RESEARCH PERFORMANCE PROGRESS REPORT

FEDERAL AGENCY:
U.S. DOE/NETL
NATIONAL ENERGY TECH LAB
3610 Collins Ferry Road
PO Box 880
Morgantown, WV 26507-0880

FEDERAL GRANT OR OTHER IDENTIFYING NUMBER BY AGENCY:

DE-FE0029059

PROJECT TITLE:
Remote Methane Sensor for Emissions from Pipelines and
Compressor Stations Using Chirped-Laser Dispersion Spectroscopy

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SUBMISSION DATE:
April 30, 2018

DUNS NUMBER: 00-248-4665

RECIPIENT ORGANIZATON:
Princeton University
Princeton, NJ 08544

PROJECT/GRANT PERIOD
10/1/2016 - 3/31/2020

REPORTING PERIOD END DATE
March 31, 2018

REPORTING TERM OR FREQUENCY
Quarterly (for period 1/1/18 to 3/31/18)

Mark Zondlo, Submitting Official

1. Cover Page (previous)

2. Accomplishments

2a. Goals

Leak rates of methane (CH_4) from the natural gas supply chain result in lost profit from unsold product, public safety and property concerns due to potential explosion hazards, and a potentially large source of economic damages from legal liabilities. Yet large measurement challenges exist in identifying and quantifying CH_4 leak rates along the vast number and type of components in the natural gas supply chain. This is particularly true of the "midstream" components of gathering, processing, compression, transmission, and storage.

This project will develop and deploy new advances in chirped laser dispersion spectroscopy (CLaDS) to make an airborne-based sensor for remote detection of methane leaks from pipelines, compressor stations, and other midstream infrastructure. Leaks of methane not detected through routine pipeline patrols and only inferred by indirect methods (e.g. dead vegetation). The proposed heterodyne-enhanced chirped modulated CLaDS (HE-CM-CLaDS) system will offer ability to perform measurements with low light returns, immunity to back-scattered light intensity fluctuations and high linearity and extended dynamic range of concentration detection.

The proposed effort will use a range-resolved, integrated-path spectroscopic technique to remotely identify leaks along pipelines and other related facilities. The instrument will be capable of being deployed on a vehicle, manned aircraft, or making three-dimensional tomographic images with appropriate flight patterns of a microdrone or by passive sampling. Manned aircraft already patrol pipelines for threat detection and visible signs of leak on monthly timescales. Yet there exist no sensors that can show the necessary sensitivity to detect leaks from such a platform. In this project, we will develop, field test, validate, and demonstrate the system over a pipeline corridor. The system proposed here will target the following specifications:

- Open-path methane measurement
- Sensitivity to methane will be in the $<1 ppmv\text{-}m/Hz^{1/2}$
- Simultaneous range measurement for 3D tomographic reconstruction
- Ability to perform sensitive CH_4 measurements by scattering from natural hard-targets

The technical innovation is using range-resoled, chirped modulation-chirped laser dispersion spectroscopic detection for methane quantification, which will provide the most robust yet relatively inexpensive hardware solution while delivering sensing performance needed for the target application. The proposed method utilizes optical phase of the detected light for molecular detection and thus is insensitive to fluctuations in intensity of backscattered light within four orders of magnitude, a key feature necessary when scanning through natural hard targets. The proposed system will be validated by controlled tracer releases when integrated onto vehicle and aircraft-based platforms.

Commercial translation to the marketplace will occur by partnering with a pipeline service provider, American Aerospace Technologies, Inc., for flight demonstrations to their clients in the gas, oil, and pipeline industries. In this way, feedback on the sensor performance and attributes will be efficient and minimize delays in bringing the technologies to the private sector. Benefits of a commercial sensor with these capabilities include reductions of leaks for pipeline operators (more profit), earlier detection of leaks to avoid catastrophic explosion hazards (employee safety, public health and mitigation of property damage), and reduced methane emissions to the atmosphere (improving air quality).

2b. Major activities, results, and outcomes/achievements

Task 1: Project Management, Planning, and Reporting
Status: Completed
Deliverables: Project Management Plan was March 20, 2017 and accepted by the Project Manager via email notification on March 27, 2017.
Milestone A: Data Management Plan submitted → milestone achieved on March 20, 2017.

Task 2: Development of HE-CM-CLaDS sensor
Milestone B: Develop the HE-CM-CLaDS sensor → **accomplished** in February 2018; email and short report sent to program manager on March 22, 2018

Research progress made in the last quarter:

- **A fully functional, transportable HE-CLaDS system has been developed**

A portable optical system for remote sensing of methane has been designed according to the general configuration schematic shown in Fig. 1.

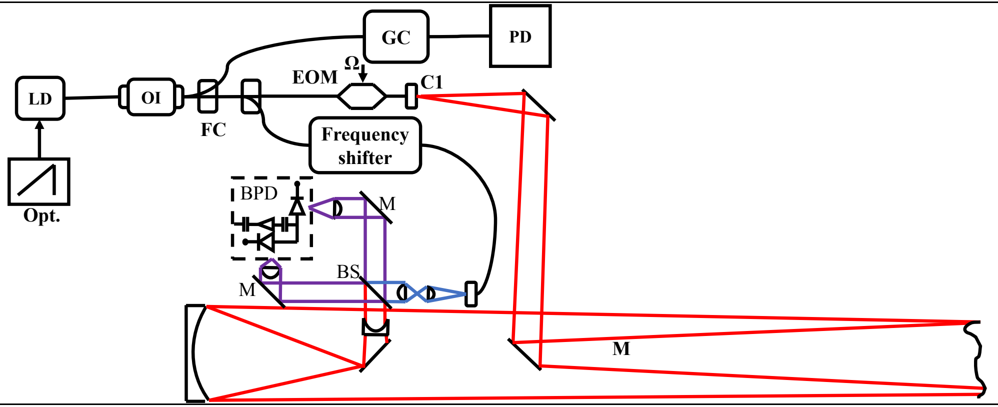
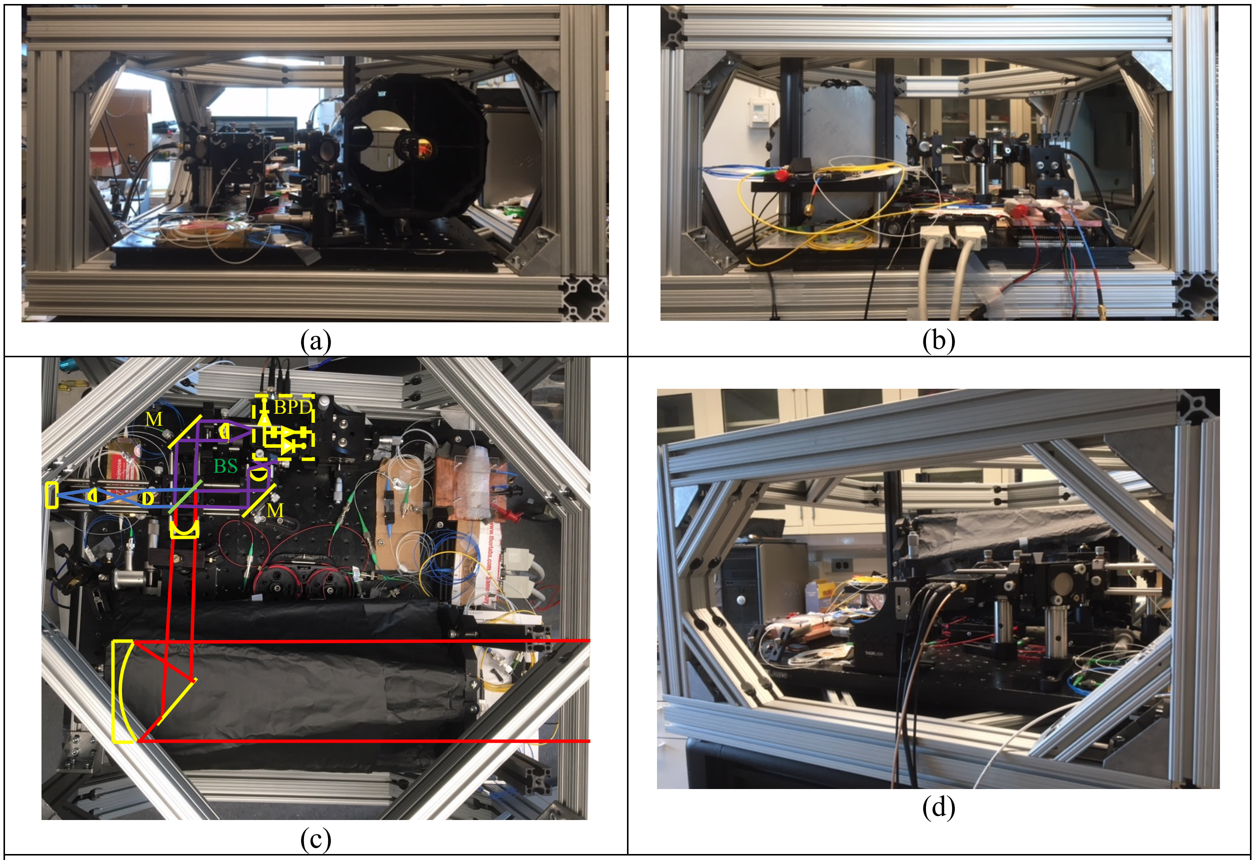


Figure 1. Configuration diagram of the HE-CM-CLaDS Systemfor methane detection

The system has been developed and configured into a transportable system which is shown in photos presented in Fig. 2 (the optical setup photographed from different directions). The free space receiving optics is highlighted in the top view photo (c).



(a) (b) (c) (d)

Figure 2. A photograph of the developed HE-CM-CLaDS system for methane detection.

The system can be easily switched between conventional CLaDS and HE-CLaDS operation mode by replacing the beamsplitter with a reflective mirror. The operational mode is selected for the particular mode of operation (retro-reflecting target vs. back-scattering from hard targets), which determines the amount of the received optical power. In case of specular reflection the received power is expected to be >10μW and conventional CLaDS is used, and for diffusive reflection the received power is expected to be <<10μW and HE-CLaDS is necessary to recover the signal.

Task 3: Laboratory testing of system parameters

Status: In-progress

Research progress made:

- **Testing of performance of the HE-CLaDS sensor**
- **Testing of heterodyne enhancement on different scattering targets**

Task 3.1: Testing of performance of the HE-CLaDS sensor

The performance of the methane sensing system was initially evaluated in terms of concentration detection limit, ranging precision and accuracy, and heterodyne enhancement. The laboratory tests of the system prototype were performed with fiber-coupled and free-space remote-sensing set up. The result of the characterization is summarized in the table 1 below.

Table 1:

	Fiber-coupled	Free-space	Method/comment
Ranging precision/accuracy (m/$\sqrt{\text{Hz}}$)	**0.05***/0.2	**0.05***/0.3	CM-CLaDS and RF chirping
CH_4 concentration precision/accuracy (ppm-m/$\sqrt{\text{Hz}}$)	**0.6***/NA	**1.81***/2.63	D-CLaDS fitting
		1.74*/2.2	CM-CLaDS fitting
		1.53*/4.53	CM-CLaDS single-point
Signal Enhancement (dB)	**9.1***	**10-20***	The ratio between HE-CLaDS and D-CLaDS CNR

*** test results that are near the target requirements of Tasks 3 and 4**

The accuracy for ranging and concentration retrieval have higher errors than the precision values because the errors are not dominated by white noise. For the ranging, it is the RF interference in near band; for concentration it is the etalon produced by transmitting optics. The parasitic etalon also overshadows the inaccuracy in ranging.

Task 3.2: Testing of heterodyne enhancement on different scattering targets

Signal enhancement depends on the receiving optical power. In fiber-coupled test, the return power is generally high, so the enhancement is not as prominent. In scattering experiments depending on the return power, the enhancement can range between 10 dB to 20 dB in the demodulated signal, as in some cases the signal is completely buried if using conventional CLaDS method. Due to the dual-side band generation of the EOM, the noise floor is also influenced by un-utilized carrier-LO beatnote, which can be improved through carrier suppression. This is achieved by biasing EOM at zero-transmission and injecting high RF modulation signal to maximize the sideband power while reducing carrier power. An example comparison of CNR and demodulated signals using carrier suppressed HE-CLaDS with conventional CLaDS is shown below. The experiment is conducted with a common road "STOP" sign as scattering target.

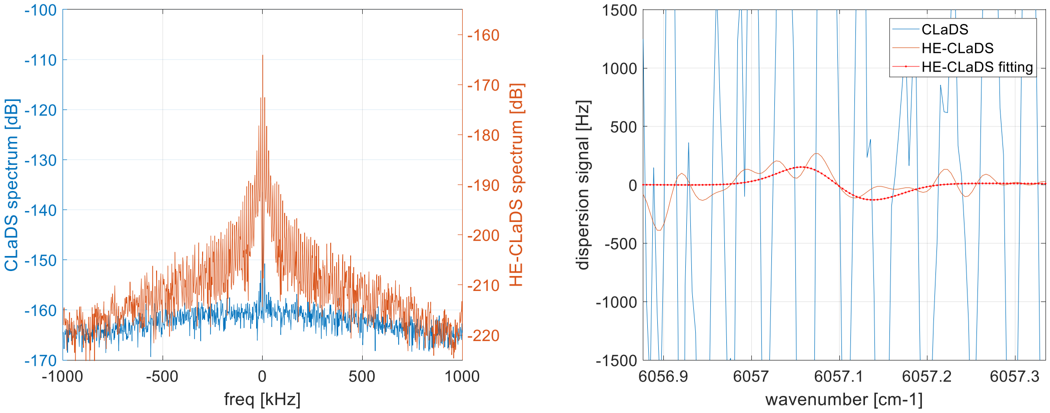


Figure 3. Spectrum (left) and demodulated signal (right) comparison between HE-CLaDS with suppressed carrier and conventional CLaDS

All the preliminary lab performance results confirm that we are on the trajectory to meet the Task 3 and Task 4 specification requirements that include: sensitivity of **<1 ppmv-m/Hz$^{-1/2}$** CH$_4$ in atmospheric air, range-finding resolution of **<0.1m**, and optical heterodyne enhancement of at least **10dB** as compared to direct optical detection.

Task 4: Outdoor testing and validation of system performance

Status: In progress

Research progress made:

An outdoor facility with a 50 m roundtrip pathlength is being developed to prepare for the outside testing in the following quarter. The system consists of a sensor head one side and the backscatter end on the opposite end. A polypropylene 20 cm inner diameter duct hose is being used to connect the two ends with 6 m sections coupled together by an aluminum piece held together by steel clamps and a worm drive. The entire enclosure will be braced against a parking garage wall and shimmed to account for any deviations of the concrete floor and wall. A visible red laser will be used to ensure concentricity within 1.5 cm along the 50 m length of the duct tube. Figure 4a shows the duct tubing and couplers, and Figure 4b shows the end plates that couple into the tubing.

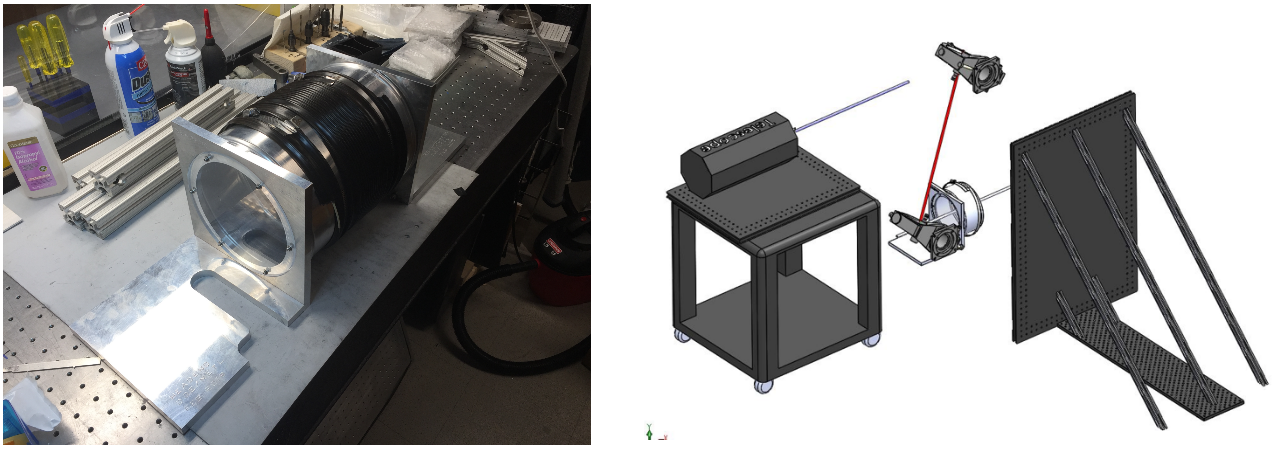


Figure 4. (left, a) Duct tubing and couplers that compose the calibration tube for outdoor testing; (right, b) Input sensor end and end scatter plate at the end of the duct tubing.

The sensor itself, consisting broadly of the laser source, telescope to collect the backscattered light, and associated optics for entry and collection beams, is shown schematically in Figure 5. The optical sensing parts will be held by a spring-dampened cage (not shown) to minimize the effects of vibrations from the eventual, airborne-based system. The outside holding the cage will be mounted to t-slot components that can mount directly to either a cart (for ease of use for the outside testing) or the aircraft (for flight testing). Figure 6 shows the location of the testing inside the Bowen Hall parking garage on the Princeton University campus. This location has a flat wall to mount the tube against, is readily accessible to the researchers, has electrical outlets, and provides shelter from precipitation. The location is adjacent to the buildings containing the laboratories of the PI and co-PI.

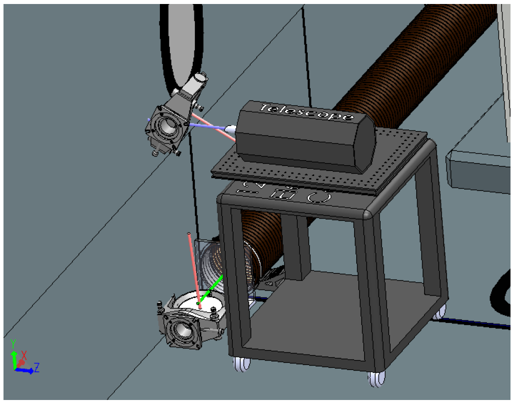


Figure 5. Schematic of the laser end of the system showing the telescope and main steering optics.

Calibration gases to be flowed into the calibration system for outdoor testing include a 2.12 ppmv CH_4 (±5%) in air and a 21.7 ppmv CH_4 (±5%) in air. Ports on the aluminum couplers will be used to introduce gas standards at known distances, and air will be pumped annularly around the downstream end around the backscatter target. A LICOR LI-7700 open-path CH_4 analyzer (2 ppbv precision at 1 Hz; accuracy ±20 ppbv) will be used to accurately determine the ambient levels of CH_4 in the air for "background" conditions. The LICOR sensor will be located at the downstream end of the tube where air flows out of the tube. The LICOR measurement is calibrated by two NOAA Global Monitoring Division standards in air, traceable to gravinemetric standards by NIST. The calibration standards are at 1872.4 ppbv (±3.0) and 1857.1 (±3.5) ppbv CH_4 in air. Overall accuracy of the path-integrated CH_4 measurements will be ±5% for static experiments and ±12% for flowing experiments, largely due to the combined uncertainties of the higher concentration trace gas standards (±5%), the optical path length (±1%), flow rates (±3%), and, for flowing experiments, the exact downstream location of fully-developed turbulent mixing at select distances downstream of the sensor (±10%).

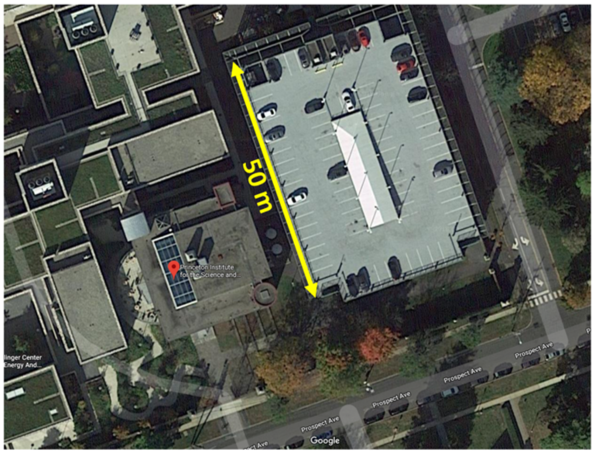


Figure 6. Location of the outdoor testing inside the first floor of a parking garage where a 50 m tube can be installed with minimal disruption as well as power and shelter from rain.

The calibration system will be coupled to the sensor outside in the next quarter, and experiments will be conducted to quantify system precision versus various backscatter targets (fully reflective to sand/soil reflectivity targets). The accuracy of the system to different path-integrated measurements of methane from ambient (200 ppmv-m, i.e. = 2 ppmv x 50 m x 2 trips) to levels more consistent with aircraft flight (2000 ppmv-m = 500 m x 2 ppmv x 2 trips) will be conducted. In addition, known amounts of methane will be added at select distances to demonstrate the uniformity of the measurement at different distances from the sensor.

All parts of the outdoor calibration facility have been fabricated and received where appropriate. The inside of the ducting has been painted "optical black" to avoid pre-mature scattering prior to the reflective target. The beam size is expected to be 10 cm, well within the 20 cm diameter of the tube.

Task 5: Development of tomographic reconstruction algorithms
Status: Not started yet, planned for August 2018

Task 6: Mobile field tests
Status: Not started yet, planned for October 2018

Task 7: Drone-based reflector target imaging
Status: Not started yet, planned for January 2019

Task 8: Airborne flight measurements
Status: Not started yet, planned for July 2019

Milestone Status Report

Milestone Title / Description	Planned completion	Actual completion	Verification method	Comments
A: Data management plan submitted	3/31/17	3/27/17	Accepted by program manager.	
B: System developed	2/28/18	2/28/18	Reported to program manager 3/22/18; appended to this report at end in Appendix B.	
C: Lab testing completed	8/31/18			
D: Field validation completed	10/31/18			
E: Tomographic algorithms	10/31/19			
F: Mobile field data collected	1/31/19			
G: Drone-based flights	9/30/19			
H: Manned aircraft flights	2/28/20			

Note: all dates extended by 5 month from the original proposal due to delays in paperwork at start but consistent with the relative timeframes in the SOPO with an effective start date of 3/1/17.

2c. Training and Professional Development
Not requested.

2d. Dissemination of Results / Outreach
No outreach events have occurred to communities of interest.

2e. Plans for Next Reporting Period
In the next reporting period we plan to transition to the outdoor testing of the developed HE-CLaDS sensor.

3. Products

Publications, conference papers, and presentations

Publications

G. Plant, Y. Chen, and G. Wysocki, "Optical heterodyne-enhanced chirped laser dispersion spectroscopy," Optics Letters 42, 2770-2773 (2017).

Books or other non-periodical, one-time publications

None.

Other publications, conference proceedings, and presentations

Y. Chen, G. Plant, and G. Wysocki, "Heterodyne Efficiency in Chirped Laser Dispersion Spectroscopy," in Conference on Lasers and Electro-Optics(Optical Society of America, San Jose, California, 2017), p. SW4L.5.

4. Participants and other collaborators

American Aerospace Technologies Inc. (AATI), the commercial partner that will be flying the sensor on aircraft in Year 3 and who will fly a drone with a reflecting target in Year 2, has provided advice on aircraft constraints. These constraints play important roles in the overall design of the sensor while there is still time to adjust to any payload issues (or orientation). A conference call occurred in January 2018 to identify any constraints in the system design for aircraft flights later in the project. The current design should integrate onto the Cessna 210 aircraft without a problem, according to David Yoel and Marty McGregor at AATI.

5. Impact (optional)

Nothing to report.

6. Changes and Problems

No changes or problems have been encountered. The project is on schedule and on specifications.

7. Special Reporting Requirements

The Milestone B report is attached after the budgetary information, on the last page of this report.

8. Budgetary Information

Attached on the next page.

Appendix A. Financial summary

	Budget Period 1								Budget Period 2					
	Q1		Q2		Q3		Q4		Q1		Q2		Q3	
Baseline Reporting Quarter	10/1/2016-12/31/2016		1/1/2017-3/31/2017		4/1/2017-6/30/2017		7/1/2017-9/30/2017		10/1/17-12/31/17		1/1/18-3/31/18		4/1/18-6/30/18	
	Q1	Cumulative Total	Q2	Cumulative Total	Q3	Cumulative Total	Q4	Cumulative Total	Q1	Cumulative Total	Q2	Cumulative Total	Q3	Cumulative Total
Baseline Cost Plan														
Federal Share	96,736.00	96,736.00	96,736.00	193,472.00	96,736.00	290,208.00	96,736.00	386,944.00	97,500.00	484,444.00	97,500.00	581,944.00	97,500.00	
Non-Federal Share	23,775.00	23,775.00	23,775.00	47,550.00	23,775.00	71,325.00	23,775.00	95,100.00	23,775.00	118,875.00	23,775.00	142,650.00		
Total Planned	120,511.00	120,511.00	120,511.00	241,022.00	120,511.00	361,533.00	120,511.00	482,044.00	121,275.00	603,319.00	121,275.00	724,594.00		
Actual Incurred Cost														
Federal Share	0.00	0.00	39,913.60	39,913.60	35,910.60	75,824.20	174,126.95	249,951.15	44,938.72	294,889.87	72,735.11	367,624.98		
Non-Federal Share	0.00	0.00	2,361.00	2,361.00	38,538.35	40,899.35	34,510.39	75,409.74	19,632.34	95,042.08	34,049.88	129,091.96		
Total Incurred Cost	0.00	0.00	42,274.60	42,274.60	74,448.95	116,723.55	208,637.34	325,360.89	64,571.06	389,931.95	106,784.99	496,716.94		
Variance														
Federal Share	96,736.00	96,736.00	56,822.40	153,558.40	60,825.40	214,383.80	(77,390.95)	136,992.85	52,561.28	189,554.13	24,764.89	214,319.02		
Non-Federal Share	23,775.00	23,775.00	21,414.00	45,189.00	(14,763.35)	30,425.65	(10,735.39)	19,690.26	4,142.66	23,832.92	(10,274.88)	13,558.04		
Total Variance	120,511.00	120,511.00	78,236.40	198,747.40	46,062.05	244,809.45	(88,126.34)	156,683.11	56,703.94	213,387.05	14,490.01	227,877.06		

Notes/Explanations to Budget Table:

Q2 and Q3 actuals are slightly different from the first RPPR that was submitted. The amounts on the first report were incorrect, but the overall cumulative total is the same.

Year 2 partial outstanding increment = $229,616

Year 3 increment expected=$364,260

Appendix B. Milestone B status summary

PROJECT TITLE
Remote Methane Sensor for Emissions from Pipelines and
Compressor Stations Using Chirped-Laser Dispersion Spectroscopy
DUNS NUMBER: 00-248-4665

Status Summary on milestone B (2/28/18) - "develop the HE-CM-CLaDS sensor"

A portable optical system for remote sensing of methane has been designed according to the general configuration schematic shown in Fig. 1.

The system has been developed and configured into a transportable system which is shown in photos presented in Fig. 2 (the optical setup photographed from different directions). The free space receiving optics is highlighted in the top view photo (c).

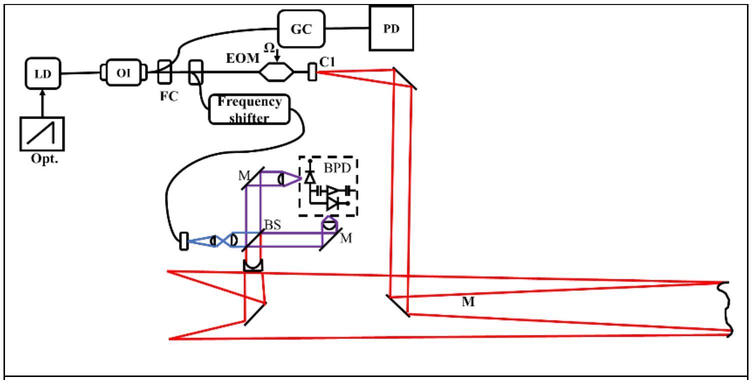
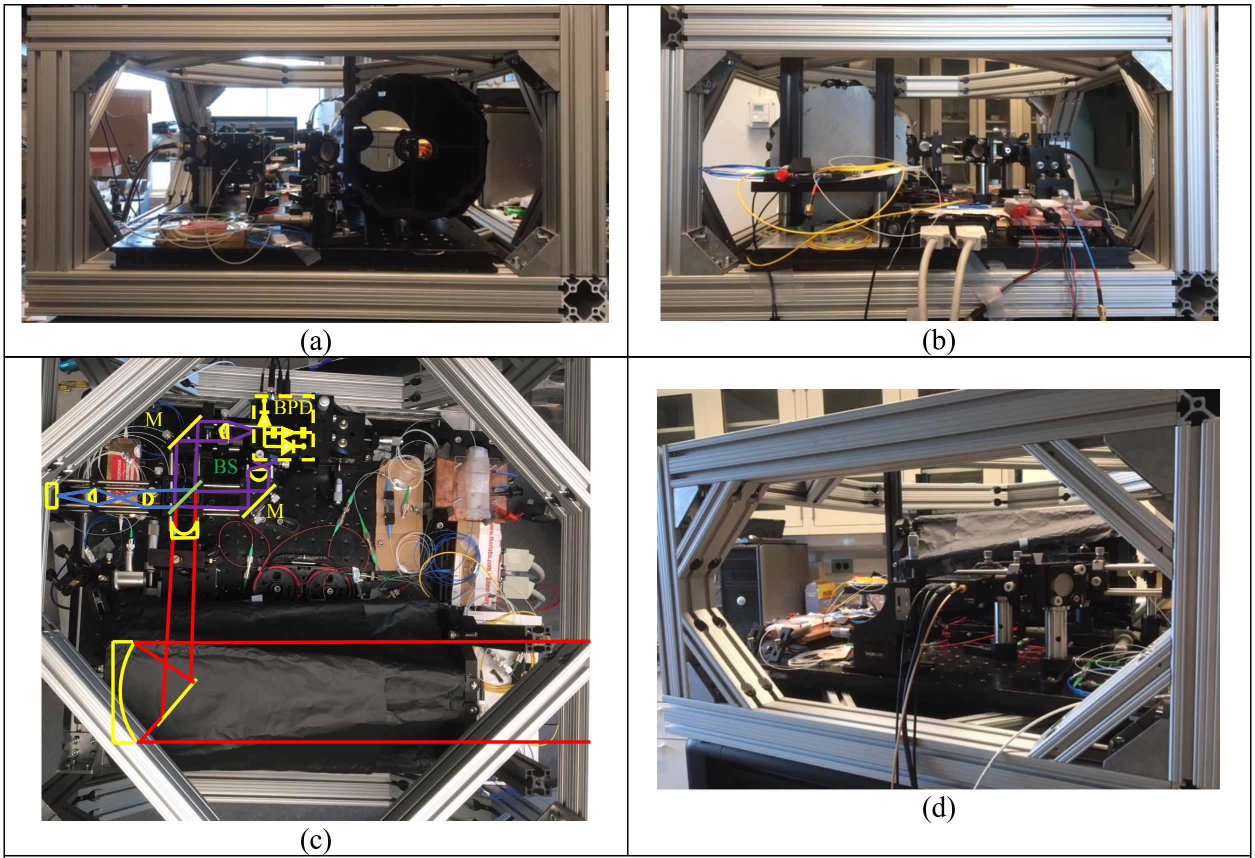


Figure 1 Configuration diagram of the HE-CM-CLaDS Systemfor methane detection



(a)

(b)

(c)

(d)

Figure 2 A photograph of the developed HE-CM-CLaDS system for methane detection.

The system can be easily switched between conventional CLaDS and HE-CLaDS operation mode by replacing the beamsplitter with a reflective mirror. The operational mode is selected for the particular mode of operation (retro-reflecting target vs. back-scattering from hard targets), which determines the amount of the received optical power. In case of specular reflection the received power is expected to be >10μW and conventional CLaDS is used, and for diffusive reflection the received power is expected to be <<10μW and HE-CLaDS is necessary to recover the signal.

The performance of the methane sensing system was initially evaluated in terms of concentration detection limit, ranging precision and accuracy, and heterodyne enhancement. The laboratory tests of the system prototype were performed with fiber-coupled and free-space remote-sensing set up. The result of the characterization is summarized in the table 1 below.

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		1.53*/4.53	CM-CLaDS single-point
Signal Enhancement (dB)	**9.1***	**10-20***	The ratio between HE-CLaDS and D-CLaDS CNR

*** test results that are near the target requirements of Tasks 3 and 4**

The accuracy for ranging and concentration retrieval have higher errors than the precision values because the errors are not dominated by white noise. For the ranging, it is the RF interference in near band; for concentration it is the etalon produced by transmitting optics. The parasitic etalon also overshadows the inaccuracy in ranging.

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All the preliminary lab performance results confirm that we are on the trajectory to meet the Task 3 and Task 4 specification requirements that include: sensitivity of **<1 ppmv-m/Hz**$^{-1/2}$ CH_4 in atmospheric air, range-finding resolution of **<0.1m**, and optical heterodyne enhancement of at least **10dB** as compared to direct optical detection.