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Development of an Airborne Sampling System for Mapping Gaseous Elemental Mercury

MESA lab

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Abstract

Atmospheric mercury monitoring typically relies on large laboratory instruments that are difficult to deploy on mobile sensing platforms. This work explores the control-oriented design of a compact cold vapor atomic fluorescence (CVAFS) detection system intended for airborne environmental monitoring. The system integrates a UV-C excitation source, optical fluorescence detection using a photomultiplier tube (PMT), and a gold amalgamation trap used to preconcentrate mercury from sampled air. Reliable detection at trace concentrations requires coordinated control of several coupled subsystems, including thermal cycling of the gold trap and stabilization of the optical detection chain.

A dynamic model of the gold amalgamation trap is developed to describe adsorption and thermal desorption behavior as a function of trap temperature and heater input. The trap is modeled as a lumped thermal system, enabling the design of a closed-loop temperature control strategy that produces repeatable mercury release pulses for fluorescence detection. In parallel, the PMT signal chain is analyzed as a measurement system influenced by photon shot noise, dark current, and electronic amplification noise. Signal conditioning and filtering strategies are evaluated to improve signal-to-noise ratio for low-level fluorescence signals.

This control-oriented framework links sampling, thermal desorption, and optical detection into a coordinated sensing architecture. The approach provides a pathway toward miniaturized mercury detection systems capable of stable and repeatable measurements, supporting future deployment on small aerial platforms for spatial mapping of atmospheric mercury concentrations.

Methods

This work applies a control-oriented subsystem modeling approach to the miniaturization of a cold vapor atomic fluorescence (CVAFS) mercury detection system.

Approach:
- *Developed a lumped thermal model of the gold amalgamation trap*
- *Characterized PMT signal chain noise sources*
- *Designed subsystem identification experiments for parameter validation*
- *Constructed architecture linking sampling, desorption timing, and fluorescence detection*
- *Used archived MERX instrument datasets to guide model assumptions*

Objective:
Reduce uncertainty in subsystem dynamics that determine detection repeatability and timing stability

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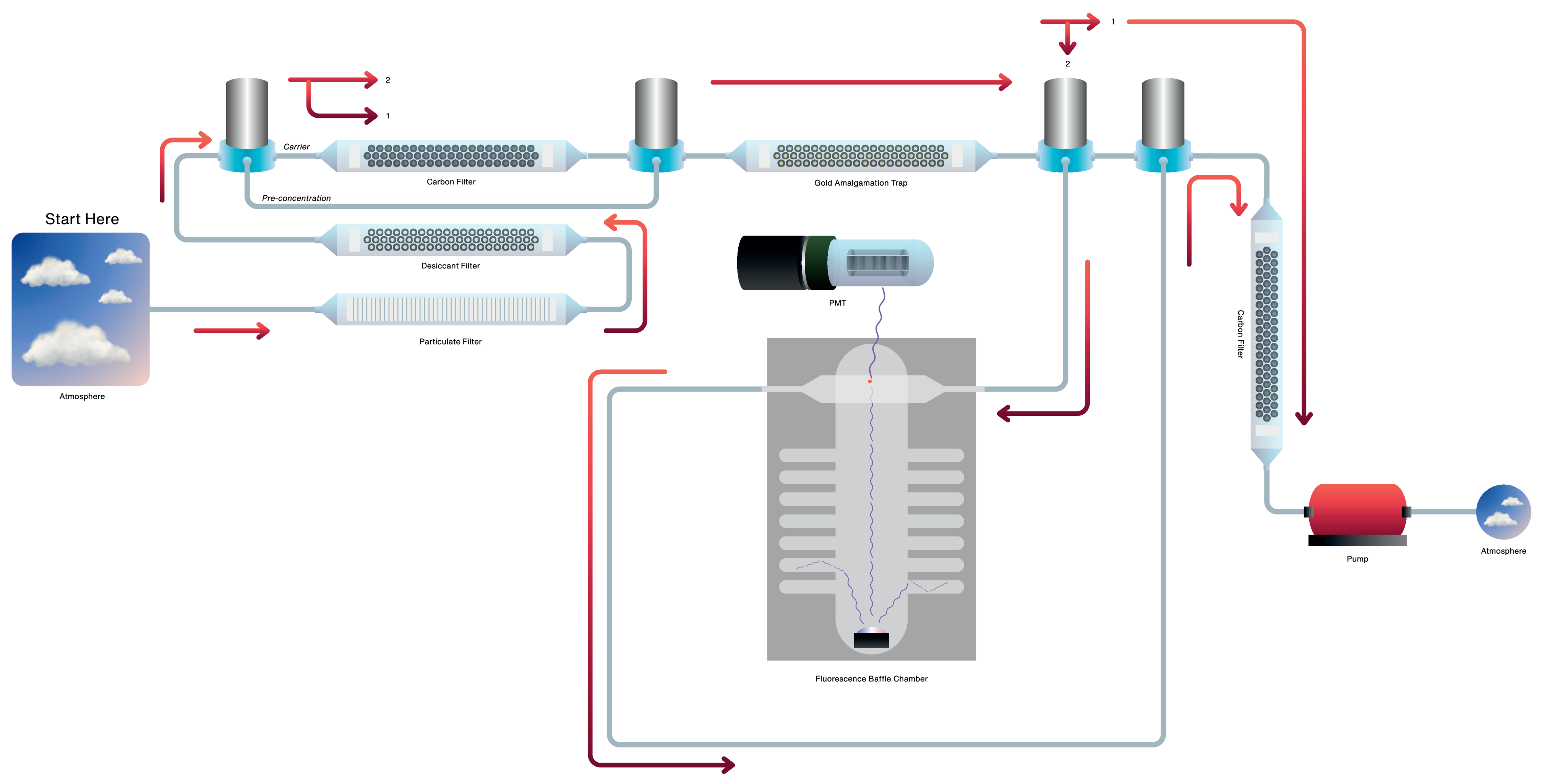
System Architecture



Gold Trap Dynamic Model

Gold trap temperature governs adsorption efficiency and release timing of mercury during measurement cycles.
Trap heating modeled as:

$$C\frac{dT}{dt} = P - hA(T - T_{amb})$$

C = effective thermal capacitance
P = heater input power
hA = convective heat loss term
Tamb = ambient temperature

Model supports prediction of:
- *heater power requirements*
- *thermal rise time*
- *desorption pulse timing*
- *repeatability of fluorescence excitation events*

Experimental Validation Framework

Subsystem identification experiments designed to validate model assumptions.

PMT dark noise test:
Measures baseline drift and noise floor

Shielding comparison test:
Evaluates EMI sensitivity and grounding strategy

Controlled light response test:
Measures detector linearity and saturation behavior

Optical baffle scan experiment:
Maps illumination pathways inside fluorescence region

Gold trap heating experiment:
Measures thermal rise time and desorption timing window
These experiments reduce uncertainty in system level timing performance.

Integrated Sampling Architecture

Measurement cycle integrates sampling, thermal release, and optical detection.

Cycle structure:
air sampling
→ mercury capture in gold trap
→ controlled thermal desorption pulse
→ UV-C fluorescence excitation
→ PMT signal acquisition

Control coordination ensures:
- *repeatable measurement timing*
- *stable excitation conditions*
- *consistent fluorescence detection response*

Supports deployment on compact airborne sensing platforms.

Thermal Control Objective

Measurement quality depends on repeatable mercury release timing.
Control objective:
Produce stable and repeatable thermal desorption pulses from the gold trap.

Desired behavior:
- *rapid heating to release temperature*
- *predictable desorption window*
- *minimal temperature overshoot*
- *cycle to cycle repeatability*

Control variables:
- *heater input power*
- *sampling duration*
- *desorption timing window*

Outcome:
Synchronized mercury release with fluorescence excitation improves measurement consistency.

PMT Signal Chain Modeling

Fluorescence detection sensitivity depends strongly on the stability of the photomultiplier tube (PMT) measurement system, which is influenced by several fundamental noise sources including photon shot noise, PMT dark current, amplifier noise, and electromagnetic interference. The signal chain is modeled as a sequential measurement pathway in which the fluorescence signal is converted to current by the PMT, amplified using a transimpedance stage, conditioned through filtering, and then digitized for analysis. The objective of this modeling effort is to improve the signal to noise ratio of the detection chain to enable reliable measurement of atmospheric mercury concentrations at the ng/m^3 level.

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