**Improvement of ASC auroral index by correcting the exposure time and its correlation with the geomagnetic variation**

Yuna Katsuyama -internship student at the Swedish Institute of Space Physics

**Abstract.**

Index representing the auroral activity in the all sky camera image (ASC auroral index) is improved by normalizing exposure time that changes automatically. Red, Green, Blue (RGB) values in the RGB color code and L value in the hue-lightness-saturation (HLS) color code are corrected using the logarithmic values of the exposure time, using two methods. Out of these two methods, I employed the method in which the corrected ASC image becomes more close to naked eye, for further analyses using the geomagnetic data. I next compared the corrected ASC auroral index with geomagnetic variation d**B**/dt. For d**B**/dt, three methods are compared using 1-sec resolution Bx data: 1-min average of |dBx/dt| that is calculated every second, standard deviation of Bx over 1 minute (std(Bx)\_60), and maximum value of 10-sec standard deviation over 1 minute (std(Bx)\_10). It turned out that the last method is optimum for the present purpose. While the correlation coefficient between aurora activity levels and geomagnetic variation is not yet good even after correcting the dynamic exposure (the correlation was indeed improved), I still see some good positive relation between them during the period when they quickly increase toward the "Local Arc Breaking" that is the special explosive auroral activity. In other words, real-time monitoring might be used for the last-minute prediction of large aurora, which is a future task. Finally, using the corrected ASC auroral index, the activity level is compared with a different aurora identification scheme using machine learning (deep-learning) method such as the probability of certain type of aurora (arc, discrete, and diffuse). The morphology using machine learning method and intensity using ASC aurora index turned out to be independent, i.e., these two methods give independent information. This independence indicates that it is promising to combine them in order to improve real-time aurora monitoring system, as a future task.

**1. Introduction**

***ASC aurora index***

Auroral activity normally has a life cycle of a slowly developing phase with a quiet arc of 0.5-2 hours followed by a sudden breaking of the arc covering entire sky while increasing the intensity at the same time. This expansion is seen both at a global scale (called an auroral substorm) and at local spots covered by one all-sky camera (ASC). With one ASC, it is difficult to identify the substorm, but almost all substorms cause local expansion with significant intensification. Nevertheless, such a "local" sudden and significant intensification of the auroral arc with expanding motion (it is called as “local-arc breaking” in Yamauchi and Brändström (2023)) is an important event in many aspects because it can be related to the substorm, and more importantly, it is related the geomagnetic activity and other ionospheric phenomena. However, for real-time observation/watching, for science, space weather monitoring, and even touristic interest, it is easy to miss the “local-arc breaking" due to its short rise time toward the “local-arc breaking”.

Therefore, it is very useful if the “local-arc breaking” can automatically be identified from the ASC images and send alerts automatically. Here there are two approaches, one is using morphology (appearance), and other using intensity (or activity level). For example, there is a real-time classification system of the auroral morphology using machine-learning methods (e.g., Nanjo et al., 2022). If not limited to real-time operation, many machine-learning methods have been developed for the classification of the auroral morphology.

On the other hand, the machine learning method is not optimum in quantifying the activity level. To fill this gap, another type of automatic quantification scheme has been developed at IRF Kiruna. This method has already been applied as a real-time alert system of the "local-arc breaking" for the Kiruna ASC using the JPEG images (Yamauchi and Brändström [2023]).

This quantification schema gives a simple set of numbers (or "index") such as area occupation of strong, ordinary, and weak aurora, as well as normalized intensity (L3 parameter as described later). Using these numbers (or index), activity level is defined as Level 6, Level 4a, etc. Also, by using these numbers, it has become possible to investigate detailed relationships between the auroral activity level and geomagnetic variations and the state of the ionosphere.

According to this system, Level 6 is as clear "local-arc breaking" and Level 4 is as a precursor for it. These levels are judged with R (red), G (green), and B (blue) values in the RGB color code and L (lightness) in the HLS color code. The first step is to classify each pixel of a JPEG image into three aurora categories (from brightest to faintest, “strong aurora”, “green arc”, and “visible diffuse (aurora)”. The second step is to get the percentage of the occupying area (pixel coverage) for each category. In addition to them, the average value of L3 values for "strong aurora" pixels is calculated for each image (called the L3 parameter). Then levels are judged using criteria summarized in Table 1.

|  |  |  |  |
| --- | --- | --- | --- |
| **Level** | **%arc condition** | **%strong condition** | **L3 condition** |
| **6** | ≥ 3 % | ≥ 0.2 % | ≥ 8 |
| **4a** | ≥ 2 % | ≥ 0.2 % | ≥ 5 |
| **4b** | ≥ 1 % | ≥ 0.1 % | %strong·L3 ≥ 1.5 % |
| **4d** | ≥ 2.5 % | ≥ 0.15 % | ≥ 8 |

**Table 1.** Criteria for the activity levels.

The auroral alert system was developed only recently and there are many rooms for improvement. The two most urgent tasks are (1) correcting different exposure times and (2) finding out the relation to geomagnetic valuation, particularly to d**B**x/dt. I performed these tasks using the Kiruna ASC data and geomagnetic data from Kiruna Atmospheric and Geophysical Observatory (KAGO) at the Swedish Institute of Space Physics (IRF). The Kiruna ASC data is stored as JPEG images, available at (https://www.irf.se/alis/allsky/krn/). Exposure time is extracted with ExifTool (https://exiftool.org/). The geomagnetic data is stored as the ascii format (https://www2.irf.se/maggraphs/iaga/interpolated\_f/).

**2. Correction of exposure time**

***Exposure time***

The Kiruna ASC uses a commercial camera (Sony alpha-7s) that employs dynamics exposure that automatically changes from <1s to 30s depending on the brightness of the sky (e.g., 2-4 sec for full moon, 3-8 sec for cloud that reflects city light, and 20-30 sec for visible arc under dark sky). Long exposure time enhances the overall brightness (all the R, G, B, L values). Fig. 1 shows the differences of brightness in images with each exposure time. In the images with 30s of exposure time, there are more stars than that with 6s of exposure time. In Yamauchi and Brändtröm (2023), the exposure time is not considered when levels are judged. Then overestimation due to long exposure time occurs.

Description: グラフ が含まれている画像

自動的に生成された説明

**Figure 1.** Jpeg images covering the same star (Jupiter) for different exposure time. Top (30s): ASC image on 2023-09-15T22:24 UTC. Bottom (6s): ASC image on 2023-09-15T23:15 UTC.

***RGB color system and HSL color code***

All commercial digital cameras use 3CCD system taking three colors representing Red (R), Green (G), and Blue (B). The jpeg image is therefore coded by RGB color code, with 8 bit (256) values each (roughly proportional to the logarithmic of number of photon: I go in detail later). On the other hand, human eye judges the color with color spectrum (Hue), color intensity (Saturation), and brightness or total intensity (Lightness). As Fig.2 shows, this color system, namely the Hue, Saturation, and Lightness (HSL) color system, has ranges of H=0° to 360° (120° is green, 240° is blue and 360° is red), S=0 to 1 (100%), and L=0 to 1 (100%). Here L=0 means black and L=1 means white. Fortunately, one can calculate these HSL values from RGB values. For example,

L = [max(R, G, B) + min (R, G, B)]/2 (1)

Therefore, L is also used as well as RGB to judge a pixel belonging to the aurora, the Moon, could etc.

Description: グラフィカル ユーザー インターフェイス

自動的に生成された説明(F. Sigernes et al., 2023)  
**Figure 2.** Horizontal cross section of the HLS color space. L =0.5 of Saturation and Color cake slice.

***Color codes and number of photon***

To represent the intensity with 256 values for each color, the color code (R, G, or B) is normally scaled logarithmic to the intensity, i.e., number of photons (#photon) for large numbers of photons while scaled linearly for small numbers of photon to the coding most effective.

*G = k \* log10(#photon)* for large *#photon* (2a)

*G =c \* #photon*  　　　　　for small *#photon* (2b)

Here I consider the case when aurora appears, which means that #photon is large enough to use (2a). For Sony alpha-7s camera that is used for the Kiruna ASC, saturation level is 12 bit (212 ), which means some value between 2049 and 4096 (actually close to 3500-4000). For example, the S-log3 coding described in Sony's technical summary (https://pro.sony/s3/cms-static-content/uploadfile/06/1237494271406.pdf) uses a value of k ≈ 64 for large G (>100). If one design the most effective color coding by assuming max ~3500, the optimum k value is 72 (i.e., 255 = 72\*log10(3500)).

*G = 72 \* log10(#photon)* (3)

Number of photon is proportional of exposure time. When very strong aurora occurs, exposure time becomes 6s, otherwise longer than 6s if no other light source (moon, cloud, twilight) exists. Then R, G, B value should be normalized to 6s of exposure time(T).

*or,*

This subtraction expression can also be approximated by a division expression.

*or,*



Same correction applies to R and B. I tested both (5) and (6).

**2.1. Normalization with L value**

As I mentioned above, Color values (R, G, B, and even L) of a star should be constant over different images after the successful correction of the exposure time. Therefore, I first examine the relationships between color values and exposure time for the brightest star in the sky. Jupiter is the brightest and stayed in the sky entire night during fall 2023. I obtained the color values of pixels on Jupiter for more than 300 minutes on the nights of 2023-10-20 (18:54 UTC to 00:20 UTC), and 2023-9-13 (20:41UTC - 02:15UTC). Fig. 3 shows the examples on 2023-10-20 and Fig. 4 shows the result for L value (I used L because it is proportional to R, G, B values according to Eq. (1)). The Results for three R, G, B values for the same images are given later. As illustrated in Fig. 3, I calculate the average of L values on 900 pixels (30x30 box) covering the same star (Jupiter).

Description: グラフィカル ユーザー インターフェイス

自動的に生成された説明

**Figure 3.** Jpeg images covering the same star (Jupiter) for different exposure time. Top-left(30s): ASC image on 2023-09-15T22:24 UTC. Bottom left: expansion of the top-left image. Top right: ASC image on 2023-09-15T23:15 UTC. Bottom right: expansion of the top-right image.

Description: グラフ, 折れ線グラフ

自動的に生成された説明**Figure 4.** Exposure time versus L values (mean of 900 pixels indicated in Fig. 3) on Jupiter for more than 300 minutes on the nights of 2023-10-20 (18:54 UTC to 00:20 UTC). Modeled curves are also drawn.

In Fig. 4, blue dots represent L values of the star pixels. I first examined against L values because, as Eq. (1) represents, L value is proportional of RGB value. The lines are modeled curves for both the subtraction case (red, Eq. (5)) and division case (green, Eq. (6)). The best fit value of the normalized lightness (Lnormalized) for Jupiter is 75:

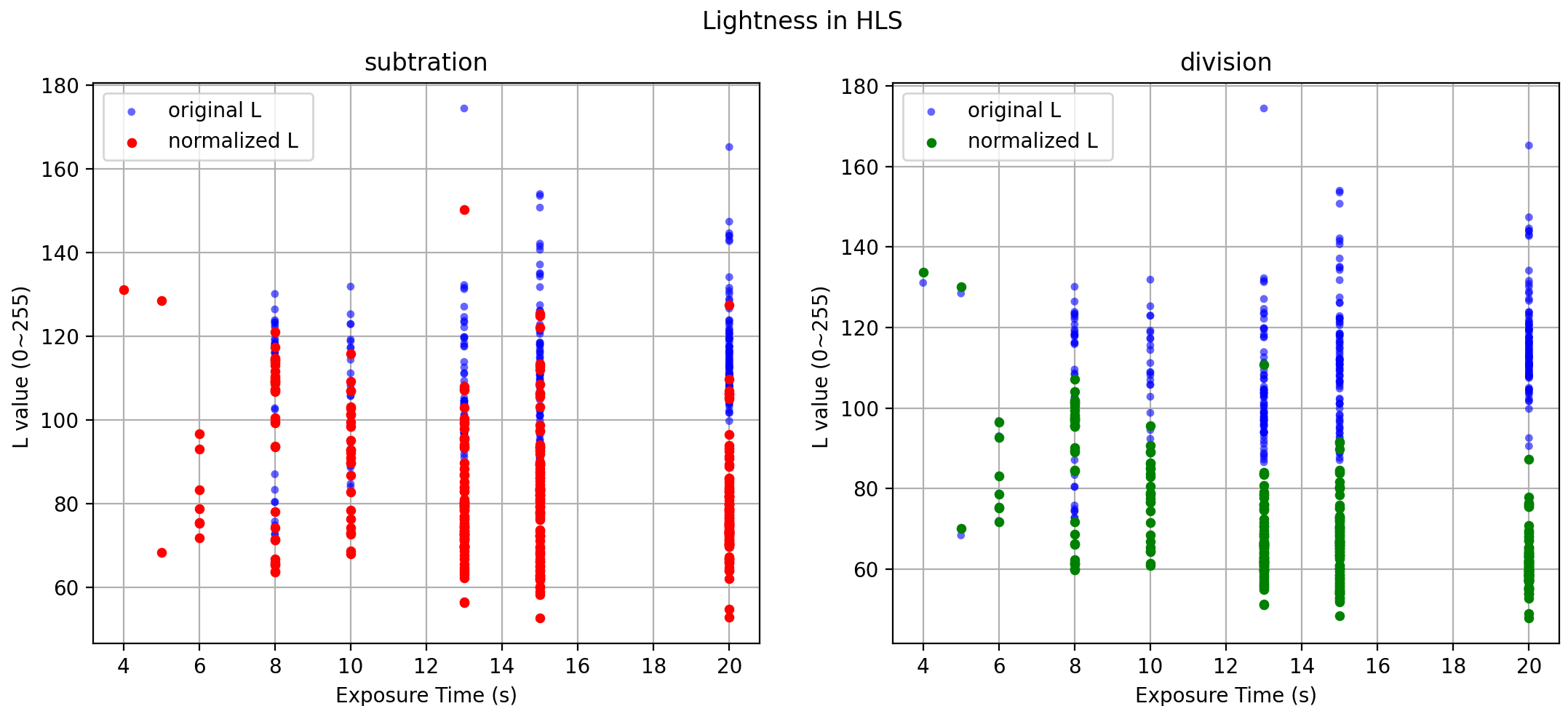
***Subtraction (Red line):***

***Division (Green line):***

(8)

Using Eq. (7) and Eq. (8), I normalized the observed L values (blue dots in Fig. 4) as

***Subtraction method(left):***

***Division method(right):***

**Figure 5.** Exposure time versus L values (mean of 900 pixels indicated in Fig. 3) on Jupiter. Blue dots are the original L value on the same time and date as Fig.4. On the left figure, L is normalized by subtraction (Eq. (9)), while on right figure, L is normalized by division (Eq. (10)).

The results are shown in Fig. 5. In Fig. 5, I also plotted for the cases of exposure time = 4s and 5s. Since the data point was too little to obtain the correct normalization, I simply added constant values e/2 for T = 5s and e2/2 for T = 4s.

Fig. 5 illustrates that the corrected L values (Lcorrected) for both cases become close to constant against the exposure time, expected. However, there is a difference: the normalized L values with subtraction method are more spread in the vertical direction compared to the division method. The result suggests that the division method might be useful for the present purpose (aurora identification) rather than the subtraction method.

Description: ダイアグラム が含まれている画像

自動的に生成された説明

**Figure 6a.** Left: raw image on 2023-09-15T22:20 UTC. Right: image after L is normalized on the same time and date with Eq. (10), i.e., division method. Exposure time is 30s.  
ダイアグラム が含まれている画像

自動的に生成された説明**Figure 6b.** The same as Fig. 6a for Eq. (9), i.e., subtraction method.

Description: ダイアグラム

低い精度で自動的に生成された説明

**Figure 7.** Left: raw image on 2023-09-15T23:15 UTC. Right: image after L is normalized on the same time and date with Eq. (10), i.e., division method. Exposure time is 6s.

Next, I compared original images and the corrected color images with Eq. (10), i.e., using the division method. An example for the longest exposure (30s) is shown in Figs. 6a and 6b. As reference, I also made the conversion for 6s exposure in Fig. 7, to make sure that the conversion reproduces the same image.

In the right panels (corrected images) of Fig. 6a, darkness of the background became close to that in Fig. 7. Even the intensity of the diffuse aurora (faint green band south of bright aurora in the north) in Fig. 6a became slightly lower than that in Fig. 7 (aurora in Fig. 6a is much less intense than that in Fig. 7). It might not be quantitatively correct, but enough for the aurora alert purpose as mentioned in the introduction.

While the intensity is rather well corrected, there remains a problem in correcting color. In fact, G/R value and G/B value of the auroral pixels became higher, particularly for smaller L value, although it does not matter as long as using only L values to decide activity levels (6, 4a, 4b). To understand this problem, I examined each of R, G, B values instead of L values.

Description: グラフ, 折れ線グラフ

自動的に生成された説明**2.2. Normalization with RGB value**

**Figure 8.** Exposure time versus RGB values (mean of 900 pixels indicated in Fig. 3) on Jupiter for more than 300 minutes on the nights of 2023-10-20 (18:54 UTC to 00:20 UTC). Modeled curves (Eq. (11) and Eq. (12)) are also drawn. Left: Red in RGB. Center: Green in RGB. Right: Blue in RGB.

***Subtraction (Red line):***

***Division (Green line):***

(12)

Same correction applies to G (and Ngreen) and B (and Nblue).

Eq. (11) and Eq. (12) are almost the same as Eqs. (7) and (9) for normalizing L value. With this modeled curve, value of R is 60(Nred) when exposure time is 6s. Ngreen is 90 and Nblue is 50. As Fig. 8 confirms, Red and Blue, both subtraction line (Red line) and division line (Green line) are successful to model color value with exposure time. Note that when I get Green value on Jupiter, aurora is covering over the pixels. Therefore, especially G value with shorter exposure time is higher than simple Jupiter values.

Description: グラフ

自動的に生成された説明**Figure 9.** Exposure time versus RGB values (mean of 900 pixels indicated in Fig. 3) for Jupiter. Blue dots are the original RGB value on the same time and date as Fig.8. Red dots are normalized RGB value with Eq. (13) and Eq. (14). Left: Red in RGB. Center: Green in RGB. Right: Blue in RGB.

Same correction applies for G and B.

Description: パソコンの画面

中程度の精度で自動的に生成された説明

**Figure 10.** Exposure time versus RGB values (mean of 900 pixels indicated in Fig. 3) Jupiter. Blue dots are the original RGB value on the same time and date as Fig.8. Green dots are normalized RGB value with Eq. (15) and Eq. (16). Left: Red in RGB. Center: Green in RGB. Right: Blue in RGB.

Same correction applies for B and G.

From Fig. 9 and Fig. 10, Red value and Blue value in RGB close to constant after normalization. And division method looks better as dots are not dispersed. Then I apply division method (Eq. (15) and Eq. (16)) to ASC images. The results are shown at Fig. 11a. Subtraction method is also applied as reference at Fig. 11b.

Description: ダイアグラム が含まれている画像

自動的に生成された説明

**Figure 11a.** Left: raw image on 2023-09-15T22:20 UTC, exposure time is 30s. Right: image after RGB is normalized on the same time and date with Fig. 6a, i.e., division method(Eq. (15)).  
ダイアグラム が含まれている画像

自動的に生成された説明

**Figure 11b.** the same as Fig. 11a for Eq. (13), i.e., subtraction method.

On the right panels of Figs. 11a and 11b, the image and aurora becomes darker than the original image such that the image becomes close to what is perceived by naked eye, like Fig. 6a and Fig. 6b. However, the arc in the north is easier to recognize in Fig. 6a (used L instead of all of R, G, B) than Fig 11.  **Therefore, I use Eq. (10) for the further analyses (see next section).**

**3. Correlation with geomagnetic variation dB/dt**

***Representing the geomagnetic variation dB/dt***

Auroral activity is known to accompany with the geomagnetic field activity (Bx, By, Bz). However, its exact relation is still unknown, particularly for the variation (d**B**/dt). This is partly because the aurora activity (2D image) has not been quantified to simple numbers such as the activity level (Level 6, 4a, 4b) or L3 parameter. With the auroral index, such comparison became possible. This is why I first normalized the L values.

The geomagnetic data at Kiruna (same location as the ASC) available with 1s resolution at https://www.irf.se/maggraphs/iaga/ (Swedish Institute of Space Physics Kiruna Atmospheric and Geophysical Observatory, 2023). I intended to get the variation for every minute because the ASC image is taken every minute (same time resolution). Here I examined three different ways to calculate index for magnetic variation. For example, the values of geomagnetic variation (dB/dt) for 2023-09-13T21:25 UTC is calculated using the one-second data from 2023-09-13 (21.24.01UTC to 21.25.00UTC).

**The three methods that examined here are:**

1. The 60-second average of the absolute value of the rate of change　|dBx/dt|
2. The standard deviation over a 60-second interval, normalized by dividing by the square root of 60.
3. The highest value among the moving standard deviation values over a 10-second interval, normalized by the square root of 10.

**3.1 Geomagnetic variation and the L3 value**

Fig. 12 shows the overview of variation of aurora activity and dB/dt. Overall, Fig. 12 indicates that there is a similar trend between geomagnetic variations and the values of L3. When you see 21:20 normalized values of L3 (average of L3 over strong aurora, as described in §2) closely resemble to the trend of geomagnetic variations. It appears that normalization of L value with exposure time is successful for this night.

Description: グラフ, ヒストグラム

自動的に生成された説明**Figure 12.** Time series of two ways of magnetic variation, cubed L, normalized cubed L. Top: vertical axis above is |dBx/dt|. Bottom: vertical axis below is std10s(Bx)/  
Data is 2023-09-13 (20:00 UTC to 01:00 UTC). Blue line is original L3 value before normalized. Green line is corrected L3 value.



**3.2 Correlation between Geomagnetic variation and auroral activity.**

For more quantitative comparison many nights, I first examined the correlation. Here parameter with continuous number like the L3 parameter is useful the parameter for the aurora activity. Similarly the auroral activity level (four stages: 6, 4a, 4b, and 4d) is better generalized because, these indicators are discrete and challenging to handle. Therefore, a new metric, 'judge,' has been defined to quantify the level classification. The aurora level determination is calculated based on the product of the pixel ratio of 'arc,' the pixel ratio of 'strong,' and the value of 'L3.' However, upper limits are set for each component. The formula for 'judge' is as follows.

*𝑗𝑢𝑑𝑔𝑒 =30∗𝑚𝑖𝑛(𝑎𝑟𝑐, 5) ∗ 𝑚𝑖𝑛(𝑠𝑡𝑟𝑜𝑛𝑔, 0.5)∗ 𝑚𝑖𝑛 (𝐿3, 20) (19)*

Description: グラフ, ヒストグラム

自動的に生成された説明

**Figure 13.** Hist gram of judge for each Levels. Vertical axis is the common logarithm of judge. Data is picked 67 days from August 2021 to April 2023

As Fig. 13 illustrates the boundary between Level 6 and Level 4a is around log10(judge) = 0.8, corresponding to judge = 6.3. And the boundary between Level 4a and Level 4b is around log10(judge) = 0.6, corresponding to judge = 4.0. As a next step, I compared judge and magnetic variation with ASC image for 20 minutes. I first made a scatter plot in Fig. 14. Considering Fig 13 result, I plotted for judge > 3.

グラフ, 散布図

自動的に生成された説明

**Figure 14.** A scatter plot of dB/dt and L3 values, corrected L3 value and Judge for the same night as Fig. 12. (2023-09-13 (20:00 UTC to 01:00 UTC)). Both vertical axis and horizontal axis is log scale. On the top is L3, center is corrected L3, and bottom is Judge. Collation coefficient is on Table. 2.

In Fig. 14, although the correlation is not good, i.e., far below 0.7 (Fig. 14 and Table 2), there is a general tendency that dB/dt increases for large auroral activity (measured by judge values). Particularly, the timings of quick increases match relatively well between the aurora activity (L3) and dB/dt in Fig. 12.

グラフ, 散布図

自動的に生成された説明

**Figure 15.** A scatter plot of dB/dt and L3 values, corrected L3 value and Judge. Data is picked 67 days from August 2021 to April 2023. I extracted time only when it is Judged Lv 6. Both vertical axis and horizontal axis is log scale. On the top is L3, center is corrected L3, and bottom is Judge.

As a reference, Fig. 15 shows the scatter plot for all 67 nights when Level 6 is observed for 2 years. The correlation for the entire points is even worse than Fig. 14, particularly for original L3 parameters. This is not surprising because different conditions (between different nights such as cloud and moon) are mixed. However, the positive relation between the judge and dB/dt remains (this also applies to Lcorr3 but not L3), and this does not tell how good the timing of quick increase matches.

To make the positive relation clearly, Fig.16 shows average of d**B**/dt in each bin of aurora activity index. Although no correlation is seen between the original L3 and d**B**/dt, correlation appears between corrected L3 (Lcorr3) and d**B**/dt. The correlation is clearer if the "judge" parameter is used.

グラフ, 折れ線グラフ

自動的に生成された説明This confirms that Lcorr3 and Judge value have a small positive relationship as Fig. 15 illustrates. The difference between Lcorr3 and L3 in terms of the relation to d**B**/dt is also seen the correlation coefficient shown in Table 2, although both are very low (about 0.5). Thus, using Lcorr3 (or judge parameter that uses Lcorr3) must be used instead of original L3 when correlating to d**B**/dt. Similarly, Table 2 also suggest that standard deviation over 10s could be the preferable index for geomagnetic variation although the correlation coefficient is very low (only 0.5).

**Figure 16**. Graph of averages of dB/dt in each bin. This is the same data as Fig. 15. Width of bin is 0.1. Horizontal axis is logarithm base 10 of L3 for left, Lcorr3 for center and judge for right. Vertical axis is a logscale.

|  |  |  |  |
| --- | --- | --- | --- |
|  | 1. |dBx/dt| | 2. std60s(Bx)/ | 3. std10s(Bx)/ |
| L3 | 0.417 | 0.301 | 0.423 |
| Lcorr3 | 0.498 | 0.352 | 0.506 |
| Judge | 0.498 | 0.352 | 0.507 |

**Table 2.** Correlation coefficient between geomagnetic variation and L3. L3is original L3 value, which is used to judge levels as one of index. Lcorr3 is corrected L3 value with exposure time. Data is 2023-09-13 (20:00 UTC to 01:00 UTC).

As a next step, I examined the opposite relation; i.e., I compared the auroral activity level (numbers of occurrence of Level 6, Level 4a, 4b, and 4d) for different levels of dB/dt. The result is shown in Fig. 17. Blue and pink area gives the histogram of each Level using L3 and Lcorr3, respectively. Where std10s(Bx)/<1.0, some Lv 6 changed into Lv 4a. It means some overestimated Lv 6 due to long exposure time is corrected. As the result, distribution of Level 6 looks like a normal distribution centered at around 0.3nT/s.



Description: グラフ, ヒストグラム

自動的に生成された説明

**Figure 17.** Histogram of std10s(Bx)/ for each level. Horizontal axis is the natural logarithm of std10s(Bx)/ . The very top is for Lv 6, the second from top for Lv 4a, the second from bottom for Lv 4b and the very bottom for Lv 4d. Blue area is for original Lv. Pink are for corrected Lv. Data is picked 67 days from August 2021 to April 2023.



**3.3 Aurora Break-up and Geomagnetic variation**

Description: グラフ

自動的に生成された説明I can even search for possible precursors of the big GIC events (big |dB /dt | events) in the ASC auroral index. (Yamauchi and Brändström [2023]). I compared existing ASC aurora index and geomagnetic data.

**Figure18.** ASC images 5min around 20:25 UTC on 23 October 2022. Black line is standard deviation of Bx for 10s of 20min around the break-up time. Gray line is judge value.

Description: グラフ, 折れ線グラフ

自動的に生成された説明

**Figure19.** Raw data of Bx.

Description: ダイアグラム が含まれている画像

自動的に生成された説明In Fig. 18, the very left ASC image at 20:23 UT shows a white (saturation) and bright arc, which is "local-arc breaking" in human eye, but such judge can be made after the arc actually breaking at 20:24 or 20:25 UT (the judge parameter increased at 20:24 UT). On the other hand, local peak of geomagnetic variation is at 20:25 UTC. At that time, aurora reached the zenith of Kiruna (covering the middle of ASC image).

**Figure 20.** ASC images 5min around 21:53 UTC on 13 January 2023. Black line is standard deviation of Bx for 10s of 20min around the break-up time. Gray line is judge value.

Description: グラフ, 折れ線グラフ

自動的に生成された説明

**Figure 21.** Raw data of Bx.

The same trend can be confirmed with Fig. 20. "local arc-breaking" occurs at 21.52 UTC (there are saturated pixels on the arc), that can be judged after the expansion at 21:53 UT (the judge parameter increased at this time). The rise of geomagnetic variation is delayed by 1 min, with again a good positive correlation during the rising. In addition, the peak of geomagnetic variation occurred when the aurora approaches the zenith. From there case study, both d**B**/dt and judge increases toward the "local-arc breaking", and geomagnetic variation gets its peak when aurora occurs when the aurora is closet to Kiruna, although higher geomagnetic variation on the global scale was expected to occur exactly when breaking-up happens.

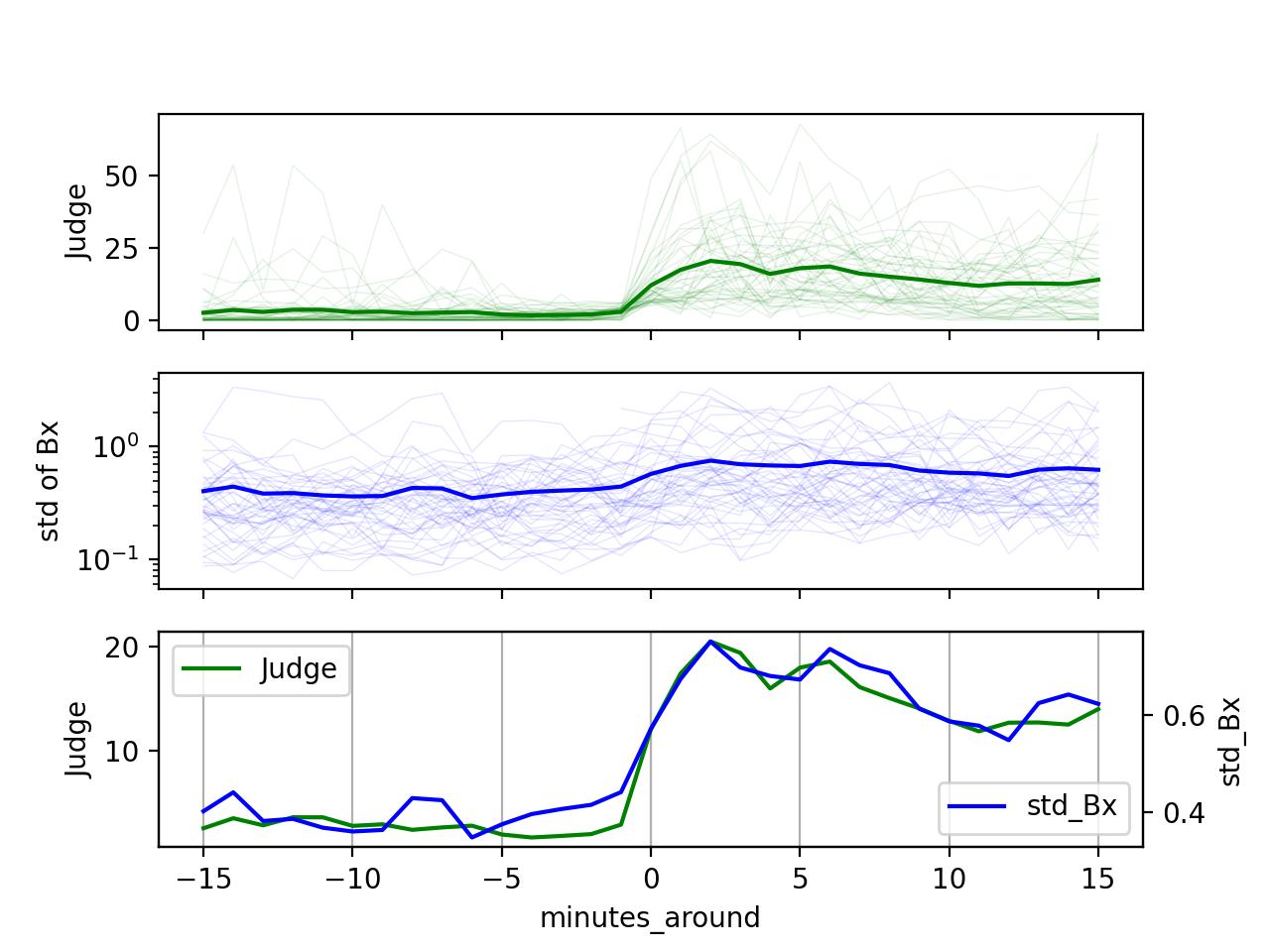
Description: グラフ, 折れ線グラフ

自動的に生成された説明

**Figure 22.** 6 ASC images around 2023-09-13T21:21 UTC. Geomagnetic variation value (black line) is moved 1minutes forward. Gray line is judge value.

In Figs. 18 and 20, there is 1-min delay between judge and dB/dt. This is partly because the value of variation is calculated based on the data from the preceding 60 seconds. Therefore, it is useful to shift the std10s(Bx)/plot by 1 minutes. Fig. 22 shows one example. Again, the good correlation is seen during the rising phase. The ASC images indicates "local-arc breaking" occurs on 21:11 UT (confirmation 21:12 UT). The good positive correlation between dB/dt and judge is again seen before the peak (last 5 minutes), but it completely disappears afterward. This explains very low correlation coefficient in Table 2.



To examine this rising-part correlation, I made superposed epoch analyses against the first Level-6 detection of independent "Local Arc Breaking" over one year (Sep 2022 - Oct 2023, total 47 events). Fig. 23 shows the results. Although these data is mixed different conditions and there is variability in the absolute values, a trend can be seen in the transition immediately before and after the breakup. If I take the average, both Judge value and dB/dt value suddenly increase 1 minutes before the "Local Arc Breaking". In addition, when two of them rise together, its rising phase lasts for a couple of minutes. This supports the trend obtained from the case study above.

**Figure 23.** Superposed epoch analyses against the first Level-6 detection of independent "Local Arc Breaking" over one year (2022-09-08 to 2023-10-22, total 47 events). Thin line represents each event. Thick line is the average. Upper: vertical axis is Judge. Center: vertical axis is logscale of |d**B**/dt|. Bottom: Average lines are plotted.

The observed positive correlation during the rising phase indicates that, if both start rising, I expect this rise continue until the "local arc breaking". **Therefore using both judge (activity level) and dB/dt is important for last-minute aurora prediction in the future.**

This also applies to the prediction of d**B**/dt. Empirically, std10s(Bx)/ > 3.0 nT/s is considered as a significant geomagnetic variation (> 10.0nT/s may start causing space weather hazard), and as its precursor, knowing the condition for std10s(Bx)/ > 1.0 nT/s is useful. Then the good correlation between d**B**/dt and auroral activity (judge) also **opens the possibility of last-minute prediction of hazardous dB/dt (>10 nT/s).**

**4. Compare with other method of real-time aurora monitoring system**

Description: グラフ, 散布図

自動的に生成された説明**Figure 24.** Scatter plots of Judge value derived from ASC index and probability of Tromsø AI (Nanjo et al., 2022). Left: probability of "arc". Center: probability of "discrete". Right: probability of "diffuse". horizontal axis is legalism of Judge value. Vertical axis is probability (%). Data is whole night of three days (2023-09-13, 2023-09-15 and 2023-09-18).

Tromsø AI, which is classification system of auroral appearance using machine learning algorism, has no collation with Judge value, which is an index of strengthen of aurora from RGB value and L in color code. Fig. 24 shows that there is no collation between probabilities of each appearances and Judge value. Although both machine learning method and quantification method are successful in monitoring the auroral condition in real-time, they represent different aspects of aurora, one is morphology and the other is intensity, and cannot replace one method by the other method. The figure confirms such independency. In order to monitor auroral condition, both morphology and intensity are so important that they should be combined in aurora real-time monitoring system. This is a task for the future.

**5. Summary of the results**

L value and RGB value are normalized with division of log of exposure time. The equation for such correction is derived by comparing the color code values of pixels on Jupiter for different exposure time. By such normalization of the exposure time, the ASC image is improved, as confirmed by comparing images with and without normalized L and RGB value in color code. This naturally improved the ASC aurora index, e.g., solved the overestimation in judging the aurora activity levels. The improvement is even seen in the collation between L3 value and geomagnetic variation.

A new metric, "judge" is defined to quantify aurora activity levels. This enables me to examine the correlation between auroral activity levels and geomagnetic variation d**B**/dt in more detail. Among three methods of calculating the geomagnetic variation (|dB/dt|, 60-sec standard deviation, and 10-sec standard deviation std (Bx)\_10s), the last method std(Bx)\_10s is found to be the most optimal. Although the correlation coefficient between "judge" (or L3) is not very good, timing of increase matches in timeseries plot, and this is confirmed by the superposed epoch analyses. If both judge value and geomagnetic variation value increase together, it can be continued until "local-arc breaking". It means that to monitor both aurora activity level and geomagnetic variation is important to predict future auroral occurrence.

On the other hand, sometimes a time gap occurs between "local-arc breaking" and the peak of geomagnetic variation, with "local-arc breaking" before of increase of geomagnetic variation by a few minutes. This can be related to the location of the aurora: the peak of geomagnetic variation is just when the aurora approaches the zenith.

Finally I confirmed that the ASC aurora index provides an independent information of the aurora activity from those of machine learning method that classifies the aurora morphology.

**6. Future task**

There is room for normalization when exposure time is shorter than 6.0s. To solve this, moon and twilight should be considered. As I found that geomagnetic variation can be used to aurora prediction, more research to integrate geomagnetic variation is needed to include it as one of the index to judge aurora activity levels. To improve automatic real-time aurora monitoring system, morphology aspect and intensity (aurora activity level) can be integrated.

**References**

Nanjo, S., Satonori Nozawa, S., Yamamoto, M., Kawabata T., Johnsen, M. G., Tsuda, T. T., and Hosokawa, K.: An a auroral detection system using deep learning: real- time operation in Tromsø, Norway, Sci. Rep., 12, 8038, https://doi.org/10.1038/s41598-022-11686-8, 2022.

Sigernes, F., Syrjäsuo, M., Lybekk, B., Trondsen, E., Clausen, L., Kellinsalmi, M. Mattanen, J., Kauristie, K., Hall, C. and Johnsen, M. G.: The Boreal Aurora Camera Constellation (BACC) – Status 2023, http://kho.unis.no/doc/BACC.pdf, 2023.

Swedish Institute of Space Physics Kiruna Atmospheric and Geo- physical Observatory (IRF-KAGO): Geomagnetic field data, Swedish Institute of Space Physics Kiruna Atmospheric and Geophysical Observatory (IRF-KAGO) [data set], https://www. irf.se/maggraphs/iaga (last access: 11 April 2023), 2023

Yamauchi, M. and Brändström, U.: Auroral alert version 1.0: two-step automatic detection of

sudden aurora intensification from all-sky JPEG images, https://doi.org/10.5194/gi-12-71-2023, 2023.