Evaluation of Indian Lightning Location Network (ILLN) and characterization of cloud-to-ground lightning over Lucknow and Shillong using an ordinary camera

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Keywords: Lightning location network, lightning characteristics, remote sensing, INSAT3D, instruments performance.

Abstract

This work is showing the performance of Indian Lightning Location Network (ILLN) and lightning characteristics around Lucknow and Shillong India. Observation of ground truth using ordinary camera show the location accuracy of lightning location network. By analysing the optically observed data the average cloud to ground lightning flash detection efficiency is 78.9 percent but some of them misclassified. In addition, throughout the observation in Lucknow, authors found the average inter-stroke intervals were 139.2 ms that ranges from 34 ms to 442 ms. Further, average multiplicity and multi-channel termination of these strokes were 2.3 and 1.2 respectively. The single-stroke flashes were below 23% out of the total number of negative cloud-to-ground flashes. In contrary to the Lucknow, all the flashes observed in Shillong seem single-stroke which have lower return stroke peak currents than Lucknow. This estimation of detection efficiency and characteristics will definitely assist to understand the different scenarios of lightning in plane and hilly area over the country and help to forecasters, and modelers.

1. Introduction

Lightning is a deadly natural event and more than 24,000 fatalities per year around the world (Holle et al., 2008). It is reported from the Indian meteorological department around 5259 fatalities in all states of India from 1979 to 2011 (Singh et al., 2015). Additionally, based on the National Crime Records Bureau record for 14 years (2001 - 2014) the average annual death rate is 2234 in India (Selvi et al., 2016). Therefore, to reduce the risk of injury, wildfire, and damages caused by lightning in dense human areas are in demand. By including numerous safety measures, Elsom et al., (2018) reported a decrease in decadal lightning fatality rates in the United Kingdom where lightning location networks were the key solution for risk reduction. Elsom et al., (2018) suggested a better detection efficiency (DE) and location accuracy (LA) of lightning location network could track the thunderstorm and suitable warning to reduce the vulnerability and similar needed to implement to other counties.

Besides, lightning plays a key role for meteorologists and essential climatic parameters (Williams 2005; Aich et al., 2018) that also used to now-casting and warning of severe convective weather and thunderstorm (Schultz et al., 2009; Srivastava et al., 2015; Bennett, 2018; Moral et al., 2018; Moon et al., 2020). In recent years, the significance of dynamics, microphysics with lightning and atmospheric electricity has progressively been more acknowledged (Lang et al., 2016; Ribaud et al., 2016; Qie et al., 2021). To observe lightning, numerous grounds and satellite-based lightning observation instruments have been developed in global, regional and local scale (Boccippio et al., 2000, 2002; Chauzy et al., 2002; Shao et al., 2006; Rodger et al., 2006; Goodman et al., 2013; Srivastava et al., 2017; Hui et al., 2020;).

Lightning has multiple terminology and before moving further a brief introduction of lightning are discussed. As shown in figure 1 there are mainly two kind of lightning one occurs in cloud called intra cloud (IC) and another reaches to ground called cloud to ground (CG) lightning. CG lightning is initiated inside the cloud and move toward ground that is basically called a lightning leader, in the response of this another leader from the ground move towards the leader that is called upward connecting leader. In somewhere in the air, they make contact that is known as attachment point and finally the entire accumulated charge tries to discharge by this point called return stroke (shown as blue colour in figure 1). Many times, all the charges may not neutralize in single return stroke and another lightning leader may follow the same path called dart leader and few times they even make a separate lightning leader channel that call different termination point (blue/red) followed by subsequent return stroke which may be occur within 500ms. The flow of current during this process is called return stroke peak current. All together these processes called a lightning flash that may take around 1 -2 seconds to complete flash (Rakov and Uman, 2003).

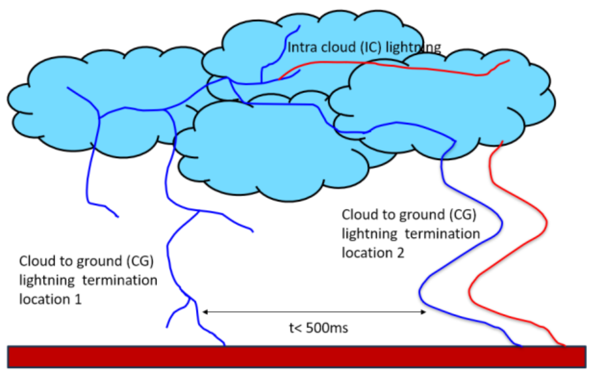

Figure 1: Illustration of lightning leaders, cloud to ground and intra cloud lightning with single channel and multichannel.

Ground based observations are mainly a sensor network that works on time of arrival (TOA) and direction finding (DF) principal and related mathematical algorithms (Cummins et al., 1998; Betz et al., 2009). Most of lightning location network work on time of arrival techniques that helps to locate the lightning event remotely which may have several errors due to various regions and validation of lightning location network is required (Srivastava et al., 2017). Once lightning location network (LLN) start working, a key issue is that to obtain the performance of these networks in terms of DE and LA (Idone et al., 1998a, 1998b). In general, relative performance with other networks (Jacobson et al., 2006; Pohjola and Mäkelä, 2013; Bitzer et al., 2013; Srivastava et al., 2017), comparison with radar reflectivity or cloud images which is another remote sensing instrument to detect clouds (Shao et al., 2006; Liu et al., 2011), human observation (Czernecki et al., 2016) are used to obtain the performance of LLN. On the other side, optical observation as ground-truth is the best and reliable method to show the performance of LLN by observing the lightning remotely in kilometres distance (Nag et al., 2011; Zhu et al., 2017).

Using a range of camera setup from 30-1000 frames/second with the high-speed video recording or even normal speed recording the numbers of cases in each storm and in total are limited to use as ground truth (Idone et al., 1998a, Nag et al., 2011; Zhu et al., 2017). Like, 37 negative flashes were reported out of 137 triggered lightning experiments on the fixed lightning position during 2004-2009 (Nag et al., 2011). Further, two natural tower lightning flashes were recorded to use a ground truth from high-speed camera in 2014 and 2016 to validate the performance of Beijing Lightning Network (Srivastava et al., 2017). Mallick et al. (2015) evaluated Earth Networks Total Lightning Network (ENTLN) using 57 flashes and found 77% DE in 3 years. In addition, 36 tree strikes data presented for the years 2007–2008 to validate the performance of at the Finnish Meteorological Institute lightning location system (Mäkelä et al., 2016). They also discussed available methods and their limitations in detailed. Overall, to obtaining percentage of optical observation as ground truth from these reliable methods is limited. In India, this is the first study of the detection efficiency verification using ground truth data set, which will help to understand the present situation and future planning to needful upgrade the Indian lightning location Network (ILLN).

In addition, these optical observations also play a key role to show the characteristics of cloud to ground (CG) lightning in the observed location in terms of polarity, inter stroke interval, multiplicity, and multi-channel terminations (Rakov et al., 1990, 2003). In general, negative CG return stroke followed by subsequent strokes that can have multiple termination points and positive CG consist only of a single stroke (Rhodes and Krehbiel, 1989; Thottappillil et al., 1992). Recently, a high number of single return stroke negative CG have been reported in local scale isolated thunderstorms using lightning location network that is unusual in general (Williams et al., 2016; Peng et al., 2020). Peng et al. (2020) proposed the negative charge region could enhance the multiplicity. In addition, flash rate and radiation sources can help to infer the possible charge structure of thunderstorm in some extend (Liu et al., 2013).

In consideration of vast application of lightning data, the Indian Institute of Tropical Meteorology (IITM), Pune established ILLN a ground-based network that have 82 sensors across India (procured from Earth Network). Until now, no study on validations of ILLN has been carried out using optical observation (remotely sensed lightning to validate by different remote sensing instruments). Therefore, here we used the reliable technique to obtain the performance of ILLN using optically observed ground truth, which is one of the consistent validation methods. Further, these optically observed ground truths help us to show the characteristics of lightning over the observation regions.

2. Data and Methodology

2.1. Indian Lightning Location Network (ILLN) and Indian National Satellite System (INSAT)

Initially, ILLN was developed around Maharashtra state and later expanded to entire country. Figure 2 shows the locations of sensors (blue square), at present ILLN have 82 sensors procured and operated by the Indian Institute of Tropical Meteorology (IITM), Pune, and data from all the sensors are directly transferred to the IITM server. All these sensors are identical and made by Earth Network that is a broadband sensor and frequency ranges from 1Hz to 12 MHz. Once the data is received in server from these sensors, the signal is used to classify the CG strokes and IC pulses and locate the flashes. Readers should keep in mind that a single flash signal could have multiple CG/IC that depends on the peaks of the signal and their cross-correlation/location algorithm. Red stars are the locations of the camera and details are in observation sites sections.

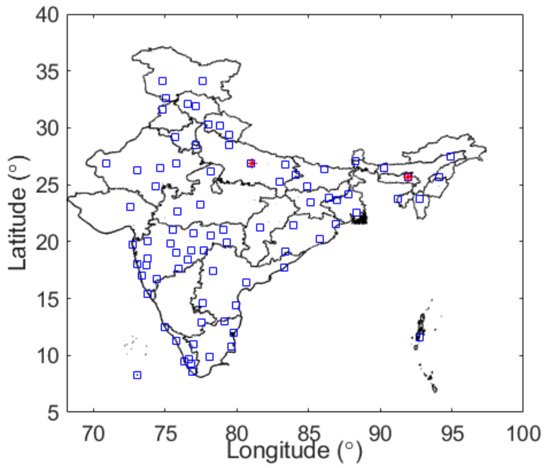

Figure 2: Locations of the lightning sensors (blue square) together with the camera (red star)

Indian National Satellite System is satellites series launched by Indian Space Research Organization (ISRO) and upgraded time to time. Presently, INSAT-3D and INSAT-3DR satellites are used for meteorological porpuse that is placed near to equator (Kumar and Sukla, 2019). The INSAT satellites have a 6 channel imager and 19 channel sounder and the collected data and related informations are available at www.mosdac.gov.in. For the present work authors have used bleaded images of clouds to show the deep convection around the study region during the observations.

2.2. Camera Details

A 16-megapixel GPS enabled smart phone mobile camera was used to record the lightning flashes. The camera is a CMOS image sensor that has an inbuilt 6-element summilux-H lens with an f/1.8 aperture. The camera video recording speed is 30 frames per second and locations and time can automatically synchronize with GPS.

2.2.1. Camera operation and methodology

The camera saves the video with an automatic naming, which has included the instant time when the camera video recording was stopped. First from these videos all the frames have been separated and timestamped that makes a set of frames for each video. First frame has been taken as reference and each pixel brightness have been compared. Once, it seems the brightness have sudden increase authors have considered them a lightning event. Further, from these events authors checked the particular frame and identified if the event is terminated to the ground. Next 15 frames have been checked that is approximately 510 ms and found the brightness get low in next frame and increases in following frames in the same channel which indicate two separate strokes of the same flash and by looking the termination at different location considered multi termination. Authors matched the optically observed flashes with ILLN data based on figure 3. Here, we shown a time window of t-3 to t+1 seconds and recording stopped in between t to t+1 seconds. The video will store a name ending to‘t’ and we considered the entire 30 frames window at't' second. 'dt' is the time left in previous interval and maximum possible error could be ±0.9 second. Once the times for each frame have been identified, we search the strokes in ILLN data with spatial domain of 100 km. If any stroke available in the given time range, we considered a valid detected observation and in case more than one stroke we selected the higher current stroke to show the location that is rare in our data.

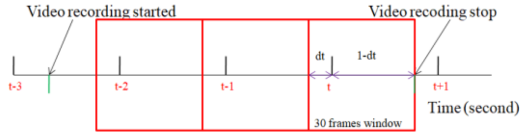

Figure 3: Synchronization process between ILLN stroke and video frames.

Table 1 and Table 2 shows the details of flashes in which flash ID was assigned based on the time of the frames in which the CG strokes were observed. The details of the CG stroke's locations and current were obtained from ILLN. Some of the rows are blank, which were not located flashes from ILLN. The camera exposure time is 34 ms and the strokes that occur within this interval will be missed out and could not be counted. Idone et al. (1998a) used 30 frame per second camera to obtain the performance of LLN and demonstrate the characteristic and additionally discussed the video recording limitations in detail. From the optical data with 30 frames per second, some characteristics of lightning flashes could not be determined and probably that is the limitation of the study. Therefore, inter stroke interval and multiplicity of strokes in our result could probable and needs further detailed investigations with high-speed camera observations and validation with lightning signals.

2.3. Observation sites

Two case study of thunderstorms and optical observations of the lightning were done. First case was in Northern part of the India at Lucknow, Uttar Pradesh and the location of the camera was Latitude 26.880388, Longitude 81.062617 obtained from mobile GPS. Similarly, second case was in northeastern part of India at Shillong, Meghalaya and the location of the camera was Latitude 25.669260, Longitude 91.911506 shown in figure 2. In addition, figure 4 and figure 9 are displaying the district boundaries of the observation sites and the cloud cover brightness temperature during the observation period.

3. Results and Discussion

3.1 Case study in Lucknow

A thunderstorm was passing over the observation area on 20 April 2020. April is a pre-monsoon summer season with low rainfall and high temperature in the Northern India region that is a plan area.

Once the thunderstorm reached enough close to the observer as brightness temperature shown in figure 4, the lightning channels were visible with the naked eyes. The camera started to record the events at 17:33 UTC and after a careful analysis of all the videos, several IC and eighteen CG flashes (41 strokes in 18 flashes) were obtained, see the details in table 1. The ILLN data have been sorted up to 100 km radius, considering the camera location as a centre point. We excluded the IC flashes from this analysis and found most CG flashes were identified as multi-stroke CGs. The validation shows ILLN was capable to locate 14 flashes in which one stroke was positive CG and two misclassified as IC. The peak current range of negative CG strokes was -12 to -35 kA and the single positive CG peak current was 39 kA (see Table 1).

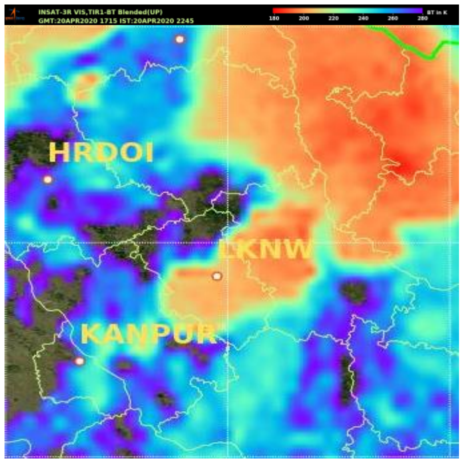

Figure 4: Brightness temperature of clouds using INSAT-3DR at 1715 UTC over Lucknow and around area.

Camera			Information from ILLN			
St	**Tr**	**t (ms)**	**Latitude**	**Longitude**	**T**	**I (kA)**
3	1	102	26.8179	81.15716	0	-23.7
1	1	-	26.8692	81.12232	0	-21.2
2	2	170	26.8387	81.08964	0	39.4
2	1	170	26.8686	81.13119	0	-16.3
1	1	-	26.8193	81.19011	0	-23.5
4	1	45	26.8521	81.12945	1	-12.2
2	1	34	26.8589	81.10767	0	-27.5
2	2	408	26.8661	81.14817	0	-22.5
3	1	85	Not located from ILLN			
2	1	170	Not located from ILLN			
5	1	51	26.871	81.1899	0	-28.3
2	1	68	27.570	81.763	0	-13.9
2	1	272	26.8596	81.233	0	-35.2
1	1	-	Not located from ILLN			
1	1	-	26.8579	81.1053	0	-20.3
2	1	34	Not located from ILLN			
3	2	289	26.8272	81.1703	0	-12.8
3	1	51	26.8971	81.2199	1	-16.2
2.3	**1.2**	**139.2**				

Table 1: Combined details of the strokes including the position from ILLN and Camera; St is stroke numbers; Tr is termination channels counted from the camera; t (ms) shows the average inter stroke interval in a flash; hhmm is hours and minutes; ss.xxxx is second up to four decimal; T represents the type CG stroke (0) or IC pulse (1) identified from the waveform, and I (kA) return stroke peak current.

https://doi.org/10.5194/isprs-annals-X-5-2024-189-2024

3.1.1 Single and multi-termination channel of multi stroke flash

Figure 5 shows a multi-stroke CG flash with single termination channel. Here red marked numbers on the frames are inter-frames and intervals between them are 34 ms. The details of this Flash ID 173310 from the camera and ILLN are shown in table 1. In the figure 5 in frame 1, no intensity and channel were visible, and in frame 2 a low-intensity channel becomes visible that is probably a lightning leader based on the visibility of the channel. Later in frame 3, first return stroke (RS) was detected as the intensity become very high although the lower part of the channel was not visible due to the slow processing of the camera. The first RS was dimmed enough and it was not visible in frame 4, then the second subsequent RS become visible in frame 5 followed by frame 6. After the second RS, again the channel was dimmed in frame 7, and become luminous in frame 8 that is the third RS. Based on the camera time we are not able to differentiate which RS were detected from the ILLN. Despite this limitation, we are able to know that only one stroke was detected in most of the flash from the ILLN.

Figure 5. A multi-stroke CG flash, one of the strokes detected by ILLN at 173310.61 UTC. The inter-frame interval was around 34 ms.

Figure 6 shows a multi termination channel of multi-stroke flash. The details of the flash are in table 1 with an assigned Flash ID 173906. Here, in frame 1 there was not any developed channel and in frame 2 first return stroke in visible that terminated at the middle of the frame and then a 134 ms cooling period was noticed until frame 6. In frame 7, another RS was observed that was right side from the termination channel 1, which is the second termination channel. In frame 8 the RS was shown with a dimmed channel intensity and later the third RS was followed by the second termination channel that is not shown here. Here, one of the strokes was detected from the ILLN at 173906.55 UTC that was the closest time with the camera time. Authors also noticed that only one stroke was located within the camera time from the ILLN that made it easy to analyse.

All the 14 flashes were within the 20 km range of the camera and located direction was eastward as shown in figure 7. That reveals the direction of the located flashes were associated with the camera directly towards the east. From the lightning density in the 1-hours interval, we approximated the direction of the thunderstorm was probably eastward or southeast (not discussed here).

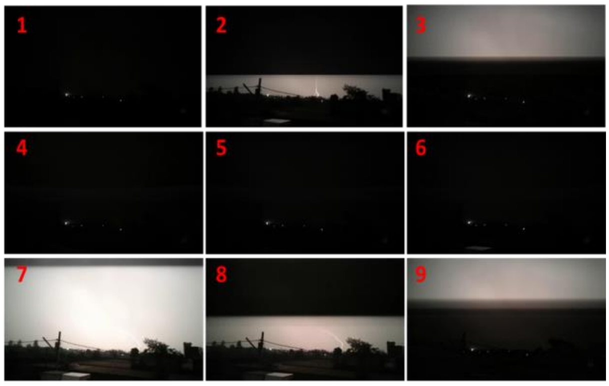

Figure 6. A multi termination channel multi-stroke CG flash, one of the strokes detected by ILLN at 173906.55 UTC. The inter-frame interval was around 34 ms.

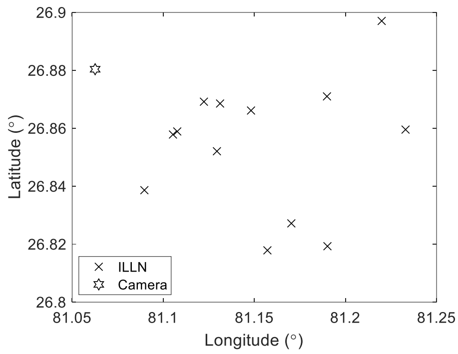

Figure 7. Spatial distributions of the strokes located from ILLN and position of the camera.

3.1.2 Characteristics in Lucknow

Most of the recorded 18 flashes were multi-stroke with an average multiplicity of 2.3 strokes per flash. It seems from our data set that multi termination channels were on average 1.2 channels per flash. Overall mean of inter-return stroke interval was 139.2 ms. These could be varying based on thunderstorm type, locations and charge structure. Based on our observational dataset, the average multiplicity and termination channel were lower although inter stroke interval was higher. Due to limited visibility, it is almost impossible to distinguish two-stroke when the leader was bright enough and subsequent stroke followed the same termination channel and lead to errors. Zhu et al., (2016) shown inter stroke interval and stroke multiplicity mean value lies around 80 ms and 4.6, respectively. Despite this, Peng et al., (2020) recently reported a higher percentage of single-stroke negative CG flashes in isolated small thunderstorms, and multiplicity were ranged from 2.2- 4.0 in different storms. Based on this, they also reported weaker stroke current in single-stroke flashes with comparison to the initial stroke of multiple-stroke flashes. Most of our observation in Lucknow shows the multi-stroke flashes and single stroke flashes were less than 23% that have been obtained by taking ratio of number of flashes which have only one stroke and total number of flashes. Williams et al., (2016) were found 87% single stroke flashes suggested an extended range of negative charge region could responsible for high percentage of multiplicity. To consistence with the previous studies and based on observational finding, we infer the thunderstorm was an extended scale negative charge region (probably tripole) that supports enhancing multiplicity.

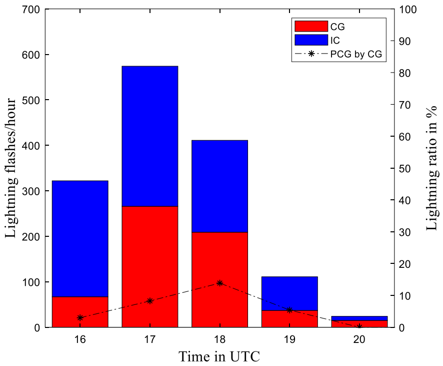

Figure 8: The number of flashes in every hour and the percentage of positive CG (PCG) by CG.

Figure 8 shows the numbers of CG flashes were around 280 and IC flashes were around 300. In addition, the percentages of positive CG flashes were 10 % at 17 UTC that is very low. It found most of the strokes were occurring North side of the observer and only few strokes are over the observer. The flash rate indicates the thunderstorm were mature stage around the 17-18 UTC. This high percentage of negative CG flashes out of total CG flashes (total lightning) that followed a decreasing trend afterward also infer the main negative charge regions were dominating in mature stage. All the 14 flashes located from ILLN were within the 20 km range of the camera and located direction was eastward. That reveals the direction of the located flashes were associated with the camera directly towards the east. From the lightning density, we approximated the direction of the thunderstorm was probably southeast (not discussed here).

3.2 Case study in Shillong

First week of May is a pre-monsoon season with comparatively high rainfall in the Northeastern Indian region, which is a hilly area. On 01 May 2021, a thunderstorm passed over the Umiam, Shillong as brightness temperature shown in figure 9, and the observer started the observation at 06:10 UTC. After a careful analysis of all the videos, several IC and CG flashes were obtained. We excluded the IC flashes and the unclear CG flashes. Remaining five clearly observed CG flashes used for the validation and we found ILLN was capable to locate four flashes in which two were misclassified as IC (see Table 2).

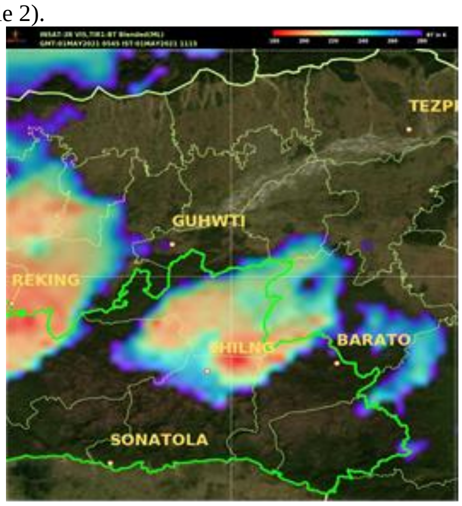

Figure 9: Brightness temperature of clouds using INSAT-3DR at 0545 UTC over Shillong and around area

Camera		Information from ILLN			
St	Tr	Latitude	Longitude	T	I (kA)
1	1	Not located from ILLN			
1	1	25.60341	91.95026	1	7417
1	1	25.52837	90.53865	0	-25766
1	1	25.55437	92.13732	0	-13516
1	1	25.81128	91.00353	1	-8963

Table 2: Combined details of the strokes including the position from ILLN and Camera; St is stroke numbers; Tr is termination channels counted from the camera; hhmm is hours and minutes; ss.xxxx is second up to four decimal; T represents the type CG stroke (0) or IC pulse (1) identified from the waveform, and I (kA) return stroke peak current.

Figure 10: Long duration CG flash observed by ordinary camera at Shillong Flash ID 063701.

Figure 10 shows a case where the flash was visible upto 204 ms from frame 2 to frame 7. It was not any luminosity enhancement from frame 3-6 and we infer a single stroke followed by continuing current. The details of the Flash ID 063701 given in table 2 and was identified as IC. In frame two there was an IC leader right side to the main lightning channel and it may possible the located lightning from ILLN belong to that leader and lead to misclassification.

3.2.1 Characteristics in Shillong

Figure 11 shows in upper panel case A that was not detected from the ILLN and were clear CG in front of the camera frame 2. In lower panel case B return stroke were on the ride side of the frame 2 and luminosity was weakening in frame 3 and after this we are not noticed any channel in entire video.

Figure 11: Case A in upper panel, the flash ID 061749 that was not detected by ILLN. Case B in lower panel, the flash ID

062016 and detected by ILLN. Here, the inter-frame interval was around 34 ms.

All the CG flashes in Shillong were single stroke that infers the geographical location can be a cause of the different characteristics of lightning in North Eastern region of India than Northern India. The negative CG peak current ranged from -8kA to -25kA and seems single stroke peak current is low compare to Lucknow cases and that is consistent to the previous studies that suggests single stroke peak currents are lower than the multi-strokes (Williams et al. 2016, Peng et al., 2020). Peng et al., (2020) observe the small isolated thunderstorms have high percentage of single flashes and suggest charge distribution inside the thunderstorm plays important role on flash multiplicity. To consistence with them, we also infer the thunderstorm around Shillong was small scale isolated during the observation. Based on these observations, authors found the characteristics of the lightning in two different topographies are different and possibly the charge structure may vary that need intense observations in detail.

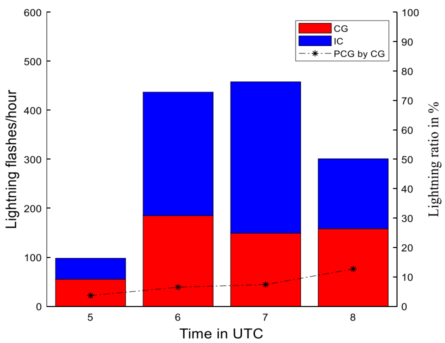

Figure 12: The number of flashes in every hour and the percentage of positive CG (PCG) by CG.

Figure 12 shows the numbers of CG flashes were around 190 and IC flashes were around 250 over the Shillong including a very low positive CG flashes at 6 UTC. It seems most of the strokes were occurring over the observer and backward of the camera at 6 UTC. Further, The CG flashes and high number of negative CG flashes sustained more than two hours over the same area. The observations infer a detailed investigations needed on understanding the dynamical-microphysical and electrical processes in plan land and hilly areas thunderstorms of India.

3.3 Detection Efficiency of ILLN

Based on table 1, it shows that a total number of flashes recorded with clear visibility were eighteen (18) and out of that fourteen (14) were detected by ILLN with two (2) misclassified as IC in Lucknow. Additionally, based on table 2, observed flashes were five (5) and four (4) were detected by ILLN with two (2) misclassifications. It is revealed that the average flash DE was around 78.9% that is 77.8 % and 80 % in Lucknow and Shillong, respectively. Authors believe that this is good DE as the optical recording was during the nationwide lockdown due to Covid-19 (from mid-March, 2020 first wave and mid-April, 2021 second wave). Throughout this period, operation of some sensors in this region could not be monitored as the places where the sensors are installed are out of bound due to lockdown. Further, these validations were within the 100 km area from the mounted camera and it may be possible some of the flashes were located outside of the range due to poor location accuracy and needs further investigation on stroke detection efficiency. In this study, the observed cases are shedding a light on the ILLN performance and finding the classification of the flashes need to improved. The observation and validation technique are also a new type method that were developed to utilize for this study. These validations encouraging enhance the density of the network and carry-on further validation, which will support improving the ILLN over India and the data could be utilized by meteorologists and forecasters for operational use.

4. Conclusion

Since the development of ILLN to detect the lightning remotely there is not any validation of these data using optical ground truth in India, which is one of the reliable validation methods. In consideration of this, the present work showing the validation of ILLN using the lightning observed by an ordinary camera at two locations. This is the first study of the detection efficiency verification and characteristics of lightning using optical data set in India, which will help to improving the Indian lightning location Network and detailed studies on thunderstorms. Optical observation shows the multiplicities of the negative flashes were 2.3 and probable high percentage of multi stroke flashes and the dominating negative CG flashes in Lucknow. Based on these observations and consistent with the literature we infer the thunderstorm was an extended scale negative charge region (probably normal tri-pole charge structure) in Lucknow. In contrary, the optically observed flashes were single stroke with lower return stroke peak currents in Shillong. Even both the observations were in pre monsoon season the topography is different and complex in northeastern hilly region than northern plan area. It may possible that these differences might be only caused by different thunderstorm and further investigations are needed. The obtained DE is 78.9% and it impresses good DE. Observations for long period are required for making robust statement on the DE of the network and lightning characteristics on various regions of India. On other hand, estimated performances of ILLN are enhancing the confidence of the national level ground-based data that is utilized by modelers, forecasters, and policymakers. Despite this, it suggested to increase the number of sensors in northern India to get more data that are accurate in case some of the sensors miss the event other sensors will fill the gap to some extent.

Acknowledgements

We are thankful for the suggestions, encouragement and data provision to complete this work to IITM, Pune, NESAC, Shillong, SAC, ISRO (MOSDAC), IMD, New Delhi, and Dr. Amit Kumar NEIGRIMS.

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