Statistical Properties of Electric Fields Produced by Cloud-to-Ground Lightning Return Strokes

Bok-Hee Lee, Dong-Moon Lee, Seung-Chil Lee and Chang-Hwan Ahn

Abstract - For the past five years, Inha University has been observing the electric fields produced by cloud-to-ground return strokes. This paper presents the summary of most recent results. Statistics on the zero-to-peak rise time, the zero-to-zero crossing time and the amplitude ratio of the second peak in the opposite polarity to the first peak were examined. The radiation electric fields produced by distant cloud-to-ground return strokes were substantially same pattern. The first return stroke field starts with a slowly increasing front and rises abruptly to peak. The rising portions of the electric fields produced by cloud-to-ground return strokes last 1 μs to a few μs. The mean values of the zero-to-peak rise times of electric fields were 5.72 μs and 4.12 μs for the positive and the negative cloud-to-ground return strokes, respectively. The mean of the zero-to-zero crossing time for the positive return strokes was 29.48 μs compared with 38.54 μs for the negative return strokes. The depths of the dip after the peak of return stroke electric fields also have the dependence on the polarity of cloud-to-ground return strokes, and the mean values for the positive and negative cloud-to-ground return strokes were 33.55 and 28.19 %, respectively.

Keywords - Radiation electric field, Cloud-to-ground return strokes, Electric field waveform, Field parameter, Bipolar pulse, Stepped leader, Statistical properties

1. Introduction

As a lightning is well known to be electrical phenomena in the atmosphere, it is quite natural to try to observe the phenomena through the measurement of electromagnetic fields. In particular, measurements of the electric field have been the subjects of numerous works dating from the earliest days of lightning researches to the present. Also the return stroke electric fields contain information on the types of lightning and the magnitude of lightning currents. Some of the more important data providing information about lightning physics have been reported in the literatures[1 ~ 3].

The cloud-to-ground lightning return strokes have been studied extensively, but many questions remain because of the varieties and dependences of thunderstorm conditions on season, latitude, and other geographical factors. A wide-band data recording system is employed to analyze the time-domain characteristics of the electric fields. Several works have presented the statistics on the wave front and the wave tail in various countries[4-7]. However the data of the electromagnetic field associated with lightning discharges are not to be obtained in Korea.

In order to develop the design rule of improved lightning protection systems, it is a great of practical value to investigate the characteristics of electric field waveform produced by cloud-to-ground lightning return strokes. The goal of this work is the determination of the parameters of electric field waveform associated with cloud-to-ground return strokes in Korea. The transient electric field measuring systems was fabricated. Statistical characteristics of the rise time of electric fields, the distribution of zero-to-zero crossing time as well as physical properties associated with cloud-to-ground return strokes are presented. All data described here were recorded during the summers of 1996 and 2000 in and around Inchon.

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2. Experiments

To carry out the time-domain measurements of the electric fields produced by cloud-to-ground return strokes, the data recording system was made as shown in Fig. 1. A hemisphere sensor of 30cm in diameter installed at a height of 1 m from the ground was used to sense the electric field. The capacitance C can be used to control the magnitude of the measured voltage and the resistance R is to allow the input voltage of the amplifier to decay with a time constant RC. A voltage follower gives the buffering of the signal from the amplifier with output to the transient signal analyzer.

The electronic circuits were installed in the shield box at the base of the supporter to reduce the external electromagnetic noises. The measuring system was calibrated

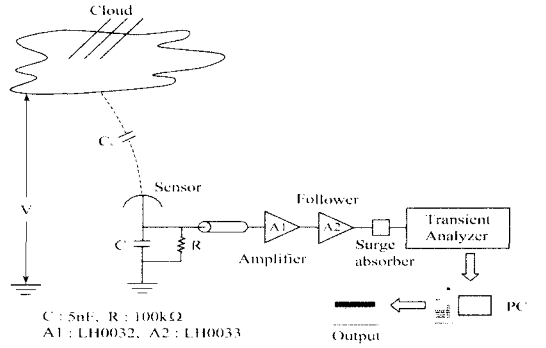


Fig. 1 Schematic diagram of the electric field measuring system.

by placing the sensor beneath a 2- by 2 m horizontal plate to which a step voltage was applied. The frequency bandwidth of the electric field measuring system is in the range of 200Hz ~ 1.56MHz and the sensitivity is 0.96mV/V/m[4]. The transient signal analyzer has the vertical resolution of 12 bit and the memory capacity of 512 kbytes per event, and the sampling time can be adjusted in the range of 100μs ~ 500μs. The transient signal analyzer was triggered by the induced electric field signal from cloud-to-ground return strokes, and it was operated in the pretrigger mode so that the electric field signals before and after the trigger pulse can be displayed.

The electric field signal was digitized every 200μs and was registered at the personal computer. This transient data recording system was stable for several years of continuous measurement. The measuring system detects the lightning activities in real-time and discriminates the features and parameters of electric field waveform associated with lightning discharges.

3. Results and Discussion

Thunderclouds are formed in an atmosphere containing cold, dense air aloft, and warm, moist air at lower levels. Cloud-to-ground return stroke occurs when some region of the atmosphere attains an electric charge significantly large that the electric field due to the charge causes electrical breakdown of the air. The average propagation velocity of streamer and stepped leader in air is approximately 107 ~ 108 cm/sec, and the electromagnetic waves corresponding to movement of electric charge or flowing current in air are radiated. Generally, the electric and magnetic fields associated with cloud-to-ground return strokes are analyzed by a model of vertical straight channel above a perfectly conducting ground. When a high current is flowing in air, the electric field can be calculated approximately by numerous current dipoles. The vertical component of the electric field due to a short current dipole Idl at the point of horizontal distance r in MKSA system of units is expressed by [8]

$$E = 30[Idl]\left(\frac{c}{j\omega c r^3} + \frac{1}{r^2} + \frac{j\omega}{cr}\right) \qquad (1)$$

where $[Idl] = I_0 e^{(j\omega - \frac{r}{c})} dl$ = retarded current dipole
ω = radiation frequency
c = velocity of light(3×10^8 m/s)
dl = length of dipole

The first term on the right-hand side of Eq. (1) is the electrostatic field, the second the induction field, and the third the radiation field. As described in Eq. (1), the electric field waveform produced by cloud-to-ground return strokes depends on the distance between the lightning strike point and the observatory station. The electric field associated with a close cloud-to-ground return stroke mainly presents electrostatic plus induction terms, and the dependence of the electric field on the distance from lightning strike point to measuring site is very ambiguous. Until now there is no statistical data of the electric fields for the close cloud-to-ground return strokes.

Fig. 2 illustrates a comparison between the typical electric fields caused by both the positive and the negative downward cloud-to-ground lightning discharges. It has been found by the measurement that the fine-weather electric field vector above the ground is directed toward the center of the earth. Conventionally an electric field at the ground is defined as positive if it is due to positive charge above ground level.

A cloud-to-ground return stroke bringing to the positive charges to the ground is denoted a positive return stroke. Thus a positive return stroke will produce a negative electric field which results from cloud-to-ground return strokes that lowers positive charge to ground. When the distance from lightning stroke point to observation station is more than 50km, the electric field waveform would appear to be due almost entirely to the radiation field term and exhibit bipolar aspect and zero crossing point[7]. With this distance of propagation, the waveform distortion does not much influence on the rise time of a return stroke electric field waveform. The electric field waveform for distant cloud-to-ground lightning discharges is characterized by slow fronts, fast transitions, subsequent peaks and overshoots in the opposite polarity as shown in Fig. 2.

Also the electric field of the positive cloud-to-ground return strokes from a long distance is very similar in most respects, except polarity, to waveform of the negative. Return stroke electric fields begin with a relatively slow front that rises in 2 to 10 μs to about half of the peak field amplitude.

The wave front is followed by a fast transition that corresponds to change of lightning current. The origin of the slow front differs from that of the fast transition. The

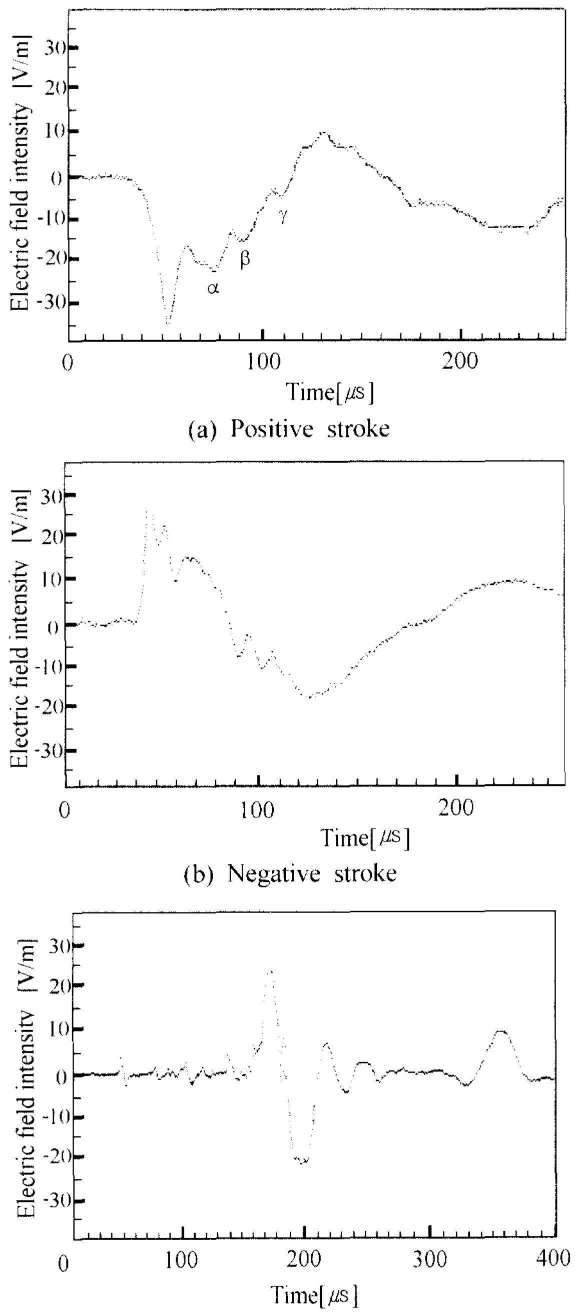


Fig. 2 Typical electric fields produced by (a) positive and (b) negative cloud-to-ground return strokes and (c) cloud lightning discharge.

slow front might be produced by the creation of a discharge ascending to connect the final stepped leader and the fast transition is due to a step-like breakdown current, respectively. The characteristic of wave tail strongly depends on the distance from the cloud-to-ground return stroke point to the measuring point. Return stroke fields exhibits some subsequent peaks (labeled α, β, γ in Fig.2(a)), with amplitudes which are a small fraction of the initial peak and which decrease with time. Unfortunately, the origin of the subsequent peaks is still not clearly understood. However, Weidman and Krider have suggested that the subsequent peaks in first return strokes are probably produced by the effects of branch channels[9]. The reversal of the electric field is probably occurred by ① the lowering of available charge from the cloud through the return stroke channel to ground and/or ② the flow of charge residing in the air around the channel into the channel and subsequently to ground[10].

The electric field waveform shown in Fig.2(c), which is the radiation field pulse produced by a cloud lightning discharge processes, is significantly different from that produced by cloud-to-ground return strokes. The electric field waveform tends to be large bipolar, and several pulses prior to the cloud lightning discharge, which are probably caused by the creation of discharge channel in some stepwise leader development, are occurred at random time intervals. The large bipolar component perhaps should be associated with the very active portion of the discharge, and it is due to a slower current pulse flowing in the channel established by the leader steps [11,12].

It is very useful to statistically analyze the electric fields produced by cloud-to-ground lightning return strokes since those involve information about the structure of a discharge channel and lightning current as a radiation source. Also, the errors introduced in statistical analyses are probably acceptably low. The electric fields, which are changeable on the distance from lightning stroke point to detecting point, are characterized by parameters such as the rise time, the zero-crossing time and the overshoot in the opposite direction, and so on. Three parameters characterizing the structure of electric fields from cloud-to-ground return strokes were statistically examined. The parameters of electric fields are closely related to the structure of a discharge channel. Fig.3 shows the definition of the electric field parameters such as the zero-to-peak rise (T_r), the zero-to-zero crossing time (T_z) and the depth of the dip after zero-crossing (D_p).

Although there is uncertainty in determining the beginning point of the electric fields, the zero-to-peak rise time is useful in describing the nature of the electromagnetic field wave front, and it becomes longer by propagation over the ground of finite conductivity[11]. The data for the zero-to-peak rise time of the electric fields produced by cloud-to-ground return strokes is a critical parameter in the area of analysis of physical properties associated with lightning phenomena. Also in the view of engineering issue, the rise time is significant factor in design of lightning surge protective devices because it is directly influenced on the response characteristics of lightning protection devices against fast transient overvoltages.

The distributions of the zero-to-peak rise time in the electric fields radiated from cloud-to-ground return strokes

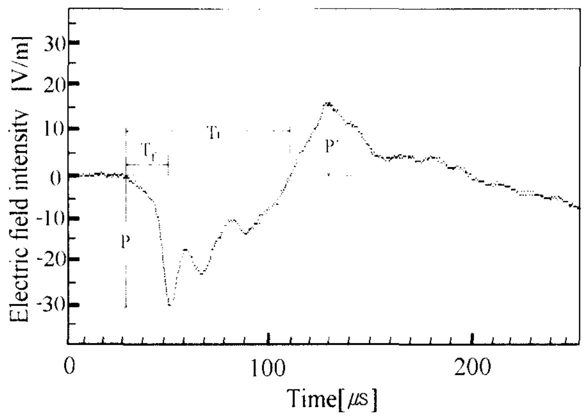
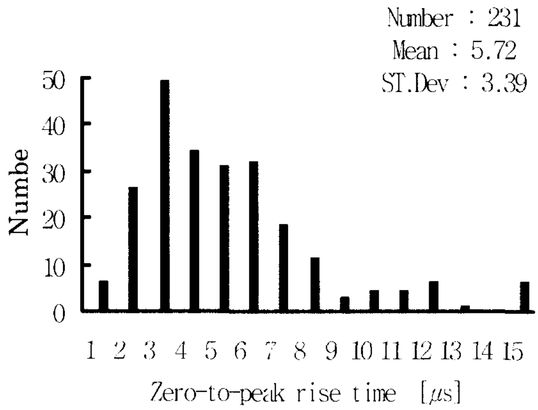
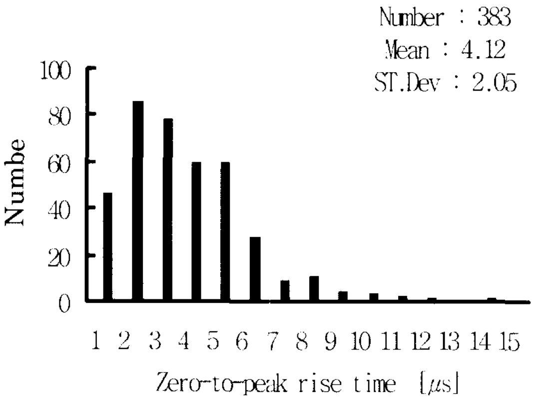


Fig. 3 Definition of parameters of the electric fields radiated from cloud-to-ground lightning return strokes.



(a) Positive



(b) Negative

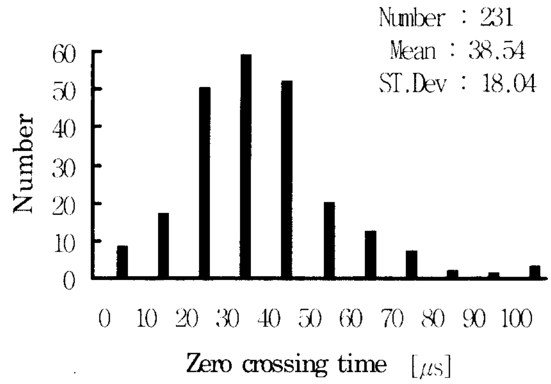
Fig. 4 Distributions of the zero-to-peak rise time of (a) positive and (b) negative electric fields.

were shown in Fig. 4, in the case of the positive cloud-to-ground return strokes the frequency of occurrence is relatively low. The occurrence number of the negative cloud-to-ground lightning return strokes in summer in Korea is much more than that of the positive. The front portion of the electric field waveform is constituted of the slow part produced by attachment of preliminary breakdown leader and the fast portion just before the peak value. The zero-to-peak rise time is substantially determined with the slow front followed by an abrupt transition, because the deviation of the fast transition portion is less than 1 μs. Therefore the nature of the zero-to-peak rise time is characterized by the attachment process of cloud-to-ground return strokes, and the dispersion of the rise time originates from discharge process of the preceding leaders.

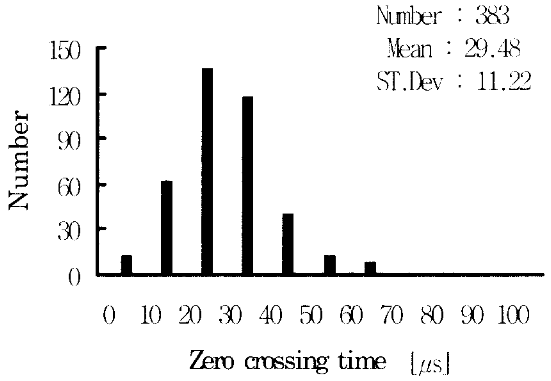
The number of data analyzed in this paper does not present the total frequency of occurrences of cloud-to-ground lightning return strokes. Data which had serious noise or which were illegible were excluded. only the 614 fine data of the electric fields (the positive: 231, the negative: 383) were analyzed in this statistics. Thus it is unable to estimate the ratio of occurrences of the positive and negative lightning return strokes. The mean value of the zero-to-peak rise time for the positive electric fields is 5.72 μs and the standard deviation is 3.39 μs. The mean value of the zero-to-peak rise time for the negative is 4.12 μs, and the standard deviation is 2.05 μs. Most of the zero-to-peak rise times for the positive and the negative cloud-to-ground return strokes are highly concentrated in the time range of 2～7 μs. The 4.12 μs mean value of the zero-to-peak rise time for the negative electric fields is approximately equal to the reported total duration of the slow front for the negative first return strokes of 4.0μs mean in North America[9].

The mean value of the zero-to-peak rise time of the positive cloud-to-ground return strokes are approximately 36% longer than that of the negative. Remarkable difference from the previous work of the author is not seen for the data in Japan[13]. Accordingly, it was known that the progress of the positive cloud-to-ground return strokes is slower than that of the negative lightning return strokes. At laboratory long air sparks, the negative leader always propagates stepwise extensions. However the positive leader may propagate continuously or stepwise and can bridge the 50 to 60% of gap separation and the transition between streamer corona and leader is very unstable in the positive polarity. The standard deviation divided by the mean is larger for the positive zero-to-peak rise times than for the negative, which implies that the positive cloud-to-ground return strokes are more irregular. Also the positive cloud-to-ground return strokes often give continuing currents of greater than 10 kA, an order of amplitude larger than for the negative. Therefore the electric field changes are sustained by continuing currents in the positive cloud-to-ground lightning return strokes.

The zero-to-zero crossing time (T_z) is the time interval between the beginning point of the electric fields and the crossing point to zero after the first peak, and it is essential to evaluate the energy quantity transmitted by lightning discharges to ground in relation to the duration of lightning return strokes. Also it has a strong depen-



(a) Positive

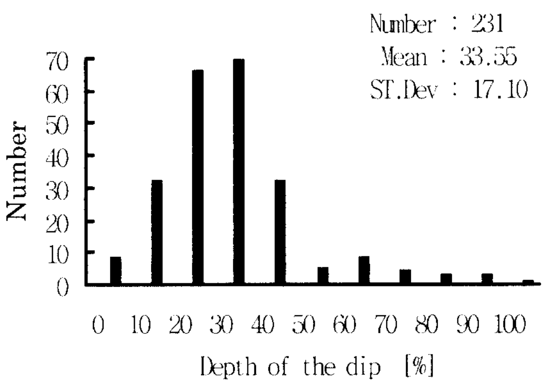


(b) Negative

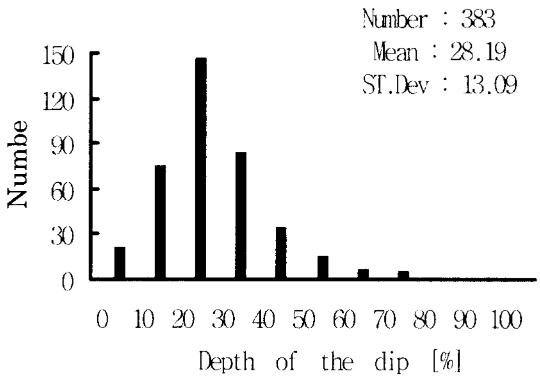
Fig. 5 Histograms of the zero-to-zero crossing time of (a) positive and (b) negative electric fields.

dence of the distance from the lightning stroke point to observatory site. The distributions of the zero-to-zero crossing time for the positive and the negative cloud-to-ground return strokes are summarized in Fig. 5.

The positive electric fields show longer zero-crossing times than the negative electric fields and larger dispersions in the distributions. The mean value of the zero-to-zero crossing time in the positive return stroke fields is 38.54 μs and the standard deviation is 18.04 μs. On the other hand, the mean zero-to-zero crossing time in the negative return stroke fields is 29.48 μs and the standard deviation is 11.22μs.



(a) Positive



(b) Negative

Fig. 6 Histograms of the depth of the dip in the electric fields of (a) positive and (b) negative cloud-to-ground return strokes.

The zero-to-zero crossing time for the positive electric fields is much longer and wider than that for the negative in the histograms. The positive return stroke field waveform is apparently more often followed by a field change indicative of continuing current than is the negative return stroke electric fields[14]. The positive continuing currents are also significantly larger than the ones produced by the negative return strokes. The difference might be caused by large continuing current with long duration in the positive cloud-to-ground return strokes. Also the zero-to-zero crossing times of the electric fields for both the positive and the negative polarities are symmetrically distributed before and after the mean value. The mean values of the zero-to-zero crossing times of the electric field waveform obtained in this work are slightly shorter than other researcher's data[15]. It was inferred that the difference might be caused by the following factors such as the measurement device characteristics, the distance from the return stroke point to the observatory site, the geographical condition, regional and seasonal effects, and so on.

The depth of the dip of the electric fields, which presents the ratio of the second peak value in the opposite polarity to the first peak value, shows the characteristics of the wave tail. The depth of the dip for the cloud-to-ground return strokes from long distance is deeper than that from close distance, because it is appreciably dependent on the distance from the lightning stroke point to the measuring point.

Fig. 6 illustrates the depths of the dip for the positive and the negative electric fields produced by cloud-to-ground return strokes. The depth of the dip is normalized by the electric field amplitude at the first peak. The depths of the dip for the positive and the negative electric field waveform are substantially distributed between 10 and 40 %. The mean depth of the dip for the positive electric fields is 33.55 % and the standard deviation is 17.10 %. Also, the mean depth of the dip for the negative polarity is 28.19 % and the standard deviation is 13.09 %. The depth of the dip for more than 90 % of the electric fields, which were observed from the negative return strokes in spring and summer in North America, was about 30 %, and the rest were about 60 % [15,16].

4. Conclusion

The electric fields radiated from cloud-to-ground lightning return strokes were measured, and their parameters and characteristics were statistically analyzed. The wave front of the radiation fields consists of a gently increasing slow front and an abruptly increasing fast front resulting in peaks. Several subsequent peaks following the first peak are superimposed by the effects of branch channels. The positive depths of the dip after the peak of return stroke fields are deeper than the negative depths of the dip. A dependence on the polarity of cloud-to-ground return stroke fields is pronounced. The mean values of all parameters for the positive cloud-to-ground return strokes are longer or larger than those for the negative. Also th e standard deviations of all field parameters described here are generally larger for the positive electric field waveform than for the negative. It can be concluded from these results that the positive cloud-to-ground return strokes is much more irregular compared to the negative. The rise time and the zero crossing time are very useful data in determination of the response time and the energy capacity on lightning arresters, protection facilities, respectively.

Acknowledgment

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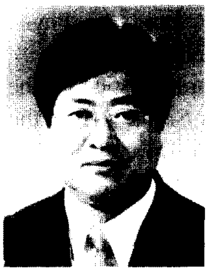

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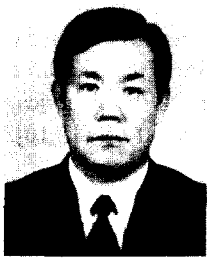

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