CONTROLLING LIGHTNING WITH LASERS

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Lightning is one of nature's most extreme phenomena. As fascinating as it is destructive, it causes billions of euros worth of damage every year. The idea of using lasers to control lightning dates back to the 1970s, but it wasn't until 50 years later, with the European Laser Lightning Rod project, that it was demonstrated for the first time that powerful lasers could guide lightning over long distances.

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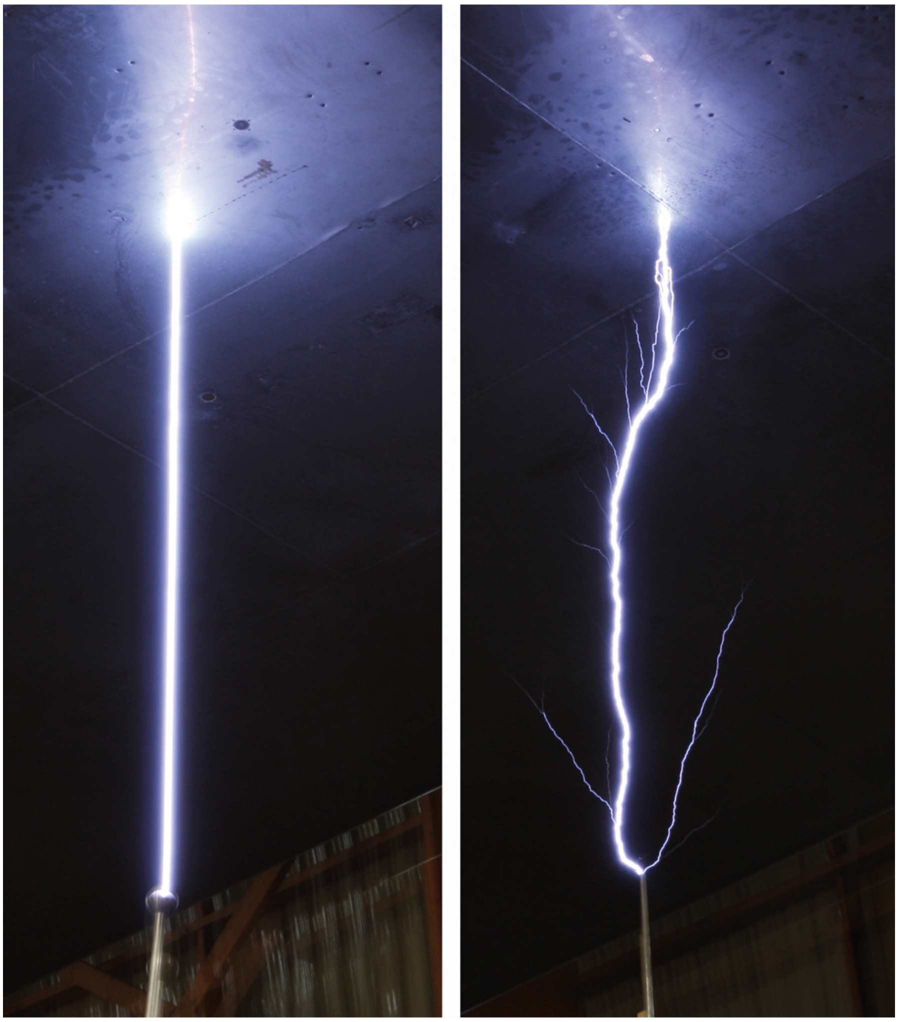
Every year, lightning is responsible for billions of euros in damage and over 20,000 deaths worldwide, triggering forest fires, power surges and disrupting air traffic at airports, since aircraft are highly vulnerable during take-off and landing.

Lightning occurs spontaneously in large cumulonimbus clouds when convection of water particles creates space charges, leading to an accumulation of electrons at the bottom of the cloud. This negative electric charge produces an electric field of the order of 50 kV/m, sufficient to initiate downward discharges towards the ground or, in some cases, even upward discharges from a tall tower or mountaintop. The main existing method of lightning protection is the lightning rod, invented by Benjamin Franklin in 1752. Consisting of a metal rod up to 100 m high, the lightning rod can protect a ground installation up to a radius of 30 m by attracting lightning discharges passing nearby.

To increase the range of action of the classical lightning rod, the idea of using a powerful laser was proposed by Ball *et al.* as early as 1974. Controlling an electrical discharge using light is a not trivial idea, as the speed of photons limits their interaction with the free electrons that form the discharge. To control the lightning flash, the laser has to modify the medium in which it propagates, *i.e.* the atmosphere. It can either ionize the air to make it conductive, simulating the effect of a metal lightning conductor that can attract discharges by bending the field potential, or it can create a preferential path for the discharge by heating the air. Both solutions rely on the laser's ability to ionize the air on its path over very long distances. The first experiments of this type were carried out in USA and Russia in the 1970s, using nanosecond pulsed lasers with an energy of several kilojoules. These high-energy lasers are capable of producing very dense but discontinuous plasmas channels, and the light energy required is very high (of the order of 600 J/m), which limits the length of the plasma column to a few meters. A first lightning guiding experiment was nevertheless carried out using this method in 1997 by

Uchida *et al.* in Fukui, Japan. The researchers twice observed a possible laser effect on lightning over a distance of 1 to 2 m, using a combination of several kilojoule nanosecond lasers focused above a tall metallic tower [1].
A major breakthrough came with the development of amplified femtosecond lasers [2]. When these ultrashort pulsed lasers are focused in the air, they generate very long and uniform plasma filaments that can reach hundreds of meters with relatively moderate laser energies. This process known as filamentation is due to a combination of Kerr self-focusing and plasma defocusing that saturate the laser intensity inside the filament. This discovery, at the end of the 90s, quickly triggered the launch of lightning control projects in Quebec with a project piloted by INRS and Hydroquebec, and in Europe with the Franco-German Teramobile project. Numerous laboratory studies were carried out with discharges of several meters produced by Marx generators (see example in Figure 1). In 2005, the first real-life campaign was organized in New Mexico by researchers from the Teramobile project [3]. The experiment consisted in producing plasma filaments at several hundred meters altitude using a TW laser operating at a repetition rate of 10 Hz. In the presence of thunderclouds, the laser was expected to guide or trigger lightning. Unfortunately, very few thunderstorms occurred during the campaign, which nevertheless enabled them to observe the emission of RF signals due to the formation of filament induced corona discharges during the thunderstorms.

Figure 1. Photograph of a 2 m-long electric discharge guided by laser filamentation (left) and without laser filament (right).



The laser lightning Rod project

The Laser Lightning Rod (LLR) project was launched 10 years later, when new laser technologies based on amplification in Yterbium:Yag crystals allowed to increase the laser repetition rate by a factor of 100. These new ultrashort lasers, developed by Trumpf scientific in Germany, were capable of maintaining a permanent hot-air channel by generating plasma filaments at high repetition rate. This greatly increased the chances of intercepting and guiding a lightning bolt. Under the impetus of the Applied Physics group at the University of Geneva and the Laboratory of Applied Optics in Ecole polytechnique (which were already the main players in the Teramobile project) a consortium was then formed with the German company Trumpf scientific, Ariane group, interested as an end user, and lightning experts from EPFL and from the University of Applied Sciences and Arts Western Switzerland. The project officially kicks off in January 2017 with a funding of €4 million from the European commission.
The site chosen for the experiment was the other key to the project's success. Selected by EPFL, it is a 120 m high radio transmission tower on the summit of Mont Saentis (Appenzell, Switzerland, 2502 m), operated by Swisscom. The Saentis tower is one of the most frequently struck by lightning in Europe, but above all, due to the presence of the mountain

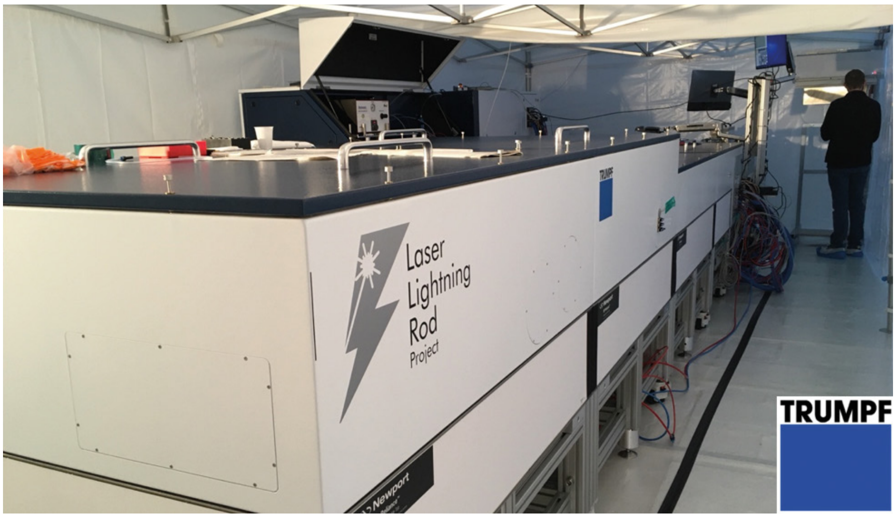


Figure 2. Photography of the laser developed by Trumpf scientific for the LLR project. (Copyright LLR project).

and the tower, the lightning that strikes the tower develops into ascending lightning precursors that start at the top of the tower. Known as upward leader, these discharges are therefore easily intercepted by the laser. This configuration is similar to that used in the pioneering experiment by Uchida *et al.* in the 90s. The first challenge was to build the world's most powerful high-average high-peak power ultrafast laser, with the aim of delivering laser pulses with an energy of 1 Joule, a duration < 1 ps at a repetition rate of 1 kHz. Trumpf's laser prototype is 1.5 meters wide, 8 meters long and weighs over 3 tons (see Figure 2). Its 5-block design means it can be transported by a cable car to the summit of Saentis, which is not accessible by car. The first two years of the project were devoted to the development of the laser by Trumpf, and to the study of lightning events at the Mont Saentis in the absence of laser.

Achieving an energy of one joule per pulse proved more difficult than expected, due to the strong thermal effects that occur at high power. In the end, including 5 amplification stages, the laser still achieved a record energy of 720 mJ at 1060 nm. After two years of development, the first tests with the laser were carried out at the former Orsay Linear accelerator laboratory in France, to characterize and optimize the filaments produced at 150 m using an enlarging telescope. Stopped for almost a year by the COVID pandemic, the project then resumed in 2021 for the final experiment, where the laser and its transport and focusing device were installed at the top of Mount Saentis.

The lightning experiment

Supervised by the University of Geneva, this 4-month installation on the top of Mount Saentis proved to be particularly complex. On the one hand, the laser had to be installed in an air-conditioned environment with filtered air, because at high average power, dust in the amplifiers can easily damage the entire chain. It •••

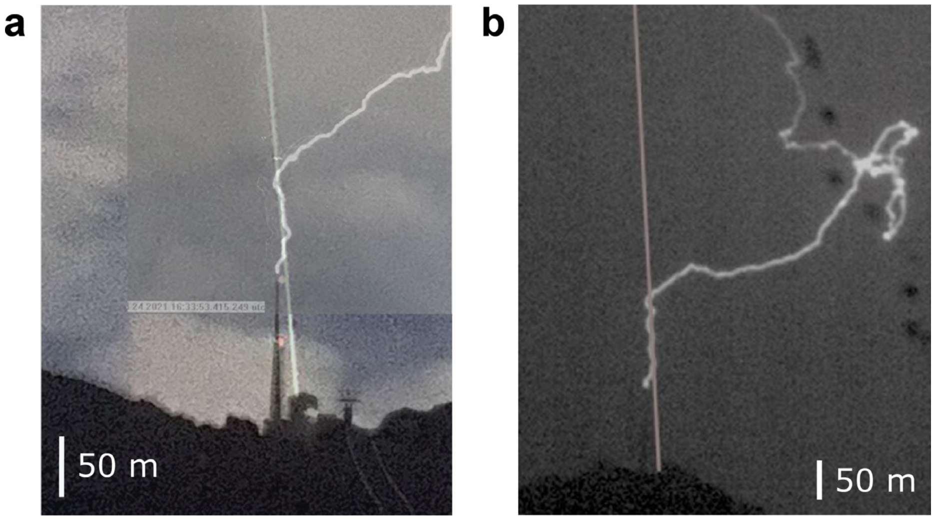


Figure 3. Images of the laser guided lightning flash recorded by two cameras over Mont Saentis on July 24 2021. Reproduced from [4]. CC BY 4.0

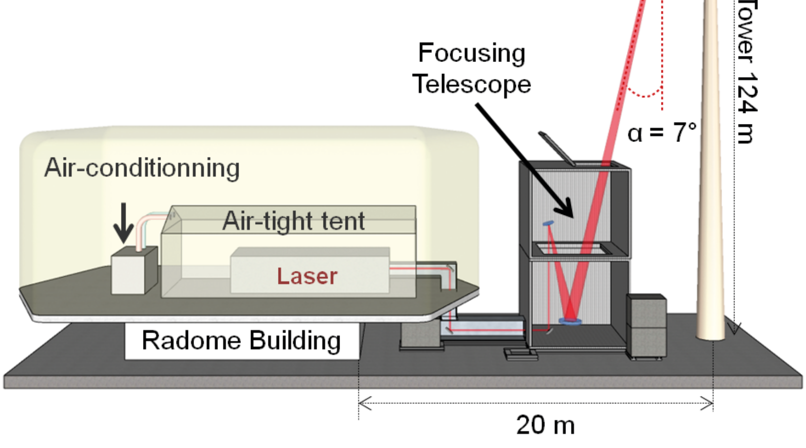
was also necessary to build a 3 m high telescope shelter to direct and focus the laser beam, and to cover the entire laser path between the building and the sending telescope. The installation of this shelter required the helicopter transport of two 10' high containers and 20 tons of concrete to stabilize the structure, which had to withstand winds of 80 km/hour. In addition, a special device was designed to protect the telescope's exit optics from the heavy rain that accompanied the storms, and the whole experiment had to be connected to a generator during each storm, to protect against frequent power cuts. The laser was then activated whenever thunderstorm activity was forecast, between July and September 2021. Beforehand, the area had to be closed to air traffic for a 5 km radius around the laser beam.

Once all these problems had been resolved, the experiment could begin in mid-July 2021. A week later, the first bolt of lightning struck the tower while the laser was in operation. Luckily, that evening, the cloud ceiling was very high and the lightning was perfectly visible from the neighboring peaks. Using two high-speed cameras positioned at different angles, the images shown in Figure 3 were recorded. It can be clearly seen that over 60 m, the lightning bolt, which starts at the top of the tower, follows the path of the laser beam. This is precisely the length over which the laser beam produces plasma filaments with this telescope configuration. Subsequently, a similar guiding effect was observed during three other lightning events, using a VHF detector capable of tracking the movement of lightning tracers in clouds, when the cloud prevents the lightning from being seen with a camera (see Figure 4).

This experiment therefore demonstrated that an intense ultrashort laser beam was capable of repeatedly guiding lightning over a distance of more than 60 m, even under difficult weather conditions, as the mountain was regularly shrouded in dense fog. Many questions remain unanswered, concerning the reproducibility of this effect, or the ability of the laser to stimulate the number of lightning discharges. But these questions

The laser system was located in the radome building, sheltered in an air-tight, air-conditioned and thermally isolated tent (see image). After exiting the tent, the laser beam was directed downwards by a conduit through the radome wall to the terrace, where a 4" folding mirror directed the beam into a beam-expanding sending telescope. The entire laser path toward the telescope, was protected by an isolated aluminium housing to prevent any beam leakage and to reduce the perturbation from the environment.

Layout of the experimental setup installed on Mont Saentis (Adapted with permission from [4].) CC BY 4.0



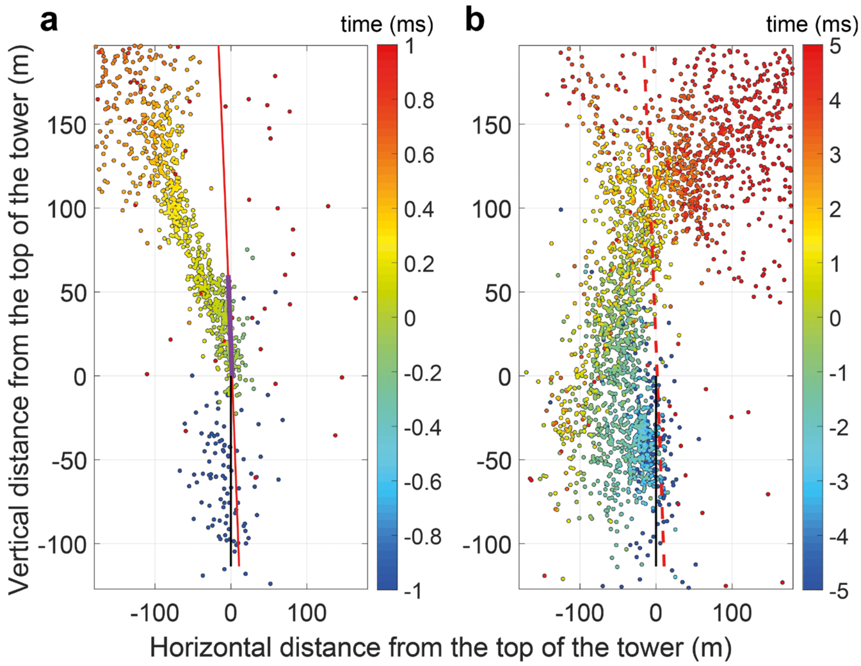


Figure 4. 2D maps of the VHF sources emitted during a lightning event with the laser on (a) and without laser (b). The laser path is shown in red. Reproduced from [4]. CC BY 4.0

would need more statistics to be answered, and installation difficulties meant that we were unable to take advantage of a large proportion of the season's lightning events. Therefore, additional experimental campaigns would be necessary to qualitatively assess the guiding efficiency of the laser filaments.

Conclusion

The Laser lightning rod experiment demonstrated that a high-repetition rate terawatt laser could guide lightning over 60 m by forming plasma filaments in the air. For lightning protection applications, the next step is to increase the length and guiding efficiency of the laser filaments, for example by doubling the laser frequency to obtain more energetic photons. Another important topic in the control of lightning will consist in the demonstration of lightning triggering with lasers. This should require the formation of long-lived conductive plasma channels, but their formation over long distances remains a real challenge [5].

REFERENCES

[1] S. Uchida, Y. Shimada, H. Yasuda, *et al.*, J. Opt. Technol. **66**, 199 (1999)

[2] X. M. Zhao, J.C. Diels, C. Yi Wang and J.M. Elizondo, IEEE J. Quantum Electron. **31**, 599 (1995)

[3] A. Mysyrowicz, J.P. Wolf, Photoniques **127**, 32 (2024)

[3] C. Herkommer, P. Krötz, R. Jung, *et al.* Opt. Express **28**, 30164 (2020)

[4] A. Houard, P. Walch, T. Produit, *et al.* Nat. Phot. **17**, 231 (2023)

[5] T. Produit, J. Kasparian, F. Rachidi *et al.* Rep. Prog. Phys. **87**, 116401 (2024)