Methods Used For the 2006 Radiance Lights

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Abstract: The Operational Linescan System (OLS) flown on the Defense Meteorological Satellite Program (DMSP) satellites, has a unique capability to record low light imaging data at night worldwide. These data are archived at the National Oceanic and Atmospheric Administration (NOAA) National Geophysical Data Center (NGDC). The useful data record stretches back to 1992 and is ongoing. The OLS visible band detector observes radiances about one million times dimmer than most other Earth observing satellites. The sensor is typically operated in a high gain setting to enable the detection of moonlit clouds. However, with six bit quantization and limited dynamic range, the recorded data are saturated in the bright cores of urban centers. A limited set of observations have been obtained at low lunar illumination were obtained where the gain of the detector was set significantly lower than its typical operational setting (sometimes by a factor of 100). By combining these sparse data acquired at low gain settings with the operational data acquired at high gain settings, we have produced a global nighttime lights product for 2006 with no sensor saturation. This product can be related to radiances based on the pre-flights sensor calibration.

Keywords: Nighttime Lights, DMSP, Radiance, Calibration

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1. Introduction

The Operation Linescan System (OLS) flown on the Defense Meteorological Satellite Program (DMSP) satellites collects both daytime and nighttime data in broad visible and thermal infrared spectral bands. At night the visible band signal is intensified a million-fold with a photomultiplier tube to enable the detection of moonlit clouds. In addition to moonlit clouds, the OLS detects lights present at the Earth's surface. The lighting types detected include cities and towns, biomass burning, gas flares and heavily lit fishing boats [Elvidge *et al*, 1997].

The gain on the visible channel is adjusted through the lunar cycle with the objective of maintaining a consistent image product for use in the visual analysis of cloud features. During periods of high lunar illuminance the electronic amplification (henceforth gain) of the OLS is set relatively low. As the moonlight diminishes, the gain is increased. The gain remains high for the periods of low lunar illuminance and is gradually lowered as the moon light increases. When there is no moonlight, the sensor is unable to detect clouds in the visible band, yielding images that only contain lights present at the Earth's surface. These are the best images for constructing maps of nighttime lights since there is no confusion between lights and moonlit clouds. However, these are also the images with the greatest level of saturation in urban cores. The conversion of the OLS nighttime visible band data to radiance units is complicated by the signal saturation in urban centers, the lack of on-board calibration, automated gain changes which occur within scanlines, and the fact that the gain changes are not recorded in the data stream. To partially address these issues, NGDC developed a strategy for collecting fixed gain data at low, medium and high gain settings and conversion to "radiance" based on the pre-flight calibration available for each of the OLS sensors. Starting in 1996, NGDC has on occasion requested and received collection of OLS data made at fixed gain settings during the new moon stages of certain lunar cycles. In 1999 NGDC produced a nighttime lights product made with these special data collections [Elvidge *et al*, 1999]. The image digital values were related to radiances based on the pre-flight calibration. The OLS lacks an on-board calibration system for the visible band. Advances in processing algorithms and recognition that dimmer lighting can be detected with the operation high gain OLS data has lead to a new round of radiance lights product development.

A new collection of fixed gain (low, medium and high) data was made in year 2006 using satellite F15. In this paper we report on the steps used to make a year 2006 radiance lights product.

2. Methods

We created two annual nighttime lights composites from the satellite F16 data collected in 2006. One product is the standard stable lights processed from the operational data. A total of 3858 orbits were found to contain operational data used for the stable lights product (Table 1). The stable lights product has saturation (DN=63) in the bright cores of urban centers, but has unsaturated detections of dim lighting in populated rural and suburban area. A second product was generated with the low, medium and high gain setting data (Table 1). The second product has unsaturated values in the bright cores of urban centers but does not detect the dimmer lighting found in the stable lights. By merging these two products, taking the unsaturated values only, we were able to successfully overcome the dynamic range limitations of the OLS.

2.1 Stable Lights

The stable lights are constructed by compositing orbital sections that meet a stringent set of criteria, namely:

1. Center half of orbital swath (best geolocation, reduced noise, and sharpest features).
2. No sunlight present.
3. No moonlight present.
4. No solar glare contamination.
5. Cloud-free (based on thermal detection of clouds).
6. No contamination from auroral emissions.

Nighttime image data from individual orbits that meet the above criteria are added into a global latitude-longitude grid (Platte Carree projection) having a resolution of 30 arc seconds. This grid cell size is approximately a square kilometer at the equator.

These products are then filtered for noise and transient sources of light (such as wildfires). This product is referred to as Stable Lights [Baugh *et al*, 2010]. The Stable Lights product is well suited for the study of the distribution of persistent light around the world. Unfortunately, there is a major shortcoming associated with this product. Because the gain is high during low-moon collection times the radiance from bright objects such as urban cores or gas flares saturates the detector and information is indiscernible (see Figure 1).

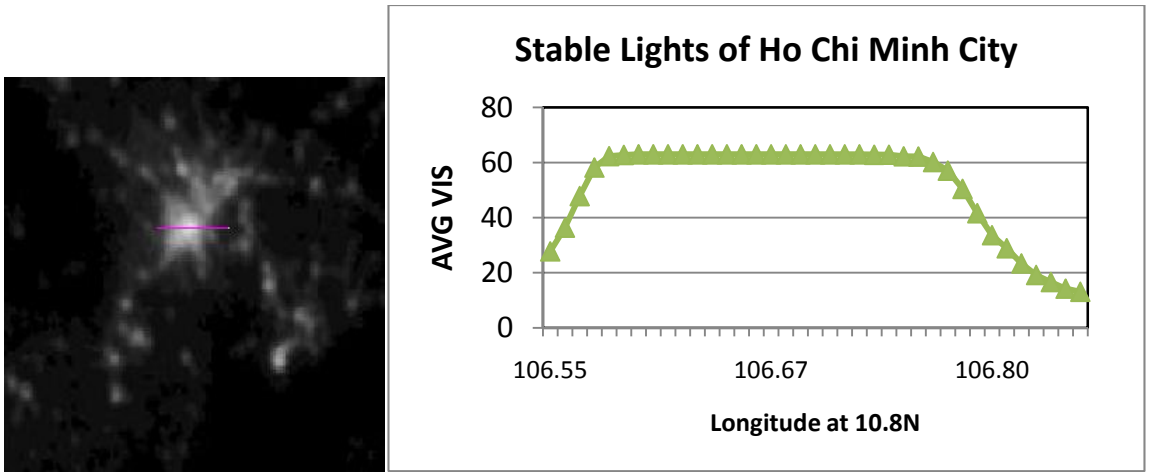


Figure 1. Stable Lights of Ho Chi Minh City. The left image shows the Stable Lights of Ho Chi Minh City, Vietnam taken by the F16 in the 2006 composite. The right plot shows the Average Visible Digital Number (DN) for an east-west transect across the middle of the city. The DN value plateaus at 63, which is the saturation value.

2.2 Fixed Gain Product:

The overall approach is to merge the observations made at various reduced gains into one merged Fixed Gain product and then to blend this with the Stable Lights. The purpose is to overcome the limited dynamic range of the OLS during its normal operational mode.

2.2.1. Instrument Gain

The instrument gain is a setting that determines how the detector converts the impinging radiance (R) into a Digital Number (DN). The relevant equations are:

$$DN = DN_{max} \, (R / R_{sat}),$$

where DN_{max} is 63 (6-bit quantization) and R_{sat} is the saturation radiance of the detector and is a logarithmic function of the gain.

$$Log_{10} R_{sat} \approx - (105.4 + G) / 20,$$

where G is the gain and the units of R_{sat} are W cm^{-2} Sr^{-1}. The fiducial value of G is 55. The coefficients of the relationship between gain and saturation were read from a pre-launch calibration graph and are subject to change as the instrument degrades.

Under operational conditions the gain is varied both along each scan line and as the satellite follows its polar orbit. The result is that even under large swings in solar and lunar illumination, an image can be created of relatively consistent contrast for visual analysis. However, the gain is not recorded in the data stream and must be reconstructed from the relative positions of the sun and moon, and onboard stored constants.

Fixed Gain situations are requested during low-moon segments of the lunar cycle when the data is less useful for USAF operations. During those periods the gain is set at a particular value and held constant for an arc of orbit over the course of a day. The gains for satellite F16 in 2006 and their characteristic properties are described in Table 1. The orbits for the fixed gain products are selected by the same criteria mentioned above for the stable lights product, except the full swath (not just the middle portion) is used for the lowest gain setting (FG15).

Table 1. Gain characteristics.

Gain Setting	**Saturation Radiance W cm^{-2} Sr^{-1}**	**Multiplier**	**Number of Orbits**
Operational	~9.55e-9	1	3858
55	9.55e-9	1	334
35	9.55e-8	10	504
15	9.55e-7	100	341

2.2.2. Low Coverage

From the number of orbits presented in Table 1, it can be seen that the Fixed Gain product contains far fewer observations than the Stable Lights product. In most places around the world, the number of coverages is adequate. There are a few locations that suffer from low numbers of observations. This is particularly seen in characteristically cloudy regions such as Indonesia, and in the far north where there is significant auroral contamination that must be avoided and is only dark enough a few months each year. Figure 2 compares the number of cloud-free observations for the Fixed Gain product and the Stable Lights. As the number of coverages increases, so does the data quality because instrumental noise is suppressed and a more characteristic value is measured for highly variable light sources.

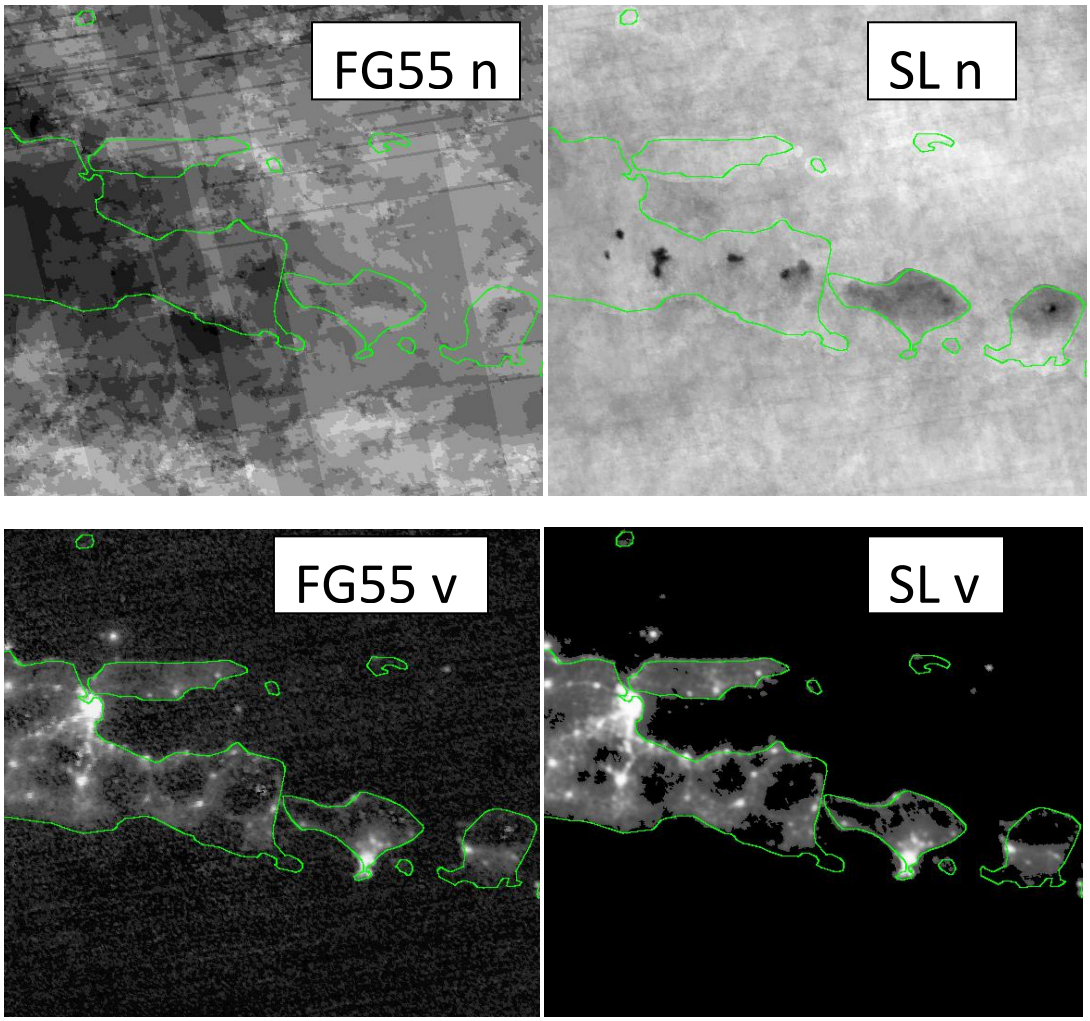


Figure 2. Cloud-free Coverage Comparison. The images labeled (FG55 n) and (SL n) show the number of cloud-free coverages over the region around Bali. Figure (FG55 n) is from the Fixed Gain 55 composite and (SL n) is from the Stable Lights. Furthermore, they are shown in different gray scales. The range of observations in (FG55 n) is from 1 (black) to 11 (white), and in contrast to (SL n), which has significantly more coverages at 16 or less (black) to 62+ (white). The second row, labeled (FG55 v) and (SL v), shows the average visual composites. There is a square root stretch applied which accentuates the lower DN values. The noise over the ocean and fuzzy delineation is apparent in the FG55 image.

2.2.3. Merging Radiances of Different Gain Settings

Developing an appropriate procedure to merge the fixed gain products (low, medium and high) has been an iterative process. Three methods were developed and tested.

Method 1: This is the simplest method. It uses a set of multipliers to combine the four composites to construct a merged composite (DN_m).

$$DN_m = (DN_{15} * n_{15} * X_{15} + DN_{35} * n_{35} * X_{35} + DN_{55} * n_{55} * X_{55}) / (n_{15} + n_{35} + n_{55}),$$

where, for each pixel, DN_i is the average value at the specified fixed gain, X_i is the multiplier, and n_i is the number of observations.

This method is demonstrated in Figure 3a, that displays an east-west transect through the city of Ho Chi Minh City in Vietnam. The three average fixed-gain settings are shown, with multipliers applied. FG55 and FG35 are saturated through the urban core. When they are averaged with the unsaturated FG15 data the result is obviously an underestimation of the city's brightness.

Method 2: One approach for addressing this problem is to screen the data to exclude saturated pixels. Since saturation occurs at DN=63, we tried setting a threshold to prevent saturated pixels from contaminating the average. Figure 3b shows the result when any pixels with a DN of 55 or higher are filtered out of the merger ("DN55"). Although the bright urban core matches the FG15 curve because no other gain settings contribute, there are two problems evident with this approach. One problem is the discontinuity around 106.68E, when FG35 is suddenly included in the merged product. The second problem is the systematically depressed DN values in FG35, even though the signal is below saturation levels.

At full spatial resolution (called "fine"), the OLS collects data with a nominal pixel size of 0.56 km. These data are spatially averaged onboard as a 5x5 pixel block and transmitted down as "smooth" data. The smooth data has a nominal spatial resolution of 2.8 km [Elvidge *et al*, 1997]. Often, saturated and non-saturated fine pixels get averaged together so the resultant data appears non-saturated. This situation is especially prevalent on the edges of cities, where the smooth data is comprised of fine pixels from both the saturated urban core and non-saturated suburban pixels. This often leads to misleadingly low DN values as the light levels approach saturation.

Method 3: In order to solve both the abrupt discontinuities introduced by threshold screening and to reduce the influence of sub-pixel saturation near bright objects, a third method was developed. This method is based on the concept of a weighted mean, where values far from their saturation level are weighted higher in the merging process. So, the formula for the simple merge would be modified by the weighting factor W_i:

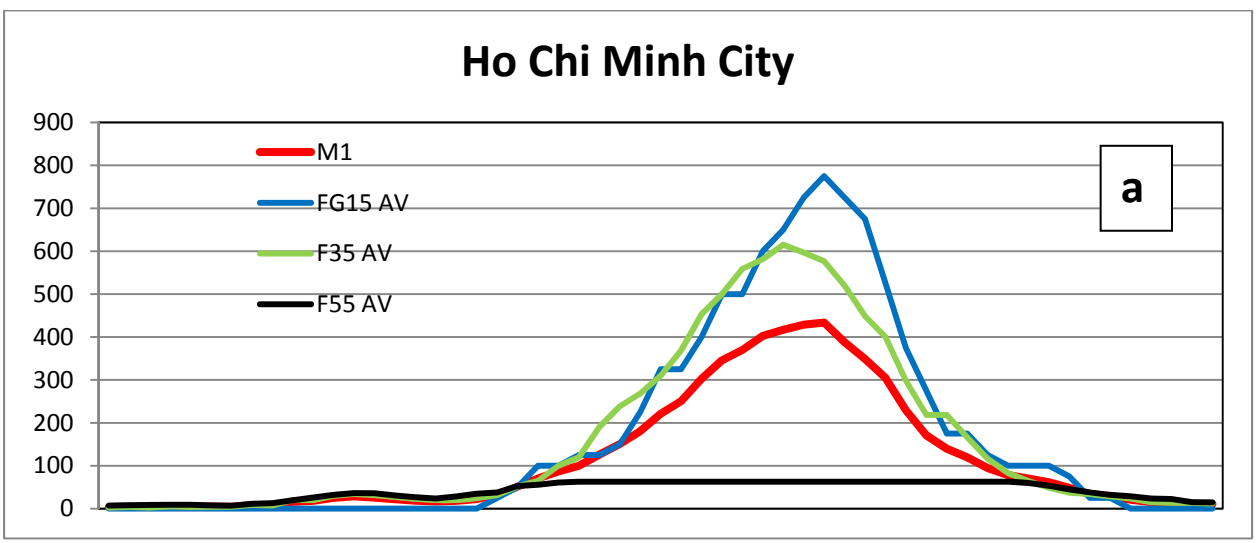
$$DN_m = (DN_{15} * n_{15} * X_{15} * W_{15} + DN_{35} * n_{35} * X_{35} * W_{35} + DN_{55} * n_{55} * X_{55} * W_{55}) / (n_{15} * W_{15} + n_{35} * W_{35} + n_{55} * W_{55}).$$

The weighting factor is calculated according to where the DN falls relative to its overlap with the range of the other fixed gains. To illustrate this method, we will use the example from the pixel at 106.68W in Figure 3. The data is presented in Table 2.

Table 2. Weighting Method Example Data

FG15 AVG	**N_{15}**	**FG35 AVG**	**N_{35}**	**FG15 RANGE**	**FG35 RANGE**	**W_{15}**	**W_{35}**	**DN_m**
675.0	4	**448.57**	7	100-6300	10-550	1	(550 – 448.57)/(550 – 10) = 101.43/540 = 0.188	(2700 + 590.32)/5.316 = **618.9**

In this example the merged value is heavily weighted in favor of the FG15 observation because the FG35 value is approaching its saturation limit. The weighting factors are not calculated symmetrically since it depends on whether the overlap is near the top or bottom of its range. The result of this weighted merge method is presented in Figure 3c.



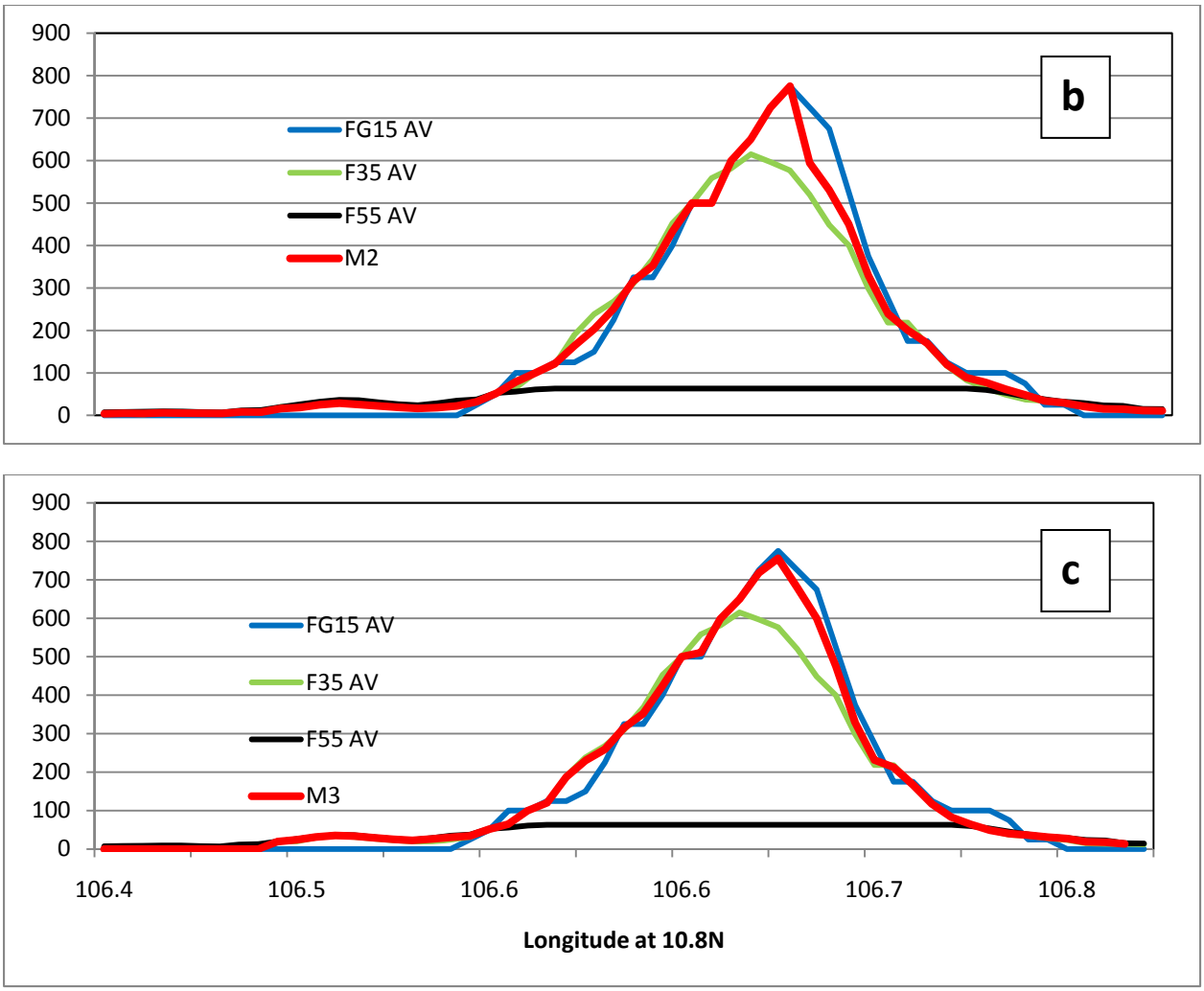


Figure 3. The East-West transect through Ho Chi Mihn City, Vietnam. The data from the fixed gain settings of 15, 35, and 55 are shown in each plot while (a), (b), and (c) show different methods of merging the data. Plot (a) is the simplest averaging and clearly underestimates the value. Plot (b) excludes data that is probably saturated, but introduces sharp discontinuities. Plot (c) is a weighted mean that discounts observations as they approach their saturation limits.

2.4. Blending the Fixed Gain and Stable Lights Products

The merged fixed gain product has the asset of being able to resolve bright lights that are usually saturated, but has the weakness of low numbers of coverages. It can be blended with the operational Stable Lights product to mitigate the problems associated with low coverages.

Similar problems arose with the merging of the fixed gain data using the simple average method (weighted by number of observations). In particular, where the operational data

approached its saturation cutoff, the abrupt discontinuation of its contribution created dark "notches" along heavily lit coastlines. To remedy this artifact, we applied a weighting scheme that gradually reduced the influence of the operational data as its value approached saturation.

One feature of the Stable Lights product is that transient bright features such as fires are screened out statistically [Baugh et al., 2010]. However, this is not the case with the Fixed Gain data. Fires are occasionally detected during Fixed Gain observations as bright spots without a corresponding Stable Light. When these fires are in remote areas where the DN value is less than 4, they are recognized as fires or some other anomalous event and are excluded from the merged product. However if the fire occurs in a region of normally dim lighting, then the one-time event is mistaken for a persistent light (see Figure 4). To address this problem, we set a rural fire test. If the pixel is ordinarily dimly lit (Stable Lights < 10) but the Fixed Gain product is a factor of 10 larger than the Stable Lights product, then it is most likely a fire and the Fixed Gain data is excluded. The factor of ten is somewhat arbitrary but was selected from qualitative analysis of the data.

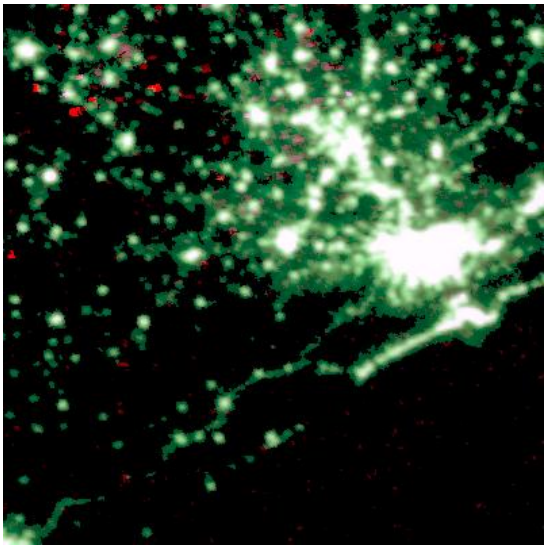


Figure 4. Fires around Sau Paulo, Brazil. This is a Red-Green-Blue composite image where the Red plane is the Blended product without testing for rural fires, the Green and Blue planes are the blended data where rural fires are excluded. The Red plane is stretched to accentuate the fires.

3. Results

The main result is the creation of a nighttime lights data product that enhances the value of both the thorough coverage of the operational Stable Lights product and the expanded dynamic range of the Fixed Gain observations (see Figure 5). Secondarily, the process revealed many complications associated with combining images of different gains and blending that image with

the operational data. The techniques developed to address these hurdles will be used to create other radiance calibrated images.

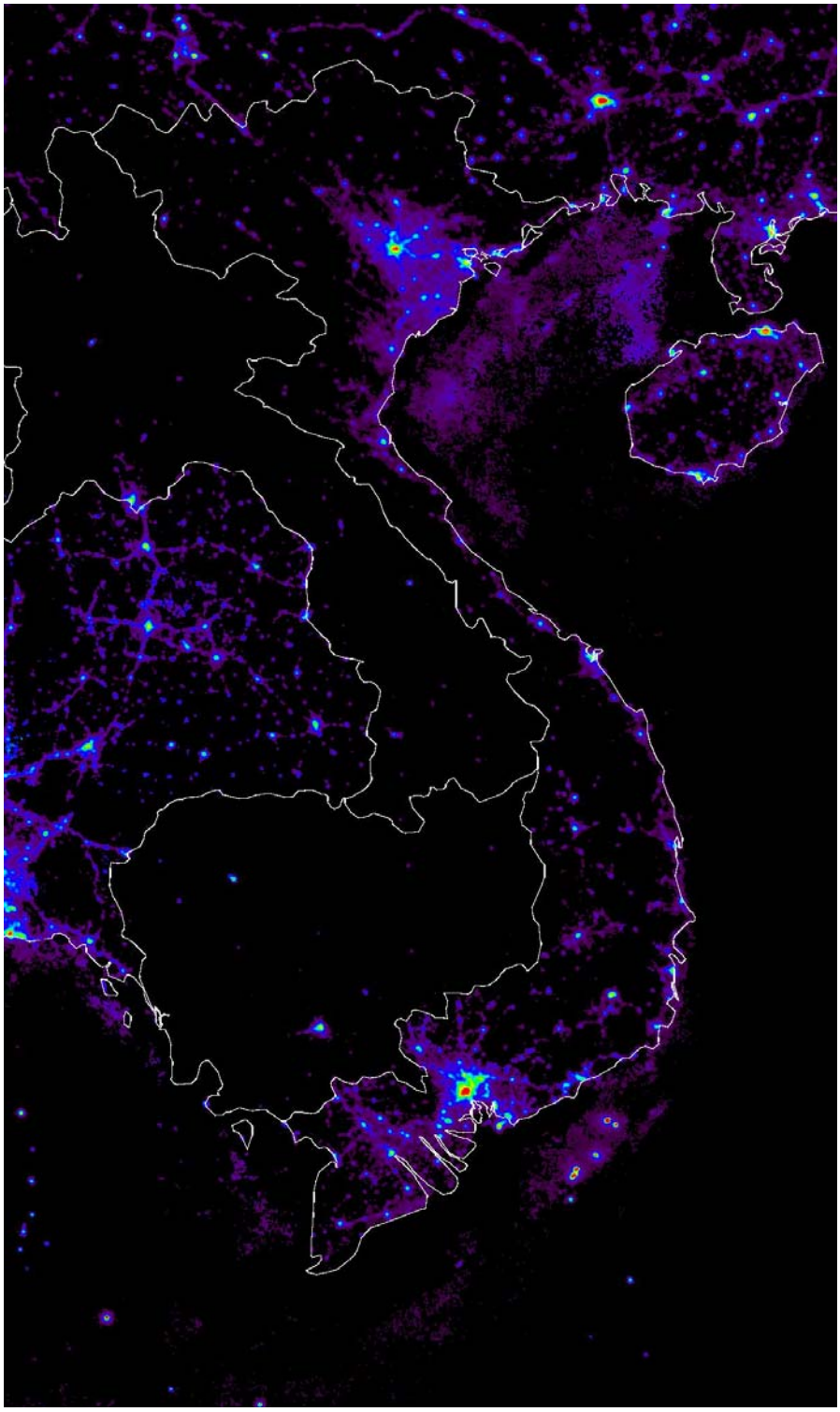


Figure 5. Radiance calibrated nighttime lights image of Vietnam from year 2006.

4. Conclusions

Future work includes creating similar products for the other years that we have obtained Fixed Gain data for. Once all the individual years are assembled, they will be intercalibrated to each other. The intercalibrated products will serve as time series tracking the changes of urban lights over the past fourteen years.

The 2006 radiance lights described here is available at: http://www.ngdc.noaa.gov/dmsp/download_radcal.html

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