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ALL-FIBER DIAL/DOPPLER LIDAR AT 1.65 MICRON FOR REMOTE DETECTION OF METHANE LEAKS

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ABSTRACT

A 1.65 μ m CH₄/Doppler fiber lidar has been developed at ONERA. This coherent detection lidar, named VEGA, is designed for remote detection and characterization of methane leaks at several hundred meters of distance. During a measurement campaign in October 2018, it has been field-tested for the first time on an industrial test platform developed by TOTAL E&P, in which controlled methane leaks were generated. The VEGA lidar, at a distance of 200 m, has performed successful methane and wind measurements. The system opens new perspectives for industrial and environmental monitoring.

1. INTRODUCTION

Several issues can arise from incidental methane leaks around oil & gas facilities, mainly i) health and safety for the working staff, ii) environmental impact as CH₄ is a high warming-effect gas, iii) financial impact for facilities operators. Numerous passive and active sensors have been previously developed for remote monitoring of gas leaks (see examples in [1][2] and [3][9] respectively), but it was found that some progress were still to be made. This motivated a partnership project called NAOMI (started 2014) between TOTAL E&P and ONERA. As for active system, it was especially pointed out that there was no single instrument able to measure simultaneously the wind and the methane concentration (inputs required to evaluate leak rates), even more at several hundred meters of distance from a leak point. To fill the gap, ONERA has developed the first all-fiber and dual-function CH₄/Doppler lidar system. This new lidar is called VEGA (VEnt & GAZ - french for "Wind & Gas"). After a five-year development, the VEGA lidar has been successfully deployed

for its first field-test campaign in October 2018. This two-week campaign took place on the TADI platform (Transverse Anomaly Detection Infrastructure) developed by TOTAL E&P on the industrial site of Lacq in Pyrénées-Atlantiques (Southwest of France). We report on VEGA results obtained during this campaign.

2. VEGA FIBER LIDAR

The VEGA lidar demonstrator, as deployed during the campaign, is depicted in fig.1.



Figure 1: VEGA fiber lidar during TADI campaign

It is based on a coherent architecture for Doppler measurement, but uses a laser emitter suited to a methane absorption transition at 1.65 μ m. The principle of a dual-function DIAL/Doppler coherent Lidar has been previously demonstrated for CO₂ measurements [10] with a solid state emitter and a free-space lidar architecture. By contrast, VEGA is the first DIAL/Doppler system addressing the CH₄ molecule, and its all-fiber design makes it a robust, easy-to-align, versatile lidar system.

The laser emitter is based on a MOPFA architecture (Master Oscillator Power Fiber Amplifier). Continuous wave semi-conductor seed lasers at $1.65\ \mu\text{m}$ are pulsed and amplified in a specially-designed Raman fiber amplifier, up to $10\text{-}20\ \mu\text{J}$ with $20\ \text{kHz}$ repetition rate. The pulse duration is $100\text{-}200\ \text{ns}$, enabling $15\text{-}30\ \text{m}$ lidar range resolution. A single-mode fiber is used to emit the laser pulses into the atmosphere, such that the beam quality factor M^2 is very close from unity, an important feature for coherent detection. An optical switch is used to alternate between the ON-line and OFF-line seed lasers. The emitted wavelength can be controlled and calibrated using a fiber-input gas-cell filled with pure CH_4 . This control loop was kept open at this stage, since it was verified beforehand that the free running frequency stability of the seed laser was good enough for the application. The exit laser beam is magnified up to $112\ \text{mm}$ in diameter, and then focused at a distance of $200\ \text{m}$. A two-axis scanner allows directing the beam toward leak points, and/or performing scanned measurements. The lidar is set in monostatic configuration to make lidar signal collection easier. The scanner mirrors, magnification lenses, and beam circulator between emission and reception paths are the only free-space optics of the system. A high-bandwidth AC-coupled InGaAs detector is used for detection. The lidar signal is digitized with an 8-bits $250\ \text{MHz}$ bandwidth digitizer. The overall demonstrator size is about $1.7\ \text{m}^3$, and power consumption is below $400\ \text{W}$.

3. TADI CAMPAIGN

The TADI platform is a unique facility developed by TOTAL E&P, located in Lacq (Pyrénées-Atlantiques, southwest France). It allows generating controlled releases of methane and carbon dioxide from several leak points, such as tanks, stacks, or canes, with various leak rates between $0.3\ \text{g/s}$ and $300\ \text{g/s}$. The campaign lasted two weeks from 8th to 19th October 2018. No less than 25 companies were participating, testing either optical or acoustic detection systems. ONERA has deployed two prototype infrared cameras on elevated platforms, to observe and characterize gas leaks at short distance ($<50\ \text{m}$), whereas two lidar demonstrators were deployed at

longer distance ($>200\ \text{m}$). These included an OPO-based multi-gas solid-state lidar named GAZ-L (presented in another paper), and the CH_4 /wind fiber lidar VEGA, on which we focus here. During the two weeks, 82 controlled releases of CH_4 and 25 of CO_2 were generated, allowing for all participants to test their equipment and demonstrators in a variety of weather and gas release conditions.

Figure 2 shows examples of gas release scenes, as seen by VEGA lidar's pointing camera. In many cases, trees were present in the background, allowing performing at the same time range-resolved measurements (RR-DIAL) from aerosols backscattering, and integrated-path measurements (IP-DIAL) from background targets. On the other hand, releases from the stack (bottom left picture), with no background, made possible the recording of regular lidar signals, fading away without hard target disturbance, which was also interesting to examine noise behavior as a function of distance.

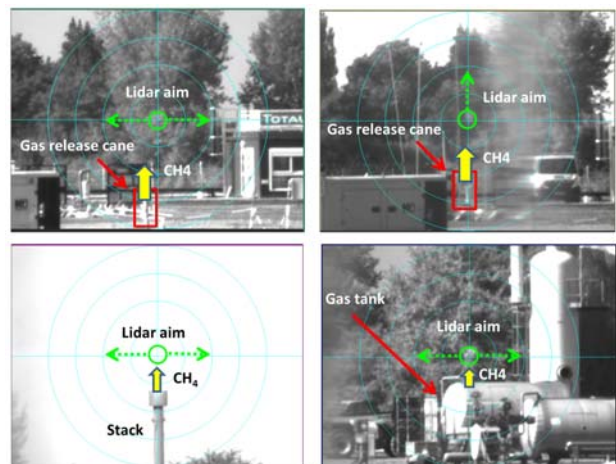


Figure 2 : Examples of gas release scenes (green dots shows typical scan directions)

4. VEGA RESULTS

Though this was its first measurement campaign, the VEGA lidar proved to be robust and reliable on the field, showing no significant performance variations during two weeks, despite important temperature and humidity variations.

Hereafter we present an example (among many) of measurement realized with the lidar. For this test, the gas release was performed on a stack

(bottom-left on fig.2) with a 10g/s leak rate, located 200 m away from the laser. The lidar line-of-sight is fixed. Figure 3 first shows the recorded lidar signal intensity (expressed through its CNR or Carrier-to-Noise Ratio) at the unabsorbed wavelength λ -OFF, as a function of time and distance. This illustrates how the CNR was optimized for a distance close to 200 m, by focusing the laser beam. This also shows that there was significant and rapid variations of the aerosol load, due to proximity of construction works in this industrial site, and to aerosols emission by the (dusty) stack itself.

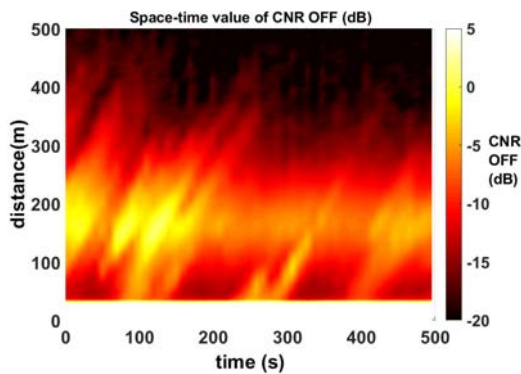


Figure 3. Evolution of the CNR at λ -OFF as a function of time and distance (10 sec averaging)

Figure 4 shows the time evolution of the lidar CNR at λ -OFF and λ -ON, at a distance of 204 m, i.e. behind the stack. Very clear drops off from the ON-line signal can be seen, signing the presence of absorbing methane. The leak starts at $t=130$ s and stops at $t=450$ s.

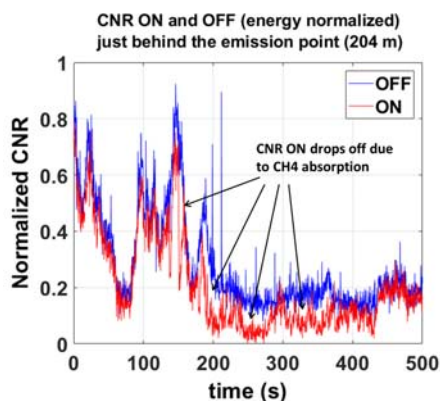


Figure 4. Compared time evolution of the CNR at λ -OFF and λ -ON just behind the stack (no averaging)

Figure 5 shows the same phenomenon but as a function of distance instead of time. It illustrates that the discrepancy between the ON and OFF signal slopes occurs only after 200 m, where the stack is located.

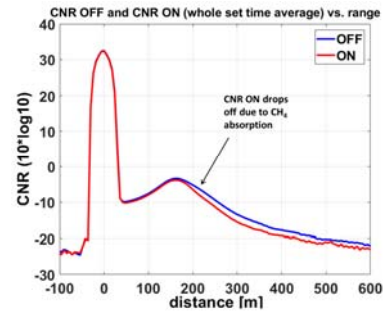


Figure 5. Compared range evolution of the CNR at λ -OFF and λ -ON (500 s averaging)

Combining space and time information together and making use of the classical DIAL equation [10], Figure 6 finally shows the measured CH_4 concentration as a function of time and distance. The CH_4 plume is very well detected at 200 m, though it appears intermittent in time (either because of gas release variations, or because of the wind moving the plume out of the fixed line-of-sight). A maximum concentration of 815 ppm is recorded here for 30 meters resolution (200 ns pulses) and 15 meters sampling grid (overlap factor=2). One can notice that the measurement noise increases rapidly behind the gas plume. This is because the plume absorbs most of the light at the ON-line wavelength.

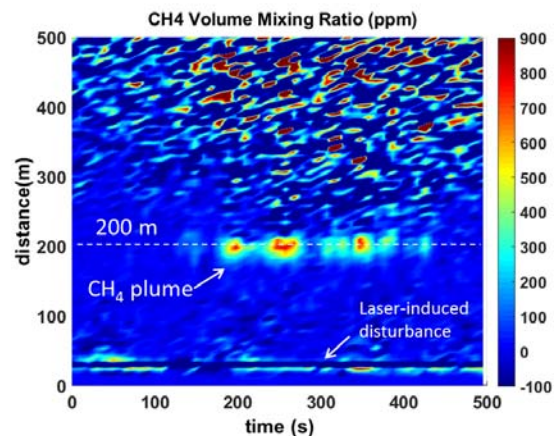


Figure 6. CH_4 volume mixing ratio (in ppm) as a function of time and distance (10 sec averaging)

To evaluate the system detectivity, the standard deviation of the derived CH₄ Volume Mixing Ratio is computed during the first 100 seconds in Figure 6 (i.e. in the absence of methane plume). At 200m and for 10 seconds averaging time, we obtain a detectivity $\sigma_{\text{det}}=20$ ppm @ 1σ , for a peak value recorded at 815 ppm (thus a Signal to Noise Ratio SNR=41). Likewise, it can be estimated that the lidar range, if the stack had been located further, would have been between 550 and 600 m for this experiment (but assuming an un-optimized beam focus still at 200 m, and a 10 seconds averaging time ; the range could be increased by re-optimizing those settings).

In addition to these results, the VEGA lidar also measures simultaneously the wind speed (projected onto the line-of-sight) thanks to its Doppler function. Figure 7 shows the measured wind value with respect to time and distance. A positive wind (i.e toward the background in our convention) is recorded. At 200 m, a significant variation of the radial wind speed is recorded around 300s, which correlates with the ‘gap’ seen on the CH₄ map at the same time (Figure 6). This can be due to the rotation of the wind vector, pushing the plume out of the line of sight.

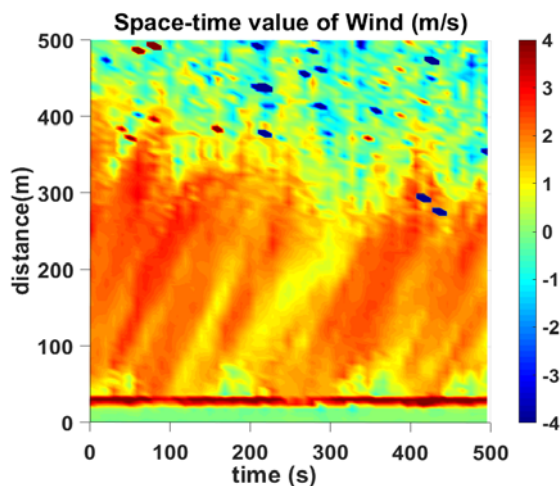


Figure 7. Wind speed (in m/s) as a function of time and distance (10 sec averaging)

CONCLUSION

During its first test campaign, the VEGA Lidar has demonstrated high robustness and reliability, and also its ability to measure simultaneously range-resolved profiles of methane concentration (with high detectivity), of wind speed, and of the relative evolution of the aerosol load. Data recorded during the two-week TADI campaign are very rich. Beyond what has been shown here, they also contain IP-DIAL data, scan lidar data, and multi-wavelength data. Detection of methane was obtained for a 3-decades span of gas release rates between 0.3 g/s and 300 g/s. Nevertheless, lots of analyses remain to be done, and VEGA lidar data must also be compared to other instruments data like infrared cameras. One of the next step will be to use CH₄ concentration and wind speed measurement abilities together, in order to estimate a leak rate directly. Finally, the lidar itself can also be improved in many ways.

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