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Design Optimization for High Sensitivity Two-Color LII

Gregory J. Smallwood, David R. Snelling, Robert A. Sawchuk, Dan Clavel, and Daniel Gareau

Institute for Chemical Process & Environmental Technology, National Research Council Canada
Building M-9, 1200 Montreal Road, Ottawa, Ontario, Canada K1A 0R6

Motivation:

- IPCC National Greenhouse Gas Inventories Programme now focusing on emission estimation of aerosols relevant to climate change
  - –there is a need to measure black carbon levels in the atmosphere at *microgram per cubic metre* or lower mass concentrations
- emission standards for Diesel particulate matter (PM) are being lowered dramatically, resulting in the adoption of Diesel particulate filters (DPFs) by manufacturers
  - –there is a need to measure solid carbon levels in the exhaust and in dilution tunnels at *microgram per cubic metre* or lower mass concentrations
- develop high sensitivity LII to measure soot concentration at ambient levels for monitoring emissions from post-2007 Diesel engines, urban air quality, black carbon in atmosphere, and emissions from aircraft at altitude

Goal:

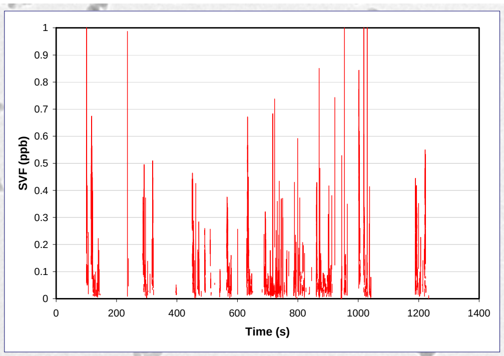
- retain low fluence and two-color pyrometry features of auto-compensating laser induced incandescence (AC-LII)
- limit for measuring soot concentration with our Mobile II AC-LII system is about 5 ppt (nearly 10 μg/m^3)
- target for high sensitivity AC-LII system is a measurement limit of 0.05 ppt (~0.1 μg/m^3) or less
- requires a 100-fold improvement in sensitivity

Approach:

- Optimize all aspects of the laser-induced incandescence method
  - –laser
  - –beam generation optics
  - –sampling cell
  - –receiver collection optics
  - –receiver filters and dichroics
  - –photodetectors
  - –signal detection and digitization electronics
  - –signal analysis software

Initial Optical Concept:

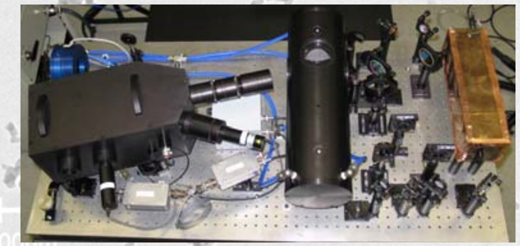
- maximize signal collection
  - –low f# lenses
  - –high peak transmission interference filters
  - –higher centre wavelength for lower wavelength channel interference filter
  - –wider bandwidth on interference filters
- implemented on enhanced sensitivity Artium ES-LII-200 and on a prototype high sensitivity LII system
- less than expected improvement



2007 heavy duty Diesel engine measured with enhanced sensitivity LII in dilution tunnel after diesel particulate filter (Artium ES-LII-200). This instrument was able to measure to below 1 ppt, but dropped below the noise limit for much of the cycle (no valid data to report).

Improved Optical Concept:

- optimize laser sheet geometry, probe volume dimensions, and collection optics in concert
- use Lagrangian invariant principle to constrain design of collection optics and receiver
  - –preservation of the Lagrangian invariant is essential for a lossless optical system
  - –minimum product of numeric aperture and aperture diameter cannot be improved upon
  - –**$L = NA_1 \times R_1 = NA_2 \times R_2$ = constant** for optimum design
- probe volume diameter based on maximum practical Lagrangian invariant of receiver optical system
- probe volume depth set by desired laser fluence and maximum available laser energy
- crossing angle minimized, but constrained by practicality



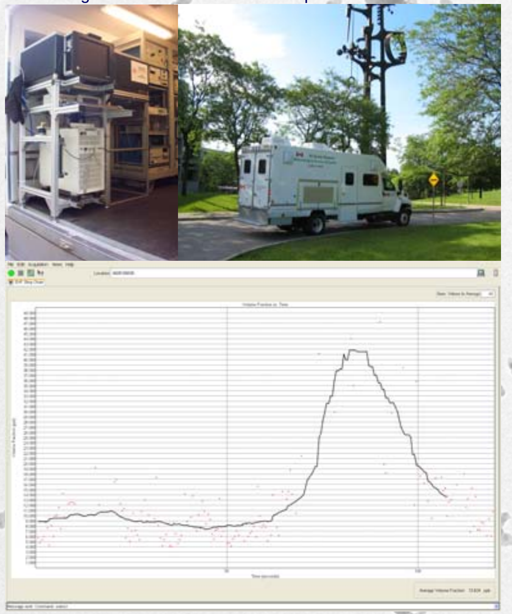
Optical layout of first generation high sensitivity system HS-LII-1

Optical Design for HS-LII-1 (First Generation)

- maximum practical design for receiver uses 50 mm dia. optics (dichroic mirrors, interference filters, lenses)
  - –this limits the Lagrangian invariant to L = 0.3 mm
  - –improvement of 4x over previous 25 mm design
- use of wider bandwidth and "square" bandpass interference filters
  - –improvement of ≥ 2x over previous design
- larger receiver aperture
  - –integrating sphere spectral radiance calibration enables much larger probe volume diameter
  - –improvement of 80x over previous 1.75 mm dia.
- crossing angle of 15° lengthens probe volume
  - –improvement of 2x over previous 35° design

Other Enhancements for HS-LII-1

- laser with 4x more energy was implemented, but with 532 nm excitation instead of 1064 nm to potentially perform elastic scattering measurements
- photomultipliers with a larger active area selected to preserve the Lagrangian invariant
- large diameter laminar flow sample cell



Ambient black carbon levels measured on coast of British Columbia, with photos of CRUISER vehicle and HS-LII-1

Result for HS-LII-1

- first implementation has ~50x greater sensitivity than previous best LII system
- now constrained by noise
  - –actual calibration shows more sensitivity
  - –Q-switch noise from laser dominates signal
- data was acquired on the West Coast of Canada, proving the feasibility of ambient real-time black carbon concentration monitoring
- although functional, instrument had poor S/N at lowest concentrations

Enhancements for HS-LII-2 (Second Generation)

- photomultipliers with greater cathode radiant sensitivity
- low noise PMT/pre-amplifier/differential amplifier circuits
  - –single circuit board with common ground plane
  - –gold alodine Faraday cages for circuits
  - –shielded and grounded cables
- improved interference filter for higher wavelength channel
- laser with 1064 nm excitation
  - –avoid unintended pickup of scattered 532 nm radiation
- signal averaging (multipulse operation)
- new sheet formation optics with antireflection coatings to produce a slightly higher fluence
  - –less expansion of the laser beam and lower losses

Comparison of Sensitivity for a Number of AC-LII Systems

System	λ_1 (nm)	RCS (W/m^3·sr·Volt)	Increase relative to Mobile II	λ_2 (nm)	RCS (W/m^3·sr·Volt)	Increase relative to Mobile II
Mobile II	397	$2.54 \cdot 10^{10}$	–	782	$4.22 \cdot 10^{10}$	–
HS-LII-1	445	$9.43 \cdot 10^{5}$	26,900x	746	$4.41 \cdot 10^{8}$	95.7x
HS-LII-2	445	$9.14 \cdot 10^{5}$	27,800x	753	$1.36 \cdot 10^{7}$	3100x
Artium LII-200	402	$4.39 \cdot 10^{8}$	57.9x	782	$4.62 \cdot 10^{9}$	9.13x
Artium ES-LII-200	447	$2.20 \cdot 10^{8}$	115x	829	$1.91 \cdot 10^{9}$	22.1x

Further Work:

- field evaluation of HS-LII-2 will begin shortly
- anticipate issues due to high sensitivity
  - –pick up of single photon events from room lights
  - –detection of laser flashlamp radiation
- eventual application to experiments demanding high sensitivity LII

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