2019 International Symposium on Lightning Protection (XV SIPDA), São Paulo, Brazil, 30th September – 4th October 2019.

Säntis Lightning Research Facility: A Summary of the First 10 Years and Future Outlook

Marcos Rubinstein
IICT
University of Applied Sciences Western Switzerland
Yverdon-les-Bains, Switzerland
marcos.rubinstein@heig-vd.ch

Farhad Rachidi
EMC Laboratory
Swiss Federal Inst. Of Technology (EPFL)
Lausane, Switzerland
farhad.rachidi@epfl.ch

***Abstract*— We present the Säntis Lightning Research Facility. The Säntis Tower is hit by lightning some 100 times a year, making it a unique site for lightning research. We describe the tower instruments used for the direct measurement of the lightning current at two different heights. We also describe the wideband electric and magnetic field measurement sensors installed near the tower, the field mill for the measurement of slow electric fields and the high-speed video camera near the tower. Other, temporarily loaned instruments are also briefly described. Examples of some of the data that have been gathered and analyzed are presented and the outlook and future plans of the facility are presented.**

Keywords—Lightning measurements; Instrumented Towers; Upward lightning

I. INTRODUCTION

Lightning is a cause of deleterious effects on electronic equipment, infrastructure, forests and it is also responsible for loss of human life and livestock. The risk of death to humans has decreased, mostly in developed countries, due to protective measures and to risk awareness and knowledge of the appropriate course of action when thunderstorms approach. However, other risks, such as, for instance, the risk of disturbance and damage of power generation, transmission and distribution systems, are not only still present, but they are increasing as renewable energy sources and smart-grid control electronics continue to be integrated into power systems. In addition to the increase in the number of potential victims of disturbance, lightning itself may become more energetic and frequent due to the influence of climate change on weather phenomena.

It is therefore important, given the issues that were just outlined, to develop and optimize appropriate lightning protection strategies against the responsible lightning processes using quality lightning data.

The knowledge of the lightning channel-base current is of great importance because it can be used as a basis to study the effects and protection against direct strikes and indirect electromagnetic effects.

The most widely used direct lightning measurement results to date are still those obtained by Prof. Berger and his team from the 1950s through the 1970s in Southern Switzerland. Their results were obtained using instrumentation that, although modern at the time, had a frequency bandwidth limited to some hundreds of kHz and, due to the limited time of each recording, did not include the full lightning time span.

Instrumented towers have been used for many decades to measure lightning currents. Towers with effective heights greater than 100 m are of special interest nowadays since upward lightning is often initiated from these tall grounded objects. Upward lightning is responsible for damages to wind turbines, communication towers, tall buildings, and whose current characteristics are similar to those of lightning triggered by aircraft and rockets. It is due to upward lightning that the local lightning incidence increases when tall structures are erected. This is not due to the attractive area of the tall structures but to the occurrence of new, upward lightning flashes that would not otherwise strike the sites where the new structures are installed. One such structure is the Säntis Tower, which is the subject of this paper and which was remarked thanks to the enhancement it provoked in the lighting incidence. Several research projects funded since 2009 by the Swiss National Science Foundation, the State Secretariat for Education and Research, and the European COST Action P18 led to the identification of the Säntis tower in Northeastern Switzerland as the best candidate for direct current measurements and to its instrumentation for that purpose shortly after. A picture of the Säntis Tower is shown in Fig. 1.

The Säntis tower is consistently struck by lightning some 100 times a year. This makes the tower a steady source of direct experimental lightning data.

The Säntis Tower is 123.5 meters tall. It sits on top of a 2502 m tall Mount Säntis, which is the tallest mountain of the siliceous limestone sedimentary rock Alpstein mountain complex [1].

The tower has an inner metal structure of 2.5 m mean radius with an outer Plexiglas structure of 6 meters mean diameter. The diameter of the tower base is 8 meters and is sustained by a set of metal supports allowing the structure to sway slightly under heavy winds.

Several towers of increasing length were erected throughout the years at the same site, starting with a weather station in 1880, followed by an 18-m tall TV antenna installed in 1958, which was itself replaced in 1976 by an 84 m tall structure that served

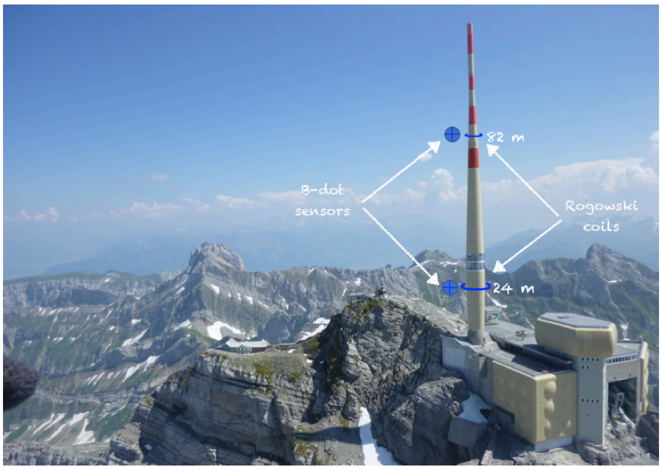

Fig. 1. The Säntis Tower. Rogowski coils and B-dot sensors are shown at 24 m and 82 m.

as a telecommunications tower, and which was superseded in 1997 by the current tower. Interestingly, the thunder day count at the site exhibited step-like increases every time a taller tower replaced the previous one. Down-steps were also observed during the periods when a tower had been dismantled to construct the new one.

The current structure is a telecommunications tower operated by Swisscom Broadcast and the site is also used as a weather station.

II. Instrumentation

In the first nine years of operation of the station, nearly 1000 flashes have been recorded and analyzed. The analysis of part of the data can be found in [2].

When the Säntis Tower was first instrumented in 2010, sensors to record the lightning current waveforms and their time-derivatives were installed. The currents and current derivatives are presently measured at two different heights, 24-m and 82-m AGL, using, at each height, a Rogowski coil and a multigap B-dot sensor. The measured signals are transmitted over a fiberoptic link to a National Instruments PXI-5122 high-speed digitizer set to record each detected lightning flash with a measurement window of 2.4 s at a sampling rate of 50 MS/s [2], [3]. A schematic view of the sensors at the two heights is shown in Fig. 1.

The Säntis Lightning Research Facility has been operational since 2010 and it currently includes an expanding array of sensors as well as remote monitoring and control capabilities. The permanent as well as temporary instruments used at the facility are presented in the next subsections.

A. Current Measurements

Rogowski coils and multigap B-dot sensors are installed to measure, respectively, the current and current-derivative waveforms. A set of sensors (Rogowski coil and B-dot) is installed at each of two different heights, 24 m and 82 m along the tower.

Fig. 2. Still frame from a high-speed video of an upward positive flash to the Säntis Tower.

Due to the Rogowski coils' limited high frequency response, especially built multigap B-dot sensors with a 20-MHz bandwidth were placed against the outside of the core mast of the tower to measure signals proportional to the derivative of the lightning current. The design of the B-dot sensors is based on the proposed design published in the 1960s by Baum, Breen, Giles, O'neill, and Sower [4], [5].

B. High-Speed Video

A Phantom high-speed video camera was added to the facility in 2018. The camera is installed about 4 km north of the Säntis tower, on the Kronberg mountain, in a storage room with a view toward the tower that Kronberg Luftseilbahn AG graciously allows us to occupy with our instrument. A single frame from the high-speed video of an upward positive flash captured on July 2nd, 2019 is shown in Figure 2.

C. Field Measurements

To measure the electric and magnetic fields, a low-frequency field mill and wideband electric and magnetic field sensors are installed inside a dome a short distance away from the mast. In addition, wideband field sensors are also installed 14.7 km away from the tower, on the roof of a 20-m tall building belonging to the company Huber & Suhner. In addition to the close and intermediate electromagnetic field sensors, the wideband vertical electric field is also measured in Northwestern Austria, at a distance of 380 km, by way of a wideband flat plate antenna belonging to ALDIS (Austrian Lightning Detection and Information System) in Vienna.

D. Other Measurement Sensors

Other equipment that has been brought to the facility on a temporary basis include a lightning mapping array (LMA) belonging to the Polytechnic University of Catalunya in 2017, capable of detecting and locate VHF sources from different processes during lightning flashes to the tower, a recently installed Interferometer, manufactured by New Mexico Tech, and sensors for high energetic X-ray and Gamma-ray radiation, some belonging to Uppsala University and others to the University of California Santa Cruz.

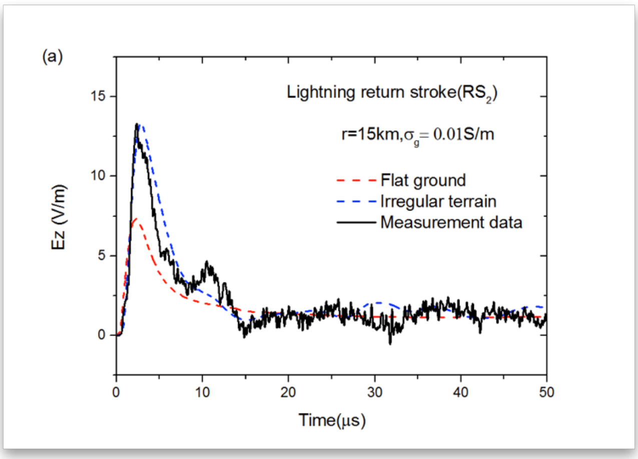

Fig. 3. Vertical electric field at 15 km associated with a return stroke in a flash to the Säntis. Solid line: measured waveforms. Red dashed line: simulated waveforms assuming a flat ground. Blue dashed line: simulated waveforms taking into account the terrain profile. Ground parameters: σg = 0.01 S/m and εrg =10. Adapted from [10].

III. Salient Results

In the years since the current measurement instrumentation was first put in operation, the number of successfully recorded flashes has grown to nearly one thousand. Part of the measurement and analysis work that is currently being done at the Säntis is dedicated to the study of the conditions that would be conducive to the initiation of lightning in the presence of a Terawatt Laser beam. This work is being done in the context of the Laser Lightning Rod (LLR) H2020 European project. The Terawatt Laser, which is expected to be installed next to the tower in 2020, is currently being built for this specific application by one of the project partners, Trumpf AG, in southern Germany.

The lightning data that have been gathered to present from lightning to the Säntis Tower consist of 85% negative, 12% positive and 3% bipolar flashes. The majority of the flashes (about 97%) are of the upward type.

A selection of the results obtained at the measurement facility is given in what follows.

A. *Negative Flashes*

The current data obtained since the put in operation of the facility constitute the largest dataset available to date for upward negative flashes. The analysis has contributed to the characterization of the different types of currents and electric field pulses that are associated with this type of flash. This has led to new models for the physical processes involved in their generation and it has corroborated the statistical similarities between pulses in upward and downward lightning (e.g., [6], [7]).

B. *Characterization of Positive Flashes*

Although positive lightning flashes are considerably less frequent than negative flashes, they are of great practical importance since they are associated with especially high currents and charge transfer values and therefore represent a higher risk regarding lightning-originated fires and the protection of power and electronic equipment.

Measurements made at the Säntis tower resulted in the characterization of two distinct types of upward positive flashes based on the current measured at the base of the channel [8]. These two types are similar to those observed by Berger [9]. Type-I upward lighting flashes are characterized by the presence of a large unipolar current pulse, typically preceded by bursts of fast pulses superimposed on a continuous current. Type-II flashes, on the other hand, differ from Type-I flashes in the absence of the large unipolar pulse but they exhibit longer durations and higher amounts of charge transfer.

C. *Propagation over irregular terrain*

Simultaneous field and current measurements together with FDTD simulations have allowed the study of propagation of the radiation from lightning over mountainous terrain taking advantage of the Alpine region where the Säntis tower is located. The effect of the rough terrain on the fields can be observed in Fig. 3, from which it can be concluded that the assumption of a flat terrain can lead to errors in the peak values of the fields of the order of 40% and that it is possible to obtain excellent agreement between measured and simulated fields by using a 2D-FDTD approach [10]. This result has important implications for the remote estimation of the lightning currents in lightning location systems.

D. *Performance of European Lightning Detection Network for Upward Flashes*

The availability of the channel-base current and the exact lightning strike location make instrumented towers an excellent ground-truth for the evaluation of the performance of lightning location systems. A performance analysis of the European lightning detection network (EUCLID) was performed using data obtained on lightning currents measured at the Säntis Tower in 2016. The performance of the EUCLID lightning detection network was evaluated in terms of detection efficiency, location

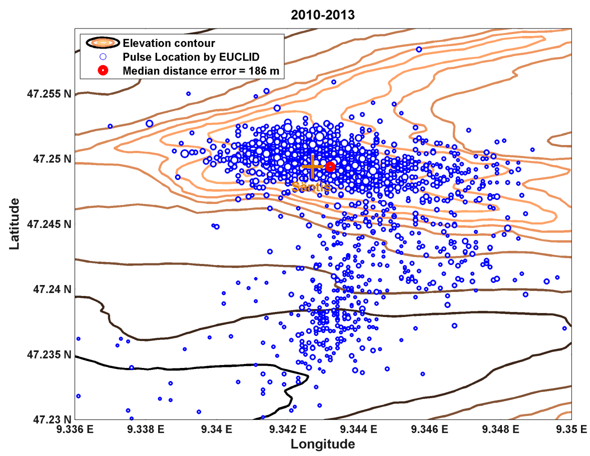

Fig. 4. Plot of EUCLID pulse locations for upward negative flashes in the region of the Säntis tower from 2010 to 2013. The size of the circles is proportional to the current peak measured at the Säntis. The length and width of the shown area are respectively 3.34 and 1.06 km. Adopted from [11].

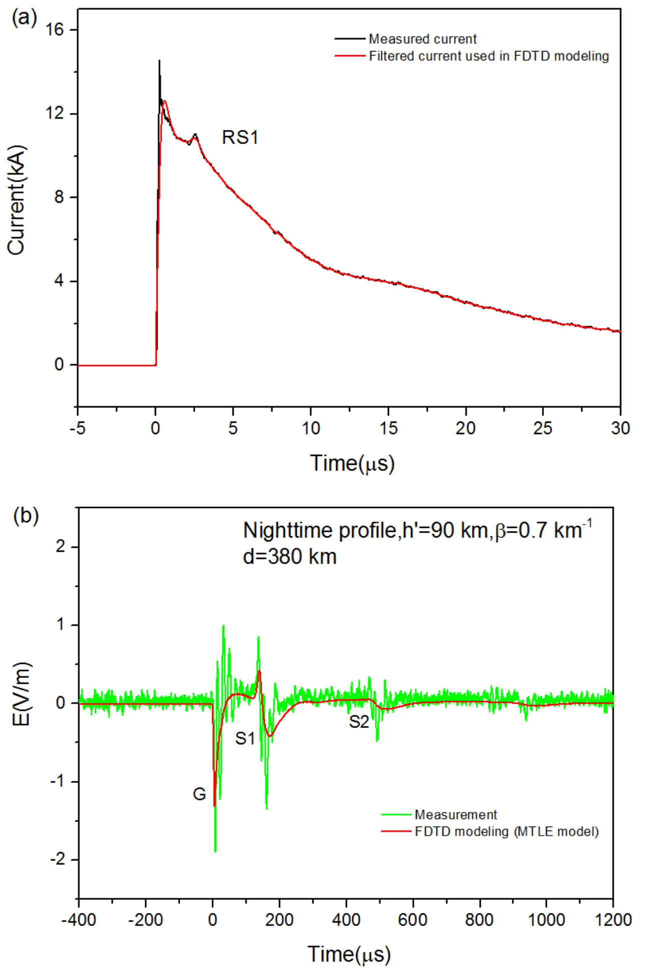

Fig. 5. Current and electric field waveforms produced by the first return stroke of the nighttime upward flash that occurred on 21 October 2014 at 20:23:22. (a) Measured current (black) and 2-MHz low-pass filtered (red) current used in FDTD simulations. (b) Measured (green) and simulated (red) E-field waveforms at 380 km. Adapted from [12].

accuracy and peak current estimates for upward flashes [11]. Figure 4 shows a map of the locations of pulses detected by the EUCLID system corresponding to strikes to the Säntis tower. The comparison of the locations given by the system and the actual location of the tower, as well as the amplitudes measured directly at the tower and those reported by the lightning location systems were analyzed to assess the performance of the lightning location system.

E. Lightning-ionosphere interactions

Simultaneous measurements of currents from upward lightning strikes to the Säntis tower and of wideband electric field waveforms at 380 km constitute the first ever measurements of that type that feature ionospheric reflections for natural upward flashes in the field waveforms. The 380 km field measurements represent, in addition, the longest distance at which natural upward lightning fields have been measured simultaneously with their causative currents [12]. Intervals between the ground wave field signatures and those of the skywaves were used to evaluate ionospheric reflection characteristics during daytime and nighttime based on the so-called zero-to-zero and peak-to-peak methods. Fig. 5 shows a plot of the current and electric field waveforms produced by the first return stroke of the nighttime upward flash that occurred on 21 October 2014. Fig. 5b shows the comparison between measured and simulated fields at 380 km.

IV. OUTLOOK

The Säntis Tower has been consistently struck by lightning 100 times or more every year over the past ten years. This one of a kind, life-size laboratory for experimental lightning research is currently being exploited by the EMC laboratory of the Swiss Federal Institute of Technology, Lausanne and the Advanced Communication Systems Group of the University of Applied Sciences Western Switzerland, Yverdon-les-Bains. The two research groups are working to make this remarkable facility into an international center for lightning research so that it can be made available to other research teams worldwide.

The measurement system has been extended to include different types of sensors, some of which have been installed on a temporary basis. The system will continue to be extended and enhanced in the future to include permanent energetic radiation sensors, lightning mapping sensors, dedicated atmospheric data sensors, and by increasing the bandwidth, dynamic range, and measurement time window of the existing instrumentation.

V. CONCLUSIONS

We presented the Säntis Tower Lightning Research Facility that includes the Säntis Tower, which has been hit by lightning consistently 100 or more times a year for the past decade. We described the instrumentation at the tower for direct current and current derivative measurements, fast and slow electromagnetic fields, and high-speed video in the tower vicinity and the vertical electric field at 380 km. We also described the lightning mapping and high-energetic radiation instruments that have been or are being used on a temporary basis at the facility. We presented salient results obtained from the analysis of the data recorded during the first decade of operation and we described the future plans and the outlook for the facility.

Acknowledgements- This work was supported in part by the Swiss National Science Foundation (Project No. 200020_175594) and the European Union's Horizon 2020 research and innovation program under grant agreement No 737033-LLR. The instrumentation of the Säntis tower was made possible thanks to the contribution of many individuals, including (in alphabetical order) Mohammad Azadifar, Prof. Arturo Mediano, Amirhossein Mostajabi, Prof. Mario Paolone, Prof. Davide Pavanello, Dr. Carlos Romero, Dr. Alexander Smorgonskiy, Antonio Sunjerga. Our appreciation is also due to our international colleagues (in alphabetical order): Prof. V. Cooray, Dr. G. Diendorfer, Dr. L. He, Dr. D. Li, Prof. J. Montanya, Prof. C.A. Nucci, Dr. H. Pichler, Prof. V.A. Rakov, Prof. D. Smith, Dr. W. Schulz. We would like to express our gratitude to Mr. Marc Bodenmann from Kronberg Luftseilbahn AG for allowing us to use part of the catering facility to house our high-speed camera. We also would like to express our sincere gratitude to Mr. Walter Haas of Swisscom Broadcast and to Swisscom AG for their logistical support.

REFERENCES

[1] T. McCann, “The Geology of Central Europe: Mesozioc and cenozoic,” 2008.

[2] C. Romero, F. Rachidi, M. Paolone, and M. Rubinstein, “Statistical distributions of lightning currents associated with upward negative flashes based on the data collected at the Säntis (EMC) tower in 2010 and 2011,” *IEEE Trans. Power Deliv.*, vol. 28, no. 3, pp. 1804–1812, 2013.

[3] M. Azadifar *et al.*, “An update on the charaterictics of positive flashes recorded on the Säntis Tower,” in *Lightning Protection (ICLP), 2014 International Conference o*, 2014, pp. 777–781.

[4] C. E. Baum, “Maximizing frequency response of a b-dot loop,” *Sens. Simul. Notes*, vol. 8, p. 218, 1964.

[5] C. Baum, E. Breen, J. Giles, J. O’neill, and G. Sower, “Sensors for electromagnetic pulse measurements both inside and away from nuclear source regions,” *IEEE Trans. Antennas Propag.*, vol. 26, no. 1, pp. 22–35, 1978.

[6] M. Azadifar *et al.*, “Fast initial continuous current pulses versus return stroke pulses in tower-initiated lightning,” *J. Geophys. Res. Atmospheres*, vol. 121, no. 11, pp. 6425–6434, 2016.

[7] L. He *et al.*, “An Analysis of Current and Electric Field Pulses Associated With Upward Negative Lightning Flashes Initiated from the Säntis Tower,” *J. Geophys. Res. Atmospheres*, vol. 123, no. 8, pp. 4045–4059.

[8] C. Romero, F. Rachidi, M. Rubinstein, M. Paolone, V. A. Rakov, and D. Pavanello, “Positive lightning flashes recorded on the Säntis tower from May 2010 to January 2012,” *J. Geophys. Res. Atmospheres*, vol. 118, no. 23, 2013.

[9] K. Berger, “Blitzstorm-Parameter von Aufwartsblitzen,” *Bull Schweiz Electrotech*, vol. 69, pp. 353–360, 1978.

[10] D. Li *et al.*, “On lightning electromagnetic field propagation along an irregular terrain,” *IEEE Trans. Electromagn. Compat.*, vol. 58, no. 1, pp. 161–171, 2016.

[11] M. Azadifar *et al.*, “Evaluation of the performance characteristics of the European Lightning Detection Network EUCLID in the Alps region for upward negative flashes using direct measurements at the instrumented Säntis Tower,” *J. Geophys. Res. Atmospheres*, vol. 121, no. 2, pp. 595–606, 2016.

[12] M. Azadifar *et al.*, “Analysis of lightning-ionosphere interaction using simultaneous records of source current and 380 km distant electric field,” *J. Atmospheric Sol.-Terr. Phys.*, vol. 159, pp. 48–56, 2017.