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Highly Distributed Data Acquisition on Wind Turbines with PAK

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Summary

As possible inland locations of wind turbines are mostly nearby populated regions, noise emissions have to be reduced to a minimum. These usually origin from rotating or vibrating parts. By applying accelerometers, microphones, and rotation sensors it is possible to correlate all relevant quantities, determine transfer functions and locate possible sound sources. In order to achieve meaningful results, data has to be collected at the nacelle, on the blades, the rotor, the tower itself and at various positions on ground level. Due to the size of a wind turbine, the application of sensors is rather difficult as cable lengths should be kept short for a high signal quality. Wiring distant positions is also quite costly. Moving parts, e.g. the rotor, do not allow a fixed wiring or a connection between distant locations. Further, the effects of environmental conditions, such as streets, creeks or even animals, have to be taken into account for the exact determination of the emitted noise. Hence, it seems reasonable to independently collect data at distributed measurement positions and use WLAN for data transfer. This allows an extremely flexible setup and still achieves phase synchronicity by using fiber optical cables or if possible a highly precise GPS clock.

1. Introduction

Wind energy is frequently considered as a key factor for the transition from nuclear to regenerative energy sources. Due to the dependency on environmental conditions, turbines require wind for operation. Possible inland positions are quite limited and often determined quite near to populated areas. Noise created by the turbine obviously influences the surrounding environment and disturbs residents nearby. Hence, the emitted noise has to be kept as low as possible, which is regulated by various standards, such as the IEC 61400-11 in Europe. These usually precisely describe the measurement method, including applied sensors, sensor positions, and the analysis that have to be executed. Currently the focus is set on sound power, 3rd octaves and tonalities computed at different so called wind bins. The quite complex measurement task has to consider various environmental conditions, such as wind speed and direction, the topography and has to deal with challenges setting up the measurement system.
Nevertheless it seems reasonable to apply further sensors, in order to be able to determine noise sources. This way it is possible not only to determine whether a wind turbine fails to fit the required standards, but also determine where alterations in the design have to be made. While the standard setup uses only few sensors and is not depending on phase synchronization, due to the alignment of averaged values with 60 s averaging time, an advanced R&D setup requires a by far more complex and careful measurement setup.
As quite large distances have to be covered in order to measure vibrations, rotational speed and emitted sound, the measurement setup can be quite costly and time-consuming. Furthermore the surrounding areas near the wind turbine as well as streets, creeks, buildings and animals have to be considered and eventually overcome during the setup itself.

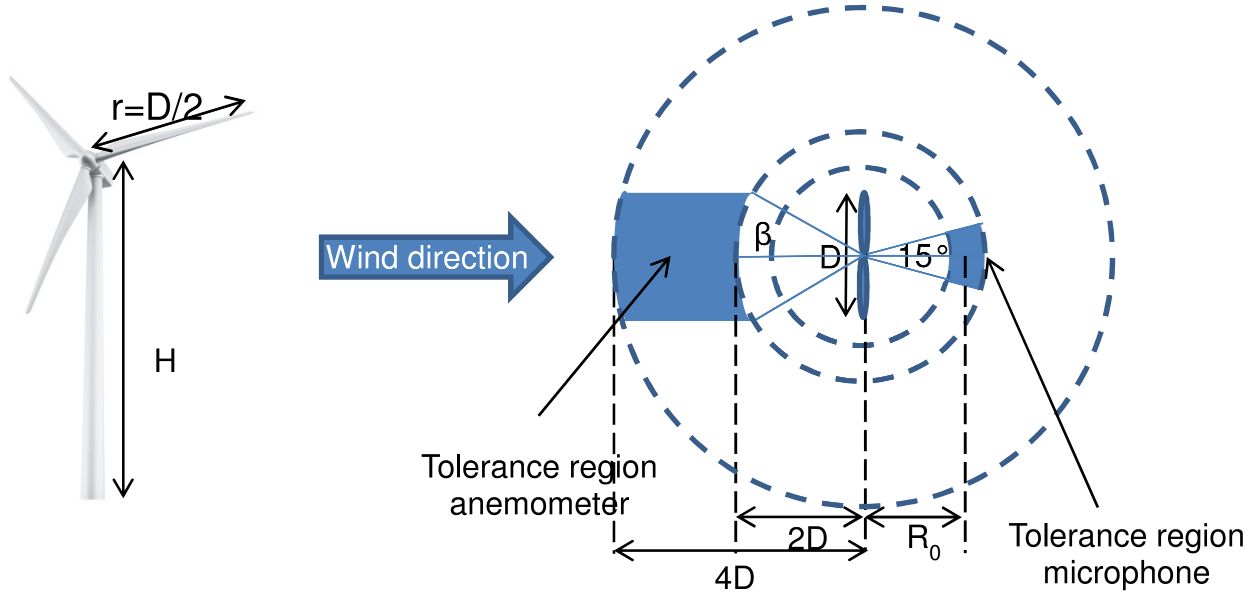

Figure 1: Top view of the basic measurement setup in accordance to IEC 64100. The possible locations for microphone and anemometer are indicated in blue

Unfortunately, the setup is further depending on environmental conditions, such as the wind direction and gondola position, which do not allow a fixed setup and requires frequent changes in the worst case. All analyses require a sufficient amount of data for each wind bin and each possible operational mode. Otherwise it would not be possible to sufficiently correlate unwanted effects to their cause. This requires a rather flexible system, allowing for rapid changes of the setup and a smart data organization supporting the user in finishing his task quite fast.
The present treatise will be structured as follows: In section 2 we will give a brief overview on the measurement setup required by the IEC 61400 and suggest some extensions for research and development, where possible noise sources are taken into account. Challenges with the standard and extended setup will be addressed in section 3, where both technical and environmental aspects will be covered. Subsequently possible approaches for a highly distributed setup will be presented in section 4, which is not only able to gather distributed data, but easy to setup. Section 5 contains a short conclusion of the presented solutions and will show up some possible developments in the future.

2. A Measurement Setup for IEC 61400 and parallel Engineering

The IEC 61400 requires a quite strict measurement setup, regulating applied sensors, sensor positions, and the dedicated analysis. As the analysis usually requires measurements of the operating noise and is corrected by the according background noise at the same microphone position. Hence, only the operating noise is taken into account without disturbing environmental noises.

2.1 The IEC 61400 Measurement Setup and Method The measurement setup is straight forward and is basically illustrated in Fehler! Verweisquelle konnte nicht gefunden werden..

Microphone and anemometer positions basically depend on the hub height H and the diameter of the rotor D. The optimum distance between tower and microphone is given by

$$R_0 = H + \frac{D}{2}, \pm 20\% \text{ , (1)}$$

while the microphone is positioned in a *15%* corridor behind the gondola. In case the wind direction and hence the gondola position changes, the microphone has to be rearranged and a new background noise has to be acquired. The anemometer is positioned in a distance in between *2D* and *4D* within the corridor

$$\beta = \frac{z - z_{ref}}{H - z_{ref}} (\beta_{max} - \beta_{min}) + \beta_{min} \quad (2)$$

in a height of apx. $z = 10\ m$ if possible and $z_{ref} = 10\ m$. Furthermore data monitored by the wind turbine itself, such as weather data at hub height, rotational speed, pitch, gondola position and produced electrical power have to be taken into account. While it seems obvious to record the noise during the operation of the turbine (ON – operation noise), an additional background noise BG, recorded at the exactly same position when the turbine is turned off, is required in order to be able to eliminate environmental influences. These can be other turbines located nearby, streets, wind, rivers, etc. which must not be taken into account within the analysis step.

2.2. An extended R&D setup While the previously described method is used to evaluate a wind turbine and judge whether it passes or fails the ordinances, it is inevitable to determine sound sources during the development process or after an installed turbine fails the evaluation. Hence, it seems reasonable to measure possible sound sources simultaneously, which can be correlated to wind bins, where the analysis show high sound powers or perceptible tones.

Most of the sounds are usually generated by moving parts, such as the blades, the gear box and the tower itself. Here both rotational speed and vibration have to be considered as possible noise sources. Although microphone arrays can be used for sound localization, as stated by R. Ramachandran and R. Dougherty, their use is frequently dismissed due to the effort and cost in the design and construction of an array. Its dimensions have to be quite large in order to cover low frequencies and a high resolution. Most arrays are only capable to determine whether the noise is emitted by the gondola or the blades, which does not represent sufficient information for troubleshooting or possible redesigns. Hence, other solutions need to be determined.

Therefore, we suggest further sensor positions on gondola, blades and tower, as exemplary illustrated in **Fehler! Verweisquelle konnte nicht gefunden werden.**. These include accelerometers, which will support the detection of noise sources and the determination of possible transfer paths, as suggested by J. Putner et al. Further, these can be aligned to the recorded sounds and be included in the frequency analysis. The gondola is further equipped with additional microphones, which can be correlated to the distant microphone easily. In a last step the gear box is equipped with sensors picking up rotational speed, allowing the correlation of frequencies in air and structure borne vibrations to the current state of the wind turbine. In total an additional amount of 10 microphones, 2 rotational sensors and 60 accelerometers are used to analyze the wind turbine in depth.

Figure 2: Exemplary positions for additional accelerometers, microphones and rotational sensors

3. Challenges for a Standard Measurement Setup

It is commonly agreed that meaningful measurements require suitable measurement positions. While it frequently seems easy to determine points of interest, it is a challenging task to collect the data from varying points simultaneously. Both technical and environmental issues have to be overcome in order to conduct a reliable measurement.

3.1 Technical issues The first thing coming to one's mind are technical issues with cabling. An old rule of thumb states that the distance between sensor and measurement frontend has to be kept as short as possible. Various reasons lead to this assumption. First of all cables and cabling cost money. In order to achieve a high signal quality and keep the signal to noise ratio (SNR) high, cables require a high quality standard. Furthermore, it is quite laborious to apply sensors at distant positions and connect these with a centralized frontend. Besides economic reasons signal quality has to be taken into account. Various sensors can be used with a quite limited cable length anyways. Table 1 shows some selected maximum cable lengths. Although ICP® and microphones can be driven with quite long cables without any problems; others have by far shorter ranges, especially considering charge and strain gauges. Obviously the average length is by far smaller than an average wind turbine with a hub height of approximately 100 m and an average blade with 73 m length. Hence, it is required to find a suitable solution for each applied sensor.

Furthermore it is frequently not possible to apply cables, e.g. between hub and nacelle, as there are moving parts in-between and OEMS usually do not install a loop through for a wide range of signals.

Sensor Type	Maximum length
Microphones	100 m
ICP®	100 m
Strain Gauges	10 m
Hot Strain Gauges	5 m
Charge	15 m

Table 1: Overview of maximum cable lengths for selected sensors

3.2 Environmental Challenges As wind turbines are usually rather located in a more or less public region than in an acoustic test bench, environmental conditions have to be taken into account additionally to the previously mentioned technical limitations. These are primary influenced by the surrounding topology, as illustrated in Fehler! Verweisquelle konnte nicht gefunden werden., where trees, creeks, streets, buildings or even animals can embody obstacles one has to overcome. All these factors harden a direct cabling with a centralized data acquisition system. Furthermore, wind turbines are usually built in farms, where noise emitted by neighboring plants is influencing the acoustic analysis. Obviously other objects may also disturb the measurement. Therefore possible sensor positions are even more considering wind speed and direction. Nevertheless, the IEC 61400 requires the recording of a so called background noise at each microphone position. This will be used to correct the recorded operating noise according to the corresponding wind speed; in addition the measurement setup has to be rather flexible in order to cover all possible combinations of power curves, wind directions and wind speed. Consequently both the hardware setup and the data management have to be designed in an easy to handle manner, where little effort is required to change the required settings.

Figure 3: Exemplary influences on the measurement setup. The trees, the street and neighboring wind turbines influence the acoustic measurement

4.0 Distributed Data Acquisition

The previously mentioned limitations for data acquisition in complex environments, such as a wind turbine, require a specialized system allowing distributed data acquisition near the points of interest. Such a system has not only to overcome the presented difficulties and provide correct data at a reasonable effort and cost. A few possible solutions will be presented in the following sections.

4.1 Common Approaches Within the last few years various approaches for distributed data acquisition have been implemented and have been applied in a wide range of applications. Fehler! Verweisquelle konnte nicht gefunden werden. illustrates possible setups with differing scope and level of performance.

The most common setup is shown in Fehler! Verweisquelle konnte nicht gefunden werden.**.a)**. Here, the analog signals from a wide range of sensors are collected and digitalized by one central PAK MKII frontend. The data is subsequently transferred to a Workstation or Laptop via LAN or WLAN. Data is stored with a maximum rate of 40 MB/s, corresponding to 48 channels sampled with 204.8 kHz and quantized with 24 bit. The main advantage of a direct link to a PC is the possibility to monitor the measurement and therefore the wind turbine online. Further, it enables the engineer to conduct analysis, such as spectra, psychoacoustics, and order tracking, online, which allows immediate conclusions and trouble shooting. As already mentioned in **Section 3**, the length of cables, especially for sensors, appears to be crucial. Hence, a first step in more reliable distributed data acquisition has been installed applying multiple PAK MKII frontends, as illustrated in Fehler! Verweisquelle konnte nicht gefunden werden**.b)**. All frontends can now be placed near the required sensor positions, keeping the length of cables short. The distance between frontends is basically only limited by the network connection used for data transfer. Applying fiber optics distances of approximately 1 km have been achieved in operating conditions. Further it is now easily possible to increase the channel count, without the need of more powerful controllers. The data digitalized by each frontend is now again transferred to a central PC. The maximum transfer rate is limited by the network and accounts for 40 MB/s. While a wide range of analysis is not depending on phase synchronization, e.g. alignment of averaged values or the overall level, especially transfer functions can only be determined correctly in case the data is aligned even in the phase information. Commonly frontends use individual clocks and therefore sample at slightly varying time stamps. Because of that a centralized clock is required and distributed via fiber optics, as indicated in red in Fehler! Verweisquelle konnte nicht gefunden werden..**b)**. In this way a phase error of 0.2% is achieved at a frequency of 10 kHz. With a growing amount of sensors and the desire for high sampling rates, the current maximum data rate of 40 MB/s is limiting for the

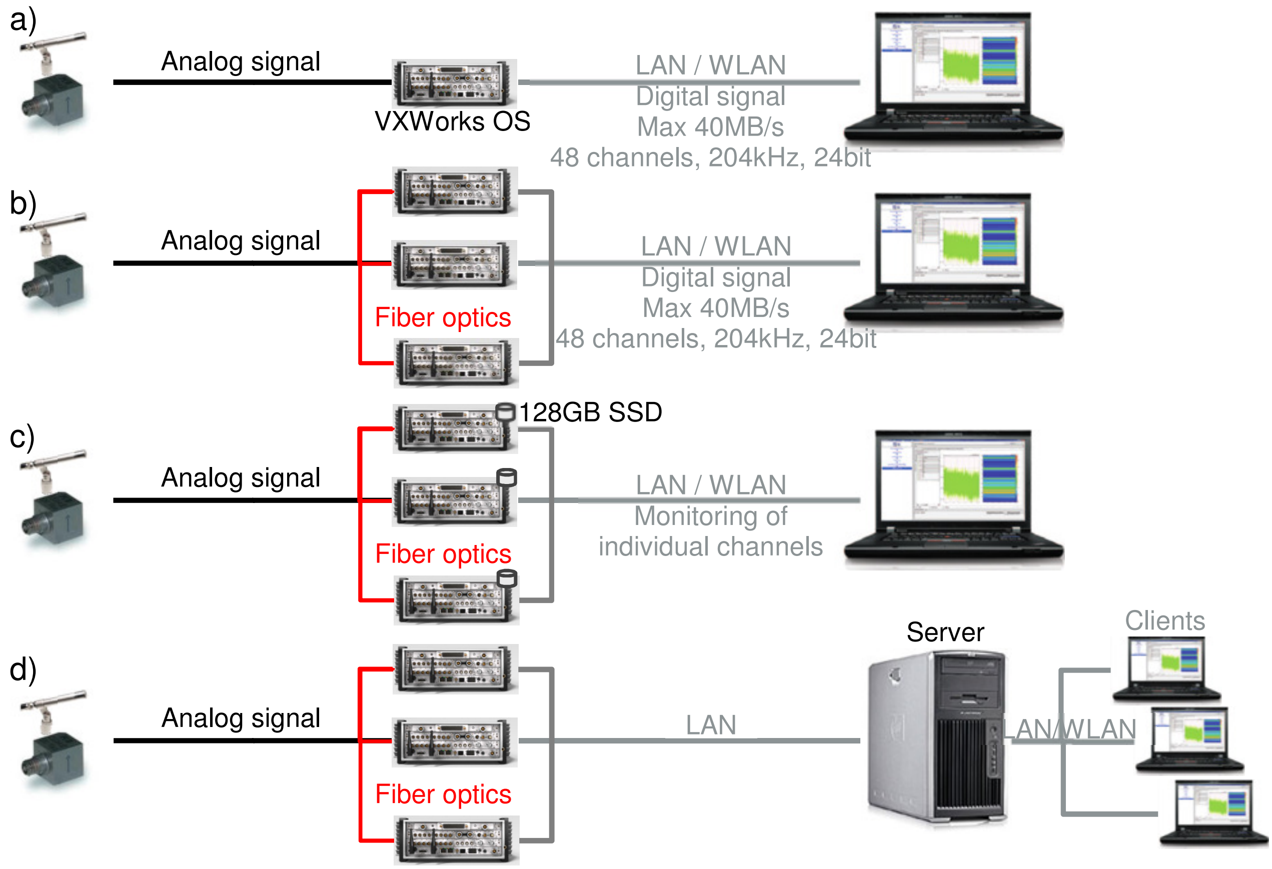

Figure 4: Overview of different approaches for distributed data acquisition. a) A centralized frontend and immediate data transfer to a PC. b) Multiple synchronized frontends and centralized data storage on a PC. c) A cluster of synchronized frontends with local storage and a monitoring system. d) A cluster of frontends within a server-client setup, allowing data distribution to selected clients without interference to the current measurement campaign

measurement task. Therefore the approach illustrated in Fehler! Verweisquelle konnte nicht gefunden werden..**c)** is applied for high channel counts and a vast amount of data. Each PAK MKII frontend is now equipped with an internal SSD, the so called Local Storage, where the data is stored in the first place. A selected amount of channels can nevertheless be transferred to a PC for monitoring and analysis purposes. This way each individual frontend is able to store 40 MB/s on the internal hard drive, allowing a seemingly unlimited amount of channels with sampling rates up to 204.8 kHz. Phase synchronization is once more achieved by applying a centralized clock and its transfer via fiber optics. Due to the system's stability and the limited amount of data that has to be transferred to the PC a direct link through WLAN is also possible. After finishing a measurement campaign, the data stored on the single frontends is transferred to a PC via network and merged to one large dataset. This way the user can work with a single set and has no further effort in data management.

4.2 A Server-Client based topology In order to analyze a wind turbine in detail not only a large amount of sensors is required but also a long phase of data acquisition – all possible wind speeds and power curves have to be captured – is needed. With the setup described in **Figure 4c)** the PAK system enables the engineer to monitor and record data from distributed measurement points over a long time. Nevertheless it is frequently required to access data for other purposes, e.g. providing data for colleagues from other departments like aerodynamics, acquire data only in case predefined events occur or even change parts of the setup without interrupting either monitoring or data recording. Therefore a Server-Client based technology has been introduced in the past, allowing fast and reliable access to selected data, as illustrated in **Figure 4d)**. The data acquired by the individual frontends is managed by a central

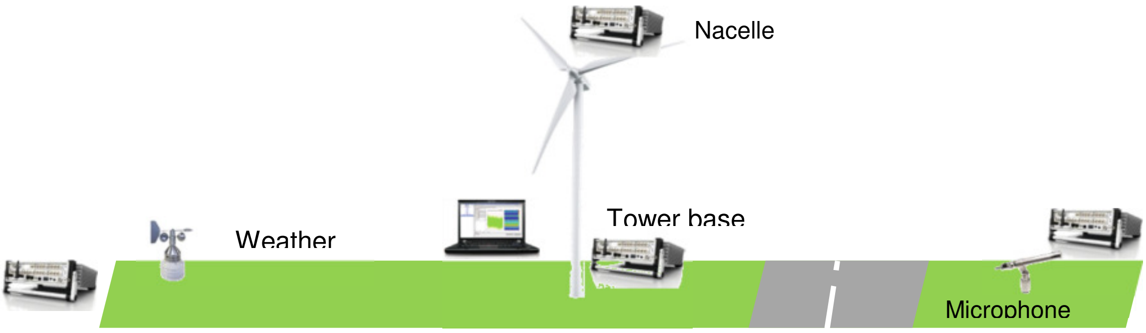

Figure 5: Exemplary wireless setup for a measurement campaign at a wind turbine

server. Its task is monitoring the measurement in the first place and managing changes in the measurement setup. In the second place its task is to distribute data to attached clients. These can be connected during any phase, either at the start of the measurement or even during the measurement itself, and record and analyze the entire data or only a selection of channels of interest. The server is now capable to fulfill the clients request or deny it and provide only a specified selection of data. This is important as not all the users should be able to access all relevant operational data of the wind turbine. E.g. a consultant for blade design does not necessarily need the currently emitted electrical power and the current rotational speed of the gear box. Data access is hence limited to a predefined user group.

4.3 A Wireless Solution The previously described approaches for data acquisition still require at least one cable to each frontend. These are usually Ethernet cables for data transfer and fiber optics for phase synchronization. Although the number of long cables can be kept quite low and both Ethernet and fiber are standardized and affordable cables, these cannot be applied in each situation. Therefore we suggest an entirely wireless solution as illustrated in Fehler! Verweisquelle konnte nicht gefunden werden.. As can be seen all PAK MKII frontends are placed directly at the points of interest keeping the rest of the cables as short as possible. Applying local storage enables the user to set up a WLAN at the technical limits, as the transferred data is negligibly. Only control command, such as start stop or automated range detection, are transmitted. In case at least some of the channels have to be monitored, only the selected ones are transferred without interfering with the measurement. Even in case the wireless network fails, the measurement will be continued with full data integrity.

5.0 Conclusions and Outlook

In the present treatise we have provided an overview on current state of the art data acquisition for acoustic analysis of wind turbines. While the setup required by the IEC 61400 is only used to evaluate a wind turbine and only considers electrical power, wind speed and sound pressure at predefined positions, we suggest extending the setup to a wide range of additional sensors. These collected data can be subsequently used within the R&D process in order to determine the reasons for possibly disturbing tones or high sound power levels. This is usually performed by applying rotational speed, acceleration and sound pressure. As distances between desired sensor positions are quite large and cabling cannot be handled easily in every situation, a distributed data acquisition system is presented. PAK MKII frontends can be placed near the sensor location, guaranteeing a high quality signal, and the reliable storage on internal hard drives. If required, phase synchronization can be achieved with one additional fiber.
Nevertheless further developments and research will take place in the future to enhance the measurement and simplify the setup. As a first step an entirely wireless solution, where even phase synchronization is granted, has to be found. Therefore a central clock, which is in sync even over large distances, has to be established. First trials have shown promising results using the GPS clock, which is highly precise, and can be used to trigger at the exactly same time stamps and providing low phase error.

The current setups can be performed rather fast and flexible. Yet they require an expert, as there are various error sources that have to be monitored. Further it is designed as “One man System” where one operator can setup and monitor the measurement. He also has to observe and detect unusual events in which the measurement has to be triggered. As especially the

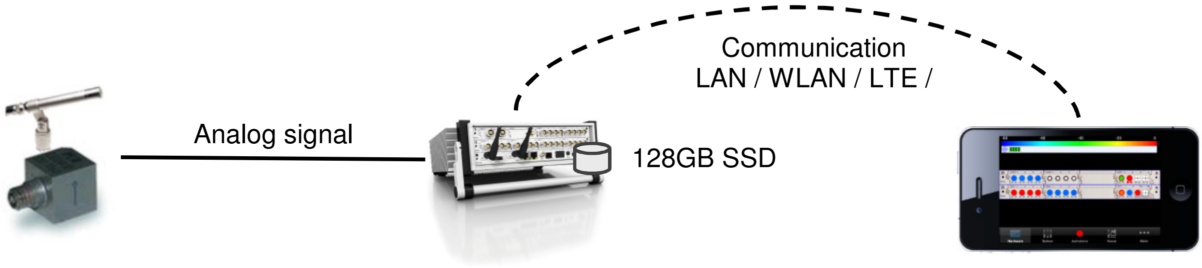

Figure 6: A look into the near future: Individual PAK MKII frontends are monitored with smart devices

monitoring task is rather exhausting and experts are quite expensive, a remote solution needs to be designed. As an alternative parts of the population living nearby could be instructed to trigger the measurement in case of unusual events. Therefore **Fehler! Verweisquelle konnte nicht gefunden werden.** allows a peak into the near future. Each PAK MKII frontend is equipped with an additional processing unit and a server. This will provide all data required for operation and transfer it to a smart device based on iOS or Android. All the controls can be easily performed and only the data required for visualization purposes is transferred to the smart device. This will allow the access and monitoring from almost any point in the world, provided an operational internet connection, and easy handling.

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