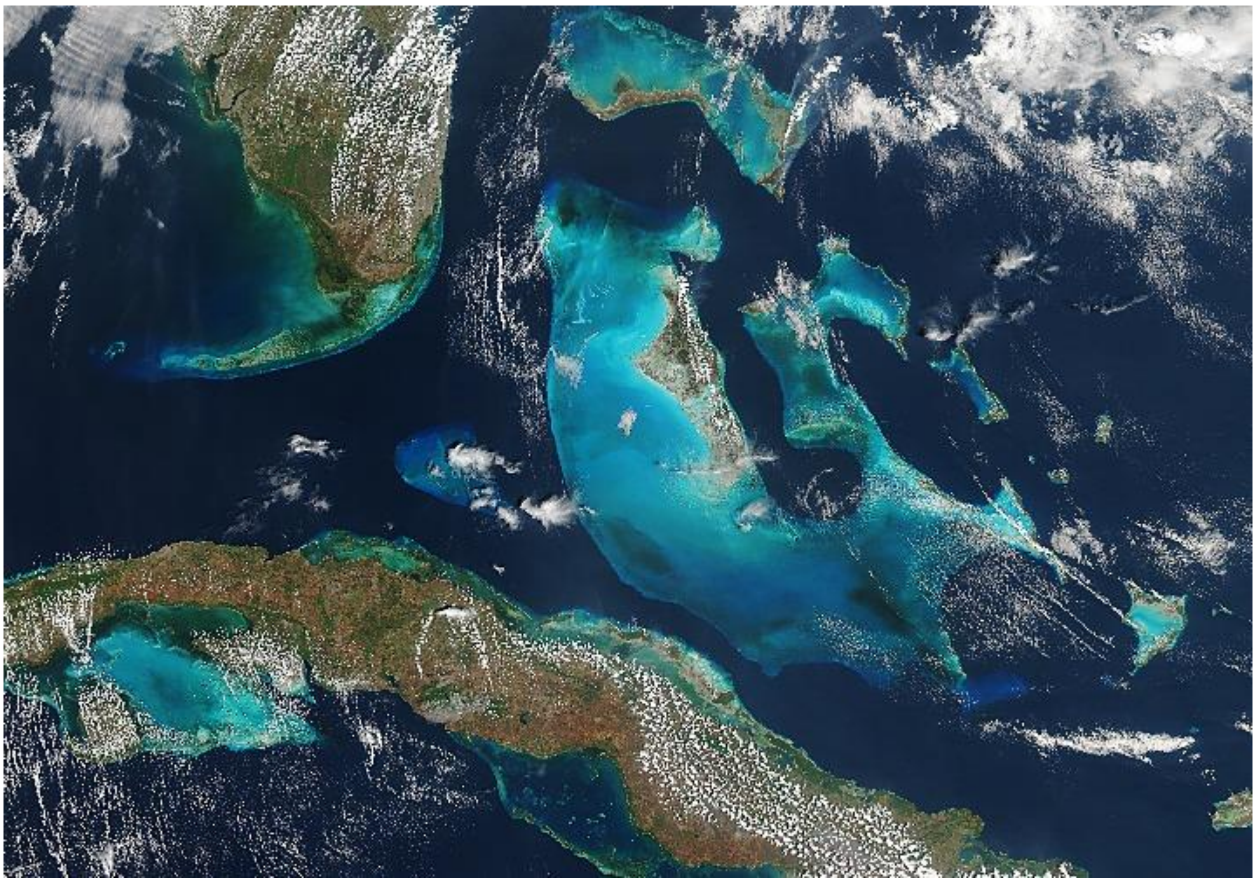
Creating Reprojected True Color VIIRS Images: A Tutorial



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1. Introduction

The Visible Infrared Imaging Radiometer Suite (VIIRS), on board the Suomi National Polar-orbiting Partnership (SNPP) spacecraft, has been providing continuous coverage of the earth since its launch in October 2011. The spacecraft has an equatorial crossing time of 1.30 pm local time. Data from the VIIRS instrument is transmitted both (i) in real time via the HRD (High Rate Data) Direct Broadcast and (ii) once per orbit via SMD (Stored Mission Data recorded to the on-board SSR [Solid State Recorder]) to the ground station at Svalbard, Norway.

Although the VIIRS sensor derives its heritage from three sensors - Advanced Very High Resolution Radiometer (AVHRR), the Operational Line Scanner (OLS) and the Moderate Resolution Imaging Spectroradiometer (MODIS) - the MODIS sensor can be considered its primary predecessor. Like MODIS, VIIRS is a nadir viewing, cross-track observing sensor that collects scene spectral radiance in multiple channels spanning the visible through infrared regions. Like MODIS, its visible channels include the red, green and blue channels. The existence of these channels enables VIIRS, like MODIS, to visualize the earth scene in true color.

The VIIRS true color image is a rendition of the sensor scan in natural colors and thus can be considered the equivalent of a ‘photograph’ of the earth scene. True Color images, if constructed correctly, produce remarkable depictions of our home planet. VIIRS is able to provide such images at a relatively high resolution of 375m. Each VIIRS scan (scan rate = 1 scan/1.7864 seconds) is about 3000 km across track and 12 km along track. A VIIRS true color image can span multiple scans and can be mosaiced as necessary to cover a region of interest. True color images are used in multiple earth science disciplines to visualize earth features and phenomena and as background images to provide more context to other earth science data overlaid on them.

The objective of this document is to explain how sharpened, re-projected, high resolution VIIRS true color images can be created from VIIRS calibrated and geolocated top of atmosphere reflectances. Tools, developed for creating VIIRS True Color images, are also presented.

1.1 Credits

- This tutorial represents an evolution of techniques originally developed for MODIS. The MODIS techniques and principles were presented in the following article:

  Gumley, L., Descloitres, J., & Schmaltz, J. “Creating Reprojected True Color MODIS Images: A Tutorial”, Version 1.0.2, 14 January, 2010.

  This tutorial follows the structure of the latter MODIS article to provide continuity for legacy users. However the techniques and principles have been modified as necessary and extended to fit the VIIRS paradigm.

- The techniques for generating VIIRS true color images, as presented in this article, have been implemented in the BlueMarble software package. BlueMarble was developed by the Direct Readout Laboratory (DRL), NASA/GSFC. The software continues to improve and evolve through a collaborative process. True Color Images produced with BlueMarble are expected to be equally good or better than True Color images generated through other existing institutional software that are based on the principles presented here.

- BlueMarble's reprojection capability utilizes the JPROJ.4 Java Native Interface (JNI) to the PROJ.4 Cartographic Projections Library. The PROJ.4 library was initially developed by the U.S. Geological Survey (USGS) and is currently being maintained/enhanced by the Open Source Geospatial Foundation (OSGeo).

- The CVIIRS_SPA, presented in this article as the way for generating corrected reflectances, was co-developed by the NASA Land Science Team and the DRL at NASA/GSFC.

- The ImageMagick Linux utility, presented in this article as a way of enhancing the VIIRS True Color image, is free software maintained by the ImageMagick Studio LLC and is distributed under the Apache 2.0 license. ImageMagick is approved by the OSI (Open Source Initiative) and has been recommended for use by the OSSCC (Open Source Software Collaboration Counseling).

1.2 Required Software

Users will need to download the following software in order to create VIIRS True Color images. These software packages are all freely available.

Software	**Link for download**
CVIIRS_SPA	https://directreadout.sci.gsfc.nasa.gov/?id=software
BlueMarble	https://directreadout.sci.gsfc.nasa.gov/?id=software
Imagemagick	http://imagemagick.org/index.php

CVIIRS_SPA and BlueMarble have been developed to run on 64-bit Linux platforms. They are self-contained and include all source code and supporting packages (e.g., python, Java, proj4, HDF4/HDF5 libraries). This makes them very easy to install (just untar the package tarballs). Moreover, since these two software packages utilize DRL's algorithm wrapper technique, they are very easy to operate either as standalone packages or as plug-ins to the IPOPP (International Polar Orbiter Processing Package) framework. Please refer to the corresponding User's Guides (available along with the packages) for more details. Detailed information about all DRL technologies is available at the DRL Web Portal: http://directreadout.sci.gsfc.nasa.gov

NOTE: BlueMarble can also create sharpened, high resolution, reprojected MODIS True Color Images. See BlueMarble User's Guide for details.

ImageMagick is a Linux utility and is required to optionally enhance the final True Color Image. Please refer to http://www.imagemagick.org/ for installation instructions.

2. VIIRS True Color Fundamentals

The VIIRS instrument has 22 bands that include 16 moderate resolution (750m) bands, 5 imaging resolution (375m) bands, and a Day Night Band (DNB). For the purposes of generating a True Color image, the spectral bands of interest are the red, green and blue bands. They are as follows:

RGB Bands	Bandwidth (μm)	Spatial Resolution
M5 (Red)	0.662-0.682	750m
I1 (Red)	0.6 – 0.68	375m
M4 (Green)	0.545-0.565	750m
M3 (Blue)	0.478-0.488	750m

2.1 Procedure Outline

The steps for creating a VIIRS True Color Image are outlined in Figure 1. The steps are explained in details in the following sections. However a quick overview of the steps should be helpful at this point. The first step is to create corrected reflectances for the VIIRS M5, I1, M4, M3 bands using the CVIIRS_SPA. The next steps can all be done using the BlueMarble software. They involve sharpening the M3 and M4 bands, reprojecting the I1 and the sharpened M3 and M4 bands, creating and enhancing the 8-bit RGB brightness values, creating the image file, and finally enhancing the image file using ImageMagick.

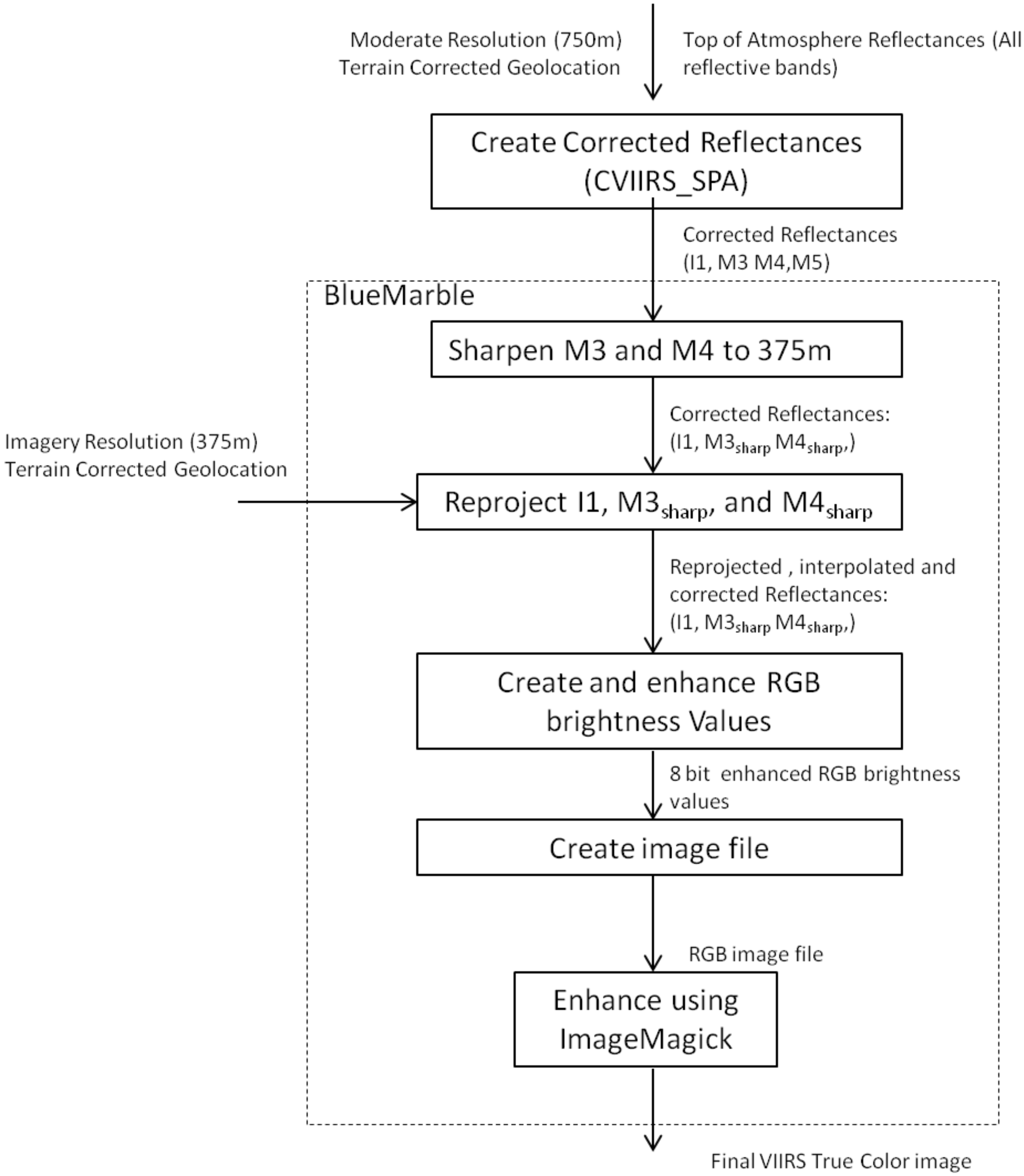

Figure 1: Steps to Create a Sharpened, Reprojected VIIRS True Color Image

2.2 Required Input Products

The following data products are required for creating VIIRS True Color Images:

VIIRS Moderate Resolution MX band Calibrated/Geolocated TOA Reflectances, x=3,4,5,7,8,10,11
VIIRS Imagery Resolution IX band Calibrated/Geolocated TOA Reflectances, x= 1,2,3
VIIRS Moderate Resolution Terrain Corrected Geolocation
VIIRS Imagery Resolution Terrain Corrected Geolocation

These products may be available in different file formats depending on the source. Data products are available from the NASA research archives or the NOAA operational archives. For the purposes of this tutorial, we use data from the NOAA CLASS (http://www.class.noaa.gov) operational archive. Data products from CLASS are in HDF5 format and are S-NPP CDFCB (Common Data Format Control Book) compliant. Note that SDRs can also be generated from RDRs (Raw Data Records) using the C-SDR_SPA (available for download from the DRL Web Portal). This tutorial will use the following SDR set as an example input dataset:

SVM03_npp_d20130323_t1850298_e1856084_b07270_c20130324005610824762_noaa_ops.h5
SVM04_npp_d20130323_t1850298_e1856084_b07270_c20130324005610825035_noaa_ops.h5
SVM05_npp_d20130323_t1850298_e1856084_b07270_c20130324005610825305_noaa_ops.h5
SVM07_npp_d20130323_t1850298_e1856084_b07270_c20130324005610825853_noaa_ops.h5
SVM08_npp_d20130323_t1850298_e1856084_b07270_c20130324005610826134_noaa_ops.h5
SVM10_npp_d20130323_t1850298_e1856084_b07270_c20130324005610822487_noaa_ops.h5
SVM11_npp_d20130323_t1850298_e1856084_b07270_c20130324005610822812_noaa_ops.h5
SVI01_npp_d20130323_t1850298_e1856084_b07270_c20130324005609862393_noaa_ops.h5
SVI02_npp_d20130323_t1850298_e1856084_b07270_c20130324005609862763_noaa_ops.h5
SVI03_npp_d20130323_t1850298_e1856084_b07270_c20130324005609863069_noaa_ops.h5
GMTCO_npp_d20130323_t1850298_e1856084_b07270_c20130324005610015889_noaa_ops.h5
GITCO_npp_d20130323_t1850298_e1856084_b07270_c20130324005610053512_noaa_ops.h5

NOTE: Please select the appropriate SDR datasets to cover the region and time of interest. The observation time is usually available from the filename. SNPP CDFCB compliant HDF5 VIIRS SDR files have the following naming convention:

XXXXX_npp _dyyyyMMdd_thhmmssS_ehhmmssS*.h5

Where XXXX refers to the SDR short name; yyyy, MM, dd represents the year, month, and day of month for the start of the swath; the first hh, mm, ss, S represents the hour, minutes, seconds, and 10^{th} of a second for the start of the swath and the second hh, mm, ss, S represents the end time of the swath. NOAA CLASS provides online tools to search data for a region of interest. More than one file set may be needed depending on the extent of the time and region of interest.

NOTE: The input products also include VIIRS I and M bands other than the red, green, and blue bands. This is only because the CVIIRS_SPA corrects all reflective bands and thus requires all of them as input. The subsequent true color generation procedure however uses only the red, green, blue corrected reflectance data products.

3. Creating a VIIRS True Color Image

STEP 1: Create Corrected Reflectances

The CVIIRS_SPA creates the VIIRS Corrected Reflectance products by performing simple atmospheric correction for the VIIRS visible, near-infrared, and short-wave infrared bands (bands M5, M7, M3, M4, M8, M10, M11, I1, I2, and I3). It corrects for molecular (Rayleigh) scattering and gaseous absorption (water vapor and ozone) using climatological values for gas contents. It requires no real-time input of ancillary data, and performs no aerosol correction. The VIIRS Corrected Reflectance products created by CVIIRS_SPA are based on the 6S Radiative Transfer Model.

Installation of CVIIRS_SPA is easy. Just download, untar and gunzip the CVIIRS_SPA tarball. Please refer to the CVIIRS_SPA User's Guide for detailed instructions and prerequisites.

The following is an example of a command line to run the CVIIRS algorithm ($CVIIRS_SPA_HOME is assumed to point to the SPA/CVIIRS directory and $DATADIR is assumed to point to the data directory).

```
$CVIIRS_SPA_HOME/wrapper/CVIIRS/run \
viirs.svm03 $DATADIR/SVM03_npp_d20130323_t1850298_e1856084_b07270_c20130324005610824762_noaa_ops.h5 \
viirs.svm04 $DATADIR/SVM04_npp_d20130323_t1850298_e1856084_b07270_c20130324005610825035_noaa_ops.h5 \
viirs.svm05 $DATADIR/SVM05_npp_d20130323_t1850298_e1856084_b07270_c20130324005610825305_noaa_ops.h5 \
viirs.svm07 $DATADIR/SVM07_npp_d20130323_t1850298_e1856084_b07270_c20130324005610825853_noaa_ops.h5 \
viirs.svm08 $DATADIR/SVM08_npp_d20130323_t1850298_e1856084_b07270_c20130324005610826134_noaa_ops.h5 \
viirs.svm10 $DATADIR/SVM10_npp_d20130323_t1850298_e1856084_b07270_c20130324005610822487_noaa_ops.h5 \
viirs.svm11 $DATADIR/SVM11_npp_d20130323_t1850298_e1856084_b07270_c20130324005610822812_noaa_ops.h5 \
viirs.svi01 $DATADIR/SVI01_npp_d20130323_t1850298_e1856084_b07270_c20130324005609862393_noaa_ops.h5 \
viirs.svi02 $DATADIR/SVI02_npp_d20130323_t1850298_e1856084_b07270_c20130324005609862763_noaa_ops.h5 \
viirs.svi03 $DATADIR/SVI03_npp_d20130323_t1850298_e1856084_b07270_c20130324005609863069_noaa_ops.h5 \
viirs.gmtco $DATADIR/GMTCO_npp_d20130323_t1850298_e1856084_b07270_c20130324005610015889_noaa_ops.h5 \
viirs.mcrefl $DATADIR/CVIIRSM_npp_d20130323_t1850298_e1856084.h5 \
viirs.icrefl $DATADIR/CVIIRSI_npp_d20130323_t1850298_e1856084.h5
```

The viirs.xxxxx are the input labels and is used to specify the path to the corresponding SDR input. The viirs.mcrefl and the viirs.icrefl are the output labels. They are used to specify the paths to the VIIRS Moderate Resolution Corrected Reflectance output HDF file and the VIIRS Imagery Resolution Corrected Reflectance output HDF file respectively.

CVIIRS Reflectance Product File Formats: The following table contains descriptions of datasets within the VIIRS Moderate and Imagery resolution Corrected Reflectance HDF4 products.

CVIIRS HDF4 Output Files	HDF4 Dataset Name	Dataset Description
CVIIRS Moderate Resolution Corrected Reflectance HDF	CorrRefl_01	M5 Corrected reflectances
	CorrRefl_02	M7 Corrected reflectances
	CorrRefl_03	M3 Corrected reflectances
	CorrRefl_04	M4 Corrected reflectances
	CorrRefl_05	M8 Corrected reflectances
	CorrRefl_06	M10 Corrected reflectances
	CorrRefl_07	M11 Corrected reflectances

CVIIRS Imagery Resolution Corrected Reflectance HDF	CorrRefl_08	I1 Corrected reflectances
	CorrRefl_09	I2 Corrected reflectances
	CorrRefl_10	I3 Corrected reflectances

The arrays named ‘CorrRefl_01’, ‘CorrRefl_03’, ‘CorrRefl_04’ and ‘CorrRefl_08’ contain the scaled corrected reflectances for VIIRS Bands M5 (Red), M3 (Blue), M4 (Green) and I1 (Imagery resolution Red) respectively. The values are stored as 16-bit signed integers with a scale factor of 0.0001. The following equation can be used to retrieve the unscaled corrected reflectance in reflectance units.

Unscaled corrected reflectance= Scaled corrected reflectance * 0.0001

NOTE: BlueMarble automatically does the needed conversions. Refer to Section 4.0 “Running BlueMarble” if you just want to create a VIIRS True Color Image.

STEP 2: Sharpen the M3 and M4 Bands to 375m

NOTE: Steps 2 to 6 have already been implemented in the BlueMarble software package. You may skip to Section 4.0 “Running BlueMarble”, if you just want to create a VIIRS True Color Image.

VIIRS has a high resolution red band (I1) at 375m. However its green and blue bands (M4 and M3) are available only at the lower 750m resolution. This implies that in order to create a high resolution 375m True Color image, the M4 and M3 bands must be resampled to 375m. However, simply resampling from 750m to 375m will not adequately capture the sub pixel differences at the 375m resolution. In short the resampled 375m M4 and M3 will not be sharp enough. Sharpening can be done by computing the spatial resolution ratio between a low resolution (I1 resampled to 750m resolution) and a high resolution band (I1 in its native 375m resolution) and then incorporating it into the M3, M4 resampling process. The steps for resolution sharpening are presented below.

First, the spatial resolution ratio is computed from the low and high resolution VIIRS red bands.

$$R = I1^* / I1$$

where

R	spatial resolution ratio
I1*	VIIRS I1 first resampled to 750m resolution and then resampled back to 375m. The double resampling process creates an unsharpened 375m red band.

I1 VIIRS I1 at native 375m resolution

Then the sharpened VIIRS Green (M4) and VIIRS Blue (M3) are computed by

$M4_{sharp} = M4^* / R$

$M3_{sharp} = M3^* / R$

where

$M4^*$, $M3^*$ Bands M4 and M3 (750m resolution), resampled to 375m

$M4_{sharp}$, $M3_{sharp}$ Bands M4 and M3 sharpened to 375m

The spatial resolution ratio embodies the difference in low and high resolution red bands. It is assumed that this ratio applies across the other two bands, and thus can be used to construct the sharpened high resolution green and blue bands. While this method works well (see Figure 2) for creating sharpened true color images, its scientific validity should be evaluated before applying it elsewhere.

Resampling for resolution sharpening: The sharpening algorithm requires the 375m I1 band to be resampled to 750m, and the 750m I1* (See above), M4 and M3 bands to be resampled to 375m. Since the VIIRS 375m scan is perfectly aligned with the 750m scan (i.e., four 375 pixels lie inside one 750m pixel; see Figure 3), you may use a general purpose resampling tool to resample the 750m swath into a 375m swath and vice versa. For up-sampling, this amounts to taking each 750m pixel and creating four contained 375m pixels with the same reflectance value. For down-sampling this amounts to taking the four 375m pixels in the 750m pixel and averaging them to create a single 750m pixel.

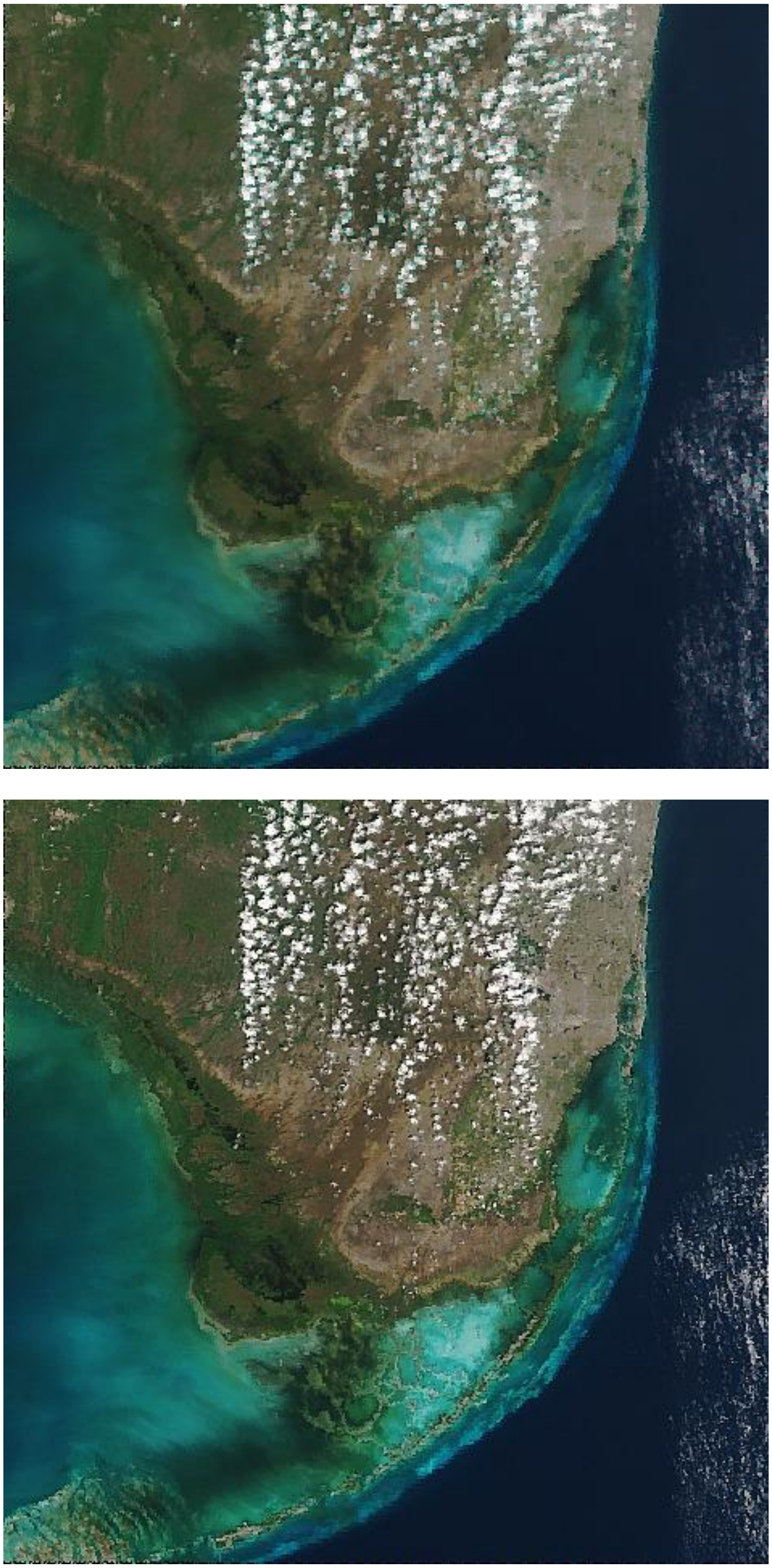

Figure 2: VIIRS true color images at 375m resolution.
Top: unsharpened; Bottom: sharpened

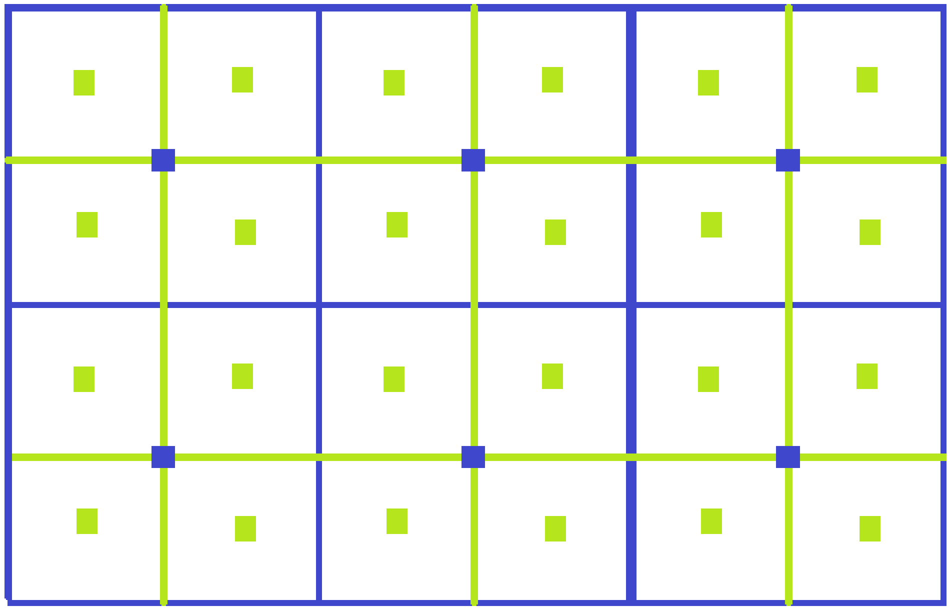

Figure 3: VIIRS 750m (blue) and 375m pixel (green) registration

STEP 3: Reproject I1, $M3_{sharp}$, $M4_{sharp}$

At this point the 375m I1, $M3_{sharp}$, $M4_{sharp}$ bands are in swath format. They need to be projected into a desired projection grid for better visualization. The Imagery resolution terrain corrected geolocation should be used as the input geolocation for the projection operation.

NOTE: Implementing a reprojection module involves understanding of projection systems, interfacing with projection tools and/or libraries, designing and implementing an adequate interpolation mechanism, handling fill values, dropouts and bowtie trim pixels, etc. The BlueMarble software package already incorporates a re-projection engine to perform reprojection and other related functions for the specific purpose of creating VIIRS True Color image. Refer to Section 4.0 "Running BlueMarble" if you just want to create a VIIRS True Color Image. BlueMarble currently supports geographic and stereographic projections. Other projections will be supported in the future. The stereographic projection capability utilizes the JPROJ.4 Java Native Interface (JNI) to the PROJ.4 Cartographic Projections Library.

STEP 4: Create and enhance RGB brightness values

The corrected and reprojected reflectance values for the I1, $M3_{sharp}$, and $M4_{sharp}$ bands are in floating point. They should now be scaled into 8-bit brightness values using a linear mapping. For example, a typical conversion would linearly scale floating point reflectances in the range 0.0 to 1.1 to brightness values in the range 0 to 255. For scenes containing no clouds, a reflectance range of 0.0 to 0.8 may be more appropriate.

Next, a non-linear enhancement technique should be used to adjust the brightness values for the I1, $M3_{sharp}$, and $M4_{sharp}$ bands. The enhancement is designed to increase the brightness of darker pixels such as land or water. The following table lists the set points for the non-linear enhancement.

Non Linear Brightness Enhancement Table (non-cloud)

Input Brightness	**Output Brightness**
0	0
30	110
60	160
120	210
190	240
255	255

The set points imply that brightness values between 0 and 30 should be linearly scaled between 0 and 110, brightness values between 30 and 60 should be linearly scaled between 110 and 160, and so on.

NOTE: The non-linear enhancement technique presented here is same as the one that was recommended for MODIS. Jacques Descloitres at NASA/GSFC developed it for enhancing MODIS True Color Images. Note that this enhancement table was designed for scenes which do not contain bright clouds.

STEP 5: Create an image file

Once you have linearly scaled brightness values, and applied the non-linear enhancement, the resulting brightness values can be used to create the image file. The mapping of the VIIRS bands to RGB channels in the image file should be as follows:

I1 → Red Channel; $M4_{sharp}$ → Green Channel; $M3_{sharp}$ → Blue Channel

NOTE: BlueMarble can create the true color image products in either geotiff or png formats. It uses Java Advanced Imaging (JAI) libraries to create and manipulate images. Refer to Section 4.0 “Running BlueMarble” to create a VIIRS True Color Image.

STEP 6: Enhance using ImageMagick

The final step is to use the ImageMagick toolkit to improve the image appearance. The image appearance can usually be improved by enhancing the lightness and saturation of the image, and by applying a sharpening algorithm. Depending on user requirements, ImageMagick can also be used to create an image in Web-friendly formats such as JPEG and/or to create lower resolution versions of the final image. The following script shows how this can be achieved using the ImageMagick convert program:

```
#!/bin/csh
# Script to convert a VIIRS true color 375meter reprojected image
# to JPEG format at 375 meter, 750 meter, and thumbnail resolution
# using the ImageMagick 'convert' utility
convert -quality 85 -modulate 105,125 -sharpen 3 TRUECOLOR.tif  TRUECOLOR_375m.jpg
convert -modulate 105,125 -geometry 50% TRUECOLOR.tif  TRUECOLOR_750m.jpg
convert -geometry 150x150 TRUECOLOR_750m.jpg TRUECOLOR_thumb.jpg
```

The first call to the ‘convert’ utility sets the JPEG quality to 85%; lightness enhancement to 5%; saturation enhancement to 25%; and a Laplacian sharpening operator to a radius of 3 pixels in order to create a JPEG version of the 375 meter resolution image. The second call creates a 750 meter resolution JPEG image with the same lightness and saturation enhancements. The third call to ‘convert’ creates a thumbnail true color image.

NOTE: The Blue Marble package allows the specification of a 'resolution' parameter to allow creation of lower resolution (e.g., 750m and thumbnail size) images. Refer to Section 4.0 “Running BlueMarble” for using the BlueMarble package to create a VIIRS True Color Image.

4. Running BlueMarble

BlueMarble takes a VIIRS Imagery resolution Corrected Reflectance product, VIIRS Moderate resolution Corrected Reflectance product and VIIRS Imagery resolution Terrain Corrected Geolocation as input and produces a sharpened VIIRS True Color image product. BlueMarble can create the image products in geotiff format. The geolocated GeoTIFF images are Geographic Information System (GIS)-ingestible and can also be opened by standard image viewers. BlueMarble also provides utilities to overlay land/sea and political boundary shapefiles.

Installation of BlueMarble is easy. Just download, untar and gunzip the BlueMarble tarball. Please refer to the BlueMarble User's Guide for detailed instructions and prerequisites.

The following is an example of a command line to run the BlueMarble VIIRS sharpened True Color algorithm ($BM_HOME is assumed to point to the SPA/BlueMarble directory, $DATADIR is assumed to point to the data directory and $OUTDIR is assumed to point to the output directory):

```
$BM_HOME/algorithm/DRL_scripts/viirs_truecolor.sh \
 cviirsm "$DATADIR/CVIIRSM_npp_d20130323*" \
 geodir $DATADIR \
 outdir $OUTDIR \
 projection stereographic resolution 375 \
 centerlat 23.25 centerlon -82.0 width 1000 height 1000
```

Description of command line labels:

1. The ‘cviirsm’ label is used to specify the pattern to use to find VIIRS Moderate Resolution Corrected Reflectance Products for processing within quotes (e.g. "../testdata/input/CVIIRSM_npp_d20130323*"). The VIIRS Imagery Resolution Corrected Reflectance Product should be in the same directory.

2. The ‘geodir’ label is used to point to the path to the directory containing the VIIRS Imagery Resolution Terrain Corrected Geolocation Products corresponding to the Corrected Reflectance products.

3. The ‘projection’ label can be either (a) ‘geographic’ or (b) ‘stereographic’. If not specified, the parameter defaults to ‘stereographic’.

4. The 'resolution' label is used to specify the resolution in projection space for the output image product. When using the geographic projection, resolution should be specified in degrees. When using the stereographic projection, resolution should be specified in meters. When not used the 'resolution' parameter defaults to 375m for stereographic and 0.00375 degrees for geographic projections.

5. The four parameters ‘centerlat’, ‘centerlon’, ‘height’, ‘width’ define the Region-of-Interest (ROI). 'centerlat' and 'centerlon' represent the center of the ROI used in output image product. They should be specified in latitude/longitude degrees. For stereographic images, this point also represents the center of projection. The 'height' and 'width' parameters are used to specify the north-south and east-west extents of the ROI respectively. For stereographic projections, 'height' and 'width' are to be specified in km. For geographic projections, the 'height' and 'width' are to be specified in latitude/longitude degrees. These four ROI parameters are optional; If not provided, swath imagery will be produced for all matching inputs specified using the 'cviirsm' label.

6. The ‘outdir’ label is used to specify the directory where output imagery will be produced. The directory, if it exists should be empty. Otherwise the script will create the directory as long as the path to it is valid. When the ROI labels are used, the 'outdir' directory will contain ROI subset imagery for each input that overlaps with the specified ROI and the final mosaiced image created by compositing all the component subset images from each overlapping input.

When ROI labels are not used, the 'outdir' will contain swath imagery for each matching input.

5. Contact Us

We look forward to receiving your input as we continue to evolve this tutorial and associated software in response to user needs. Questions and comments about this tutorial should be addressed to the DRL via the Contact DRL mechanism at the DRL Web Portal: http://directreadout.sci.gsfc.nasa.gov/?id=dspContent&cid=66