Dynamic Photoacoustic Spectrosopic Sensor: The Poor Man's LIDAR?

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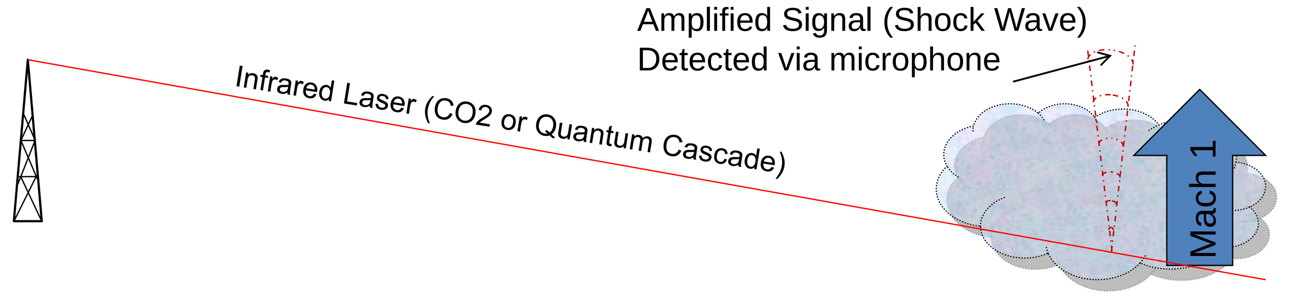
Abstract

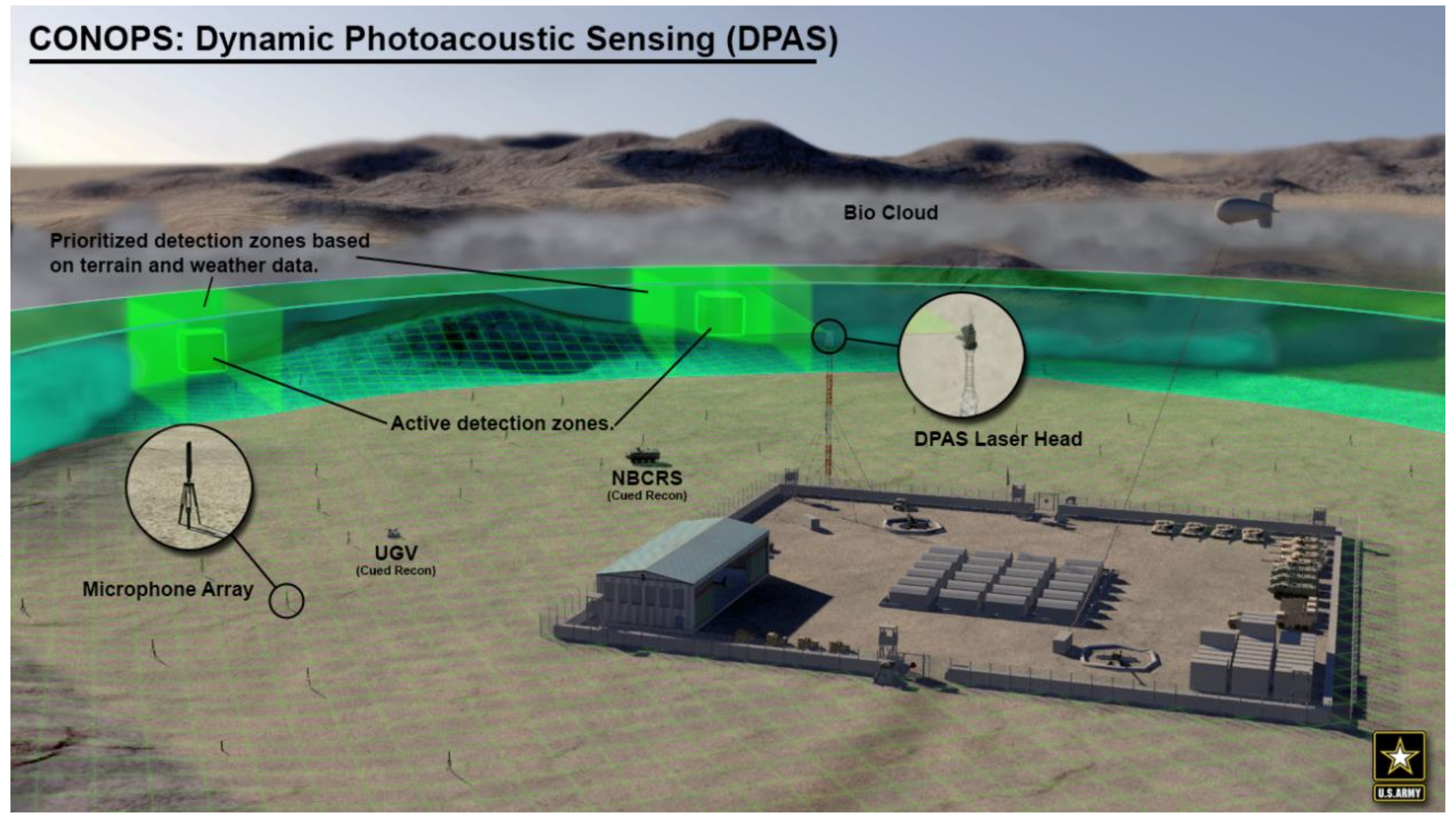
We report on progress toward the characterization of a novel phenomenology with potential application as a sensitive volume sensing infrared analysis technology involving mature components – a tunable infrared laser and a sensitive microphone – with a demonstrated capacity to provide molecular signature information while obviating the need for an expensive cryocooled infrared photon detector.

The phenomenon, which we dub Dynamic Photoacoustic Spectroscopy, or DPAS, is readily implemented using simple lasers, optics, and a microphone. The mid infrared pump laser is tuned to resonant vibrational absorption features of the distant chemical species (vapor or aerosol plume) in order to generate a photoacoustic report from the target, and swept through the volume at mach 1. As the photoacoustic report from molecular species is emitted isotropically, the successive emitted photoacoustic signals that evolve as the laser is swept along a short path containing additional target species also emit their characteristic report, and because the pump source is swept at the speed of sound, the acoustic signal emitted along the swept path adds in a constructive manner to amplify the resulting signal.

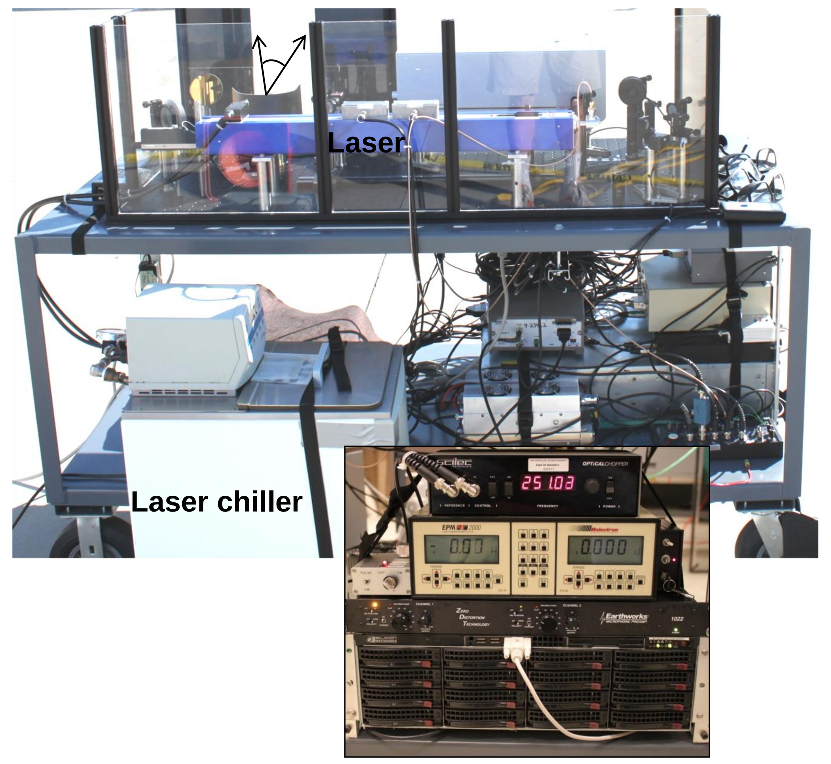
This collaborative project consists of three main legs which will be discussed: first, the construction and characterization of a laboratory bench was performed by MIT-LL; second, the development of a signature library and signal phenomenology model is underway led by ECBC; third, innovative optical architectures for steering and focusing the source beam, and the resulting acoustic signal are being investigated at the U.S. Army Research Laboratory. Results to date have demonstrated the applicability of the approach to sensing chemical threats that present as vapors or aerosols, and further demonstrated the signal to background characteristics of the technology. Efforts are under way now to advance our understanding of the underlying physics that enables the observed performance and to develop novel optics that will enable the demonstration of an integrated monostatic sensor.



- Dynamic Laser Photoacoustic Spectroscopy concept
- Concept presented in a DTRA-funded crowdsourcing initiative
- Laser tunes on and off resonant absorption features to generate a thermal pulse when an absorber is present
- The laser is swept at the speed of sound, the acoustic signal emitted along the swept path adds in a constructive manner to amplify the resulting signal
- Target serves as a gain medium for the ***amplified*** signal
- Sensing volume is small (cm) relative to traditional approaches (10's of m)
- Photoacoustic spectroscopy is a mature science, with volumes of literature published for ***vapor, chemical aerosol, and bioaerosol*** signatures
- Leverages our institutional knowledge on how to exploit agent infrared signatures for detection and identification
- While the sensing system construct is novel and infantile, the ***components*** (CO2 laser and microphone receivers) are highly **mature**



DPAS Mobile Data Collection Bench



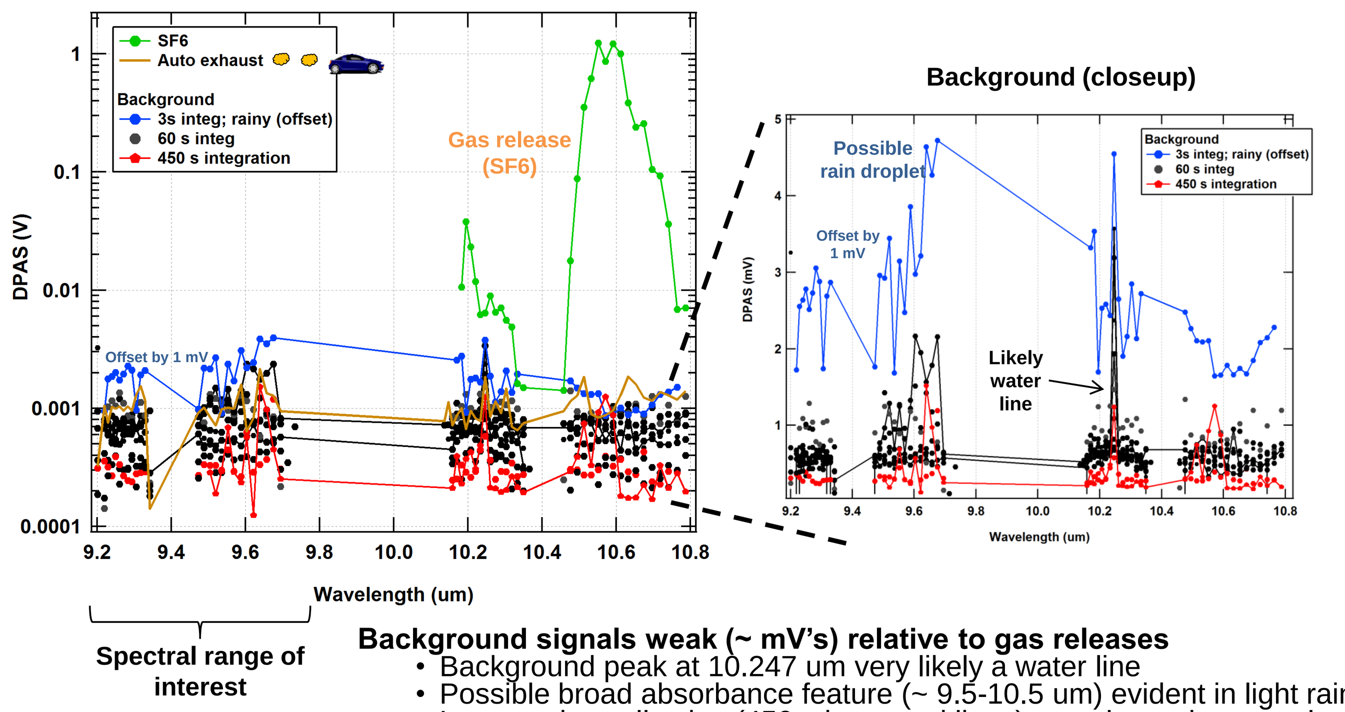
Transportable cart designed for outdoor operation

Optical Breadboard
- Tunable CO2 laser (9.2 – 10.8 um)
- Focusing telescope optics (5x mag)
- Rotating mirror (2-40 Hz)
- Trigger reference diode
- Red alignment/visualization beam

Electronics Cart
- Data acquisition computer: multi-channel DAQ board (100 KHz dual channel sample; 1 kHz high-pass RC filter)
- Microphone preamplifier
- Mirror control system
- Optical power meters
- Laser chiller

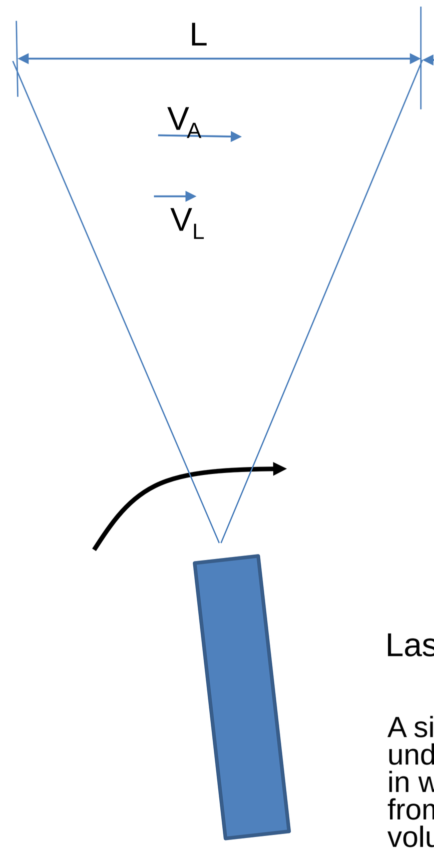
Also (not shown):
- 50 kHz bandwidth microphone with multiple parabolic collectors

Results: Summer Outdoor Measurement Campaign



Background signals weak (~ mV's) relative to gas releases
- Background peak at 10.247 um very likely a water line
- Possible broad absorbance feature (~ 9.5-10.5 um) evident in light rain
- Lower noise collection (450 s integ; red lines) reveals weak spectral features above noise

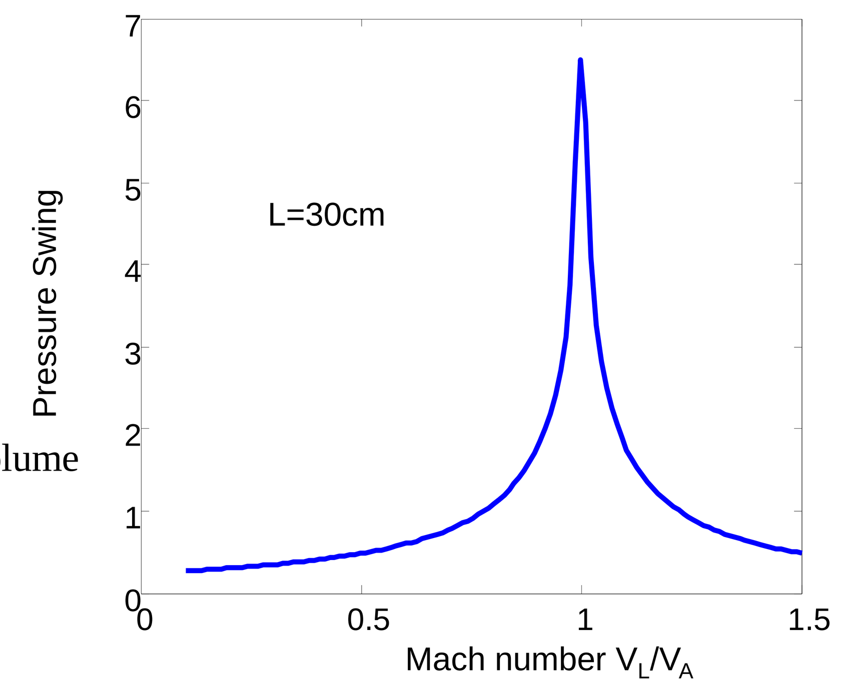
DPAS Performance Modeling



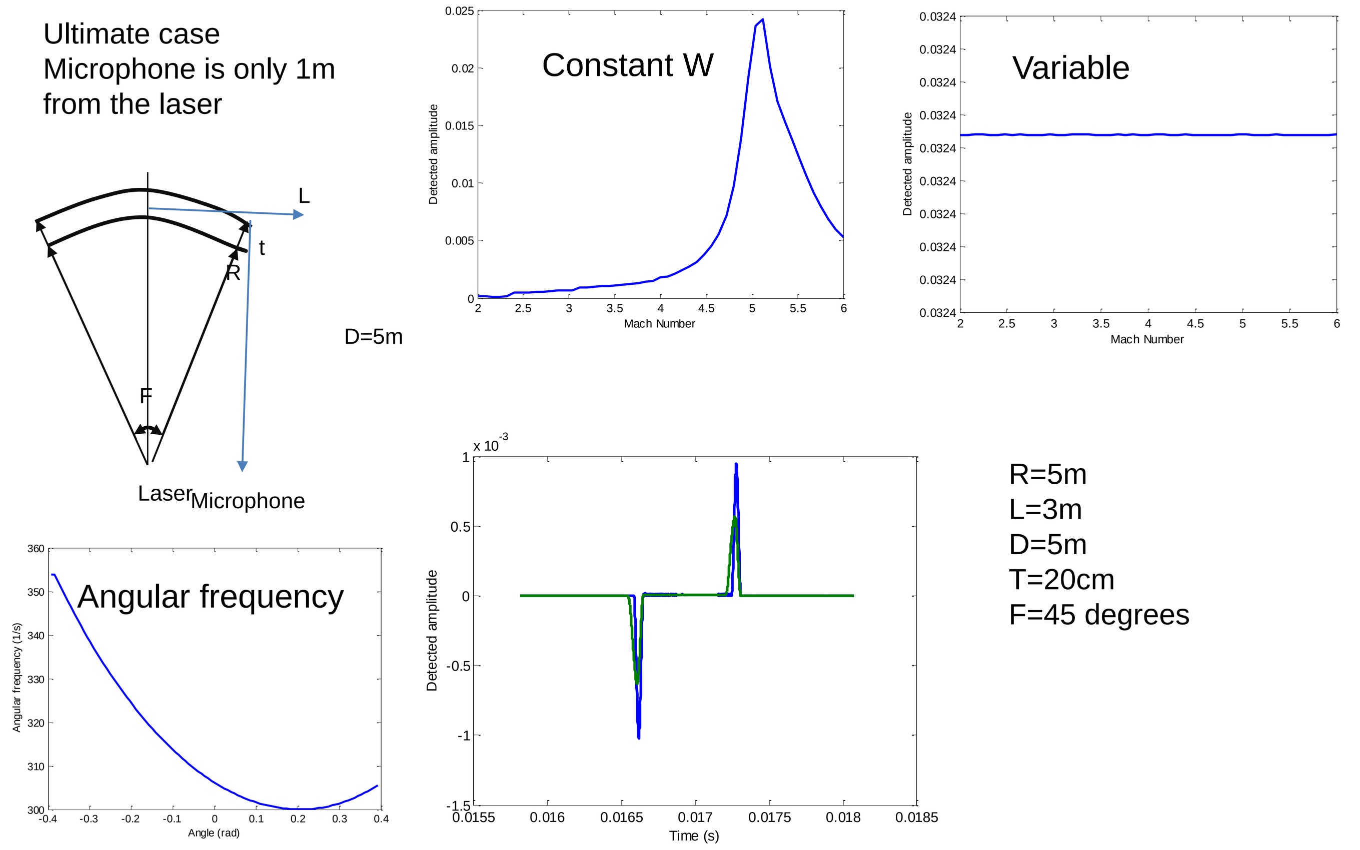
$$\nabla^2 p - \frac{1}{v_a^2}\frac{\partial^2 p}{\partial t^2} = -\frac{\beta}{c_p}\frac{\partial q}{\partial t}$$

p pressure
β-thermal expansion
c_p specific heat
v_a acosutic velocity
q absorbed power per volume

A singularity is predicted at Mach 1, under the optimum DPAS condition in which the emitted acoustic energy from molecules in the sensing volume add coherently.



Towards Remote Sensing with the DPAS Phenomenon



In this modeled scenario, the laser beam is swept at a variable angular frequency such that a Mach 1 component of motion develops in the direction back to the laser transmitter. The model predicts that a component of the DPAS signal would be detectable in this geometry.

Conclusions

The DPAS phenomenon has been demonstrated on vapor and aerosol targets under laboratory conditions, and an outdoor data collection campaign. It revealed a favorable signal to noise ratio for the data collection system. Detection limits on the order of the part per trillion vapor sensitivity and ~36 micrograms/m^3 have been demonstrated using the DPAS optical breadboard with a CO_2 laser. Concepts for a remote sensing architecture are under investigation, with preliminary modeling results suggesting that options exist that will direct the DPAS signal back toward the transmitter.

References

Allan D. Pierce and Yves H. Berthelot "Validity of linear acoustics for prediction of waveforms caused by sonically moving laser beams", J. Acoust.Soc.Am. 83 (3), March 1988.
K. P. Gurton, R. Dahmani, D. Ligon, and B. V. Bronk "In situ measurement of the infrared absorption and extinction of chemical and biologically derived aerosols using flow-through photoacoustics," Appl. Opt. 44(19), 4096–4101 (2005).
K P. Gurton, M. Felton, R. Dahmani, and D. Ligon "In situ infrared aerosol spectroscopy for a variety of nerve agent simulants using flow-through photoacoustics", Appl. Optics, 46(25) 6323-6329, 1 September 2007.
K. P. Gurton, M. Felton, and R. Tober, "Selective real-time detection of gaseous nerve agent simulants using multiwavelength photoacoustics," Opt. Lett. 37(16), 3474–3476 (2012).
Wynn, C. M., Palmacci, S., Clark, M. L. and Kunz, R. R. "Dynamic photoacoustic spectroscopy for trace gas detection", Appl. Phys. Lett. 101, 184103-1-4 (2012).
Xing Chen, Dingkai Guo, Fow-Sen Choa, Chen-Chia Wang, Sudhir Trivedi, A. Peter Snyder, Guoyun Ru, and Jenyu Fan "Standoff photoacoustic detection of explosives using quantum cascade laser and an ultrasensitive microphone", Appl. Opt., 52(12), 2626-2632, 20 April 2013.
Wynn, C. M., Palmacci, S., Clark, M. L. and Kunz, R. R. "High-sensitivity detection of trace gases using dynamic photoacoustic spectroscopy", Opt. Eng. 53(2), 021103 (Aug 28, 2013).
R. M. Sullenberger, M. L. Clark, R. R. Kunz, A. C. Samuels, D. K. Emge, M.W. Ellzy, and C. M. Wynn "Trace aerosol detection and identification by dynamic photoacoustic spectroscopy", Optics Express, 22(S7), A1810-A1817, 15 December 2014.

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