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:
October 31, 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
September 30, 2018

REPORTING TERM OR FREQUENCY
Quarterly (for period 7/1/18 to 9/30/18)

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 <1ppmv-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 → milestone achieved in February 2018; email and short report sent to program manager on March 22, 2018

Task 3: Laboratory testing of system parameters

Milestone C: Laboratory testing of system parameters → milestone achieved on Aug. 31, 2018; for a summary, please see Appendix B – Task 3 Project Status Report in this quarterly report

Research progress made during the reporting period:

- **New implementation of the real-time FPGA processing in HE-CLaDS**
- **Real-time FPGA processing of HE-CLaDS data enabled by lower frequency acoustic optical modulator (AOM)**
- **Further characterization of the system**

As described below, the real-time FPGA processor allows for the incorporation of a digital demodulation scheme, thereby improving performance and duty cycle. In the past rounds of tests and experiments, a 200 MHz fiber coupled AOM has been used in HE-CLaDS configuration. Carrier-suppressed dual sideband is chosen as the current modulating method for the probing beam. With 200 MHz upper frequency shift from the carrier frequency as an LO, and two sidebands 1GHz away from carrier, the data acquisition must cover at least 500 MHz bandwidth to allow phase noise cancellation. In the past, the acquisition and digital demodulation have usually been performed using a fast RF spectrum analyzer with 512 MHz bandwidth and 600 MS/s sampling rate. This severely limited the duty cycle of the instrument because each IQ data set was limited to 700 ms duration while a few seconds were required for data transfer and processing. Therefore, an FPGA demodulation and long-term tests were only possible using an analog demodulation scheme, which suffers from phase distortion due to RF circuit nonlinearity.

By implementing a new 35 MHz AOM frequency shifter we have narrowed down the bandwidth required to demodulate the heterodyne enhanced beatnotes to within 130 MHz provided by the data clock rate of the FPGA IQ demodulator. This should allow for all-digital demodulation and real-time data processing with the FPGA hardware. The spectral coverage shown in Figure 1a demonstrates the difference in bandwidth required with 200MHz AOM vs. 35MHz AOM. Figure

1b shows the digitally acquired and demodulated data using both devices. Data acquired using the 35 MHz AOM is slightly noisier due to smaller return power, but no additional demodulation error is visible.

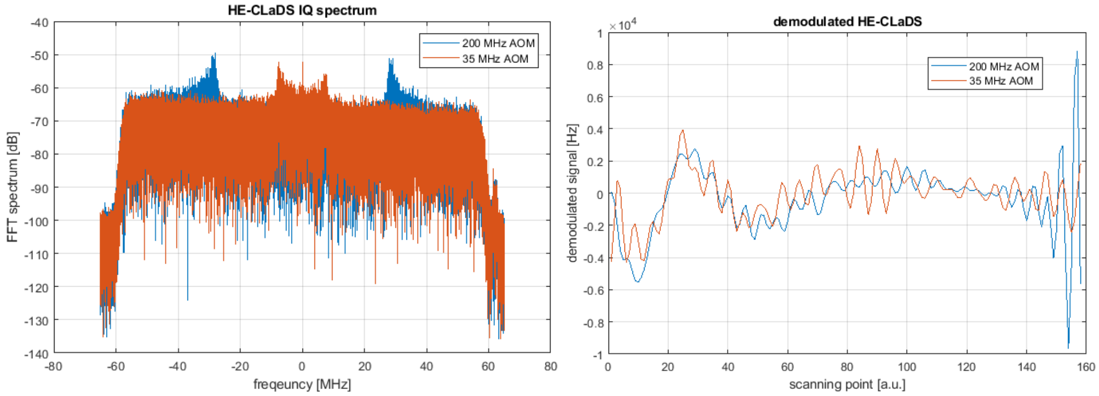


Figure 1 a. FPGA demodulated HE-CLaDS signal using 35 MHz AOM (left) and b. Allan deviation of the acquired data to demonstrate real-time processing

A new version of FPGA firmware is currently under development to allow the demodulation of both HE-CLaDS signal and direct CLaDS signal using a single FPGA platform. The simplest form of phase noise cancellation adopting IQ self-mixing has been added, and the first set of long-term digitally demodulated real-time HE-CLaDS data has been collected. An example of the demodulated signal using a fiber coupled 20% methane cell is shown in Figure 2a. Since this new configuration has been primarily implemented to enable long-term data acquisition, this capability has been tested first before further optimization of the system. A dataset demonstrating this capability was acquired continuously over >2000 s with real-time processing provided by the new FPGA program. Figure 2b shows the Allan deviation of this long-term measurement.

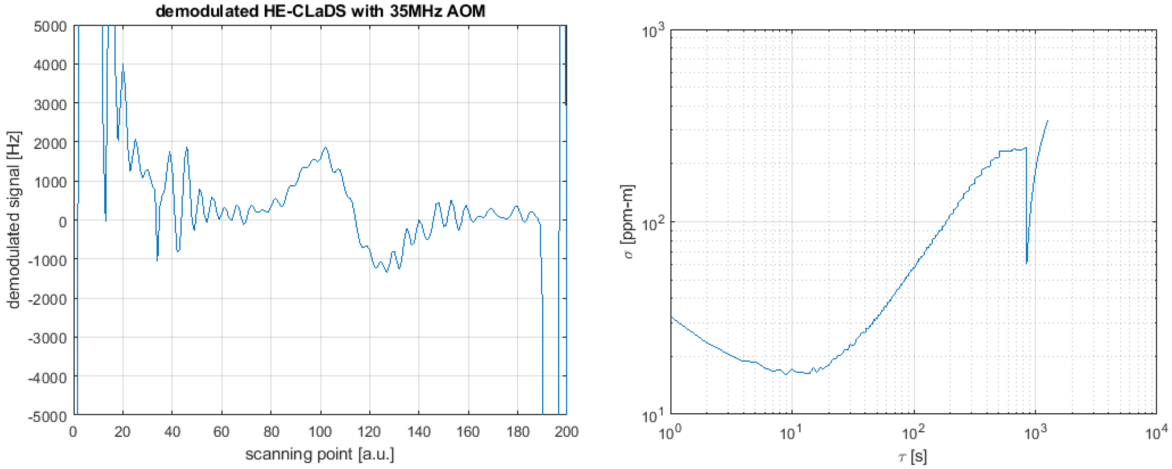


Figure 2 a. FPGA demodulated HE-CLaDS signal using 35 MHz AOM (left) and b. Allan deviation of the acquired data to demonstrate real-time processing

The system is now capable of truly dual-mode operation with HE-CLaDS and direct CLaDS demodulation performed digitally in the FPGA platform. In the next stage of this development an optimized digital filtering will be added to suppress drifts visible in Fig. 2b. Due to the change in demodulation scheme we will also need to repurpose the FPGA algorithm to make the HE-CLaDS demodulation compatible with the ranging measurement. Since the new FPGA implementation requires an increased program size, the main challenge in this step will be related to limits of the hardware, where the registers, look-up tables (LUTs), DSP slices etc. now occupy above 80% of the available resources, with flip-flop usage approaching 100%. A compromise between functionality and flexibility may need to be made to allow all desired capabilities to fit within one program.

Task 4: Outdoor testing and validation of system performance

Status: In progress

In the previous quarterly report, we demonstrated the performance of the system outside with an enclosed 50 m calibration tube. Known and relevant concentrations of methane were added to the tube with changes from 7 ppmv to 2 ppmv methane (ambient) observed. These levels are consistent with what would be expected for pipeline leaks. The normalized sensitivity was around 7 ppmv-m, meaning a plume of 7 ppmv that is one meter thick would be readily observeable (or some combination thereof, e.g. 70 ppmv at 0.1 m thick). These levels were about an order of magnitude higher than free space conditions in the hallway, and significant beam clipping in the 50 m tube was observed which caused an outright and unrecoverable loss of signal before even reaching the backscattered target at the end. Such a situation was not likely in real world testing. Going to a larger diameter tube could have helped to address the issue, but the uneven floor and wall over this long distance resulted in significant beam clipping.

To address this issue, instead of having the full enclosed 50 m tube at the known and given concentration of methane, we have since developed a more realistic scenario where the beam passed through ambient air and only entered the calibration tube over the last 5 m. This would be analogous to a pipeline leak patrol flight where the downward looking sensor would generally see ambient air for most of the path-integrated sample, except for a narrow plume near the ground. Further, logistically, this would be easier as we could use a larger diameter and stiffer tube for the calibration system, though at the added cost of increased size and weight. Figure 3 shows a photograph of the next generation calibration system. The far end of a 12” diameter PVC tube of 5 m in length was placed 50 m away from the sensor. The PVC tube was stiffer and larger than the previous calibration system, and the total weight of the calibration tube was 52 kg (110 lbs.). With the larger aperture, the full laser beam was now hitting the backscattered target, and no beam clipping was observed. Based upon preliminary testing, the new system has shown shown sensitivity in the range of several ppmv-m, which is consistent with our earlier hallway tests. Ongoing analyses are examining sensitivity as a function of backscattered signal return.

By introducing calibrated flows of methane along the 5 m enclosed end, the sensitivity can be further validated. Standards of 20 ppmv (±5%), 100 ppmv (±2%), and 950 ppmv (±2%) methane in air are being tested, equivalent to integrated pathlengths of 380, 680, and 2080 ppmv-m (accounting for the 90 m roundtrip at 2 ppmv methane in ambient air), respectively. These tests demonstrate the linearity of the system, as well as the sensitivity of the measurement to the location of the leak along the laser path.

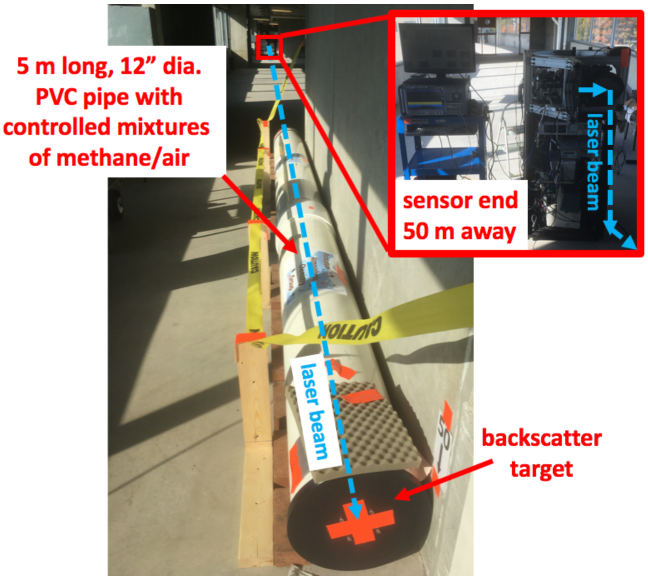


Figure 3. To simulate more representative conditions, a second calibration facility was developed where known amounts of methane were only introduced along the last 5 m of the 100 m roundtrip optical path length. This setup is more consistent with a leak near a pipeline, with a dominant signal of ambient methane elsewhere.

Research progress made:

Task 5: Development of tomographic reconstruction algorithms

Status: In progress, started in the last month of this report

One aspect of the field testing is to mount a reflective device on a drone and point the laser beam at the drone and collect the integrated signal that reflects back to the instrument. As the drone flies around at different locations and distances, a tomographic reconstruction of the methane leak can be made. The rationale for this part of testing is that manned aircraft patrols along pipelines are not always possible in areas of high population and development, but nimble microdrone-based flights would be less of an issue. Here, a microdrone is considered as ones that have wingspans or rotary blades of 1 m or less (e.g. a small hexacopter). To develop algorithms to make such maps, we will assume that a leak takes the form of a Gaussian distribution of concentration in three dimensions with a leak height of 1 m above the ground. Simulated path-integrated transects will be conducted at known distances, heights, and select angles with respect to the wind direction, and these data will be used to reconstruct

Task 6: Mobile field tests

Status: Not started yet, planned to begin October 2018

Task 7: Drone-based reflector target imaging

Status: Not started yet, planned to begin 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	Report to project manager.	Report appended to Q4 quarterly report.
C: Lab testing completed	8/31/18	8/31/18	Laboratory tests per SOPO and Task 3 test plan.	Task 3 Project Status Report appended to this Q6 report at end in Appendix B.
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 months 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.

Y. Chen, A. Hangauer, and G. Wysocki, "Path-averaged Methane Sensing Using Range-resolving Chirped Laser Dispersion Spectroscopy," in Laser Applications to Chemical, Security and Environmental Analysis (Optical Society of America, Florida, 2018), p. LTu5C-4.

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. Additional efforts will begin in the next reporting period to plan integration issues.

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 C / Task 3 Project Status Report is attached in Appendix B at the end of this report. This is a deliverable per the contract schedule.

8. Budgetary Information

Attached on the next page, Appendix A.

Appendix A. Financial summary

	Budget Period 1															
Baseline Reporting Quarter	Q1		Q2		Q3		Q4		Q5		Q6		Q7		Q8	
	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		7/1/18-9/30/18	
	Q1	Cumulative Total	Q2	Cumulative Total	Q3	Cumulative Total	Q4	Cumulative Total	Q5	Cumulative Total	Q6	Cumulative Total	Q7	Cumulative Total	Q8	Cumulative Total
Baseline Cost Plan																
Federal Share	78,189.71	78,189.71	78,189.71	156,379.42	78,189.71	234,569.13	78,189.71	312,758.84	78,189.71	390,948.55	78,189.71	469,138.26	78,189.74	547,328.00	118,775.20	666,103.20
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	23,775.00	166,425.00	23,775.00	190,200.00
Total Planned	101,964.71	101,964.71	101,964.71	203,929.42	101,964.71	305,894.13	101,964.71	407,858.84	101,964.71	509,823.55	101,964.71	611,788.26	101,964.74	713,753.00	142,550.20	856,303.20
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	101,204.77	468,829.75	161,466.71	630,296.46
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	36,310.08	165,402.04	19,957.42	185,359.46
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	137,514.85	634,231.79	181,424.13	815,655.92
Variance																
Federal Share	78,189.71	78,189.71	38,276.11	116,465.82	42,279.11	158,744.93	(95,937.24)	62,807.69	33,250.99	96,058.68	5,454.60	101,513.28	(23,015.03)	78,498.25	(42,691.51)	35,806.74
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	(12,535.08)	1,022.96	3,817.58	4,840.54
Total Variance	101,964.71	101,964.71	59,690.11	161,654.82	27,515.76	189,170.58	(106,672.63)	82,497.95	37,393.65	119,891.60	(4,820.28)	115,071.32	(35,550.11)	79,521.21	(38,873.93)	40,647.28
Notes/Explanations to Budget Table:																(estimated
																per Sept.
																payroll)
BP1: 10/1/16-6/30/18	$ 547,328.00															
BP2: 7/1/18-3/31/20	$ 593,876.00															

Appendix B: Task 3 Project Status Report

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 C (8/31/18) - "Laboratory testing of system parameters"

The recipient was required to meet the following **success criteria in the laboratory**:

At the end of this task the HE-CM-CLaDS system was fully functional and provided:

- sensitivity of **<1 ppmv-m/Hz$^{1/2}$** CH_4 in atmospheric air,
- range-finding resolution of **<0.1m**,
- optical heterodyne enhancement of at least **10dB** as compared to direct optical detection

A copy select slides relevant to Milestone C and Completion of Task 3 from a presentation to DOE NETL program managers on July 25, 2018, follow.

All success criteria have been met for Task 3, as detailed in the presentation on July 25, 2018 and in the slides that follow on the next pages.

Task 3: Research progress made

- Progress towards Decision Point #1 criteria

TECHNICAL GO/NO-GO DECISION POINT 1

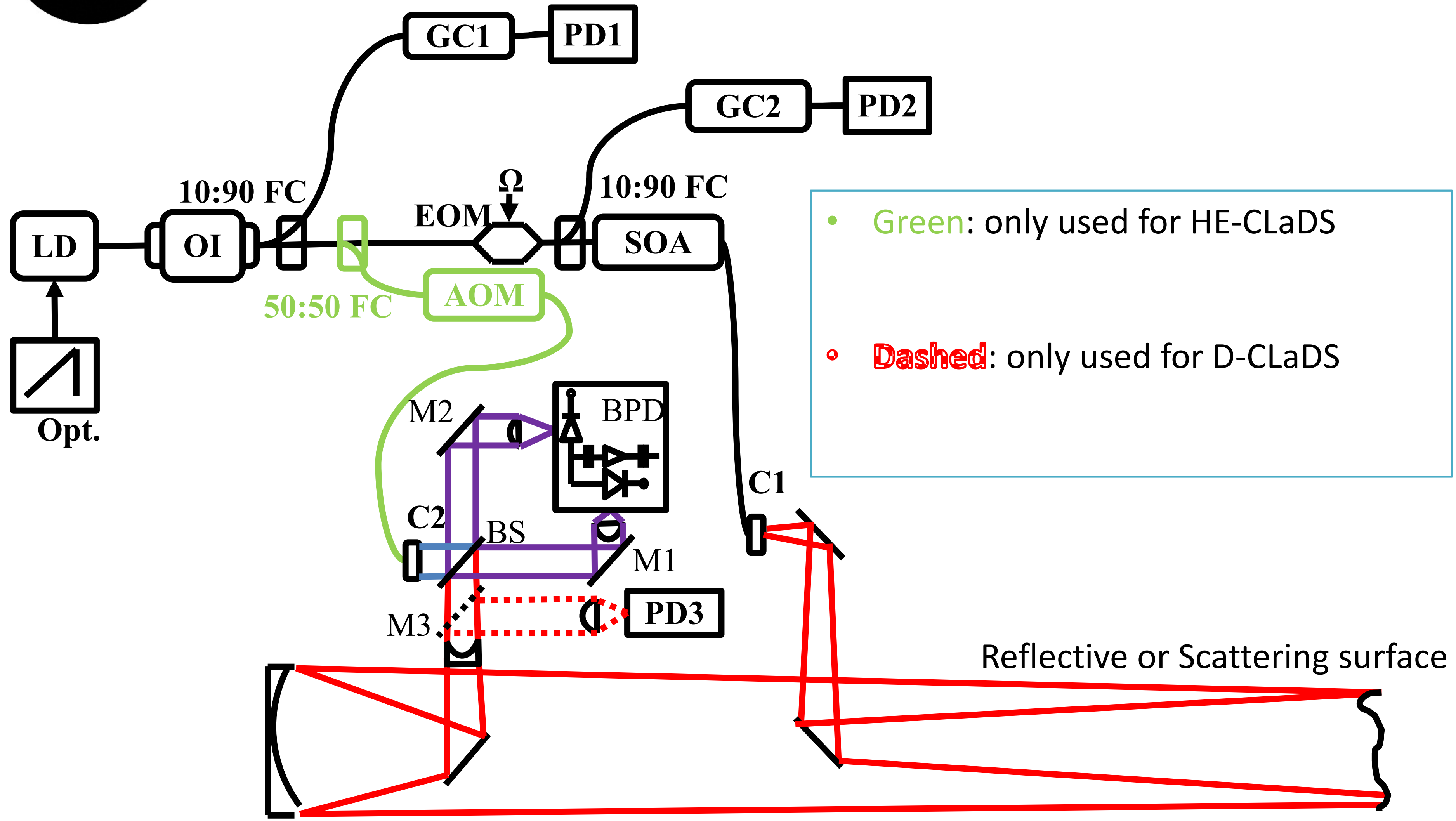
The recipient shall meet the following **success criteria in the laboratory**:

At the end of this task we expect the HE-CM-CLaDS system to be fully functional and provide:

- sensitivity of **<1 ppmv-m/Hz$^{1/2}$** CH_4 in atmospheric air,
- range-finding resolution of **<0.1m**,
- optical heterodyne enhancement of at least **10dB** as compared to direct optical detection

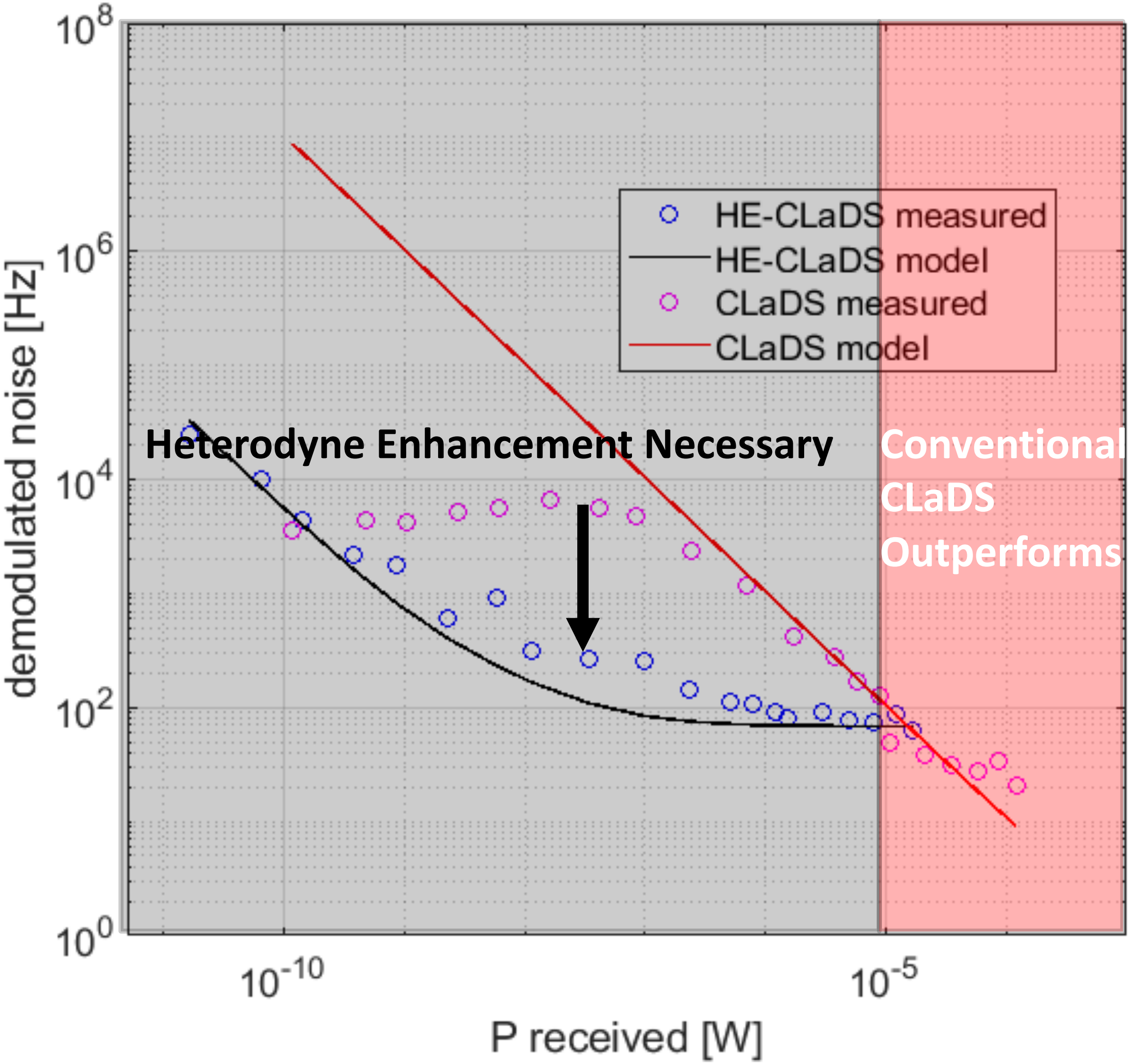
- Outdoor testing in the 100 m round-trip outdoor calibration system has started

Two mode (HE)-CLaDS system



- Green: only used for HE-CLaDS
- Dashed: only used for D-CLaDS

System performance as a function of received optical power



Heterodyne Enhancement Necessary

Conventional CLaDS Outperforms

Two mode (HE)-CLaDS system

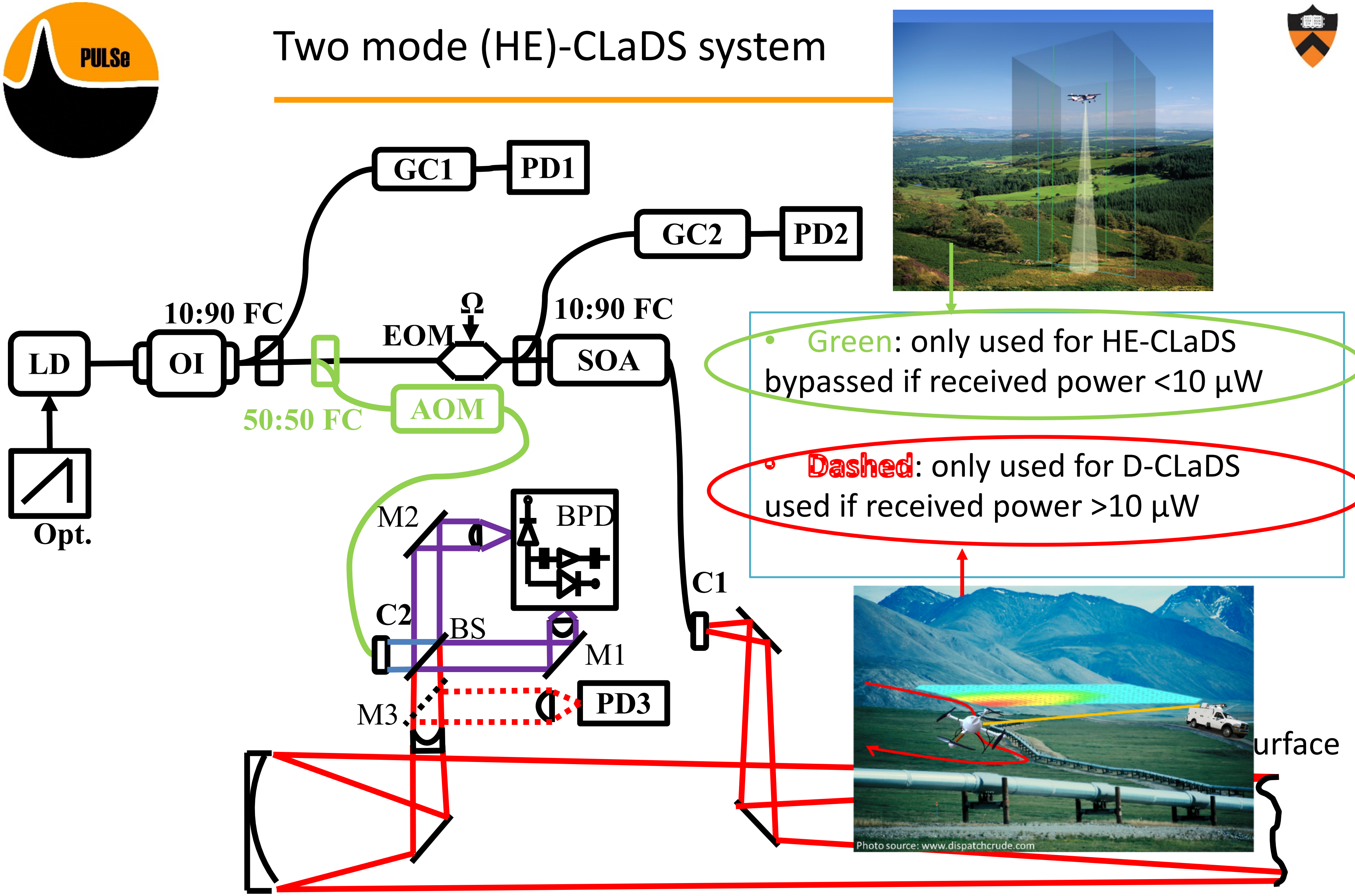
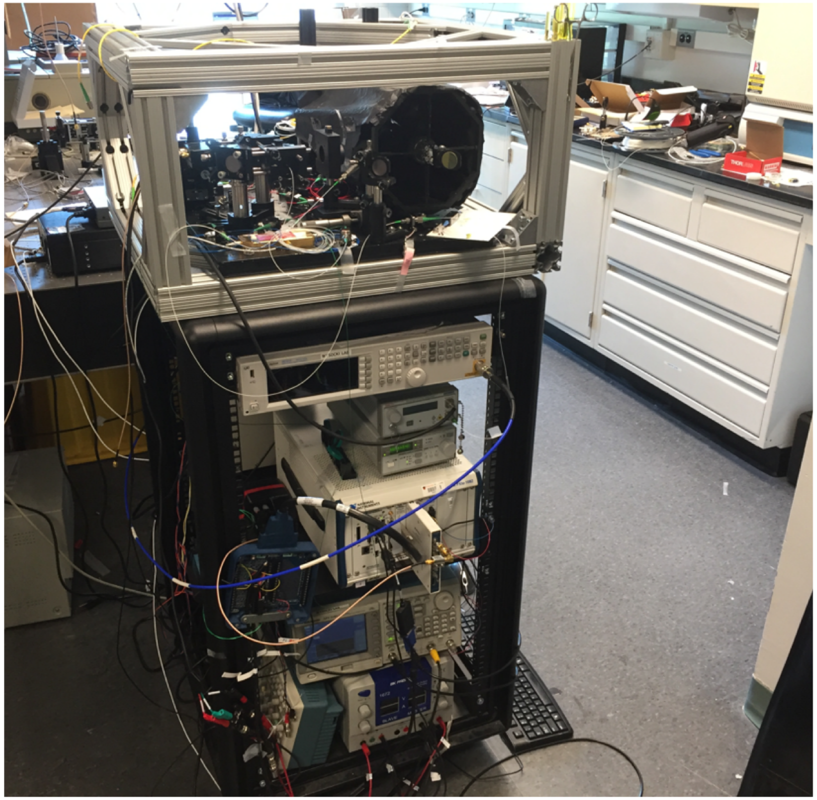


Photo source: www.dispatchcrude.com

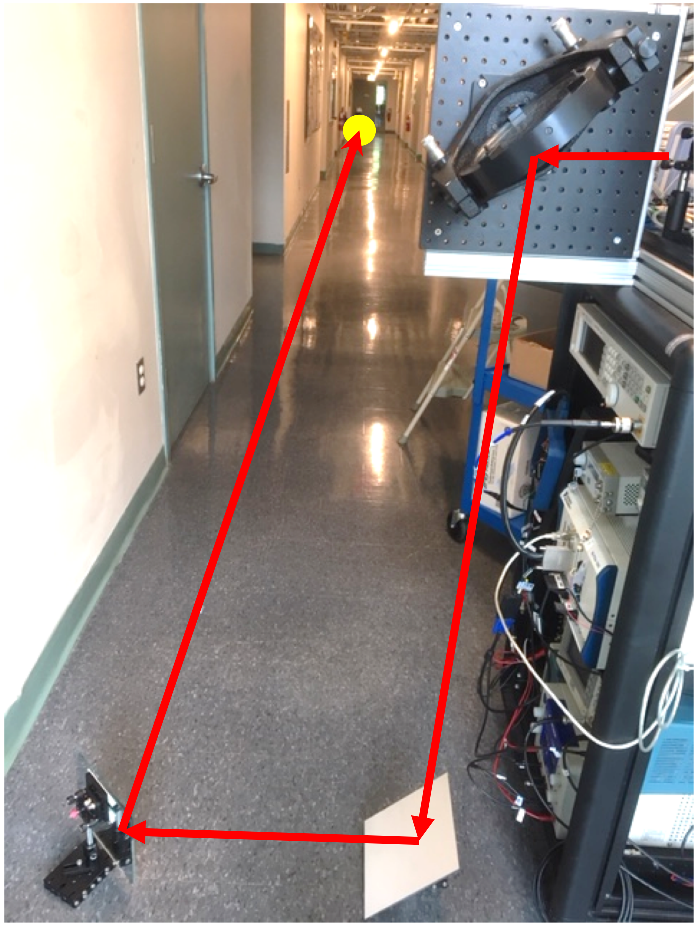
- Green: only used for HE-CLaDS bypassed if received power <10 µW
- Dashed: only used for D-CLaDS used if received power >10 µW

Laboratory and hallway testing

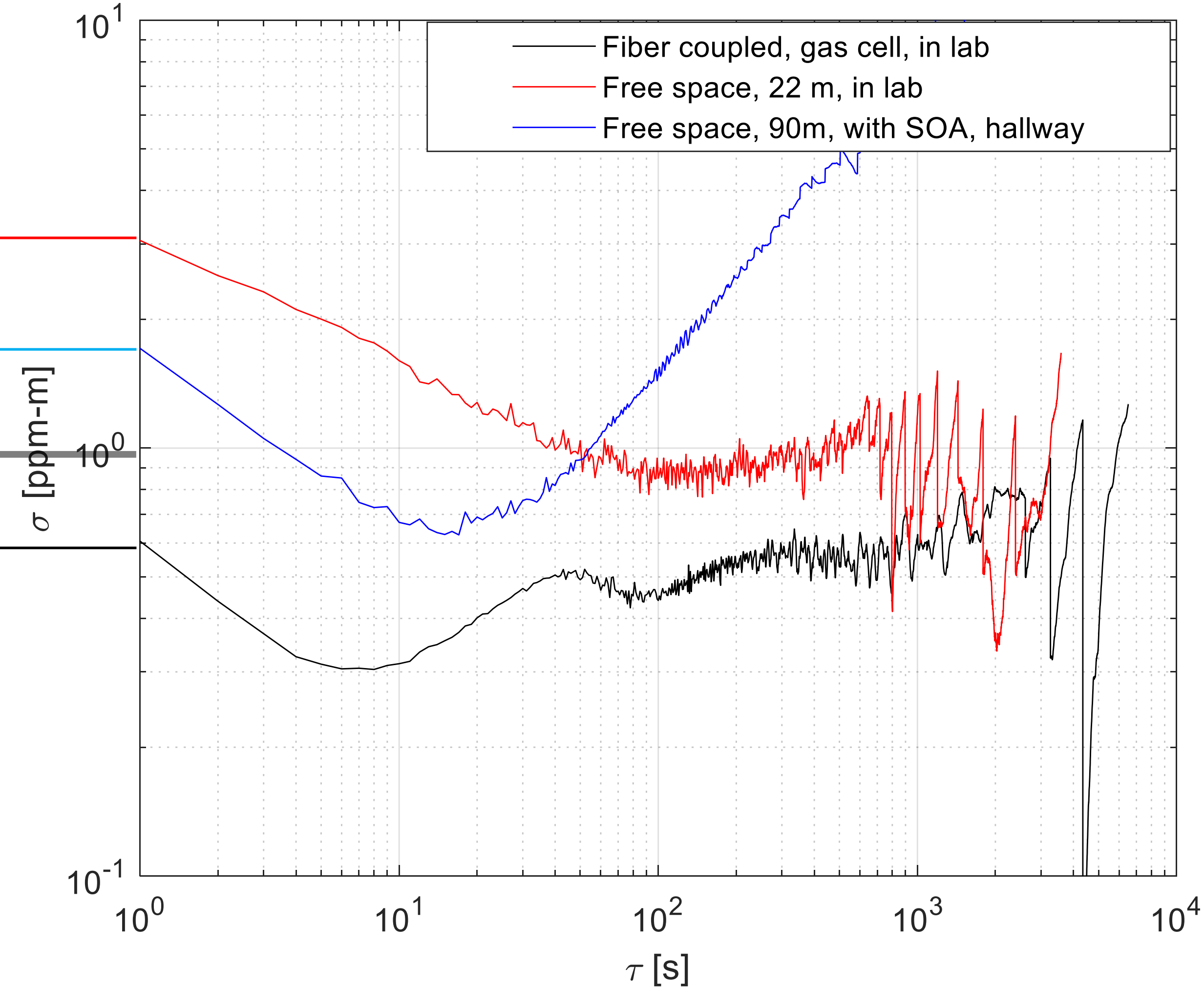
In-lab testing
(optical paths up to 22m round trip)



Hallway testing
(optical paths up to 90m round trip)



Concentration Measurement Precision



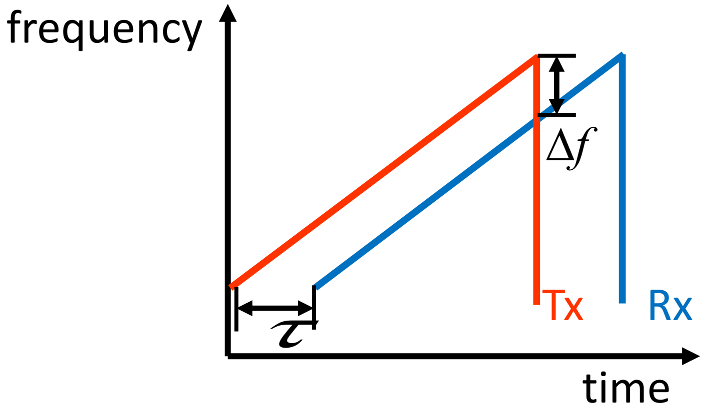
3.0 ppm-m/√Hz

1.7 ppm-m/√Hz

Goal: 1ppm-m /√Hz

0.6 ppm-m/√Hz

Range resolving CLaDS



$$\Delta\phi(t) = 2\pi[-S_{RF}\tau t + S_{RF}\tau^2 \underline{-\Omega_0\tau} + \varphi(t)]$$

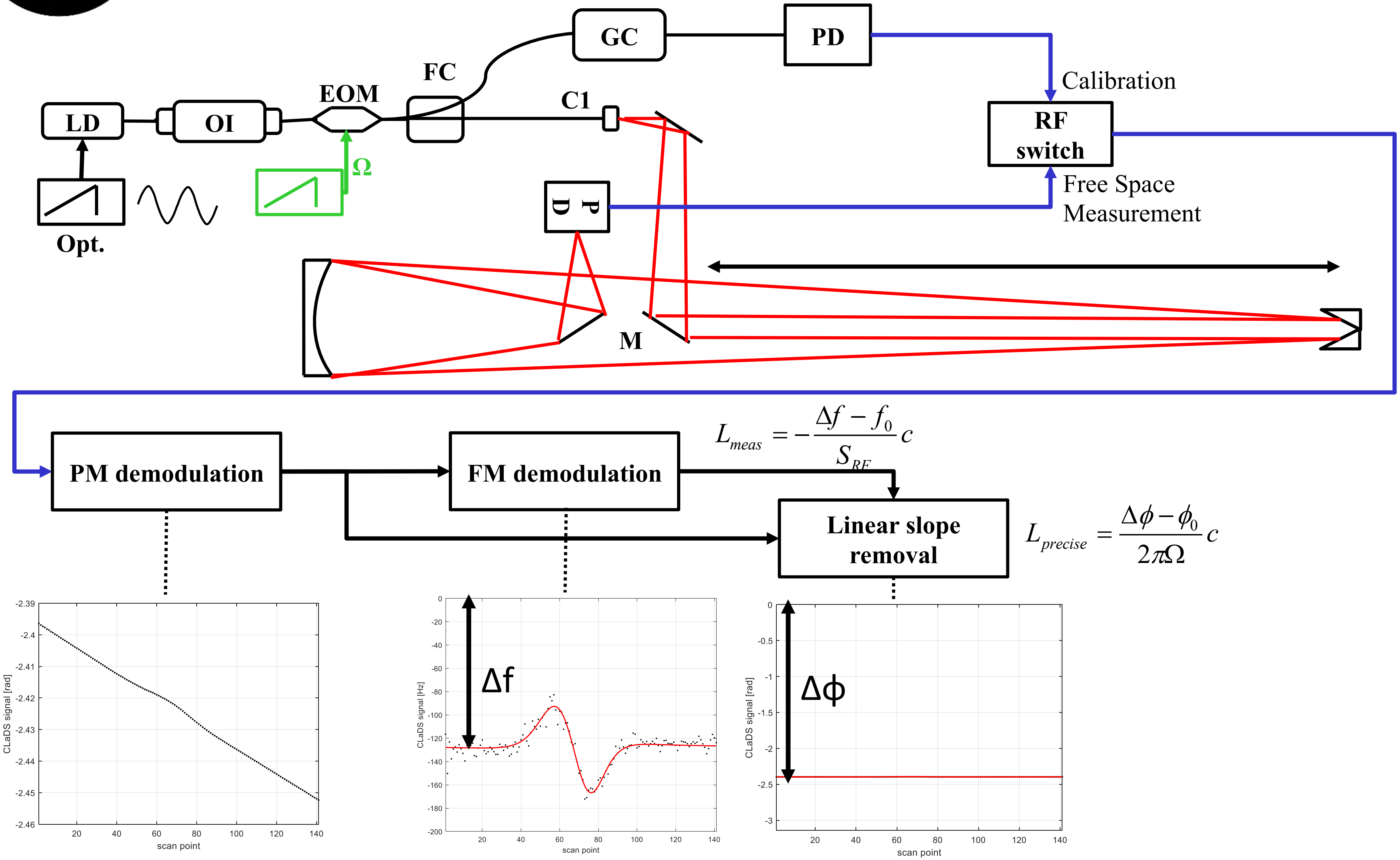
$$\Delta f(t) = \frac{1}{2\pi}\frac{d\phi}{dt} = \underline{-S_{RF}\tau} + \frac{1}{2\pi}\frac{d\varphi}{dt}$$

Optical frequencies w/o RF chirping

Optical frequencies w/ RF chirping

(exaggerated by 5x10^4)

Range resolving CLaDS for remote sensing

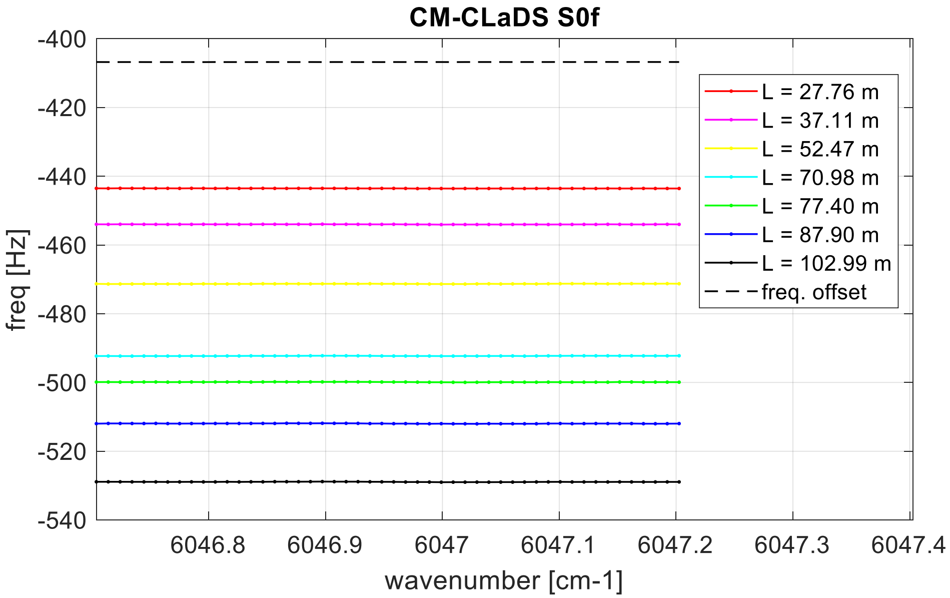


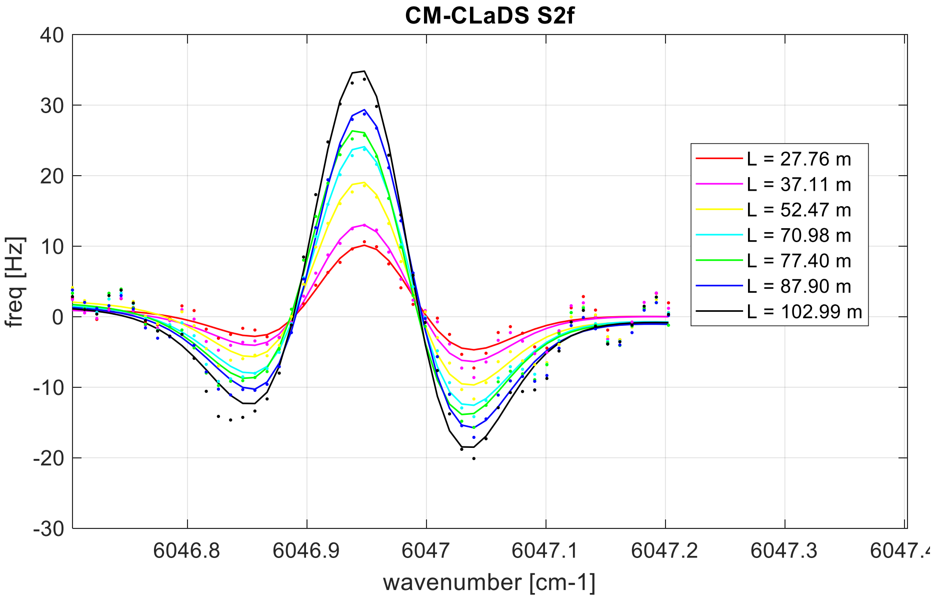
$$L_{meas} = -\frac{\Delta f - f_0}{S_{RF}} c$$

$$L_{precise} = \frac{\Delta \phi - \phi_0}{2\pi\Omega} c$$

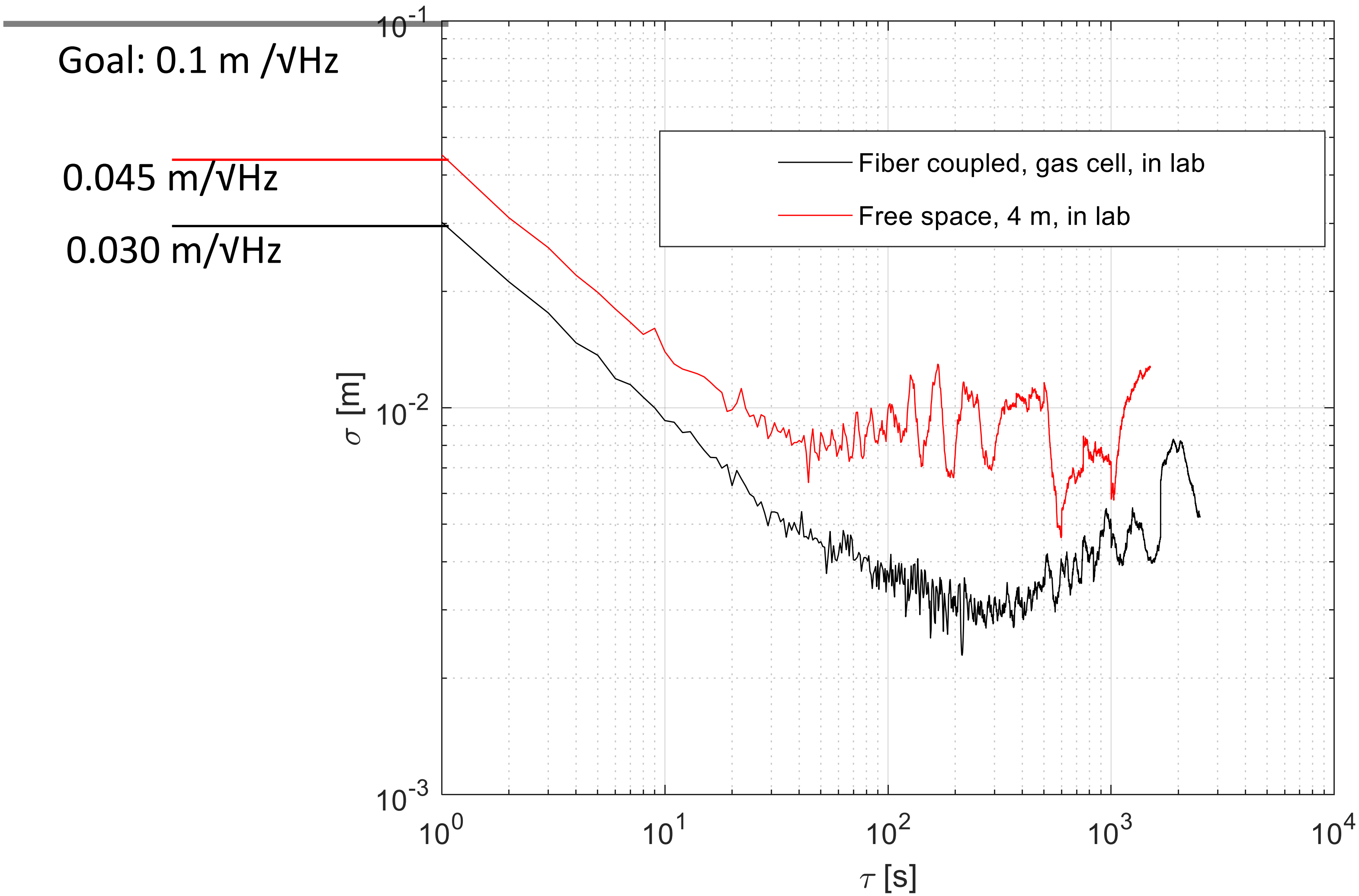
Free space measurements

S_{RF}=340 MHz/s
$f_{ramp,RF}$ = 10 kHz
$f_{mod, opt}$ = 50 kHz





Ranging Measurement Precision

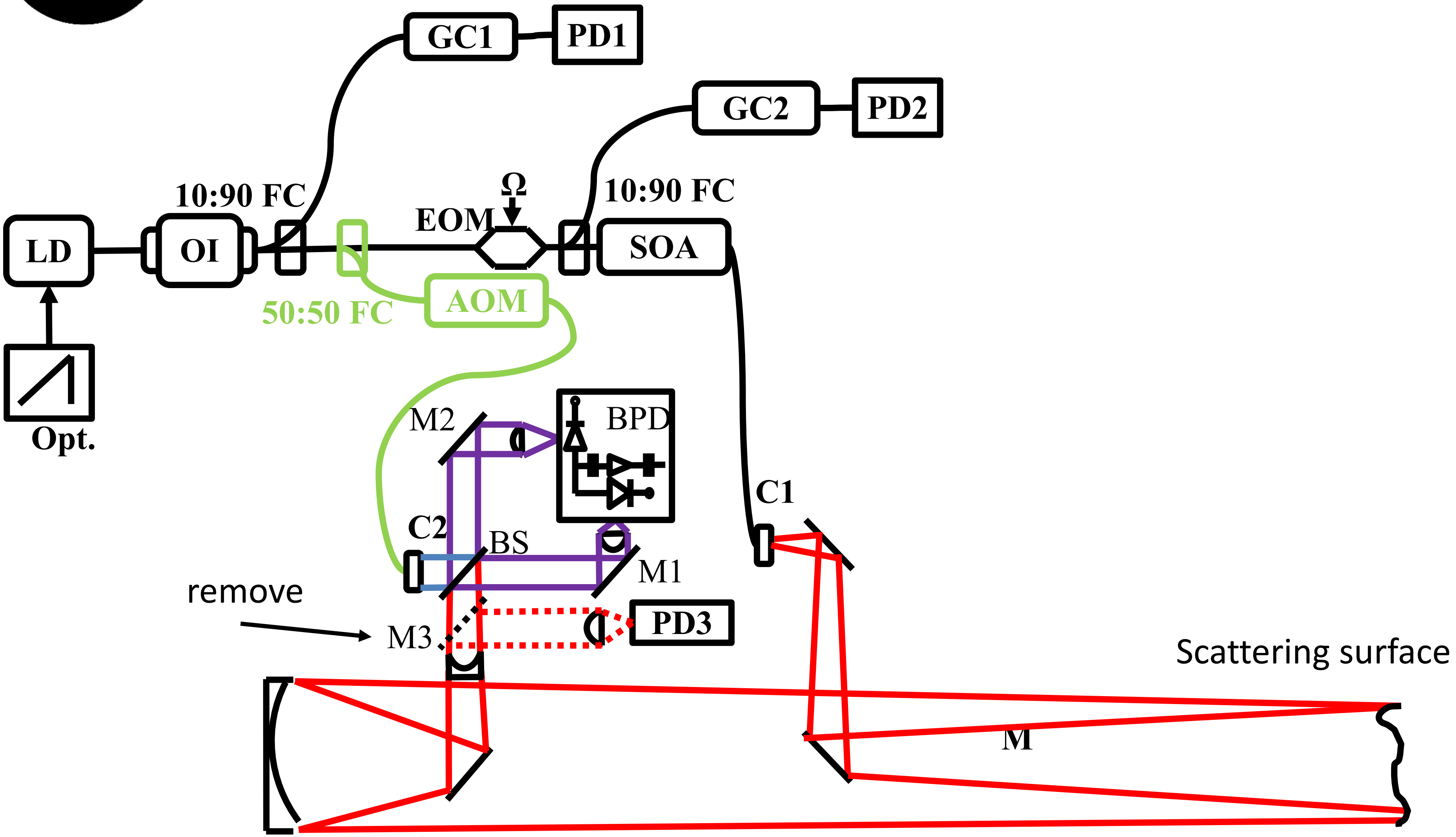


Goal: 0.1 m /√Hz

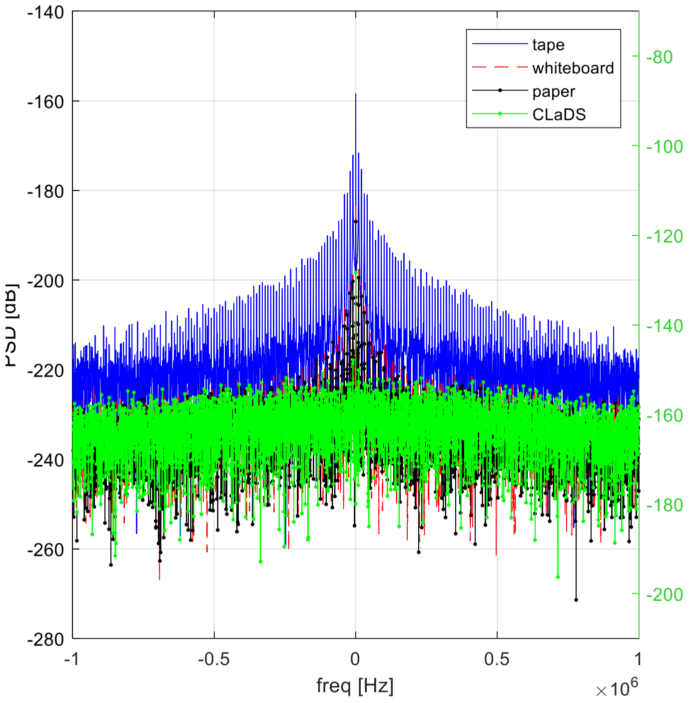
0.045 m/√Hz

0.030 m/√Hz

HE-CLaDS system



Heterodyne Enhancement with Scattering Targets

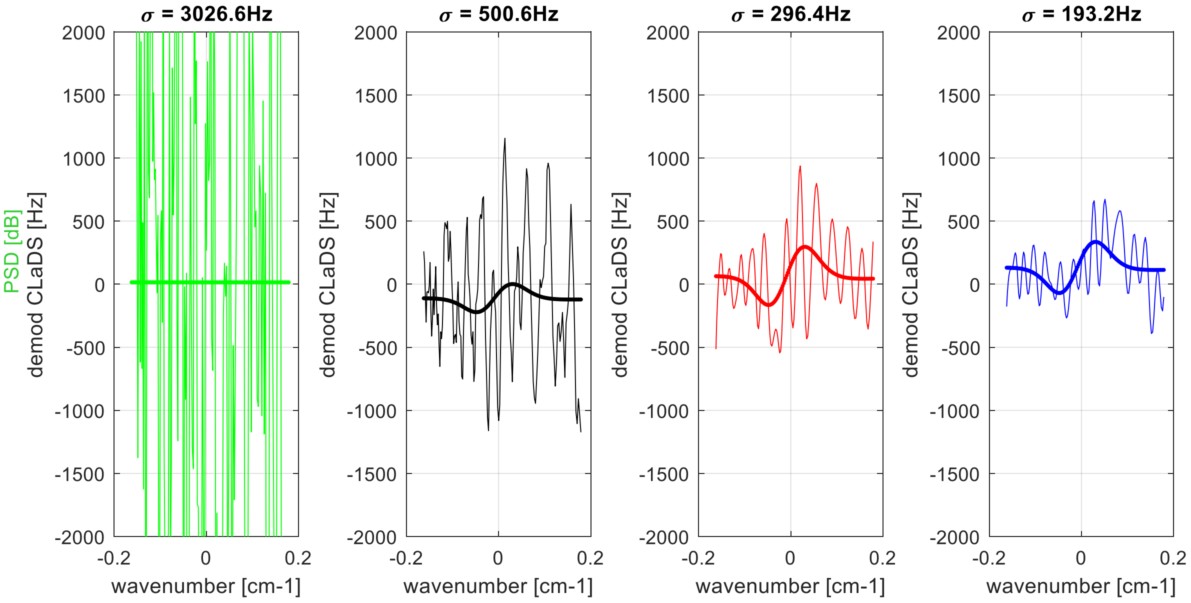


Conventional CLaDS

Paper

Whiteboard

Reflective tape



Effective CNR enhancement from residue noise: 15.6 dB 20.2 dB 23.9 dB

Goal: 10 dB

All success criteria in the laboratory have been met

- Concentration Measurement Sensitivity
  - Goal: In lab < 1 ppm-m/√Hz

0.6 ppm-m/√Hz

- Ranging Measurement Precision
  - Goal: In lab < 0.1 m/√Hz

0.03 m/√Hz

- Heterodyne-Enhancement

10 - 24 dB

  - Goal: In lab > 10 dB increase in Carrier to Noise Ratio (CNR)