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Impact study of the “Millau Bridge” on the local lightning occurence

Stéphane Pédeboy
Météorage
Pau, France
sp@meteorage.com

Mehdi Toullec
Météorage
Pau, France
mt@meteorage.com

***Abstract*— It is well known that lightning flashes preferably strike tall objects because they considerably enhance the local electric field favoring the attraction and the connection of downward leaders leading to return strokes. Depending on its total height, a given structure may not only attract but also trigger upward lightning. Based on lightning data collected by Météorage, the French national operator, a study was made on a 20-year period in the vicinity of one of the tallest structure ever built in France, the “Millau Bridge”, to analyze its effective impact on the local lightning activity. The result clearly showed a local enhancement of lightning occurrence since 2005 after the bridge has been terminated, mainly due to the 90m masts supporting the road deck but not directly due to the height of the piers themselves. Interestingly, because of the high lightning location accuracy of the French Lightning Detection System, it was possible to demonstrate that the most central masts are concerned by the lightning occurrence enhancement possibly because they are free from the natural protection offered by the surrounding elevated terrain. Finally, a detailed review of individual flashes striking the bridge showed that 45% to 60% of the total flashes are upward lightning flashes, as expected because of the height of the bridge, with no particular seasonal effect.**

Keywords—Upward lightning; Tall objects; Lightning density; Lightning Locating System (LLS);

I. INTRODUCTION

Lightning usually strike grounded tallest objects because they tend to considerably enhance the local vertical electric field because of their elongated shape. The sharper and longer the object the stronger the electric field at its extremity. This effect, that is at the basis of the theory of operation for lightning rods, favors the appearance of an upward connecting leader at the tip of the object. As the latter is closer to the cloud than other connecting leaders starting at the ground level it increases the chance of interception and connection with a downward leader leading to a huge lightning current discharge between the cloud and the ground, namely “the return stroke”. However, some studies have shown that objects exhibiting a height equal to or greater than 100 m are likely not only to attract downward initiated discharges but to also trigger upward flashes [1]. Interestingly, when such objects are located on the top of a mountain, the resulting electric field enhancement benefits also form the presence of the elevated terrain. Based on this phenomenon, several research experiments aiming at studying the physic of lightning, are using instrumented towers on top of mountains across the world to increase the chances a return stroke produces and expand this way the number of measurements dataset [2][3][4]. On another hand, this effect is also a big concern in term of lightning protection since a man-made tall building may considerably increase the local lightning risk.

Using remote sensing techniques, Lightning Locating System (LLS) can monitor the lightning activity occurring over large areas [5]. Based on the detection of lightning-related radiated electromagnetic fields in the VLF/LF frequency range they provide accurate data on both Cloud-to-Ground (CG) return strokes or Intra-Cloud (IC) discharges. Depending on applications it is possible to analyze a particular lightning flash or make statistics. Based on Météorage’s lightning dataset, this study aimed at evaluating the real impact a tall object can produce on its local lightning environment. The choice was made to consider the vicinity of the “Millau Bridge”, one of the tallest man-made object ever constructed in France, that is culminating at 343m above the ground level. At first, the evolution of the local lightning density is analyzed before the construction, during the works and after the bridge has been put in operation in order to check the potential impact on lightning occurrences introduced by the bridge itself. Secondly, a detailed analysis of the flashes occurring in the very close vicinity of the bridge is carried out in order to detect upward lightning signatures from the stroke data collected by Météorage.

II. INTRODUCTION TO THE “MILLAU BRIDGE”

The “Millau Bridge”, also called “The Millau Viaduct”, was designed by Michel Virlogeux, a French structural engineer and Norman Foster, a British architect. This cable-stayed bridge is the tallest bridge ever constructed in the world. It spans the valley of the River Tarn near Millau in southern France and is a part of the A75-A71 highway that links Paris to Béziers and Montpellier (fig. 1). An interesting comparison with the Eiffel Tower allows to see the real height of the viaduct.

Figure 1 – Drawing showing a general overview of the bridge with corresponding dimensions (http://www.animatif.com/)

The works started on the 16th of October 2001 for a four-years construction period. The bridge was formally inaugurated on the 14th of December 2004, and opened to traffic on the 16th of December. It is made of seven piers supporting the road deck linking the two slopes of the valley. One 87m mast is installed on every pier to support the deck thanks to eleven pairs of steel cables themselves formed of one central strand with six intertwined strands. Each strand is protected against corrosion and the external envelope is itself coated along its entire length with a double helical weather-strip.

Table 1 - Individual height of the seven piers in respect to the ground level.

Heights of the piers

P1	P2	P3	P4	P5	P6	P7
94.501 m (310 ft 0.5 in)	244.96 m (803 ft 8 in)	221.05 m (725 ft 3 in)	144.21 m (473 ft 2 in)	136.42 m (447 ft 7 in)	111.94 m (367 ft 3 in)	77.56 m (254 ft 6 in)

With such a height, the Millau Bridge is expected to highly interact with nearby thunderstorms. During the works, Eiffage subscribed to the "Lightning Warning Service" provided by Météorage to protect workers. A very nice example of such interaction between the bridge and a thunderstorm is shown on the photo in figure 2 where it can be seen lightning discharges attaching the tip of every seven masts. Actually, they all are upward lightning initiated by a strong positive CG flash exhibiting a peak current greater than 100 kA appearing in the background and triggered by every masts.

Figure 2 – Nice photography showing upward ligning flashes on August 2013 ©Bruno Auroy

Of course, it is very likely such lightning flashes would not produce without the Millau Bridge. Consequently, this photography perfectly introduces the purpose of this study and illustrates the problematics related to tall objects and their impact on the local lightning activity and their capability to trigger upward lightning.

III. MÉTÉORAGE'S LIGHTNING DATA

Météorage has being operating the French national LLS since 1986 consisting in a network of 19 VLF/LF sensors dispatched across France and interconnected with compatible foreign sensors. This results in a better coverage of the system at the borders and guaranty homogeneous performances on all the territory. The Météorage' system locates CG flashes and subsequent strokes and a good fraction of IC discharges [6]. A recent study, not yet published, based on electric fields and high speed video camera records showed the flash and stroke detection efficiencies (DE_{Flash} and DE_{stroke}) are respectively 97% and 94% in 2015. This recent result in consistent with results from similar measurement campaigns aiming at determining DE_{stroke} and DE_{Flash} as it can be seen on table 2.

Table 2 – Evolution of the Météorage's LLS DE_{stroke} and DE_{Flash} over France

Year	Nb Flashes	DE_{Flash}	Nb Strokes	DE_{Stroke}	Location Accuracy
2015	**119**	**97%**	**245**	**94%**	**120 m (78)**
2014	264	96%	582	87%	280 m (127)
2013	151	95%	520	82%	120 m (144)

The relative location accuracy is estimated to be about a median value of 120m [2]. This parameter determines the dispersion error or the measurement repeatability achieved by the LLS when it locates strokes using pre-existing channels. The absolute location accuracy traduces the error distance between computed and the real stroke locations (see table 2). The overall performances of Météorage's LLS permit to rely on accurate lightning data and relevant observations for this study.

IV. METHOD

The first objective of this study aimed at demonstrating an increasing trend in lightning occurrence can be observed since the "Millau Viaduct" has started being constructed. Thus, three distinct periods were precisely chosen to compute the lightning stroke density corresponding to the times where a) the bridge was not yet constructed (this period being taken as a reference), b) the piers were being erected and c) the bridge was terminated and put in operation. It is expected the comparison of the lightning density on those different chronological periods will show a practical evidence of a lightning enhancement resulting from the presence of this tall object. The lightning stroke density was computed for each period on the same 200 x 200m cells grid encompassing the area of the bridge. Similarly, the same color scale ranging from 0 (white), meaning no data, to 10 (brown) meaning a high lightning density, was used on all analyzed periods. This allowed a straightforward temporal comparison facilitating the detection of an increasing trend. The small cells size has the advantage to spot accurately high density regions. The choice in using the stroke density instead of the traditional flash density was driven by the hypothesis that mostly upward lightning produced on the bridge. Such lightning often exhibits a lot of subsequent discharges that are likely to be detected as return strokes by the Météorage's LLS. As a result, it is preferable using stroke data to compute lightning density for this application.

The second objective is to review in details the stroke data collected on a 11-years period after the "Millau Bridge" was terminated in order to detect upward lightning signatures on the different masts sustaining the road deck. No VLF/LF system can discriminate the direction of propagation of a given discharge including the initiating stage of an upward initiated flash consisting of a self-propagating upward leader. However, this preliminary leader is generally followed by several discharges like either return strokes or M-components that might be detected by VLF/LF systems [8]. In some cases, a neighboring CG or IC flash can trigger the upward leader from a tall object. Recent studies mentioned a nearby strong +CG might change the electrical charges distribution in the cloud in the way favorable conditions are created to initiate an upward lightning by a tall grounded structure. Finally, the special design of the "Millau Bridge" is likely, as shown in figure 2, to trigger simultaneously several discharges. Therefore, according to these observations, the second part of this study relied on two different patterns to identify upward lightning signatures based a review of time consistent strokes occurring within some hundreds of milliseconds and at a maximum distance of 500m from a given mast. As the separation distances between the masts is about 350 (fig. 1) some strokes were likely to be affected to more than one mast. In this case, a stroke was considered to be related to the nearest mast that is an assumption consistent with the Météorage's LLS location accuracy. Then a group of consistent strokes was considered as being a part of an upward lightning flash when a +CG exhibiting a peak current equal or greater than +30 kA occurred at a maximum distance of 40 km in advance of few tenth of milliseconds in respect to the dating of the first stroke of the group. The groups not related to +CG flashes but exhibiting strokes hitting different masts with time intervals smaller than 10 milliseconds were also considered as upward lightning flashes.

V. Results

A. The lightning density before the Millau Bridge

From January 1995 to December 2001 the bridge was not yet built. The future location of the bridge can be estimated thanks to the road drawn in the background map that represents the current geography. As expected, the lightning density distribution is quite homogeneous and no particular enhancement in the area of concern (red rectangle) is visible. This result was expected as no tall object capable of enhancing the local electric field is present in this area yet. Because, of the high grid resolution and the relatively short period of data used in this analysis a lack of data can be noted in the no colored areas.

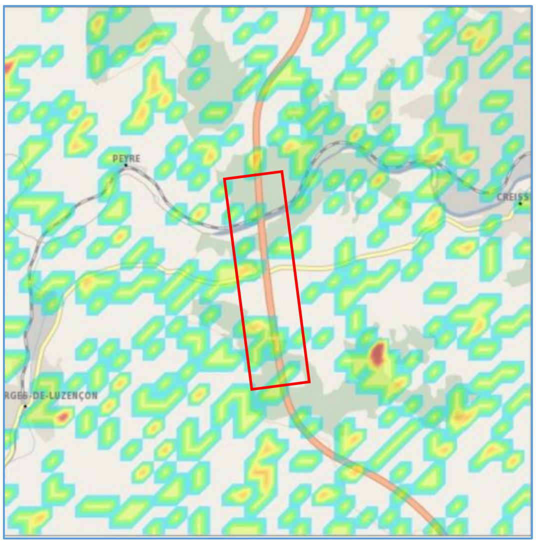

Figure 3 – Lightning stroke density before the works started (in red the area of concern)

B. The lightning density during the piers construction period

The map in figure 4 corresponds to the period between April 2002 and December 2003 when the piers were being constructed. A detailed analysis of the region along the road where the works are being done showed a possible lightning occurrence enhancement compared to the stroke density of the previous period when no works had started.

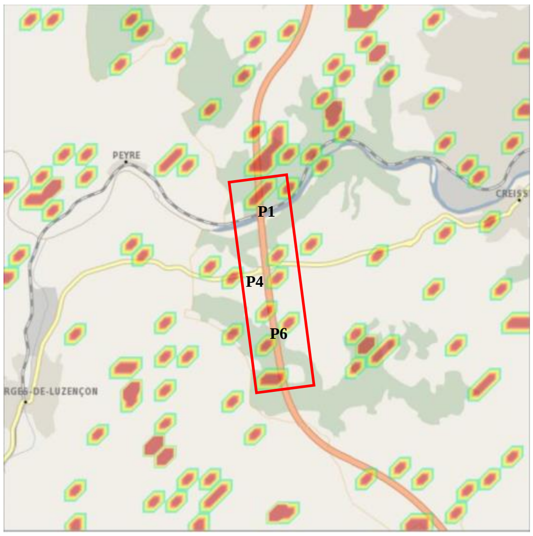

Figure 4 - Lightning stroke density when the piers were constructed

One can note on figure 4, very close to P1, P54 and P6 piers positions, lightning density spots related to the occurrence of at least one stroke. Such a little lightning enhancement could be either related to the piers themselves, according to their height, or to the presence of cranes used to carry up concrete and material for the construction. A detailed analysis of these individual strokes showed 3 strokes produced in 2002 out of which 2 during the same thunderstorm. In 2003, 6 one-stroke flashes were located close to a pier all of them occurring during different thunderstorms. Despite the detected lightning activity was weak during this period, possibly because of the lack of data due to the short period of analysis, one can consider an effect related to the works being done at that time. A review of the detected strokes showed no evidence of upward lightning signature on neither piers nor cranes tips.

C. The lightning density since the bridge is terminated

The third period being considered started in January 2005 after the bridge was constructed and fully operational to end on December 2015. The enhancement of lightning density is clearly visible on figure 5 where one can see three hot spot in particular along the road all related to a pier, and particularly in the vicinity of piers P4, P5 and P6. It can be noted on figure 5 two areas in south-west and north-west of the bridge where lightning density is high. These regions correspond to the elevated terrain overhanging the valley that is particularly exposed to lightning. This trend was less visible in figure 3 because the period of analysis is almost two times less in duration and so less lightning occurrences were detected.

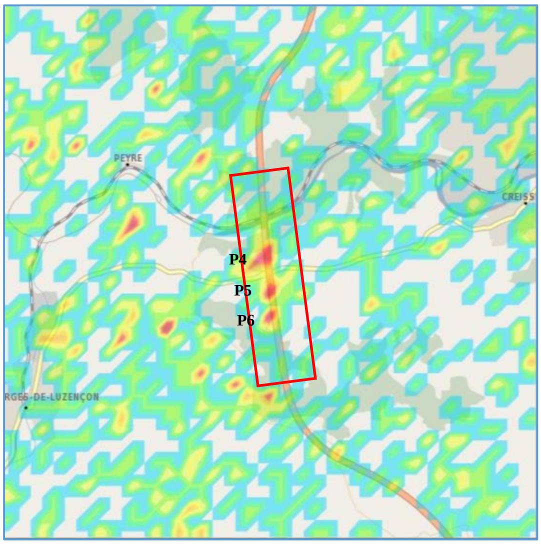

Figure 5 - Lightning stroke density after the works terminated

D. The upward lightning on the "Millau Bridge"

Between January 2005 and December 2015, 115 discharges composed of 92 CG strokes and 23 IC discharges, possibly misclassified by the system, were located close to the masts (<500m) of the "Millau Bridge". In some cases, M-components are discriminated as IC discharges by the Météorage's LLS because of their short duration, reason why IC data were taken into account in the analysis. From this dataset it was possible to identify 46 one-stroke flashes and 18 multi-stroke flashes out of which 55% struck at least two different masts, the remaining hitting one mast only. Interesting to note that P3, P4 and P5 represent about 84% of the stroke attachments.

All individual multi-stroke flashes were reviewed to determine whether or not it can be classified as an upward lightning based on the methods previously described (see chapter IV). This analysis showed that 10 of them were preceded by some tenth of milliseconds by an intense +CG, from 38 kA to 115 kA, at a distance ranging between 8 km and 40 km away from the bridge. This result confirmed the real nature of upward flashes for these flashes. In addition, two more flashes exhibited subsequent strokes striking at least two different masts within an inter-stroke delay shorter than 5 milliseconds. This means they triggered quasi simultaneously that is a typical signature of upward flashes generated by the "Millau Bridge". Therefore, a total of 12 upward flashes consisting of 69 individual discharges struck the "Millau Bridge" in a period of 11 years after its construction. The occurrence of upward flashes often happened several times during the same thunderstorms. As an example, on the 2014/11/28, a total of 5 upward flashes occurred on the same day out of which 2 of them produced in a delay of about 10 minutes. Finally, the time distribution of these upward lightning did not show any seasonal trend. About 7 of them (60%) produced during the period between June and early September, the remaining 5 occurring in November, the same day. However, the yearly distribution showed upward lightning were mostly observed between 2012 and 2015.

VI. Discussion

According to the results in figure 5, the enhancement of the lightning density in the vicinity of the "Millau Bridge" is clearly visible since the bridge has been terminated. The small location errors committed by the Météorage's LLS permitted to spot the positions of the masts labelled P4, P5 and P6 in particular. This is interesting to note these masts are not installed on the tallest piers (see table 1) tending to demonstrate the total height of the ensemble "pier-mast" produces no impact on the lightning enhancement. The very little increase noticed during the piers construction period seems to confirm this observation. Indeed, apart some -CG strokes striking either piers or cranes, no objective enhancement is visible during this period and particularly at the end when the piers were finished. Of course, the lack of evidence might also be related to the short period of the analysis.

However, according to the results from the most recent period, more important is the height of the masts and their relative position on the bridge. Indeed, the masts located at the entrances of the bridge are neither (P7) or less struck by lightning (P1 and P2) compared to the other masts in the middle of the bridge which are involved in most of strokes attachments (84%) each at an equivalent rate. The hilly terrain surrounding the bridge may reduce the effective height of P1, P2 and P7 and therefore mitigate the attractive effect of the nearby masts whereas those located in the middle of the bridge are free from this natural protection.

The detailed analysis of the characteristics of every individual flash located close to the bridge permitted to estimate 12 upward flashes, composed of 49 return stroke or IC discharges, were detected on one or several masts at a time. From this data set, 10 upward flashes were preceded by an intense +CG tending to demonstrate the situation represented by the photo in figure 2 is not a rare event, on the contrary as it can produce several times during the same thunderstorm in very short delays (5 to 10 minutes).

The patterns used to identify upward lightning may suffer from strong limitations that leads to some failure in flash classification. The presence of an intense +CG in tenth of millisecond in advance seems to be a good proxy that is well described in literature. The same remark for flashes exhibiting subsequent strokes on different masts quasi-simultaneously (less than 5 msec). This pattern is consistent with the particular structure of the "Millau Bridge" offering seven tall masts for simultaneous lightning attachments. However, 6 flashes were left out because they did not match with any of these patterns despite their strokes were all located on one mast making them serious candidates for upward lightning. Theoretically the one-stroke flashes might also be a part of upward lightning signature considering some subsequent strokes may have not been observed by the system because of the weakness of their electromagnetic radiation but this is less probable.

It is interesting to note the majority (83%) of upward flashes was detected since 2012. This could be due to natural effects but also to the improvement of the Météorage's LLS after an upgrade of the sensors and the lightning processor. A meteorological conditions review should help understanding whether this phenomenon is real or due to a lack of performances in lightning detection.

Finally, because of the limited patterns used to identify upward lightning signatures in conjunction to a potential lack of performance in lightning detection before 2012, the number of upward lightning flash occurrences computed in this study might be underestimated. However, with 52 strokes in 12 flashes the contribution of upward flashes initiated by the “Millau Bridge” is about 45% of all the local lightning activity. This figure rises to 60% when the 6 “left out” flashes are taken into account.

VII. CONCLUSION

This study aimed at demonstrating the impact of a tall object, namely the “Millau Bridge”, on the local lightning activity. Indeed, such a structure is likely to either attract downward or trigger upward lightning. The analysis of the stroke density before the bridge construction showed a visible enhancement of lightning activity after the construction. In particular, 3 central masts are mostly concern in the enhancement, probably because they are free from the natural protection of the surrounding hilly terrain. The analysis of the period when the piers were being constructed showed several lightning strokes occurred either on the piers or on the nearby cranes. An interesting result showed the height of the masts is mainly involved in the enhancement of the lightning density and particularly because the masts trigger upward discharges. However, no relation was found between a possible enhancement and the height of the piers.

A detailed review of individual flashes located on every masts of the bridge permitted to determine that at least 12 upward lightning flashes occurred during 2005 and 2015. Because of the limitations introduced in the patterns used to identify upward lightning signatures this latter result might be underestimated. However, the proportion of discharges triggered by the masts was estimated to range between 45% to 60% of all discharges. Interesting to note, no upward lightning flash was detected when the piers were being erected.

Further work must be carried out to improve the patterns of upward lightning signatures based on VLF/LF lightning data. In addition, a meteorological situation analysis should help understanding the mechanisms involved in the initiation of upward discharges in the “Millau Bridge” region.

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