor vegetation contrast over land. (B) Enhanced color showing sun glint effect over ocean and saturated high clouds due to their high reflectance components.

Fig 8A shows a GOES-16 natural true color RGB image without Rayleigh scattering corrections. In such images, it is common to see a general haziness over the image particularly over ocean toward the limb of the satellite-viewing angle. To correct for these, a Rayleigh scattering correction algorithm will be needed which requires information about the particular satellite viewing angles for each image.

Fig 8B shows a GOES-16 enhanced true color RGB image showing the effect of sun glint over ocean. This feature can be very pronounced, especially over water when the sun and satellite are properly aligned.

5 Conclusions

A number of approaches have been documented to generate true color images from the ABI on the GOES-16. These approaches are complicated since the ABI does not have a “green” (0.55 µm) spectral band. Even with this limitation, fairly representative true color RGB images can be built. The method for generating color images is discussed, along with corresponding examples from the EPIC. Following guidelines highlighted in this paper, algorithms for generating GOES-16 true color RGB images on the fly was successfully developed and evaluated at the National Weather Service (NWS) Operations Proving Ground (OPG). In partnership with NWS Advanced Weather Interactive Processing System (AWIPS-II) team, the University of Wisconsin-Madison (CIMSS) has developed a python version of this code which has been integrated into AWIPS-II for use by each Weather Forecast Office (WFO). This makes it possible for all AWIPS-II users to automatically generate GOES-16 true color RGB images relying entirely on already existing GOES-16 data within their local environment. There are several places to acquire free, real-time, true color images of GOES-16 ABI on the web including the UW-Madison Space Science & Engineering Center (SSEC) Geostationary Image Browser and SSEC's RealEarth (which is also available for smart phones).

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Data supporting the analysis and conclusions in this paper can be accessed through the NOAA CLASS (Comprehensive Large Array-data stewardship System): https://www.class.ncdc.noaa.gov.

To experiment with combining ABI bands to build color composite imagery, see: http://cimss.ssec.wisc.edu/goes/webapps/satrgb/satrgb_ABI_fd_realtime.html or http://cimss.ssec.wisc.edu/goes/webapps/satrgb/satrgb_ABI_2017_14May_18utc_fd.html. For sample G16 RGB using the LUT approach, see: http://rammb-slider.cira.colostate.edu/

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