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# Conceptual design for an ultra-sensitive bioaerosol detection system

Julian Soltau*[a], Arne Walter[a], Lea Fellner[a], Marian Kraus[a], Karin Grünewald[a], Frank Duschek[a]
[a]German Aerospace Center, Institute of Technical Physics, Im Langen Grund, 74239 Hardthausen

## ABSTRACT

The detection of aerosols in general and bioaerosols more specific has gained an increased importance in multiple fields. While environmental scientists are increasingly interested in the impacts of aerosols onto climatic effects, researchers in the security sector are looking for ways to remotely detect dangerous substances from safe distances. Additionally, due to the corona pandemic, the detection of bioaerosols has gained significant relevance in sectors like public health, transportation, and aviation. As a result, more accurate, i.e. sensitive and specific, measurement equipment is needed. Here we present the design concept for a new sensor system designed to measure thin bioaerosol clouds. For the detection air samples are excited with laser light to generate a signal based on laser induced fluorescence. The fluorescence is collected in an integration sphere to optimize signal. Inside the integration sphere multiple sensors are placed, each combined with a filter to exclude all signals not belonging to a certain, agent specific wavelength interval. Through the intelligent combination of spectral intervals, a specific characteristic of the studied air sample is measured. Based on the measured characteristic a classification is performed to determine the category of the sample. Development aims at testing indoor air quality in real time.

**Keywords:** bioaerosols, aerosol detection, laser-induced fluorescence, real-time

## 1. INTRODUCTION

### 1.1 Motivation

A release of biological hazards requires a fast detection as well as a fast assessment to determine suitable counteractions. While the threat through contaminated surfaces is long known and has a lot of ongoing research regarding the safe detection of hazardous substances and the corresponding decontamination, the COVID-19 pandemic demonstrated the incredible danger of aerosols for the spread of biological hazards as well as the lack of options to detect them. This clearly demonstrated the need of means for the detection of bioaerosols, which is not just limited to the security sector but also effects the public health and transportation sectors as closed spaces with limited air circulation are the most vulnerable regarding the spread of aerosols. While the impact on the transportation sector is one of the most severe it is not limited to transportation, other public space like schools or hospitals are also heavily affected by this. Therefore, new means to detect bioaerosols are needed to prevent the build up of dangerous aerosol concentrations by an early detection.

### 1.2 Goals

Our goal is to develop a new ultra-sensitive monitoring system for the detection of bioaerosols. The monitoring system itself should be able to automatically detect bioaerosols within its direct vicinity and perform a classification of the detected substances in order to provide a threat assessment. This requires a compact sensor system, which can be deployed at various locations. Furthermore, the system needs to work without a human operator as it is meant to continuously monitor the surrounding area while providing its information in real-time, in contrast to a system that is only deployed if there are already suspicions regarding a potential contamination. In order to fulfill this task, the sensitivity of the system has to be optimized for thin aerosols, which allows a fast detection and corresponding fast counteractions. The concept for such a monitoring system for indoor environments will be described in this paper.

*julian.soltau@dlr.de; phone: +49 629828794; www.dlr.de

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## 2. SYSTEM CONCEPT

### 2.1 Requirements of an aerosol monitoring system

In order to provide meaningful information, an aerosol monitoring system needs to fulfil a series of requirements. First of all, there are the problems caused due to the intrinsic nature of bioaerosols within indoor environments as their individual concentrations are typically very low compared to the other particles within the air. This makes a very high sensitivity mandatory for the monitoring system to be able to reach the necessary detection limits. Furthermore, other substances present in the measured volume will interfere with the measurement leading to artifacts within the signal that are unrelated to the substance of interest. Those detection artifacts make a very high specificity a requirement for the monitoring system.

Aside from the requirements resulting of the aerosols themselves there are also functional requirements in order for the monitoring system to be valuable. First of all, there is the capability to provide information about potentially dangerous aerosols in real-time. If the monitoring system were only capable of recording data, which has to be analyzed on a separate computer later on its value would be greatly diminished as the exposure to a hazardous substance can only be verified in the aftermath in contrast to a direct warning. Additionally, the system needs to be able to operate continuously without interruptions and while it does so it also has to adhere to standards of operational safety. Both of these requirements mostly affect the specific design of the system rather than the fundamentals of the detection, but are also essential for an effective use of the system.

Similarly, the choice of components is also important. Without considering the current scarcity of electrical components, the different requirements have implications for the usable components and those implications are not necessarily compatible. For example, the detectors used in the system need to have a very high sensitivity in the spectral region of the signal and have a high angular acceptance in order to provide to reach the required detection limit, while also featuring a readout timing that still allows a real-time processing of the recorded signal.

### 2.2 Design concept

For the method of detection laser-induced fluorescence (LIF) was chosen as it is already successfully used in the standoff detection of bacteria [1]. This success is based on the fluorescence of multiple amino acids, which are present in all pathogens and thus makes it possible to detect those. Furthermore, fluorescence yields higher amounts of signal when compared to other options like Raman spectroscopy. The larger signal is of importance for us as the higher signal yields help with the very low detection limits. For our system the excitation will be performed by the use of pulsed UV lasers with the wavelengths of 266 nm and 355 nm. The resulting fluorescence spectra are expected to be in the range of 300 to 700 nm. Out of this range a selection of 7 – 32 spectral channels will be used for the classification of the measured sample.

For the collection of the generated signal an integrating sphere will be used. This allows an almost full coverage of all angular directions and therefore, the full collection of the signal. Through reflections inside the integrating sphere the signal photons are redirected inside the sphere until they reach an exit, which will have a detector in order to measure the exiting photons. For the detection multiple detectors will be placed on the sphere with each of them having a spectral filter in front of them making it possible to assign specific spectral channels to specific detectors. By doing this each detector will represent a specific spectral channel and all detectors together will form the set of selected channels used for the classification. Another advantage of the integrating sphere is the closed setup, which will ensure part of the operational safety as the laser light used for the LIF detection is contained within the sphere. Therefore, no problems are expected regarding eye safety or the scattering of laser light inside the room.

The signal measured by the detectors will be readout and the measured data will then be processed by a FPGA. There a preprocessing of the data will be performed to optimize the performance of the following classification. For the classification the recorded spectra will be evaluated via machine learning. The necessary model will be trained based on previously measured data. The focus of the classification will be to detect biological aerosols and evaluate their threat. Beyond the processing of the data, the FPGA will also be used to control the monitoring system.

## 3. THEORETICAL EVALUATION

To verify that the signal generation within the monitoring system is sufficient to be measurable an estimation of the signal was performed. The equation used was inspired by LIDAR calculations, but was heavily modified as the detection mechanism is fluorescence and this is not a ranging application. The used equation is the following:

$$P_{\text{Signal}} = P_{\text{Source}} * G * \sigma * T.$$

$P_{\text{Signal}}$ is the measurable signal, $P_{\text{Source}}$ represents the excitation energy, $G$ describes the detection volume, $\sigma$ is the fluorescence cross section and $T$ the combined signal losses within the detection volume. For the sake of simplicity, the calculation was performed for the excitation with a single laser pulse but the generated signal is the same for the excitation over multiple pulses as long as the sum of the pulse energies is the same.

For the practical implementation this combination will be determined by three factors: The pulse energy of the laser, its repetition rate and the time available per measurement, which limits the amount of pulses in combination with the repetition rate. Each of these factors has their own limits. For the pulse energy these are the cost and size of the laser on one hand but also a saturation of the fluorescence on the other hand as only a limited number of particles is inside the detector volume and at some point, all of them are already in an excited state. The repetition rate is limited by the cost and size of the laser as well but also by the speed of the readout electronics. Regarding the time the main limitation is the requirement of a real-time measurement, which allows measurement windows in the order of seconds at most.

In contrast $G$ is mostly determined by geometrical aspects of the sensor system. The size of the beam spot as well as the dimensions of the aerosol stream inside the system are relevant to calculate the detection volume from the intersection of both areas. With this information the number of particles in the detection volume can be determined based on the concentration of the aerosol. The number of the particles in conjunction with the substance specific fluorescence cross section $\sigma$ yields the number of expected fluorescence interactions. For this calculation different substances and thus fluorescence cross sections have been used in order to understand the expected signal for different kinds of aerosols. The cross sections used were taken from [2].

Lastly, the signal losses in the detection volume given by $T$ have to be considered. There are multiple kinds of absorption losses, which are relevant as the signal can be absorbed by different particles in the detection volume or in the reflection process due to the reflection coefficient being lower than 100%. Furthermore, the signal photons can be scattered out of the system or outside of the acceptance angle of the detector.

Figure 1 gives an impression of the expected sensitivity of the monitoring system as calculated by the formula. While this plot shows a clear correlation, it cannot necessarily be extrapolated for any energy or concentration as it is influenced by saturation and quenching effects, which lead to a different behavior. For this plot a concentration was assumed as measurable if $P_{\text{Signal}}$ is in the order of $10^3$ photons. While lower amounts of signal are certainly detectable this value was chosen as losses of the detector are not yet included, which gives us greater freedom in the choice of the detectors later on. Furthermore, the higher signal means that noise from the electronics will not affect the measurement as much as it would for smaller signals.

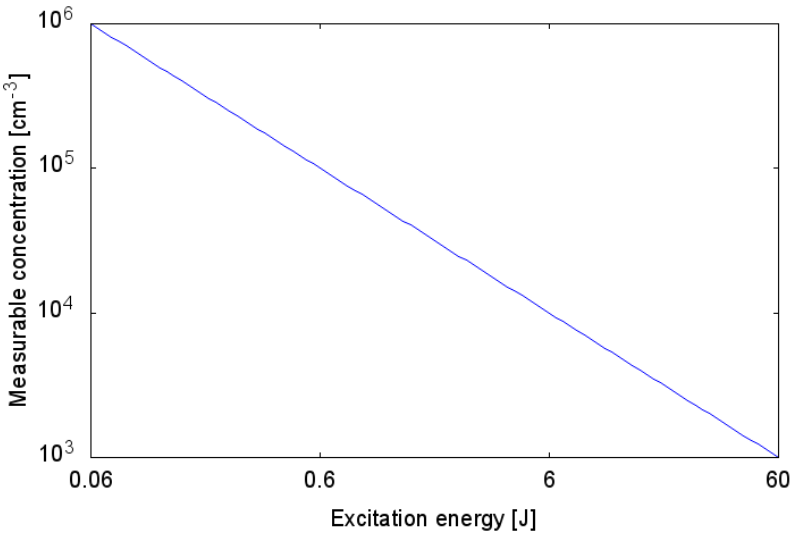


Figure 1. The calculated measurable concentration according to our estimation based on the used excitation energy for a fixed signal strength of $10^3$ photons.

## 4. CONCLUSIONS AND FUTURE WORK

### 4.1 Summary

Through this paper, we have presented the concept for a new bioaerosol monitoring system. The system is still in the design phase and is therefore still prone to changes and optimizations based on new insights. However, based on our estimation we are confident that concentrations down to $10^5$ cm$^{-3}$ can be detected with our planned monitoring system. Also, the detection of aerosols with lower concentrations is not outside the picture as the excitation energy is limited by multiple factors, which still leave room for tuning and can therefore be used to push towards a lower detection limit.

Further advantages of the proposed system are its capability to automatically detect hazardous aerosols without the need of a human operator. It can simply be placed at a designated location and operate there, given it has a power connection and means to transfer its data. The data transfer is at the current time not within the scope of the concept as the primary focus is the development of the detection capabilities. But when the system reaches a state where it can be used in practical scenarios, the addition of a dedicated external interface will enable it to be integrated into larger systems.

### 4.2 Future Work

Currently we are working on a simulation modelling the behavior of the signal photons inside the integrating sphere in order to analyze sources of signal loss. The focus here is to identify the individual causes, like absorption inside the sphere, scattering outside the detection area or signal photons hitting the detector outside its acceptance angle, and quantifying their respective impact on the overall signal loss. The results of this simulation will then be used to optimize the systems geometry and further reduce the loss of signal photons.

In parallel to the simulation we are also running first test in laboratory to see if our calculations are reliable and if some adaptations are needed. Furthermore, the lab test will be used to co-validate the simulation results and provide direct feedback on the optimizations performed.

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