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CZECH TECHNICAL UNIVERSITY IN PRAGUE

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Faculty of Electrical Engineering
Department of Radioelectronics

Ph.D. Thesis

Radio Detection of Electromagnetic Phenomena in the Atmosphere

Integrating Advanced Instrumentation and UAVs for Enhanced Atmospheric Research

Jakub Kákona

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/ Declaration

Prohlašuji, že jsem předloženou práci vypracoval samostatně a že jsem uvedl veškeré použité informační zdroje v souladu s Metodickým pokynem o dodržování etických principů při přípravě vysokoškolských závěrečných prací.

V Praze dne 26. 6. 2024

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Abstrakt / Abstract

Tato disertační práce se zaměřuje na využití rádiové detekce pro zkoumání elektromagnetických jevů v atmosféře. Hlavní pozornost je věnována integraci nových meteorologických přístrojů, radiových přijímačů, telemetrických systémů a bezpilotních prostředků (UAV) do výzkumu atmosférických jevů. Práce přináší detailní analýzu atmosférických dat získaných prostřednictvím leteckých a pozemních měření. Jejich přímé využití je potom nasměrováno k hlubšímu pochopení dynamiky bouří a atmosférických elektromagnetických událostí. Popisované experimenty demonstrují, jak aplikace pokročilých měřících technologií může zlepšit pochopení specifických atmosférických jevů.

Překlad titulu: Rádiová detekce elektromagnetických jevů v atmosféře (Implementace pokročilé instrumentace a bezpilotních prostředků pro atmosférický výzkum)

This dissertation explores the use of radio detection for studying electromagnetic phenomena in the atmosphere, focusing on the development and integration of advanced radio receivers, meteorological instruments, mobile measurement platforms, telemetry systems, and unmanned aerial vehicles (UAVs). It presents a comprehensive approach to capturing and analyzing atmospheric data, offering insights into the complex dynamics of storms and electromagnetic events. Through a series of experiments, including atmospheric flights and ground-based measurements, the research demonstrates the potential of novel technologies to enhance the understanding of atmospheric processes, contributing significantly to the field of atmospheric sciences.

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I had decided to write the relatively wide introduction part, because I hope that form should explain the context required to understand some tradeoffs created during the entire work. It also allows a reader to capture the broad spectrum of activities which without the explanation could seem unrelated. Therefore at the beginning of my research I had worked on the Bolidozor network. The Bolidozor is a type of forward scattering radio meteor detection network, which uses the signal from french military radar GRAVES (https://spp.fas.org/military/program/track/graves.pdf) non cooperatively. That means the signal transmitted by the GRAVES is scattered by meteor trails in the atmosphere and is really easy to receive the reflections on broad parts of Europe even with using a simple ground plane antenna. There are a few motives to deal with that. The first, the most obvious one, the radar observation of meteors are weather and daytime independent in contrast to yet widely known visual based observation using the cameras. That radio observation should fix that limitation where visual based observation networks have impaired sensitivity for a significant portion of the time. Another motivation is the possibility to enhance precision of velocity estimation of the meteoroid, because there is a significant effect of doppler transition observed on the reflected signal. The existence of a doppler shifted "head echo" on meteor reflection was the core handle, because I had planned to use it to estimate the meteor trajectory from signals received by multiple stations. That seems to be feasible, because there were successful attempts (M. A. Vallejo, ea4eoz, 2016 et. al.) to calculate a meteor vector in the atmosphere based on these doppler shifted signals.

The trouble begins with the fact that there is no easy way to verify that the calculated trajectory is correct or incorrect. The one issue roots in the situation that radio signals received by Bolidozor network have a detected meteor every few seconds which complicates clear assignment of the specific visual observation to the calculated trajectory. Especially in cases where a digital video camera occasionally has a few seconds latency or inaccuracy. The second issue is caused by the situation that GRAVES radar guaranteedly lightens only a relatively small fraction of the atmosphere, but there are also side radiation lobes. The primary enlightened part is located above south europe where there were little video detection networks at that time. The GRAVES radar also has a side transmission from its antenna, but these transmissions are not stable and also there is not exactly known enlightened area.

That results in a very few meteor events, which could be used for trajectory verification by using the local video based meteor detection networks here in the Czech Republic. To resolve this problem I had decided to switch from GRAVES radar transmission to the local transmitters which are more suitable for local meteor detection. I had selected the VOR beacons for airplane navigation. These beacons have definitely reduced transmission power compared to GRAVES, but according to the numerical model I constructed the meteor radar based on that transmitters could be feasible with the use of state-of-the-art radio components.

Figure: Reflection from airplanes clearly visible at the received signal from the VOR transmitter (Prague OKL). The doppler shift curves are related to the airplane trajectories.

Unfortunately that new approach requires a complete redesign of the signal processing and construction of the new receiver. That receiver should be capable of reception of multiple VOR transmitters at once, because the frequencies of VOR transmitters are allocated in such a way that neighboring transmitters have significantly different frequencies to enhance the airplane navigation safety and reliability. That results in the requirement of processing the 10MHz of signal bandwidth instead of the previous 192 kHz including a wide dynamic range of signal input, because this bandwidth will be likely affected by the strong nearby signals like reflection from the airplanes visible in fig ??. These requirements on the receiver redesign were way beyond the initial project funding available; it is also beyond my alone manpower. Therefore I had steppily realized that the newly developed instruments needed to have commercial applications to avoid reliance on unreliable and discontinuous systems of scientific founding. As a result I had to search for possible commercial applications that required the new instruments. That also explains why the majority of the newly developed instruments described in section ?? are currently commercially available. For the case of the new radio receiver I found following areas of possible applications:

- Meteor trail detection and localisation
- LEO satellites down-link ground station
- Atmospheric electrical and ionization events observation

Luckily there arise an opportunity to cooperate at CRREAT project which main aim was study of high-energy atmospheric events, where electromagnetic events in atmosphere (electrometeors) observations fits well and at the same time are vital requirement. In the frame of that project I had designed the new receiver (described in chapter ??) concept with all mentioned applications in mind. That allows that construction of the receiver could be implemented with significant assistance of other members of the CRREAT team or external collaborators and with the use of CRREAT funding. But at the same time, there is a threat that the observation of lightning has the similar issues as the Bolidozor's radio meteor observation, because computing an location of lightning occurrence is definitely possible, but there is non trivial task to verify that the result is relevant. The requirement to build the ability to verify the calculated results, branched out in the broad range of different work packages, which needs to be solved to gather relevant information about lightning or more generally atmospheric electricity from multiple sources. I describe ground based, airborne and remote sensing instruments in detail in the chapter ??. But for the overview of the tasks, firstly the lightning should be detected, the antenna should be calibrated, and the electric field needs to be measured at the same time. The lightning also needs to be simultaneously captured on high-speed cameras for geometric triangulation etc. That is why I need to design and operate the multiple measurement systems carried by car on ground and also in airborne vehicles presented and used in the following thesis.

Chapter 1
Introduction

1.1 Scope of the thesis

The objectives of this dissertation are to address and clarify several unresolved phenomena related to thunderstorms, particularly the initiation and development of lightning. This research aims to develop and utilize new tools for the detection and scientific observation of lightning events within thunderstorms. The focus will be on understanding the relationship between ionizing radiation and lightning, as well as developing innovative mobile instruments required for detailed storm observation. The specific tasks to be undertaken are as follows:

- **Development and Implementation of Lightning Detection Apparatus**: Mobile experimental apparatus capable of radio detection and localization of lightning events and ionizing radiation, considering the expected spatial scales, will be designed and deployed. Data will be collected using radio detectors, high-speed cameras, and ground-based electric field measurements.
- **Analysis of Spatial and Temporal Characteristics of Lightning Discharges**: The propagation of lightning, emitted radio signals, and associated electric fields will be studied. Methods for visualizing lightning discharges that avoid misinterpretation as ground strikes and more accurately reflect the physical principles of lightning development and radio signal emissions will be developed.
- **Enhancement of Measurement Techniques with in-situ atmospheric monitoring**: New instruments such as stratospheric balloons and unmanned aerial vehicles (UAVs) (especially unmanned autogyro) for in-situ measurements of electric fields and ionizing radiation will be developed. The new electric field mill and a semiconductor-based ionizing radiation detector will be integrated into the UAV.

The results of this research are expected to provide a deeper understanding of lightning initiation and propagation. At the same time it offers improved detection and observation techniques that can inform future studies, about relation to ionizing radiation with direct practical applications in meteorology and atmospheric physics.

The activity of storms is associated with many phenomena whose nature is not yet fully understood or clarified. This includes the process of thundercloud electrification and the subsequent electric discharges, which are the most prominent manifestation of thunderstorms. As a result, weather forecasting and nowcasting of storm activity and related dangers are often very unreliable.

As one of many related phenomena, storm activity is also associated with the generation of ionizing radiation[1–7]. It is assumed that the source of this radiation is bremsstrahlung generated by electrons accelerated by an electric field in the thunderclouds[6–10]. These electrons that are accelerated to relativistic velocities are called relativistic runaway electron avalanches (RREAs), which are then interacting with the atmosphere [11]_[12]. This causes a phenomenon that is to be often called terrestrial gamma-ray flash (TGF) [13] or other phenomenon like thunderstorm ground enhancement (TGE) [14]_[15]. For both, the source of the radiation is thought to be somewhat associated with the RREA; the main difference is the time span in which they occurs [11]_[12]. Although it has not been experimentally proven. Furthermore, recent experimental results show that there is evidence of other ionizing radiation manifestations generated by the thunderstorms. For example, there has been experimental evidence of the interaction of high-energy photons with the atmosphere causing nuclear reactions [16]. The ionizing radiation that is thought to be associated with storm activity was measured using satellites in orbit around the Earth (e.g. [17]), aircrafts flying inside or in the vicinity of storm clouds [18]_[19]_[20] or high mountain observatories e.g. [21]_[22]_[23]. Currently, there are only a few measurements that could confirm the existence of ionizing radiation at lower altitudes, except for special storms that occur during the winter season in Japan, where storm clouds emerge low above the ground [24].

One of the most interesting measurements performed until now is the combination of radio signal and ionizing radiation. That experiment includes the mapping of a radio signal emitted by lightning [25] [26]. There also exist TGF observations with a simultaneous lightning mapping using radio signals [27]. Despite these very detailed observations, the exact location of the source of the ionizing radiation emergence as a result of electric fields within the storm cloud remains unknown (Belz, J. W., et al. `Observations of the origin of downward terrestrial gamma-ray flashes.` Journal of Geophysical Research: Atmospheres 125.23 (2020): e2019JD031940.).

Moreover, the TGFs were only rarely successfully measured at the ground level (https://doi.org/10.1029/2021JD036130, Dwyer, J. R., et al. `Observation of a gamma-ray flash at gr` Journal of Geophysical Research: Space Physics 117.A10 (2012)., Wada, Yuuki, et al. `Downward terrestrial gamma-ray flash observed in a winter thunderstorm.` Physical Review Letters 123.6 (2019): 061103.).

There also should be noted that lightning phenomena manifest not only in the familiar forms that could be observed from ground-level but extend into near-Earth space, presenting phenomena such as sprites, elves, gigantic jets, and also TGFs. All of these are powered by the intense electromagnetic and quasi-electrostatic fields related to lightning discharges. However, the specific properties of lightning discharges that lead to these high-altitude phenomena remain a subject of ongoing research, with studies leveraging both ground- and satellite-based observations to map global occurrence rates (Inan, 2015)1. At the ground level the lightning discharges that could be observed, are classified into negative, positive, and bipolar. (Rakov, n.d.). The taxonomy of lightning includes a range of discharges: cloud flashes (intracloud, intercloud, and cloud-to-air) and cloud-to-ground (CG) discharges, the latter accounting for about 25Observations in tropical regions have introduced further classifications, including intra-cloud discharges, cloud-to-cloud, cloud-to-air, and express the polarity of lightning by ground-to-cloud, and cloud-to-ground discharges, noting the significant damage and disturbances caused especially by cloud-to-ground and ground-to-cloud flashes (Mehranzamir et al., 2014)3. Research into specific phenomena like ball lightning, sprite lightning reveals the versatility and is out of scope of this thesis, opening possibilities for further exploration of these rare and unique events (Horvath, 2014)4. While the general mechanics of lightning—its initiation and propagation—have been linked to specific atmospheric conditions such as the presence of graupel, ice, and hail, highlighting the relationship between lightning types and the microphysical characteristics of the convective regions, many aspects, including the differential occurrence rates and damaging potential of positive versus negative discharges, still invite further investigation (Ribaud et al., 2016).

Intracloud lightning discharges are known for their characteristic radio pulses, which consist of a uniform burst pattern. These bursts are described as a distinctive waveform characterized by a fast, large amplitude pulse followed by a smaller, slowly varying overshoot. The full width at half maximum of these pulses measures 0.75 s, with inter-pulse intervals of 5 s (Krider, Radda, Noggle, 1975)1. The `compact intracloud lightning discharge` (CID), a particular type of intracloud lightning, is described as a bouncing-wave phenomenon. This involves multiple reflections occurring at both ends of the radiating channel, contributing to its fine structure and accompanying high-frequency (HF) and very high-frequency (VHF) radiation bursts (Nag Rakov, 2009)2. An interesting characteristic of radio frequency emissions during thunderstorms is their nature compared to weaker emissions. The strongest pulses typically occur in isolation or at the beginning of leader progression. These pulses are sometimes associated with rapid electric charge relaxation and are not necessarily accompanied by visible light emissions. In instances where these pulses initiate, they are followed by an upward-progressing leader (Jacobson, 2003)3. The study of lightning-induced radio pulses has been also expanded by observations from the satellites, which identifies additional characteristics in these emissions. Some exhibit steep roll-offs of power within certain frequency ranges, while others demonstrate flat-spectrum behavior. This distinction indicates the somewhat varied nature of lightning's electromagnetic emissions (Jacobson, Knox, Franz, Enemark, 1999)4. For cloud-to-ground (CG) flashes, the structure typically includes a sudden start with a stepped leader, in contrast to cloud-to-cloud (CC) flashes that initially showcase a slower train of noise pulses. These RF radiation patterns from lightning display a distinct structure based on the type of lightning flash, differentiating between the abruptness of CG flashes and the gradual initialization of CC flashes (LeVine, 1978).

1.2 Key radio signatures of lightning events

1.2.1 K-changes

K-changes, or K-complexes, refer to a specific pattern of rapid waveform change observed in VLF (Very Low Frequency) and LF (Low Frequency) radio signals from lightning. They indicate a sudden change in the current flow or channel geometry within cloud-to-ground or intracloud lightning discharges. These signals are characterized by abrupt, intense alterations in amplitude.

1.2.2 Narrow Bipolar Events (NBEs)

NBEs are distinct, intense radio pulses with a very short duration, typically a few microseconds, and are considered the most powerful natural VHF (Very High Frequency) sources in the Earth's atmosphere. They exhibit a remarkably narrow bipolar pulse shape and are believed to result from a rapid discharge process within thunderclouds, possibly associated with the initiation stages of lightning.

1.2.3 Sferics

`Sferics` is short for atmospherics, the term used for radio waves emitted by lightning discharges. These signals, spanning a broad range of frequencies but most commonly observed in VLF and LF bands, represent the electromagnetic signature of distant lightning's return stroke. Sferics carry distinctive timing information, making them valuable for long range lightning detection and location systems.

1.3 Literature Review and state of the art

Atmospheric electromagnetic phenomena have been identified by many studies [ ] as mandatory physical property influencing atmospheric radiation processes. These phenomena, including lightning, sprites, and other events, are also a significant part of the formation of cloud structures and significantly impact the movement and characteristics of atmospherically relevant subsystems (Artekha Belyan, 2013). The evolution of radio transmission has been the earliest methods of regular observation of atmospheric electricity (e.g. sferics). Rapidly revealing the existence of atmospheric charge structures like the ionosphere and its variation, forming the atmospheric waveguide allowing propagation of radio waves produced by lightning over long distances. Research has also delved into the dynamics of geomagnetic pulsation regimes and their interaction with the Earth's magnetosphere, reflecting the interactions resulting from powerful solar flares (Parkhomov et al., 2021). In parallelly ongoing meteorological research, the integration of advanced technologies from aviation starting from balloons led to discovery of cosmic radiation [https://inspirehep.net/literature/1623161, doi:10.1038/136718a0]. The balloon observations were combined with radio transmission to be automated in the form of radiosondes [https://www.jstor.org/stable/26242290]. That technology has been improved and used for decades, until the most recent stage of this evolution in employment of Unmanned Aerial Vehicles (UAVs) [https://doi.org/10.1016/j.chemosphere.2020.126867]. Another significant contribution of radio engineering in meteorology is the invention of the radars, which are used for remote sensing of atmospheric structures. The remote radio sensing and in-situ measuring methods are also combined to obtain multiple perspective views on electric phenomenons. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2006JD008187 The increasing requirements on lightning safety during space race significantly enhance the technology of ground-based equipment such as electric field mills and radio based lightning detection and mapping systems [https://ntrs.nasa.gov/api/citations/19780014357/downloads/19780014357.pdf, https://doi.org/10.4271/700939, https://doi.org/10.1109/TEMC.2009.2023450]. The state of the art of this radio based technology utilizes large area arrays for observation in the form of non-intrusive methods to determine atmospheric electric fields (Trinh et al., 2017) and also mapping of lightning evolution and structure. Notable examples of these systems are New Mexico Tech's Lightning Mapping Array (LMA) [https://doi.org/10.1002/2016JD025159], FALMA [https://doi.org/10.1002/2018GL077628], community based network Blitzortung.org and also LOFAR radio telescope [https://doi.org/10.1002/2017JD028132]. Based on mentioned instruments which were originally developed directly for scientific purposes or safety engineering. There also emerges a lot of commercial products and services for civil lightning awareness. As examples there could be mentioned the Vaisala lightning sensors [https://doi.org/10.1541/ieejpes.132.529], WWLLN [10.1029/2021RS007293] and LINET [https://doi.org/10.1007/978-1-4020-9079-0_5].

1.3.1 Summary of Initial Assumptions

The following scientific assumptions provide the foundation for following research. While they represent the initial understanding in the field, this dissertation will critically examine and test these assumptions to enhance or refine the knowledge of thunderstorm phenomena:

- Research in phenomena in thunderstorms, such as ionizing radiation production has often focused on the peaks of electric fields associated with the initiation of lightning [Kolmašová, et. al., 2015]
- Lightning discharges are generally considered to be short-duration events typically ranging from tens microseconds [Kolmašová, et. al., 2015], to up to 350 milliseconds [Rakov Uman, 2003; López et al., 2017]
- The spatial extent of lightning discharges is believed to be limited to approximately 15 kilometers from the initiation point [Thottappillil et al., 1992; López et al., 2017] It is commonly accepted that ionizing radiation is generated before or during lightning events, primarily in a vertical direction parallel to the electric field intensity vector [Enoto et.al., 2017]
- Much of the existing research on lightning discharges focuses on the return-stroke phase, a key phase of cloud-to-ground discharges [Uman, 1969; Berger et al., 1975; Dwyer et.al. 2012]

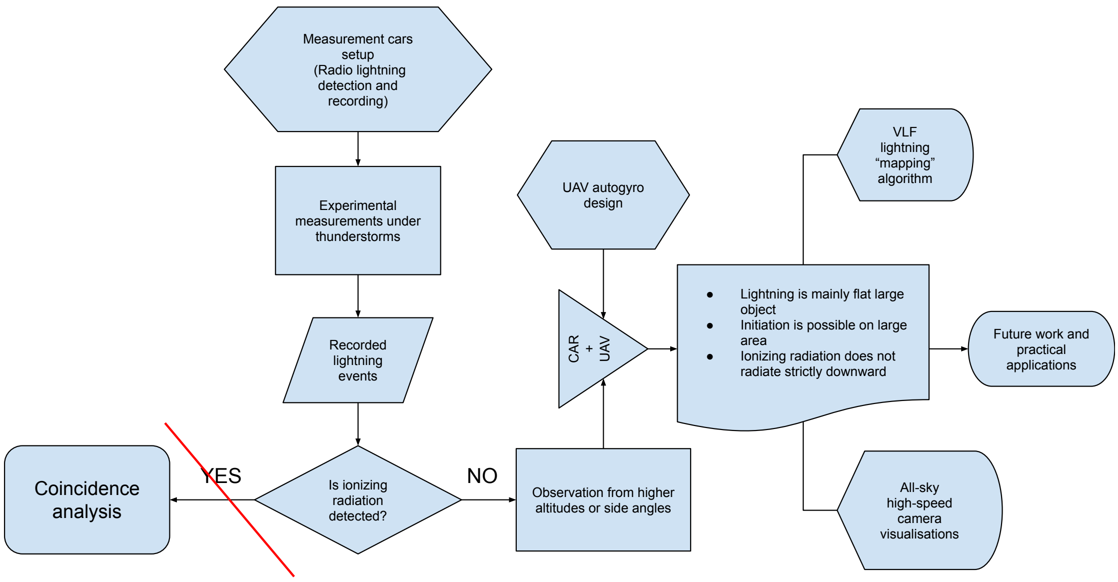
1.4 Contributions

Based on the theoretical framework and assumptions outlined in the `Literature Review` chapter, I developed a comprehensive research methodology. This methodology includes the use of measuring vehicles and unmanned aerial vehicles (UAVs) to improve the detection of radiation phenomena associated with thunderstorms. The primary objective is to position detection devices as close to or beneath the storm core as possible, thereby increasing the likelihood of capturing relevant radiation events.

The main research methodology is based on the following key components:

- **Utilization of Measuring Vehicles:** I use the measuring vehicles equipped with specialized instruments for detecting radio signals and ionizing radiation. These vehicles also serve as mobile platforms, providing the necessary ground support for the UAVs. They are at the same time equipped with a range of auxiliary devices to capture the interrelationships between the measured data. For example, scintillation detectors for ionizing radiation must account for the influence of temperature changes on sensitivity, and disdrometers are used to measure the intensity and type of precipitation that can wash radon products from the atmosphere, causing increased radiation levels, which could be easily inappropriately interpreted as TGE.
- **Deployment of UAVs for Radiation Detection:** The multiple UAVs, that are equipped with detectors for ionizing radiation. The UAVs are tasked with locating and identifying sources of ionizing radiation in the atmosphere. This method leverages the strong presumption that the intensity of generated ionizing radiation diminishes with increasing distance from its source. The UAVs provide data on ionizing radiation that is difficult to obtain from ground-based measurements alone. Therefore UAVs are supposed to observe thunderstorms cooperatively with measuring cars.

The flowchart depicted in fig. 1.1 illustrates a high-level workflow of the research. It begins with the setup of measurement cars equipped with radio lightning detection and recording capabilities including an all-sky high-speed camera on the two cars. Experimental measurements are then conducted under thunderstorms, with recorded lightning events analyzed for the presence of ionizing radiation. These attempts lead to insights such as the flat, large object nature of lightning, the possibility of lightning initiation process over large areas, and the observation that ionizing radiation does not radiate strictly downward. Parallel to this, the UAV autogyro and other instruments are designed to aid in these measurements. Observations are then supposed to be made from higher altitudes or side angles to enhance data collection. Then the data from both the measurement cars and UAVs needs to be combined.



[workflow]
Figure 1.1. Simplified workflow for detecting and analyzing lightning radio signals and ionizing radiation using measurement cars and UAVs.

To address the general unavailability or limitations of commercially available instruments, as well as issues with data quality due to closed design and lack of transparency in internal data filtering processes, I developed several bespoke instruments. These custom-made tools were essential to ensure reliable measurements. Notably, the following instruments were developed to meet the specific needs of this research:

- **Lightning Radio Signal Receivers:** These instruments were used to implement a method for triggering data recording by lightning signals, ensuring high sensitivity to natural lightning while minimizing false positives from man-made signals. This innovative solution is detailed in the section [Lightning Triggered Recording].
- **Unmanned Autogyro for atmospheric measurements:** To address the lack of available unmanned systems capable of measuring ionizing radiation or electric fields within storm clouds, I developed an unmanned autogyro designed for atmospheric measurements under various weather conditions. Unlike traditional measurement balloons, which are unsafe and yield sporadic results due to limited control, the autogyro offers precise control and stability even in turbulent conditions.

- **Measurement Support Systems:** Design and integration of an instrument toolset that allows simultaneous detection and recording of lightning event signals, electric field distribution, ionizing radiation, camera recordings, and meteorological data. The detailed design of these instruments is presented in the chapter [Proposed Instrumentation]. Measuring vehicles are also equipped with systems for wind speed and direction measurement, and sensor orientation recording, necessary for UAV launch from the car platform, landing, flight control, and lightning localization.

The contributions of the designed instruments to the understanding of thunderstorm-related phenomena are demonstrated through various experiments. These experiments are described in detail in the chapters [Subsequent Experiments] and [Results and Conclusions]. The measuring vehicles and UAVs' ability to relocate flexibly and conduct ground measurements at storm sites significantly enhances the future capability to capture and analyze storm-related ionizing radiation events.

1.5 Outline of the thesis

The initial part of the thesis, titled `Lightning Triggered Recording`, describes the construction and test of a device engineered to automatically capture data from lightning events. The chapter has been one of the initial work packages because the described methods enable the recording of instruments synchronized with the lightning. That is the essential feature needed for the every additional described steps of the following research.

This is attributed to the fact that within the scope of storm evolution, lightning can be seen as occurring in relatively brief and sparse periods compared to the more extended spans of storm activity without lighting (an supposedly also without an ionizing radiation), as discussed in the chapters ?? and ??. Simultaneously, the flow of individual ionizing radiation particles or photons during TGF or TGE, spans a broad spectrum of possible energy levels. That does not permit the setting of an exact recording threshold at the individual instrument, given the sensitivity capabilities of available equipment. Therefore, ionizing radiation detectors, and the majority of other instruments, like radio receivers and high-speed cameras, are required to capture event data throughout its actual occurrence, and this data fragment should subsequently be analyzed to examine the underlying phenomena.

Therefore these instruments are at the same time examples of scientific devices capable of generating an enormous amount of data. Such volumes of data are (with the actual technology level) difficult to store within the intervals between events, e.g. lightning. That is the main rationale behind the need to create a reliable method of triggering the recording of all instruments depending on lightning activity to store event-based data fragments.

In the `Proposed Instrumentation` chapter, are explored the exact designs of the innovative tools and devices engineered to especially to improve study of lightning in thunderstorms and the related atmospheric phenomena. The design and development of these instruments were initially guided by literature listed in the chapter ??, which suggested typical lightning properties that early experiments soon called into question. This suspicion led to multiple iterations in the construction of instrumentation, as the original assumption of lightning's brevity—thought to correlate the event data with the vertical development of lightning channels over tens of milliseconds—proved grossly underestimated, as the actual ranges of these events are several orders of magnitude greater. This situation also changes the requirement on examined electric field gradients, because the vertical gradient detection needs to be exchanged by a horizontal or more ideally the 3D space distribution. The chapter discusses the rationale behind the instrument development, its design principles, and how these advancements improve upon existing technologies. It also details the experimental setup and integration of these tools into broader research methodology, emphasizing their future potential to significantly advance the understanding of atmospheric electricity.

However, because it was necessary to first verify the developed instruments on more deterministics processes than direct measuring during a storm activity, a large number of supportive experiments were conducted, which served to verify the properties of the instruments and their supporting subsystems. These experiments included flights of stratospheric balloons and UAVs as well as ground measurements with the similar instrumentation either at stationary or mobile measuring stations. The chapter on `Subsequent Experiments` therefore documents the extensive preparatory work necessary to validate proposed instruments' efficacy before their direct application in thunderstorms research.

The `Results and Conclusions` chapter synthesizes the insights gained from the application of the developed instruments in the field, reflecting on the contributions this research has made to the field of atmospheric sciences, particularly in understanding lightning phenomena. It evaluates the effectiveness of the newly developed instrumentation in capturing comprehensive lightning data, discusses the impact of these findings on existing theories, and considers their practical implications. Furthermore, it outlines future research directions, suggesting areas where further investigation could yield substantial advancements in the study of atmospheric electricity with the additional use of similar instrumentation. This final section underscores the thesis's role in enhancing scientific knowledge and its potential for real-world applications in weather forecasting and safety measures.

Chapter 2
Lightning triggered recording

Because recording and then processing the large amount of data captured continuously over thunderstorm development is technically difficult (the technical difficulties are detailed in the chapter Proposed Instrumentation, specifically in sections describing radio and camera instruments), it is needed to have the ability to determine the precise time of lightning event, with a low rate of false detections. That requirement is enhanced by the fact that data recording is triggered by every false detection, which takes several minutes. This interval creates a “blind” dead time during which the instrumentation is unable to capture another event. To solve that issue, multiple iterations of a mobile measurement system and detectors, which are triggered by electromagnetic emissions produced by lightning, have been developed. Although optical, radio-wave (electromagnetic), and infrasound-based lightning detection methods exist, the radio-wave detection method is considered to be the most suitable for the intended application, due to its detection range and relative insensitivity to meteorological conditions (hail, snow, rain, and sunlight) at the time of the lightning discharge. It is also considered suitable for the near-to-real-time detection of lightning. The another requirement of the proposed system is being capable of the precise detects of lightning with a precision in order of several kilometers in position and better than millisecond in the time. The widespread method used for radio lightning detection is based on the detection of the magnetic part of an electromagnetic field generated by lightning. Examples of instruments using this method available for comparison in the Czech Republic include the use of the SLAVIA magnetic loop antenna [28] and the stations of the lightning detection system deployed in the Blitzortung.org network [29]. However, these systems are not designed to be highly portable, nor to be used as a measurement trigger source in offline and stand-alone operation, making it necessary for us to find a mobile, lightweight and low power consumption lightning detector. Based on sources in the literature review section /ref suggests the development and implementation of algorithms for real-time lightning detection in ground-based systems pose that topic to an already solved problem, which is only a part of more sophisticated lightning location and mapping systems. Unfortunately lightning detection in these systems is based on signal level detection. The signal level seems to be set to individual stations based on the analysis of datastream coming from the station by the network server. That simple solution is not suitable to detect lightning in generic electromagnetic noisy environments and requires station placement in electromagnetically quiet areas. There also exists a conference paper 10.1109/ICISE.2010.5689931 introducing an adaptive signal detection algorithm based on short-time energy detection and Constant false alarm rate (CFAR) for real-time VHF intracloud lightning signal detection. This adaptive approach is promising to enhance the performance of lightning detection systems in ground-based setups by dynamically adjusting to varying signal characteristics, but unfortunately the statistics of noise background needs to be known. Therefore that could be hardly used for mobile measurements. Therefore there is not an existing solution which could be obviously used for the planned research.

2.1 Off-the-shelf lightning detection

Initially I investigated the lightning triggering device based on AMS AS3935 integrated circuit and using a coil antenna. The device meets the requirements of mobility, and low power consumption. For measurements coincidence between ionizing radiation and lightning on aboard aircraft as example, the compact physical size of the device is also a considerable advantage, therefore the solution seems to be promising. Then I compared the performance and reliability of the detector with the Blitzortung lightning detection network. I choose Blitzortung as a network which has a good deployment in central Europe where the mobile measurements were performed. Therefore two detection systems were selected for atmospheric discharge detection in this study: the device based on the AMS AS3935 integrated circuit and a coil antenna and the Blitzortung lightning detection network [12]. Both these lightning detection systems use radio emission reception at VLF frequencies. The devices differ in the design and realization of the antennas and implementation of the lightning detection algorithm. The device equipped by AMS AS3935 uses LIGHTNING01A MLAB module with a coreless coil antenna connected as a resonant LC circuit (Figure 1). The resonant frequency of the coil antenna (MA5532-AE) with temperature insensitive C0G ceramic capacitors is matched at 500 kHz ± 3.5 According to manufacturer description the integrated circuit processes signals based on the signal level threshold detected by a comparator. If the comparator triggers, the proprietary signal processing unit algorithmically analyzes the signal. The output of the signal processing algorithm implemented in the AS3935 circuit consists of a classification of signal relevance: lightning discharge (8), artificial disturbance (4) or high noise level (1). The algorithm also determines the approximate distance and the estimated energy of the lightning discharge based on signal shape. The internal registers configuration for a measurement described below was set to “outdoor mode” by AFE_GB control register. All other registers are kept with implicit values. The circuit diagram including the AS3935 is shown in figure 2. The integrated circuit is powered by a 3.6 V from one primary lithium-thionyl chloride cell without usage of an integrated LDO (low drop-out) stabilizer. An I2C (Inter-Integrated Circuit) bus is used for communication with a data logger that also records data from pressure and temperature sensors. A GPS (Global Positioning System) receiver is used for logging of the precise time. The data is stored on a SDcard in a module [14]. A block diagram of the interconnections is shown in figure 3. The used firmware for the device is available at [15].

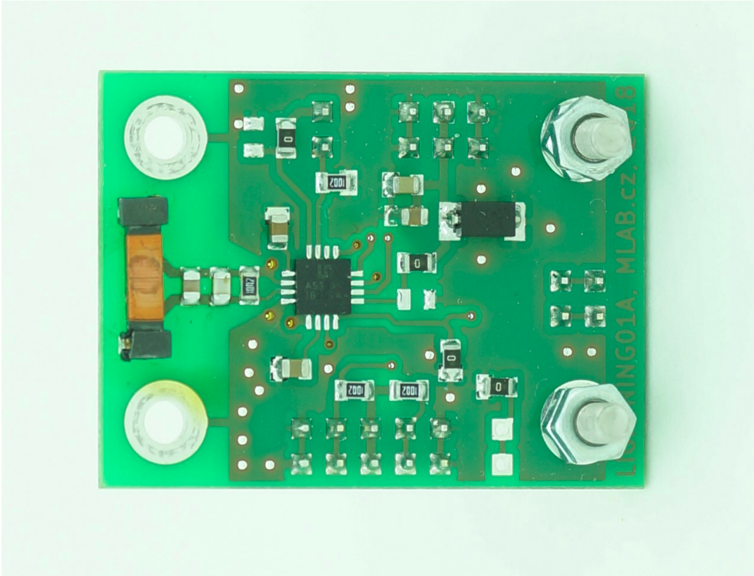


Figure 2.1. The bottom side of the LIGHTNING01A module [23]. The antenna coil is visible on the left. The tuning capacitors and Q limiting resistor are mounted on the right side from the antenna.

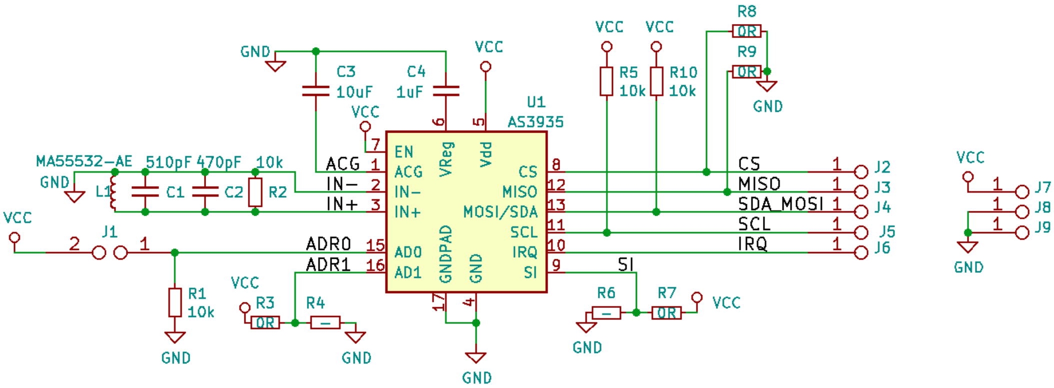


Figure 2.2. Schematic diagram of the lightning sensor based on commercially available AMS AS3935 IC (module LIGHTNING01A [23]).

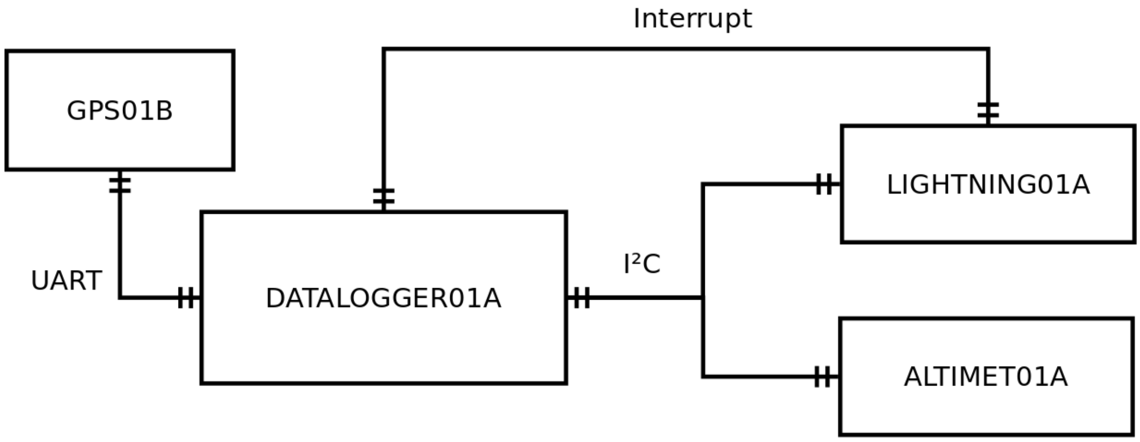


Figure 2.3. Schematic block diagram of the examined lightning detector. Detailed schematics of modules are available at [14], [22-24].

The time response of the lightning detector was tested in the laboratory prior to field measurements using a power signal generator with a wire loop of 60 mm diameter. The wire loop was placed at a distance of 30 mm from the antenna. The interrupt output was captured by an oscilloscope. Response time to a rectangular signal was 93 ms ($\pm$1 ms). The rectangular signal pulse was classified by the internal algorithm as a disturbance ("DIVIS4" output in the log file). The response time to the received signal was found not to be constant for each signal. Some pulses were classified as lightning ("DIVIS8" in log file) by the proprietary algorithm where response time was only a few milliseconds. Due to the time delay introduced by the algorithm, the device could be potentially used for triggering of other measuring devices by using a pretrigger recording buffer of maximal algorithm latency plus lightning duration. For a lightning event duration of less than 900 ms, a one second pre-trigger buffer was found to be suitable.

The proposed system, powered by a one LS33600 cell, can operate continuously for five days. Power consumption is dominated by the GPS receiver. Lifetime of the system without GPS is approximately three months. For measurements in the field, the instrument is mounted on the roof of a measurement car inside a waterproof plastic box as shown in figure 4.

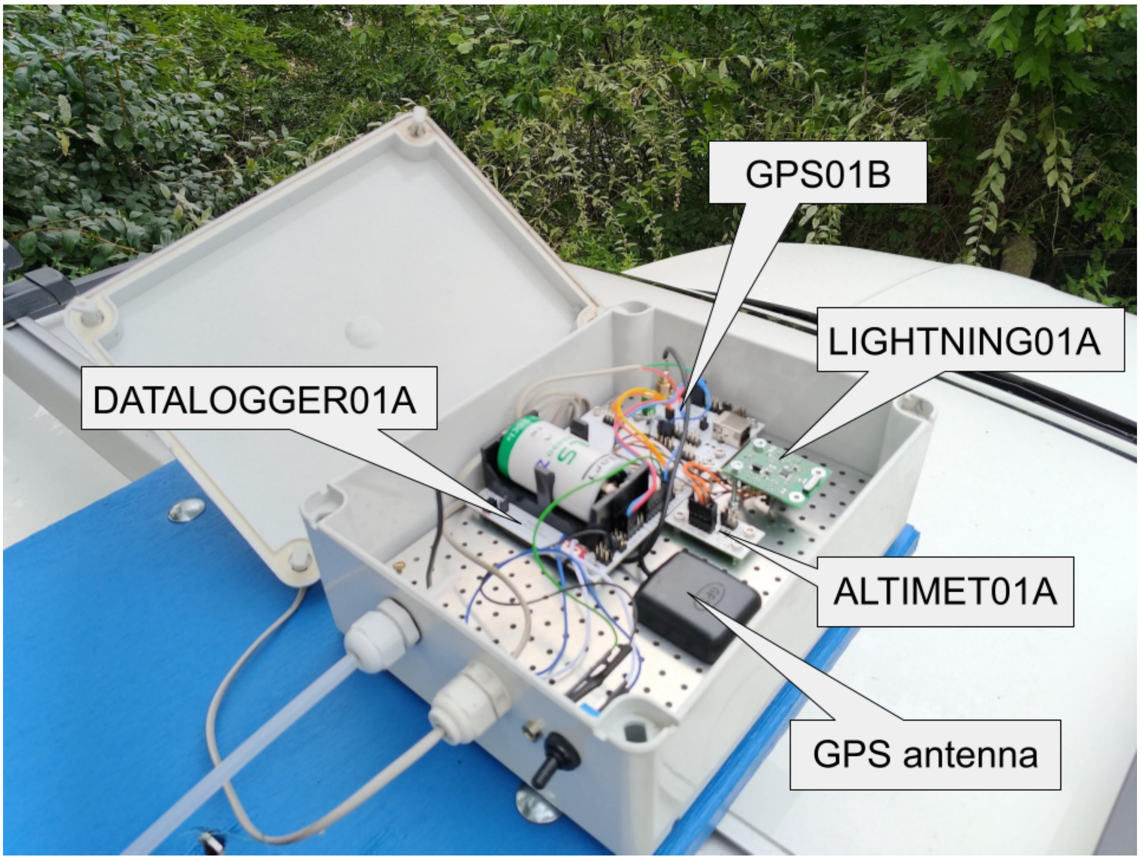


Figure 2.4. The examined deployment on the roof of a car. The module LIGHTNING01A [30] with antenna is located in the upper right corner of the box. Module with battery is DATALOGGER01A [31]. GPS receiver [32] is located in the upper left corner with connected black GPS antenna. Rest module beside LIGHTNING01A is ALTIMET01A [33].

[DIVISEK01_Deployment]

2.2 Blitzortung network

The second investigated option of triggering was the use of the Blitzortung.org network. Blitzortung.org is a World-Wide Low-Cost Community-Based TDOA Lightning Detection and Lightning Location Network [29, 34]. Blitzortung.org collects signals which are received by a combination of multiple magnetic loop antennas and electric monopoles deployed at network stations [34]. The configuration, implementation and sensitivity of stations are not uniform. There are multiple causes for these differences. e.g. - the network members have different hardware versions, different quality of maintenance and the antennas are mounted at different locations [1].

Such variance of network parameters could be considered as beneficial because it increases sensitivity to different lightning signal types. The most common implementation of the magnetic loop antenna in Blitzortung.org network sites consists of several loops of shielded coaxial cable, where the inner conductor is used for the magnetic loop itself and one end of the shield is connected to the antenna amplifier ground. The antenna is not tuned to specific resonant frequency. However, the goal of the station operators is to maintain the highest achievable resonant frequency [https://www.blitzortung.org/Documents/TOA_Blitzortung.pdf].

[1] https://www.blitzortung.org/en/station_list

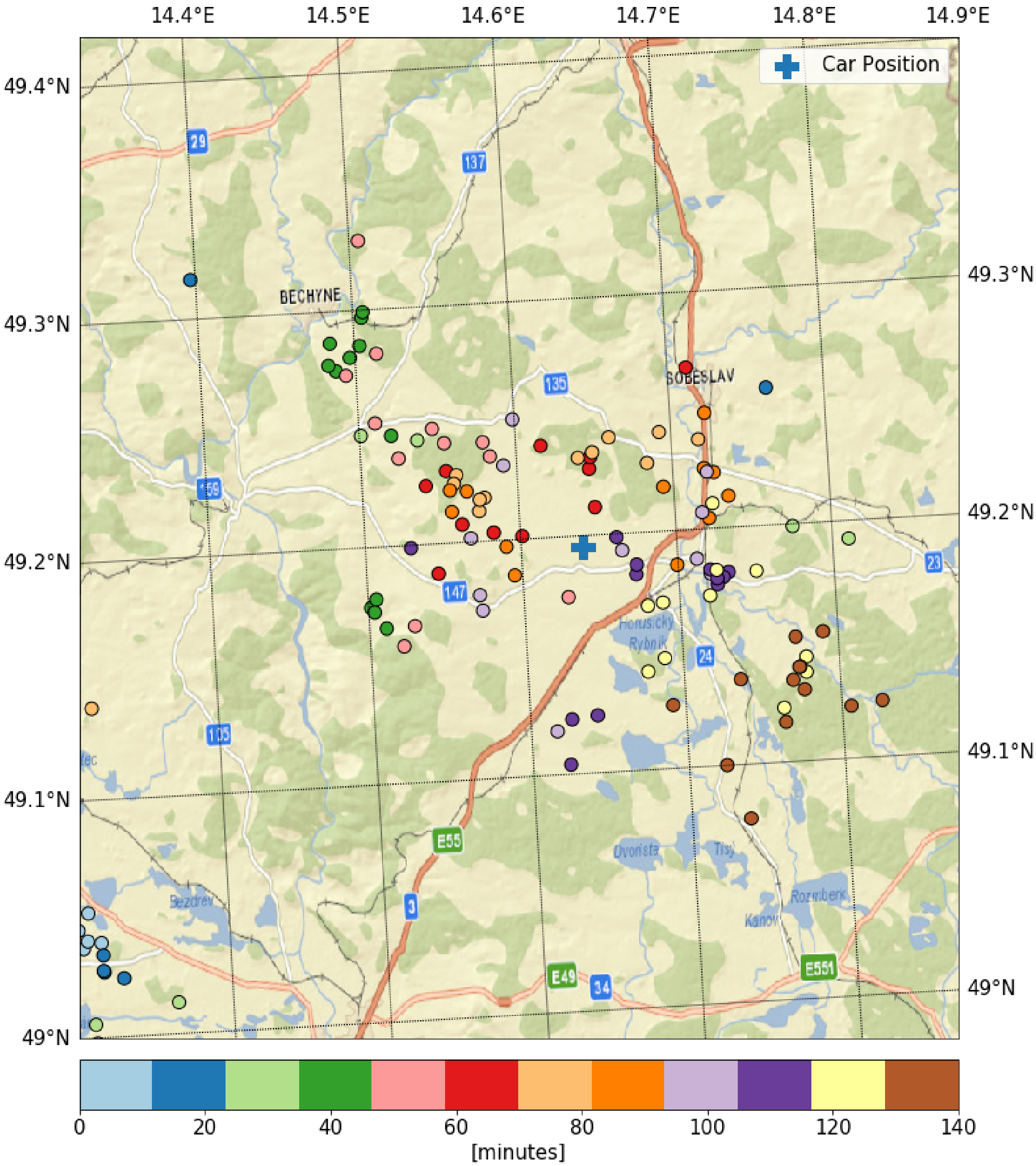
The Blitzortung controller outputs a 256 byte signal fragment covering the pulse with a time resolution of 1.95 s along with the timestamp of the trigger and metadata of the station location, GPS signal quality and validity of data. Detailed signal processing is carried out on the network server. The final results of the data processing in the Blitzortung network is the approximate location of the sources of each captured pulse. The signal processing is carried out in two steps. In the first step, a starting point is computed by a time of arrival algorithm [35] from the first four time stamps corrected for time of group arrival [36]. In the second step, a numerical method is used to minimize the sum of squared distances to the hyperbolic curves.

In order to use the Blitzortung as a recording trigger both the processed data from the server and use of the station itself were investigated. The usage of the Blitzortung station hardware was relatively quickly abandoned, because the station is not constructed to trigger on lightning signals in proximity of the thunderstorm. Therefore the station usually reaches something like an "overange" which is called an "interference mode" in Blitzortung.org terminology [2]. Practical result is that the station is not able to generate relevant triggers to lightning. Instead, it triggers very frequently. Sometimes the opposite situation arises - the Blitzortung station is able to see lightning far away, but is not able to trigger lightning in a near vicinity. The situation is dependent probably on the storm development and the terrain. Whatever, in both cases the station trigger output is not usable for triggering other devices. There is a possibility that the situation could be resolved by changing the Blitzortung station firmware, unfortunately the firmware is closed source, similarly to the exact implementation of location algorithms used on the servers.

2.3 Comparison of different triggering methods

During the triggering method development, the devices were regularly tested by a car measurement campaign. There could be shown an example of data captured during a thunderstorm near the village Borkovice, Czechia (car position 49.1949915 N, 14.639835 E, at altitude 427 m a.s.l.) on August 3, 2019 as shown in figure [37].

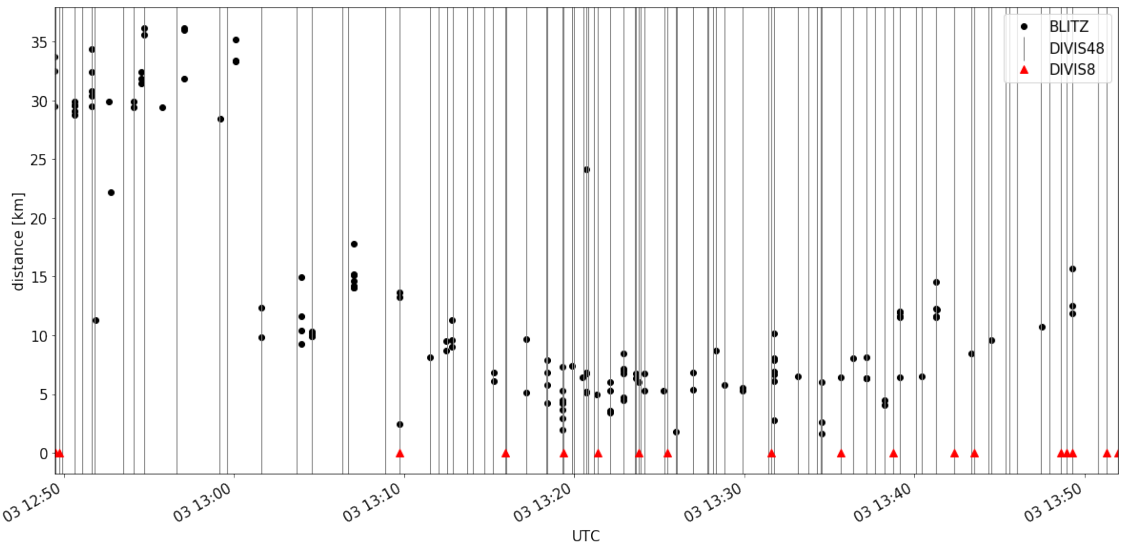
[2] `https://info.lightningmaps.org/doku.php?id=en:hardware:red:operation:interference`



[lightning_times]

Figure 2.5. The position and timing of a thunderstorm at Borkovice. The circles are positions of lightning registered by the Blitzortung network. Colour depends on the relative time of lightning after a measurement car stops. The car position is marked as a blue cross.

The timestamp of lightning detected by LIGHTNING01A was recorded with a 1 s accuracy. The Blitzortung network provides timestamps down to a 1 µs accuracy. Fig. 2.6 shows all lightning triggered signals in all devices over a time period from 12:49 to 13:52 UTC, a time interval during which the car did not change position. LIGHTNING01A distinguished between artificial discharges (depicted in the Fig. ?? as DIVIS4) and natural lightning (depicted in the figure as DIVIS8). Coincidences between LIGHTNING01A and Blitzortung.org detections are shown in Tab. 2.1. Nearest detections around the measurement car are depicted on the map in Fig 2.5. Tab. 2.1 and Fig. ?? are generated by algorithms realized by Jupyter notebooks [41]. Final assessment of binary time events data was done by a similar approach as described in a work [42].



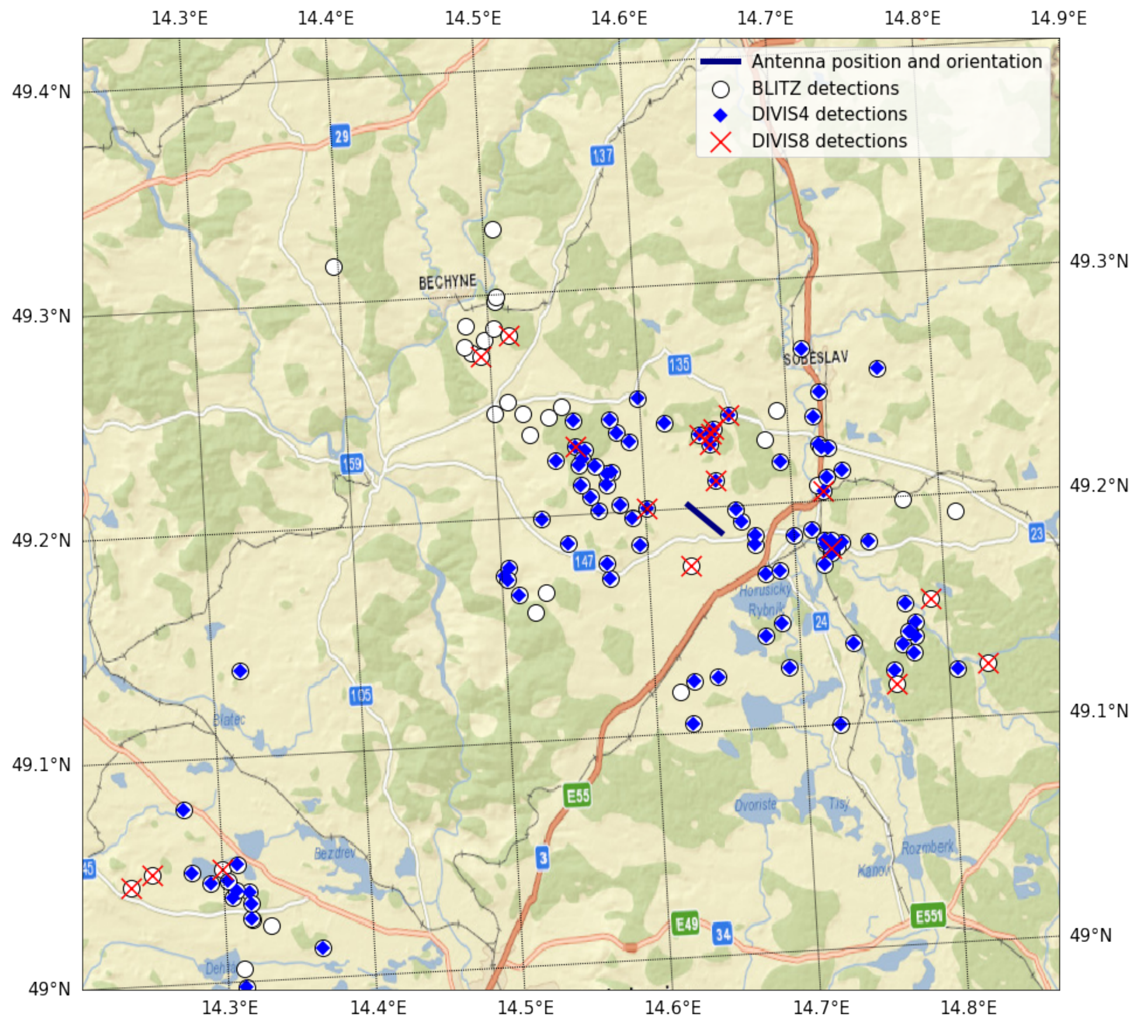
etection_timeseries]

Figure 2.6. Detections of the two studied methods. For Blitzortung there are detections labeled as BLITZ, vertical axis corresponds to the distance between the Blitzortung.org location and the fixed position of the LIGHTNING01A deployment. Vertical lines represent all LIGHTNING01A's detections (DIVIS48). Triangles pointing to detections recognized by LIGHTNING01A as lightning (DIVIS8). For LIGHTNING01A the vertical axis is not relevant, because the sensor does not provide a precise distance.

	Count	BLITZ5	BLITZ10	BLITZ20	BLITZ30
DIVIS48	DIVIS4	DIVIS8			
BLITZ5	19	1.000	1.000	1.000	1.000
0.947	0.895	0.368			
BLITZ10	78	0.462	1.000	1.000	1.000
0.872	0.846	0.141			
BLITZ20	109	0.358	0.844	1.000	1.000
0.798	0.734	0.147			
BLITZ30	123	0.317	0.756	0.894	1.000
0.797	0.732	0.138			
DIVIS48	128	0.164	0.453	0.492	0.539
1.000	0.875	0.156			
DIVIS4	110	0.173	0.491	0.527	0.573
1.000	1.000	0.018			
DIVIS8	18	0.111	0.222	0.278	0.333
1.000	0.111	1.000			

[t1]

Table 2.1. Table of coincidence rates among detectors. The presented values are the proportion of detections in the row-labeled detector for which there is at least one coincident detection of the column-labeled detector. The Blitzortung network is represented by virtual detectors BLITZ5, BLITZ10, BLITZ20 and BLITZ30, which are considered triggered upon a registered lightning in a 5 km, 10 km, 20 km and 30 km radius respectively around the LIGHTNING01A deployment. DIVIS48, DIVIS4 and DIVIS8 is the LIGHTNING01A detector with different filtering of candidate detections, DIVIS48 having the most lenient filtering. Count represents the absolute number of events measured for detector/conditions in each row.



ection_coincidences]

Figure 2.7. Map of Blitzortung.org detections with LIGHTNING01A coincidences displayed. White marks show positions of all Blitzortung.org detections in the region and time period of interest. If a Blitzortung.org detection coincides with a DIVIS4 or DIVIS8 detection, an additional blue or red mark, respectively, is placed.

The records produced by LIGHTNING01A allow to pinpoint the absolute time of detected event within a ± 1 s window. As a basic evaluation of LIGHTNING01A's fitness to trigger other measurement instruments, where coincidences were counted among LIGHTNING01A detections and detections from Blitzortung.org in multiple predefined radii. The coincidence rates obtained are presented in table 2.1. Events were considered coincident if they fell within a ± 1.5 s time window. This value for the window width was selected such that the absolute time uncertainty of LIGHTNING01A records, the latency of LIGHTNING01A response, and the duration of lightning phenomena, which may conceivably be in the order of hundreds of milliseconds, were accounted for. For window widths in the range of ± 1.2 s to ± 2.0 s, the coincidence rate between any pair of detectors does not differ by more than 0.05 from the table value, which corresponds to the window width of ± 1.5 s.

For illustration, those of Blitzortung.org detections which were coincident with LIGHTNING01A detections were picked out, and these are plotted on a map in figure 2.7. It should be noted that none of the systems compared here has 100% detection efficiency [??].

If Blitzortung.org is postulated as a reference system, it can be seen that LIGHTNING01A (see the column DIVIS48 in the table) covers 94.7% of Blitzortung detections in the range of 5 km (BLITZ5) and more than 79% in the range of 30 km (see the line BLITZ30 in the table). The detection of long-distance lightning is possibly influenced by the directional characteristics of the antenna. The sensitivity of the antenna (measured in the number of coincident lightning) is higher in the direction perpendicular to the antenna orientation (see figure 2.7; compare the sector around 49.0° N, 14.3° E with 49.3° N, 14.5° E).

It can be seen from table 2.1 that the proprietary lightning detection algorithm implemented in the AMS chip, which is supposed to distinguish lightning from man-made disturber, cannot be relied upon. Only 36.8% of lightning detected by Blitzortung.org are considered as lightning by LIGHTNING01A (DIVIS8). Therefore, all DIVIS8 and DIVIS4 events (DIVIS48) have to be considered. However, 42.7% of DIVIS4 detections are not registered by Blitzortung at distances up to 30 km. These are likely to be false detections or detections beyond the evaluated range of 30 km. Blitzortung.org network and LIGHTNING01A detector differ not only in sensitivity, but also in usability due to issues of network connectivity, power requirements, device size, and noise filtering capabilities. For most of these parameters, the LIGHTNING01A device was found only partially suitable as an electromagnetic lightning detector used in this work for terrain measurement. Blitzortung.org is designed to filter noise signals (false detections) by a network of detectors. Consequently, Blitzortung.org gives a useful trigger after the signal has been processed by a network server. It is done in seconds and it is too slow for the mobile measurement purposes. LIGHTNING01A has limited ability to reject autonomously noise signals which is important to avoid filling a memory of other instruments by data captured by false trigger signals, but this ability is not sufficiently robust.

However, the findings looked initially promising, because LIGHTNING01A is a lightweight, highly mobile, battery operated lightning detection system based on the AS3935 integrated circuit with possible application of radiation measurement in thunderstorms on board of aircraft.

This LIGHTNING01A is a suitable only for triggering terrain measurement devices (lightning discharges mapping device, ionizing radiation detectors, electric field measurement, etc.) with presumption that triggered devices are capable to record the data in interval at a least from one second before the trigger to one second after the trigger, which is caused of uncertainty of lightning trigger output from the AS3935 chip.

Additionally, for applications like ionizing radiation measurements, the sensitivity is considered too high, since lightning more than 10 km away from the ionizing radiation measurement venue is not of interest. The sensitivity of the AS3935 device can be decreased by increasing the level of the lightning detection threshold. This can be done by setting the internal SREJ or WDTH registers of the AS3935, as shown in figure 20 or 21 in the datasheet [??], but this also affects the overall sensitivity of the device. Therefore, the false negative rate for near lightning is increased.

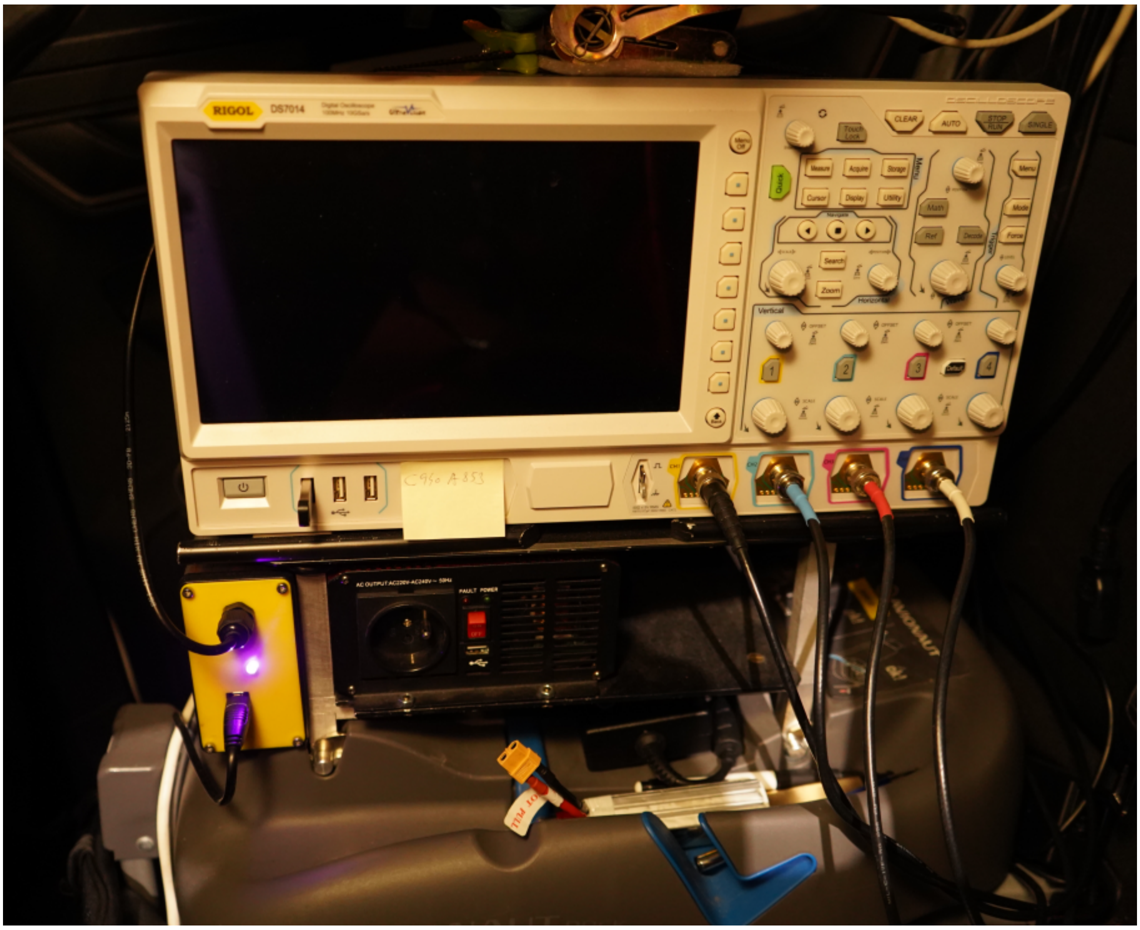
Only a slight directional sensitivity of the antenna was observed. This could theoretically be compensated by pointing the AS3935's antenna (or the whole measurement car) towards the thunderclouds; however, for close lightning within a 5 km radius, this effect is negligible. In conclusion I found out that a detector based on the currently widely used detection chip AS3935 has limited usability for purposes of lightning recognition and is not able to detect some discharges. Further search is therefore necessary in order to find a more reliable way of lightning detection and triggering during storm development.

2.4 Additional investigation of triggering methods

Since the previously mentioned method using existing commercially available solutions for triggering recordings proved to be insufficient during actual measurements, it was necessary to explore further possibilities. From the signal detection theory, if the signal is known and determined, the signal can be detected by using signal replication and correlation method or the matched filter method. However the lightning signal is time-space random and mostly uncertain (see typical lightning pulse description in Introductory chapter). Therefore there is only option to use the energy detection to detect the lightning signal. That approach is examined in the following paragraphs.

2.4.1 Using the oscilloscope to generate recording trigger

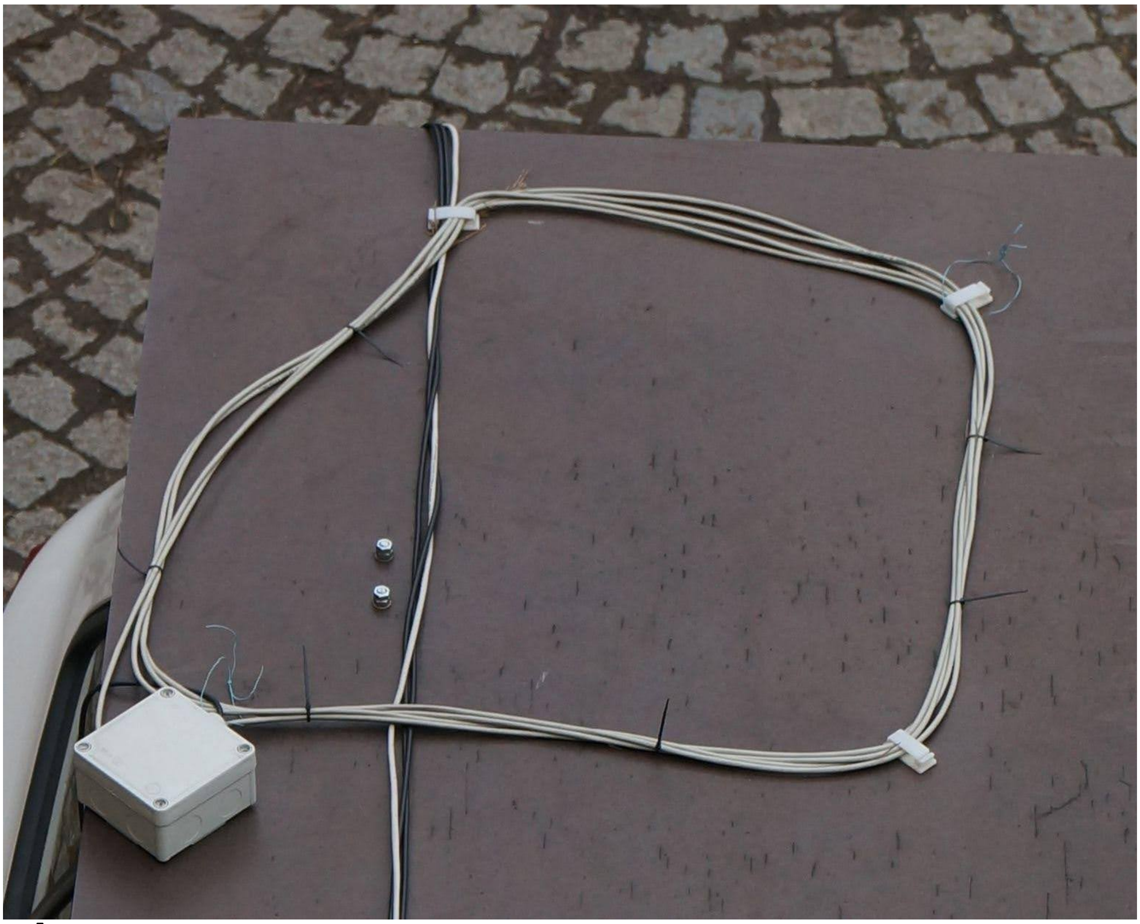
Because, the initial use of a VLF antenna or magnetic loop seemed to be suitable for capturing lightning signals in required quality. The additional search for trigger method was focused on the suitable signal analyzing methods.



[mounted_oscilloscope]

Figure 2.8. Oscilloscope used for lightning triggered recording on board of CAR1.

To address this challenge, a full-featured, fast desktop oscilloscope equipped with deep memory and with sophisticated trigger settings based on signal characteristics was utilized. Initially, a single loop VLF antenna made of UTP cable, originally developed for the Ionozor project, was connected to one of the oscilloscope channels. The antenna design was based on the use of VLFANT01 module, with the 10 m length, STP cable coiled into four loops (STP antenna). The STP antenna loops was placed horizontally directly at the plywood base mounted on the car roof. See Fig ??. for details. The oscilloscope was mounted on the back seat of the car by ISOFIX base and directly powered by a stack of Li-pol batteries totalling to 96 V. That solution was selected to completely avoid a possibility of noise generated from on board 230 V switching power supply in the testing car. Subsequently, various trigger settings on the oscilloscope during thunderstorms were tested. The most effective setting turned out to be one that activated the recording (oscilloscope trigger output) based on a combination of threshold level and pulse length. This result is logically justified by the fact that a lightning discharge is a high-energy event involving charge transfer over a significant duration. In a basic explanation, the height of the observed pulse corresponds to the rate of change in the magnetic field, and the duration corresponds to the charge being transferred. That trigger setup proved itself immune enough that the oscilloscope could be also later powered by 230 V power generated from 12 V car on board power by switching power supply, despite the fact the signal recording itself was heavily affected by interference coming from that power supply. Another advantage of that oscilloscope-based setup was this trigger setting ultimately allowed for the recording of the full length of the lightning discharge signal up to few seconds. However, the price for such a possibility was a long storage time corresponding to many minutes of dead time. The information gathered from these experiments and subsequently obtained from the recorded signals led to questioning of the assumptions stated in the introductory chapter. According to the structure of the signal, it was clear that the event was neither temporally nor spatially limited as described by assumptions based on literature and described in section (Introduction). To confirm this suspicion, however, it was necessary to obtain further supporting data, which led to the need to use an additional range of instruments and to mitigate the large deadtime introduced by oscilloscope recording.



[loop_antenna]

Figure 2.9. The one of initial variants of STP loop VLF antenna mounted on the measuring car CAR1 has a resonant frequency of 100 kHz. Its signal was directly sampled by an oscilloscope placed inside the car.

2.4.2 Manual trigger method

Although the trigger solution implemented with an oscilloscope proved relatively effective, it has certain drawbacks. One of the main limitations is the necessity to set the pulse level and pulse length parameters for each storm, and sometimes even for each phase of the storm. This characteristic resulted in the omission of some clearly visible lightning events, which the operator in the car was able to see, but the oscilloscope did not trigger. Although this disadvantage can be theoretically eliminated by using the `force trigger` button on the oscilloscope, such a solution was uncomfortable and also assumed that the oscilloscope was already booted up and set to the appropriate mode at the time. It thus appeared that a probably more suitable solution would be to add a button for manual trigger operation for all devices, regardless of oscilloscope state. That was achieved by adding a button to the car's gear lever as is depicted in the photo ??. This manual approach not only allows triggering of instruments before the oscilloscope is set, but it is also a comfortable solution for the driver to trigger while driving in a storm, where the driver often sees lightning in the storm, but resetting the oscilloscope while driving is not possible, as it would also have to dynamically change with the approaching storm.

Experimentally was also tested on a solution where multiple people sat in the vehicle, each visually monitoring their sector for the occurrence of lightning with a button in hand. That experiment has the result that the increase of sensitivity of multiple people is not proportional to increased manpower required. However, this visual based manual approach has multiple effects on recorded data. One of them is significantly decreased sensitivity of the human-generated trigger during daytime storms. There are even daytime storms where a person is unable to detect the occurrence of lightning discharges, but the trigger from the oscilloscope is recorded. Another effect, or perhaps more accurately a characteristic, is that such an implemented trigger is selective and lightning detected by this method contains a higher proportion of return strokes.

[Manual_button]

Figure 2.10. Manual triggering button mounted on manual gear lever suitable to be operated by the car driver during the thunderstorm.

The exploration of the manual and oscilloscope-based triggering methods has concluded that the most suitable solution is a combination of an algorithmic approach based on comparing the pulse height to a threshold and measuring its minimum duration before a trigger is executed. Additionally, a manual trigger is required to cover edge cases where the algorithmic trigger is not yet well-calibrated, but there is clear evidence of lightning. The specific implementation of the algorithmic trigger is discussed in subsequent chapters ??. It also takes into account the fact that the time delay incurred by using a manual trigger is less significant than the overall duration of the lightning. Therefore the resulting delay is not predetermined by a specific phase of the lightning, where the trigger will respond to.

Chapter 3
Proposed Instrumentation

To be able to record the different processes occurring during thunderstorms, the three cars were equipped with the specialized measuring equipment. The aim is to verify the hypotheses considering the relation between thunderstorm and ionizing radiation stated in the ?? chapter, because these cars were able to move to locations with predicted storm activity and thus flexibly react to specific storm developments, and perform ground measurements directly at the lightning site.

In order to determine the necessary parameters of lightning activity (lightning events' timestamps, lightning type, and location), the measuring cars, see Fig. ?? (CAR0 and CAR1), were equipped with a high-speed all-sky camera and radio receivers. The cars were used to transport and power the instruments in proximity to thunderstorms, and the car cabin also served as partial protection for the instrument operator.

The equipment of cars is not uniform as it is gradually improved and also the purpose of each car slightly differs.

[CRREAT_CAR0]

Figure 3.1. Measuring CAR0 with instruments mounted on the roof platform. Other cars were equipped similarly. The differences of instrumentation are depicted in diagrams.

3.1 High-speed all-sky Cameras

The two cars were equipped with high-speed all-sky cameras. Their purpose is to capture the lightning event evolution in parallel with recording from the other instruments, especially radio receivers.

Chronos 1.4 camera CR14-1.0-16M [chronos_datasheet] was mounted in a waterproof SolidBox 69200. The box is covered with a plexiglass dome with the manufacturer designation Duradom 200mm depicted in Fig high_speed_allsky_camera.

Chapter 4
Subsequent Experiments

Chapter 5
Summary of results

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Requests for correction

[rfc-1] Tady musím doplnit obrázek obrázek detekce meteorů z více stanic

[rfc-2] Tady musím doplnit obrazek odrazů od starlinku

[rfc-3] Tady musím doplnit obrázek