PHYSICAL SCIENCES INC.

30 November 2006

U.S. Dept. of Energy
National Energy Technology Laboratory
P.O. Box 880
Morgantown, WV 26507-0880

Attention: Mr. Richard Baker

Subject: Semi-Annual Progress Report #4

Reference: DE-FC26-04NT42268

Enclosure: One Paper Copy

Dear Mr. Baker:

Physical Sciences Inc. (PSI) is submitting the enclosed document in support of the referenced contract. This is provided in accordance with the terms of the Cooperative Agreement. As you are aware, this report is submitted simultaneously to the NETL repository in Pittsburgh.

Thanks again for the opportunity to participate on this program. Please do not hesitate to contact the undersigned or M. Frish at (978) 689-0003 if you require additional information

Sincerely,

Richard A. Sasso

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PSI-1454

High Altitude Aerial Natural Gas Leak Detection System

Semiannual Progress Report No. 4
Covering the Period
April 2006 through September 2006
for
Contract No. DE-FC26-04NT42268

Prepared by:

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NETL Cooperative Research Project Progress Report

Report Prepared by:
Mickey B. Frish, Richard T. Wainner, Joseph R. Morency and Matthew C. Laderer

1. **DoE Award Number**: DE-FC26-04NT42268
   Recipient: Physical Sciences Inc.

2. **Project Title: High** Altitude Aerial Natural Gas Leak Detection System
   Principal Investigator: B. David Green

3. **Report Date:** November 20, 2006
   Reporting Period: April 2006 – September 2006

4. **Executive Summary**

The objective of this program is to develop and demonstrate a cost-effective and power-efficient advanced standoff sensing technology able to detect and quantify, from a high-altitude (> 10,000 ft) aircraft, natural gas leaking from a high-pressure pipeline. The advanced technology is based on an enhanced version of the Remote Methane Leak Detector (RMLD) platform developed previously by Physical Sciences Inc. (PSI). The RMLD combines a telecommunications-style diode laser, fiber-optic components, and low-cost DSP electronics with the well-understood principles of Wavelength Modulation Spectroscopy (WMS), to indicate the presence of natural gas located between the operator and a topographic target. The system includes an optical transceiver and an electronic controller. The transceiver transmits a laser beam onto a topographic target and receives some of the laser light reflected by the target. The controller processes the received light signal to deduce the amount of methane in the laser's path.

The currently-available lightweight, handheld, battery-powered RMLD provides a maximum range to the topographic target of 100 ft. For use in the airborne platform, we are modifying three aspects of the RMLD, by: 1) inserting an optical fiber laser amplifier to increase the transmitted laser power from 10 mW to 5W; 2) increasing the optical receiver diameter from 10 cm to 25 cm; and 3) altering the laser wavelength from 1653 nm to 1618 nm. The modified RMLD system provides a path-integrated methane concentration sensitivity ~3000 ppm-m, sufficient to detect the presence of a leak from a high capacity transmission line while discriminating against attenuation by ambient methane.

During the previous reporting period, covering the third six-months of the 27-month project, we completed long-range outdoor ground testing of the airborne sensor. These tests demonstrated that:

- The system receives adequate backscattered laser power from a target at 2000 m range
- The system responds rapidly to transient methane leaks
- System noise within the leak measurement bandwidth (i.e. the minimum detectable rapid change in path-integrated methane concentration) is about ~2500 ppm-m

- Slow drift of amplifier characteristics, resulting from ambient temperature changes, limits measurement of absolute path-integrated methane concentration to about 15,000 ppm-m

In the current reporting period, covering the fourth 6-months of the 27-month project, we:

- Explored the amplifier operating parameter space in an attempt to better understand and reduce noise and drift
- Completed preparation for a system flight test, including coordination with a local transmission pipeline operator.
- Extended the project completion schedule by three months to accommodate the flight test, scheduled for the week of 9 October.

Unfortunately, we received notification at the end of this reporting period that the pipeline operator was withdrawing from the planned test. As this report is being written, PSI has been unable to secure an alternative test site where a significant leak could be created, and has therefore abandoned the planned flight test. Instead, PSI is simulating the flight test using a methane-filled plastic bag mounted on a automobile that drives through the laser beam at speeds comparable to a slow-flying aerial survey aircraft. The test results will be documented in the Final Report.

5. Results of Work During Reporting Period

Summary of Previously Reported Work Completed

During the previous reporting periods, we

- Received the optical fiber laser amplifier
- Characterized the amplifier performance
- Evaluated methane detection limits of the Amplified RMLD
- Assembled and aligned the high-altitude optical transceiver
- Combined the transceiver and amplified laser to form the complete sensor system
- Completed an initial matrix of outdoor ground field tests observing stationary targets
- Detected transient methane leaks
- Characterized system performance

The principal results of the work completed prior to the current reporting period demonstrated that:

- The system receives adequate backscattered laser power from a target at 2000 m range
- The system responds rapidly to transient methane leaks
- System noise within the leak measurement bandwidth (i.e. the minimum detectable rapid change in path-integrated methane concentration) is about ~2500 ppm-m
- Slow drift of amplifier characteristics, resulting from ambient temperature changes, limits measurement of absolute path-integrated methane concentration to about 15,000 ppm-m

Figure 1 illustrates the system performance when illuminating a water tower at 2000 m range. A gas leak within the laser's optical path was simulated by filling the receiver telescope with methane. The response to adding methane is clear in the right hand portion of Figure 1.

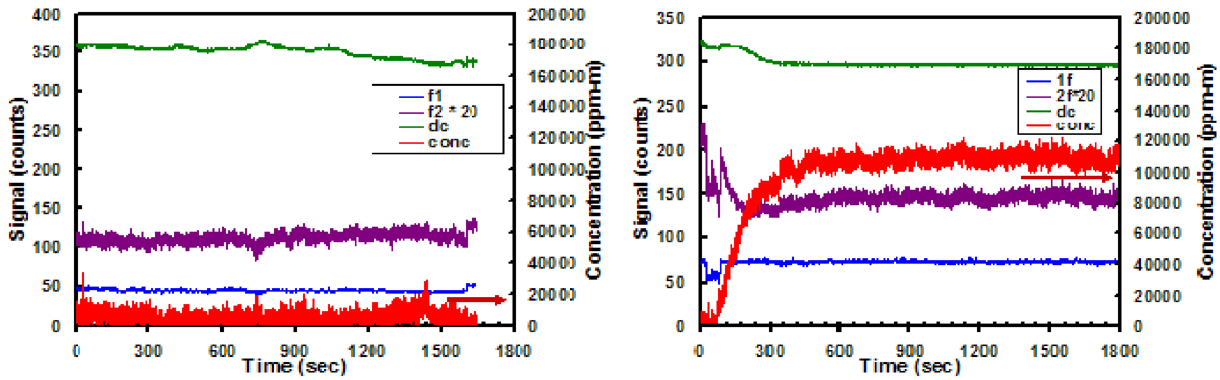

Figure 1. Time record of WMS signals from a water tower at ~2000m using the EDFA-amplified laser. (left) No CH_4 added. (right) At ~60sec, 10%CH_4 (balance N_2) begins flowing into the telescope.

Figure 2 illustrates the drift of the lock-in amplifier output signals, and the computed concentration, over a period of several days, with no methane in the optical path. The drift manifests as a slowly varying change in the zero point or offset of the 1f and 2f signals from which concentration is deduced (as described in earlier reports). The rms drift magnitude corresponds to about 15,000 ppm-m. We recognized the underlying cause of the drift as due to distortion by the EDFA of the sinusoidal amplitude modulation imposed on the seed laser that is input to the EDFA. The distortion creates a 2f component which is interpreted as methane in the optical path. If this signal was constant over time, it could be measured once and subtracted as an offset from subsequent measurements. But its temporal variation precludes such a correction. Therefore, in the current reporting period, we attempted to understand and mitigate the source of drift.

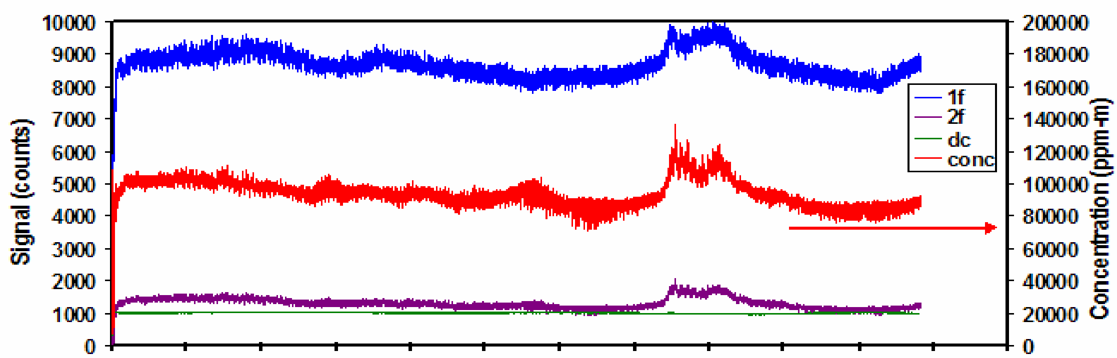

Figure 2. 65-hour time record of WMS signals from a beam dump employing the EDFA-amplified laser.

In the current reporting period, covering the fourth 6-months of the 27-month project, we:

- Explored the amplifier operating parameter space in an attempt to better understand and reduce noise and drift
- Completed preparation for a system flight test, including coordination with a local transmission pipeline operator.
- Extended the project completion schedule by three months to accommodate the flight test, scheduled for the week of 9 October.

EDFA characterization

The EDFA manufacturer (Keopsys), when asked, described three potential sources of amplifier distortion and drift, and some recommendations for characterizing and potentially reducing these effects. They are:

1) EDFA dynamics: The amplifier dynamics act much like an electronic filter with a time constant determined by the erbium metastable state lifetime. When input seed laser power changes, there is a lag in amplifier response due to time needed to excite or de-excite erbium atoms. Thus, a sinsoidally modulated input amplitude will have an output modulation at the same fundamental frequency. The amplitude and phase of the output modulation will depend on the modulation frequency. Since the metastable state lifetime is some fraction of a millisecond, the RMLD's 10 kHz modulation may be a particularly bad operating point. Also of note, as input power changes, the ratio of amplified laser power to amplified stimulated emission (ASE) also changes. Thus, our measure of total output power vs time is likely not an accurate representation of power at the seed laser wavelength vs time.

   Recommendation: Map output modulation amplitude vs modulation frequency. Consider changing modulation frequency based on results. Keopsys believes higher frequencies will be better.

2) Gain-tilt: The amplifier gain depends on wavelength. As wavelength modulates, gain changes introducing an amplitude modulation. Since our wavelength modulation is quite small compared to the amplifier gain curve bandwidth, this is likely to be a small effect. However, the gain curve is temperature dependent, so proper warm-up is necessary for stability.

   Recommendation: If possible, map gain vs wavelength in our operating range. This is difficult because laser gain is not easy to distinguish from ASE.

3) Temporal drift of amplitude modulation characteristics: Changes in fiber temperature affect gain curve, metastable state lifetime, and fraction of laser power carried in core vs clad. All of these affect output response to input modulations.

Based on these recommendations, we built a laboratory apparatus that enabled us to perform Wavelength Modulation Spectroscopy at modulation frequencies ranging from 1 – 100,000 Hz. The apparatus comprised a benchtop laser driver, a lock-in amplifier, and an analog-to-digital signal processor.

Figure 3 compares seed laser power input waveforms with EDFA output waveforms for modulation frequencies ranging from 20 Hz to 100,000 Hz. Previous work, and additional data not shown here, demonstrated that the EDFA output wavelength is identical to the input wavelength. Because the seed laser wavelength varies linearly with power, the plot of seed laser power vs time is also a plot of both seed and amplified laser wavelength vs time.

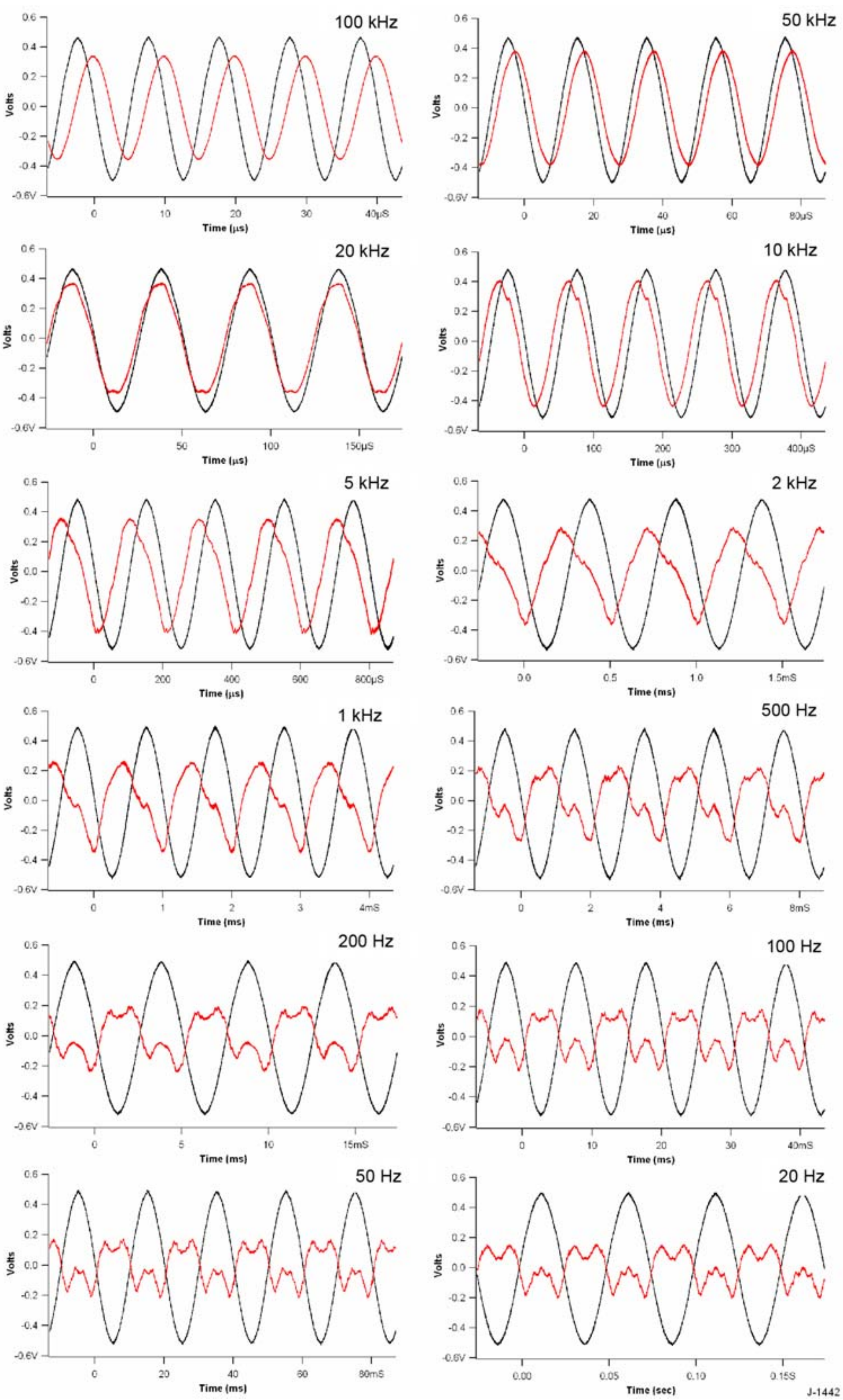

Figure 3. Seed layer (black) and amplified laser (red) power waveforms at modulation frequencies from 20 to 100,000 Hz.

The data of Figure 3 confirm that the EDFA distorts the input waveform and that the harmonic content of the distortion depends on the modulation frequency:

- At low modulation frequencies (<100 Hz), the EDFA output power clearly varies non-linearly with input wavelength. This non-linear response creates a second harmonic (i.e. 2f) contribution to the amplified laser waveform. At the low frequencies, this 2f contribution corresponds to a concentration offset that exceeds 10^6 ppm-m.

- As modulation frequency increases, the amplitude of the EDFA output at the modulation frequency (i.e. the 1f signal) increases while the distortion diminishes. At 100 kHz, distortion is no longer obvious and the EDFA output power appears to be an undistorted sinusoid that follows the seed laser with a ~90 deg, phase lag.

The latter observation suggests that operating the EDFA at 100 kHz modulation frequency will yield less distortion-induced drift than operation at lower frequencies. To test this hypothesis, we used a pair of lock-in amplifiers to demodulate the detector output signals at 100 kHz and 200 kHz, yielding the 1f and 2f signals vs time. Figure 4 illustrates the results. It shows the 1f, 2f, and 2f/1f (proportional to concentration) data vs time for a period of nearly two hours. These data were acquired with the amplified laser beam transmitted through a 50 cm long optical cell. Initially, the cell is filled with only room air. At 950s. the valve to the methane supply was opened briefly, and at 1100s the cell was evacuated. At 1500s the cell was filled with neat methane, yielding a path-integrated concentration of 500,000 ppm-m. Then the cell was closed and monitored. During the monitoring period (which lasted about 8 hours), the measured concentration drifted by 23,600 ppm-m, while the noise (defined as rms deviation of individual samples around a 1s average) is about ~4500 ppm-m. These values are comparable to those measured at 10 kHz modulation frequency. Thus, we conclude that, while modulation at 100 kHz provides less distortion and thus a smaller offset than modulation at 10 kHz, the offset drift and noise at the two modulation frequencies are comparable. Thus, there is no practical advantage of the higher modulation frequency. This completed our work to characterize the amplified RMLD system.

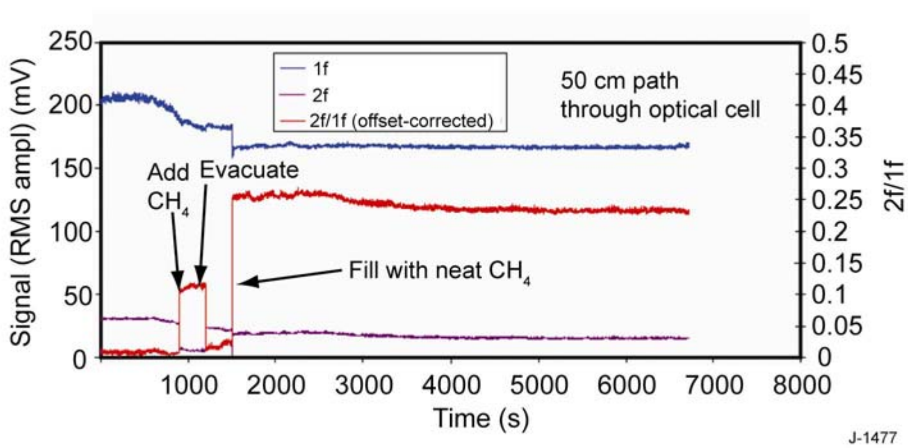

Figure 4. WMS signals recorded at 100 kHz modulation frequency.

Flight Test Preparation

During this reporting period, PSI completed plans for a flight test of the airborne RMLD system. The Flight Test Plan, attached as Appendix A of this report, describes the details.

The plan requires a gas (or methane) leak rate of 5000 scfh for a duration of about 2 hours. Initially, we had intended to simulate such a leak using several cylinders of methane to be released at an undefined location. As we were starting to identify a location, we made contact with the operator of a local high-pressure gas transmission pipeline. The local operator agreed to participate in the tests by (safely) releasing gas at a nearby metering station. Plans were made to perform these tests during the week of October 11, 2006. On October 3, the pipeline operator informed PSI that approval for the test was required from a third party, the owner of a LNG storage tank co-located with the metering station. For security reasons, the third party disapproved of flights over the LNG tank and forced cancellation of the planned tests.

6. Milestones Not Met

Planned milestones for this reporting period were: Completion of Flight Test Readiness, Completion of Flight Tests, and Completion of data analysis and altitude scaling. Due to the planned flight test schedule, the latter two milestones were postponed. Section 9 below provides more detail.

7. Cost and Schedule Status

Figure 5 plots actual expenditures of DoE funds compared to expenditures planned in accordance with the Research Management Plan. The project has been extended for three months beyond the original completion date. The rate of expenditures is in accordance with the extended plan, and is commensurate with the work completed.

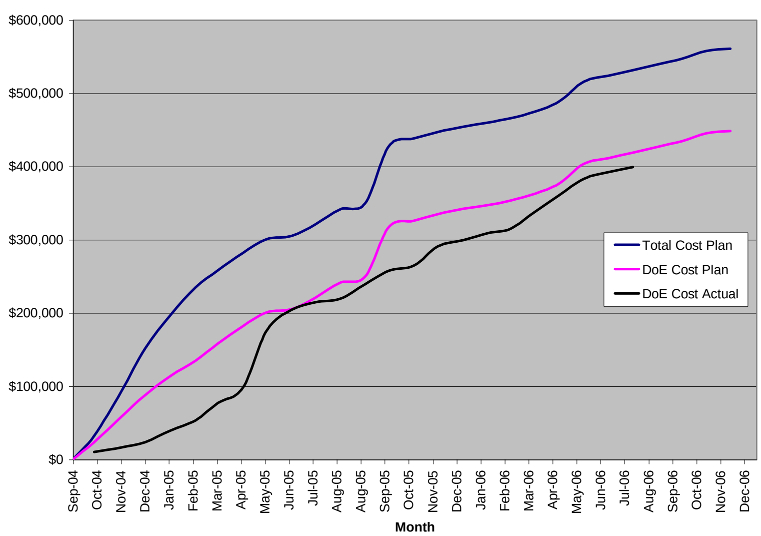

Figure 5. Planned and actual costs.

8. Summary of Significant Accomplishments

We have completed our study of EDFA characteristics and their impact on the Wavelength Modulation Spectroscopy detection technique. While the EDFA performance is not as good as we had expected prior to this program, the knowledge gained from this work is very valuable for identifying characteristics that will enable future performance improvements.

9. Problems and Delays

As described in Section 5 above, the planned flight test was cancelled at the end of this reporting period. PSI has been unable to locate an acceptable local site that can accommodate a substatial gas release. We have chosen, instead, to simulate the flight test with a ground test using a platform that mounts on a car and holds a 1 square meter transparent plastic bag filled with diluted methane. The bag will provide a path-integrated methane concentration that simulates a leak plume. Our airborne RMLD system will be mounted on the roof of our building and will capture the signature from the simulated leak at the car drives by at speeds comparable to half the aircraft speed. This test, albeit imperfect, will provide the data required to verify the capability for leak detection from an aircraft and demonstrate that our altitude scaling expectations function as predicted.

We expect to complete the simulated flight test by November 30, 2006 and finish the data analysis and altitude scaling milestone by December 31. These milestones complete the technical work of this project and will be documented in the Final Report.

10. Technology Transfer Activities

PSI and our cost share partner Heath Consultants have received significant interest in a low-altitude version of the aerial RMLD, one that survey transmission pipelines from a helicopter flying at altitudes ~500 ft AGL. This can be accomplished using the RMLD Control Unit, without the EDFA, coupled with the large transceiver developed for the high-altitude RMLD. PSI and Heath are discussing means for addressing this opportunity.

Appendix A
Airborne Remote Methane Leak Detector (aRMLD) (EP) Flight Test Plan
Version 1

Purpose and Overview

This document describes the test plan for the experimental flight testing of the airborne remote methane leak detector (aRMLD). The aRMLD is envisioned as a future product, based on the currently-available handheld RMLD, to be installed on aircraft that will fly over natural gas pipelines and survey for natural gas leaks. The data storage function of the software interface will enable matching of detected leak signals with geographical location. The interface will also enable the acquisition of data that will assist in creating a clear definition of the performance required for leak detection strategy, in finding effective methods of survey, and in the assessment of potential barriers to acceptance.

The EP configuration utilizes an enhanced (over RMLD) interface, with a laptop computer for data display and storage, that incorporates input from a video camera that supplies an image of the scene that the aRMLD is surveying.

The entire operation is allocated 5 working days, 2 for installation and ground testing, 2 days for flight tests, and 1 for contingency.

Installation / Ground Tests:

Air Platform:	Cessna 207
Contractor:	Gamm Air, Inc. (Pottstown, PA) (www.gammair.com)
Pilot:	Len Subik
Payload Specifications:	
Maximum payload:	xxxxx lbs
Surveying port:	22” diameter open hole (7” interior floor to external skin)
Survey Equip. Headspace:	46”

Figure A-1. Gamm Air's Cessna 207, cabin with photographic equipment installed, and exterior view of camera port.

Sensor Hardware:

Transceiver:	12 inch dia. x 48" Newtonian telescope (10 inch *f*/4.7 primary) with side-mounted laser beam launch and monochrome video camera.
Laser Amplifier:	Keopsys 5W Erbium-doped Fiber Amplifier (EDFA) (28Vdc, 6A)
Laser / Signal Controller:	PSI single-PCB laser controller and WMS signal processor (battery-powered)
Computer:	Windows-based laptop with LabWindows graphical interface and datalogger. (battery-powered)

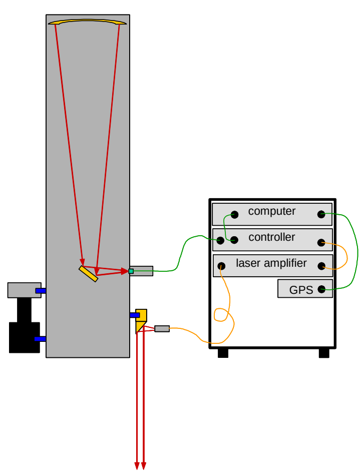

Figure A-2. Mobile natural gas leak sensor computer-interfaced component schematic. (shown with optional GPS input).

Installation scheme: Laptop with sensor operator. Shock-absorbed rack-mounted EDFA and Controller positioned near survey hole, strapped down with cargo straps. Transceiver suspended in hole with 4-legged frame with vibration-damping mounts. (see Figure 3)

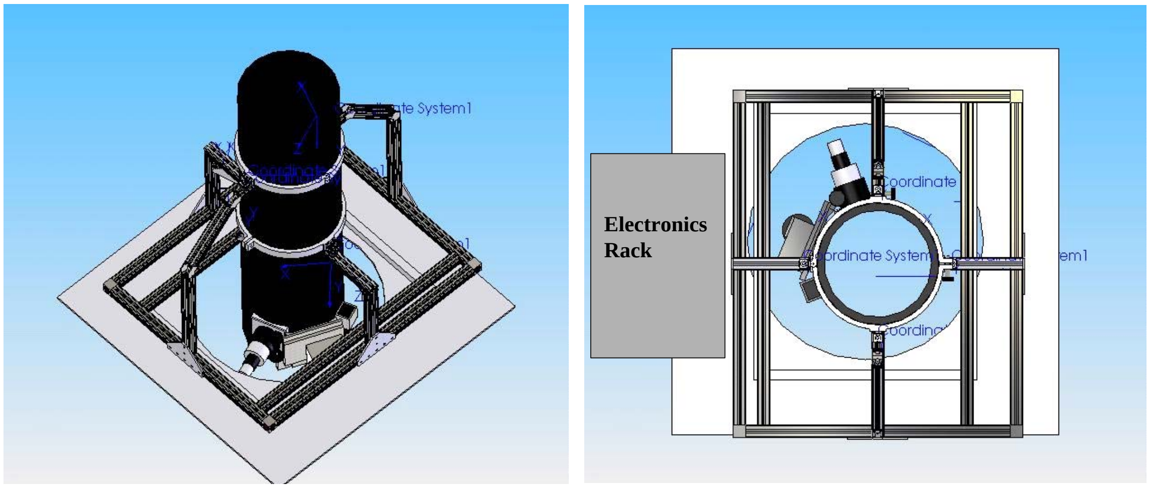

Figure A-3. Airborne remote methane leak detector mounting apparatus drawing.

Ground Tests:

Operability: Test all equipment for operability, especially high power draw EDFA.

Alignment: Transceiver will be pre-aligned. Fine alignment after installation is not possible. Check for potential misalignment during installation with a preconstructed laser beam-to-telescope f.o.v. template.

Noise from air platform: Record signals with engine off (airport electrical supply) and with engine on (aircraft electrical supply). Also determine potential for leaving EDFA running (warming up) during switchover from one supply to the other.

<u>Flight Tests:</u>

Ground support: A person or team will be required on the ground at the predetermined leak site to control the regulation of the natural gas leak. A wind sock will be installed at the site as a leak location marker and wind indicator.

Leak Rates: Leaks will be generated at one of two flow rates, nominally distinguished ‘high’ or ‘low’. The high flow rate will be ~5000 SCFH and the low flow rate will be ~1000 SCFH. If the leak is to be generated by gas cylinders, multiple cylinders will need to be utilized in either case. A 300 ft^3 cylinder will last only 18 min at the low flow rate and 3.6 min at the high flow rate. In order to develop a realistic leak plume, the leak should begin at least 15min

	before the aircraft flies over and the sensor performs its survey. Coordination with the airborne survey will be made by turning the leak on at a prescribed time, and similarly timing the first flyover to occur at a prescribed time.
Flight Test 1:	The surveys on this test day will utilize the high leak flow rate. The test will be broken into 4 segments, delineating 4 different altitudes: 500m, 1000m, 2000m, and 3000m. At each altitude, there will be 4 passes over the leak site; 1 back & forth pass parallel to the ground wind direction, and 1 back & forth pass orthogonal to the ground wind direction. Approximately 15 minutes will be required at each altitude.
Flight Test 2:	The surveys on this test day will utilize the low flow rate. Depending on observed signal responsivity to the high flow rate from the day before, this flow rate may be adjusted up or down from 1000 SCFH to better record informative data. Again, the 1 hr test will be broken into surveys at 4 altitudes and 8 passes at each altitude, like flight test 1.

<u>Software:</u>

Input Signals:

WMS circuit board:	10 Hz digital data that include: Serial number. Error codes. Detected gas (PPM-M) Battery level. Preamp DC level. TDL modulation level. TDL drive current. TDL temperature. F1 value. F2i, F2q, and F2 values.
Camera:	30fps analog (1V_{p-p}) video data

Data Processing:	All input signals provided by the WMS board are to be recorded at 10 Hz. These data will be processed after flight to evaluate leak detection success. Real-time processing algorithms will be utilized, but it is likely that temporal drifts of instrumental offsets will complicate real-time analysis. Data analysis will identify the methane leak as a rapid change in methane signal compared to background. Each of the return-power normalized phase-orthogonal components of the F2 signal (i.e. F2i/F1 and F2q/F1) will be analyzed, thus minimizing the effect of phase drift on the offset.

Data Display: LabWindows graphical interface. Includes:

- Scrolling graphical displays (with adjustable axes):
  - Gas concentration
  - Received laser power (1f)
  - Absorption signal (2f)
  - Total light received at detector (dc)
  - Laser temperature
- Numerical readouts:
  - Laser operating parameters: I_{dc}, I_{ac}, T_{laser} (user-adjustable)
  - Battery voltage
  - Errors / warnings
- Video rate updating image from camera

Data Storage: Toggle switch control in LabWindows graphical interface.
Data stored:

- All WMS input signals (10 Hz)
- Video image file (Compressed, if possible) (User-selectable storage rate (incl 'off'). Default 3Hz.) (Time-stamped to sub-second accuracy)

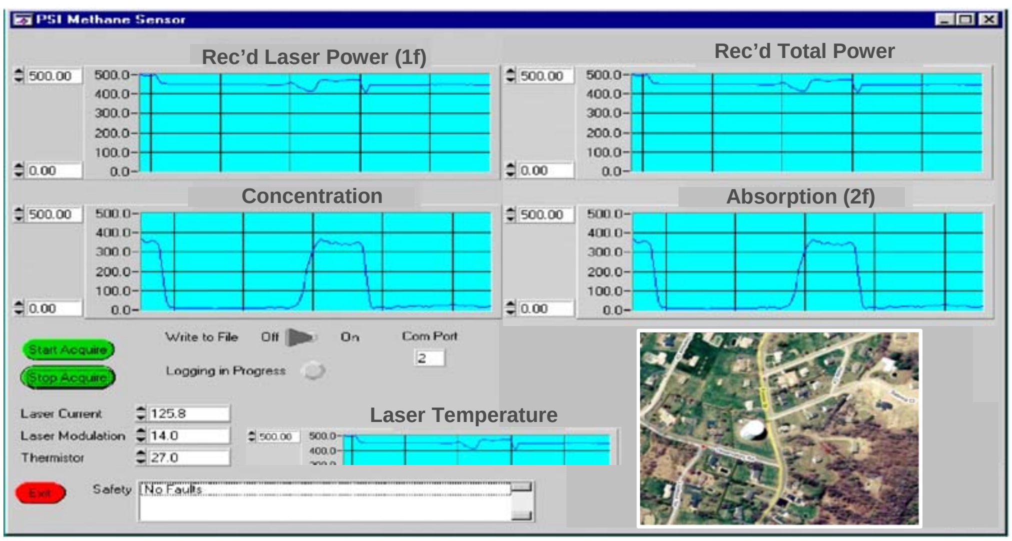

Figure A-4. Example computer control software user interface.