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Evaluation of the consistency of DMSP-OLS and SNPP-VIIRS night-time light datasets

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Abstract: Night-time light remote sensing is used to monitor human impact on earth's surface. DMSP-OLS was the famous source of night-time light data until the release of a newer version of night-time light remote sensing satellite: SNPP-VIIRS, which has several improvements over DMSP-OLS. However, the dissemination of DMSP-OLS datasets was ceased for public use after 2013. The SNPP-VIIRS satellite products are available from April 2012. Due to this unavailability of the datasets prior to 2012 for VIIRS and after 2013 for DMSP, raises the major importance of homogeneous long term datasets in understanding the impact of the past and to have a comparative and change analysis prior and later to 2013. Due to the need of a long term homogeneous datasets, the evaluation of the consistency of the DMSP-OLS and SNPP-VIIRS has been foreseen. For this, both the datasets are harmonized temporally, spatially and radiometrically. The study presents the inter-calibration between DMSP and VIIRS using pseudo invariant features (PIFs). For extracting suitable PIFs, combinations of Getis Ord statistics (Gi*) and coefficient of variation (CV) are used on 3×3 and 5×5 pixel window sizes. Various thresholds are applied to Gi* and CV and the optimal combination is selected to identify suitable PIFs. Logarithmic and power functions are used for DMSP and VIIRS to find the optimal fit. The calibrated image is validated against socio-economic indicators: Gross State Domestic Product (GSDP) and Electricity consumption (EC). The model is found to be a good fit at national scale (India) but doesn't fit very well on regional scales. Significant improvements can be made to ensure better consistency by the application of different techniques of harmonization, selection of PIFs and application of the inter-calibration model.

Key words: DMSP-OLS, SNPP-VIIRS, Inter-calibration, Simulation, socio-economic indicators

1. Introduction

Night-time light imagery is a unique source which provides a distinct view of Earth's surface and human activities. It has been observed by various studies, that night lights have a significant importance in monitoring the earth surface activities and atmospheric phenomena. Night-time visible imaging was initiated by the Defence Meteorological Satellite Program (DMSP) Operation Linescan System (OLS) in 1960s. This mission was the only source of night time visible images until the launch of Suomi National Polar-orbiting Partnership's visible Infrared Imaging Radiometer Suite (SNPP-VIIRS) in October 2011 which continued the acquisition of night time visible images with some quality enhancements over DMSP-OLS.

The DMSP satellite of the U.S Department of Defence provides a global coverage every 24 hours. The on board OLS sensor acquired images in visible, near infrared and thermal infrared region of the electromagnetic spectrum. It was the longest running time series of night time lights data (Huang, et al., 2014). DMSP-OLS had an oscillating scan radiometer with two spectral bands: Visible Near infrared (VNIR) for Night-time Light (NTL) and thermal Infrared. The night-time overpass is between 20:30 and 21:30 UTC. The data is reported in Digital Number (DN) values on a six-bit scale that ranges from 0 (no light) to 63 (maximum light). A total of 9 satellites from F10 to F18 have collected OLS data. The data is mainly of three types: stable lights, radiance calibrated and average digital number (Doll, 2008).

SNPP-VIIRS provides imagery during the day as well as at night. It has a greater sensitivity in comparison to DMSP-OLS and can reveal urban details. VIIRS has better spatial resolution than OLS (742 m), wider radiometric detection range, vast reduction in the pixel footprint, wider dynamic range, finer quantization, in-flight calibration and considerable better geometric quality. It also eliminates the critical problems of saturation, blooming and the lack of on-board calibration that DMSP has (Elvidge et al., 2017). Additionally, Day-Night Band (DNB) pixels don't expand and distort towards the edge of the scan as in DMSP-OLS data. (Seaman, 2013).

1.1 Need for relative normalization (Inter-Calibration)

VIIRS DNB has many key improvements over DMSP-OLS, but both have a common fundamental purpose of detection of clouds using moonlight as an illumination source. Also, the stable lights datasets obtained from both sensors have proven to be beneficial in natural and social sciences (Elvidge et al., 2017). Due to the lack of DMSP datasets in the last 6 years, it is not possible to use these data for long-term analysis until the present time, which would provide a great insight for understanding the various application perspectives in a long run. Pandey et al. (2017) reviewed various methods for inter-calibration of DMSP-OLS and highlighted future possibility of inter-annual correction using VIIRS.

1.2 In multi-temporal socio-economic context

Various studies have shown the possibility of correlations between NTL and several known demographic and economic variables. Since the NTL data is globally uniform and continuously measured, it constitutes an important data source where reliable statistics are otherwise lacking (Henderson et al., 2012). Night time lights images provides potential possibilities to quantify the socio-economic variables with accuracy and spatial information. NTL data can provide essential foundation on estimation of GDP, population, electric power consumption, greenhouse gas emissions, poverty index and other parameters on the basis of spatio-temporal continuity, independence and objectiveness. Previous studies of Ghosh et al. (2010) and Mellander et al. (2015) have indicated the importance of NTL as a proxy for measuring economic growth of a nation, especially when the statistics show important shortcomings.

The main aim of the research is to evaluate the consistency of annual DMSP-OLS and SNPP-VIIRS datasets and to develop a statistical model for the inter-calibration using Pseudo Invariant features (PIFs), and also to validate the model at different scale level against socio-economic parameters.

2. Study area and datasets

The study area selected for this research was entire geographical span of India (6.45° N to 37.6° N and 68.7° E to 97.25° E). India is bounded by Arabian Sea on the southwest, Indian Ocean on the south and Bay of Bengal on the southeast. It shares the land boundary with China, Bhutan, Myanmar, Bangladesh, Pakistan and Nepal. India is world's second most populous country with the number of residents reported roughly as 1.3 billion (Ministry of Home Affairs, 2011). India is a diverse country with variations in the development at various regional and state levels. It covers areas of illumination regions which depicts the heterogeneity of luminosity spread over the whole country. This diversity and variations make it suitable to study the growth from the NTL images and to encounter differences in radiances at national and regional scales.

The datasets of DMSP-OLS and SNPP-VIIRS are taken from NOAA. The datasets are available in GeoTIFF format. The DMSP-OLS data is available annually under Version 4 stable light products from 1992 to 2013. The annual product of the year 2013 was used. The SNPP-VIIRS-DNB datasets are available monthly from April 2012 to December 2017. The monthly composites from January to December for the year 2013 were used. The DMSP-OLS images are available as global tiles, having stable 6-bit radiometric quantization. This stable light product is resampled at a resolution of 1 km and is provided by the NOAA in WGS84 coordinate system. From the global tile, the region of India is extracted for the research.

Due to unavailability of the annual composite of SNPP-VIIRS-DNB for the year 2013, there is a need for an annual composite to temporally harmonize VIIRS with DMSP-OLS. For this, the annual composite for VIIRS 2013 is created using monthly images of India from January 2013 to December 2013 excluding the month of May. This exclusion is done to avoid improper outputs due to the presence of data artefacts in May 2013 (Cao, 2013).

3. Methodology

Flow chart representing the methodology adopted for this research is shown in figure 1.

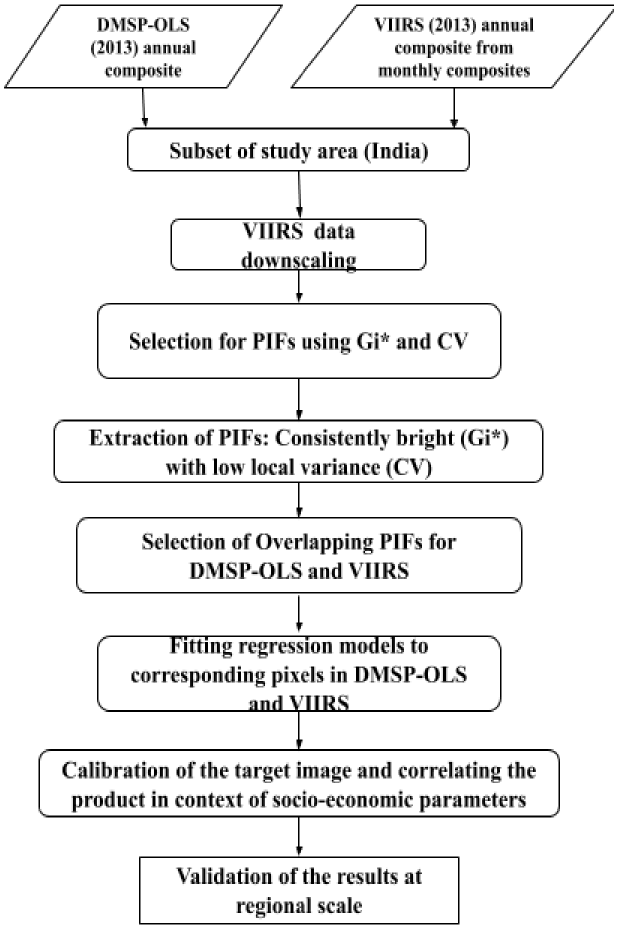

Figure 1: Flow chart representing the methodology adopted for this research

3.1 Masking for background removal

3.1.1 DMSP: Saturation correction

One most important issue in DMSP dataset is the saturation of the pixel's values in the bright cores of the urban areas. This leads to loss of information of the correct light intensities and loss of urban variations. This leads to incorrect analysis where the saturated regions are considered. This saturation takes place due to the limited dynamic range and 6-bit quantization of DMSP-OLS. This issue needs to be resolved for proper analysis of the variation in the luminosity. For this reason, values=63 are masked out.

3.1.2 VIIRS: Point based sampling

The unwanted data in the VIIRS dataset is due to the presence of negative radiances and the radiances due to the presence to the airglow effect in the uninhabited regions where the probability of illumination is zero or very low (Seaman et al., 2014).

Point-based Analysis is performed by the selection of uninhabited regions like rivers, forests and dark regions using Google map layer (Land use map). These regions are considered to have a lower or zero probability of illumination according to the land use cover. The suitable value in these regions combined can be deducted from the overall values as a threshold. This is done by selection of the mean value and masking of all the values below it.

This technique is approached in two ways: By calculating the range and statistics and by manual inspection. Figure 2 shows the various uninhabited regions near the capital city of India, Delhi. These areas are selected for calculating the threshold.

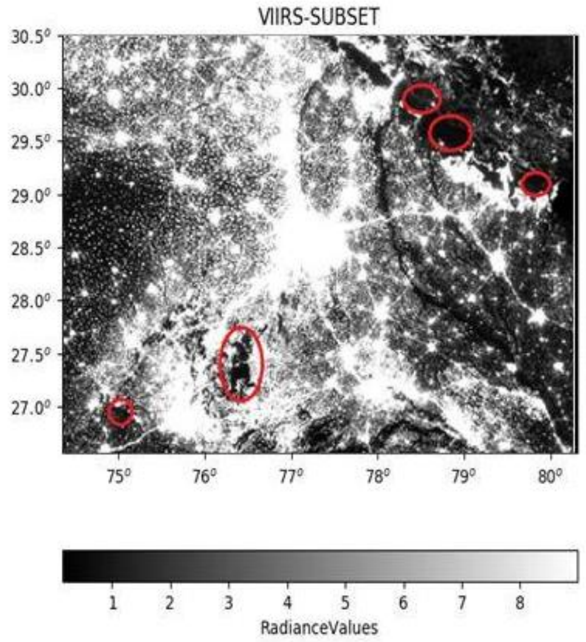

Figure 2: Representation of the subset area selected and uninhabited regions identified

3.2 Extraction of Pseudo Invariant Features (PIFs)

Extraction of Spatially homogeneous clusters and regions with low spatial variability gives PIFs. For identifying PIF, Gi* statistics, and coefficient of variation are combined (Mukherjee, 2017). This selects relatively bright clusters with low local variability. In this case, the Gi* is estimated and 90% and 95% significance levels are combined with the CV at five threshold levels of 5%, 10%, 15% and 20% in 3×3 windows and five threshold levels of 3%, 5%, 10%, 15% and 20% in 5×5 windows. The estimations of Gi* and CV is carried out for DMSP and VIIRS individually. The next sections explain the Gi* and CV in selection of PIFs.

3.2.1 Getis ord statistics (Gi*)

Gi* is a local indicator of spatial association (LISA). It is a measure of identifying significant clusters spatially of hotspots or cold spots. It is famous for hotspot analysis, where hotspots depict high-value clusters (Gi*>0) and cold spot depict low-value clusters (Gi*<0). Gi* computation results in z-scores which indicate a place of a particular value relative to mean and standard deviation in a dataset. The value of z equal to zero (z=0) means the value of the statistic is equivalent to mean, value less than zero (z<0) means the value is less than mean and the value greater than zero (z>0) means value greater than the mean. It considers the value of the points and their neighbouring pixels with a fixed distance d, where all the values within the distance d are considered for computation. It is calculated by comparing local averages to global averages by the analysis of spatial weights. The clusters are formed due to the concentration of weighted points defined in a local area.

Gi* statistic is a local version of Gi statistic, the difference is that the Gi exclude the value of a particular point and only computes its neighbouring pixels with a certain distance d. Gi* provides statistical significance to the hotspot analysis. The values of Gi*>=1.645, Gi*>=1.960, Gi*>=2.576 and Gi*>=3.291 in the computation denotes 90%, 95%, 99% and 99.9% of significance level respectively are calculated for DMSP and VIIRS.

3.2.2 Coefficient of variation

CV is a standard measure of variability, defined as:

$$cv = \frac{S}{\underline{x}}$$

Where,
S is the measure of standard deviation and of the radiances measurements, $\underline{x}$ is the mean of radiance measurements in a predefined window.

CV is calculated for DMSP-OLS 2013 and VIIRS composite aggregated images on 3×3 and 5×5 windows. The calculations are done on the original images of the datasets of DMSP and VIIRS (composited and aggregated) clipped for India. Various thresholds of low variances are considered which are further used in attaining adequate PIFs. The thresholds of 3%, 5%, 10%, 15% and 20% are calculated.

3.3 Calculation of Net PIFs

After the individual PIF calculations of both the datasets, the net PIFs are calculated. The Net PIFs gives the overlapping PIF pixels free from the background noise of DMSP and VIIRS datasets. From this, the mask was already prepared in the previous steps. The mask generated was multiplied by the Total PIFs to calculate the Net PIFs after the background removal. These Net PIFs were used for extracting the values from original images of DMSP and VIIRS from inter-calibration.

The following steps are followed in the calculation of the PIFs:

- DMSP PIFs = Gi* AND CV
- VIIRS PIFs = Gi* AND CV
- Total PIFs = DMSP PIFs AND VIIRS PIFs
- Net PIFs = Total PIFs × Total mask

Net PIFs generated using Gi*>1.645 and CV<20% for India is shown in figure 3. Number of pixels calculated for DMSP PIFs, VIIRS PIFs, Total PIFs and Net PIFs are shown in table 1.

3.4 Inter-calibration model

This research adopts inter-calibration of VIIRS data with respect to DMSP. The Inter-calibration model is based on the temporal overlap of DMSP and VIIRS images. For this, the common Net pseudo invariant features (Net PIFs) were considered and the corresponding values from DMSP and VIIRS are extracted. Logarithmic and Power model are applied for inter-calibration and the best suited one is picked for simulation.

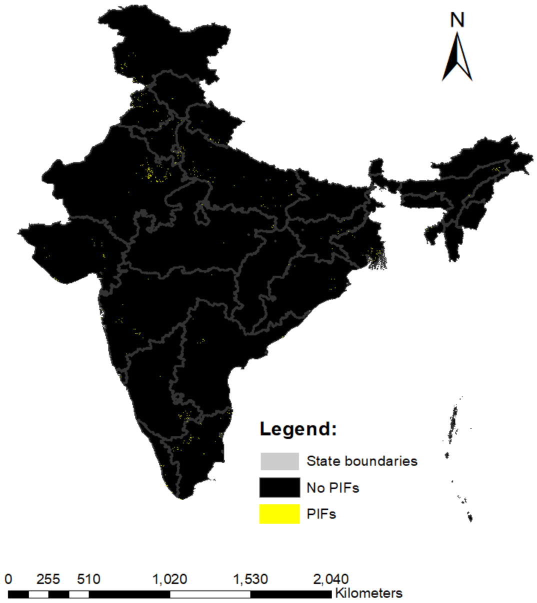

Figure 1: Net PIFs generated using Gi*>1.645 and CV<20% for India

Using logarithmic function

The relationship between DMSP and VIIRS fits the logarithmic model:

$$y = a * log\ log\ (x)\ + b$$

Where, x denotes VIIRS calue, y denotes the DMSP/OLS value, a and b are coefficients.
Inter-calibration equations:

$$y\ (dmsp) = a * log\ log\ (viirs)\ + b$$

Where y signifies the calculation of calibrated (simulated VIIRS) by altering the equation with coefficients.

Using power function

The power function is found to improve the comparability and to describe the non-linear relationship between the two dataset (Li et al., 2017).

$$y = ax^b$$

Where, x denotes VIIRS value, y denotes the DMSP/OLS value, a and b are coefficients.
Inter-calibration equations:

$$y\ (dmsp) = a(viirs)^b$$

Where y signifies the calculation of calibrated (simulated VIIRS) by altering the equation with coefficients.

3.5 Calculation of Sum of Lights (SOL) Index

The sum of light (SOL) index is the sum of all pixel values of the night-time light image defined by a particular area. SOL index checks the efficiency and consistency of the inter-calibration process. It is calculated for different states of India for DMSP and simulated/calibrated VIIRS. This is done to evaluate the differences and errors in the inter-calibration. For this, as the shape file of administrative boundaries of India was considered. The SOL is calculated using Zonal statistics which calculated the sum of values state-wise. SOL for the simulated image is calculated after the equalization to the value range of DMSP.

Table 1: Number of pixels calculated for DMSP PIFs, VIIRS PIFs, Total PIFs and Net PIFs

	VIIRS PIFs	
Gi*>1.645	CV<3%	No PIFs
(3X3 window)	CV<5%	34
	CV<10%	1061
	CV<15%	5935
	CV<20%	16597
Gi*>1.645	CV<3%	No PIFs
(5X5 window)	CV<5%	No PIFs
	CV<10%	24
	CV<20%	951
	DMSP PIFs	
Gi*>1.645	CV<3%	96264
(3X3 window)	CV<5%	160656
	CV<10%	815609
	CV<15%	1151764
	CV<20%	1327312
Gi*>1.645	CV<3%	13749
(5X5 window)	CV<5%	30815
	CV<10%	340570
	CV<15%	686836
	Total PIFs	
DMSP AND VIIRS	CV<5%	22
(3X3 window)	CV<10%	786
	CV<15%	4747
	CV<20%	14131
DMSP AND VIIRS	CV<10%	20
(5X5 window)	CV<15%	814
	Net PIFs	
Total PIFs X Total Mask	CV<10%	330
(3X3 window)	CV<15%	2942
	CV<20%	10626

3.6 Correlation with socio economic indicators

Two famous indicators are considered for testing the inter-calibrated model at national and regional scales which are: Gross State Domestic Product (GSDP) and Electricity Consumption (EC) for the year 2013.
GSDP in India accounts for the sum of the values added by all the industries for the states and union territories. State-wise Gross Domestic Product for India at the current prices on 2011-2012 series was considered for the financial year of 2013-2014. The GSDP is measured as

Indian Rupees (in crore i.e., 10^7). State-wise total energy consumption by ultimate consumers in India was considered for the final year of 2013-2014. The Electricity consumption state-wise has a unit of Gigawatt hours (GWh).

4. Results and discussion

4.1 Extraction of PIFs

PIFs are spatially homogeneous and of low local spatial variability (Refer to section 3.6). The two regions of spatial homogeneous clusters and with low local variances are integrated (using Boolean AND) between outputs of various thresholds applied. Figure 3 shows the Net PIFs calculated using the value of Gi*>1.645 and CV<20% which gives 10,626 pixels of concern. These are the major cities of India having more illumination as compared to the other regions. Table 1 lists the calculations made for Gi* and CV individually for DMSP, VIIRS and the ANDing result for the Net calculation.

4.2 Relationship between DMSP-OLS and SNPP-VIIRS

4.2.1 Logarithmic relationship

- At 15% CV threshold: the acquired points from the Net PIFs (2942) are extracted from DMSP and VIIRS and the data is applied to the Model: a*log(x) +b. The Model fits with the value of R^2=0.805.
- The Coefficients of the model fit are found to be a=36.957 and b=12.185.
- At 20% CV threshold: the acquired points from the Net PIFs (10626) are extracted from DMSP and VIIRS and the data is applied to the Model: a*log(x) +b. The Model fits with the value of R^2=0.775. The coefficients of the model fit are found to be a=38.669 and b=12.071. Figure 4 illustrates the fitting of the points for Log Model.

4.2.2 Power relationship

- At 15% CV threshold: the acquired points from the Net PIFs (2942) are extracted from DMSP and VIIRS and the data is applied to the model: $a \cdot x^b$. The Model fits with the value of R^2=0.734. The
- Coefficients of the model fit are found to be a=14.758 and b=0.448.
- At 20% CV threshold: the acquired points from the Net PIFs (10626) are extracted from DMSP and VIIRS and the data is applied to the model: $a \cdot x^b$.

The model fits with the value of R^2=0.702. The coefficients of the model fit are found to be a=14.904 and b=0.471. Figure 5 illustrates the fitting of the points for Power Model.

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4.3 Simulation of VIIRS dataset

The simulation or calibration of VIIRS datasets (predicted DMSP) is performed by selecting the optimal model. This is done based on the value of R-square. The suitable model developed with the adequate number of PIFs is found to be the logarithmic fit at 20% threshold of CV. The related coefficients are extracted and original VIIRS image is calibrated using:

Predicted DMSP = 38.67 * log(VIIRS)+12.07

The simulated image is then equalized to DMSP by clipping the greater values above 63 and removing the negative values.

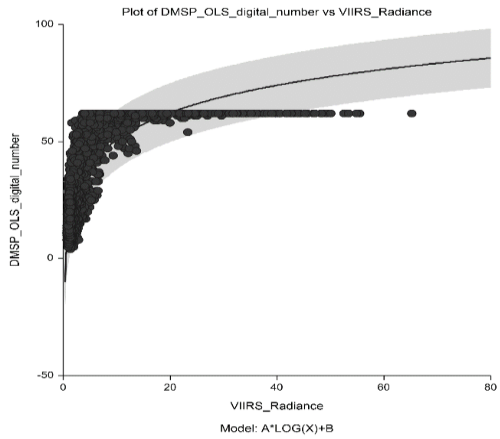

Figure 2: Logarithmic model fit line and the distribution of the points of extracted PIFs from DMSP and VIIRS at 20% CV threshold

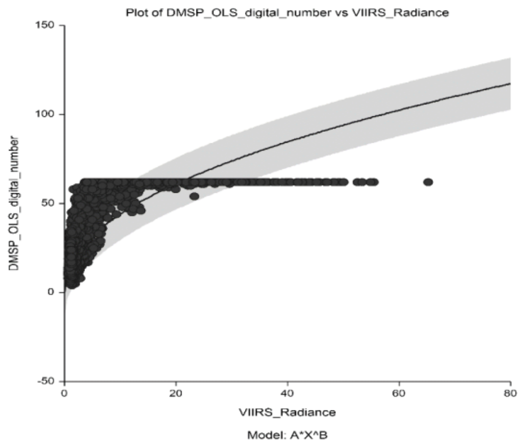

Figure 3: Power model fit line and the distribution of the points of extracted PIFs from DMSP and VIIRS at 20% CV threshold

Figure 6 show the normalized and equalized image of VIIRS in the range of DMSP dataset. This simulation is further used to correlate with socio economic indicators for the year 2013.

The simultaneous comparison between DMSP and VIIRS has been made to know about the accuracy of the simulation. The attempt in this research is been made for a single year 2013, but the idea applies to many years and can be used in a series analysis. This can be further researched and used for different datasets in future.

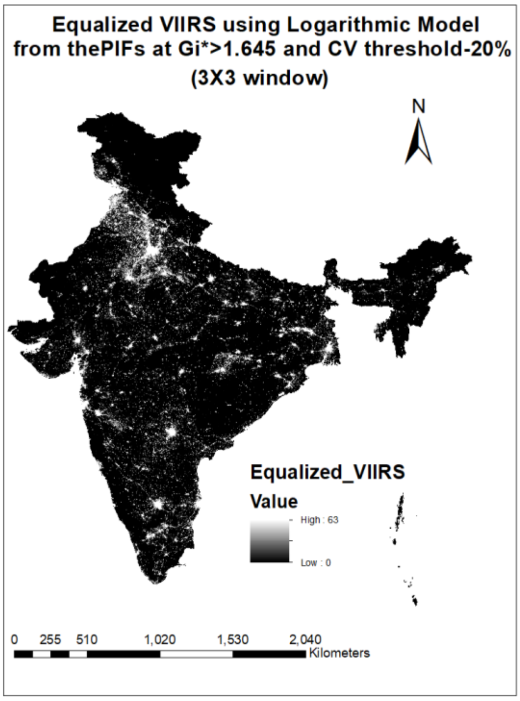

Figure 4: Equalized simulated VIIRS (Predicted DMSP) image from the Log model

4.4 Validation with socio-economic Indicators

4.4.1 National level

Gross state domestic product

DMSP

The equation of the straight line relating SOL and state-wise gross domestic product for the year 2013 of 29 Indian states has been evaluated. The value of R-Squared, the proportion of the variation in SOL that can be accounted for by variation in State wise GSDP for 2013, is found to be 0.716. The correlation between SOL and State wise GSDP 2013 is found to be 0.846.

Simulated VIIRS (predicted DMSP)

The equation of the straight line relating SOL and state-wise gross domestic product for the year 2013 of 29 Indian states has been evaluated. The value of R-Squared, the proportion of the variation in SOL that can be accounted for by variation in State wise GSDP for 2013, is found to be 0.606. The correlation between SOL and State wise GSDP 2013 is found to be 0.778.

Electricity Consumption

DMSP

The equation of the straight line relating SOL and State-wise electricity consumption for the year 2013 of 30 Indian states has been evaluated. The value of R-Squared, the proportion of the variation in SOL that can be accounted for by variation in State wise electricity consumption for 2013, is found to be 0.867. The correlation between SOL and State wise electricity consumption is found to be 0.931.

Simulated VIIRS (Predicted DMSP)

The equation of the straight line between simulated SOL and State-wise electricity consumption for the year 2013 of 30 Indian states has been evaluated. The value of R-Squared, the proportion of the variation in SOL that can be accounted for by variation in State wise electricity consumption for 2013, is found to be 0.690. The correlation between simulated SOL and State wise electricity consumption 2013 is found to be 0.831.

4.4.2 Regional level

Five regions or zones considered are: North, North East, East, West and south. The SOL index is calculated zone wise and validated against GSDP and EC for DMSP and VIIRS individually.

Gross state domestic product

Gross state domestic product is correlated with SOL index of DMSP and SNPP-VIIRS. The coefficient of determination of comes out to be 0.905 for DMSP but comes out to be significantly low for simulated VIIRS, 0.529. The relationship seems stronger with the original DMSP than that of simulated VIIRS (Predicted DMSP) equalized to the level of DMSP.

Electricity consumption

Electricity consumption by ultimate consumers is correlated with SOL index of DMSP and SNPP-VIIRS. The coefficient of determination comes out to be 0.936 for DMSP but comes out to be significantly low for simulated VIIRS, 0.539. The relationship seems stronger with the original DMSP than that of simulates VIIRS (Predicted DMSP) equalized to the level of DMSP.

Figure 7 and 8, shows the variability in the relationship of DMSP and VIIRS with GSDP and EC of the year 2013 zone wise. Also, from the state wise variations in the values of sum of light (SOL) for DMSP-OLS and SNPP-VIIRS datasets. It is observed that the model underestimates the values of simulated VIIRS almost in all states except the states of Jammu & Kashmir, Jharkhand, and Meghalaya.

4.5 Discussion

The study innovates at calculating the common invariant regions for the former and the newer source of NTL data and developing an inter-calibration model. The research focused on harmonization and inter-calibration of DMSP and VIIRS for a consistent dataset the study makes use of the resources available for public use and finding out the ways in which the objectives are achieved satisfactorily. The inter-calibration process helps to radiometrically harmonize both the datasets. The process is accomplished by the use pseudo invariant features as the target sites for modelling the relationship between the two datasets. For the calculation of the PIFs, methods of Gi* and CV are applied. The PIFs are used for intercalibration and simulation of VIIRS in harmony with DMSP. The logarithmic function was fitted to VIIRS with function coefficients and inter-calibrated/simulated VIIRS (Predicted DMSP) image was drawn. The simulated image range was observed from -165.95 to 138.247. This range was made saturated from values greater than 63 and negative values were removed. The range was then equalized to DMSP by converting the radiances to the integer. This step has radiometrically harmonized VIIRS with the level of DMSP.

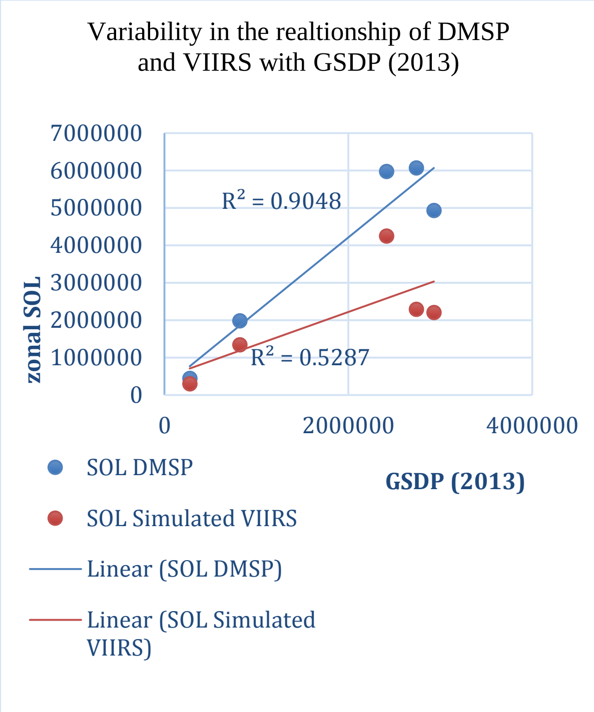

Figure 5: Relationship of zonal SOL against GSDP 2013 (Rs. In crore)

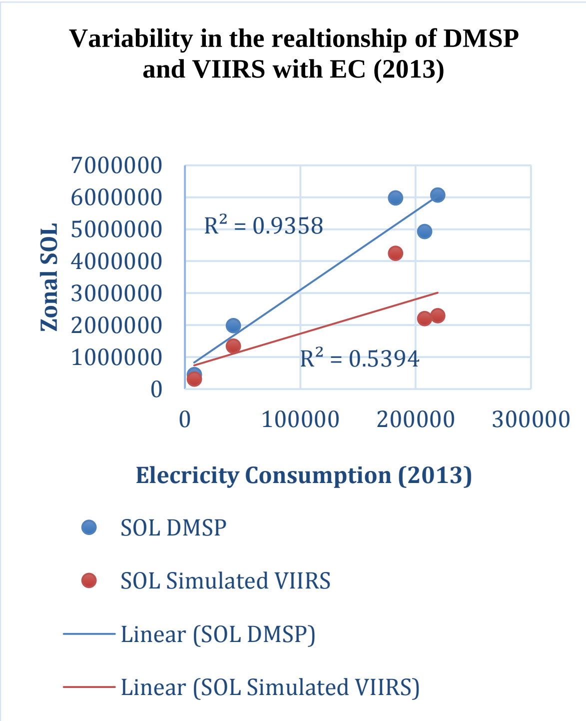

Figure 6: Relationship of zonal SOL against EC 2013 (GWh)

After simulation, SOL was calculated for simulated VIIRS (Predicted DMSP) and original DMSP which are assessed against Gross state domestic product (GSDP) and Electricity consumption (EC) for the year 2013-2014. The indicators were collected state-wise and the correlation was found at the national level and on regional levels covering northern, north eastern, eastern, western and southern regions of India.

4.6 Limitations of the approach

The inter-calibrated model generated using the methodology adopted cannot be directly applied to the consequent years after 2013 for making a consistent time series of DMSP. This is because the DMSP data are not radiometrically correct. The DMSP data needs pre-processing for the correction of saturation problem and blooming effect. However, piece wise fitting of regression line can produce a better fit of the inter-calibration model. The approach takes monthly images and then the annual composite is constructed using averaging techniques. This doesn't include the sensor's parameters and the consideration of lightning due to other sources. This affects the performance of the inter-calibrated model.

5. Conclusions

For the importance and necessity for consistent night-time light datasets, harmonization and inter-calibration of the two datasets are performed. For harmonization, the foremost requirement to ensure the equality on the basis of temporal, spatial, spectral and radiometric harmonization. Here, the VIIRS dataset is altered to make it consistent to DMSP. This requirement is fulfilled by monthly compositing for temporal harmonization spatial aggregation for spatial harmonization and inter-calibration for radiometric harmonization. The two datasets are already spectrally harmonized, collecting the night-time lights in one specific band.

For inter-calibration, pseudo invariant features were used as target sites denoting the regions where the light does not drastically vary and are spatially homogeneous and stable. The PIFs calculated are made free from the saturated pixels in DMSP and background noise in VIIRS are used for simulation successfully.

The validation was performed on National level covering the states of India and at regional levels covering the zones and their corresponding states. This research finds out that the inter-calibrated Model performs well on the national scale but doesn't perform well at regional scales. Improvements can be made to ensure better consistency by applying different harmonization techniques, selection of PIFs and inter-calibration model selection.

For instance, ancillary products such as Normalised Urban Areas Composite Index (NUACI) (Liu et al., 2015) data can be used to remove non-urban areas which have DN values in DMSP/NTL data. This can help in improving the inter-calibration process.

Moreover, the blooming effect can be attempted to remove using optimal thresholding technique as described by Liu et al. (2015). Inter-calibration within all DMSP/NTL datasets is also necessary since it involves various satellites with different radiometry. This process may automatically bring 2013 dataset also in uniformity.

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