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A comparison of channel-base currents and optical signals for rocket-triggered lightning strokes

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Abstract

A comparative analysis has been performed of the channel-base current and light waveforms for four rocket-triggered lightning strokes. It has been found that the current and light signals at the bottom of the channel exhibit a linear relationship (direct proportionality) in their rising portions. However, just after the peaks the linearity disappears, and the light signals usually decrease faster than the currents during the next several microseconds. Later, this trend is reversed and in some cases the light signals show another rising trend, even when the currents continue to decrease. The linear light/current relationship for the rising portions of the waveforms appears to be the same for different strokes. The findings support the idea of evaluating the variation of return stroke current along the lightning return stroke channel using light signals, provided that evaluation is limited to the rising portions of those signals and assuming that the light/current relationship observed at the bottom of the channel holds at other heights.

Keywords: Electrical discharge; Lightning; Return stroke; Electrical spark

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1. Introduction

Knowledge of the current distribution as a function of time along the return stroke channel is very important for lightning return stroke modeling (e.g., Thottappillil et al., 1997; Rakov and Uman, 1998). An inference from optical observations, as suggested by Jordan and Uman (1983), seems to be the only practical way to evaluate the current distribution along the channel. In order to perform such an evaluation, the relation between the current and the light intensity is needed. There are several publications addressing this relation (e.g., Flowers, 1943; Idone and Orville, 1985; Colvin et al., 1987; Gomes and Cooray, 1998). Generally, as the electrical discharge current increases, the emitted light signal also increases (Flowers, 1943). Idone and Orville (1985) found a strong correlation between lightning peak current and peak luminosity for the return strokes within each of two New Mexico rocket-triggered flashes they analyzed. However, Idone et al. found an apparent disparity between the rise-times of the two signals. Colvin et al. (1987) presented the light/current relation for laboratory discharges with peak currents of 50 kA and 100 kA and a rise-time of several hundred microseconds. A hysteresis-type relation between the current and light is shown in their Fig. 11. The light intensity follows the current only at the very initial stage of the signal. Gomes and Cooray (1998) investigated the light/current correlation for various laboratory spark discharges. They found a linear relationship not only between the current amplitude and the light amplitude but also between the current rise-time and light rise-time. Since some of these studies are for laboratory sparks, as opposed to lightning, and some of them lack convincing data, the relation between lightning return stroke current and its associated light intensity is in need of further research. In this paper, we examine the light/current correlation using the channel-base currents and optical signals generated very close to the current measurement point in rocket-triggered lightning strokes.

2. Instrumentation and data

All data reported here were obtained during the rocket-triggered lightning experiments conducted during summer 1997 at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida. Information on the ICLRT is found in papers by Uman et al. (1997) and Rakov et al. (1998). For the lightning current measurements, a 1.0-mΩ coaxial current measuring resistor (shunt) was used. The upper frequency response of the shunt was about 20 MHz. Output signals from the shunt were transmitted through a fiber optic link to a LcCroy 9400A digitizing oscilloscope operating at a 25-MHz sampling rate and with 8-bit amplitude resolution. The oscilloscope was set to record the current from about 400 A to 100 kA. For the optical measurements a digital optical imaging system ALPS (Automatic Lightning Progressing Feature Observation System) that was specifically designed for recording the luminous progression of lightning discharges was used (e.g., Wang et al., 1999a). The version of ALPS used in this study consists of a conventional camera lens, a photodiode array module, large dynamic range amplifiers, a multi-channel digitizer, and a personal computer system, and has been described in detail by Wang et al. (1999a). The photodiode array module was composed of

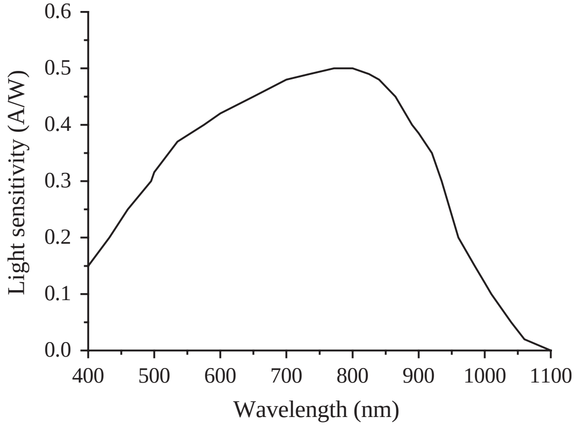

Fig. 1. Spectral response of the pin photodiodes used in the present study (from manufacturer's specification). The light sensitivity on the vertical axis was measured as the output current of the photodiode per watt of light input.

256 (16 × 16) pin photodiodes. Each of the photodiodes has a spectral response illustrated in Fig. 1 and a time response of less than 3 ns. The spectral response is more or less similar to that of the photodiodes previously used in lightning research by other researchers (e.g., Guo and Krider, 1982; Mach and Rust, 1989). The output from the photodiode is proportional to the instantaneous light input. The ALPS can operate at a time resolution (inter-frame interval) from 100 ns to 50 ms with either internal or external trigger and can record up to 16,000 frames for each event with up to 16,000 frames of pre-trigger. The inter-frame interval used in the present study was 100 ns, and thus the resulting total recording time per event was 1.6 ms. The ALPS was installed 250 m from the rocket launcher and viewed an effective area of 50 × 50 m^2 in a vertical plane just above the tip of a grounded metallic rod mounted on the rocket launcher, yielding a spatial resolution of about 3.6 m. ALPS data are typically used to analyze the propagation characteristics of lightning leaders and return strokes. Some results obtained using ALPS at the ICLRT have been previously published by Wang et al. (1999a,b). For the present study, the light signals from only the lowest channel section, having a length less than 3.6 m, were used for comparison with the corresponding current waveforms. This is the first measurement of the light signal generated very close to the current measurement point.

The current recording instrumentation and ALPS were triggered simultaneously when the channel-base current exceeded the preset threshold level of 1 kA. For precise

Table 1
Summary of the return stoke data used in the present study

No.	Date and time (UTC)	Return stroke peak current (kA)	10-to-90% current rise-time (μs)
1	19-Jun-97, 21:49:43	5.3	3.9
2	24-Jun-97, 19:30:09	12.2	0.8
3	26-Jun-97, 20:26:02	20.5	0.4
4	26-Jun-97, 20:37:07	12.0	0.9

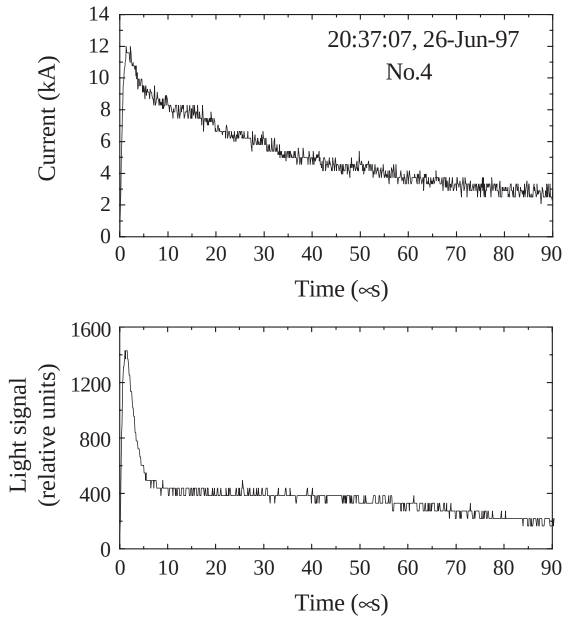

Fig. 2. Channel-base current and light waveforms of the return stroke in the flash triggered at 20:37:07, 6/26/1997 (event No. 4) at Camp Blanding, Florida.

comparison, the current and light signals are aligned using their peak derivatives and/or overall wave shapes.

Four triggered lightning strokes, listed in Table 1, were found to be suitable for the present study. These four strokes occurred in four different triggered flashes. All the flashes are typical of negative rocket-triggered lightning discharges that are characterized by an initial stage usually followed by one or more dart leader/return stroke sequences (Wang et al., 1999c). The strokes analyzed here are all the first strokes following the initial

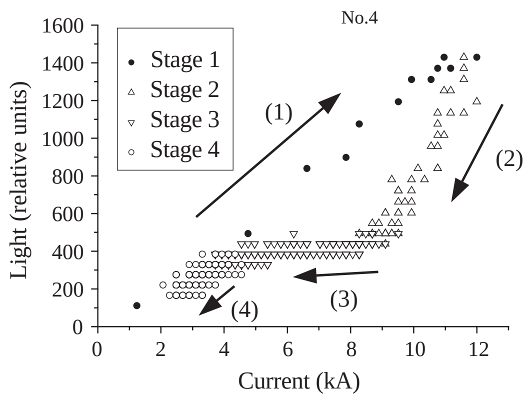

Fig. 3. Scatter plot of the current and light signals shown in Fig. 2. Four stages are labeled: (1) 0–1.3 μs, (2) 1.3–7.0 μs, (3) 7.0–55.0 μs, (4) > 55.0 μs.

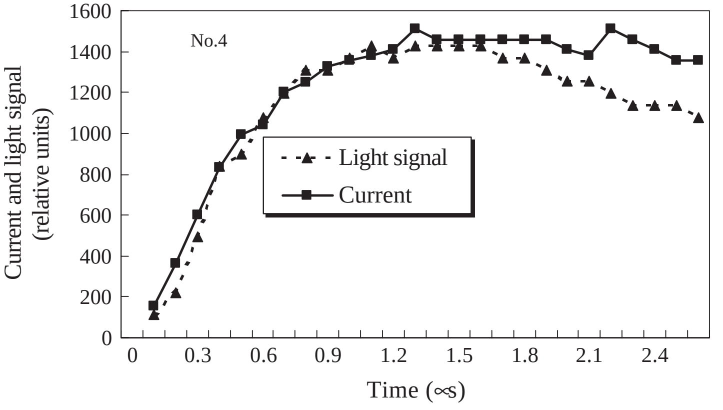

Fig. 4. Comparison between the current and light waveforms shown in Fig. 2 for the initial 2.7 μs.

stage. Their return stroke peak currents and current 10-to-90% rise-times are also included in Table 1. The four return strokes exhibit peak currents ranging from 5.3 to 20.5 kA and rise-times ranging from 0.4 to 3.9 μs. Among these four return strokes, strokes 2 and 3 have been previously examined in studying the lightning attachment process (Wang et al., 1999a).

3. Analysis and results

Fig. 2 shows the correlated channel-base current and nearly-channel-base light waveforms of the first (after the initial stage) return stroke in a flash triggered at 20:37:07, 6/26/1997. The time “0” on the horizontal axis corresponds the onset of the recorded electrical current and does not have any specific physical meaning. Fig. 3 presents the scatter plot of the current versus the light intensity in the event presented in Fig. 2. From these two figures, the relation between the current and the light can be divided into four stages. In stage 1 (from $t=0$ to $t=1.3$ μs), both the current and light

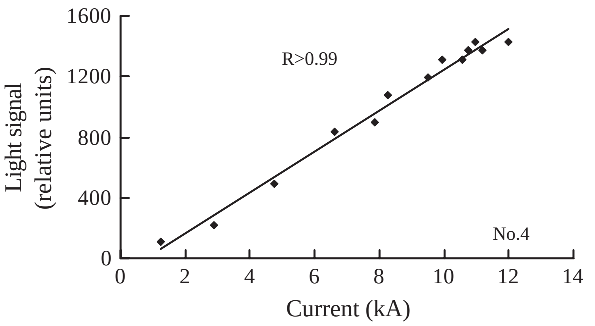

Fig. 5. Scatter plot of the current and light intensity for the rising portions of the waveforms shown in Fig. 4. Data points in this figure correspond to stage 1 of Fig. 3.

increase sharply, and they exhibit a strong linear relationship. The time-expanded waveforms for the initial 2.7 μs are shown in Fig. 4. In this figure, both the current and light signals are presented in arbitrary units such that their peaks are equal. As evident in Fig. 4, prior to the peaks that occur at 1.3 μs, the light signal follows the current very closely. The corresponding scatter plot and linear regression line are shown in Fig. 5. The correlation coefficient is greater than 0.99. In stage 2 (from $t=1.3$ μs to $t=7$ μs), both the current and light signals decrease, but the decrease in light signal is much more pronounced than the decrease in the current. In stage 3 (from $t=7$ μs to $t=55$ μs), the light signal remains at a more or less constant level, but the current exhibits a continuing

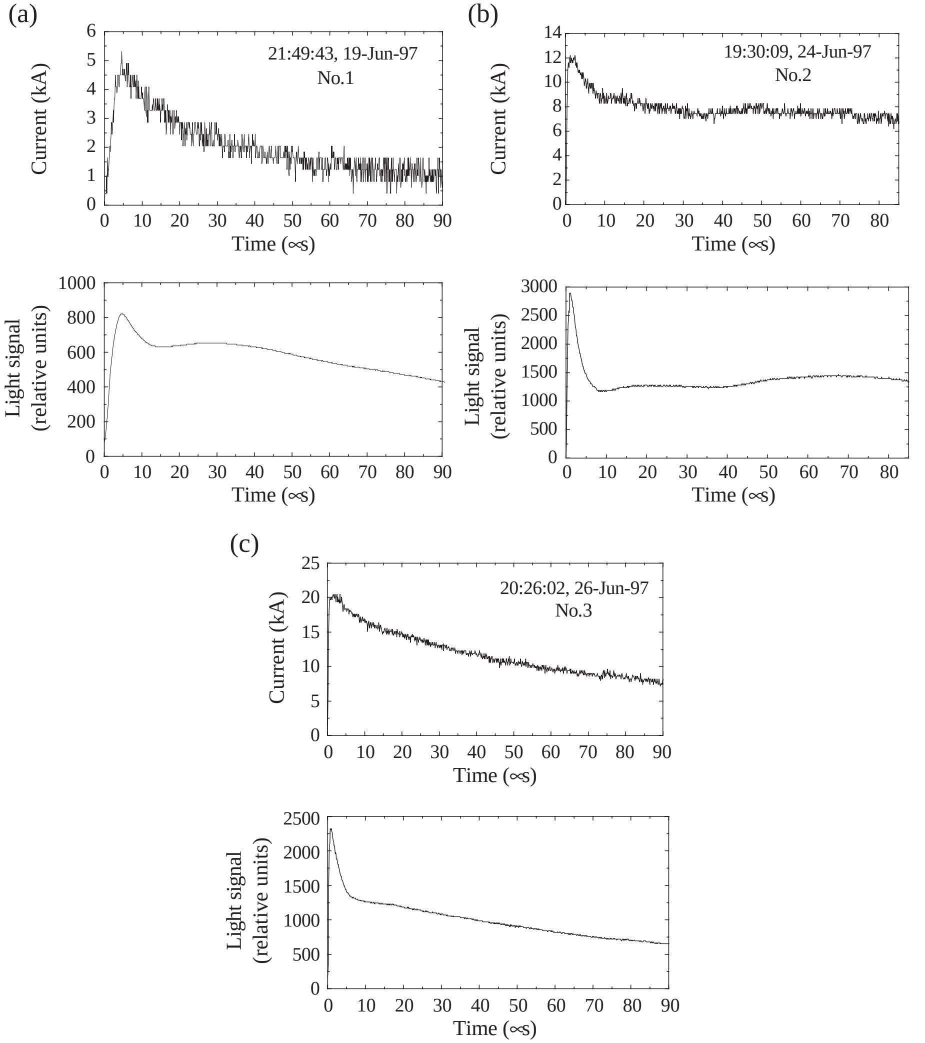

Fig. 6. Channel-base currents and light intensity of return strokes No. 1, No. 2, No. 3 listed in Table 1.

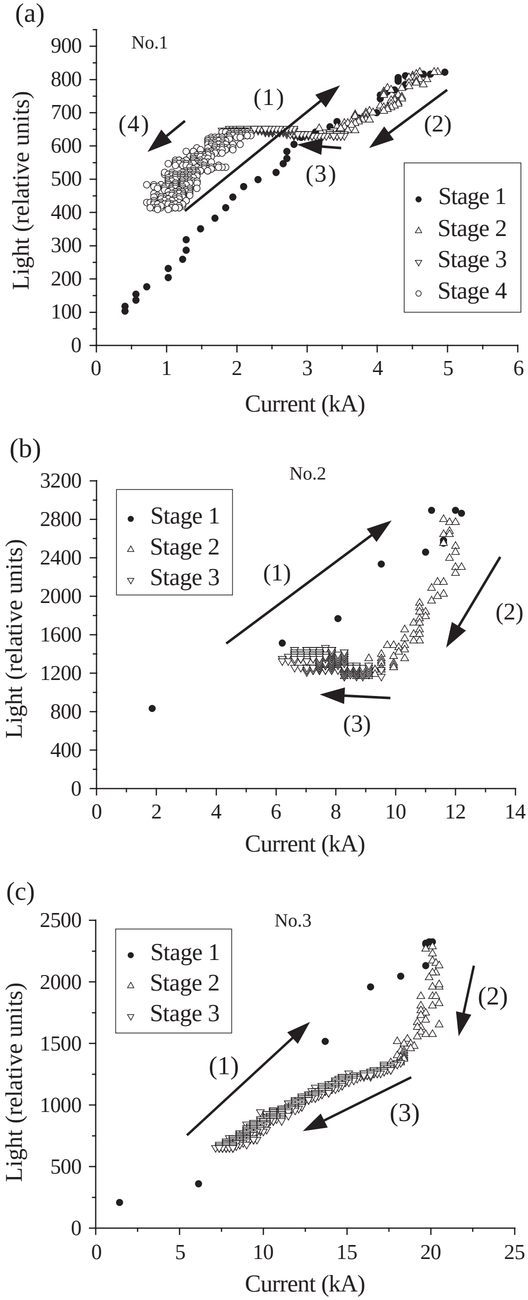

Fig. 7. Scatter plots for the channel-base current and light intensity shown in Fig. 6. In (a), four stages are labeled: (1) 0–4.6 μ s, (2) 4.6–12.0 μs, (3) 12.0–35.0 μs, (4) > 35.0 μs; in (b), three stages are labeled: (1) 0–1.2 μs, (2) 1.2–9.0 μs, (3) > 9.0 μs; in (c), three stages are labeled: (1) 0–1.0 μ s, (2) 1.0–6.0 μs, (3) > 6.0 μs.

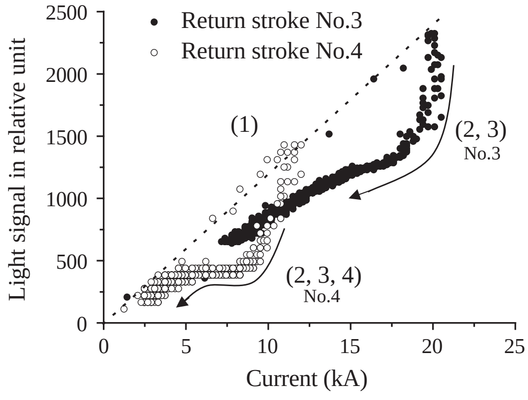

Fig. 8. Superimposed scatter plots for the channel-base current and light intensity for return strokes No. 3 (Fig. 6c) and No. 4 (Fig. 2).

decrease. In stage 4 (after $t = 55$ μs), both the current and the light signal show a relatively slow decay.

Fig. 6 presents the channel-base current and light waveforms of the other three return strokes listed in Table 1. The relative units in Fig. 6a, b and c are not necessarily the same since those three strokes were recorded under different visibility conditions and with different camera lens. Fig. 7 gives the corresponding scatter plots. As seen in Fig. 7, all the strokes show a linear relationship between the current and light intensity for the rising stages of the waveforms, up to the peaks, corresponding to stage 1 in Fig. 7. During stage 1, the correlation coefficients for those three stokes are, respectively, 0.99, 0.97, and 0.99. After the peaks, return strokes No. 2 and No. 3 show a decrease in light intensity similar to that described above. The light signal of return stroke No. 1, which is the weakest one among the four events listed in Table 1, exhibits a slower decrease than the other three events. This difference is also seen in the scatter plots of Fig. 7.

For return strokes No. 3 and No. 4, not only the optical recording system was set at the same sensitivity, but also their visibility conditions should be the same, since they were triggered in similar weather conditions within a time interval of only 11 min. This allows us to superimpose the current-light scatter plots for the two strokes, already presented in Figs. 3 and 7c, for their direct comparison. The result is shown in Fig. 8. During the rising stage of return stroke currents, the two return strokes follow the same linear trend (slanted dashed line in Fig. 8). During the falling stage, the trends differ (see (2, 3) for No. 3 and (2, 3, 4) for No. 4 in Fig. 8).

4. Discussion

A typical return stroke is initiated when a downward leader and its associated upward connecting leader connect. This process involves an intense ionization process that causes a rapid increase in channel conductivity and collapse of the longitudinal electric field. The resultant return stroke current wave propagates upward. The product of the channel current and the longitudinal electric field constitutes the electrical power input (per unit channel length). This input power heats the return stroke channel which expands rapidly. Through these processes, the input electrical power is converted to light radiation, other electromagnetic radiation, and acoustic shock wave. The issue of lightning energy balance remains the subject of debate (e.g., Rakov and Uman, 1998). It is expected that the higher-current strokes are associated with larger light output.

Our results indicate that for each individual return stroke, during the rising stage of the current and light, including their peaks, those two parameters show a linear relationship. Furthermore, the linear relationships found in the rising portions for different strokes appear to be the same. After the peaks, the relationship becomes more complex.

Return stroke light signals as a function of height are often used to infer the associated current variation (e.g., Jordan and Uman, 1983). Our results suggest that a direct inference is valid only during rising stages of the current and light waveforms.

Idone and Orville (1985) examined the correlation between peak light intensity (L_R) and peak current (I_R) for 39 subsequent return strokes in two New Mexico triggered lightning flashes. Significant correlation was found for the following pairs of parameters: L_R vs. I_R, log L_R vs. log I_R, log L_R vs. I_R, log L_R vs. I_R^2. If different return strokes do have a common linear relationship between their currents and light intensities, as shown in Fig. 8, the results reported by Idone and Orville (1985) are easily understood.

Gomes and Cooray (1998) investigated the light/current correlation for laboratory spark discharges that had various current rise-times (up to 16 μs) and current amplitudes (up to 3.5 kA). They found a linear relationship not only between the current amplitude and the light amplitude but also between the current rise-time and light rise-time. Our results obtained for triggered-lightning return strokes are surprisingly consistent with those reported by Gomes and Cooray.

Colvin et al. (1987) presented a hysteresis-type relation for the currents and light signals for laboratory discharges. Although our results also show some kind of hysteresis behavior, they apparently differ from their results in two respects. First, the light signal in their experiments follows the current waveform only at the very initial stage as opposed to the whole rising stage in our study. Second, the hysteresis curves presented by Colvin et al. (1987) do not have any tendency of crossing between the rising and decaying stages. In our data, all the hysteresis curves show a tendency to cross. This implies that the lightning light signal tends to last longer than its corresponding current. Note that the current rise-times in the experiments by Colvin et al. (1987) are several hundred microseconds, much longer than those observed for lightning return stroke. This may be the primary reason for the disparities between the results obtained by Colvin et al. (1987) and those presented here.

After the peak, the return stroke light signal usually decreases faster than the current during several microseconds. It is likely that the light waveform is more closely related to the power waveform, which is narrower than the current waveform (see, for example, Figs. 6 and 7 of Rakov and Uman, 1998, and Uman et al., 1968). The power waveform exhibits a faster decay due to the collapse of the longitudinal electric field (Miki et al., 2002).

It should be pointed out that, since the sample size is relatively small (only four strokes), the results reported here are in need of verification with additional experimental data. Further, from the physics viewpoint, one might ask (1) why the light intensity of a return stroke should be proportional to its current prior to their peak values, (2) why different return strokes exhibit a common linear light/current relationship. To answer such questions, additional information, such as the longitudinal electric field, temperature, and radius of the lightning return stroke channel as a function of time, is probably needed.

5. Conclusion

We have compared channel-base current waveforms and light waveforms near the channel base for rocket-triggered lightning return strokes. It has been found that the current and light signals at the bottom of the channel exhibit a linear relationship during the entire rising stage, up to the peak value. The linear relationship found in the rising portions for different strokes appears to be the same. The findings support the idea of evaluating the variation of return stroke current as a function of channel height from the variation of light signals, provided that evaluation is limited to the rising portion of the waveforms. During several microseconds after the current and light peaks, the light intensity usually decreases faster than the current. Later, this trend is reversed and, in some cases, the light signal shows another rising trend even as the current keeps decreasing.

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