Photo-Thermal Interferometric (PTI) Particulate Absorption Monitor

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Introduction

Our project addresses the measurement of radiative forcing of aerosols, specifically energy-releated aerosols, which is currently a focus of the Department of Energy (DOE) Atmospheric System Research (ASR) Program (AA Workshop, 2016). Aerosol particles affect the radiative balance of the earth directly, by scattering and absorbing solar and terrestrial radiation, and indirectly, by acting as cloud condensation nuclei.

Knowledge of the partitioning of solar and terrestrial atmospheric extinction between scattering and absorption is thus critical to the understanding of radiation transport through the atmosphere. At present, the uncertainties in the magnitude of aerosol-induced radiation forcing still pose a critical limitation on the accurate quantification of both direct and indirect effects of aerosols on climate. Accurate measurement of the absorption by aerosols in the atmosphere is problematic because of their low magnitudes, as particle absorption far from urban centers may be less than 5 Mm⁻¹. The filter-based instruments which currently are the primary means of measuring absorption, while precise, have issues with accuracy in the presence of high non-BC backgrounds due to inherent issues with their operation and measurement methodology.

We chose to focus on PTI technology for specific reasons:

1. PTI is one of two proven technologies (photoacoustic spectroscopy - PAS - being the other) that directly measure particulate absorption and can meet the stringent US DOE stated requirements (i.e. sensitivity goal of 1 Mm⁻¹ (2σ at 10⁻⁶ averaging) with a response time of 5 s).
2. PTI technology provides several potential advantages compared to PAS technology, including the freedom to operate over a wide range of frequencies (but minimum overlap with environmental noise and that enable investigation of particle-dependent heating rates); and,
3. PTI technology has not been developed to the extent of PAS technology (e.g. multiple commercial PAS instruments are currently on the market, whereas there is only one recently developed commercial PTI instrument).

Prototype Results

We achieved the following results during this project, using a 405 nm heating laser:

1. Developed a phase sensitive demodulation of the PTI signal to remove mirror heating signal from the gas/particle signal; and,
2. Conducted multiple gas-phase NO₂ calibrations to test prototype sensitivity and stability, and,
3. Quantified the noise levels and compared with manufacturer’s stated levels.

- Phase sensitive demodulation of gas-phase NO₂ signal and mirror heating, due to their different rates of heating the surrounding gas.
- NO₂ gas phase calibration exhibiting a sensitivity of ~1000 pm/ppm NO₂.
- NO₂ calibrations during 405 nm heating laser powers of 100mW (red line) and 150 mW (blue line) demonstrated linear dependence on heating laser power.
- Our lowest measurement of spectrally resolved noise (1σ, 1s) equivalent to ~1 ppb NO₂.

PTI optical design tested during this study,

PTI design:

- The PTI interferometric process for the purposes of interpreting results and illuminating technical advances in their design.
- Preliminary studies using direct overlap of excitation laser and reference arm of the interferometer increased signal levels by a factor of 2-3X.
- Successful construction and testing multiple optical configurations of a prototype PTI system.
- Developed signal processing methods to investigate PTI signals, including phase demodulation methods that enabled us to separate sources of absorption signals (gas-phase or particle-phase from mirror signals).
- Identified and addressed environment-based acoustic and vibrational noise.
- Initiated the development of a numerical model of the photothermal interferometry (PTI) process for the purposes of interpreting results and illuminating technical development pathways.
- Our focus on the optical configuration encouraged the BNL team to reconsider their method of operation and the setup and calibration software are proprietary.
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- The PTI developed at BNL utilizes a Folded Jamin interferometer design, which provides quadrature information on the phase shift between paths, which provides quadrature information on the phase shift between paths.

Advantages:

- The PTI interferometric, along with control and calibration software is a commercial product and thus is readily available.
- The two-beam design allows long path lengths with a small length difference, promising high sensitivity and leveraging advantages of common-mode rejection.
- The fiber optic probe allows flexibility in optical system design. Its output beams can be matched into a variety of optical designs with long paths.

Disadvantages:

- The interferometer sensitivity is far less (1-2 orders of magnitude) than the folded Jamin design in the BNL research-grade PTI system.
- The method of operation and the setup and calibration software are proprietary.
- The optical fiber is sensitive to vibrations and movement.

BNL PTI

- The PTI developed at BNL utilizes a Folded Jamin Interferometer design based on a proprietary technology.
- During this study, BNL investigated whether the BNL PTI could be
  (1) operated with increased overlap between the heating beam and the interferometer arm,
  (2) operated in a mode that does not require continuous quadrature lock,
  (3) operated at slower frequencies (i.e., higher signal levels) - currently restricted due to a slow RC-filter roll off on the feedback circuit.

BNL PTI is based on a Folded-Jamin interferometer design:

- Maximum common rejection of vibrations
- Preliminary studies using direct overlap of excitation laser and reference arm of the interferometer increased signal levels by a factor of 2.3X.
- Operating without active quadrature lock at typical 88 Hz, enabled an increase of ~2.5 % in signal amplitude.
- Proof-of-principle that the PTI could be operated with intermittent quadrature lock to increase signal and reduce dependence upon proprietary circuits.
- BNL PTI is based on a Folded-Jamin interferometer design.
- Maximum common rejection of vibrations.
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Conclusions and Acknowledgement

Successfully constructed and tested multiple optical configurations of a prototype PTI system built around a commercial interferometer using a 405 nm 1W diode laser modulated at 15-30 kHz.

- Successful construction and testing multiple optical configurations of a prototype PTI system built around a commercial interferometer using a 405 nm 1W diode laser modulated at 15-30 kHz.
- Calibrated our prototype PTI system with absorbing NO₂ gas, showing a sensitivity of ~1000 pm / ppm NO₂ (1σ, 1s) equivalent to ~1 ppb NO₂.
- Estimate of the noise level for our prototype PTI system is 24 Mm⁻¹ in 1 second, or 8 Mm⁻¹ in 10 seconds.
- We demonstrated response to absorbing particle “puffs”.
- Developed signal processing methods to investigate PTI signals, including phase demodulation methods that enabled us to separate sources of absorption signals (gas-phase or particle-phase from mirror signals).
- Identified and addressed environment-based acoustic and vibrational noise.
- Initiated the development of a numerical model of the photothermal interferometry (PTI) process for the purpose of interpreting results and illuminating technical development pathways.
- Our focus on the optical configuration encouraged the BNL team to reconsider their method of operation and the setup and calibration software are proprietary.
- The optical fiber is sensitive to vibrations and movement.
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References: