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Abstract :- NRSC has installed total 27 VLF lightning detection sensors (LDS) across the country which includes 6 LD-350 sensors and 21 LRX-1 sensors. These sensors are long range VLF sensors having their detection range up to 800 km with more than 98% confidence within 300 km range. The network is put in a way to have 50% overlap to enable high geolocation accuracy and maintain redundancy. At present network covers North-East, East Coast, Central and Southern part of India. As per the World Meteorological Organization (WMO) criteria, Time Of Arrival (TOA) method was implemented on NRSC-LDS network. The NRSC-LDS network data was validated with existing Indian Institute of Tropical Meteorology (IITM)/India Meteorological Department (IMD)network which has mandate of now-casting the lighting occurrences. The NRSC-LDS network data is indented to generate Atmospheric lighting ECV, first such attempt world-wide. The ECVs can further be utilized for various atmospheric and disaster support studies.

Keywords: Atmosphere, Lightning, ECV

NRSC- Technical Report

Title:

NRSC- Lightning Detection Sensor Network: Time Of Arrival (TOA)method based Geolocation and Essential Climate Variable Generation

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Alok Taori&Arun Suryavanshi

Title:

NRSC- Lightning Detection Sensor Network: Time Of Arrival (TOA)method based Geolocation and Essential Climate Variable Generation

Abstract

NRSC has installed total 27 lightning detection sensors (LDS) across the country which includes 6 LD-350 sensors and 21 LRX-1 sensors. These sensors are long range VLF sensors having their detection range up to 800 km with more than 98% confidence within 300 km range. The network is put in a way to have 50% overlap with near located sensors to enable high geolocation accuracy and maintain redundancy. At present network covers North-East, East Coast, Central and Southern part of India. In 2016, WMO introduced cloud to ground lighting occurrence as one of the Essential Climate Variable (ECV). As per the World Meteorological Organization (WMO) report, high precision geolocation of lightning occurrence can be obtained by Time of Arrival (TOA) methods. The TOA method was implemented on NRSC-LDS network to attain the WMO prescribed accuracy. The NRSC-LDS network data was validated with the existing Indian Institute of Tropical Meteorology (IITM) data which India Meteorological Department (IMD) uses as their mandate is the now-casting the lighting occurrences. Present work is a novel first of its kind effort, where, NRSC-LDS network data is utilized to generate Atmospheric lighting ECV. The ECV can further be utilized for various atmospheric and environmental impact studies, which is a unique and innovative concept in the climate change studies being carried out world-wide.

1. Preamble:

Understanding the atmospheric lightning flashes/strikes and their occurrences is one of the most important questions of the Earth's climate science. Real-time, lightning data have profound importance in climate science, air quality research, and atmospheric nitrogen budget, apart from this being one of the major natural disasters (*Price, 2000; Romps et al. 2014*). Keeping these is view Lightning Detection Sensor (LDS) network was conceptualized at NRSC in the year 2016 and in the year 2017 NRSC established LDS at 6 locations viz., Kolkata, Ranchi, Raipur, Bhubaneswar, Nagpur and Visakhapatnam.

In terms of the space borne exploration, Lightning Imaging Sensor (LIS) on board the Tropical Rainfall Measuring Mission (TRMM), provided snap-shot information and did help in characterizing the occurrences of lightning. At present, a GOES-R mission is launched to cover American/ Europe sector using the Global Lightning Mapper (GLM) sensor. However, for the exact monitoring with temporal characteristics and societal applications such as identification of potential danger zones and now-casting, only ground based Very Low Frequency (VLF)receivers have been found very useful since more than a decade. Using this method, few countries, such as USA, Brazil, Poland, Finland, Japan, etc. have established a very dense network of long-range lightning detection sensors. In Indian sector, India Meterological Department (IMD) through Indian Institute of Tropical Meteorology (IITM) has initiated such a network (Sensors from Earthnetwork, USA in 84 numbers as of June 2020).

Based on the initial network, it was shown that NRSC LDS network is capable of detecting the lighting flashes/strikes and identification/delineation of potential danger/vulnerable zones using single sensor data was feasible (*Taori et al., 2018, 2020*). These reports pointed that errors in individual sensor and magnetic direction-finding method used can be large to an extent of 500 m. Further sometimes due to local static charges induced by electrical noise can also be treated as flashes which basically are noise. In this regard, the World Meteorological Organization (WMO) stated that triangulation and Time of Arrival (TOA) algorithm is the best suited when it comes to the accuracy of positioning of lightning flashes is concerned.

Based on understanding raised from initial LDS network about the errors, artefacts and limitation of the geolocating the lightning occurrences, NRSC planned the expansion of the LDS network with a combination of six BoltekLD-350 and twenty one LRX sensors (*Taori et al., 2020*). The Boltek LRX sensors are long range sensors which work on time of arrival (TOA) algorithm where correlated lightning flashes are determined based on GPS stamped waveforms. The LD350 sensors are highly accurate at near range and shall be used for the estimation after removal of noise and artifacts. An overlapping field analysis suggests that about 64 LRX sensors (having range of >300 km) shall be able to provide nationwide uninterrupted monitoring of atmospheric lightning phenomena.

Present report explains the methodology adopted for the detection of atmospheric lightning flashes and also compares the results obtained from configured sensors with the existing IITM sensor network. After the comparison, the essential lightning climate variable is also generated as per the WMO criteria.

GCOS suggested lightning ECV

Product	Definition	Frequency	Resolution	Req. Uncer.	Stab.	Standard/ References
Number of Lightnings	Total number of detected flashes in the corresponding time interval and the space unit. Space unit should be equal to the horizontal resolution and the accumulation time to the observing cycle	1 day	10 km	-	-	MTGEURD[1]

Source: https://gcos.wmo.int/en/essential-climate-variables/lightning/ecv-requirements

2. Objectives of NRSC LDS network:

The broad objectives of NRSC LDS network are as following.

1. Detect the phenomena of lighting occurrences, in particular cloud to ground lighting flash/strike occurrence characteristics,
2. Identification of potential danger zones and vulnerable area
3. Use the network for Atmospheric Science Research Applications
    - Create a data base for the number of lighting flashes with their geolocations and time of occurrences to update the impact of climate changes in India.
    - Generation of Essential Climate Variable (ECV) as per the WMO criteria & its impact on the atmospheric constituents.
    - Calibration and validation for any future space borne lightning detection sensors
4. Investigate the usage of LDS data as input in weather forcasting models for developing a possible alert system

3. Methodology of lightning detection and geolocation

Working principal of Sensor:

The sensors used in the NRSC LDS network are primarily Boltek LRX-1 with 6 LDS-50. The receiver antenna is omni directional which, in case of LD-350, detects the frequency ranging from 50 kHz to 500 kHz, while, the LRX-1 operates at frequency rang of 1 Hz - 30 MHz. These frequency ranges are found to be highly suitable to detect the cumulus processes including the lightning which arise due to thunder cloud (e.g. Pessy et al., 2009). This antenna has interface with a global positioning system (GPS) antenna for accurate time stamping of the signal received. This tuned with the sky wave oscillation caused by the spherics which are GPS referenced provides the range of the lighting occurrences. The waveform received is in the form of '$A.\cos(wt+\varphi)$', which provides amplitude 'A', frequency 'w' and phase 'φ' information. Through correlated frequency and phase differences the range is estimated. This LDS also uses gated magnetic direction finder to estimate the direction of lightning occurrences.

In order to detect the atmospheric lightning detection, the system employs a plurality of at least four geographically-separated lightning detection sensors. Each receiver consists of an LDS sensor and a timing signal receiver, which are synchronized to within 100 ns through Global Positioning System (GPS) clock.

Geolocation of Lightning Occurrences:

Each of the ground flash/strike detection stations is connected via internet lines to a central analyser (at present located at RRSC-Central, Nagpur).When a lightning flash occurs, the electromagnetic pulse emitted is detected by each receiver, which records the time of detection of the ground stroke. The signal will arrive at each receiver site at a different time, dependent on the distance from the event. Each receiver then samples its internally synchronized clock and records the exact time of detection at that particular receiver. This time data is then transmitted over the communication link from the receiver to the central analyser. The ranging methods of lightning occurrences are either magnetic direction finding or based on Time of Arrival (TOA) of signal. After a series of investigations, the World Meteorological Organization (WMO) recommended the use of time of arrival method (*WMO GCOS Report, 2016*). This is due to the criterion that maximum error in the location assessment of lighting occurrence should not exceed 100m. In TOA method central analyser carries out a calculation of the lightning occurrence location after correlating the waveforms with accurate time by multiple sensors near simultaneously as described in the following.

TOA Method:

Time of Arrival is the simplest and most commonranging technique, most notably used in the Global Positioning System (GPS) (e.g.,*Lee, 1986,Shi and Ming, 2016*) that employ the trigonometrical and numerical techniques

Trigonometrical technique:

This method is basedon knowing the exact time that a signal was sent from the target, the exact time the signal arrives at areference point, and the speed at which the signal travels (usually the speed of light). Once these are known, the distance from the reference point can be calculated using the simple equation:

$$d = c * (T_{arrival} - T_{sent})$$

where c is the speed of light. Using this distance, the set of possible locations of the target can be determined. In two dimensions, this yields a circle with the equation:

$$d = \sqrt{\{x_{ref} - x\}^2 + \{y_{ref} - y\}^2}$$

where (x_{ref}, y_{ref}) is known position of the reference point, i.e., the sensor location. Once this set is calculated for enough reference points (at least 3), the exact position of the target can be calculated by finding the intersection.

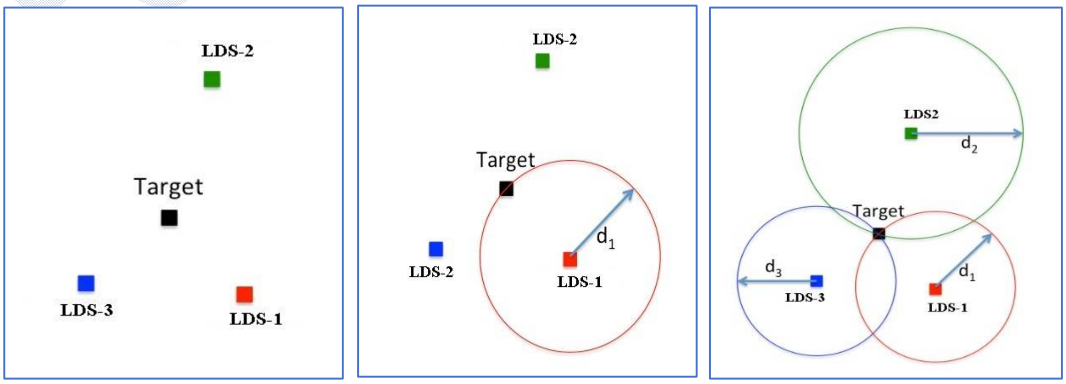

Figure 1. TOA method using trigonometric technique of geolocation

In this example, we have a lightning flash as the Target (black) surrounded by three sensors (red, green, and blue).At time *t1*, a signal is received at sensor-1 from the Target, which is received at *t2*at sensor-2. The distance (*d1*)between the Target and sensor-1 is calculated, then the circle of possible locations is drawn, as shown in middle figure. This process is repeated for Sensor-2 and Sensor-3, which yields two more circles, as shown in right-side figure. It is clear in that the target lies at the intersection of the three circles. Thus, the geolocation of the lighting flash occurrence is calculated. As the number of sensors detecting the same target becomes 4 or more, we get the standard deviation of the location providing error estimation of the location calculated.

Numerical Method:

In a numerical TOA positioning system, the clocks of the four stations and the object are assumed to be synchronized, where the stations' positions are well known. The TOA measurements between the object and the stations are multiplied by the known signal propagation speed in the mediam to yield range measurements. Thus,

(x_i, y_i, z_i), i = 1 to 4, where i is the known position of station i,

r_i,i= 1 – 4, is the range measurement between the object and station i, and (x, y) is the unknown position of the lightning occurrence.

The TOA measurement equation is written as

$(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 = r^2$,i= 1 - 4. ---(1)

Substituting i= 2,3,4 in Eq. (1) and subtracting each of the three equations from Eq. (1) when$i$= 1 , we get three equations of the form

$(x_i-x_1)x + (y_i-y_1)y + (z_i-z_1)z = A_j /2, i = 2,3,4$ --- (2)

Where,

$Aj = (r_1^2 - r_i^2) + (x_i^2 - x_1^2) + (y_i^2 - y_1^2) + (z_i^2 - z_1^2), j = 1,2,3$

From the set of three equations expressed in (2) *z* and *y* can be cancelled out using to get an explicit expression for '*x*' independent of '*y*' *as*

$$x = \frac{1}{2}\frac{(I_4 I_5 - I_3 I_6)}{(I_2 I_5 - I_1 I_6)} \quad \text{---(3)}$$

Similarly, we can obtain an explicit expression for *y* independent of *x as*

$$y = \frac{1}{2}\frac{(I_1 I_4 - I_2 I_3)}{(I_1 I_6 - I_2 I_5)} \quad \text{---(4)}$$

And

$$z = \frac{1}{2}\frac{(I_7 I_{10} - I_8 I_9)}{(I_7 I_{12} - I_8 I_{11})} \quad \text{---(5)}$$

Where,

$I_1 = (Z_3 - Z_1)(X_2 - X_1) - (Z_2 - Z_1)(X_3 - X_1)$

$I_2 = (Z_4 - Z_1)(X_2 - X_1) - (Z_2 - Z_1)(X_4 - X_1)$

$I_3 = (Z_3 - Z_1)\, A_1 - (Z_2 - Z_1)\, A_2$

$I_4 = (Z_4 - Z_1)\, A_1 - (Z_2 - Z_1)\, A_3$

$I_5 = (Z_3 - Z_1)(Y_2 - Y_1) - (Z_2 - Z_1)(Y_3 - Y_1)$

$I_6 = (Z_4 - Z_1)(Y_2 - Y_1) - (Z_2 - Z_1)(Y_4 - Y_1)$

$I_7 = (Y_3 - Y_1)(X_2 - X_1) - (Y_2 - Y_1)(X_3 - X_1)$

$I_8 = (Y_4 - Y_1)(X_2 - X_1) - (Y_2 - Y_1)(X_4 - X_1)$

$I_9 = (Y_3 - Y_1)\, A_1 - (Y_2 - Y_1)\, A_2$

$I_{10} = (Y_4 - Y_1)\, A_1 - (Y_2 - Y_1)\, A_3$

$I_{11} = (Y_3 - Y_1)(Z_2 - Z_1) - (Y_2 - Y_1)(Z_3 - Z_1)$

$I_{12} = (Y_4 - Y_1)(Z_2 - Z_1) - (Y_2 - Y_1)(Z_4 - Z_1)$

Eq's (3), (4) and (5) are the mathematical formulas of a computer algorithm to calculate the position of an object using TOA measurements. The computation of each position component is independent of the other components. Thus, allowing to only calculating the position component of interest. In the present work we have kept z absent (z=0) to make the calculations simple. Therefore, we calculate only *x* and *y* coordinates of the lightning occurrences.

4. LDS Network and Processing

At present NRSC has LRX sensors deployed at 21 locations in India such as to cover North-East, East Coast, Central and Southern part of India. current LDS network established by NRSC is shown in figure 2.and the network is likely to expand for covering those vulnerable and under-covered optimally and to adhere the WMO requirements.

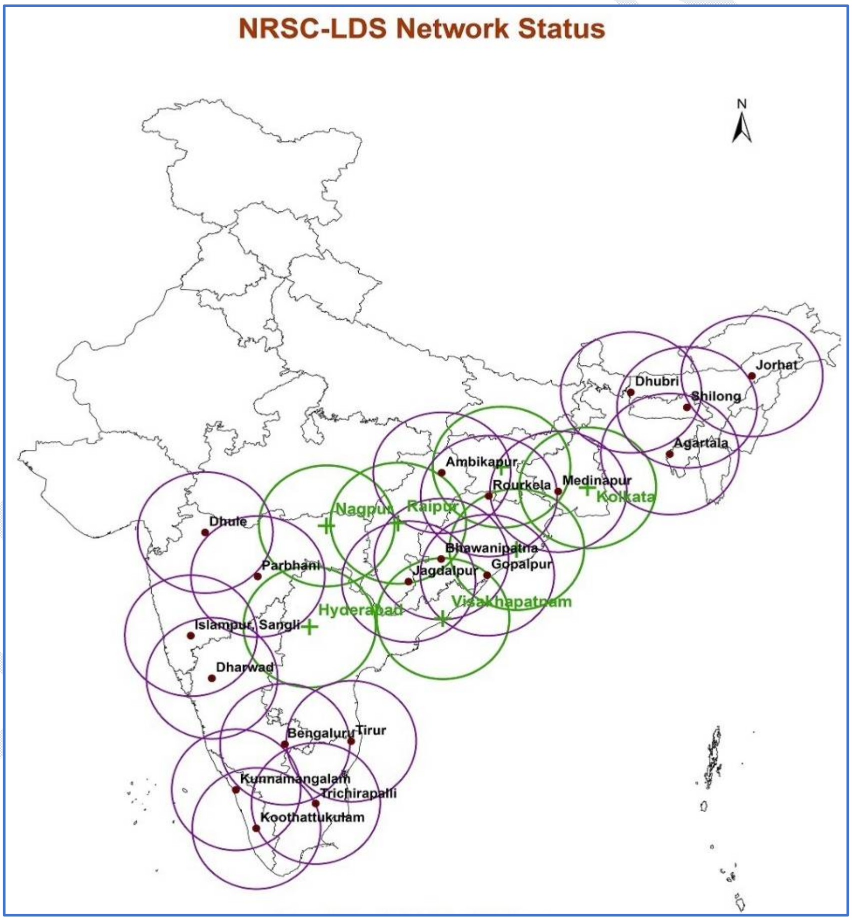

Figure 2: The NRSC-LDS network as of May 2020. The circle represents 300 km radius of sensor where signals are received with 98% confidence level. Green fonts show the host having LD350 sensors while purple fonts represent LRX-1 sensor establishments.

All the LDS locations are time synchronized with NRSC/RRSC server and all the measurements carry GPS time-stamping. Every lighting flash generates a static electrical pulse. The static pulse must be smoothed so that electrical noise arising by the local electrical noise (e.g., TV towers, Telephone lines, Cell phone towers, power grid, improper earthing) shall be either notched or smoothed out by appropriate temporal averaging.

As the thunderstorm develops, static discharge starts and this static electrical pulse is transmitted by every host to the NRSC/RRSC server. The TOA calculations are then carried out by the server as shown in figure 3 and retrieved data is saved in MySQL database.

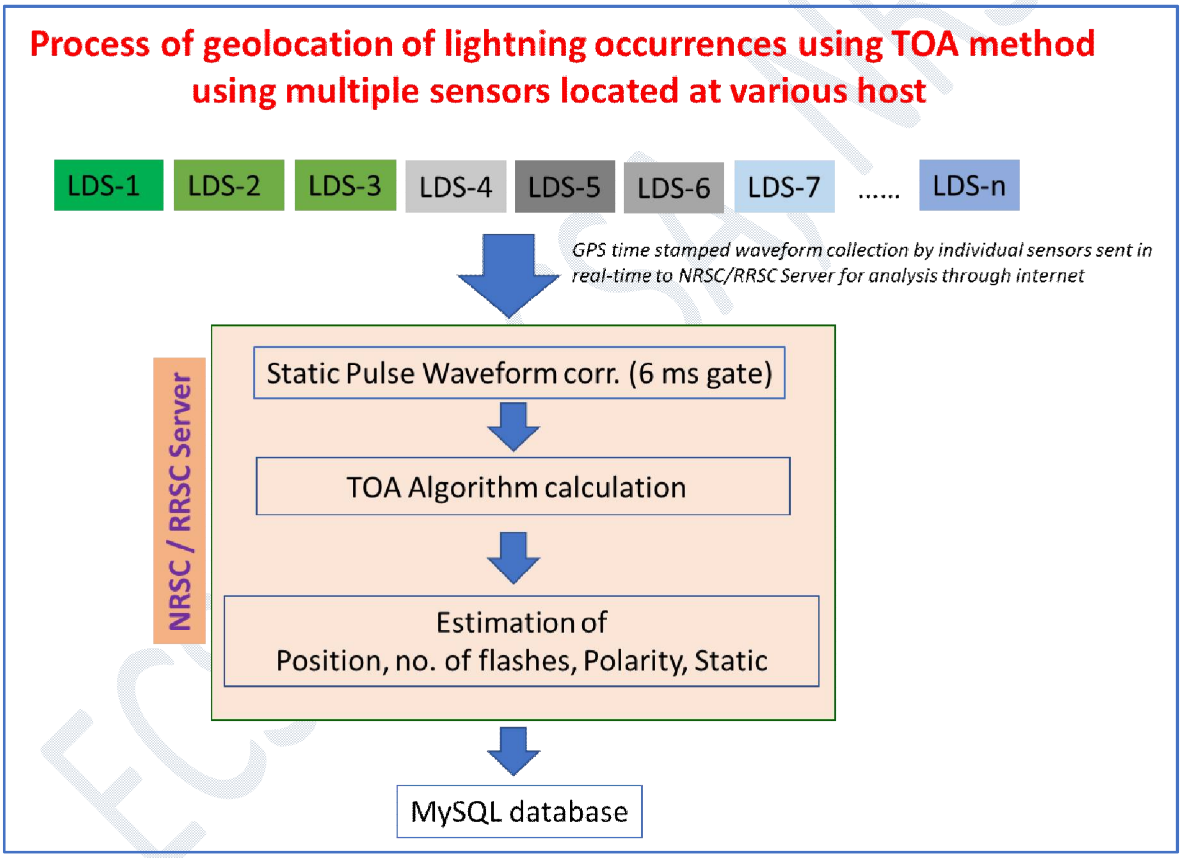

Figure 3. Processing of signal received from LDS stations for geolocating the event

Before carrying out the TOA calculations we need to ascertain that waveform received are optimized for the ambient electrical noise. Following is an ideal example which suggests that in case of large noise noted in the waveform can be optimized by doing FFT smoothening (figure 4). Once this is performed on a specific location, largely it remains stable. However, it needs to be checked regularly.

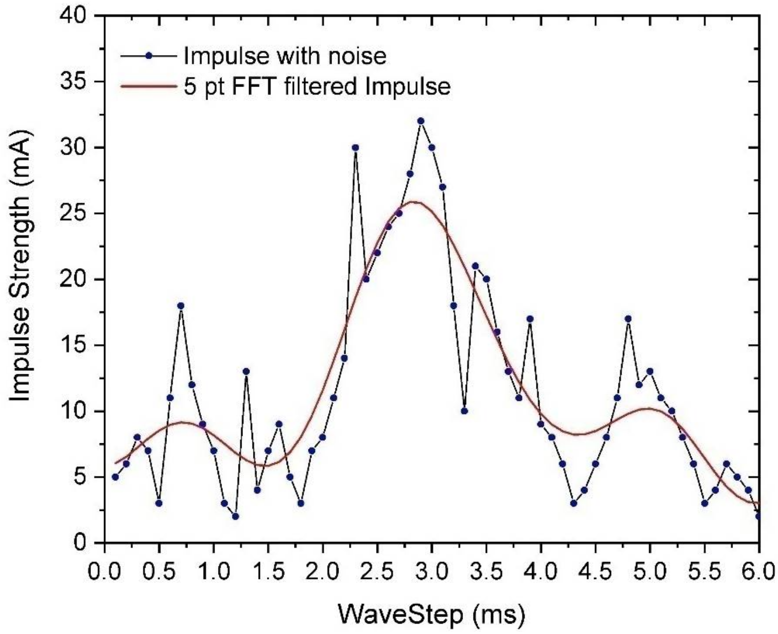

Figure 4. Smoothening of individual stations static discharge waveform

Once the above smoothening is performed, one shall assure that the clocks of all the LDS stations are properly synchronized with the tremble GPS attached with each LDS/LRX antenna. This is in general carried out while installation of the LDS units at their respective host locations, however, needs to be checked regularly.

Typical time to carry out the TOA calculations and geolocation analysis online is about 30 seconds. The requirement for error estimation is that at least 4 LDS shall record the event, so that through the standard deviation of the estimated location, an error can be assessed. This criterion is also suggested by the WMO and has been followed by so far existing lightning detection networks. We assess the variation of error estimates and number of sensors using the real data obtained by NRSC LDS network using the TOA algorithm from all the sensors. Error analysis reveal the positional accuracy to be within 100meters when an event is monitored simultaneously by more than 6detectors. Finding of the error estimates are shown in figure 5.

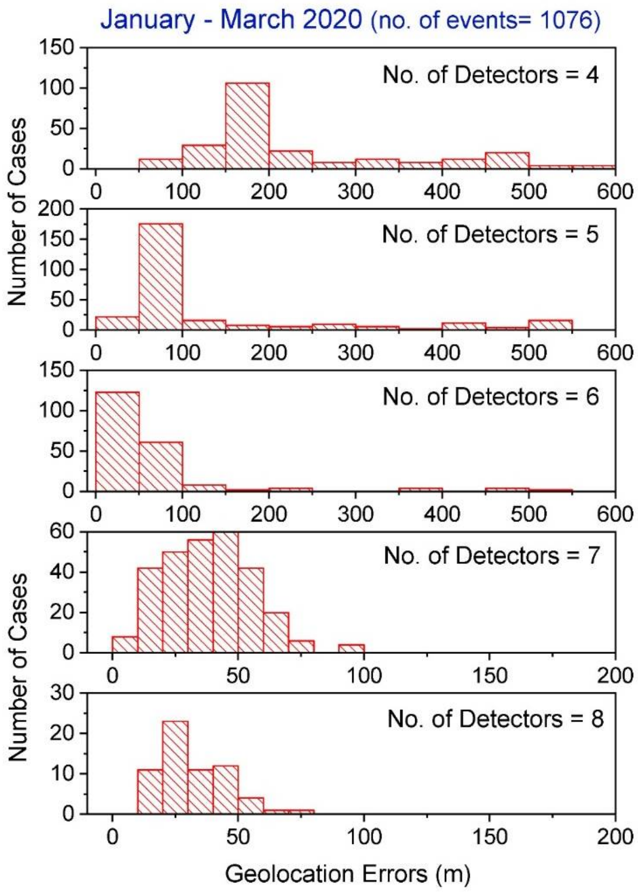

Figure 5: Variation of errors with number of detections online for monitoring one lightning occurrence.

It is evident from the figure 5that every event shall be monitored by at least 6sensors. This also suggests that there shall be at least 5 sensors in nearby region with overlap of 50 percent ranges with each other to achieve all the time an error below 100 m for positional accuracy of lighting occurrences.

It is important to mention here that though LD-350 data has high accuracy in nearby locations where sensor is placed, the local static discharge noise becomes an issue in reliability of data. This is because of increasing numbers of mobile signal towers, high power transformers, electric power lines for metro etc.. Therefore, moving from a pure magnetic direction finding method (as in case of LD-350) to TOA method is sensible. This is shown in figure 6, in which, post processed signals received from LD-350 are compared with LRX, TOA derived signals are compared.

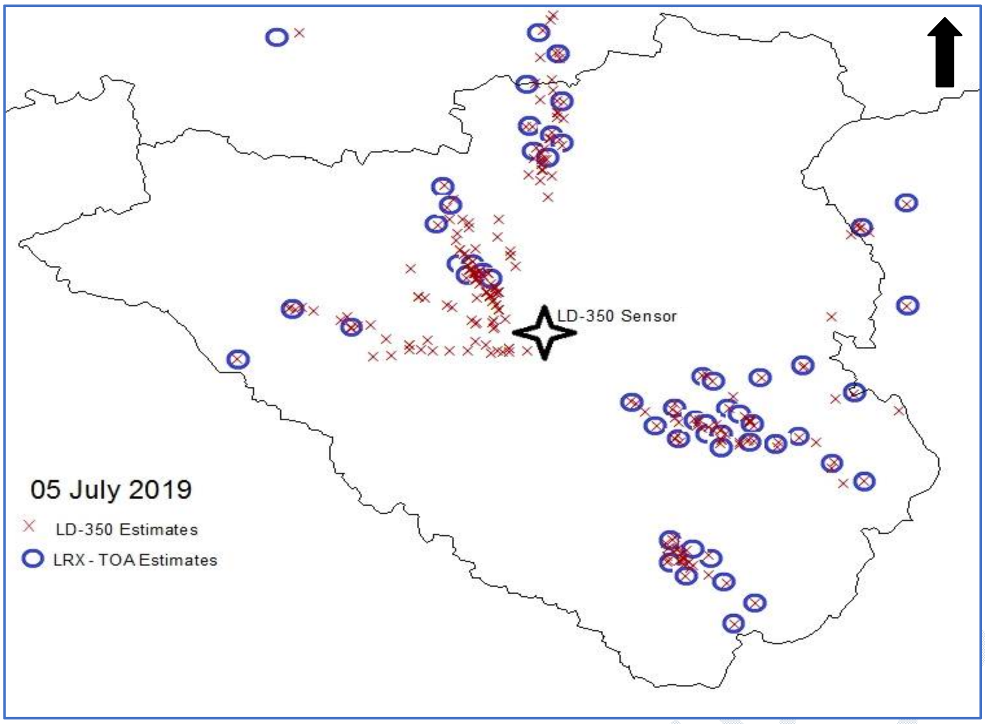

Figure 6. Comparison of LD-350 data with LRX data over Nagpur on 05 July 2019

The location of LD-350 sensor in Nagpur is shown as the star. In the figure 6, it is clear that both the data show the occurrences of lighting at similar locations. It is also noted that LD-350 show more number of occurrences which may be due to its very high sensitivity for capturing any kind of electrical discharge. In particular, the discharge in the westward direction which are not captured by LRX data are due to the metro rail passing nearby and a high tension line nearby. As these discharges cannot be accounted and corrected in LD350, we are not sure about the validity of these discharges. However, as the LRX data is based on correlated signals from at least 4 sensors, we believe them to be true representative of the lightning related discharges, i.e., cloud-to-ground lightning flash/strike occurrence.

5. Comparison of data with existing network

This is to note that Indian Institute of Tropical Meteorological (IITM)/ India Meteorological Department (IMD) has a Lightning detection network which is powered by Earth-Network, USA sensors named as IITM-LLN. Till date they have established a network of 86 sensors throughout the country. The aim of the IITM-LLN is to detect the cloud to ground lightning occurrences and now-caste the occurrences based on the network data and model (*Dr. Sunil Pawar, personal communication, 2019*). Though it is debatable whether IITM-LLN data it is totally reliable, in the absence of any other means of validation, we have cross-correlated out measurements with them. As direct point-to-point comparison may not provide appropriate information due to the lesser density of NRSC-LDS sensor population, we carry out 2-dimensional correlation of images having national coverage.

F*igures 7, 8, 9&10* showcase sample images depicting the number of lightning flashes over the Indian subcontinent while *Table 1* show results of the correlation analysis.

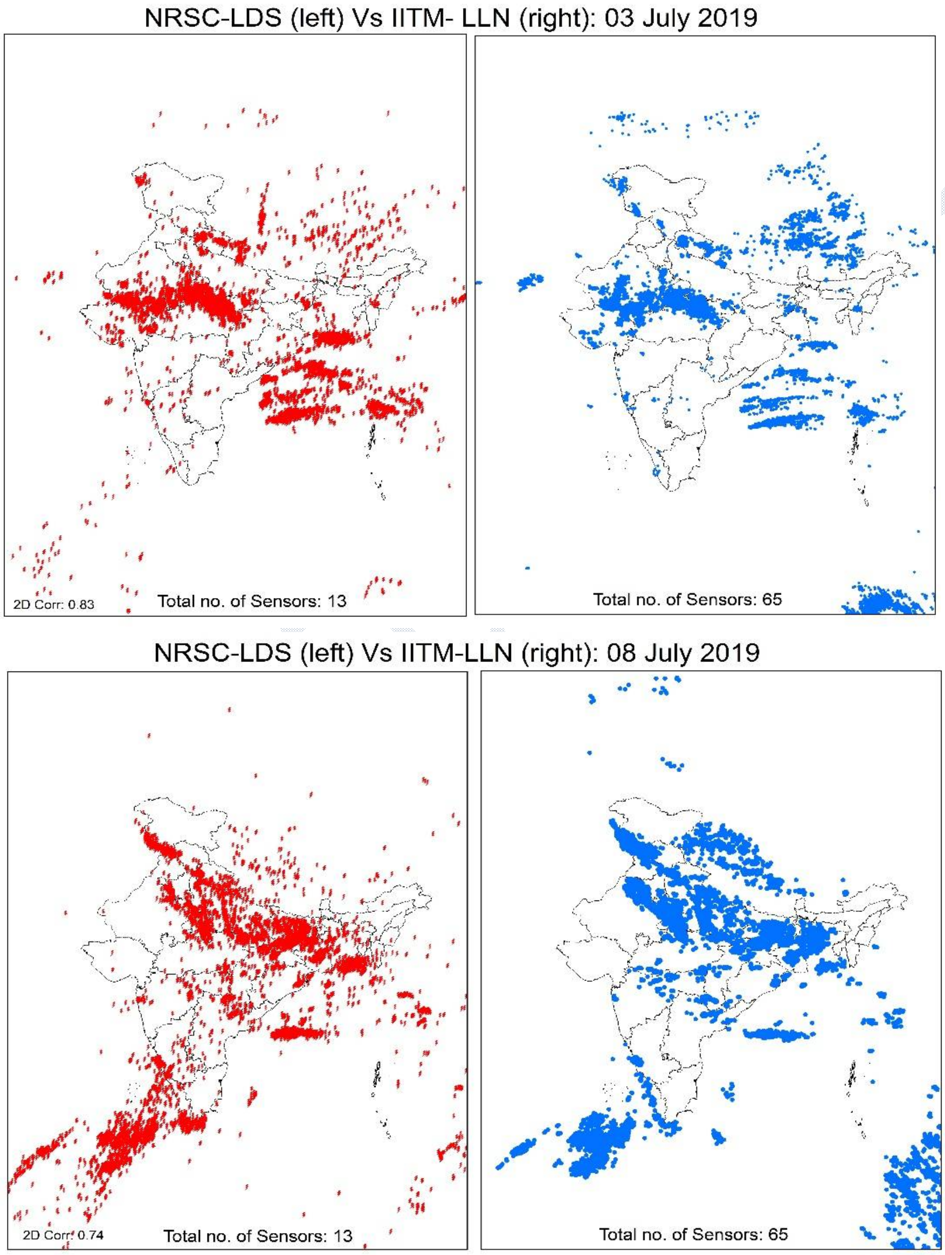

Figure 7. Comparison of NRSC-LDS and IITM-LLN lightning detection networks for 03 and 08 July 2019

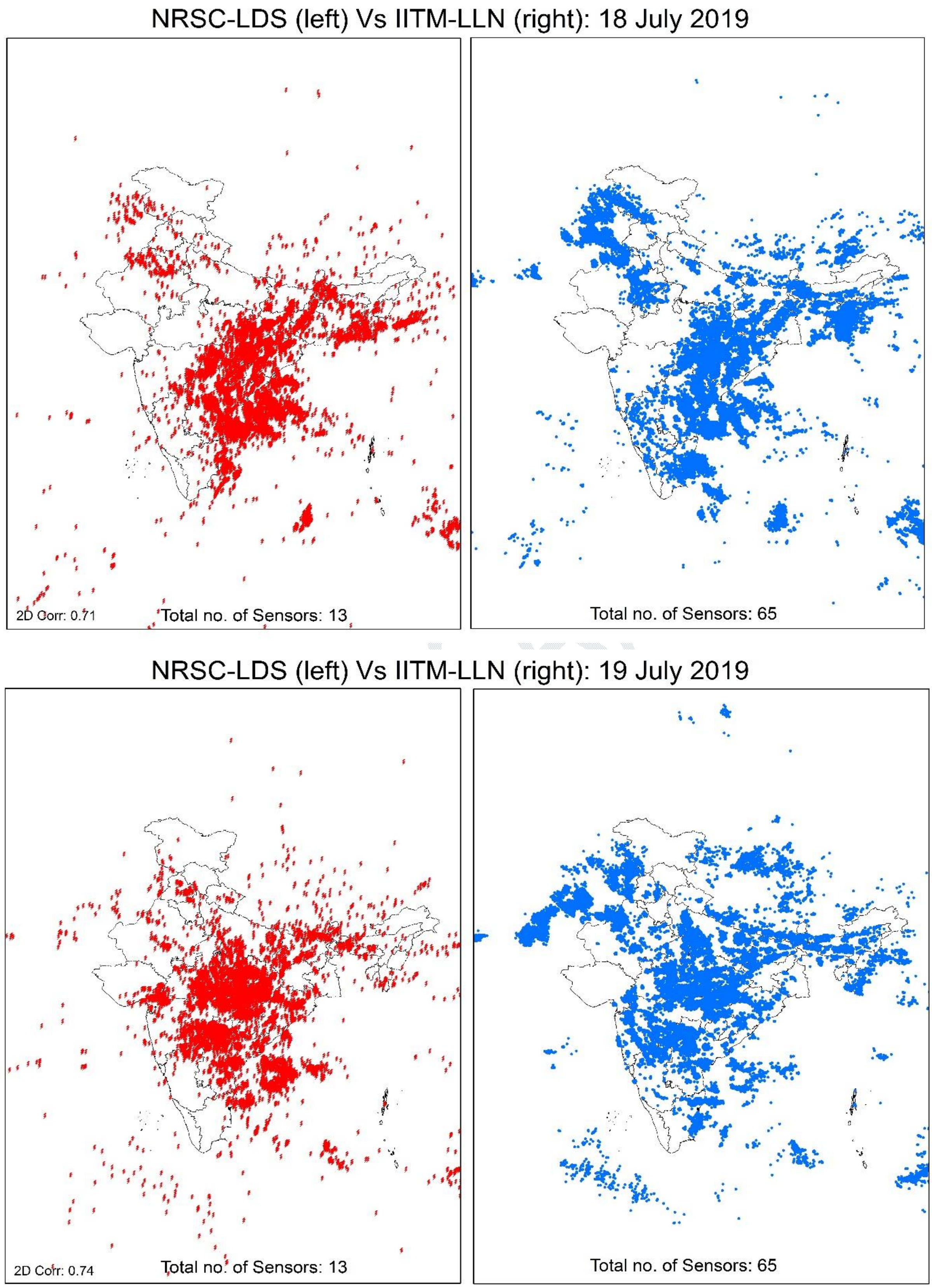

Figure 8. Comparison of NRSC-LDS and IITM-LLN lightning detection networks on 18 and 19 July 2019

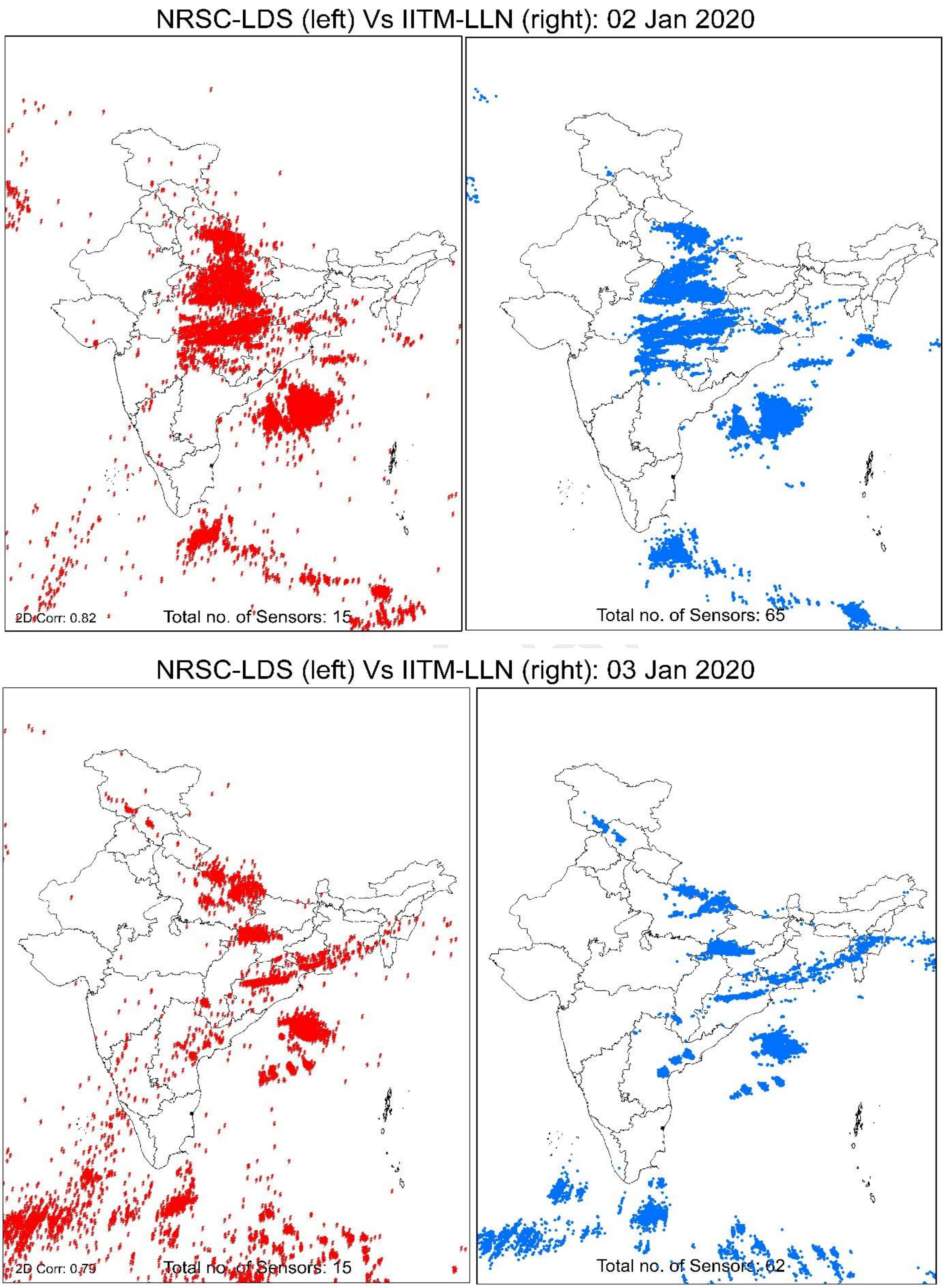

Figure 9. Comparison of NRSC-LDS and IITM-LLN lightning detection networks on 02 and 03 January 2020

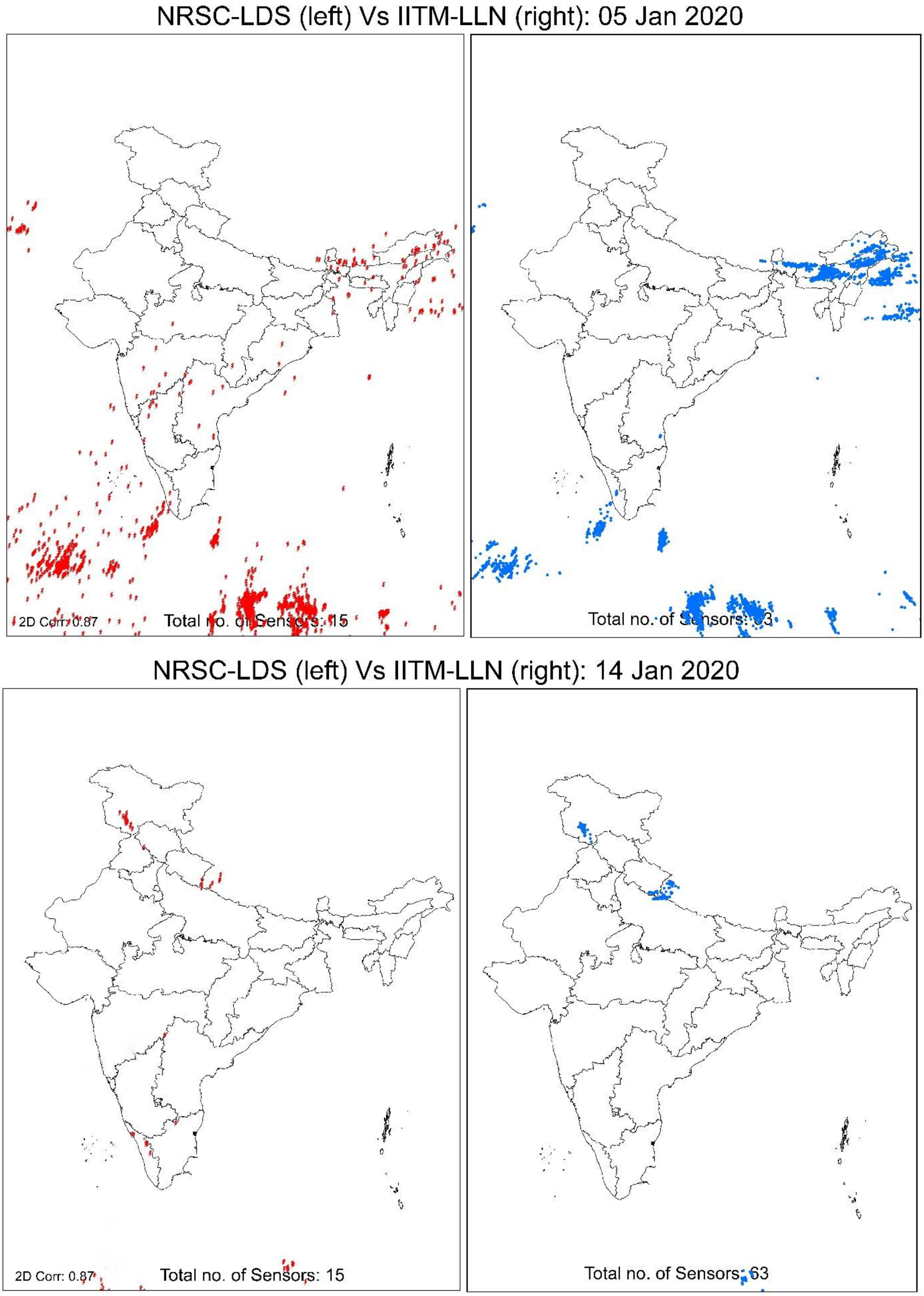

Figure 10. Comparison of NRSC-LDS and IITM-LLN lightning detection networks on 05 and 14 January 2020

Date	Corr Coeff
03-Jul-19	0.83
04-Jul-19	0.81
05-Jul-19	0.76
06-Jul-19	0.84
07-Jul-19	0.78
08-Jul-19	0.74
09-Jul-19	0.79
10-Jul-19	0.73
11-Jul-19	0.78
12-Jul-19	0.75
13-Jul-19	0.81
14-Jul-19	0.76
15-Jul-19	0.72
16-Jul-19	0.8
17-Jul-19	0.81
18-Jul-19	0.71
19-Jul-19	0.74
20-Jul-19	0.77
21-Jul-19	0.78
22-Jul-19	0.71
23-Jul-19	0.81
24-Jul-19	0.81
25-Jul-19	0.76
26-Jul-19	0.84
27-Jul-19	0.78
28-Jul-19	0.74
29-Jul-19	0.79
30-Jul-19	0.73
31-Jul-19	0.78
01-Aug-19	0.75
02-Aug-19	0.81
03-Aug-19	0.76
04-Aug-19	0.72
05-Aug-19	0.8
06-Aug-19	0.81
07-Aug-19	0.71
08-Aug-19	0.74
09-Aug-19	0.77
10-Aug-19	0.78
11-Aug-19	0.71
12-Aug-19	0.81
13-Aug-19	0.76
14-Aug-19	0.72
15-Aug-19	0.8
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17-Aug-19	0.71
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22-Aug-19	0.81
23-Aug-19	0.76
24-Aug-19	0.72
25-Aug-19	0.8
26-Aug-19	0.81
27-Aug-19	0.71
28-Aug-19	0.74
29-Aug-19	0.77
30-Aug-19	0.78
01-Jan-20	0.81
02-Jan-20	0.82
03-Jan-20	0.79
04-Jan-20	0.76
05-Jan-20	0.87
06-Jan-20	0.78
07-Jan-20	0.77
08-Jan-20	0.79
09-Jan-20	0.8
10-Jan-20	0.81
11-Jan-20	0.82
12-Jan-20	0.79
13-Jan-20	0.77
14-Jan-20	0.87
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17-Jan-20	0.79
18-Jan-20	0.76
19-Jan-20	0.87
20-Jan-20	0.78
21-Jan-20	0.77
22-Jan-20	0.79
23-Jan-20	0.8
24-Jan-20	0.81
25-Jan-20	0.82
26-Jan-20	0.79
27-Jan-20	0.77
28-Jan-20	0.87
29-Jan-20	0.81
30-Jan-20	0.82
31-Jan-20	0.79
01-Feb-20	0.76
02-Feb-20	0.87
03-Feb-20	0.78
04-Feb-20	0.77
05-Feb-20	0.79
06-Feb-20	0.8
07-Feb-20	0.81
08-Feb-20	0.82
09-Feb-20	0.79
10-Feb-20	0.77
11-Feb-20	0.87
12-Feb-20	0.8
13-Feb-20	0.79
14-Feb-20	0.77
15-Feb-20	0.79
16-Feb-20	0.81
17-Feb-20	0.82
18-Feb-20	0.77
19-Feb-20	0.8
20-Feb-20	0.71
21-Feb-20	0.74
22-Feb-20	0.75
23-Feb-20	0.76
24-Feb-20	0.8
25-Feb-20	0.82
26-Feb-20	0.78
27-Feb-20	0.79
28-Feb-20	0.76
29-Feb-20	0.87
01-Mar-20	0.78
02-Mar-20	0.77
03-Mar-20	0.79
04-Mar-20	0.8
05-Mar-20	0.81
06-Mar-20	0.82
07-Mar-20	0.79
08-Mar-20	0.77
09-Mar-20	0.87
10-Mar-20	0.81
11-Mar-20	0.82
12-Mar-20	0.79
13-Mar-20	0.76
14-Mar-20	0.87
15-Mar-20	0.78
16-Mar-20	0.77
17-Mar-20	0.79
18-Mar-20	0.8
19-Mar-20	0.81
20-Mar-20	0.82
21-Mar-20	0.79
22-Mar-20	0.77
23-Mar-20	0.87
24-Mar-20	0.81
25-Mar-20	0.82
26-Mar-20	0.79
27-Mar-20	0.76
28-Mar-20	0.87
29-Mar-20	0.78
30-Mar-20	0.77
31-Mar-20	0.79
01-Apr-20	0.8
02-Apr-20	0.81
03-Apr-20	0.82
04-Apr-20	0.79
05-Apr-20	0.77
06-Apr-20	0.87
07-Apr-20	0.8
08-Apr-20	0.79
09-Apr-20	0.77
10-Apr-20	0.79
11-Apr-20	0.81
12-Apr-20	0.82
13-Apr-20	0.77
14-Apr-20	0.8
15-Apr-20	0.71
16-Apr-20	0.74
17-Apr-20	0.75
18-Apr-20	0.76
19-Apr-20	0.8
20-Apr-20	0.82
21-Apr-20	0.78
22-Apr-20	0.78
23-Apr-20	0.77
24-Apr-20	0.79
25-Apr-20	0.8
26-Apr-20	0.81
27-Apr-20	0.82
28-Apr-20	0.79
29-Apr-20	0.77
30-Apr-20	0.87

Table 1. Results of 2D correlation analysis between NRSC-LDS and IITM-LLN network

We further scalled down the comparison to state level 'Odisha' where NRSC LDS network is having good coverage with 5 sensors nearby while the IITM has a network of 9 sensors. *Figure 11* shows the comparison wherein we can see that majority of the times the lighting occurrences are noted by both sensors with sometimes location differences which were not evident in the pan India figures (figs 6-9). Table 2 explains the statistics of the differences in the lighting occurrences.

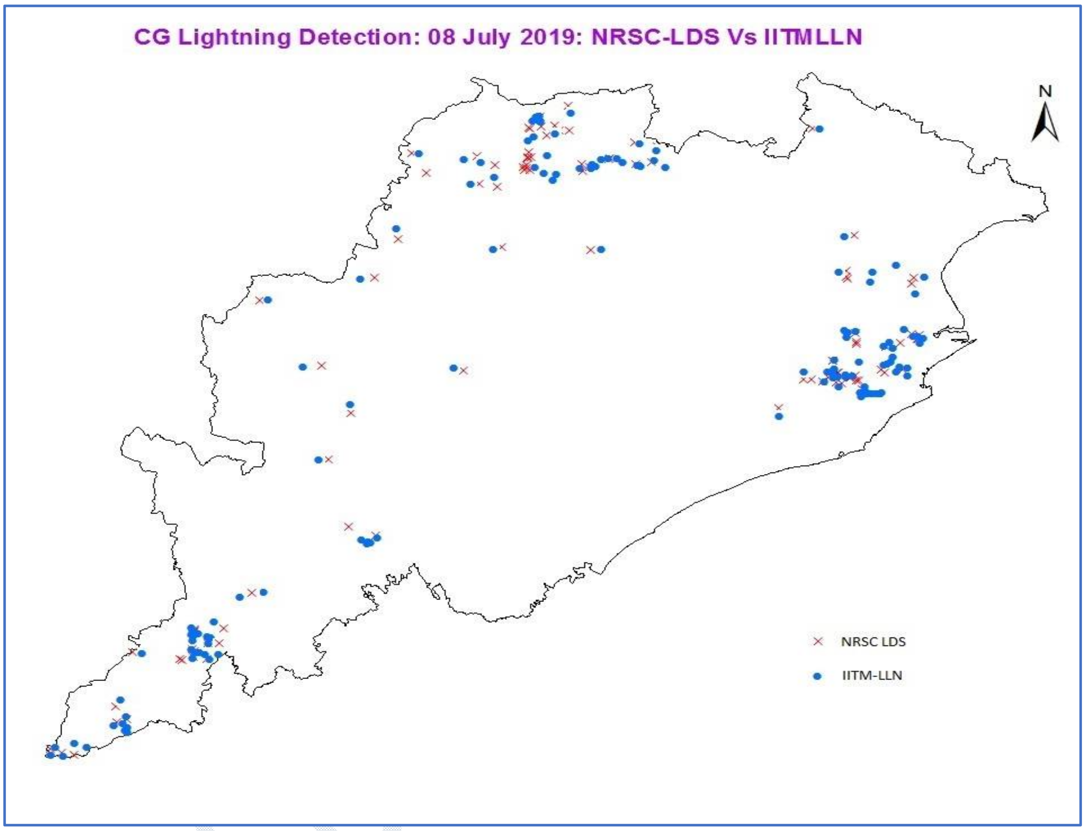

Figure 11. Comparison of NRSC-LDS and IITM-LLN lightning detection networks in a state level grid.

Date	**Total no of CG Flashes** (max observed by any network)	**Common Flashes**	**Unique to IITM-LLN**	**Unique to NRSC-LDS**
03 July 2019	26	14	8	4
08 July 2019	126	108	12	6
02 Jan 2020	465	384	56	25
03 Jan 2020	634	578	34	22

Table 2. Statistics of lighting occurrences in Odisha by LDS and LLN.

It is evident from figures 7-11 and table 1& 2 that in spite of having different detectors and locations of the detectors, majority of the lighting occurrences are captured by NRSC-LDS network. The differences may essentially because population density of sensors. As the number of sensors increase statistical significance and redundancy improves.

Comparison with Ground Truth:

There are a number of occasions when NRSC-LDS network detected the phenomena while the IITM-LLN did not. As several times ground information was taken by our collaborators, we found NRSC network providing correct information. At the same time, there are very few instances when NRSC-LDS network did not detect the phenomena while the IITM LLN did. *Table 3* provides these instances for January 2020– April 2020 duration. These detections were made by visual inspection by the person, hence, there may be a human error which can be as large as 50 km as.

Date	Location	NRSC-LDS	IITM-LLN
03-Jan-20	Rourkela	yes	no
07-Jan-20	Raipur	yes	no
14-Jan-20	Kozikode	yes	no
20-Jan-20	Sangli	no	yes
26-Jan-20	Kolkata	yes	no
04-Feb-20	Jorhat	no	yes
09-Feb-20	Shilong	no	yes
13-Feb-20	Trichi	yes	no
16-Feb-20	Thirur	yes	no
03-Mar-20	Bhawanipatna	yes	no
08-Mar-20	Bhubaneswar	yes	no
09-Mar-20	Dhule	yes	no
13-Mar-20	Ranchi	yes	no
19-Mar-20	Jagdalpur	no	yes
24-Mar-20	Gopalpur	yes	no
02-Apr-20	Medinipur	yes	no
08-Apr-20	Hyderabad	yes	no
12-Apr-20	Shilong	yes	no
15-Apr-20	Nagpur	yes	no
18-Apr-20	Rourkela	yes	no
20-Apr-20	Benguluru	no	yes
24-Apr-20	Dhule	no	yes
28-Apr-20	Parbhani	yes	no
29-Apr-20	Kolkata	yes	no

Table 3. Comparison of network detection performance based on manual ground observations

6. Generation of Essential Climate Variable (ECV)

Lightning occurrences recorded at respective LDS nodes across India are pushed to LDSLRX server located at Nagpur. In this way entire database has been built and hosted on LDSLRX server with MYSQL workbench database. MYSQL database is quite powerful to cater the need of archiving huge database and compatible to various operating systems and programming platforms. Microsoft Visual studio is one of the compatible platforms for MYSQL and hence preferred for querying and data extraction purpose. Database scheme (Current) has details in terms of latitude, longitude, strike type, strike current, strike polarity with date and time.

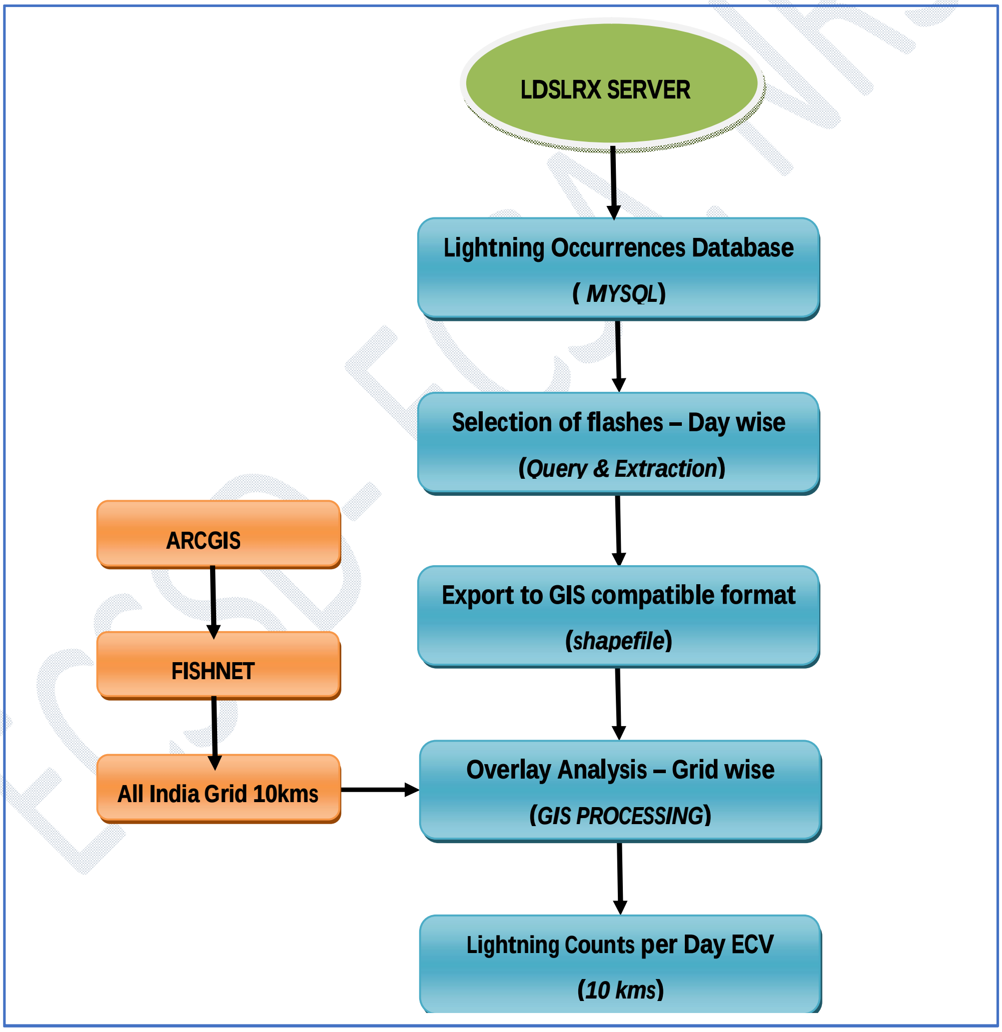

Figure 12. Flow Chart for Creation of Lightning Count per Day per 10 km ECV

Main objective of ECV generation is to deliver lightning counts occurred over 10km by 10km area per day. Hence 10 km cell size grid was generated using FISHNET tool of ARCGIS software. This grid constitutes 96000 grid cells covering Indian region. As ECV need to be on daily basis, selection was applied on database for a particular day so that processing load on database is minimized. Visual basic .net programming interface was used for data extraction purpose. Such selected records then converted to GIS compatible format i.e. shapefile. GIS processing - overlay analysis was performed using 10km grid file and day specific shapefile to give lightning counts for each grid cell for that particular day. In this way output is lightning counts per day ECV in the form of 10km x10km grid cells. Figures 13 shows the prepared grids having 10 km x 10 km resolutions and the NRSC LDS gridded data of 29 May 2020 to prepare map of ECVs.

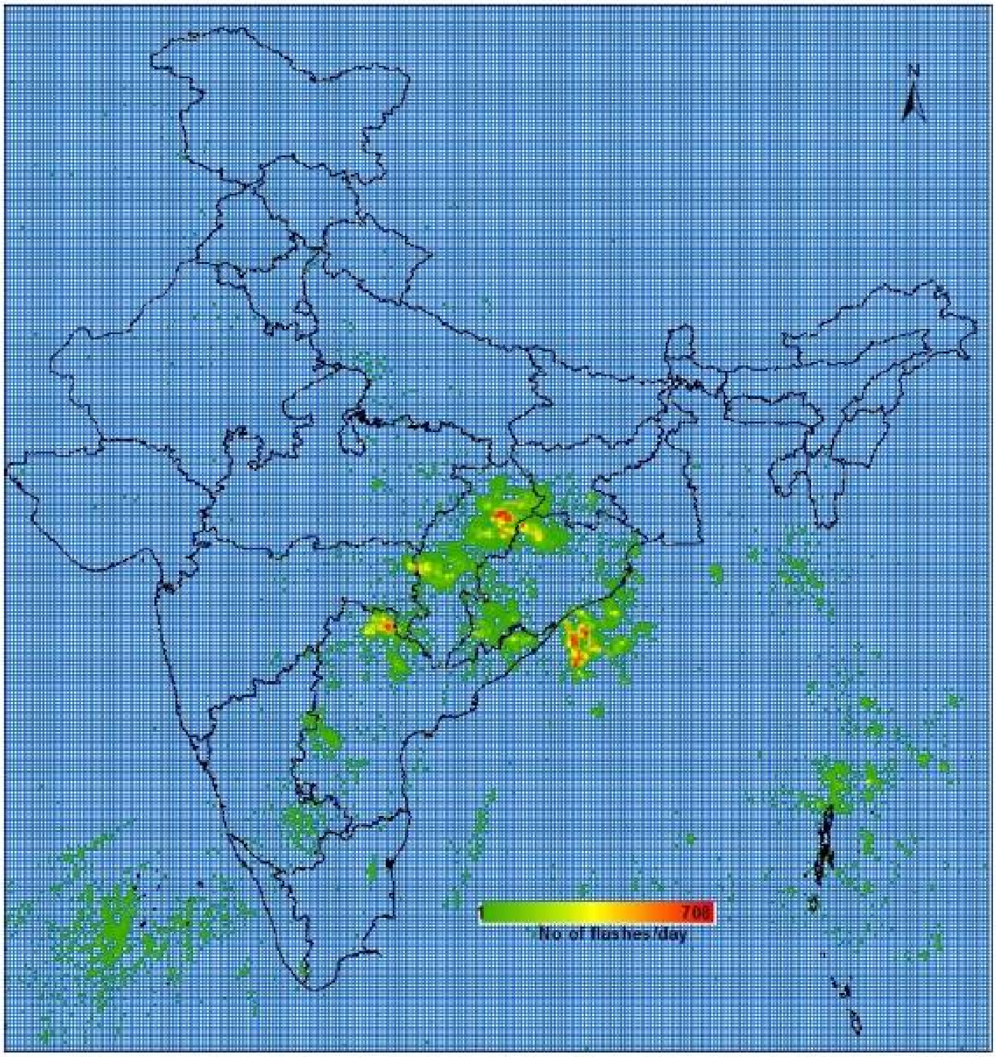

Figure 13. LDS data averaged over the 10 km x 10 km grids for the preparation of ECVs

After these grid analyses the data can be showcased as map or .shp file for appropriate showcasing or distribution for the users. When a user clicks on a location, the map provides information on the number of cloud-to-ground strikes/ flashes per day per 10 km x 10 km grid which is defined as the atmospheric lightning ECV by WMO. Few sample maps exhibiting the spatial variation of ECVs are shown in figures 14& 15.

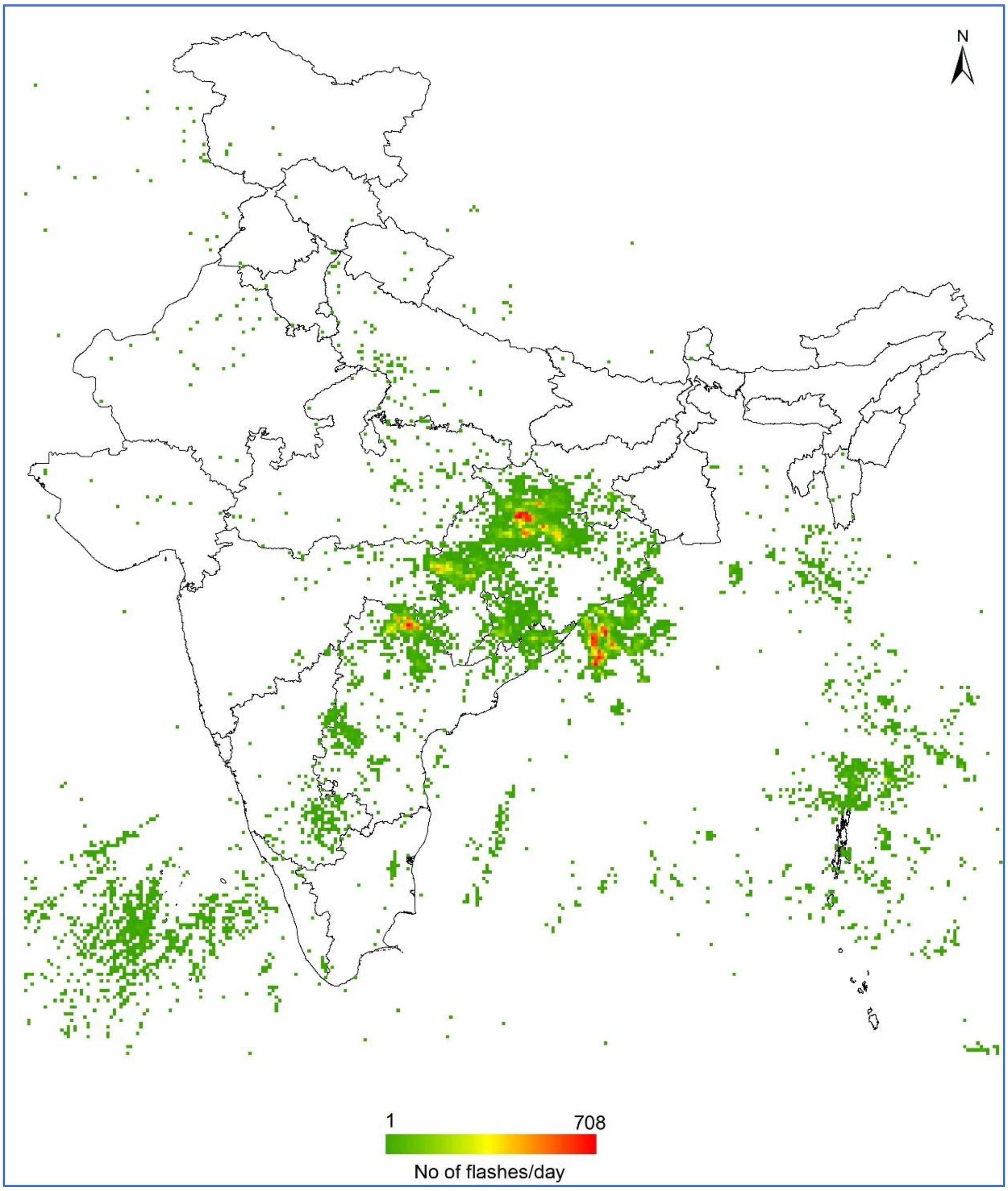

Figure 14. A final lightning ECV map showing the distribution and vulnerability on 29 May 2020.

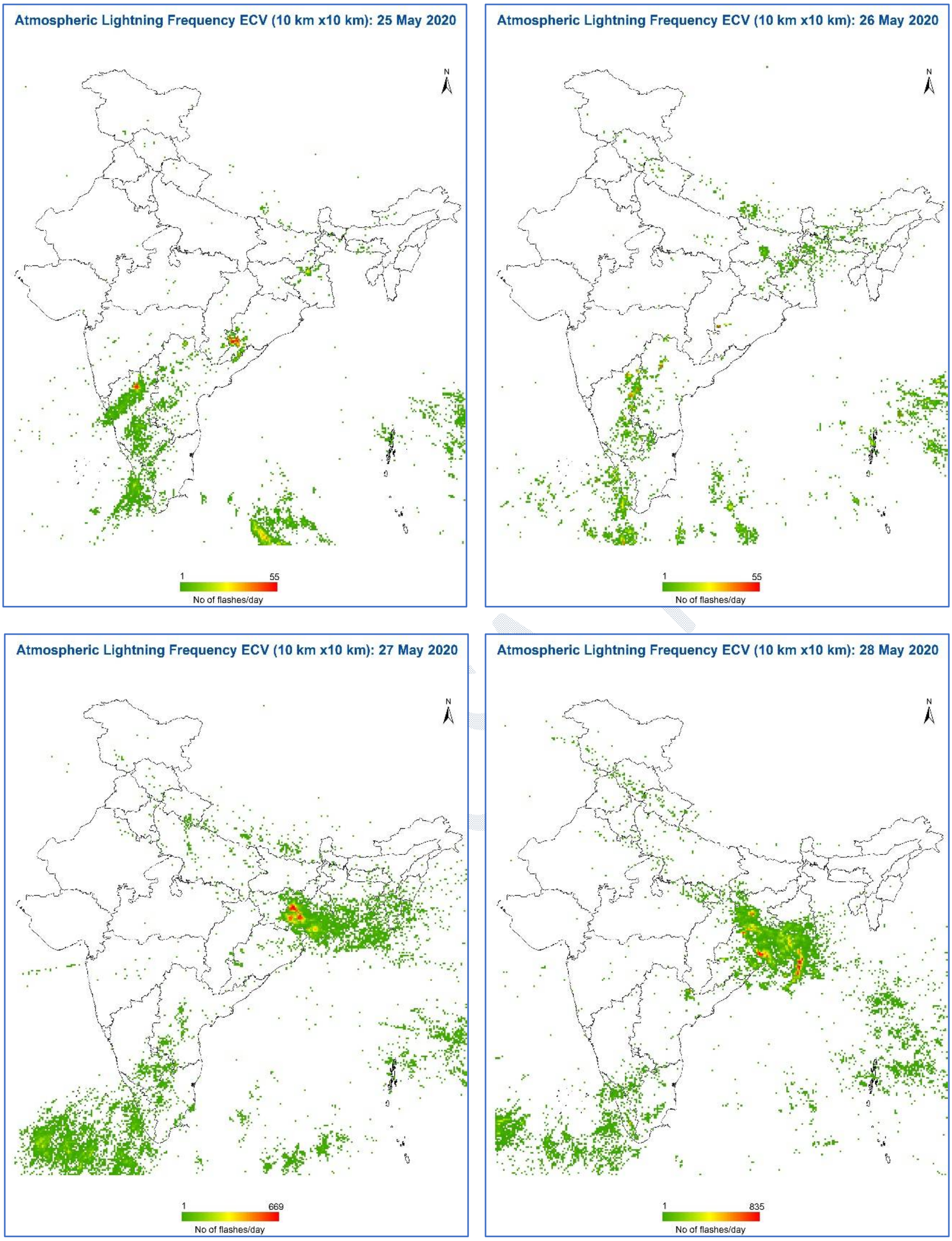

Figure 15. Sample ECV maps during 26 – 28 May 2020

So far, there is no institute worldwide which is providing atmospheric lightning products. Therefore, making this ECV and publishing it for scientific usages would have high impact in scientific community.

7. Identification of Vulnerable Zones

The identification of are where lightning occurrences are higher needs at least 3 years of multi-season data. However, the vulnerability is classified as the region where more frequent high energy cloud to ground flashes occur. This is clarified in figures 16& 17. Figure 17 show the lighting occurrences throughout India on 03 September 2020.

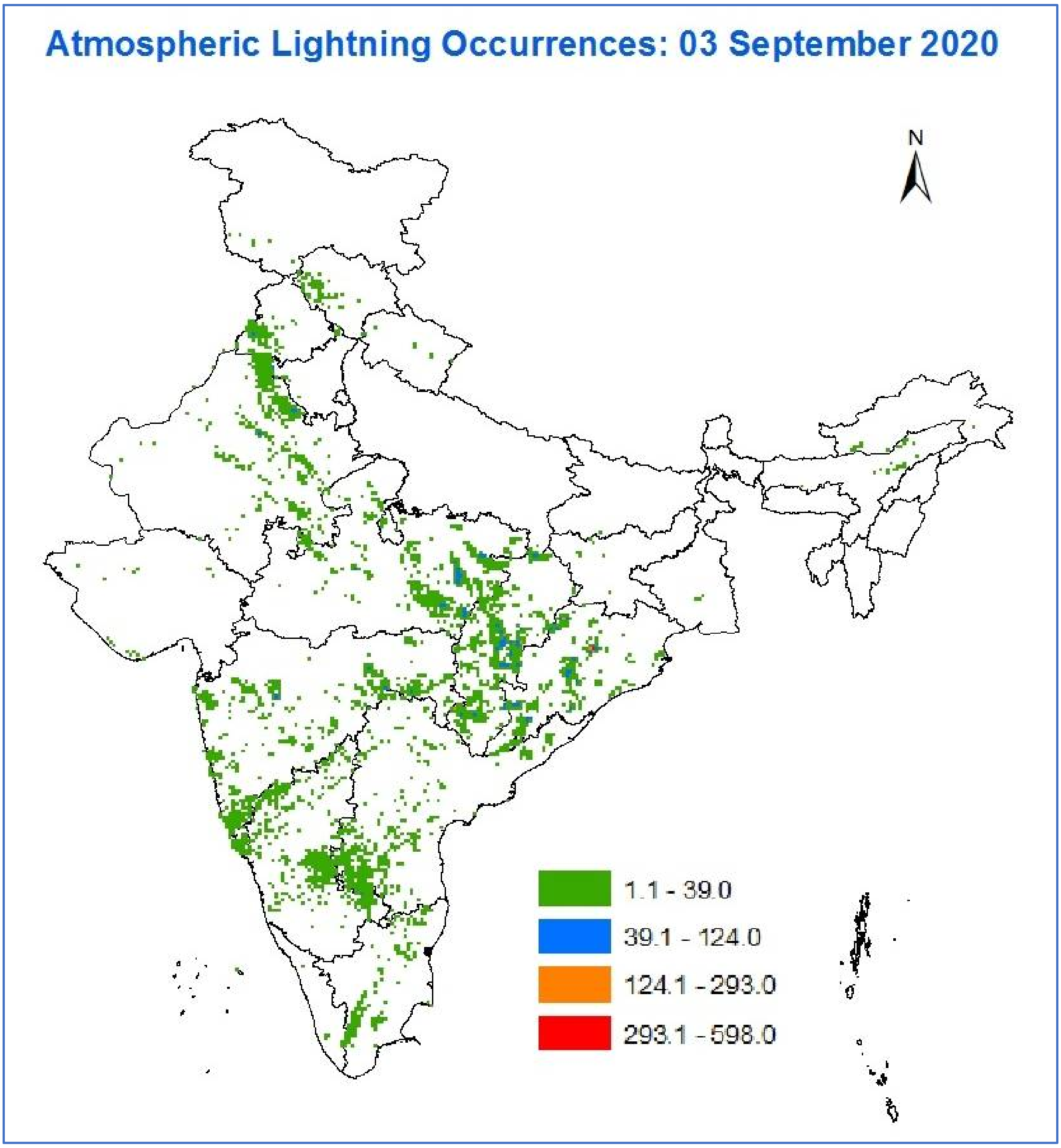

Figure 16. Sample CG lightning occurrence map on 03 September 2020

It is clear in the figure that Odisha, Jharkhand, Bihar and West Bengal had more number of lighting occurrences. Based on layer analysis we can get the taluka-wise occurrence statistics on pan-India basis which can help the policymakers. The same day plot blown up for the Odisha state with sample analysis is shown in figure 17. In the figure, Taluka boundaries are shown as shaded area while the lightning occurrences are depicted as red symbols.

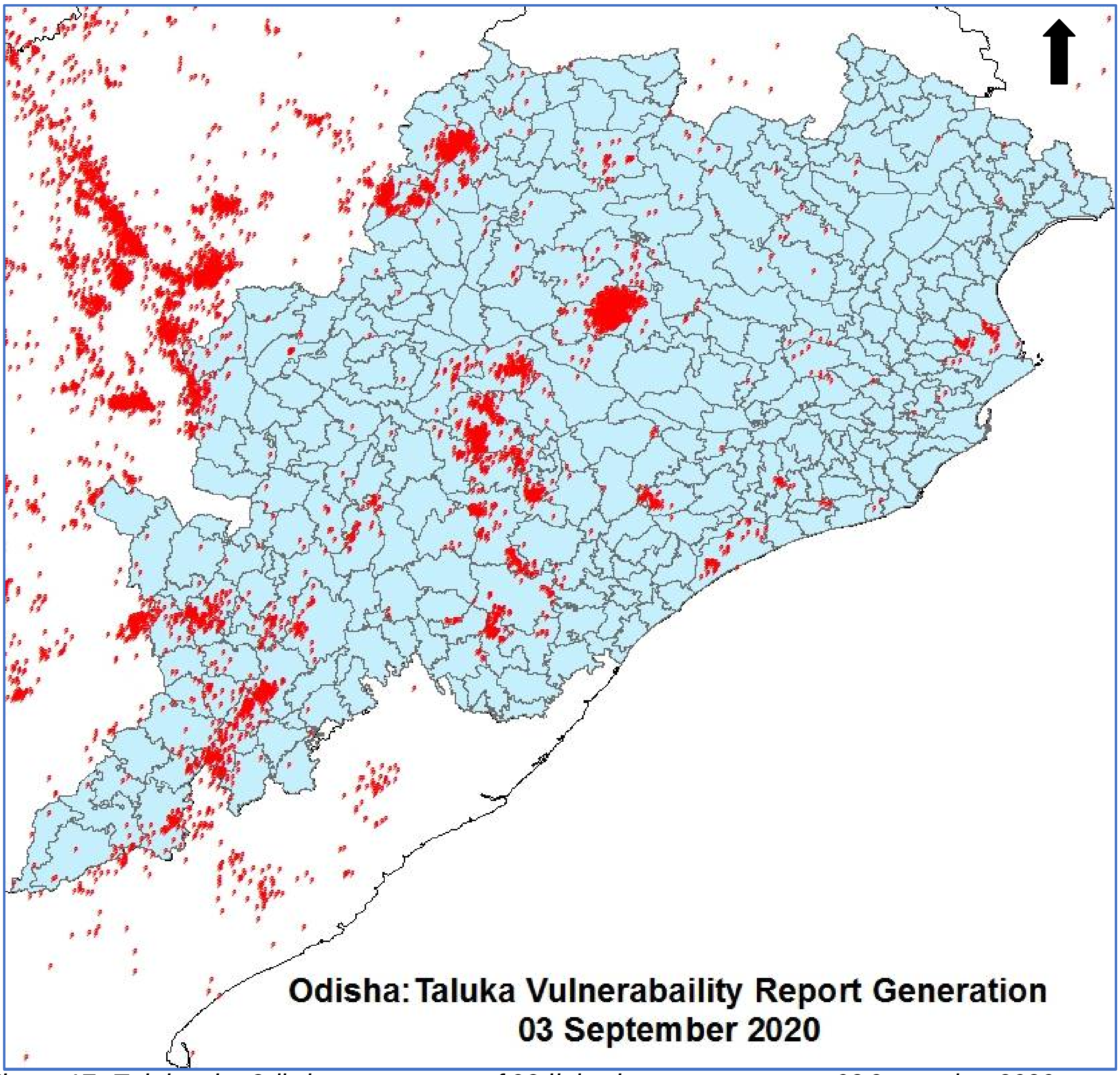

Figure 17. Talukawise Odhsha state report of CG lightning occurrences on 03 September 2020

The administrative reports for the lighting occurrences can be made using by the overlay analsysis. A sample statistical report for Odisha is shown in table 4.

03/09/2020	Odisha	Anugul	ATHMALLIK	6
03/09/2020	Odisha	Anugul	CHHENDIPADA	412
03/09/2020	Odisha	Anugul	KANIHA	2
03/09/2020	Odisha	Anugul	KISHORENAGAR	964
03/09/2020	Odisha	Anugul	TALCHER	2
03/09/2020	Odisha	Baleshwar	JALESWAR	1
03/09/2020	Odisha	Bargarh	AMBABHONA	123
03/09/2020	Odisha	Bargarh	ATTABIRA	3
03/09/2020	Odisha	Bargarh	BARPALI	1
03/09/2020	Odisha	Bargarh	GAISILET	1
03/09/2020	Odisha	Bargarh	PADAMPUR	2
03/09/2020	Odisha	Bargarh	PAIKMAL	1
03/09/2020	Odisha	Bargarh	SOHELLA	2
03/09/2020	Odisha	Bhadrak	BASUDEBPUR	1
03/09/2020	Odisha	Bhadrak	CHANDABALI	42
03/09/2020	Odisha	Bhadrak	DHAMANAGAR	2
03/09/2020	Odisha	Bhadrak	TIHIDI	5
03/09/2020	Odisha	Balangir	KHAPRAKHOL	9
03/09/2020	Odisha	Balangir	LOISINGA	1
03/09/2020	Odisha	Balangir	SAINTALA	1
03/09/2020	Odisha	Baudh	BOUDH	126
03/09/2020	Odisha	Baudh	HARBHANGA	2
03/09/2020	Odisha	Baudh	KANTAMAL	28
03/09/2020	Odisha	Cuttack	MAHANGA	1
03/09/2020	Odisha	Cuttack	TANGI-CHOUDWAR	2
03/09/2020	Odisha	Debagarh	BARKOT	3
03/09/2020	Odisha	Debagarh	REAMAL	26
03/09/2020	Odisha	Debagarh	TILEIBANI	1
03/09/2020	Odisha	Dhenkanal	BHUBAN	3
03/09/2020	Odisha	Dhenkanal	GANDIA	6
03/09/2020	Odisha	Dhenkanal	ODAPADA	1
03/09/2020	Odisha	Dhenkanal	PARAJANG	1
03/09/2020	Odisha	Gajapati	MOHANA	31
03/09/2020	Odisha	Gajapati	NUAGADA	79
03/09/2020	Odisha	Gajapati	R. UDAYGIRI	8
03/09/2020	Odisha	Ganjam	BELLAGUNTHA	1
03/09/2020	Odisha	Ganjam	BHANJANAGAR	4
03/09/2020	Odisha	Ganjam	DHARAKOTE	4
03/09/2020	Odisha	Ganjam	DIGAPAHANDI	1
03/09/2020	Odisha	Ganjam	JAGANNATHPRASAD	7
03/09/2020	Odisha	Ganjam	SORADA	15
03/09/2020	Odisha	Jajapur	SUKINDA	1
03/09/2020	Odisha	Jharsuguda	JHARSUGUDA	50
03/09/2020	Odisha	Jharsuguda	LAKHANPUR	115
03/09/2020	Odisha	Kalahandi	BHAWANIPATNA	11
03/09/2020	Odisha	Kalahandi	DHARAMGARH	2
03/09/2020	Odisha	Kalahandi	GOLAMUNDA	2
03/09/2020	Odisha	Kalahandi	JAYAPATNA	2
03/09/2020	Odisha	Kalahandi	JUNAGARH	2
03/09/2020	Odisha	Kalahandi	KARLAMUNDA	1
03/09/2020	Odisha	Kalahandi	KESINGA	1
03/09/2020	Odisha	Kalahandi	KOKASARA	1
03/09/2020	Odisha	Kalahandi	LANJIGARH	32
03/09/2020	Odisha	Kalahandi	NARLA	4
03/09/2020	Odisha	Kalahandi	THUAMUL-RAMPUR	19
03/09/2020	Odisha	Kandhamal	BALIGUDA	112
03/09/2020	Odisha	Kandhamal	CHAKAPAD	2
03/09/2020	Odisha	Kandhamal	DARINGBADI	87
03/09/2020	Odisha	Kandhamal	G. UDAYAGIRI	44
03/09/2020	Odisha	Kandhamal	K.NUAGAON	40
03/09/2020	Odisha	Kandhamal	KHAJURIPADA	7
03/09/2020	Odisha	Kandhamal	KOTAGARH	28
03/09/2020	Odisha	Kandhamal	PHIRINGIA	263
03/09/2020	Odisha	Kandhamal	PHULBANI	43
03/09/2020	Odisha	Kandhamal	RAIKIA	52
03/09/2020	Odisha	Kandhamal	TIKABALI	23
03/09/2020	Odisha	Kandhamal	TUMUDIBANDHA	1
03/09/2020	Odisha	Kendrapara	KENDRAPARA	1
03/09/2020	Odisha	Kendrapara	PATTAMUNDAI	2
03/09/2020	Odisha	Kendrapara	RAJKANIKA	3
03/09/2020	Odisha	Kendujhar	BANSPAL	2
03/09/2020	Odisha	Kendujhar	GHATGAON	4
03/09/2020	Odisha	Kendujhar	HARICHANDANPUR	2
03/09/2020	Odisha	Kendujhar	KENDUJHAR	1
03/09/2020	Odisha	Kendujhar	TELKOI	2
03/09/2020	Odisha	Khordha	BANAPUR	1
03/09/2020	Odisha	Khordha	JATANI	6
03/09/2020	Odisha	Khordha	KHORDHA	3
03/09/2020	Odisha	Koraput	BOIPARIGUDA	12
03/09/2020	Odisha	Koraput	BORIGUMMA	7
03/09/2020	Odisha	Koraput	DASAMANTAPUR	133
03/09/2020	Odisha	Koraput	JEYPORE	21
03/09/2020	Odisha	Koraput	KORAPUT	120
03/09/2020	Odisha	Koraput	KOTPAD	5
03/09/2020	Odisha	Koraput	KUNDRA	4
03/09/2020	Odisha	Koraput	LAMPTAPUT	87
03/09/2020	Odisha	Koraput	NANDAPUR	22
03/09/2020	Odisha	Koraput	NARAYANPATNA	1
03/09/2020	Odisha	Koraput	POTTANGI	1
03/09/2020	Odisha	Koraput	SIMILIGUDA	2
03/09/2020	Odisha	Malkangiri	KALIMELA	6
03/09/2020	Odisha	Malkangiri	KHAIRPUT	9
03/09/2020	Odisha	Malkangiri	KORKUNDA	9
03/09/2020	Odisha	Malkangiri	KUDUMULGUMA	39
03/09/2020	Odisha	Malkangiri	MALKANGIRI	2
03/09/2020	Odisha	Malkangiri	PODIA	3
03/09/2020	Odisha	Mayurbhanj	BETANATI	1
03/09/2020	Odisha	Mayurbhanj	KARANJIA	2
03/09/2020	Odisha	Mayurbhanj	SHAMAKHUNTA	1
03/09/2020	Odisha	Mayurbhanj	SULIAPADA	1
03/09/2020	Odisha	Nabarangapur	DABUGAN	1
03/09/2020	Odisha	Nabarangapur	JHARIGAN	1
03/09/2020	Odisha	Nabarangapur	KOSAGUMUDA	27
03/09/2020	Odisha	Nabarangapur	NAWARANGPUR	28
03/09/2020	Odisha	Nabarangapur	NANDAHANDI	1
03/09/2020	Odisha	Nabarangapur	PAPARAHANDI	112
03/09/2020	Odisha	Nabarangapur	RAIGHAR	7
03/09/2020	Odisha	Nabarangapur	TENTULIKHUNTI	14
03/09/2020	Odisha	Nabarangapur	UMARKOTE	3
03/09/2020	Odisha	Nayagarh	BHAPUR	1
03/09/2020	Odisha	Nayagarh	DASAPALLA	4
03/09/2020	Odisha	Nayagarh	NUAGAON	1
03/09/2020	Odisha	Nayagarh	ODAGAON	45
03/09/2020	Odisha	Nuapada	BODEN	6
03/09/2020	Odisha	Nuapada	KHARIAR	1
03/09/2020	Odisha	Nuapada	KOMNA	109
03/09/2020	Odisha	Nuapada	NUAPADA	23
03/09/2020	Odisha	Puri	ASTARANGA	1
03/09/2020	Odisha	Puri	DELANGA	2
03/09/2020	Odisha	Puri	KAKATPUR	1
03/09/2020	Odisha	Puri	KANAS	3
03/09/2020	Odisha	Puri	KRUSHNAPRASAD	44
03/09/2020	Odisha	Puri	SATYABADI	5
03/09/2020	Odisha	Rayagada	BISSAM CUTTACK	1
03/09/2020	Odisha	Rayagada	GUDARI	5
03/09/2020	Odisha	Rayagada	GUNUPUR	5
03/09/2020	Odisha	Rayagada	KASHIPUR	38
03/09/2020	Odisha	Rayagada	KOLNARA	1
03/09/2020	Odisha	Rayagada	MUNIGUDA	1
03/09/2020	Odisha	Rayagada	PADMAPUR	5
03/09/2020	Odisha	Sambalpur	DHANKAUDA	2
03/09/2020	Odisha	Sambalpur	JAMANKIRA	2
03/09/2020	Odisha	Sambalpur	JUJOMURA	7
03/09/2020	Odisha	Sambalpur	KUCHINDA	1
03/09/2020	Odisha	Sambalpur	NAKTIDEUL	30
03/09/2020	Odisha	Sambalpur	RENGALI	1
03/09/2020	Odisha	Sundargarh	BALISANKARA	1
03/09/2020	Odisha	Sundargarh	BARAGAON	1
03/09/2020	Odisha	Sundargarh	GURUNDIA	27
03/09/2020	Odisha	Sundargarh	HEMGIR	200
03/09/2020	Odisha	Sundargarh	KOIDA	5
03/09/2020	Odisha	Sundargarh	KUANRMUNDA	1
03/09/2020	Odisha	Sundargarh	LAHUNIPARA	1
03/09/2020	Odisha	Sundargarh	LEPHRIPARA	102
03/09/2020	Odisha	Sundargarh	SUBDEGA	3
03/09/2020	Odisha	Sundargarh	SUNDARGARH	3
03/09/2020	Odisha	Sundargarh	TANGARAPALI	3

Table 4. Taluka wise lightning occurrence reports shown as Date, State, District, Taluka and number of CG flashes.

The statistical report such generated can be passed on to the associated state departments and possibly to the responsible authorities through the NRSC disaster support services on daily basis. However, as far as the vulnerability is concerned, it is the multi-year, multi-season data which makes a big impact for the development of sustainable support establishments. Together, plan to feed the LDS data to an appropriate model are afoot with aim of possible nowcasting.

8. Current Limitation: It is important to state here that the present network have good coverage in East Coast, Central and Southern part of India. Therefore, the geolocation accuracy is high at these part of the country (<100 m error more than 95% of the occasions). Though, prominant lighting occurrences in Western and Northern region of India are captured well by the network, accuracy of geolocation is less than 100m only about 30% of the occasions. This indicate a need of having sensors in Northern and Western regions of India to achieve the pan-India efficiency of 95% or higher.

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