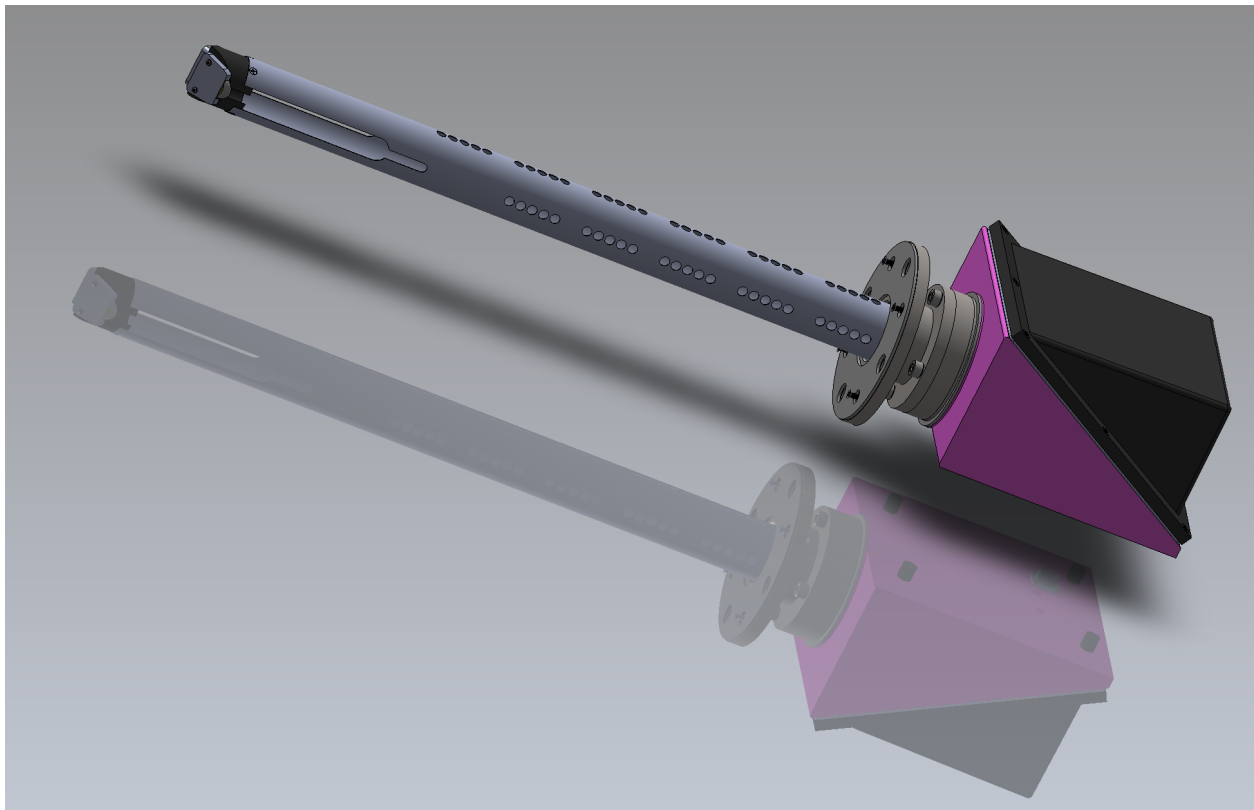


# White Paper: Development of a High-Precision In-Situ NDIR Platform

**Abstract:** This paper details the design of a robust, in-situ Non-Dispersive Infrared (NDIR) analyzer. By leveraging the STM32F4 processing core and proprietary electro-optic signal chains, the platform achieves < 2% Full-Scale (FS) accuracy. We explore the integration of opto-mechanical stability, low-noise analog design, and advanced firmware algorithms required for modern industrial emissions monitoring.



## Section 1: The Physics of In-Situ NDIR

### 1.1 Principles of Absorption

At the core of the platform is the Beer-Lambert Law, which defines the relationship

between light intensity and gas concentration:

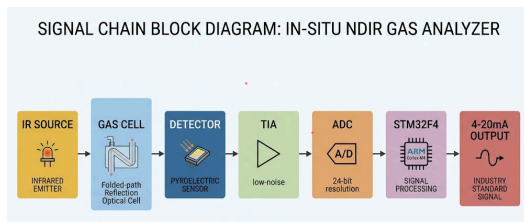
$$I = I_0 \cdot e^{-\epsilon c L}$$

Where:

- $I$  is the detected intensity

- $I_0$  is the initial intensity (reference)
- $\epsilon$  is the molar absorptivity
- $c$  is the gas concentration
- $L$  is the optical path length

Achieving 2% accuracy requires precise control over the path length ( $L$ ) and the elimination of background interference from other gases.



## 1.2 The In-Situ Advantage

Traditional extractive systems suffer from sample transport lag and condensation risks. Our in-situ platform eliminates the need for heated sample lines, providing a real-time T90 response. This necessitates a design that can withstand vibration, thermal cycling, and high particulate matter (PM) within the stack.

## Section 2: Opto-Mechanical Engineering

### 2.1 The Optical Bench Architecture

Stability begins with the mechanical chassis. The bench utilizes a folded-path reflection geometry. This allows the probe to remain compact while effectively doubling the optical interaction length, enhancing sensitivity for trace-level measurements of SO<sub>2</sub> and NO.

### 2.2 Material Selection & Thermal Stability

To prevent spectral drift, the optical cell is constructed from high-grade aluminum with specialized internal coatings. Window materials—typically Sapphire or Calcium Fluoride (CaF<sub>2</sub>)—are selected for high IR transmissivity and resistance to corrosive flue gases. The cell is maintained at a constant temperature (typically 180 degrees C) via a PID-controlled heating circuit to prevent acid dew point condensation.

## Section 3: Electro-Optic Signal Chain

### 3.1 IR Source Modulation

The system utilizes a high-energy, broadband IR source. Rather than mechanical chopping, we implement High-Frequency PWM modulation. This reduces mechanical failure points and allows the firmware to implement synchronous demodulation to filter out 1/f noise and ambient thermal radiation.

### 3.2 Low-Noise Analog Front-End (AFE)

The current generated by pyroelectric detectors is in the nano-ampere range. Our AFE features:

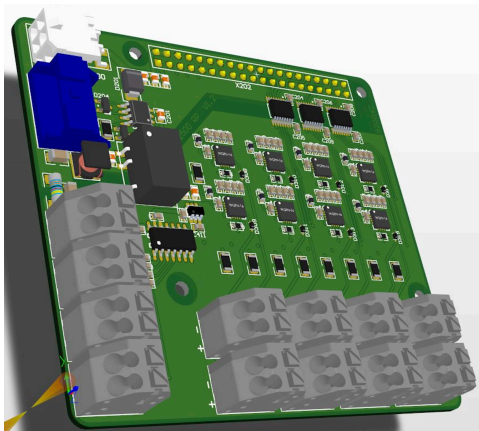
- Transimpedance Amplifier (TIA): Utilizing ultra-low bias current op-amps to preserve signal integrity.
- Active Filtering: Multiple-stage Sallen-Key filters to remove high-frequency switching noise before digitization.

- 24-bit ADC: High-resolution digitization ensures that the STM32F4 has enough "bit-depth" to resolve concentration changes at the 2% accuracy threshold.
- Layer 4: High-speed digital signals (PWM, SPI, I2C). By separating the "noisy" PWM drive from the sensitive TIA traces, we maintain the signal-to-noise ratio (SNR) required for high precision.

## Section 4: Hardware & PCB Architecture

### 4.1 STM32F4 Processing Power

The STM32F4 (Cortex-M4) was selected for its hardware Floating Point Unit (FPU) and Digital Signal Processing (DSP) instructions. These allow for real-time execution of complex compensation matrices without latency.



### 4.2 Altium PCB Design Strategy

The PCB is a 4-layer design optimized for EMI/EMC compliance.

- Layer 1: Sensitive analog signals and detector interface.
- Layer 2: Solid ground plane for noise shielding.
- Layer 3: Power distribution.

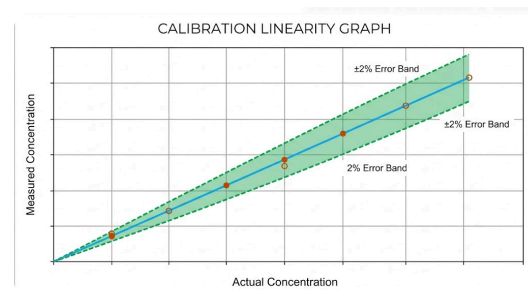
## Section 5: Firmware & Signal Processing

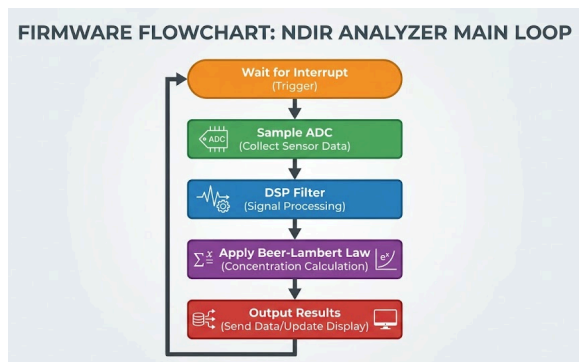
### 5.1 Synchronous Demodulation & Filtering

The firmware implements a software-based Lock-in Amplifier. By correlating the detected signal with the IR source's PWM frequency, we can extract the true absorption signal even in high-vibration or electrically noisy environments.

### 5.2 Non-Linearity & Cross-Sensitivity

NDIR absorption is inherently non-linear. The STM32F4 firmware applies a multi-point polynomial curve fit to linearize the output. Furthermore, cross-sensitivity algorithms compensate for interference from water vapor (H<sub>2</sub>O) or CO<sub>2</sub>, ensuring the targeted gas reading remains accurate.





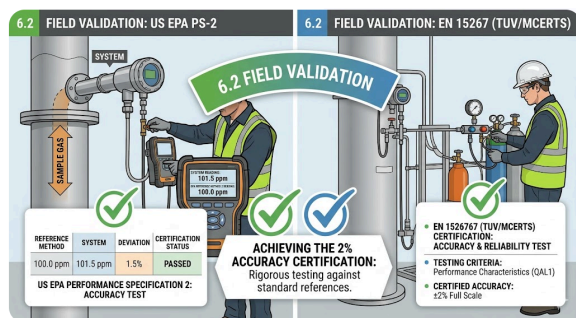
## Section 6: Compliance & SIL 2/3 Integration

### 6.1 Functional Safety by Design

In modern power plants, analyzers are part of a Safety Instrumented System (SIS). Our platform includes internal diagnostic loops:

- Source Health Monitoring: Detecting IR filament degradation before failure.
- Reference Channel Tracking: Utilizing a dual-beam approach to compensate for optical window fouling. These features allow the system to meet SIL 2/3 reliability requirements (IEC 61508).

### 6.2 Field Validation



To achieve the 2% accuracy certification, the system undergoes rigorous testing against US EPA Performance Specification 2 and EN 15267 (TUV/MCERTS).

## Conclusion

The development of this **High-Precision In-Situ NDIR Platform** represents the synthesis of advanced spectroscopy and robust industrial engineering. By integrating high-speed digital signal processing with the **STM32F4 core** and adhering to rigorous **SIL 2/3** safety standards, **Indusmation LLC** offers a field-proven architecture capable of achieving unmatched accuracy in emissions monitoring. This complete technology transfer framework ensures that global partners can scale high-precision instrumentation while meeting the most demanding environmental and safety certifications.