John Edwards

Signal Processing Plays a Key Role in Environmental Research Projects

Keeping people and ecosystems alive and healthy is perhaps the 21st century's biggest challenge

Despite the impressive technological strides made over the years, human lives still depend very much on the natural environment. Fortunately, technology can now be used to help address critical environmental concerns in air quality, soil condition, and weather events. In all of these areas and many others, signal processing is supporting the ability to provide immediate and long-term observations and insights.

Efficient air-quality monitoring

It's generally accepted that the efficient monitoring of airborne particulate matter (PM), particularly particles with an aerodynamic diameter measuring less than 2.5 μm (PM2.5), is an important step toward sustaining and improving public health.

Acknowledging this fact, researchers at the Max Planck Institute for the Science of Light have developed a novel way to continuously monitor a local environment for both the size and optical properties of individual airborne particles. The technique utilizes optical forces to automatically capture airborne particles and then propel them into a hollow-core fiber where they can be studied and counted, providing a potentially better way to monitor air pollution levels.

On-the-fly particle metrology uses both advanced optics and signal processing to continuously monitor the size and refractive index of individual airborne particles in an open atmosphere, says research team leader Shangran Xie (Figure 1). "It can overcome several limitations of … existing methods, offering the ability of simultaneous measurement of particle size and refractive index, which can assist in identifying particle material, real-time particle metrology, highly reproducible results, and unlimited device lifetime," he explains.

Current commercially available particle counters are limited to counting

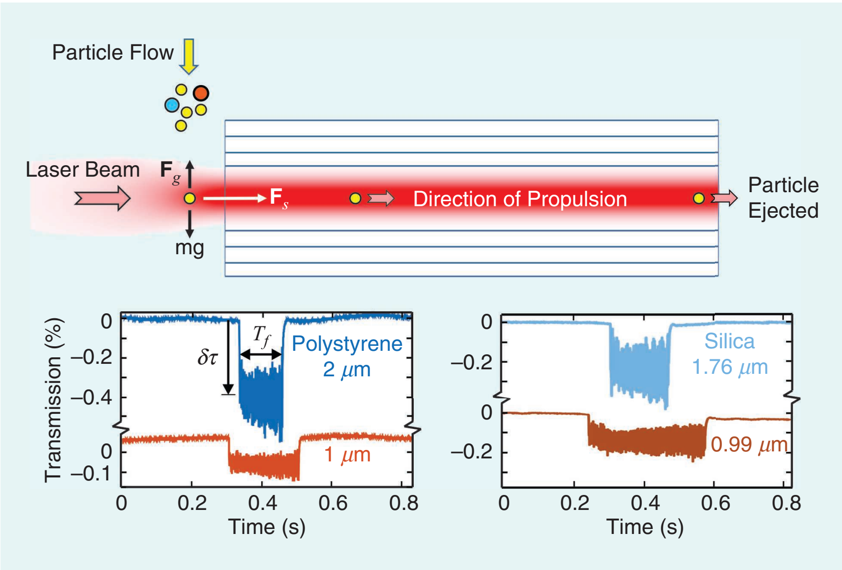

FIGURE 1. An on-the-fly particle metrology, developed by researchers at the Max Planck Institute for the Science of Light, uses both advanced optics and signal processing to continuously monitor the size and refractive index of individual airborne particles in an open atmosphere. (Source: Max Planck Institute for the Science of Light; used with permission.)

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the number of airborne particles. If more detailed particle data are needed, the existing standard technique requires manual sampling with sophisticated equipment. While the combined approach can provide a full span of particle information, it's not a continuous measurement and can't provide real-time feedback on the pollutant.

The new technique promises to provide a reliable way to rapidly and continuously characterize airborne particles. "It can not only count the number of particles, which is related with the level of pollution, but also can provide detailed information on particle size distribution and chemical dispersion in real time," Xie says. "The configuration is also very simple; it's highly possible to build a shoe-box-sized device able to continuously monitor airborne PM2.5 particles in urban areas and industrial sites."

Xie reports that he and his team have been working on particle trapping and analysis in hollow-core photonic crystal fiber for years, gaining, over time, a deep understanding of particle scattering within a hollow-core fiber. "Inspired by the need for particle detection in air pollution monitoring, we think our fiber and the corresponding data processing procedure may offer a better solution," he says.

The new analysis approach traps airborne particles inside a laser beam by optical forces and propels them forward by radiation pressure. The trapping force is strong enough to overcome gravitational force on very small particles, such as PM2.5. The approach also automatically aligns the particles within the hollow-core fiber. Postalignment, laser light propels the particle into the fiber, forcing the laser light inside the fiber to scatter and create a detectable reduction in the fiber transmission.

At the project's heart is a novel signal processing algorithm that the researchers designed to retrieve useful information from the particle-scattering data in real time. A photodetector is used to convert the original optical signal into an electrical signal. "The goal of signal processing in our technique is to retrieve, as precisely as possible, the particle size and its refractive index from the fiber transmission signal," Xie states.

The fiber carries two types of information: transmission drop data created by particle scattering and time-of-flight information and the time it takes a particle to travel through the fiber. "Having these two [types of] information in hand, an algorithm based on particle scattering theory can be integrated into the signal processer to unambiguously retrieve the particle size and refractive index," Xie says.

A significant remaining signal processing challenge is dealing with a relatively weak transmission drop signal. "Normally, a single particle would only introduce a less than 1% signal drop; the signal we are [now] facing is a tiny drop lasting for tens of milliseconds on top of a strong dc background." Another concern is the particles that pass through the laser beam without being captured. "Those particles will introduce spikes in the signal which cannot be properly retrieved by the algorithm," Xie comments.

The biggest challenge the team now faces is finding an algorithm that can further translate particle number, size, and refractive index into PM2.5 concentration data as well as a description of the types of pollutants detected. "To do this, advanced signal processing algorithms on data classification … may be required to quickly identify the pollution type based on the known database," Xie says. "In other words, we need to further bridge the gap between the data in the lab and information for the end users."

Looking forward, Xie is hoping to further advance the system's particle characterization. "For instance, it may be possible to monitor the particle shape or surface roughness by analyzing the scattering patterns from the fiber endface or from the side," he says. "This can give additional information on the residence time of pollutants in the environment."

Improving tornado detection and tracking

University of Mississippi researchers believe that "listening" to tornadoes via infrasound will lead to significantly earlier and more accurate tornado warnings.

Despite the rapid advances in meteorological technology, detecting and tracking tornadoes remains a formidable task. More than 24,400 tornadoes have been reported across the United States since 2000, according to the National Centers for Environmental Information. Over the same period, tornadoes have killed almost 1,500 people and resulted in billions of dollars in damage.

Radar is unable to reliably detect tornadoes, states Roger Waxler, a University of Mississippi research associate professor of physics and astronomy and a principal scientist at the National Center for Physical Acoustics (NCPA). The wavelengths are too long and upward looking to generate accurate reports, he explains. Therefore, tornado warnings are currently issued solely on the basis of visual observations and/or confirmations.

Addressing this issue, significant effort has been poured into the development of short wavelength radar systems that might be able to detect tornadoes directly, perhaps by the debris generated by the tornado's funnel. "But these would require line-of-sight and would be blocked by hills, tree cover, and so on," Waxler observes.

Acoustics promise a better approach. Since sound doesn't depend on line-of-sight, it can detect tornado activity directly. An added benefit is that acoustic technology is generally less costly than radar systems, Waxler notes. "Tracking from acoustic technologies could assist in providing better estimates of locations to investigate and tornado passage times," he adds.

Joining Waxler in investigating acoustics' potential to detect and track tornados is Garth Frazier, a senior research scientist at NCPA and a University of Mississippi research associate professor of electrical engineering. Another key team member is Carrick Talmadge, also a senior NCPA research scientist and a University of Mississippi research associate professor of communication sciences and disorders.

For the past several years, the team has explored the potential of infrasound arrays that incorporate anywhere from five to 10 sensors. The sensors are installed directly on the ground in semipermanent locations, measuring approximately 50 x 50 meters, that change on a seasonal basis (Figure 2). "We deploy a network of arrays based on guidance from meteorologists with the goal of covering a regional area," Frazier says.

In the current research phase, data are continuously logged at 1,000 samples/s by the Coordinated Universal Time-synchronized sensors, which run on solar-augmented battery power. "Periodically, the data are downloaded from the sensors during site visits, but this might be only once per several months," Frazier notes.

Using storm report information available on U.S. National Oceanic and Atmospheric Administration websites and the Iowa Environmental Mesonet website at Iowa State University, selected time periods of data are analyzed using array processing algorithms. "Signal processing is one of the three pillars of the technology, with the other two being infrasound sensors and long-range atmospheric sound propagation modeling and prediction," Frazier says.

The collected data are typically decimated to a lower rate, such as 100 Hz, prior to array processing. "Additionally, we high-pass filter to remove most signal fluctuations below 0.1 Hz," Frazier notes. The project uses three algorithms to estimate the directions of arrival and measured signal levels: a maximum likelihood approach based on the complex Wishart distribution, a signal subspace approach, and multiple signal classification. "All of the array signal processing is performed in the frequency domain," he adds.

The researchers selected the three specific signal processing approaches for their ability to resolve multiple sources simultaneously along different azimuths. "In two cases in Alabama, we have followed two tornadoes simultaneously," Frazier says. "In addition to storm-generated infrasound, we have to contend with anthropomorphic infrasound, especially from urban areas and industrial plants in particular."

During the course of their research, the team found that tornadic storms produce sound in various frequency bands. "Almost all of the long-range detections—50–100 km—we have observed have been in the band from 1 Hz to 10 Hz, and most of those have been in 2 Hz to 5 Hz," Frazier reports.

Much work remains to be done before that system can be used to generate reliable tornado warnings. "From a signal processing point of view, we still need to automate the entire processing pipeline into a real-time framework," Frazier says. Currently, all data processing is performed offline in either Python or Octave.

FIGURE 2. Tornado-detecting infrasound arrays, developed by University of Mississippi researchers, incorporate anywhere from five to 10 sensors. (Source: Shea Stewart/University of Mississippi; used with permission.)

The primary challenge the team now faces is frequent low signal-to-noise ratio issues. Wind noise created by intrinsic turbulent pressure fluctuations in the atmosphere surface layer combined with the interaction of wind and the sensor housing has been a particularly nagging concern.

The researchers also still need to perfect their real-time, bearings-only, 2D multiple-target tracking algorithms to provide accurate geolocations when multiple arrays detect and follow the same tornadoes. This task promises to be particularly challenging given the significantly different time delay that exists between sound emission and measurement at different sensors as the tornado travels along its path.

Another complicating factor is long-range atmospheric propagation, which can cause the average speed of sound between the source and receiver to vary when detected from different directions. "We have solved this problem for the single target case using a Bayesian framework that updates the state vector at the previously estimated emission time then propagates forward to the newly estimated emission time—the reverse of Kalman filtering steps," Frazier explains. "These calculations require the use of a ray-tracing model for the sound propagation that depends on a local vertical profile model of wind and temperature."

Waxler believes that the technology has reached the stage where it's time to begin moving toward small-scale demonstration test systems, including data telemetry for remote processing. "There's a clear path to the signal processing implementations that are still required," he says. "There will possibly be hiccups in the data transmission process, but the only way to address these is to begin to gain experience."

Sensor promises larger crop yields using less fertilizer

Soil ecosystems provide most of the antibiotics used to combat diseases, control the movement of water and chemical substances between the Earth and its atmosphere, and function as the source and storage media for gases that are critical to sustaining life, such as oxygen, carbon dioxide, and methane.

Facing rapid global population growth, climate change, and increasing competition for land resources, there's an urgent need to find a way to quickly and efficiently analyze and monitor soils. Being able to rapidly and reliably measure levels of soil phosphate—a finite and nonrenewable resource that stays in a complex biogeochemical environment—is particularly urgent since there have been calls for a global effort to utilize phosphate fertilizers as efficiently as possible.

Researchers at Kansas State University's industrial engineering department, working with their counterparts at educational institutions worldwide, are developing graphene sensor-based systems that can map and monitor soil phosphate levels while generating insightful real-time data. The project aims to help researchers and farmers understand soils better while increasing crop yields and minimizing the use of phosphate fertilizers (Figure 3).

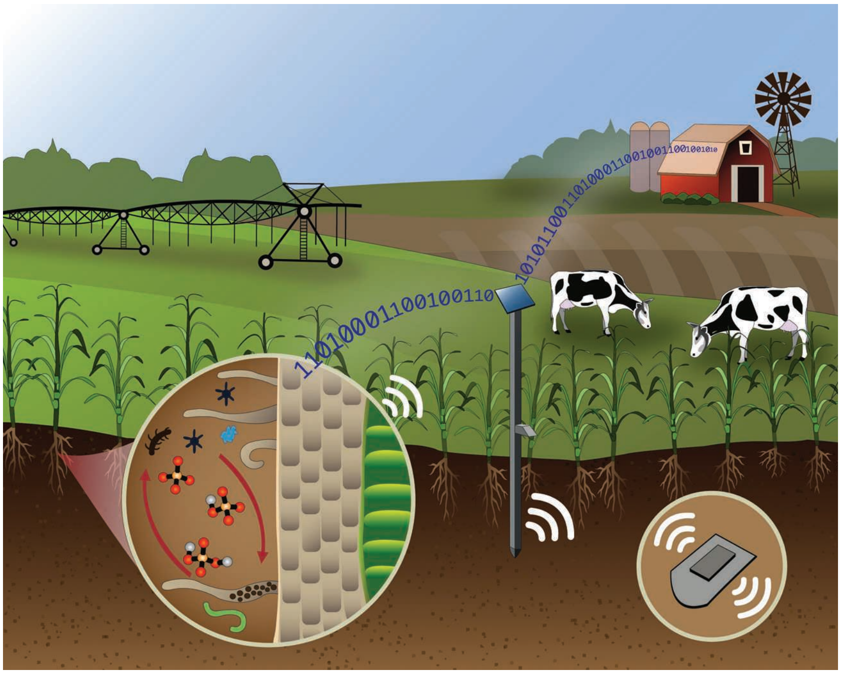

FIGURE 3. Printed graphene electrochemical sensors, combined with pH sensors and soil moisture sensor arrays on mechanically flexible substrates, deployed in the soil for phosphate sensing. A wireless circuit in combination with a custom-built impedance analyzer will transmit the data to the acquisition center. (Source: Suprem Das/Kansas State University; used with permission.)

While phosphate is a key crop nutrient, it's currently difficult for farmers to quickly and reliably map soil phosphate content levels since the process requires sending samples to a lab. Mapping and monitoring soil with portable and affordable sensors promise to provide a more accurate understanding of how soil composition changes over time, helping farmers to apply phosphate fertilizers only to the areas where it's most needed.

The project's researchers are focusing their efforts on two major areas: a soil sensor made of graphene (an atomically thin 2D carbon material) and a hardware-supported signal processing architecture. "Exploiting the interaction of phosphates with graphene will produce a characteristic signal read by an impedance that will be carefully collected and processed by the signal processing hardware," explains principal investigator Suprem Das, an assistant professor in industrial manufacturing systems engineering at Kansas State University's Carl R. Ice College of Engineering. "Therefore, identifying the fundamental impedance related to phosphates as well as discriminating signals from interfering species in the soil during the signal processing are important parts of our research," he says.

Signal processing plays a dual role in the project, which is funded by the U.S. National Science Foundation and U.K. Research and Innovation. "First, electrical signals from the soil collected by the sensor board need to be carefully analyzed to get the accurate estimate of phosphate content, so in situ processing of the signals is very important," says project co-investigator Biswajit Ray, an assistant professor of electrical and computer engineering at the University of Alabama in Huntsville. "Second, the phosphate content value needs to be transmitted wirelessly with limited power sources and [on a] resource-constrained hardware platform, so careful hardware design will be important," he adds.

The researchers plan to present data in a way that will allow end users to focus on the task at hand while ignoring the complex science underpinning the technology. "This technology is primarily aimed at the farming industry so that we can achieve a more sustainable agriculture," explains Adrien Chauvet, a lecturer in physical chemistry at the University of Sheffield as well as the project's primary United Kingdom investigator. "Such a technology would allow farmers to literally map the phosphate content of their crops, with an approximate square-mile resolution, live." The researchers envision a field deployment that includes multiple sensor boards distributed over a large area. Each board will be capable of measuring local phosphate content and transmitting the information to a control station.

Chauvet is confident that the technology has a promising future. "As a scientist, I see this project as the first step of a long-lasting collaboration that will go beyond the creation of the actual device," he states. "If we can prove that this sensing strategy works, then we can expand it and apply it to other minerals and heavy atoms."

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