Spatial Variation of the Correlated Color Temperature of Lightning Channel

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Abstract

In this paper, we studied the spatial variation of the correlated color temperature (CCT) of lightning channel. We also discussed the energy of lightning channels relating to the CCT. First we applied digital image processing techniques to lightning images. In order to reduce the chromatic aberration, we created the reduction technique algorithm of the chromatic aberration on digital still images. We applied the reduction technique of the chromatic aberration to digital still images, and then the obtained results was mapped to the \(xy\)-chromaticity diagram. The CCT of the lightning channel was decided on the \(xy\)-chromaticity diagram. From results, the spatial variation of the CCT of the lightning channel was confirmed. Then the energy associated with the CCT was discussed.

Keywords: Color analysis, Lightning, Correlated color temperature, Lightning channel

1. Introduction

Lightning have been studied in many fields e.g. meteorology, Earth and planetary science, physics, and electrical engineering. Although many properties of lightning have been obtained so far, there are many unsolved problem. Recently, since the electric discharges, sprites, elves, etc. in the upper atmosphere and the terrestrial gamma-ray flashes were discovered, the lightning more attract attention because lightning and these phenomena in the

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upper atmosphere are closely related to each other. [1]

In recent years, the studies of lightning using the high-performance and high speed camera have been reported [2–4]. Lightning is a very high speed and very large natural phenomenon. Thus direct measurement of the properties of lightning is difficult. Usually properties of lightning is indirectly observed by using the radar, camera, or some sensors. It can be considered that the studies of lightning using high-performance digital video and/or still camera will increase with improvement of digital devices.

The color of lightning changes depending on the time and place. It is considered that the lightning may be diagnosed by analyzing the color of lightning. In color science and photometry, the light of light sources are analyzed using the CCT. Although in general, light sources (e.g. LED lamp, fluorescent lamp, etc.) are not the Planckian radiator, the CCT are used to specify the properties of the light sources. It was reported that lightning is optically thin, that is, not the Planckian radiator [5]. However we consider that the properties of lightning channel may also be obtained by analyzing the CCT. Therefore we studied the CCT of lightning channels.

The purpose of the present work is to study the spatial variation of both the CCT and the energy of lightning channels. In this work, we analyzed the CCT of lightning flash images performing digital image processing based on OpenCV [1]. From results, we confirmed the variation of the CCT of the lightning channels. Then connecting with the CCT, we discussed the spatial variation of the energy of the lightning channels. It is concluded that both the CCT and energy of lightning channels change spatially.

2. Lightning images and extraction of lightning channel

2.1. Lightning images

We used two lightning flash images shown in Fig. 1. The images were captured in Chikusei City, Ibaraki Prefecture, Japan, on October 27th, 2008. The images were saved as uncompressed files and optical filters, e.g. ND filters, did not be used. For this reason, it is considered that the information deterioration on the digital images is minimized. Therefore the lightning flash images (used in this work) can be used to analyze colors of the lightning channels.
2.2. Extraction of lightning channels

We have to extract lighting channels from the lightning flash images (Fig. 1). We can see many unwanted parts for the color analysis (e.g. buildings, artificial light sources, and cloud luminescence accompany with a lightning flash) in the images. These unwanted parts are unnecessary to analyze colors of the lightning channels. Thus we extracted the lightning channels in the images by applying digital image processing techniques. The extracted lightning channels are shown in Fig. 2.

The extraction method is based on masking of digital image processing. The extraction procedure is as follows: (1) Inpainting, (2) Smoothing (blur), (3) Sobel edge detection, (4) Thresholding, (5) Smoothing (median filter), (6) Filling process, (7) Thinning process, and (8) Masking. We run in turn the image processing above using OpenCV library [1]. Step (6) and (7) in the extraction procedure are created by our work.
3. Reduction technique of chromatic aberration

In this section we explain a reduction technique of chromatic aberration in the lightning flash images. Usually, in a image created by the optical system, chromatic aberration is unavoidable. When we analyze lightning channels on digital images, the chromatic aberration should be removed from the images. Figs. 3 and 4 show the example of the chromatic aberration on the lightning channel in the CG and IC flash images. The insets on Figs. 3 and 4 show the enlarged lightning channel, which have the size 30 × 30 pixels. Along the lightning channels in the insets (Figs. 3 and 4), the red and blue color is running. This spread is the chromatic aberration. In order to see the chromatic aberration in detail, as an example we plot the pixel value on the line between two pale blue lines in the insets (see Figs. 3 (Right) and 4 (Right)). In Figs. 3 (Right) and 4 (Right), the vertical axis denotes the pixel value which have the range 0 – 255 (256 levels), and the x-axis denotes the line between the two pale blue lines. From the variation of the pixel values, we can see that there is the difference of the spread of the pixel value for the R-, G-, and B-components. This spreads attribute to the chromatic aberration. The chromatic aberration is unnecessary to analyze the color of the lightning channel. Usually, in optics, it is well known that the green light has a smaller dispersion of the chromatic aberration than the red and blue light. This fact indicates that, in Figs. 3 (Right) and 4 (Right), the effect of the chromatic aberration near the peak of the green is smaller. Hence, in order to eliminate the chromatic aberration, we created Algorithm 1. This algorithm extract the RGB components (R, G, B) at the peak of the G-component of lightning channel, namely, the RGB components at the part of the smaller effect of the chromatic aberration. Figs. 5 and 6 show images applied the Algorithm 1 to the extracted lightning channels shown in Fig. 2 (a) and (b). The left side of Figs. 5 and 6 contains the saturated pixels reaching 255, but the right side of Figs. 5 and 6 does not contain it.

4. Variation of the correlated color temperature of the lightning channel

We have studied the variation of the CCT of the lightning channels shown in Figs. 5 and 6. As indicated by Uman and Orville, lightning opacity is thin. That is, lightning is not the Planckian radiator. Therefore, we cannot identify the temperature of the lightning channel by considering the
Fig. 3: (Left) Original CG flash image and the insets which is the enlarged figure of the lightning channel. The size of the enlarged figure is $30 \times 30$ pixels. (Right) Pixel values for the RGB components ($R$, $G$, $B$) along with the line between two pale blue lines in the inset. The red solid square, green solid triangle, and blue solid circle denote the pixel value of $R$-, $G$-, and $B$-components, respectively.

Fig. 4: (Left) Original IC flash image and the insets which is the enlarged figure of the lightning channel. The size of the enlarged figure is $30 \times 30$ pixels. (Right) Pixel values for RGB components ($R$, $G$, $B$) along with the line between two pale blue lines in the inset. The red solid square, green solid triangle, and blue solid circle denote the pixel value of $R$-, $G$-, and $B$-components, respectively.
Algorithm 1 Reduction algorithm on the chromatic aberration.

// (x, y): coordinate in the image.
// Red(x, y): Pixel value of the red component at the (x, y) coordinate.
// Green(x, y): Pixel value of the green component at the (x, y) coordinate.
// Blue(x, y): Pixel value of the blue component at the (x, y) coordinate.
// RGB(x, y): Pixel value consisting of Red, Green, Blue at the (x, y) coordinate.

for y = 2 to image height − 2 do
  for x = 2 to image width − 2 do
    if Green(x − 2, y) < Green(x − 1, y) < Green(x, y) > Green(x + 1, y) > Green(x + 2, y) then
      RGB(x, y) ← (Red(x, y), Green(x, y), Blue(x, y))
    else
      RGB(x, y) ← (0, 0, 0)
    end if
  end for
end for

Fig. 5: CG lightning channels applied Algorithm 1 to the images Fig. 2(a). The left side figure contains the saturated pixels reaching 255, but the right side does not contain it.
Fig. 6: IC lightning channels applied Algorithm 1 to the images Fig. 2 (b). The left side figure contains the saturated pixels reaching 255, but the right side does not contain it.

color temperature. However the color of the light emitted from the lightning is meaningful, since the color contains the information in the interior of lightning channels. Thus we draw attention to the CCT of the lightning channels.

4.1. Correlated color temperature

We describe conversion methods from sRGB color space to the CIE XYZ color space. The color space of the lightning flash images (Fig. 1) is sRGB [7]. The CCT is discussed on the \(xy\)-chromaticity diagram. Fig. 7 (left) shows the CIE 1931 \(xy\)-chromaticity diagram in which the sRGB color triangle and the Planckian locus are depicted. Fig. 7 (right) shows an enlarged figure near the Planckian locus in which the Planckian locus (thick line), the equal \(\Delta uv\) lines of \(\pm 0.02\Delta uv\) along with the Planckian locus, and the isotemperature lines (thin lines) crossing with the Planckian locus are depicted. The length of the isotemperature lines is \(\pm 0.02\Delta uv\). The CCT is generally discussed in the range \(\pm 0.02\Delta uv\).

To analyze the lightning channels (Figs. 5 and 6) based on the CCT, we have converted the sRGB color space to the CIE XYZ color space. Here are the conversion method from the sRGB color space to the CIE XYZ color space [7].

We first divide the nonlinear \(sRGB\) components, \(R_{sRGB}\), \(G_{sRGB}\) and \(B_{sRGB}\),
by 255 and then we obtain the normalized values,

\[
R'_{sRGB} = \frac{R_{sRGB}}{255},
G'_{sRGB} = \frac{G_{sRGB}}{255},
B'_{sRGB} = \frac{B_{sRGB}}{255}.
\]

Then the normalized nonlinear sRGB components, \(R'_{sRGB}, G'_{sRGB}\) and \(B'_{sRGB}\), are transformed to linear sRGB components, \(R_{linear}, G_{linear}\) and \(B_{linear}\), as follows:

If \(R'_{sRGB}, G'_{sRGB}, B'_{sRGB} \leq 0.04045\), then

\[
R_{linear} = \frac{R'_{sRGB}}{12.92},
G_{linear} = \frac{G'_{sRGB}}{12.92},
B_{linear} = \frac{B'_{sRGB}}{12.92}.
\]

else if \(R'_{sRGB}, G'_{sRGB}, B'_{sRGB} > 0.04045\),

\[
R_{linear} = \left(\frac{R'_{sRGB} + 0.055}{1.055}\right)^{2.4},
G_{linear} = \left(\frac{G'_{sRGB} + 0.055}{1.055}\right)^{2.4},
B_{linear} = \left(\frac{B'_{sRGB} + 0.055}{1.055}\right)^{2.4}.
\]

The linear sRGB components \(R_{linear}, G_{linear}\) and \(B_{linear}\) are converted to the CIE XYZ system by the equation \(\mathbf{8}\):

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} =
\begin{bmatrix}
0.4124 & 0.3576 & 0.1805 \\
0.2126 & 0.7152 & 0.7220 \\
0.0193 & 0.9701 & 1.0830
\end{bmatrix}
\begin{bmatrix}
R_{linear} \\
G_{linear} \\
B_{linear}
\end{bmatrix}.
\]

Using the tristimulus value \(X, Y,\) and \(Z\) the chromaticity coordinates \(x, y\) on the \(xy\)-chromaticity diagram are expressed by

\[
x = \frac{X}{X + Y + Z},
y = \frac{Y}{X + Y + Z}.
\]
4.2. Correlated color temperature of the lightning channels

Applying the conversion method mentioned above, we obtained the CCT of the lightning channel. Figs. 8 and 9 denote the projected points for the CG and IC lightning channels shown in Figs. 5 and 6 respectively. In Figs. 8 and 9, the Planckian locus (thick line), the isotherm lines crossing the Planckian locus and the equal ∆uv lines of ±0.02∆uv are also depicted. From Figs. 8 and 9 it is found that many points distribute in the range ±0.02∆uv, but there are also points distributing outside of the range ±0.02∆uv. Since the CCT is discussed in the range ±0.02∆uv, in this work we focus only on the points in the range ±0.02∆uv. The projected points for the CG lightning is mainly concentrated in the narrow CCT range, about 6000 – 7000 [K], but that for the IC lightning distribute in the wide range: about 6000 – 50000 [K].

In order to look at the spatial variation of the CCT of the lightning channel, we remapped the projected points on CIE 1931 xy-chromaticity diagram shown in Figs. 8 and 9 to the former 2-dimensional images (see Figs. 10 and 11) inheriting the CCT. The projected points within the equal ∆uv lines of ±0.02∆uv were remapped, but the outside points of the equal ∆uv lines of ±0.02∆uv were eliminated. Furthermore in Figs. 10 and 11 to emphasize small variation of the CCT, we narrowed the CCT range to 6000 – 7000 [K] for the CG flash and to 6500 – 50000 [K] for the IC flash. The color bars in Figs. 10 and 11 indicate the CCT. The ranges of the color bar are 6000 – 7000 [K] for the CG flash and 6500 – 50000 [K] for the IC flash. Figs. 10 (left) and 11 (left) contain the saturated pixels (255), but Figs. 10 (right) and 11 (right) do not contain. In Figs. 10 and 11 the lightning channel was thickened to 5 pixels, because the extracted lightning channel is very thin, namely confirming the variation of the CCT is very difficult. Notice that the color on the color bar is to emphasize the variation of the CCT, and does not coincide with the actual color as to the color temperature of the Planckian radiator.

5. Discussion

5.1. Identification of the lightning events in the CG and IC lightning images

We have identified the strike points of the CG lightning image (Fig. 1 (Left)) using lightning data in Table 1. The data in Table 1 denote the lightning events in 9:15–10:15 in the investigation area in Chikusei City, Ibaraki Prefecture, Japan, on October 27th, 2008. The investigation area is
Fig. 7: (Left) CIE 1931 xy-chromaticity diagram in which the sRGB color triangle and the Planckian locus are depicted. (Right) enlarged figure near the Planckian locus where the thick line denotes the Planckian locus and the thin lines denote the isotemperature lines. The length of the isotemperature lines is $\pm 0.02\Delta uv$.

Fig. 8: All projected points for the CG lightning channel shown in Fig. 5. The thick line denotes the Planckian locus. The thin lines crossing the Planckian locus are the isotemperature lines. The thin lines along the Planckian locus are the equal $\Delta uv$ lines of $\pm 0.02\Delta uv$. The left side contains the saturated pixels reaching 255, but the right side does not contain.
Fig. 9: All projected points for the IC lightning channel shown in Fig. 6. As with Fig. 8 the Planckian locus, the isotemperature lines, and the equal ∆uv lines of ±0.02∆uv are depicted. The left side contains the saturated pixels reaching 255, but the right side does not contain.

Fig. 10: CG lightning images represented by the CCT. The left side contains the saturated pixels reaching 255, but the right side does not. The lightning channel was thickened because the extracted lightning channel is very thin and confirmation of the variation of the CCT is very difficult.
Table 1: Lightning data in 21:15 – 22:15 JST in the investigation area in Chikusei City, Ibaraki Prefecture, Japan, on October 27th, 2008. The data was provided by Franklin Japan Corporation. The data includes ID numbers, time (JST), the location (WGS84) of lightning strike points, the polarity (+/-), the estimated peak current (kA), and CG/IC index. The latitude and longitude are given in decimal degrees. JST is expressed by JST = UTC + 9 hours.

| ID | Time (JST) | Lightning location | Polarity | Current (kA) | CG/IC |
|----|------------|--------------------|----------|--------------|-------|
|    | (ns)       | Latitude           | Longitude|              |       |
| 1  | 21:17:6:591327450 | 36.3683°N | 139.9669°E | – | 6 | CG |
| 2  | 21:18:27:558320409 | 36.3536°N | 139.9745°E | – | 13 | IC |
| 3  | 21:18:27:589571036 | 36.3428°N | 139.9891°E | – | 28 | CG |
| 4  | 21:18:27:735903133 | 36.328°N | 139.9989°E | – | 9 | CG |
| 5  | 21:20:40:116117691 | 36.3649°N | 139.9905°E | – | 68 | CG |
| 6  | 21:20:40:148843700 | 36.3569°N | 139.9951°E | – | 12 | CG |
| 7  | 21:21:19:214825550 | 36.3473°N | 139.978°E | + | 7 | CG |
| 8  | 21:22:12:826584983 | 36.3561°N | 139.9834°E | – | 31 | CG |
| 9  | 21:22:12:849340650 | 36.3965°N | 140.0426°E | – | 13 | CG |
| 10 | 21:23:2:212293887 | 36.334°N | 140.0356°E | + | 14 | CG |
| 11 | 21:23:58:705277763 | 36.3595°N | 140.0087°E | – | 11 | CG |
| 12 | 21:24:10:326889443 | 36.3608°N | 139.98°E | + | 8 | IC |
| 13 | 21:25:18:83780450 | 36.3327°N | 140.052°E | – | 15 | CG |
| 14 | 21:25:18:83784281 | 36.3583°N | 140.0108°E | – | 21 | CG |
| 15 | 21:25:18:108304626 | 36.3747°N | 139.9733°E | – | 6 | CG |
| 16 | 21:25:39:614264250 | 36.3662°N | 139.9693°E | + | 7 | IC |
| 17 | 21:28:9:397386500 | 36.3708°N | 139.9782°E | – | 19 | IC |
| 18 | 21:28:9:418860575 | 36.3836°N | 140.077°E | – | 5 | CG |
| 19 | 21:29:41:912989800 | 36.3322°N | 139.9863°E | + | 5 | IC |
| 20 | 21:32:15:530283215 | 36.316°N | 140.0776°E | – | 35 | CG |
| 21 | 21:32:15:603968541 | 36.376°N | 140.0589°E | – | 11 | CG |
| 22 | 21:33:12:666414500 | 36.3266°N | 140.0708°E | + | 14 | CG |
| 23 | 21:33:12:667979150 | 36.3639°N | 140.032°E | + | 7 | IC |
| 24 | 21:34:0:937847200 | 36.3565°N | 140.0204°E | + | 11 | IC |
| 25 | 21:41:58:745186600 | 36.3424°N | 140.0718°E | + | 8 | CG |
| 26 | 21:44:16:176844671 | 36.338°N | 140.0767°E | – | 43 | CG |
| 27 | 21:44:16:187369400 | 36.3374°N | 140.1224°E | – | 7 | CG |
| 28 | 21:46:29:646441950 | 36.3721°N | 140.0536°E | + | 5 | IC |
| 29 | 21:46:29:847440271 | 36.4008°N | 140.0779°E | + | 31 | CG |
| 30 | 22:3:21:489762200 | 36.3375°N | 140.1234°E | – | 7 | IC |
Fig. 11: IC lightning images represented by the CCT. The left side contains the saturated pixels reaching 255, but the right side does not. As with Fig. 10, the lightning channel was thickened.

The data in Table 1 were commercially provided by Franklin Japan Corporation. The provided data were observed by the Japan Lightning Detection Network (JLDN) operated by Franklin Japan Corporation. The detection efficiency of the JLDN is greater than 90% for CG flashes and 40% for IC flashes. The median location accuracy is better than 0.5 km. The data in Table 1 include ID numbers, time (JST), the location (lat. and long.), the polarity (+/-), the estimated peak current (kA), and CG/IC index. The locations of lightning events are given by World Geodetic System 1984 (WGS84) and latitude and longitude are given in decimal degrees. The time in Table 1 is based on the Japan Standard Time (JST), where using Coordinated Universal Time (UTC), JST is expressed by JST = UTC + 9 hours.

We have investigated the geographic locations of the lightning events in Table 1. Fig. 12 shows the locations of the CG and IC lightning events in Table 1 and the photographing location. In Fig. 12, the CG and IC lightning events are denoted by the red and blue balloons, respectively. The yellow pushpin indicates the photographing location. Approximate directions of the two lightning strike points in Fig. 1 (Left) are denoted by the yellow lines. The red lines near the photographing location (yellow pushpin) denote the field of view of the CG flash image (Fig. 1 (Left)). The blue lines near the photographing location (yellow pushpin) are the field of view of the IC flash image (Fig. 1 (Right)). In Fig. 12, there are some candidates of the two
strike points in the CG flash image (Fig. 1 (Left)) along the two yellow lines. Therefore it is difficult to identify the lightning strike points using only the geographical location.

We look at the time of the lightning events in Table 1. We have depicted to Fig. 13 the schematic illustration of the time with respect to the lightning events and the exposure duration of the CG and IC flash images (Fig. 1 (Left) and (Right)). Fig. 13 (a) shows the individual times of the IC flash events in Table 1 and there are 9 IC flash events in 9:15 – 10:15 JST. Fig. 13 (b) shows the individual times of the CG flash events in Table 1. In Fig. 13 (b), there are 21 lightning events in 9:15 – 10:15 JST, while it seems that there are 14 lightning events. Namely, seven CG flash events are overlapping because these events occurred nearly simultaneously. Fig. 13 (c) shows the exposure duration for the CG and IC flash images in Fig. 1 (Left) and (Right). The beginning time of the exposure is 21:31:33 JST for the CG flash and is 21:36:09 JST for the IC flash. The exposure duration for the CG and IC flashes are 36 and 39 second, respectively. By comparing Fig. 13 (b) and (c), it follows that the flash events, ID: 20 and 21, are most appropriate to the CG flash events of Fig. 1 (Left) where the ID numbers are shown in Table 1. Thus we determined that the lightning event of the ID: 20 is the right side of the lightning strikes in Fig. 1 (Left). Similarly the lightning event of the ID: 21 is the left side of the lightning strikes in Fig. 1 (Left).

On the other hand, we cannot identify the IC flash shown in Fig. 1 (Right). In Fig. 13 (a), there are no flash events near the time 21:36:09 JST which is the beginning time of the exposure for the IC lightning events shown in Fig. 1 (Left). In the case of IC lightning, the detection efficiency of JLDN is about 40%. It is considered that the IC flash event in Fig. 1 (Right) could not be detected.

5.2. Correlated color temperature and energy of the lightning channel

We discuss both the CCT and related energy of the lightning channel removed the saturated pixels reaching 255. In general, it can be considered that the saturated part of the lightning channel have higher energy. But we cannot know the accurate information for the saturated pixels of the lightning image. Hence, we study the CCT and the related energy of the lightning channel removing the saturated part, namely we used Figs. 10 (right) and 11 (right).

We think that the CCT is related to the energy of the lightning channel. Usually, the spectra of the short wavelength increase with increasing the
CCT. Thus it can be considered that lightning channels having higher CCT have the higher energy than the other channels. As for the CCT of the CG lightning channel (Fig. 10 (right)), we can find that the CCT around the right strike channel (ID: 20) is relatively higher than the other channel. The CCT around the right strike channel (ID: 20) distribute in about 6500 – 7000 K and this CCT are displayed gradually by using the colors from yellow to green. The CCT around the left strike channel (ID: 21) and other branch channels distribute in about 6000 – 6500 K and are displayed gradually by using the colors from red to yellow. As stated above, the right strike channel (ID: 20) have higher CCT than the others. Thus we consider that in Fig. 10 (right), the right strike channel (ID: 20) have higher energy than the left strike channel and other channels. Moreover, from Table 1 the currents of the left and right strike channels (ID: 21 and 20) are $I_{ID:21} = 11$ kA and $I_{ID:20} = 35$ kA. Namely, $I_{ID:20} \geq I_{ID:21}$. This means that the energy of the lightning channel having larger current is higher than that having the lower current.

From Fig. 11 (right), which was removed the saturated pixels, it is found that the CCT of the IC lightning channel mainly distribute in the range about 7000 – 20000 K and is gradually displayed by the colors (green – cyan). We can also find that there are the slight pixels in about 20000 – 50000 K gradually displayed by the colors from cyan to blue to purple.

From Fig. 10 and 11, we found that the CCT of the lightning channel changes spatially. This also means that the energy of the lightning channel changes spatially. Totally, the CCT on the IC lightning channel is higher than the CG lightning channels. This indicate that the energy of the IC lightning channel shown in Fig. 11 (Right) was higher than the CG lightning channel shown in Fig. 1 (Left).

We add the discussion for the saturated pixels on the lightning channel. In Fig. 10 (left) and 11 (left) the yellow channels having 6500 K (disappear in Fig. 10 (right) and 11 (right), respectively) are the saturated channels. The corresponding channels in the original images shown in Fig. 1 (Left) and (Right) are seen more brightly. It is reported by Idone and Orville [9], Gomes and Cooray [10], Wang et al. [11], and Zhou et al. [12] that there exists a strong positive correlation between the channel current and light intensity of lightning channel. For the above reason, it can be considered that the current on the saturated part is high, although the details on the saturated part cannot be known. It can be summarized that the bright channel on the saturated part have high current and high energy. Furthermore, Rubenstei et
al.\cite{13} and Rakov et al.\cite{14} reported that there is a positive linear correlation between the peak current and the leader electric field change. It is considered that the electric field changes around the bright channel having the saturated pixels is large.

6. Conclusions

From Fig.\ref{fig:10} and \ref{fig:11} we have found that the CCT of the lightning channel changes spatially. This also means that the energy of the lightning channel changes spatially. Since the lightning images (Fig.\ref{fig:1} (Left) and (Right)) were
Fig. 13: Schematic illustration of the time (JST) for the (a) CG and (b) IC flash events shown in Table II and for (c) the exposure duration of Fig. I. The beginning time of the exposure is 21:31:33 for the CG flash and is 21:36:09 for the IC flash. The exposure duration for the CG and IC flashes are 36 and 39 second, respectively.

captured by exposing the image sensor, the amount of light captured by the image sensors in the still camera was integrated in the exposure time 36 second for the CG flash and 39 second for the IC flash. For this reason, we did not analyze the temporal variation. If high-speed video camera is used, the more details of the spatio-temporal variation of both the CCT and energy of the lightning channel will be obtained.

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