Development of a UV C LED based cold vapor fluorescence detector for field deployable mercury sensing

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Abstract

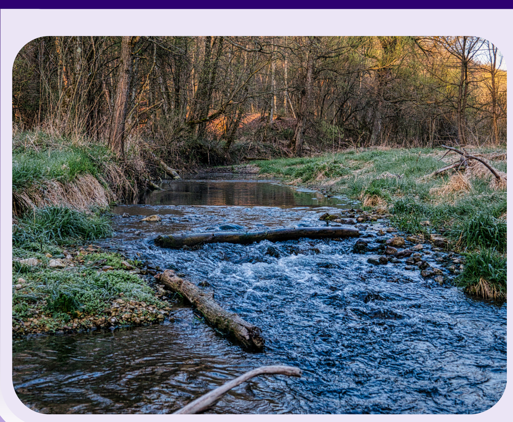
Atmospheric mercury is a persistent neurotoxin, yet high sensitivity field measurements still rely on bulky, power intensive cold vapor fluorescence analyzers that are difficult to deploy outside controlled laboratory environments. This project addresses the challenge of developing a compact, low power mercury detector whose behavior is quantitatively understood well enough to guide safe, linear, and sensitive operation.

We are designing a UV C LED based cold vapor fluorescence system in which a 254 nm LED illuminates a mercury bearing flow cell through a light pipe and baffle assembly, and the resulting fluorescence is measured with a photomultiplier tube and low noise analog front end. To characterize the coupled optical electronic dynamics without relying solely on first principles modeling, we perform data driven system identification in MATLAB. Step and swept sine experiments provide input output data for fitting low order transfer function or state space models that capture gain, bandwidth, dominant time constants, and the onset of saturation. Early ARX & OE fits indicate weak validation and non-white residuals, pointing to unmodeled multiphase dynamics and timing offsets that will require refined preprocessing and phase aware excitation in future trials.

Preliminary results include completion of a literature survey on UV C LED excited mercury fluorescence, definition of the optical geometry, and first pass LED driver and PMT readout schematics. These establish feasible operating ranges and identify likely noise sources in the measurement chain, forming the basis for planned refinement of the dynamic model and hardware parameters.

By integrating experimental system identification with hardware design, this project aims to reduce design iterations and support eventual deployment of a portable, lower power mercury analyzer for environmental sensing and future field platforms.

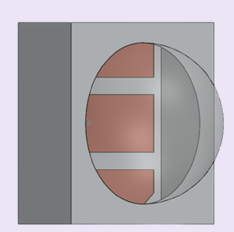
The Problem



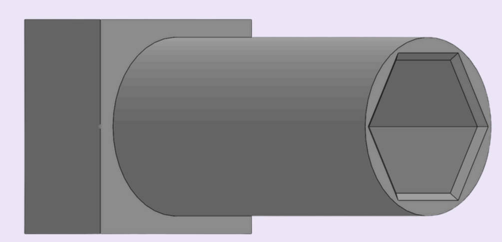
Background & Motivation

- *Cold vapor fluorescence is highly sensitive for mercury detection.*
- *Commercial systems like MERX are bulky and power heavy.*
- *UV C LEDs enable compact, low power alternatives for field use.*
- *Goal: inform design of a portable detector through optical, material, and dynamic analysis.*

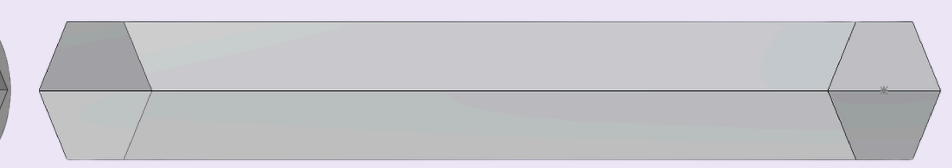
LED Couple & Light Pipe Configuration



UV C LED

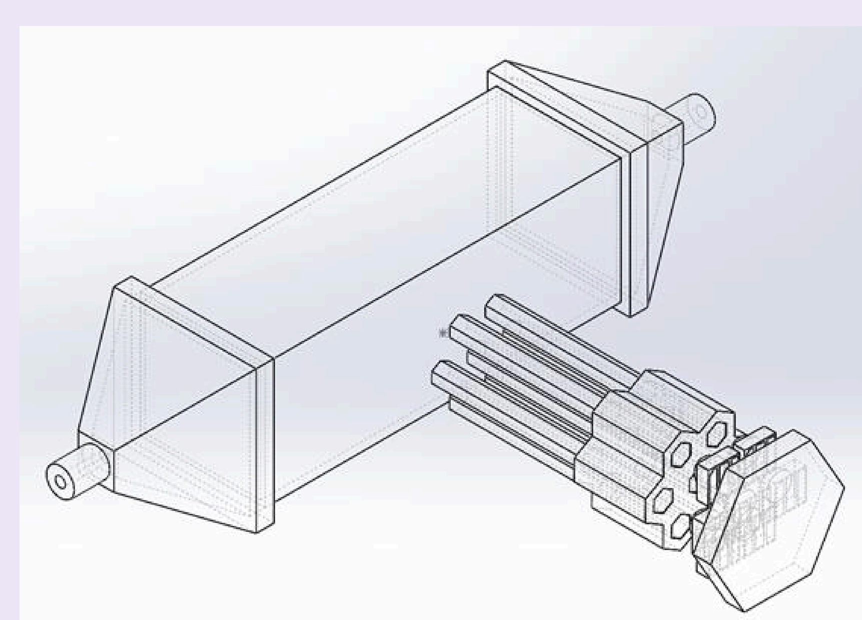


LED COUPLER

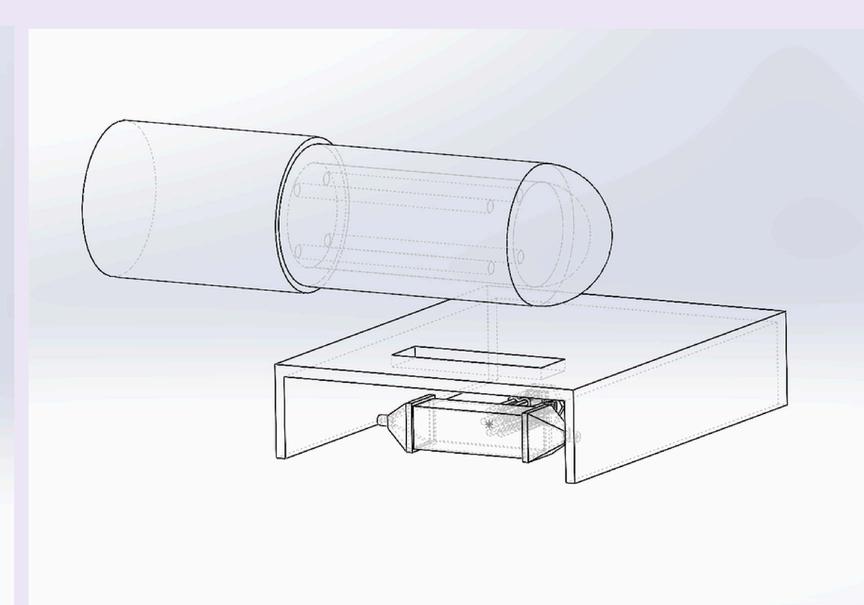


FUSED SILICA LIGHT PIPE HOMOGENIZING ROD

Hexagonally-Oriented Design Concept



Isometric view of hexagonal UV C LED arrangement positioned in front of quartz sample chamber.

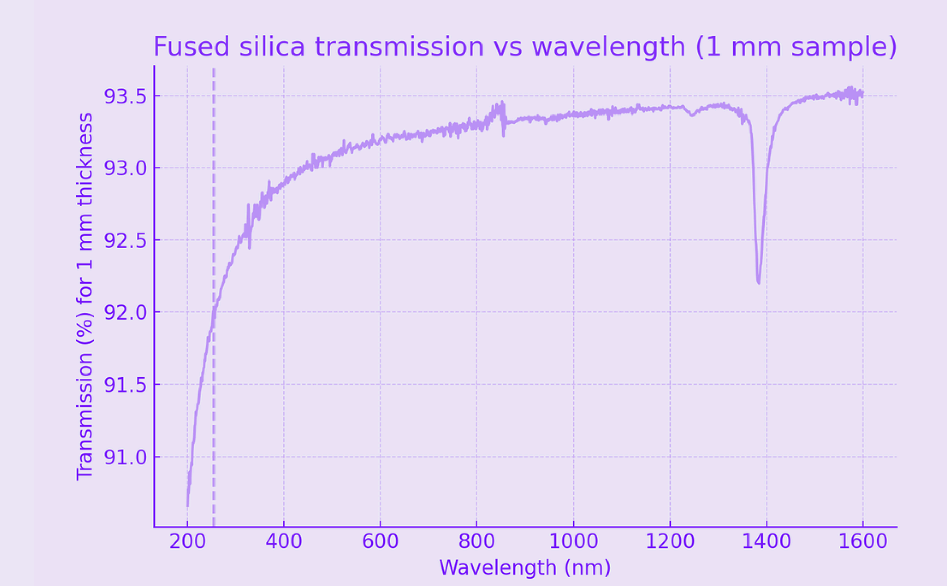


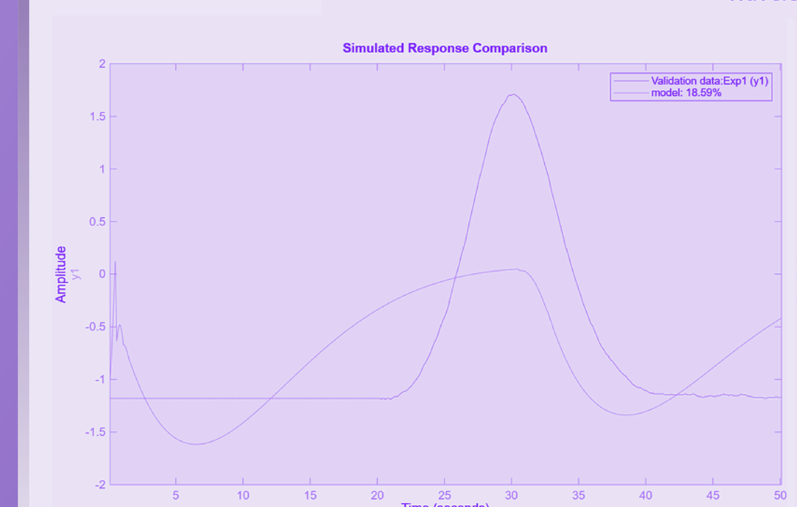
Concept of system in UV-resistant housing with photomultiplier tube.

Methods

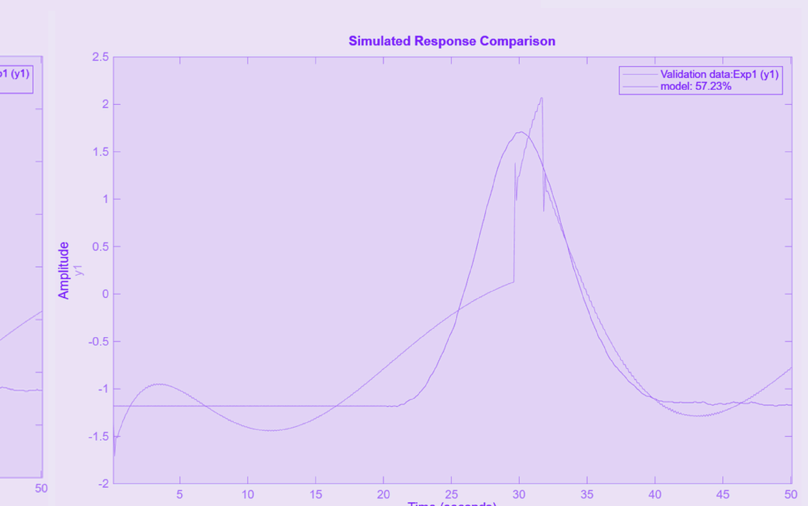
- *Analyzed MERX data in MATLAB using ARX and OE models to identify detector dynamics.*
- *Evaluated UV C LEDs and screened materials for UV stability and chemical compatibility.*
- *Developed CAD concepts for the miniaturized flow cell and optical assembly with integrated baffling and thermal management.*

Results





ARX model comparison to MERX equipment blanks.



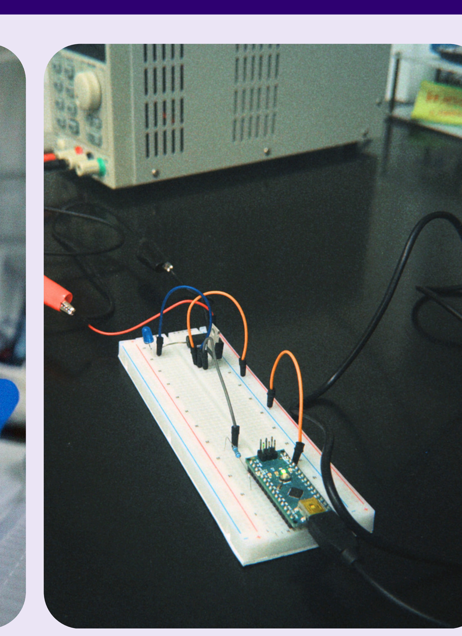
OE model comparison to MERX equipment blanks.

- *ARX/OE comparisons reveal timing delays and limited bandwidth in MERX.*
- *Models highlight need for refined excitation and preprocessing.*

Discussion

- **UV C LED feasibility:** The 254 nm LED provides sufficient irradiance; thermal management remains the main limitation.
- **Materials:** Quartz and PTFE remain stable under UV C, while several polymers fluoresce or yellow and raise the baseline.
- **MERX modeling:** ARX and OE fits were weak, with non white residuals indicating unmodeled delay, multiphase flow, and nonlinear behavior.
- **Data alignment:** Timing jitter and unlabeled trap and desorb phases reduce identifiability and limit model accuracy.
- **Computation:** Limited resources constrained model sweeps; well designed excitation and simpler structures offer better returns than brute force search.
- **AFE and control:** PMT gain should remain conservative to avoid saturation, and filter corners must exceed the detector bandwidth.
- **UAS constraints:** Mass, volume, and power limits motivate compact optics, robust mounting, and duty cycled LED operation.
- **Trade offs:** Higher LED drive improves SNR but increases heating and aging. Improved baffling reduces stray light but increases alignment and manufacturability constraints.
- **Path forward:** Use phase aligned steps or PRBS inputs, enforce explicit delays, apply regularization, and validate models on held out runs.
- **Impact:** Refined models will define safe operating envelopes and bandwidth, reducing risk in miniaturizing the detector for field or UAS deployment.

Future Work



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