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Optical Sensors for Harsh Environment Applications

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ABSTRACT

The development of a harsh environment ammonia slip sensor based on tunable diode laser absorption spectroscopy is presented. A hybrid optical sensor design, through combination of wavelength modulation spectroscopy (WMS) and alignment control, is proposed as an approach towards reliable in-situ measurements in misalignment prone harsh environments. 1531.59 nm, 1553.4 nm and 1555.56 nm are suggested as possible absorption lines for trace ammonia measurement (<1ppm at 10m path length at 500K) in gas turbine exhaust conditions. Design and performance of the alignment control system are presented in detail. Effect of misalignment related measurement degradation is investigated and significant improvement in measurement fidelity is demonstrated through the use of the hybrid optical sensor design.

Keywords: Tunable diode laser, wavelength modulation spectroscopy, harsh environment, ammonia slip, alignment

1. INTRODUCTION

In this past decade, industrial sectors of power generation and oil & gas, have seen a steady increase in the demand for lower costs, fuel savings, better efficiency, and longer asset life. As a result, higher reliability, optimized performance, and advanced analytics have become the key drivers in these sectors. Intelligent machines with fast & reliable online sensing and controls, in combination with advanced analytics, are leading to a profound transformation of the global industrial sector. Many a times, true performance enhancement requires measurement of machine parameters in harsh environments (high pressures or temperatures or both). Therefore, to support the development of advanced analytics and to augment the industrial assets with digital intelligence, harsh environment sensors are going to be increasingly important in the times to come[1].

Harsh environment sensors based on optical techniques offer some key advantages over conventional techniques, such as their speed of response, in-situ capability, ease of deployment, and their repeatability/reliability. A major application of optical sensors in the industrial space is gas monitoring, sensing, and analysis through techniques such as ultraviolet absorption spectroscopy (UV), non-dispersive infrared (NDIR), Fourier Transfer Infrared (FTIR) and Photo-acoustic Spectroscopy (PAS) [2]. All these techniques are fast, reliable, and involve minimal maintenance. For harsh environment applications, such as O&G and energy sectors, these techniques typically require gas sampling and conditioning to bring the harsh environment sample to an analyzable state or location. This can often involve undesirable delay in the measurement and unwanted maintenance of the sampling system[3]. Therefore, for control and optimization applications where response time, sensitivity and selectivity are the key requirements, laser spectroscopy techniques like Tunable Diode Laser Absorption Spectroscopy (TDLAS) offer real value [4, 5]. TDLAS, when implemented in line-of-sight [6, 7] or stand-off configuration [8], can offer true in-situ measurement capability in harsh environments with high temperatures or pressures. A TDLAS instrument can make reliable measurements through one or more transmitting windows while being completely decoupled from the harsh environment. In this paper, we present a system based on TDLAS as an effective and reliable tool to conduct real-time, highly selective, in-situ trace measurements of ammonia slip for power plant control applications. We also present the implementation challenges, particularly maintaining alignment, and present possible solutions to make the system perform in harsh industrial conditions.

2. THE NH_3 SLIP PROBLEM

Nitrogen oxides (NOx) emissions from gas turbines are strictly regulated by environmental agencies, like the EPA in the United States. A selective catalytic reduction approach (SCR) is often employed downstream of the engine exhaust to decrease the NOx concentrations in the exhaust gases before they are released into the atmosphere through the stack [9]. In the SCR, ammonia (NH_3) is injected to cause chemical reactions where NOx is reduced to N_2 and H_2O as shown in figure

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1. Depending on the SCR efficiency, NOx levels downstream of the SCR will vary. For optimal SCR performance and to avoid excess ammonia usage, the amount injected in the SCR needs to be controlled online as a function of varying emission levels. Measurement of "NH_3 slip", which refers to the excess unreacted ammonia present in the SCR exhaust, is an effective way to estimate the amount of NH_3 that needs to be injected at any given time. For example, when emissions lower over time, the NH_3 slip value will show an increase indicating that the injected amount needs to be reduced and similarly vice versa for the case of increasing emissions. The current state-of-the-art to measure NH_3 slip is a continuous emissions monitoring system (CEMS) which is a stack-based-sampling approach and involves long sampling delays of about 2- 3 minutes. Some TDLAS- based in-situ systems, deployed in the stack, have also been observed in recent years. However, both of the above systems are limited in effectiveness for SCR control by the gas travel time and composition changes between SCR exhaust and the actual measurement location on stack. Hence, there is a need to develop an in-situ, real-time sensor that can operate directly in the harsh SCR exhaust environment to measure "true" NH_3 slip value.

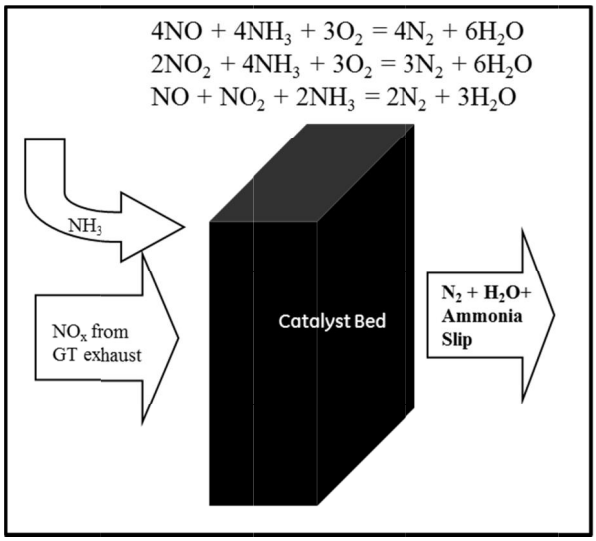

Figure 1: Schematic depicting the selective catalytic reduction (SCR) process in a typical power plant and the ammonia assisted chemical reactions leading to NOx reduction in exhaust gases.

3. SPECTRAL SIMULATION AND LINE SELECTION

The spectral region around 1500 nm is excellent for industrial ammonia detection. First, NH_3 has fairly strong vibrational overtones in this region which make ppm level detection possible. Second, this region has low fiber optic transmission loss, enabling remote or distant location of the light source and analyzer. However, usage of this spectral region for power plant exhaust application presents a major spectroscopic challenge of H_2O interference. Exhaust gases typically contain 5-10% H_2O. Figure 2a shows a HITRAN [10] simulation of 5% H_2O & 500ppm NH_3 at temperature of 500K, pressure of 1bar and path length of 10m. Please note that path length of 10m is used here because, as explained later, it is the line-of sight distance of our sensor system. It is clear from Fig 2a that H_2O has a number of strong absorption features in the 1500nm region that have potential to damage the NH_3 measurement fidelity. Therefore, it is extremely important to do a proper line selection through a trade-off between NH_3 line-strength and H_2O interference level. Also, as wavelength modulation spectroscopy (WMS) is fundamentally more sensitive to sharp spectral features, it is valuable to prioritize NH_3 lines that exhibit a relatively flat H_2O interference.

The simulations in figures 2b, 2c and 2d show a set of spectral zones in the 1500nm spectral region with minimal moisture interference on NH_3. In figure 2b, the preferred line is at 1531.59 nm due to the low and flat H_2O background. Similarly, in figures 2c and 2d, NH_3 lines around 1553.4 nm and 1555.56 nm are the preferred lines. In standard well designed TDLAS systems, the detection is often limited by interference fringes to around 1E-5 in absorbance [2].

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Therefore, for a path length of 10m, all these lines have the potential to deliver sub-ppm NH_3 measurements in a high H_2O background.

4. SENSOR DESIGN AND IMPLEMENTATION

As mentioned before, the best way to estimate the true NH_3 slip value is to directly measure it in the SCR exhaust. In case of a combined cycle power plant, the SCR is embedded within a heat recovery steam generator (HRSG) [11]. The sensor presented in this paper is designed for implementation in a HRSG. The environment inside a HRSG is fairly harsh due to high temperature of exhaust gases, engine vibrations and floating dust or impurities. To tackle these challenges, we developed a novel hybrid approach based on a combination of wavelength modulation spectroscopy (WMS) [12, 13, 14] with a misalignment correction methodology as shown in figure 3. Both these aspects are discussed in details below.

4.1 WMS Sensor

The WMS sensor consists of three elements: the launcher (or pitch), the receiver (or catch) and the NH_3 analyzer. The launcher and receiver are installed on opposite sides of the HRSG in a line-of-sight fashion. These are coupled to the HRSG walls through 2 inch quartz windows. The quartz windows are continuously purged with dry N_2 to minimize depositions. The ammonia analyzer, located in site control room, sends the 1.5µm NH_3 spectroscopy laser to the launcher through a single mode fiber optic cable. A one inch diameter lens L1 (biconvex, 1.5µm AR coated, f=10mm) collimates the 1.5µm light towards the receiver (located about 10m away across the HRSG).

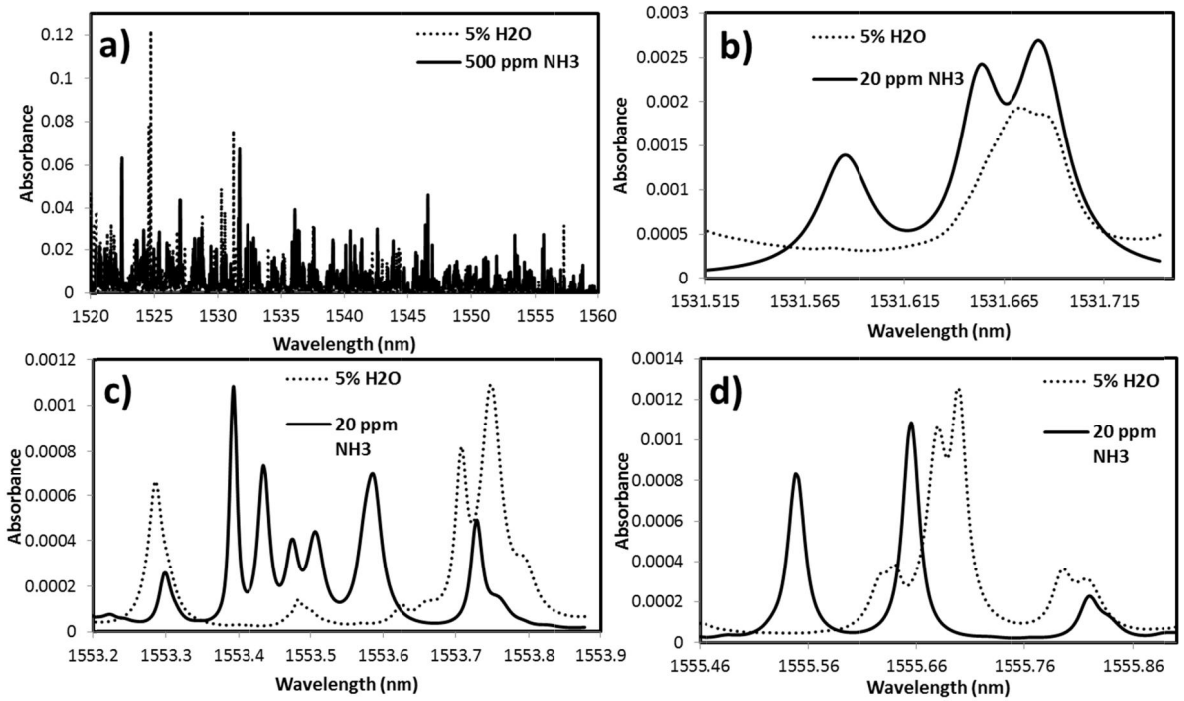

Figure 2: Spectroscopic absorbance simulations at 1.5µm (HITRAN 2012) to identify optimal ammonia absorption lines with minimal moisture interference. a) H_2O= 5%, NH_3= 500ppm, Pressure=1Bar, Temperature=500K, Path length= 10m. b) H_2O= 5%, NH_3= 20ppm, Pressure=1Bar, Temperature=500K, Path length= 10m. c) H_2O= 5%, NH_3= 20ppm, Pressure=1Bar, Temperature=500K, Path length= 10m. d) H_2O= 5%, NH_3= 20ppm, Pressure=1Bar, Temperature=500K, Path length= 10m.

The receiver employs a 2 inch diameter collection lens L2 (biconvex, 1.5µm AR coated, f=10mm) to focus the 1.5µm light on to a InGaAs photodiode. The photodiode signal is sent back to the analyzer for concentration measurement calculations. The analyzer uses a fiber coupled DFB diode laser at 1.5µm which is modulated at 10 KHz and scanned

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across the NH_3 absorption line at 50Hz. Signal from the InGaAs photodiode is analyzed using a software lock-in to generate the first harmonic (1f) and second harmonic (2f) absorption signals. . The WMS modulation amplitude is set to 2.2 to maximize the 2f signal [15]. The analyzer includes a high concentration reference NH_3 cell and a reference detector. These are used to compensate for laser wavelength & calibration drifts. The analyzer also takes sample gas temperature and pressure as inputs to estimate NH_3 concentration. These are measured through a thermocouple and a pressure sensor deployed inside the HRSG.

The choice of a WMS based sensing methodology was key towards solving two major issues related to harsh environment measurements: window clogging and beam steering. Window clogging refers to the gradual deposition of dust and impurities on the launcher and receiver windows while beam steering is caused by localized thermal fluctuations in the beam path. Both these lead to power losses and, if not tackled, can lead to erroneous signals. Normalizing the 2f signal by the 1f signal and using the 2f/1f peak value to represent NH_3 concentration proved to be a very effective way to reduce the errors introduced by power losses. Since both 1f and 2f signals are proportional to the total transmitted power, this normalization nullifies the effect of power fluctuations to deliver consistent results over time and under different operating conditions [16].

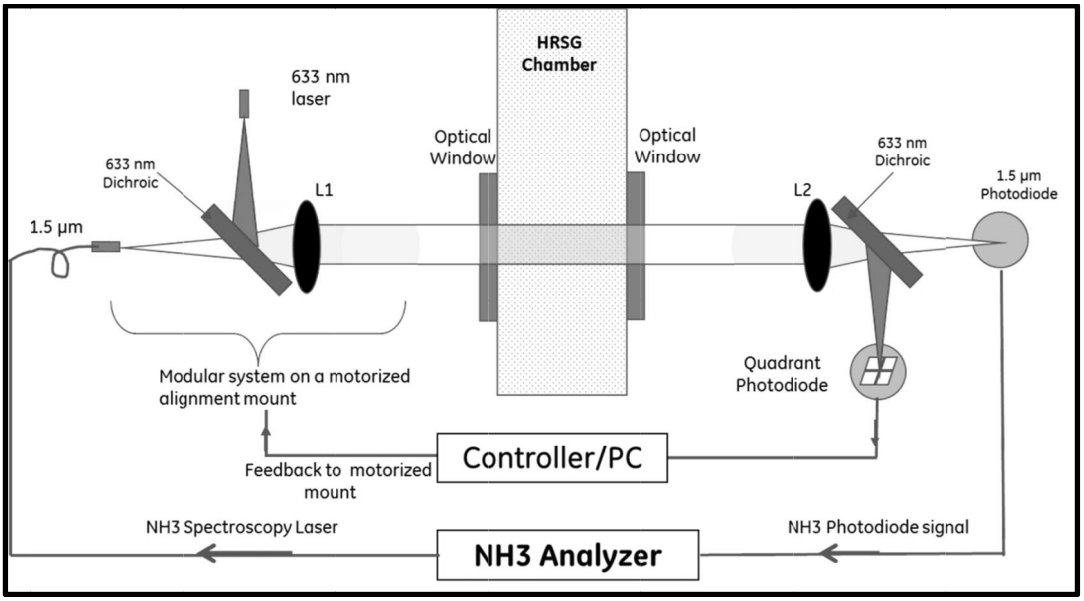

Figure 3: Schematic depicting the hybrid harsh environment ammonia slip sensor and the implementation methodology in a heat recovery steam generator (HRSG).

4.2 Alignment Control

Another major challenge in delivering 24x7 operations in a harsh environment, like the HRSG, is maintaining optical alignment. Drifts in alignment can be introduced by variable thermal expansions of the structure, mechanical vibrations, cantilever sagging effects, etc. To overcome these effects, we developed a misalignment correction system and coupled it with the WMS sensor. As shown in figure 3, a fiber coupled single mode 633nm laser (Power Technology Inc) is coupled to the 1.5µm spectroscopy laser with the use of a 633nm dichroic mirror (Thorlabs). Care is taken in initial alignment of the 633nm fiber tip to make the two lasers co-propagating. Once aligned, the positions are locked to make the launcher a monolithic unit. This is done beforehand in a controlled lab environment. The monolithic optical assembly is mounted on a DC servo motor (Thorlabs Z812) based X-Y tilt stage (Thorlabs KM100) that can control launching angle of the co-propagating beams into the HRSG. At the receiver, the beams are separated by employing another 633nm dichroic. The red beam is made incident on a quadrant photodiode (OSI Optoelectronics). The quadrant photodiode has a diameter of 10mm and is placed such that the red beam is symmetrically located with a spot size of about 4mm. The quadrant photodiode generates error voltages corresponding to the X and Y displacements and also a sum voltage

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corresponding to the total incident power. A LABVIEW based controls platform is used to read the X and Y error voltages and adjust the respective tilts of the launcher to compensate for any misalignments using a proprietary intelligent algorithm. During installation, the initial baseline alignment is done such that the two error voltages are zero and both the 633nm and 1.5µm laser powers are maximized on their respective detectors. Choice of the 633nm wavelength was based on two main considerations. First, NH_3 and other species like H_2O, O_2, CO_2 etc. present inside the HRSG do not absorb at this wavelength, hence avoiding sample induced power fluctuations of this laser. Second, as 633nm lies in the visible spectrum, it enables a practical way to install and commission the system which is otherwise very hard to do with invisible NIR wavelength.

5. PERFORMANCE OF ALIGNMENT CONTROL SYSTEM

The alignment control system was thoroughly tested in the lab before field deployment. As NH_3 is a hazardous gas, lab tests were conducted by replacing the NH_3 spectroscopy system with an Oxygen spectroscopy system. This involved changing the 1.5µm to a 760nm tunable diode laser (tuned to absorption line of O2) and replacing the 1.5µm InGaAs photodiode with a Si photodiode. Also, the tests were conducted in an open path configuration in room air at 1bar with a path length of 2m. Artificial misalignments were introduced by vibrating the optical bench on which the launcher and receiver are placed. The figure 4a shows a plot of the 2f/1f signal from the O2 spectroscopy system as a function of time under no vibrations. The two traces depict the cases with the alignment control on and off respectively. The signal repeatability in both cases is about 1.6% (σ =0.003). Hence, under no vibrations or misalignments, the alignment control system by itself does not introduce additional error into the signal. Figure 4b shows a trace of the normalized total power of the 760 nm laser in presence of simulated vibrations. As shown, when alignment control is off, the vibrations lead to a rapid alignment drift in the system and the total power drops below 10% in about 15s. However, as shown in figure 4b, the system is able to maintain alignment over time when alignment control is on. This is indicated by the total power being brought back to 100% value after every misalignment. Also, looking closely, one can note the rapid response time of the alignment correction system. For a power loss of 20%, the correction time is less than 500ms which is expected to be optimal for thermal and vibration induced alignment drifts in the field.

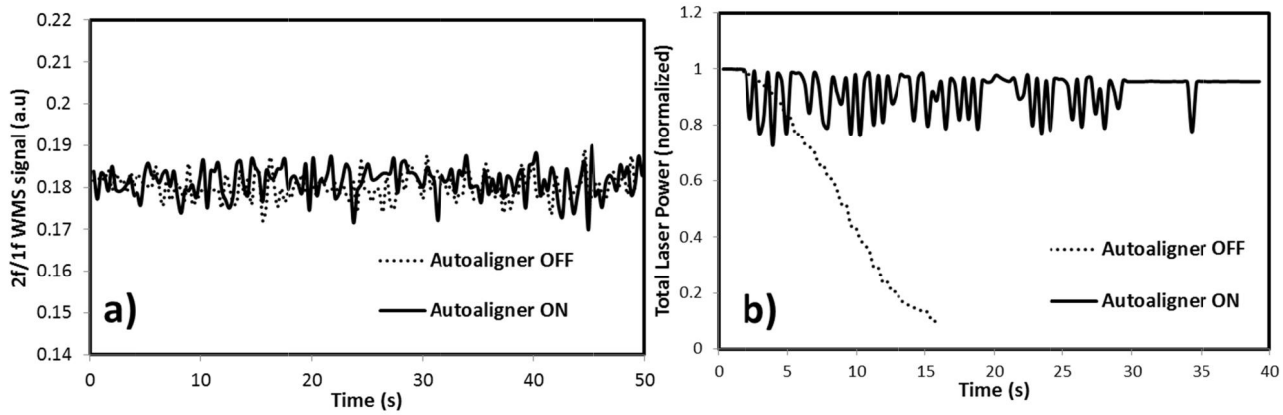

Figure 4: Experimental results demonstrating the performance of the alignment control system. a) Plot of the 2f/1f WMS spectroscopy signal as a function of time under no vibrations (with alignment control on & off). b) Plot of the normalized power of the spectroscopy laser as seen by the receiver as a function of time in presence of induced vibrations (with alignment control on & off).

Figure 5 shows the effects of misalignment related power loss on the 2f/1f signal intensity. The plots show time correlated traces of the normalized 760 nm laser power and the measured 2f/1f WMS signal with the alignment control on. As shown in figures 5a, 5b, and 5c misalignment related power losses can lead to spurious 2f/1f signals. For low laser power levels, the 1f value approaches zero and the 2f/1f parameter fails to represent the true species concentration. This effect manifests itself as spikes in the 2f/1f traces (some spikes even going out of scale of these plots). As the alignment control system corrects the misalignment, the 2f/1f signal comes back to the expected value. However, it must

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be noted that the 2f/1f trace reaches optimal value much before the laser power correction is complete. Some instances which show this effect are marked with arrows in figure 5. It is observed that 2f/1f values reach the accurate value as soon as the laser power returns to 30-40% of the maximum value. Hence, we conclude that for this sensor if the laser power drops below 30% of the maximum value, the 2f/1f value has a high potential to be erroneous. Therefore, during field measurements, we constantly track the total power of the spectroscopy laser and discard the 2f/1f values where the total power is less than 30%. Also, it is advisable to take care during the design phase to ensure that power losses caused due to misalignments are minimized as much as possible. Large area collection optics, large area detectors, and passive vibration isolation paddings (of launcher and receiver) are some approaches that work well.

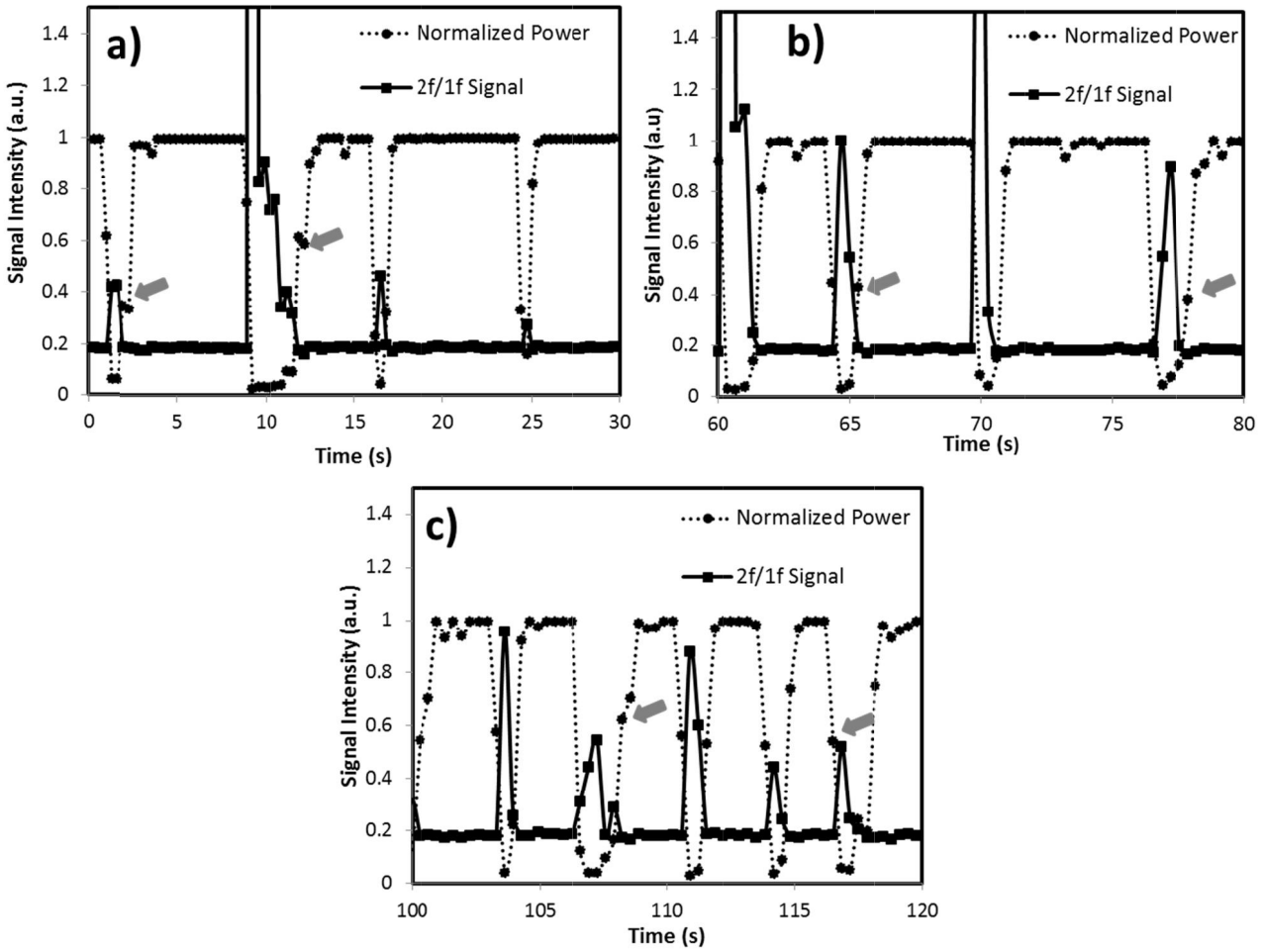

Figure 5: Experimental results showing spurious effects of optical misalignments on the 2f/1f spectroscopy signal and the achieved improvement through the alignment control system. Plots represent time correlated traces of the spectroscopy laser power (normalized) and the corresponding 2f/1f signal from O_2 in room air. a), b) and c), provide zoomed-in views at different time instances. Relevance of arrow marks described in text.

6. SUMMARY AND CONCLUSION

We have presented the development of a novel NH_3 slip sensor capable of performing in harsh environments, like a power plant exhaust.. Reliable and fast measurement of "true" NH_3 slip value, through direct measurements in the SCR exhaust are critically important for SCR control applications. Spectral simulations, keeping moisture interference in mind, helped identify 1531.59 nm, 1553.4 nm and 1555.56 nm as possible absorption lines for trace NH_3 measurement (<1ppm at 10m path length at 500K) . The hybrid sensor design, based on the combination of a NH_3 spectroscopy system and an alignment control system, was presented along with the methodology for implementation in a HRSG. The 2f/1f

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WMS approach was discussed to be advantageous towards tackling beam steering and window clogging. Finally, design and lab performance details of the misalignment control system were presented to demonstrate the value of an alignment control system for harsh environment applications.

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