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High-Altitude Balloon Flight Demonstration of LED-Based NDIR Multi-Gas Sensor for Space Applications

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Abstract

A sensor which measures the concentrations of CO and CO_2 aboard spacecraft could be used as an early fire detection system and a vital component of primary life support systems. Herein, such a sensor is presented which utilizes non dispersive infrared spectroscopy to detect gases. Design and results from testing on a high altitude baloon flight are presented. The goal of this work is to develop the hardware so that it is a rugged and viable technology for a variety of sensor applications in a variety of environments. It is, therefore, crucial that the hardware can reject heat at low pressures, survive the low-temperature operation, have low drift (stable output), remain low power, and be insensitive to humidity.

Nomenclature

NDIR = Non-dispersive infrared
LED = Light emitting diode
NH_3 = Ammonia (gas)
CO_2 = Carbon dioxide (gas)
CO = Carbon monoxide (gas)
HCN = Hydrogen cyanide (gas)
N_2O = Nitrous Oxide (gas)
$\boldsymbol{T}$ = Transmissivity [1]
I = Irradiance [$W \cdot cm^{-2}$]
I_0 = Refrence Intensity [$W \cdot cm^{-2}$]
$\boldsymbol{\lambda}$ = Wavelength [$\boldsymbol{\mu}$m]
k_λ = Spectral absorption coefficient [cm^{-1}]
E_λ = Spectral profile of the LED source [1]
L = Path length [cm]
S(T) = Line strength [$cm^{-2} \cdot kPa^{-1}$]
ϕ(T) = Line shape function [cm]
P = Local total pressure [kPa]
x_i = Mole fraction of i'th species [1]
T = Temperature [K]
T_0 = Refrence temperature [K]
TE = Thermoelectric
STP = Standard temperature & pressure
N_2 = Nitrogen (gas)

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I. Introduction

A series of low-power and lightweight gas sensors have a variety of applications in space flight, a few of which are cited in NASA's 2015 Technology Roadmaps. Topic 6.2.2.9 describes the need for an in-situ atmospheric constituent sensor for primary life support systems (PLSS) which will need to be small, be able to reject heat in enviornments with limited convection such as the Martian atmosphere, have a low sampling volume, accurate across a wide range of ambient pressures, and not be susceptible to humidity. Hazardous gas detection and fire prevention systems should be extended beyond the crew cabin to areas that may be kept at lower pressures. Such occurrence may include cargo bays, within the vicinity of fuel and oxidizer tanks, and where mission critical hardware is stored. It is, therefore, desirable to have sensors that can operate in the wide range of environments that are encountered in space missions. Such a sensor which provides these key characteristics can operate using a non-dispersive infrared (NDIR) method with LED light sources[1]. LEDs have very low power consumption (<1W), require minimal cooling compared to lasers, and exhibit minimal variations in output over the expected life of the diode; making LEDs attractive components for aerospace design. Key gases to be targeted by such a sensor are those related to metabolic functions of spacraft crew and spacecraft support systems such as NH_3, CO_2, CO, HCN, and N_2O. The sensor that is discussed here has been verified to detect both CO_2 and CO[2-4]. With minor modifications this sensor could also be used to target HCN, NH_3, and N_2O.

In this work, an LED-based NDIR sensor was designed and adapted to a package in preparation for a high-altitude balloon flight which tested its capabilities, readying it for spaceflight applications. During this process, the sensor was shown to operate in a range of environments as a demonstration of the technological suitability to these applications.

II. Theory

While the sensor may be classified as NDIR, the detection method for the sensor utilizes the principle of monochromatic absorption spectroscopy, which follows the Beer-Lambert Law. Equation 1 relates the attenuation of incident light by the molar quantitiy of absorbing species; through, the ratio of the transmitted irradiance I [$W\cdot cm^{-2}$] to the refrence irradiance I_0 [$W\cdot cm^{-2}$] when a spectrally narrow optical excitation centered at some particular wavelength $\boldsymbol{\lambda}$ [$\boldsymbol{\mu}$m] with spectral emissive profile E_λ is directed through a gas medium with spectral absorption coefficient $k_{\boldsymbol{\lambda}}$ [cm^{-1}] with an optical path length through the gas of length L [cm]. The spectral absorption coefficient $k_{\boldsymbol{\lambda}}$ is combination of various of species specific quantum mechanical parameters expressed in Equation 2; where $S_{\boldsymbol{\lambda}}$ [$cm^{-2}\cdot kPa^{-1}$] is the absorption line strength, ϕ [cm] is the line shape function, P [kPa] is the local total pressure, and x_i [1] is the mole fraction of the i'th species. For these studies, ϕ and $S_{\boldsymbol{\lambda}}$ values were determined from the HITRAN 2012 database which provides a compilation of spectroscopic parameters used to predict and simulate the transmission of light in the atmosphere.

$$\mathrm{T} = \left(\frac{I}{I_0}\right) = \int E_\lambda \exp(-k_\lambda L)\, d\lambda \tag{1}$$

$$\mathrm{k}_\lambda = S_\lambda \cdot \phi_\lambda \cdot \; P \; \cdot x_i \tag{2}$$

III. Sensor Design

This sensor utilizes three mid-infrared LEDs to cover three different wavelength regions: an LED centered at 3.6μm, a second LED at 4.2μm, and a third one at 4.7μm. Figure 1 shows the normalized spectral profiles of these LEDs overlaid with the absorption features of a few targeted species. Given that the spectral intensity of the LED's is significantly wider than the absorption cross sections of targetd species, band pass filters are employed to only transmit light on wavelegnths relative to CO and CO_2; an additional filter is also used to restrict the transmission window of the 3.6 μm LED.

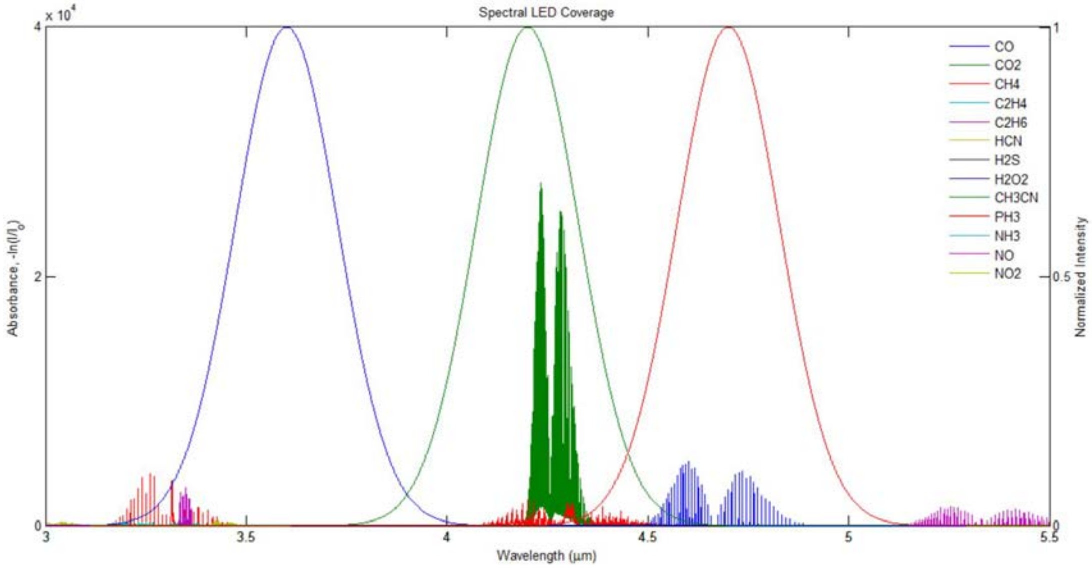

Figure 1: The absorption features of some targeted species are shown (296K) to illustrate spectral overlap between the LED emission and absorption features.

The optical path of the sensor is presented in Figure 2. Each of the three LEDs' emissions are projected through a first columating lens, band pass filtered, then through a second collimating lens. Beam splitters are then used to enable alignment of the multiple optical paths. Following alignment of the three wavesources, the light is passed through a sample cell of 8cm internal path length with transparent sapphire windows. Prior to flight, the sensor was calibrated by employing different charged mixtures into the test cell. During the high altitude balloon flight on which the sensor was tested, gasses were charged into the sample cell with a concentration of 5%CO, 5%CO_2, and balance N_2 at STP.

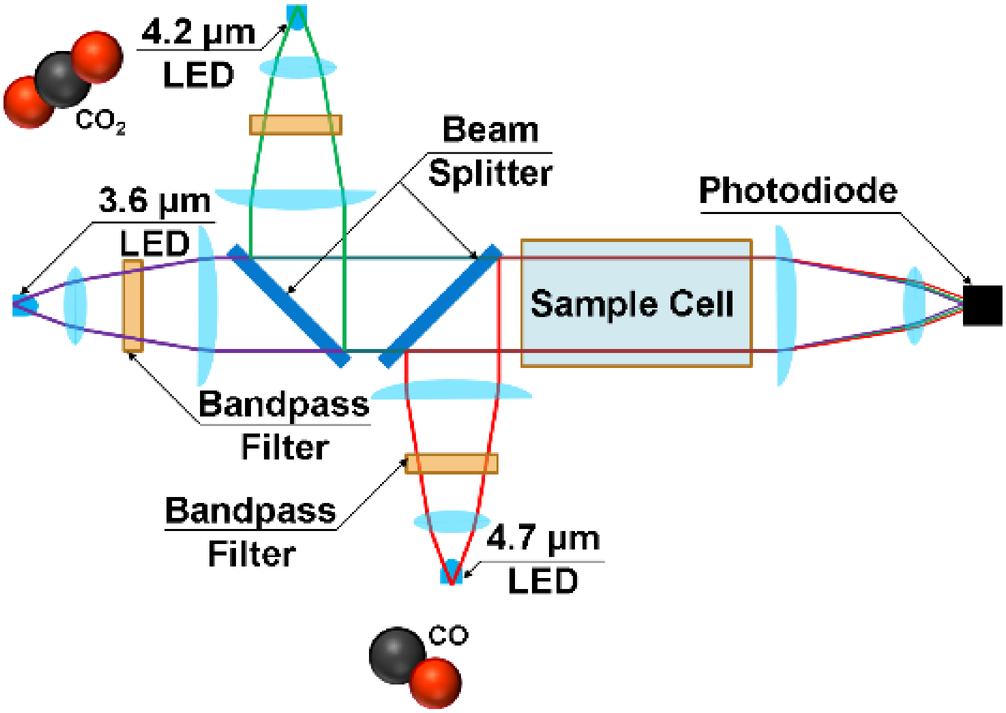

Figure 2: Beam path of the sensor.

Each of the three LEDs are focused at a single target and differentiated by using spectral multiplexing, which drives each of the LEDs at different frequencies. The output of each LED are modulated at a unique frequency by a dedicated DAQ unit, using a square-wave unity-duty-cycle function; i.e., the 3.6µm, 4.2µm and, 4.7µm LEDs were modulated at 5, 7 and 11 kHz, respectively. The LEDs were driven using Wavelength Electronics WLD3343 general purpose drivers. Each driver module receives a signal from the data acquisition unit (National Instruments cRIO9031) to generate the signal function for each LED. The cRIO also intercepts signals received from the photodiode and the various other ancillary components within the sensor.

IV. Evaluation and Test Flight

The sensor was tested on NASA's: High Altitutde Stdudent Payload (HASP), a high altitude balloon which enables testing of various scientific equipment at near space conditions. During the 15 hr 8 min flight (Figure 3), of which time nearly 13 hours was spent at float, the maximum recorded altitude was found to be 123,546 ft, with minimum temperatures and pressures as low as -54.8°F and ~0 mbar. Corresponding temperature and signal intensity profiles from each of the LEDs are presented during Figure 4.

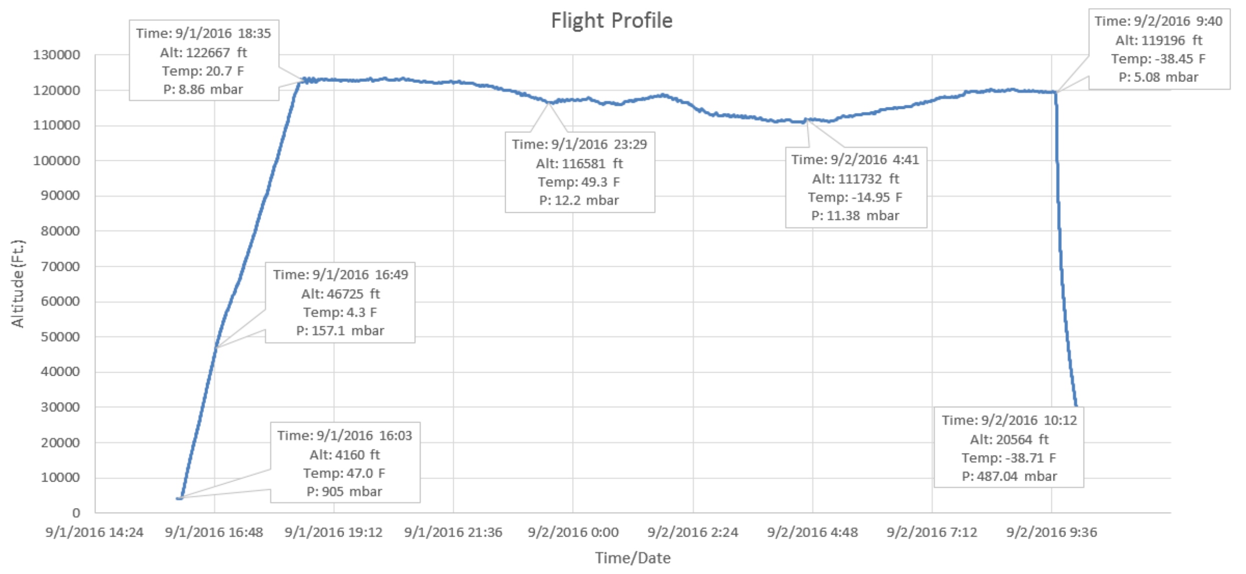

Figure 3: High altitude flight profile.

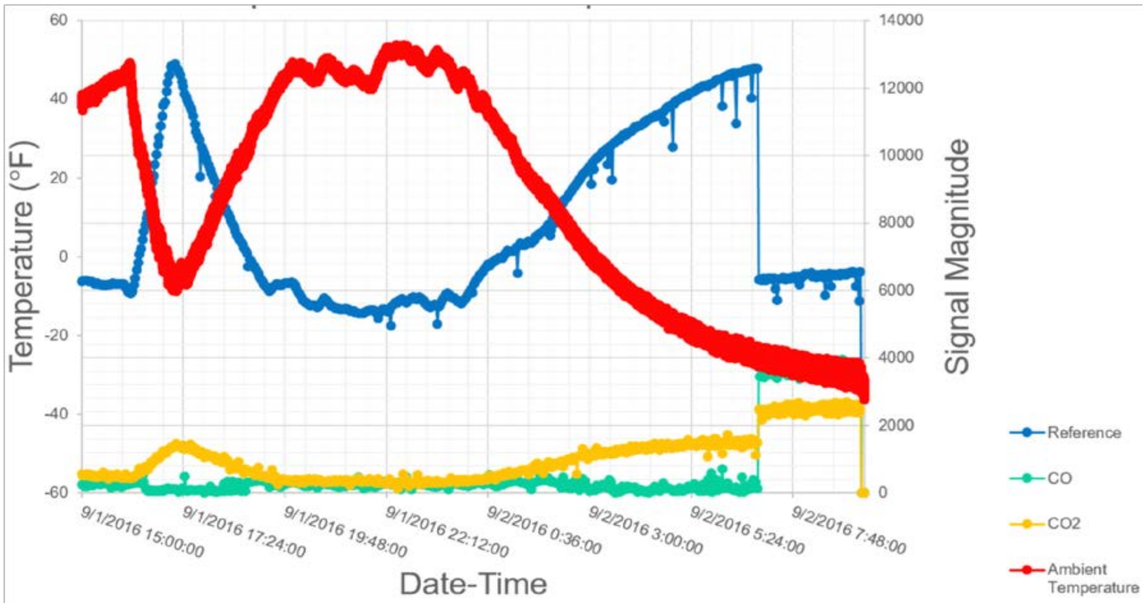

Figure 4: Temperature and recorded signal intensity.

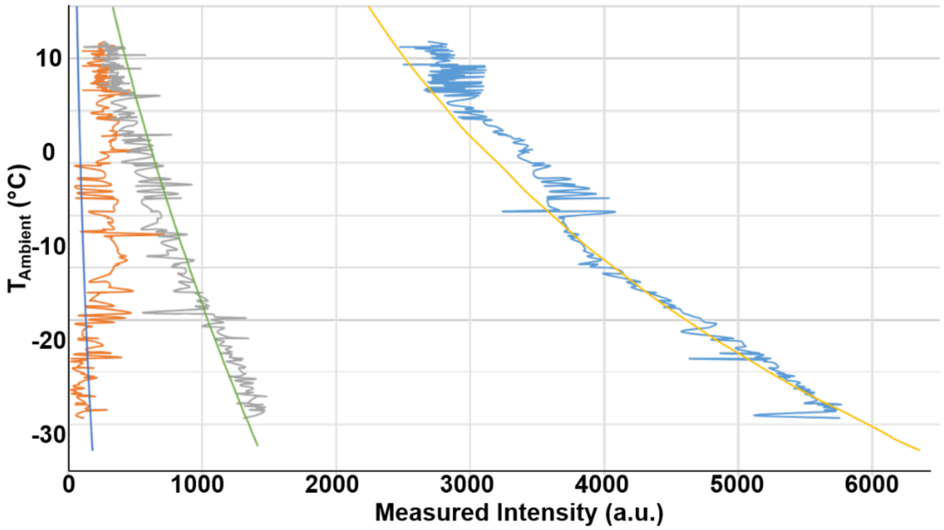

Figure 5: Measured Intensity vs. Ambient Temperature During Flight. yellow, green and blue smooth curves indicate the calculated intensity of the 3.6, 4.2 and 4.7 µm LED's respectively. With each measured intensity plotted atop.

Correlated intensity profiles are presented Figure 5 which show the observed signal intensity for each of the three LED sources along with their corresponding temperature calibration curves. While the 3.6 µm LED provides rather good intensity vs calibration, the calibration curves for the 4.2 and 4.7 µmare in need of minor tweaking to better reflect measured signal intensity.

V. Summary & Future Work

A prelimary test has been conducted for a space sensor which measures CO and CO_2 concentration using non dispersive infrared spectroscopy. Current development of the sensor is undergoing a complete redesign to enable better adaptation for space vehicles. A second high altitude balloon flight has been secured which will allow continual evaluation of the sensor at altitudes of 35km (-40°C, 1/100atm). Additional flight tests are planned to follow and may also include parabolic flights or sounding rockets to enable testing of performance in critical microgravity environments.

Our results in environmental conditions have shown that LEDs are remarkably easy to operate and maintain at optimal temperatures during service. The bulk of the difficulty encountered in both temperature and power management came from the modules used to drive the LEDs, which were selected for rapid development and simplicity. Coupling this with low-power overhead and long-life (high stability) makes this technology of great appeal to aerospace applications. As the hardware is further refined, it should become more compact with more efficient multiplexing approaches. This may take the form of tightly spaced arrays of LEDs which use custom integrated lenses. The driving electronics will also need to be refined to a more efficient design as the current system produces excessive waste heat.

VI. Acknowledgments

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VII. References

1. Villar, M., Parupalli, A., Urso, J., Partridge Jr., W. P., and Vasu, S. S. " “Non-Dispersive Absorption Sensor for Early Fire and Hazardous Gases Detection”, ," *Center of Excellence Commercial Space Transportation (FAA), 6th Annual Technical Meeting Proceedings*, 2016.

2. Thurmond, K., Loparo, Z., Partridge Jr., W. P., and Vasu, S. S. "A Light-Emitting-Diode (LED) Based Absorption Sensor for Simultaneous Detection of Carbon Monoxide and Carbon Dioxide " *Applied Spectroscopy* Vol. 70, No. 6, 2016, pp. 962-971.

3. Thurmond, K., Loparo, Z., Urso, J., Partridge Jr., W. P., Kapat, J. S., and S., V. S. "A Robust Fire and Hazard Detection Sensor for Space Vehicles Using LEDs," *Commercial and Government Responsive Access to Space Technology Exchange (CRASTE) 2015, Chantilly, VA, 6/2015.* , 2015.

4. Thurmond, K., Duenas, E., Vasu, S. S., and Partridge, W. P. "Development of a LED-Based Sensor for SImultaneous, Time-Resolved Measurements of CO and CO2 from Combustion Exhausts," *Eastern States Section of the Combustion Institute Fall Technical Meeting 2013*. Clemson, South Carolina, 2013.