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Development of a 2009 Stable Lights Product using DMSP-OLS data

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Abstract: Since 1994, NGDC has had an active program focused on global mapping of nighttime lights using the data collected by the Defense Meteorological Satellite Program's Operational Linescan System (DMSP-OLS) sensors. The basic product is a global annual cloud-free composite, which averages the OLS visible band data for one satellite from the cloud-free segments of individual orbits. Over the years, NGDC has developed automatic algorithms for screening the quality of the nighttime visible band observations to remove areas contaminated by sunlight, moonlight, and the presence of clouds. In the Stable Lights product generation, fires and other ephemeral lights are removed based on their high brightness and short duration. Background noise is removed by setting thresholds based on visible band values found in areas known to be free of detectable lights. In 2010, NGDC released the version 4 time series of Stable Lights, spanning the years 1992-2009. These are available online at *<http://www.ngdc.noaa.gov/dmsp/downloadV4composites.html>*.

Keywords: Nighttime Lights; DMSP; OLS.

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1. Introduction

Since the mid-1970's, the Defense Meteorological Satellite Program's Operational Linescan System (DMSP-OLS) sensors have been flown on polar orbiting platforms. These data have been archived digitally at the National Oceanic and Atmospheric Administration's National Geophysical Data Center (NOAA-NGDC) since mid-1992. The OLS data are available globally at a spatial resolution of 2.7 km, and consists of 2 broad spectral bands, a visible band (0.4-1.1 um), and a thermal band (10.5-12.6 um) (Figure 1).

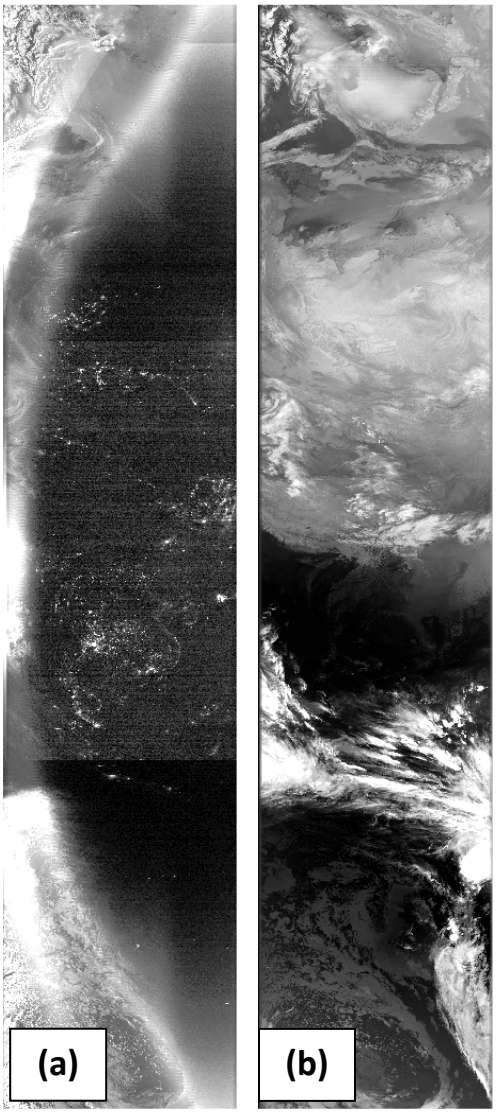

Figure 1. Nighttime portion of orbit F16200901281215 over Asia. **(a)** OLS visible band (0.4-1.1 um) **(b)** OLS thermal band (10.5-12.6 um).

The OLS is unique due to the presence of a photomultiplier tube (PMT), which intensifies the nighttime visible band signal. Originally designed to detect moonlit clouds, the PMT also allows the detection of lights from cities, fires, fishing boats, and gas flares, among others.

While the OLS is unique in its ability to collect low-light imaging data, it suffers from its coarse spatial resolution, a 6-bit quantization, and a limited dynamic range, which allows the OLS to readily saturate over urban areas.

In the past, global nighttime lights products have been generated (Elvidge et al, 1997), but attempts at separating transient light sources from persistent lights were based solely on the composite products. It became clear that many lighting types, such as fires and small towns, exhibited the same signatures in the composite products (e.g. low percent frequency of light detects, low average visible band digital numbers (DNs), and high visible band standard deviations). This paper details a new methodology for generating the global composites, and for separating the transient lights from persistent light sources by examining the distributions of the visible band DNs that go into the composite products. The result is the Stable Lights product from the DMSP-OLS nighttime data for year 2009.

2. Methods

To generate the DMSP-OLS Stable Lights composite product for year 2009, 5,085 orbits from satellite F16 were processed. Details of the processing steps follow.

2.1. OLS Flag Images

To enable the selection of only high-quality cloud-free nighttime data for inclusion in the Stable Lights product, pre-processing is done on the input OLS orbits to create flag images. Made as companions to the OLS orbits, flag images are used to place the OLS pixels into classes. Flag images are 16-bit and are processed bit-wise, so each pixel can belong to more than one class by turning specific bits on. The flag categories used in the stable lights processing are: DAYTIME, NIGHTTIME MARGINAL, ZERO LUNAR ILLUMINANCE, CLOUDS PRESENT, and NO DATA.

The DAYTIME and NIGHTTIME MARGINAL flags are set based on solar elevation. Solar elevation angles are computed using the latitude and longitude of each OLS pixel along with the time at the nadir pixel of each scan line. The DAYTIME flag bit is set for solar elevation angles greater than -6. The NIGHTTIME MARGINAL flag bit is set for solar elevation angles between -15 and -6 (Figure 2). This region of the nighttime OLS imagery covers the terminator, or the transition zone from nighttime to daytime, and is of reduced quality as compared to the darker nighttime data.

To set the ZERO LUNAR ILLUMINANCE flag, lunar illuminance values are computed using an algorithm obtained from the US Naval Observatory [Janiczek and deYoung, 1987].

This algorithm approximates the lunar illuminance present at the earth's surface as a function of lunar phase, azimuth, and elevation. The lunar phase, azimuth, and elevation are in turn computed from the latitude and longitude of each OLS pixel and the time at the nadir pixel of each scan line. The ZERO LUNAR ILLUMINANCE flag is set when the returned lunar illuminace is less than 0.0005 lux.

At times there are data dropouts within an OLS nighttime suborbit. These scanlines contain no real data, but are present as placeholders in the suborbits. The NO DATA flag is set in the flag image to correspond to these regions.

Finally, the algorithm to set the CLOUDS PRESENT flag is run after the data have been reprojected into 30 arc-second grids and will be discussed further on.

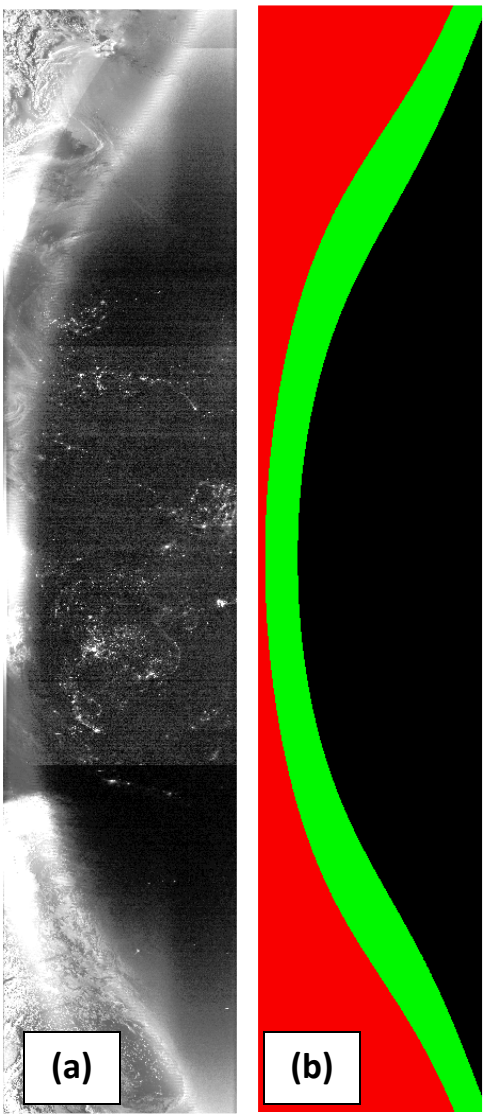

Figure 2. (a) OLS visible band – nighttime suborbit **(b)** Companion flag band, with DAYTIME shown in red, and NIGHTTIME MARGINAL shown in green.

2.2. Visual Screening

Suborbits that contain any pixels with the ZERO LUNAR ILLUMINANCE flag bit set are candidates for the Stable Lights product. These candidate suborbits are visually screened for lights due to aurora and abrupt gain changes. The abrupt gain changes are due to the varying thresholds for the maximum gain of the OLS. To avoid saturation in the OLS, maximum gain values are adjusted incrementally as the orbit shifts from night to day. These gain threshold values are changed on a weekly basis by the US Air Force but are not recorded as part of the data stream. An analyst therefore visually screens the data for these abrupt gain changes and also for the presence of aurora in the scene. The analyst chooses a start and end scanline of data to include in the Stable Lights product (see Figure 3).

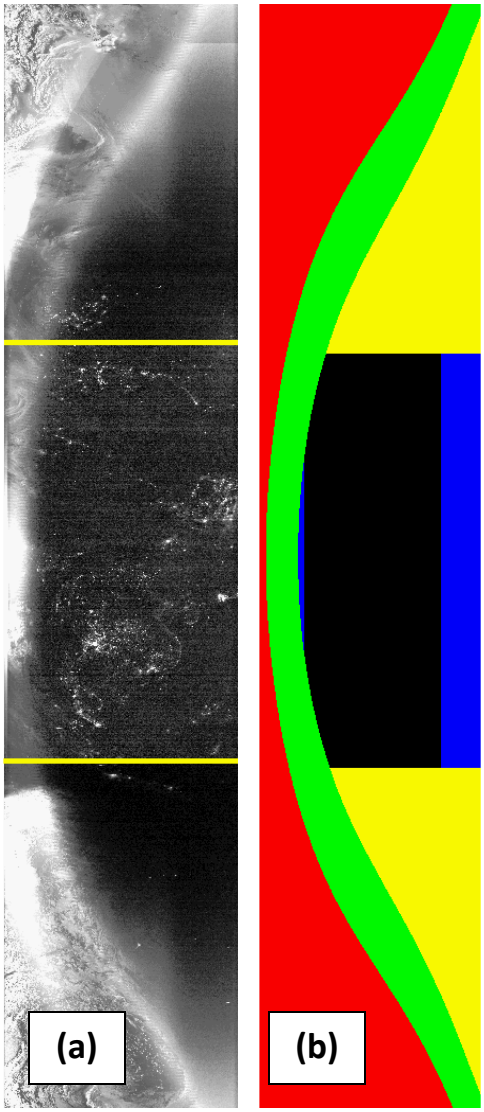

Figure 3. (a) OLS Visible Band – nighttime suborbit. Yellow lines show start and end lines chosen by an analyst. **(b)** Companion Flag band; DAYTIME is shown in red; NIGHTTIME MARGINAL is shown in green; yellow areas have been discarded by the visual line-screening process; blue areas show edge-of-scan data.

2.3. Reprojection

The visible and thermal bands of the OLS suborbits, along with their companion flag bands, are reprojected into 30 arc-second grids. Prior to reprojection, they are constrained to latitudes between 65S and 75N. A further constraint is to exclude the outer edges of the OLS swath, defined as areas with scan angles greater than 40.91 degrees (shown as blue in Figure 3b). The edges are discarded because at the edge of swath the OLS suffers from poorer geolocation accuracy, and the visible band shows a significant increase in background noise.

The reprojection software was created at the NGDC specifically to geolocate and reproject the OLS data. The geolocation algorithm assigns latitudes and longitudes to each OLS pixel based on scan angle; nadir latitude and longitude; satellite altitude, height and azimuth; and a digital elevation model of the earth's surface. The reprojection software then resamples the input OLS data and companion flag bands into output 30 arc-second grids using the nearest neighbor resampling technique. Examples of the output grids are shown in Figure 4.

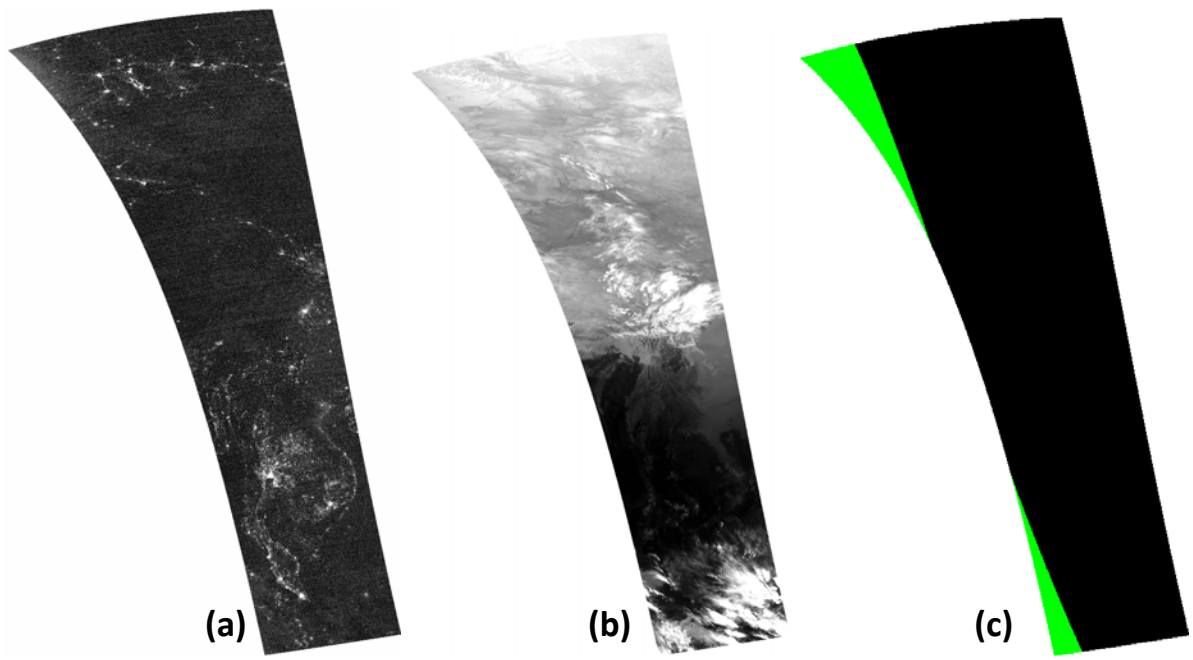

Figure 4. Data reprojected to 30 arc-second grids – mid swath only. **(a)** OLS visible band. **(b)** OLS thermal band. **(c)** Companion flag band, NIGHTTIME MARGINAL shown in green.

2.4. Cloud Masks

It is desirable to include only cloud-free data when generating the Stable Lights product, as the presence of clouds affects both the intensity and location of lights in the OLS visible band. Thick clouds can obscure a light completely, while thinner clouds diffuse the signal, making the lights appear larger but dimmer than they would have in the absence of cloud cover. Cloud masks are created for each suborbit by comparing the reprojected OLS thermal band data to modeled surface temperature grids. Areas colder than the surface temperature are cloud mask candidates.

The National Center for Environmental Prediction (NCEP) creates global surface temperature grids at 6 hour intervals, in resolutions of 0.5, 1.0, and 2.5 degrees. The surface temperature grids are part of the NCEP Global Forecast System (GFS) model runs. More information on these datasets can be found on the NCEP GFS website <*http://www.nco.ncep.noaa.gov/pmb/products/gfs/*>. The 1.0 degree surface temperature grids were used for this Stable Lights product (Figure 5).

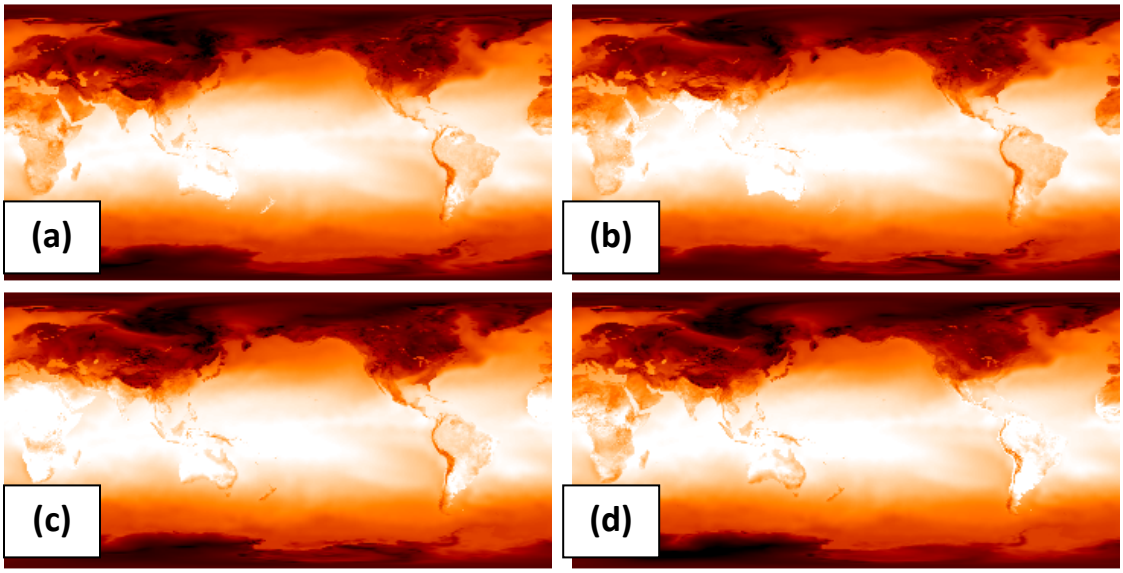

Figure 5. NCEP GFS 1.0 degree surface temperature grids for 2009/01/29. **(a)** 00:00 UT grid. **(b)** 06:00 UT grid. **(c)** 12:00 UT grid. **(d)** 18:00 UT grid

The land/sea boundaries are muted in the 1.0 degree surface temperature grids as compared to the higher spatial resolution of the OLS thermal band data. This results in the mis-identification of clouds along the land/sea interface. For example, in coastal regions with land temperatures comparatively colder than the adjacent ocean, the land areas are mis-identified as clouds. To address this issue, a land/sea lookup table was created for each 1.0 degree grid cell that straddled a land/sea boundary. The lookup table identifies the locations of the closest all-land and all-sea 1.0 degree grid cells. The requires the land and ocean regions to be processed separately.

The algorithm to create the cloud masks takes as input the reprojected OLS thermal band, and the NCEP surface temperature grid that is closest in time to the start time of the OLS suborbit. The land/sea lookup table is used to substitute temperature values, once for land, then for sea. These new surface temperature grids are cropped to match the extent of the thermal band, and are resampled using bilinear interpolation to 30 arc-second grids. Difference images are made by subtracting the thermal band from the surface temperature grids. A land/sea mask is used to mask the difference images, creating one land-only image and one sea-only image (Figure 6).

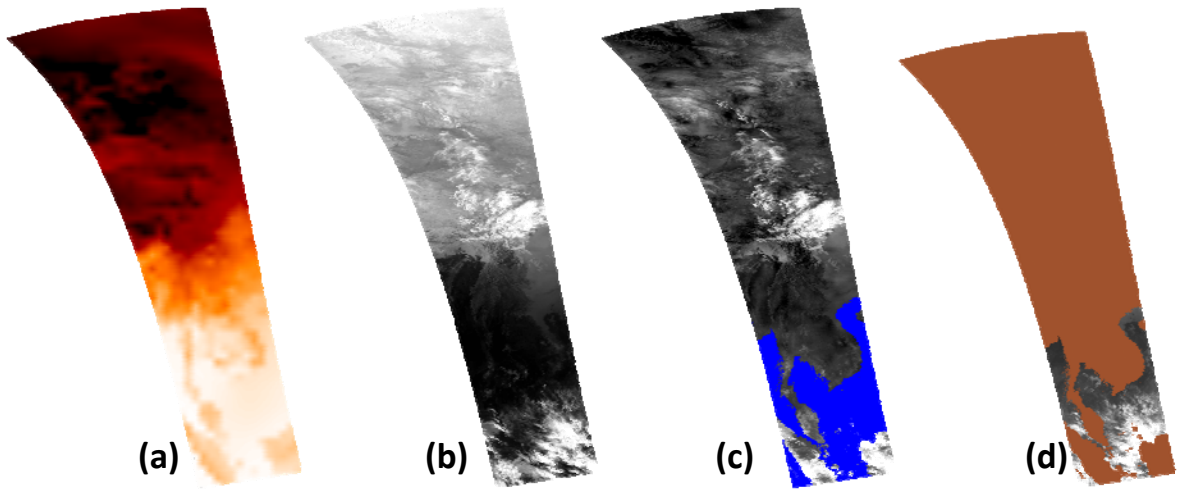

Figure 6. **(a)** NCEP GFS 1.0 degree surface temperature grid, resampled and masked to match 30 arc-second OLS thermal grid. **(b)** OLS thermal grid. **(c)** Land temperature difference image. **(d)** Sea temperature difference image.

Thermal cloud threshold values are computed by calculating the mean and standard deviation of latitudinal tiles in each difference image. At high latitudes the land/cloud temperatures converge, so thresholds are adjusted linearly with latitude as:

$$CloudThreshold = Mean(Difference) + N * Stdev(Difference)$$

$$N = 4 \qquad for\ 0 \le |lat| \le 15$$

$$N = 5 - \left(\frac{|lat|}{15}\right) \qquad for\ 15 < |lat| < 60$$

$$N = 1 \qquad for\ 60 \le |lat|$$

Difference values greater than the cloud threshold are considered clouds and are added to the companion flag grid by setting the CLOUDS PRESENT bit to 1 (Figure 7).

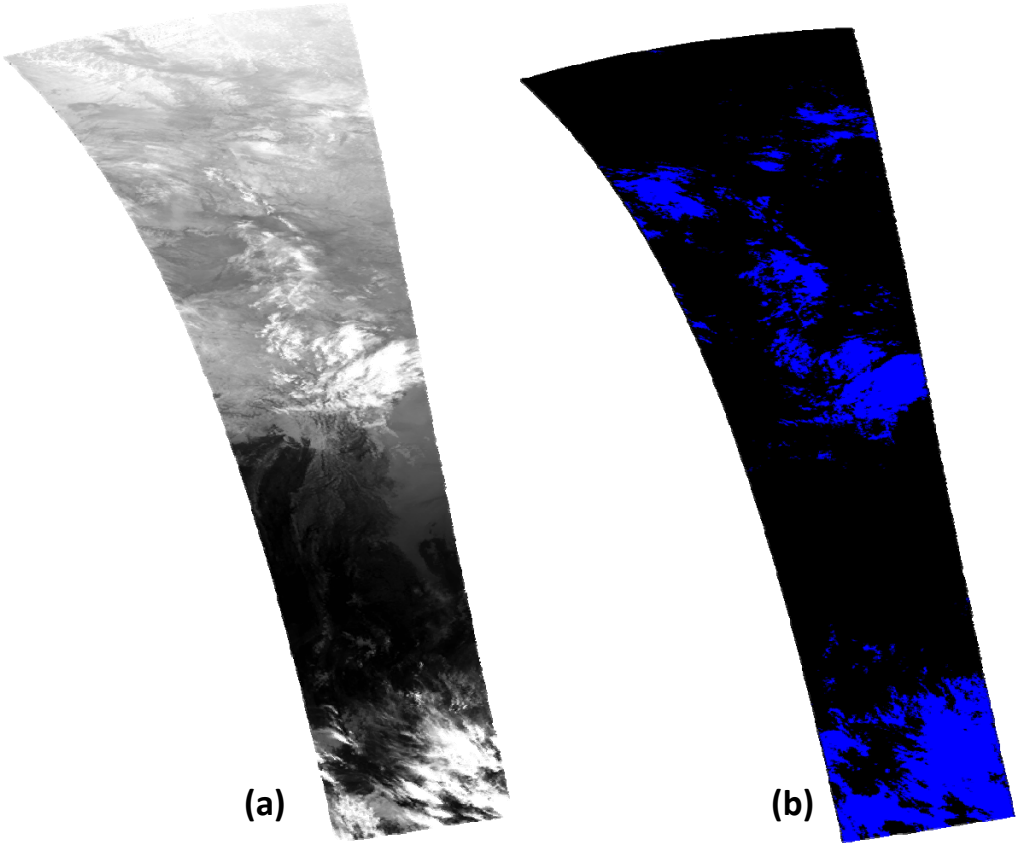

Figure 7. **(a)** OLS thermal grid. **(b)** Companion flag grid, CLOUDS PRESENT shown in blue.

2.5. Making the Composite

To create the highest quality visible band composite, data are included only if the companion flag data bits are set as:

DAYIME:	OFF
NIGHTTIME MARGINAL:	OFF
ZERO LUNAR ILLUMINANCE:	ON
CLOUDS PRESENT:	OFF
NO DATA:	OFF

The stable lights compositing process takes all input visible and flag grids, and creates a suite of output files. This includes an average visible band image, an image showing the number of cloud-free observations used, and histograms of input visible band data for each grid cell (Figure 8).

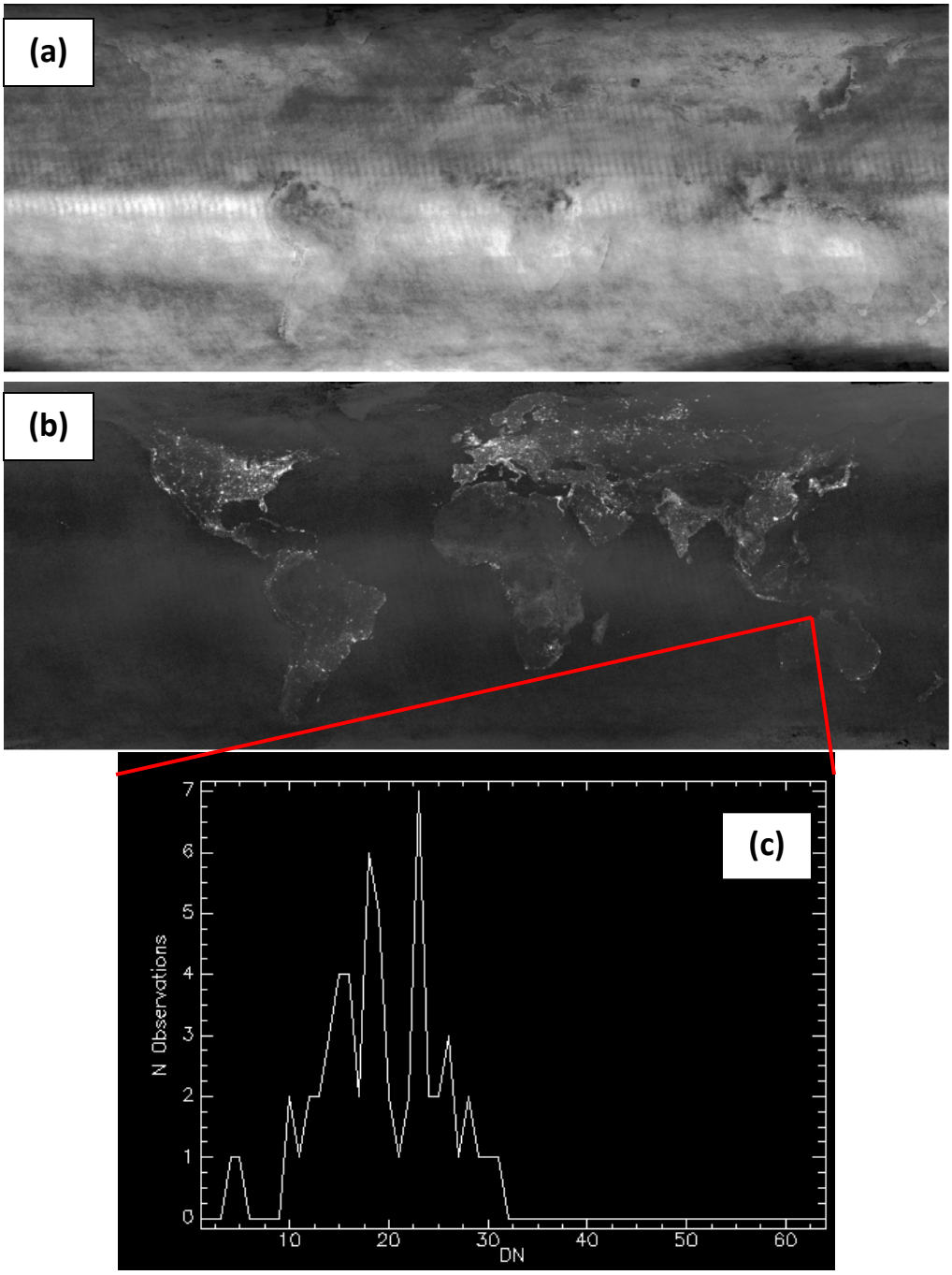

Figure 8. OLS Composite products for F162009, showing: **(a)** Number of cloud-free observations **(b)** Average visible band values. **(c)** Example visible band histogram of town in Australia.

2.6. Outlier Removal

The average visible band composite product does not distinguish between lighting types. Lights from fires, fishing boats, and other light sources remain part of this product. To create a Stable Lights product that is free from transient light sources, the composite histograms are analyzed for bright outliers.

The outlier removal algorithm is an iterative process that works with the composite histograms showing the distribution of the input visible band data for each grid cell. The algorithm works by iteratively removing the largest visible band observation, recomputing the standard deviation of the remaining observations, and then comparing the new standard deviation to that of the previous iteration. This process stops when the standard deviations converge, which is defined as a difference of less than 0.2. No convergence is declared if more than 50% of the observations are removed.

In general, for the histograms of grid cells with fires, the bulk of their observations will have low visible band DNs and fewer high DN observations spread throughout the DN range of 0-63. Grid cells with small towns will have the bulk of their observations in the lower visible band DNs, but the spread of the values will be greater than a no-light grid cell (Figure 9).

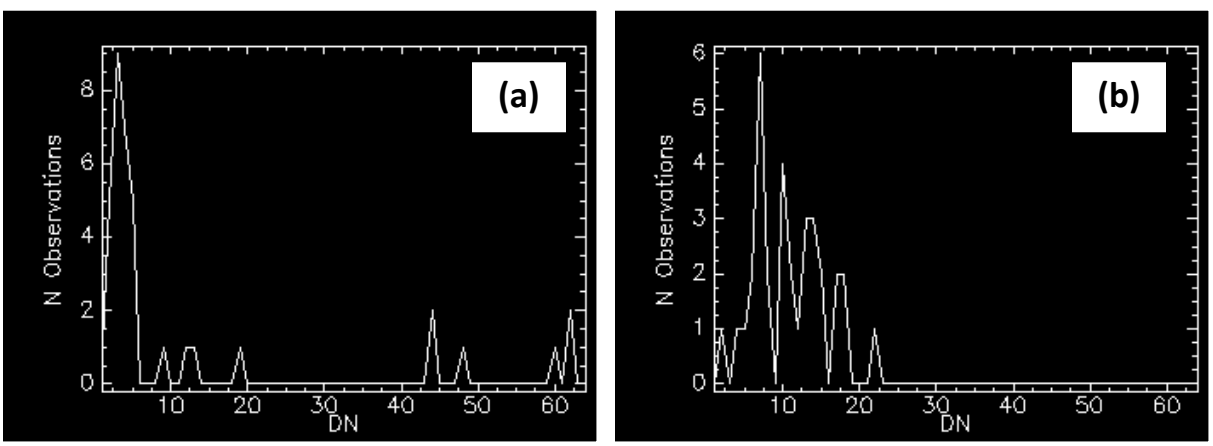

Figure 9. Visible band histogram examples of: **(a)** a grid cell containing fires. Outlier removal process removed highest 10 observations. **(b)** a grid cell containing a small town. Outlier removal process removed highest observation.

A new outlier-removed average visible band is created using the observations remaining after standard deviation convergence, or using all the observations in the case of no convergence (Figure 10).

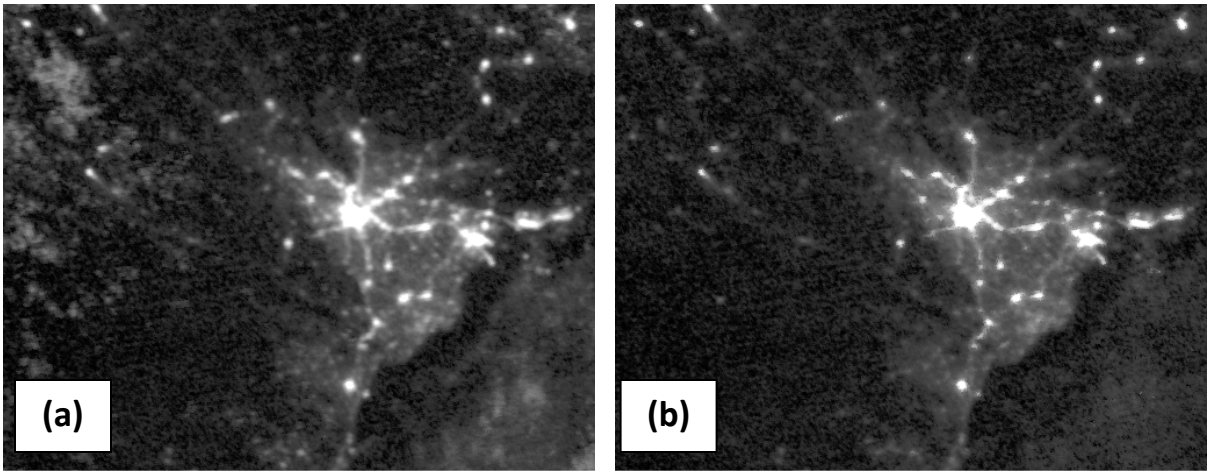

Figure 10. OLS Composite products for F162009, cropped to show the area around Hanoi, Vietnam. **(a)** Average visible band. **(b)** Outlier-removed average visible band. Note the presence of fires in the NW corner and the lights from fishing boat activitiy in the SE corner of the Average visible band that are absent in the Outlier-removed image.

2.7. Background Removal

The final step in the creation of the Stable Lights Product is to separate areas in the outlier-removed average that contain lights from those background areas where lights are not present. Even in the outlier-removed average, the background values vary significantly from region to region. Therefore local background threshold values must be computed.

To get samples of the background values in the outlier-removed average, an analyst went through the image and placed markers over areas that visually appeared light-free. The outlier-removed average is then processed in kernel-sized steps of 25 X 25 pixels. For each kernel, each of the 256 400 X 400 pixel tiles containing this kernel are examined. Areas in the kernel with values greater than the maximum light-free values from the tile are tallied as “greater than background”. A Stable Lights mask is created from areas considered “greater than background” at least 40% of the time. The Stable Lights mask is then applied to the average visible band composite to create the final Stable Lights product (Figure 11).

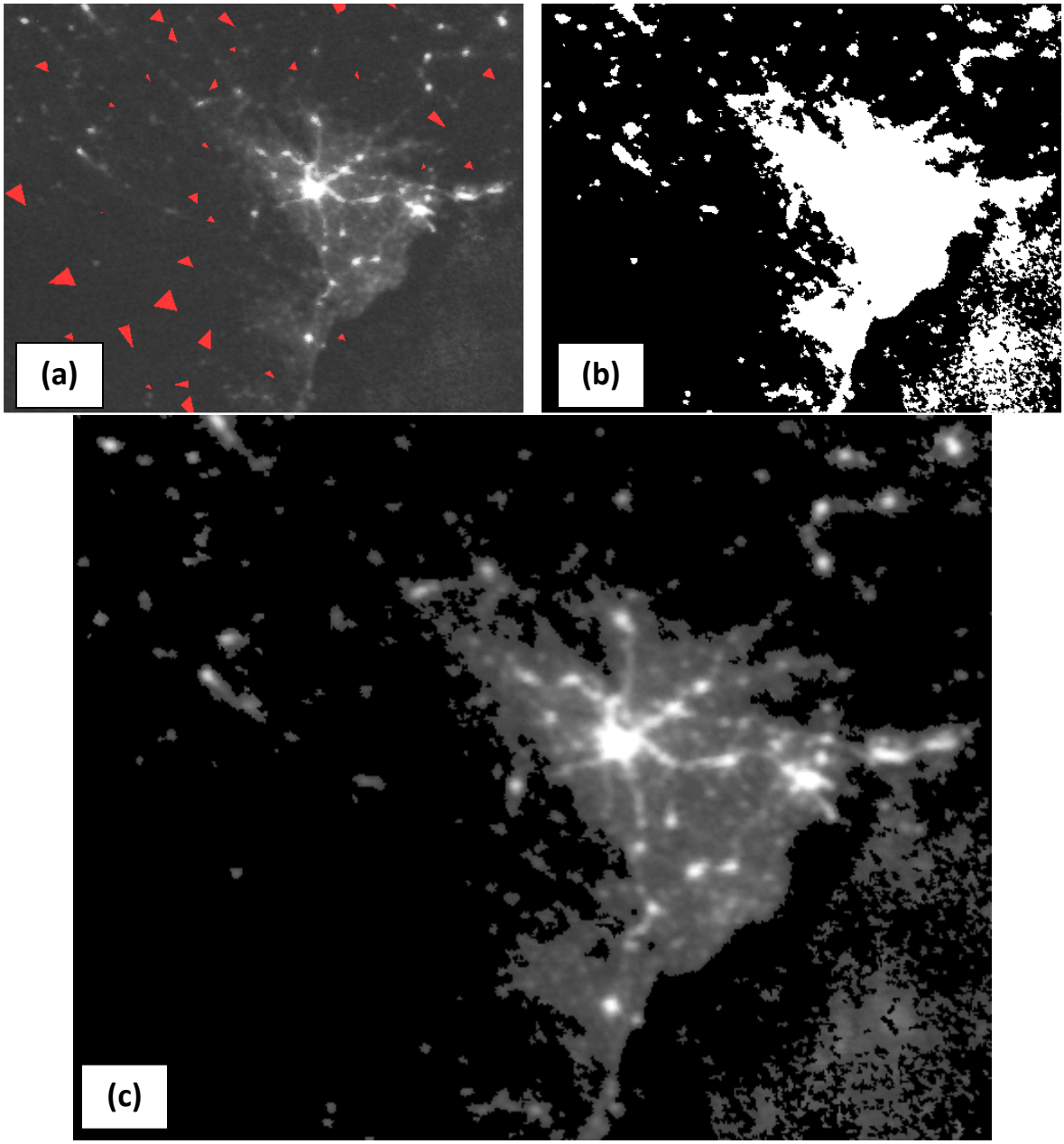

Figure 11. OLS Composite products for F162009, cropped to show the area around Hanoi, Vietnam. **(a)** Outlier-removed average visible band showing analyst-chosen light-free regions in red. **(b)** Stable Lights mask. **(c)** Stable Lights, which is the Average Visible band with the Stable Lights mask applied. Note that in this part of the world, lights from fishing boats are present over 50% of the time, so they remain part of the Stable Lights product.

2.8. Geographic Alignment

When reprojected, the DMSP-OLS nighttime data from satellite F16 consistently lands north-west of the true gound location. Ideally, the satellite ephemeris would be adjusted prior to reprojection, but that effort was beyond the scope of this project, so a post-processing correction is done.

The Landscan population grid is used as ground-truth as it is global in extent and correlates well with the Stable Lights product. Details on this product can be found on the Landscan website <*http://www.ornl.gov/sci/landscan/index.shtml*>. A cross-correlation technique is used to generate a best-fit linear translation between the Stable Lights product and the Landscan population grid. This linear translation is then applied to the Stable Lights product (see Figure 12).

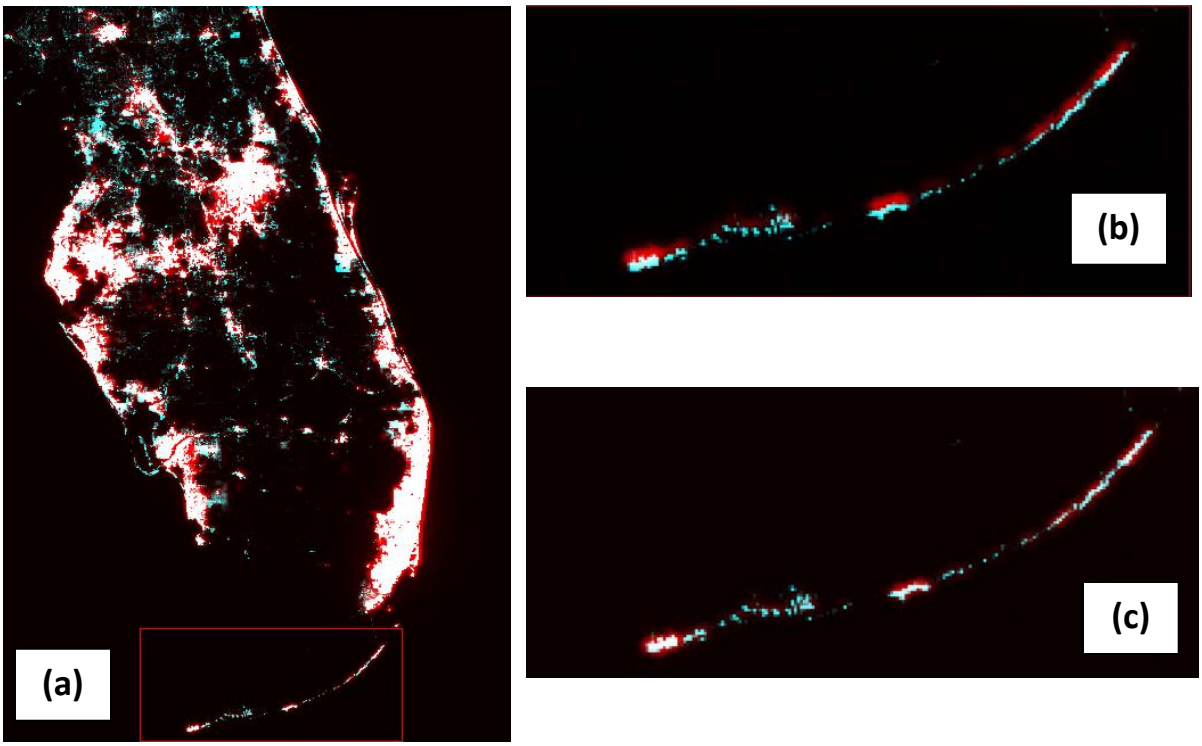

Figure 12. F162009 Stable Lights shown with the Landscan population grid over the Florida Keys, USA. The Stable Lights image is shown in red, and the Landscan population grid is shown in cyan. Areas of overlap between the two images show as white. **(a)** Image showing most of Florida. **(b)** Detail over the Florida Keys, before geographic alignment. **(c)** Detail over Florida Keys, after geographic alignment.

3. Results

The methods described have taken a year of OLS orbits from satellite F16 and produced a global Stable Lights product for year 2009 (Figure 13). The Stable Lights product is a global map showing the relative OLS visible band intensities of lit areas, where lighting deemed ephemeral has been removed and non-lit areas (background) have been set to zero. These same methods were used to process Stable Lights composites for the entire digital archive of OLS data, spanning the years 1992-2009. These are available for download at *<http://www.ngdc.noaa.gov/dmsp/downloadV4composites.html>*.

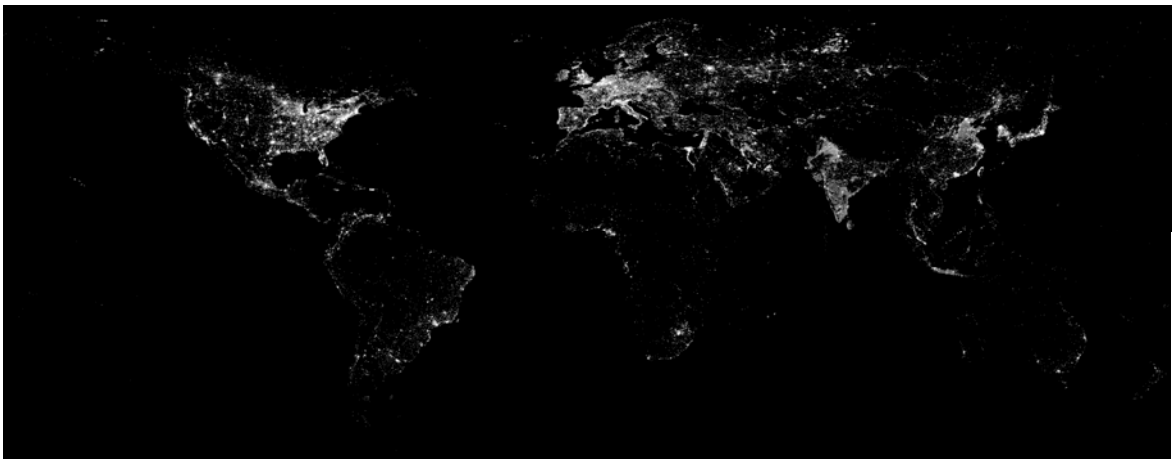

Figure 13. F162009 Stable Lights product.

4. Conclusions

The OLS Stable Lights product is a significant improvement over previous OLS composites for identifying areas of persistent lighting. The time-series of OLS Stable Lights products from 1992-2009 will enable researchers to study lighting patterns through time, and also to study those parameters for which nighttime lights might serve as a reasonable proxy, such as economic activity [Ghosh et al, 2009] or constructed impervious surfaces [Elvidge et al, 2007].

Future work will include improvements on geolocation of the OLS data at the time of orbit reprojection, a rework of the cloud masking algorithm to make use of the higher spatial resolution 0.5 degree NCEP surface temperature grids, improvements on the background removal process so that a priori knowledge of non-lit areas is not required, and work on intercalibration of the time-series to ease intercomparison of the Stable Lights products.

Acknowledgements

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