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Abstract

Ophir Corporation was awarded a contract by the U. S. Department of Energy, National Energy Technology Laboratory under the Project Title "Airborne, Optical Remote Sensing of Methane and Ethane for Natural Gas Pipeline Leak Detection" on October 14, 2002. This six-month technical report summarizes the progress for each of the proposed tasks, discusses project concerns, and outlines near-term goals. Ophir has completed a data survey of two major natural gas pipeline companies on the design requirements for an airborne, optical remote sensor. The results of this survey are disclosed in this report. A substantial amount of time was spent on modeling the expected optical signal at the receiver at different absorption wavelengths, and determining the impact of noise sources such as solar background, signal shot noise, and electronic noise on methane and ethane gas detection. Based upon the signal to noise modeling and industry input, Ophir finalized the design requirements for the airborne sensor, and released the critical sensor light source design requirements to qualified vendors. Responses from the vendors indicated that the light source was not commercially available, and will require a research and development effort to produce. Three vendors have responded positively with proposed design solutions. Ophir has decided to conduct short path optical laboratory experiments to verify the existence of methane and absorption at the specified wavelength, prior to proceeding with the light source selection. Techniques to eliminate common mode noise were also evaluated during the laboratory tests. Finally, Ophir has included a summary of the potential concerns for project success and has established future goals.

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1. Executive Summary

The Research Management Plan was prepared and submitted. This report described the main test to be performed, the Work Breakdown Structure (WBS) and major milestones.

Mr. Jerry Myers, Ophir Program Manager delivered a technical briefing outlining the project's technical approach, management plan and budget to the NETL COR at the NETL Morgantown facility on December 5, 2002. Dr. Loren Nelson, Principal Investigator from Ophir also attended.

The Technology Status Assessment was prepared and submitted. This report described the current state-of-the-art of optical, remote gas correlation sensing of methane and ethane gases.

Ophir Corporation believes it is important to have gas distribution industry input into the development and design requirements for an airborne, optical remote sensor of methane and ethane for natural gas pipeline leak detection. Ophir sent a list of informational questions to WBI Holdings, Inc. in Bismarck, ND and El Paso Pipeline Group in El Paso, TX. Attachment 1 shows the survey questions and a summary of the industry response to the questions.

An experiment was performed using the existing fence-line system, being developed by Ophir and the Environmental Protection Agency (EPA) under contract No. 68-D-02-058 to determine target reflected power from a 3.3 µm emitting blackbody source. The absorption band of interest for this sensor was centered near 3.3 µm, where the primary absorption bands occur for methane and ethane. The fence-line system was converted into a co-located transceiver, in which both the light source and the receiver optics were located together. They were then aligned and pointed at a white painted wall located approximately 10m (33 ft) away, and the processed signal return was monitored on the system computer. Even though the black body source was capable of outputting 5 Watts of broadband power, it was evident that the amount of usable in-band power being reflected from the target was insufficient to yield the desired signal to noise ratio (SNR) of 100, even at this short target distance. The best SNR seen during this test was around 10. The output power of the light source, that would be required to yield an SNR of 100 from a diffuse target at 152 m (500 ft) would need to be at least 5,000 times brighter. This would require a black body light source that would output nearly 25,000 Watts, clearly an impractical amount of broadband power.

The decision was made following the co-located transceiver test to research other absorption bands for ethane and methane, where higher in-band output, broadband light sources such as super luminescent light emitting diodes (SLED) might exist.

Ophir has spent a considerable amount of time reviewing the existing atmospheric transmission software such as Air Force Geophysics Laboratory HITRAN, LOTRAN, and FASCODE for complete absorption spectra on methane and ethane. These software databases generally are regarded as quite extensive and inclusive of all absorbing molecules and wavelengths. It is logical to assume that methane and ethane have overtone absorption bands near 1.65 µm, since the fundamental absorption band occurs for both of these gases near 3.3 µm. Indeed HITRAN showed that methane does exhibit overtone absorption between 1600 - 1700 nm, but there was no evidence in HITRAN that ethane showed similar bands. It was essential, if OPHIR was to use a single light source to detect both methane and ethane, that ethane be shown to have either narrow or broadband absorption present. Several other databases were reviewed with similar inconclusive findings. Ophir determined that it would be necessary to perform absorption spectra testing at their facility to confirm ethane overtone absorption.

The airborne optical system signal to noise ratio (SNR) determines the minimum detectable change in reflected signal due to absorption by gas species of interest, therefore the minimum absorbance (ppm*m) of detectable gases. Ophir has calculated the optical system SNR based upon such parameters as background solar noise, probe light source intensity fluctuations, variations in the reflectivity of the earth's surface and fluctuations due to air turbulence. The SNR model has produced important design guidelines for the amount of light source power needed, the noise characteristics of the detector, and the size of the receiver optics.

Significant progress has been made in determining the availability of a broadband light source in the wavelength band of interest (1600 – 1700 nm). Several technologies such as Raman fiber amplifiers, optical parametric amplifiers, and spectrally beam combined diode arrays have been proposed as the system light source. Ophir has reviewed each of these solutions and the associated cost, and is in the process of recommending the best source for the broadband gas correlation system. An exhaustive search was performed on low noise detectors and Ophir has found very low noise detectors capable of normalized detectivity of D* = 9.5E13 Jones up to 1.9 µm. These detectors will produce very low noise especially when used in a balanced detector arrangement, where common mode laser noise can easily be subtracted out from the output.

Ophir conducted laboratory testing using different light sources and detectors to measure the system sensitivity of a gas correlation system to methane gas. The currently available light sources did not allow Ophir to measure system sensitivity to ethane. Methane was seen in high concentrations, but the system noise was high enough to mask the presence of low levels of methane. Ophir has added several measurement tools and light source amplifiers to the laboratory that will lower the noise threshold and hopefully produce more accurate sensitivity measurements.

2. Experimental

2.1. Laboratory Setup for Determining Methane and Ethane Atmospheric Absorption Between 1600 – 1700 nm

In the laboratory absorption setup, Ophir used a previously purchased Ando Corporation optical spectrum analyzer, several gas cells and a CVI Laser Fiber Optic Broadband Light Source. The optical spectrum analyzer was calibrated using a 1536.204 nm laser diode and a HP86120 multi wavelength meter. Gas cells containing various methane and ethane gas concentrations were used in the optical path between the spectrum analyzer and the light source. The goal here was to produce absorption plots showing the existence of absorption lines for methane and ethane between 1600 and 1700 nm. While methane plots were available from several data sources showing absorption near this wavelength, Ophir was unable initially to locate ethane absorption scan data.

2.2. Proof of Concept Testing With Broadband Light Source at 1.63 µm

Ophir has determined through a literature survey of available gas absorption databases and experimentally that methane does contain significant absorption spectra within the 1600 – 1700 nm range. In a paper by Lackner [2002], methane spectroscopy was demonstrated using a tunable diode laser centered at 1.68 µm. The experimental measurements were performed using a Vertical Cavity Surface-Emitting Laser Diode (VCSEL) tuned across some fine absorption structure near 1687 nm. This type of laser diode typically has a narrow linewidth and is only tunable across a few tenths of a nm, and thus can only be used to resolve a small portion of the absorption features. The sample rate required for this type of narrowband detection is also quite high at 5 MHz, which limits the amount of signal to the detector. SRI International through a contract with the Gas Research Institute has also developed a ground based remote methane gas leak sensor, which uses the technique of wavelength modulation spectroscopy by tuning a narrow band laser diode over an absorption line near 1651 nm. While the industry has demonstrated that methane can be quantified using narrow band laser sources, no one has yet demonstrated that a single broadband light source can be used to sense both methane and ethane.

Ophir believes that although it has modeled the amount of expected absorption for methane and ethane and it has determined the optimal sensing wavelength, there is still enough uncertainty to justify experimentally verifying the modeled results. The modeling has indicated that an output of 1 –2 Watts of broadband power will be required. Light sources capable of these powers are not readily available, and to develop them would require a substantial amount of money. Prior to committing these development funds, Ophir believes that it is prudent to verify the modeling results as to the actual absorption versus modeled absorption.

2.2.1. Proof of Concept Testing Laboratory Setup

The basic laboratory setup used in the proof of concept testing is shown in Figure 1.

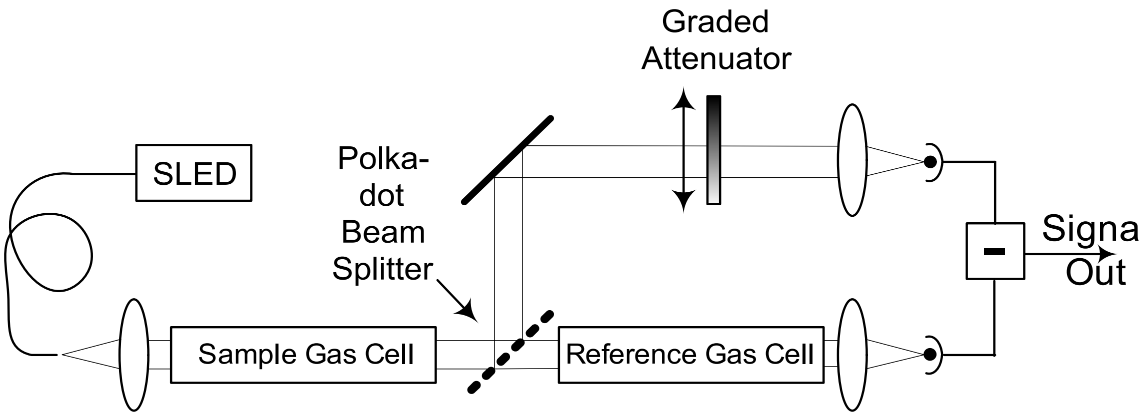

Figure 1. Proof of Concept Laboratory Setup

All of the items shown in Figure 1 are off-the-shelf with the exception of the sample and reference gas cells. The gas cells were built for the test of the fence-line monitoring system under an EPA funded contract. These gas cells are 30 cm (1 ft) long, use 1-inch optics, and can be filled or evacuated with variable gas pressures. The approximate split ratio of the polka dot beam splitter is 1:1 or 50% transmission. The graded attenuator is a linear changing neutral density filter optimized to near-IR wavelengths and is used to balance the optical inputs into the balanced detector. The balanced detector from New Focus has detectors that are optimized for responses up to about 1620 nm. The signal output of the balanced detector was connected to a Tektronix digital oscilloscope and a Signal Technology lock-in amplifier.

2.2.2. Description and Discussion of the Broadband SLED Light Source

Quite a bit of work went into locating a broadband semiconductor light source capable of outputting several milliwatts of power at wavelengths above 1620 nm. The telecommunications industry transmits over fiber optics primarily at wavelengths under 1600 nm. In regions just above 1620 nm, there are very few semiconductor light source vendors. The detector industry has seen increased request from the scientific community, especially in the area of gas spectroscopy and have addressed the need for extended range detectors by developing detectors that have spectrally flat response now up to 1900 nm. Unfortunately, broadband semiconductor light source vendors are not entering the market in great multitudes yet. Ophir did find a light source that would nominally meet the methane and ethane absorption spectra requirements. The light source chosen for the experiment is a Super Luminescent Light Emitting Diode (SLED) that is centered near 1627 nm @T= 25 °C (or 1637 nm @T= 40°C) and has a Full Width Half Maximum (FWHM) of 45 nm. This particular SLED is capable of outputting up to 12 mW of power at a tuning temperature of 25°C and 4 mW at 40°C. The output is fiber coupled with an angled FC/APC style fiber optic connector to help minimize back reflections into the SLED.

The manufacturer of the SLED originally stated that they could hand pick special hermetic sealed high temperature SLEDs with output wavelengths up to 1650 nm, but the power decrease normally associated with increasing the tuning temperatures made it impractical to use these parts (output power would only be in the mW range). Ophir has continued discussions with the SLED vendor on the development of hermetically sealed SLEDs that will output power in the mW range at wavelengths near 1700 nm. The vendor has responded with an assurance that the desired specifications can be met and has submitted a quote covering the fabrication of a new wafer and the production of a minimum quantity of 30 parts.

2.2.3. Test Procedures Used for Laboratory Methane and Ethane Absorption Testing

The main goals for the laboratory experiments are to establish the ability to detect methane and ethane absorption near 1630 nm, determine the signal to noise ratio that is possible using a balanced optical detector, evaluate the characteristics of the SLED seed source, and to better understand the methods of utilizing a balanced detector for optical signal acquisition. The basic test procedures that were followed include the following:

1. Power up the SLED using an ILX Lightwave Laser Diode Controller to control the input drive current and the internal diode temperature.
2. Plug the SLED fiber output connector directly into an optical spectrum analyzer, and compare the waveform to the manufacturer datasheets. Vary the diode temperature, holding the input drive current constant, and monitor the change in wavelength.
3. Experiment with various forms of current modulation of the diode including DC modulation, amplitude modulation using DC biased square, sine and triangular waves.
4. Connect the SLED into the laboratory setup shown in Figure 1 minus the gas cells. Experiment with using the polka dot beam splitter to create two optical beams, and direct the beams into the balanced detector.
5. Focus the light through the reference signal arm into a fiber optic coupler instead of the balanced detector, and redirect the fiber output into the optical spectrum analyzer. Check for any undesirable impacts on the output such as back reflections, which can impact the spectral characteristics.
6. Use different diode current modulations, and monitor the balanced detector outputs to determine balancing capability of detector.
7. Evaluate the overall root mean square (rms) noise level of the balanced detector output.
8. Install the reference gas cell into the setup, and fill the gas cell with pure methane. Rebalance the balanced detector output.
9. Install the sample gas cell into the setup as shown in Figure 1. Extract all residual gas concentration from the gas cell using a vacuum pump. Test the balanced detector output using various pressures of ambient air from full vacuum to atmospheric pressure, and note the balanced detector response.

10. Perform absorption analysis using varying concentrations of methane in the sample gas cell.
11. Fill the sample gas tube with ethane gas, and determine if there is any absorption seen at the balanced detector output (gas discrimination).
12. Repeat steps 9 and 10 and perform a new absorption analysis using ethane in both gas cells.

3. Results and Discussion

3.1. Verification of Methane and Ethane Absorption Spectra Within the 1600 – 1700 nm Wavelength Band

Using the setup described in section 2.1, with 100% methane introduced into the sample gas cell, the absorption spectra for the experiment for methane are shown in Figure 2. A similar test was performed using 100% ethane in the gas cell, and the results are shown in Figure 3 (the "flatter" line in both of the figures represents a reference transmission with only room air at ambient room pressure in the cell). As expected the methane showed definite absorption structure from 1620 – 1725 nm, thus confirming the other existing databases. More interestingly, the ethane showed substantial absorption structure between 1660 – 1720 nm. Some narrow band structure near 1685 nm was seen overlapping the fairly broadband component. This broadband looking signature of ethane might possibly fit very nicely with the Ophir proposed technique of using a single broadband light source. It is thought that the fine structure on top of the broadband feature will also aid in discrimination between methane and ethane.

While Ophir was excited about the presence of ethane absorption spectra, there was still a bit of apprehension about whether the broadband content was real. Some broadband content was apparent in even the fundamental absorption band, but it was not as evident as in the overtones. At this time, a second confirming set of absorption data was found to exist in the Pacific Northwest National Laboratory (PNNL) database. Available on a subscription basis and maintained by Steve Sharpe, PNNL has absorption data for several hundred compounds. The absorption spectra for methane and ethane are shown in Figure 4. The signatures of both of these compounds agree remarkably well with those produced by Ophir. It should be noted that there is some absorption overlap between the methane and ethane. This fact will require some forethought on how to discriminate ethane from methane, using a single broadband source. Gas correlation using distinct gas samples for comparison may allow for better discrimination. One very positive note is that the water vapor absorption lines shown in Figure 4 do not appear to overlap with the methane and ethane bands. This has traditionally been a significant problem to overcome when using gas spectroscopy.

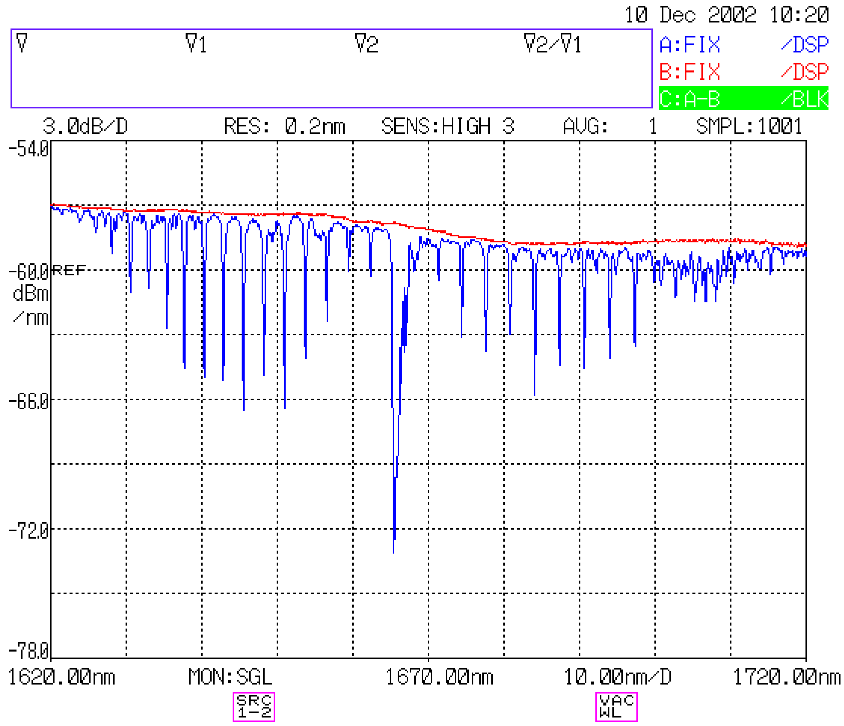

Figure 2. Ophir Experimental Observation of Methane Absorption Spectra Using 100% Methane

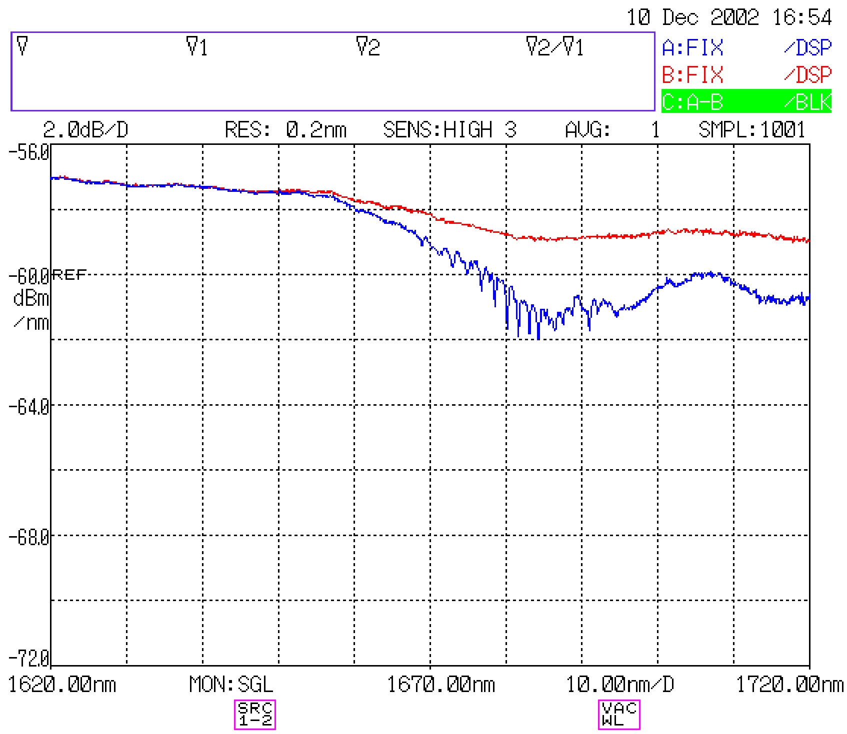

Figure 3. Ophir Experimental Observation of Ethane Absorption Spectra Using 100% Ethane

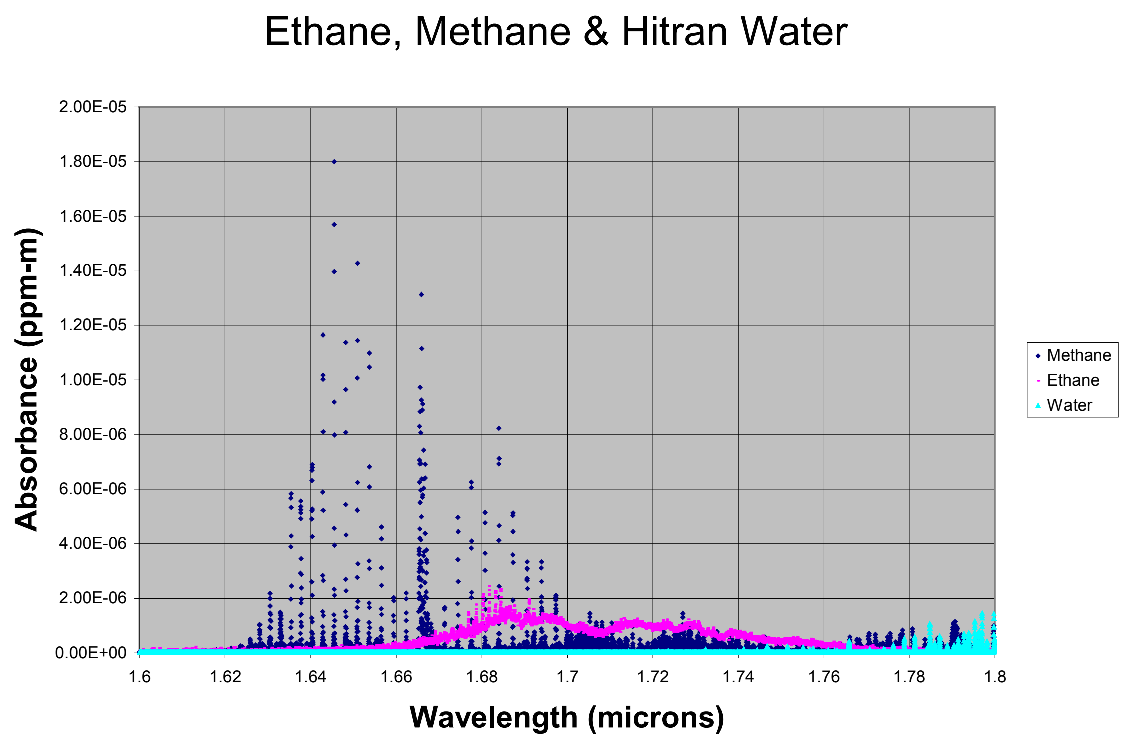

Figure 4. Ethane, Methane and Hitran Water Absorption Spectra From PNNL Database

3.2. Data Survey Results for Atmospheric Plume Dispersion of Natural Gas Pipeline Leaks

Concentration of natural gas within pipeline leaks is influenced by the size and location of the leak as well as by the environmental aspects surrounding the leak. An underground leak will dissipate the natural gas differently then an above ground leak. Types of soil will also impact the flow of natural gas to the surface. A more porous soil such as sand can be assumed to produce a more diffuse leak than would be produced by a more compact soil such as clay. Furthermore, the gas plume exiting the ground surface is greatly impacted by the atmospheric stability and local winds. Ophir conducted a literature search to better determine the natural gas plume dispersion and concentration and the impact on the pointing of the airborne optical, remote sensor.

When looking at three small hole diameters of 5.4 mm, 17 mm, and 54 mm in a pressurized pipeline of pressure 700 psi, Gopalsami [2002] determined experimentally that the plume size (diameter) with distance from the leak was not dependent upon the size of the leak hole. The plume diameter was determined to be 44 m (144 ft) at a leak distance of 100 m (328 ft) and the methane concentration was 100 ppm, for a 5.4 mm leak. The concentration of 100 ppm is well above the ambient methane levels of 1 – 2 ppm. More importantly the plume diameter was well defined even at 100 m distance from the pipeline. This fact is especially important when flying over the pipeline with the airborne sensor. Digitizing a section of pipeline with GPS coordinates, and preprogramming the flight path to these coordinates will allow the sensor to be pointed to within 20-30 m of the pipeline, well within the discernable methane concentration level.

In another study by Reichardt [2002], a preliminary modeling effort was performed looking at an axisymmetric plume derived from an exposed jet (no soil overburden) under quiescent conditions. More extensive modeling was then performed that took into account both soil effects and meteorology. Soil effects were taken across the extreme range of tightly compacted soil such as clay to non-compacted soil such as sand. In either case, a single leak path to the surface was considered unlikely. Instead, multiple leak paths would develop and the degree of compaction was assumed to be inversely proportional to the number of leak paths to the surface. For the compact soil a source leak area of 1 m^2 was assumed and at the other extreme, for a non-compact soil type an area of 100 m^2 was assumed. Two methane leak rates, shown in Table 1, were taken from calculations involving realistic hole sizes and internal pipe pressures such as might be encountered in a transmission pipeline.

Leak Scenario	**Leak Rate (scf/hr)**
.0625 inch hole with 400 psi internal pressure	324
.125 inch hole with 1000 psi internal pressure	2088

Table 1. Leak Rates Considered for Calculations Reichardt [2002]

For estimation of the atmospheric dispersion of the plume, a simple Gaussian dispersion model was used. The degrees of atmospheric stability were categorized into stability classes A through F, where class A is highly unstable and class F is highly stable. Three plume sight paths were used in the modeling of the plume dispersion but only two of these sight paths were relevant to the airborne sensor. Path 1 was looking down through the plume 5 m (16 ft) downwind at plume centerline, and path 2 was looking down through the plume 20 m (65 ft) downwind and 20 m off plume axis. The modeling results, for different atmospheric stabilities, are shown in Table 2, Table 3, and Table 4. Several of the following observations can be made that will impact the sensor pointing and subsequent detection capabilities:

- There is a huge difference in concentration between the center and the edge of the plume for all atmospheric stabilities and leak rates.
- For neutral and very stable environments, the edge of the plume at a distance of 20 m from the center shows negligible amounts of methane.
- The wind speed has a major impact on plume concentration. A wind speed of 10 m/s (22 mph) decreases the plume concentration by a factor of ten.
- While the leak area (related to soil type) impacts the concentration, it has much less impact then wind speed changes.
- A stable atmosphere leads to less dispersion downwind from the leak, resulting in a higher concentration. This is due to the decrease in atmospheric mixing in the vertical direction around the leak. Actually an airborne remote optical sensor

measures total concentration along the optical path length between the air vehicle and the ground, and the vertical dispersion of the gas may not be as detrimental as with a horizontal looking sensor.

It is very important that the airborne sensor be pointed downwind from the pipeline leak and that the flight path be over the center of the plume (higher concentration seen for Path 1 scenario). A goal of flying within 20 m downwind of the pipeline can be met when using Global Positiong System (GPS) coordinated pipeline data.

Leak Rate scf/hr	**Leak Area m^2**	**Wind Speed m/s**	**Path 1 ppm*m**	**Path 2 ppm*m**
324	1	1	845	1.17
324	1	10	84.5	0.12
324	100	1	312	7.20
324	100	10	31.2	0.72
2088	1	1	5410	7.51
2088	1	10	541	0.75
2088	100	1	2000	46.1
2088	100	10	200	4.61

Table 2. Path-Integrated Methane Concentrations – Stability Class A (Very Unstable) Reichardt [2002]

Leak Rate scf/hr	**Leak Area m^2**	**Wind Speed m/s**	**Path 1 ppm*m**	**Path 2 ppm*m**
324	1	1	2810	<0.001
324	1	10	281	<0.001
324	100	1	473	<0.001
324	100	10	47.3	<0.001
2088	1	1	18000	<0.001
2088	1	10	1800	<0.001
2088	100	1	3030	<0.001
2088	100	10	303	<0.001

Table 3. Path-Integrated Methane Concentrations – Stability Class D (Neutral) Reichardt [2002]

Leak Rate scf/hr	**Leak Area m^2**	**Wind Speed m/s**	**Path 1 ppm*m**	**Path 2 ppm*m**
324	1	1	5840	<0.001
324	1	10	584	<0.001
324	100	1	507	<0.001
324	100	10	50.7	<0.001
2088	1	1	37400	<0.001
2088	1	10	3740	<0.001
2088	100	1	3250	<0.001
2088	100	10	325	<0.001

Table 4. Path-Integrated Methane Concentrations – Stability Class F (Very Stable) Reichardt [2002]

Several other plume dispersion studies were discovered in the data search but most were related to power plant plumes, and were not relevant to natural gas pipeline leaks.

3.3. Selected Airborne, Optical Sensor Hardware Design Requirements

Based upon the natural gas company data survey and other research, Ophir has selected the following design criteria for the airborne, optical remote sensor system:

- Light source centered on the overtone absorption band near 1650 - 1700 nm.
- A single light source shall be used to sense both methane and ethane.
- The light sensitive photo detectors shall be large - area extended range InGaAs PIN photodiodes, with nearly uniform responsivity from 1400 – 1900 nm.
- Aircraft Airspeed ⇒ 161 km/hr (100 mph)
- Aircraft Altitude ⇒ 152.4 m (500 ft)
- Terrain reflectivity @1650 nm ⇒ 20 % - 50%, Source: Wolfe [1985]
- Sensor Ground Spatial Resolution ⇒ 0.5 m (1.5 ft)@100 Hz Update Rate [1]
- Weight ⇒ <200 lbs
- Size ⇒ 3 ft x 3 ft x 3 ft
- Minimal Detectable Concentration ⇒ 500 ppm * m
- Input Power Requirements ⇒ 500 W

Justification and rationale for the specification of some of these design parameters will be discussed more thoroughly later in this report. The minimal detectable concentration of the sensor may change depending upon the noise floor of the system. When comparing the modeling of plume concentration from Reichardt [2002] to the minimal detectable concentration of the Ophir sensor, one would expect to detect nearly all of the larger rate

[1] Although the airborne acquisition system will be capable of this resolution, the standard GPS locator resolution is limited to 10 – 15 m resolution.

plumes but only some of the smaller rate plumes. Controlled gas cell laboratory testing will be done at Ophir later this year to verify the sensitivity of the airborne system.

3.4. Results of Sensor Performance Modeling Under Operational Conditions

The airborne optical system SNR determines the minimum detectable change in reflected signal due to absorption by gas species of interest, therefore the minimum absorbance (ppm*m) of detectable trace gases. The detection scheme is designed to maximize signal to noise by reducing noise fluctuations inherent to optical remote gas sensing techniques.

There are five major sources of noise. The first and most significant is extraneous light collected from the sun in the wavelength band of interest. Solar flux adds to the overall system shot noise by adding shot noise to the shot noise level from the probe light source. This situation is not fatal, however. Solar noise contribution is mitigated by modulating the probe light source and using phase-sensitive detection to detect the subtle changes in the probe intensity with trace gas concentration. The modulation separates signal photocurrent from the solar photocurrent and reduces the solar shot noise to an acceptable level. Alternately, instead of modulating the probe light source intensity, the trace gas source can be effectively modulated by holding the probe intensity a constant and spatially scanning the optical beam over the potential gas source. A trace gas absorption signal is obtained using phase-sensitive detection at the spatial scanning frequency as in the previous example. Spatially scanning the probe beam has the advantage that no light is lost due to intensity modulation, consequently there is no power penalty to the resulting signal to noise ratio.

The next three identified major noise sources are addressed by the balanced detection scheme. They are probe light source intensity fluctuations, variations in the reflectivity of the earth's surface at the probe position and fluctuations due to air turbulence.

Probe light source fluctuations are due to the light generation process in the SLED. As observed by Fast Fourier Transform (FFT), the spectral density of these fluctuations can be 15 dB above the balanced detection minimum noise level. Additional noise is introduced as the probe beam moves across the earth's surface. The probe light reflectivity off of the earth's surface varies as much as 50%, due to variations in vegetation, earth, and rock types. Finally, air turbulence creates additional noise by randomly modulating the optical path between the transmitter, earth's surface, and the receiver.

Fluctuations due to surface reflectivity and air turbulence require additional noise mitigation. Since the balanced detectors photodiodes quantum efficiency has a spatial dependence, any physical mechanism that moves the focused beam on the photodiodes will contribute to extraneous system noise. A solution to mitigate this problem is to include elements in the airborne optical system that will integrate the scene profile and remove high spatial frequency components.

As part of Ophir's research effort, an estimate was made of the best possible optical signal to noise achievable with an airborne Light Detection and Ranging (LIDAR) system. Included in this calculation was the shot noise from collected light, photodetector dark current shot noise, and estimated shot noise from solar flux assuming a worse case illumination scenario (sun at zenith). This calculation also includes the radiometric aspects using an airborne system to transmit and collect light using a telescope with the largest practical aperture size (18" diameter). We assumed that the aircraft will fly at 165 meters (500 ft) Above Ground Level (AGL) at a velocity v = 100 mph and will project a diffraction-limited probe beam on the earths surface. We also assumed that the detector footprint on the earth's surface exactly matches the probe beam spot size. This requirement eliminates excessive solar noise from the desired signal.

The characteristic time τ_c associated with trace gas detection is determined from the time required for the diffraction limited beam spot at the earth's surface to move over a point source of natural gas. At 100 mph this time is approximately 10 msec. The sensor signal integration time τ should be longer than this characteristic time. The expected sensor spatial resolution will be $v\tau_c \sim 0.5$ meter.

In Figure 5 below Ophir shows the expected photocurrent i_s resulting collecting the probe beam light scattered from the earth's surface as a function of source power Probe Power (PPP). Also shown in the graph are two constant currents: the dark current from a photodiode i_D, and the expected photocurrent from the sun at zenith i_{sun}.

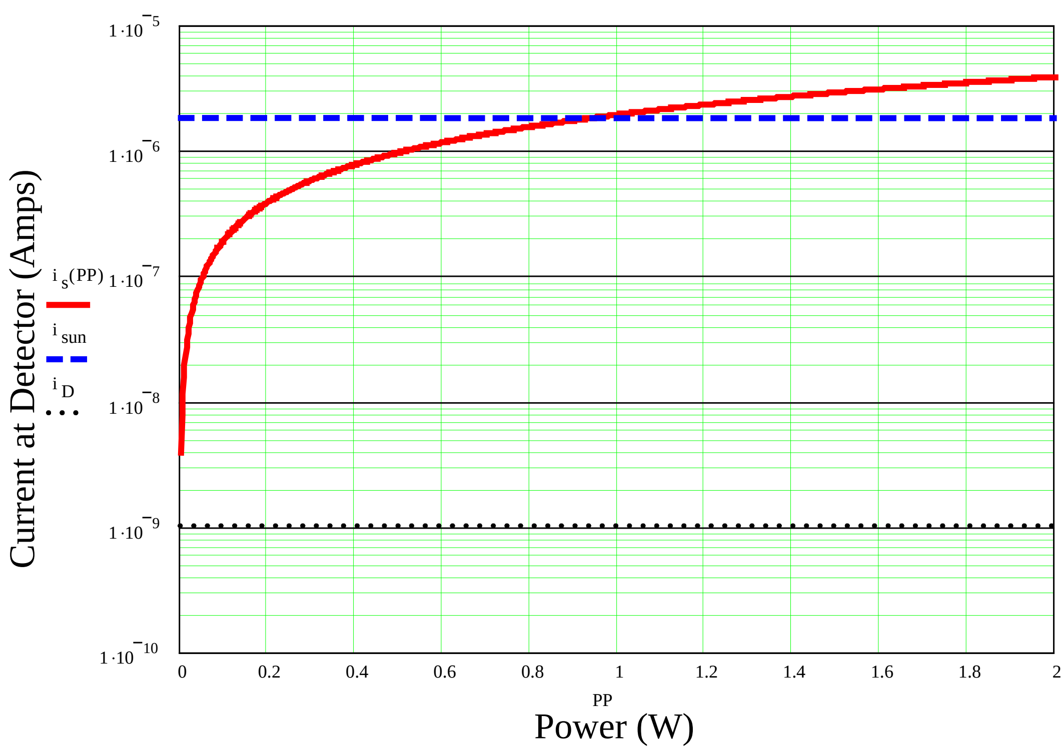

Figure 5. Expected Airborne Detector Photocurrent From Received Optical Beam Reflection per Light Source Output Power

As shown above, if no additional signal processing measures are taken, the solar photocurrent at D.C. could swamp any expected signal. However, if one modulates the transmitted beam temporarily or spatially and uses phase sensitive detection of the collected light at the modulation frequency, one can parse out the solar and signal contributions to the measured photocurrent and simultaneously reduce the shot noise contributions from the sun and photodetector dark current.

In Figure 6 the best possible signal to noise is shown as a function of transmitted probe power, assuming the probe beam is modulated and the resulting collected light is phase sensitive detected with a 20 msec integration time. The expected signal to noise from a realized traced gas optical system can be estimated from this curve by determining the reduction of collected optical power from a series of penalties associated with optical losses in the optical system.

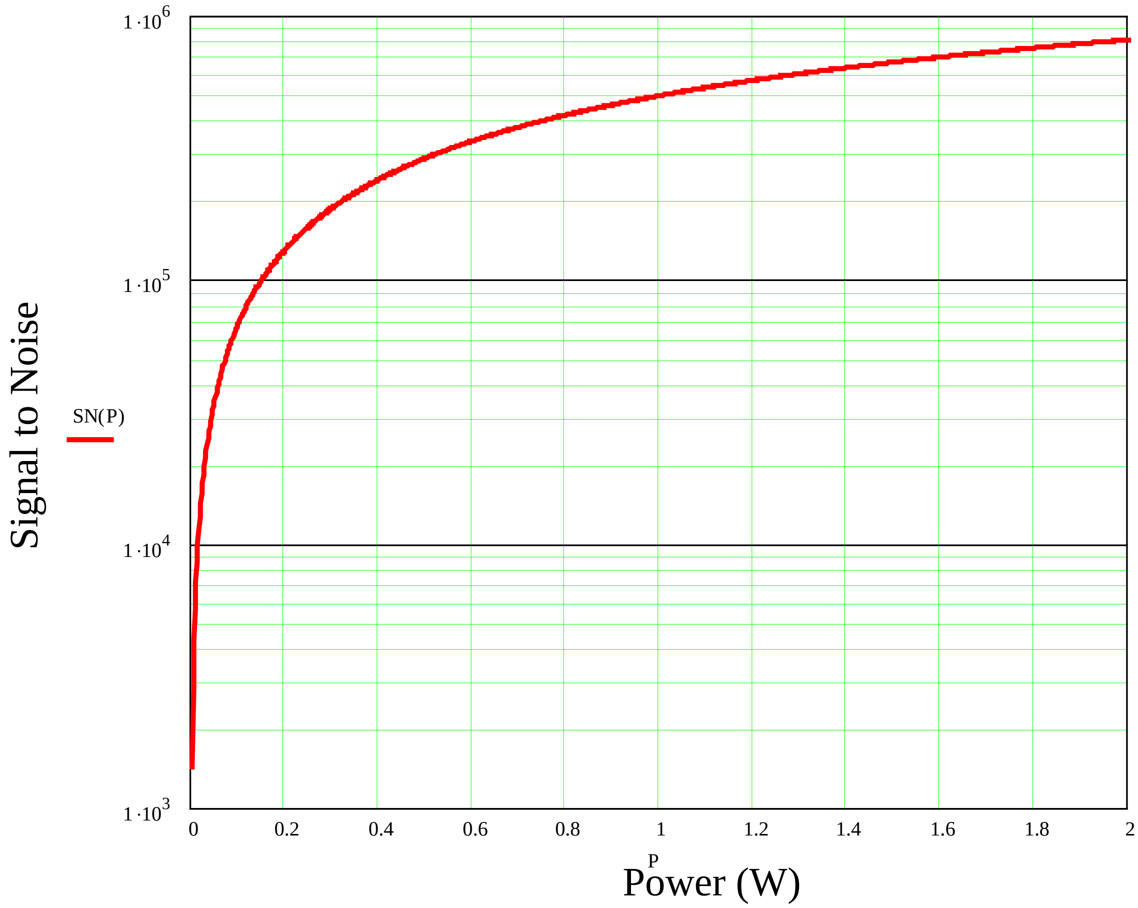

Figure 6. Maximum Possible Signal to Noise Ratio As a Function of Transmitted Source Power (Ignoring Optical Losses)

The first optical loss would be a factor of two associated with intensity modulating the transmitted probe beam. This loss would be eliminated if the probe beam intensity was held constant and its position was scanned over the earth's surface. The second loss is due to the earth's reflectivity. Surfaces such as silica sand have excellent reflectivity near

1.6 μm (ρ~0.6). Dry vegetation has a reasonable reflectivity (ρ~0.35) while in green vegetation the reflectivity is significantly reduced (ρ~0.2). The third loss is due to the optical components in the optical system, such as beam splitters and optical surfaces. These losses can be minimized by proper optical engineering design, such as using anti-reflection coated surfaces where appropriate. For purposes of this first model we are not considering losses due to atmospheric transmission. Finally, there is an additional factor of 2 loss due to the balanced detection scheme. This factor is derived from the fact that random, non-common mode noise from each photodiode in the balanced detection scheme adds at the differencing point. In the table below we list all the loss factors associated with the optical system and their origin.

Loss Mechanism	**Transmission Factor**
Temporal Probe Modulation	0.5
Earth Reflectivity	0.2-0.6
Optical System Light Loss	0.1
Atmospheric Transmission	1.0
Additional 3 db from Balanced Detection	0.5
Resulting Light Transmission	0.01 (estimated)

Table 5. Loss Factors and Their Origin Associated With the Airborne Optical System

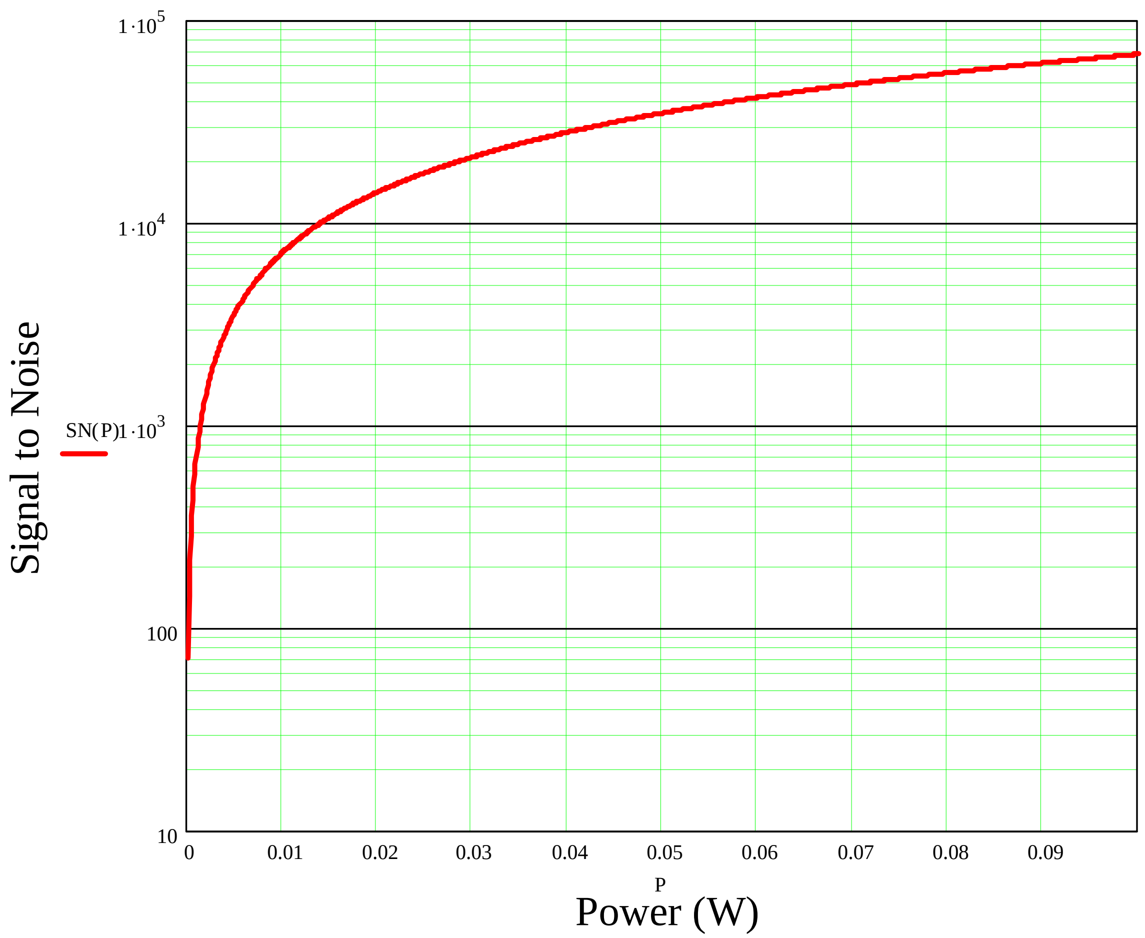

Figure 7. Maximum Achievable System Signal to Noise Ratio per Probe Power Intensity on the Earth's Surface

An estimate of the final optical signal to noise is determined by multiplying the light transmission factor times the probe beam intensity on the earth's surface, then referring to the signal to noise curve above. For a 1 Watt CW transmitter with an overall transmission of 0.01, the maximum expected signal to noise achievable is ~ 6×10^3 as shown in Figure 7 above.

The signal to noise ratio determines the minimum intensity change that can be measured in the probe beam intensity, which is approximately the inverse of the signal to noise ratio. Thus, the signal to noise ultimately determines the minimal detectable gas absorbance in ppm*m.

Theoretically, the minimal detectable absorbance is determined from the overlap integral between the probe light source spectral density and the absorbance spectra of the trace gas species. The current choice for a light source is to use a single light source for both ethane and methane and choose a center wavelength and spectral width to maximize absorption in both species. In addition to detectivity, with a single light source in a dual optical gas correlation configuration such as the airborne optical system, trace gas species detection selectivity is also a major concern. Ophir has not made any calculations regarding the detection selectivity.

For the proprietary light source, we calculate that assuming a shot noise plus 3 db noise level we will be able to see down to 300 ppm*m ethane or methane. This is more sensitivity than is required for the application. The total optical path between the transmitter, the earths surface, and back to the telescope receiver is approximately 330 meters. Assuming a 1.5 ppm natural methane background concentration, the absorbance detection for the detection scheme need not be more sensitive than approximately 1.5 x 300 or 500 ppm*m.

3.5. Transceiver Design Results

3.5.1. Selection of Transceiver Light Source

A major component of the airborne, optical remote gas sensor is the transceiver light source. As stated previously, the modeling of the gas absorption versus wavelength for methane and ethane showed the optimal wavelength for the light source to be between 1600 – 1700 nm. Gas spectroscopy traditionally uses a very narrowband light source that is tuned across a relatively narrow single absorption line. This can also be accomplished by using dual differential laser sources, where one laser is tuned across the absorption peak and the other laser is tuned across the wings of the absorption peak, and detecting the difference. These laser-based systems are generally driven at short pulse durations due to laser heating problems, and require very accurate tuning of the laser source cavity in order to achieve the necessary tuning step resolution. Subjecting the system to a high vibration airborne environment can create significant problems for such a system.

Ophir has instead chosen an easily controllable broadband light source that is not subject to the stabilizing and tuning problems associated with narrowband cavity lasers. The modulation frequency of the broadband light source can be quite high and is only limited by the integration time required by the photodetector. Ophir has extensive experience with using broadband light sources for gas absorption near the fundamental absorption lines of methane and ethane at 3.3 µm. The broadband nature of the light source allows Ophir to sense many of the absorption lines at one time thus capturing a greater percentage of possible absorption. Ophir used a black body emitter as the broadband Infra-red (IR) light source in an earlier designed fence-line gas monitoring device. Narrowband filters with a Full Width Half Maximum (FWHM) spectral range of 30 – 40 nm were used to limit the very broadband input into the photo detectors, thus reducing the overall signal noise level. Unfortunately, using these narrowband filters results in a great deal of lost light energy at the detector, since the black body emits energy all the way from visible into IR wavelengths. It became obvious from the models generated by Ophir and from the experimental co-located transceiver test at Ophir, that the 3.3 µm black body source would be insufficient for the airborne sensor. Ophir decided to design the system around overtone absorption in the 1600 - 1700 nm range. In this wavelength range, light sources such as fiber amplifiers, super luminescent light emitting diodes, and parametric fiber coupled amplifiers output light in a much narrower, more confined wavelength band. The energy density per unit wavelength is much higher than with the black body IR sources. Detectors optimized to sense light near this wavelength also have a much greater D* value, which guarantees a lower noise floor and higher SNR.

From the absorption models performed by Ophir, the amount of power to achieve the necessary SNR would need to be 1 – 2 Watts over the appropriate bandwidth. Ophir spent a good deal of time contacting vendors, who could develop high output sources in the mid-IR wavelength near 1600 – 1700 nm. Many of these companies were non-responsive, no longer in business, or not able to build to Ophir's light source specifications. Ophir was able to isolate four potential vendors and of these four vendors, three continue to remain as potential light source vendors. Ophir is currently working with these vendors to better understand the proposed design techniques, design advantages or disadvantages, and the associated cost. While there appears to be several potential design solutions for the broadband light source, the availability and associated engineering cost seems to be the driving issues.

High output fiber amplifiers are commercially available within the normal telecommunications S, C and L Bands between 1450 nm and 1610 nm, but are unavailable within the methane and ethane absorption bands and will require a custom build. Fiber amplifiers require an optical seed source centered near the desired output wavelength, an optical pump source, and the fiber amplification medium. Unfortunately, there are no commercially available seed sources above 1610 nm, and a substantial amount of non-recurring engineering (NRE) cost will be required to develop these sources. One vendor has stated that the development of the seed source is certainly possible, and has submitted a quote to Ophir of $117,000 to help cover the NRE (estimated to be near $40,000) plus acquire a minimum quantity of 30 pieces. When amortizing the cost over a production quantity of 30 systems, the per unit cost certainly looks more attractive. The development of the rest of the amplifier including the pump source and the fiber medium has been roughly quoted at $50,000, for a total cost of $167,000. Clearly, this amount of money falls outside the normal scope of the contract hardware costs. More discussion will be forthcoming on this concern in later sections of the report.

Another proposed technology for the broadband light source is that of a parametric fiber coupled amplifier. Preliminary modeling performed by a second vendor has shown that a parametric amplifier when coupled with a fiber output can output a tunable and broadband light source in the absorption region of interest. One advantage for using a parametric amplifier is that the seed source used within the amplifier mixer does not need to be of the same wavelength as the output. In fact, the seed source may quite likely fall into the telecommunication S-Band, where there will be a choice of commercial sources. The vendor would like to perform more simulations to verify the potential of this type of source. No cost data is available yet, on the development of the broadband output parametric amplifier.

According to another vendor, the best solution to meet the requirements is to develop a spectrally beam combined laser diode array tuned within a single cavity. This approach would probably use a diode bar of emitters. The output would be made up of the sum of different narrowband wavelengths. Here, the problem is once again obtaining laser diodes in the 1600 – 1700 nm range. This vendor has given Ophir a preliminary quote to develop a light source of $120,000.

3.5.2. Transceiver Balanced Detector

To achieve the required SNR for the system, Ophir has chosen very low noise, Thermal Electric Cooler (TEC) cooled photo detectors to limit the amount of dark noise, thermal noise, and 1/f noise. The extended range InGaAs detectors are commercially available with four stage TEC coolers, capable of being tuned to T = -85°C and providing an impressive normalized detectivity D* = 9.5E13 Jones. Theoretically, the system noise is limited to the shot noise level of the signal, which is proportional to the square root of the average DC current flow through the photo detector. By eliminating all common mode noise sources and unwanted background illumination sources, the system noise can be reduced dramatically. One method of reducing the common mode noise and unwanted signals is to use a balanced detector circuit (developed by Phillip C. D. Hobbs [1991]) to subtract out all common mode signals, such as background solar flux and laser/light source noise. While the shot noise remains unaffected, the overall SNR increases due to the absence of undesirable common mode signals. According to literature in New Focus Application Note 14, the Nirvana family of auto-balanced photo detectors can reduce common-mode laser noise by more than 50 dB. The balanced detector as a result, has the ability to detect very small signal fluctuations on a large background DC signal

Typical uses of the balanced detector are in the area of absorption spectroscopy, where lasers are tuned across certain well-defined absorption spectra lines. The laser sources usually have quite narrow line widths, on the order of several MHz. These balanced detector circuits work well with these laser sources since the amplitude noise of the sample beam is coherent with that of the detected main signal beam, and subtraction of the two photocurrents cancels the common mode noise components. Ophir proposes the use of a balanced detector in a more non-traditional application using a broadband non-laser light source. There is not a great deal of literature concerning the use of balanced detector circuits in the cancellation of common mode noise within a broadband light source, but theory indicates that this method should work well. One of the main problems with using a dual beam balanced detector is that small changes in polarization between the two signals can adversely impact noise cancellation. Broadband light sources are more immune to these polarization changes, since there is not a strong polarization component to the light source.

Ophir has been actively testing a balanced detector system with a broadband source in the laboratory over the past two months. Details from these tests will be presented in the next section of this report.

3.5.3. Software Integration and User Interface

National Instruments (NI) LabView software was chosen as the software platform for the airborne sensor. A copy of LabView Full Development System for Windows was ordered and received. Ophir has extensive experience working with LabView from the previous gas absorption work with the fence-line monitoring system. Ophir also plans on using a suite of digital signal processing software available from NI to add quick, powerful signal processing algorithms to increase the system signal detection capabilities.

Work has been started on developing the look and feel of the system computer user interface. The display will likely include the following components:

- Display the methane and ethane levels in ppm∗m. This display will probably be in the form of dynamically changing horizontal graphs, with concentration in the vertical axis and time in the horizontal axis. In the fence-line monitoring system, Ophir used an alternative display for concentration by using a dynamic vertical bar graph showing real time (averaged) concentration in ppm*m for both methane and ethane. Both of these types of displays are easily implemented with LabView.
- A selectable option for a FFT may be incorporated into the display. By looking at this display, one could discern noise levels of the signal through the frequency spectrum.
- A menu listing multiple digital processing options will likely be incorporated into the user display. The options chosen here will depend upon the dynamics of the terrain ground cover and the strength of the absorption signal.
- Estimated wind speed and wind direction.
- GPS route and real time aircraft position tracking display. Ophir will use a company owned hand-held GPS device that incorporates manufacturer software designed to display real time routing and tracking data on a Personal Computer (PC). The display software has been verified by Ophir to work with a standard PC.
- Zoomed video display of the ground from an onboard camera that has been aligned to the transceiver. Video images will be recorded and time stamped.

3.5.4. Airborne System Computer

A literature survey was completed identifying commercially available ruggedized PCs and laptop computers. After conversations with several computer vendors, Ophir has concluded that a semi-ruggedized computer is the best choice for the application. The greatest problem with portable computers is the fragility of the hard disc drives (HDDs). Ophir has experienced on several occasions the unpleasantness of failed HDDs, while working in the field. A second issue is the display readability in a daylight or sunlight environment. The semi-ruggedized family of Toughbook® laptop computers from Panasonic Corporation, advertise that they have a fully potted HDD, a daylight readable display, and a magnesium alloy case. The temperature operating range for the airborne system is probably not extreme, since the air compartment where the system will be operating in is environmentally controlled. The price of the Panasonic laptops is less than half of the fully ruggedized model, and they operate with a much newer, faster Pentium® 4 Processor.

3.6. Procurement and Assembly of Airborne Prototype

The design of the transceiver has been delayed from the original schedule in lieu of some unscheduled concept laboratory testing. There has been some hardware purchases made primarily for the laboratory test setup. While most of the equipment is to be used in the laboratory, there may be some equipment or accessories that may be utilized in the final airborne sensor design especially specialized optics. Total expenditures for hardware have amounted to $11,000 or just over 20% of the proposed Supplies/Materials budget.

3.7. Laboratory Testing Results

3.7.1. Characterization of the SLED Light Source

The DC biased fiber coupled SLED light source was directly coupled into the optical spectrum analyzer and the power density over wavelength was displayed. Ophir noted a very close agreement between the analyzer data output and the vendor supplied output curves. Temperature tuning of the diode also showed similar close agreement. No unusual wavelength specific perturbations were seen in the analyzer display, which meant that the optics within the package was producing no non-linear artifacts. Initially, the SLED current was driven only with a DC bias. Modulating the source has the potential to yield better noise characteristics especially when using a lock-in amplifier to lock in to the modulating frequency. By reducing the sampling bandwidth of the system, the overall rms noises can be reduced. Modulating the source in the linear region by applying an AC wave modulation on top of the DC bias yielded a linear output waveform. Any attempt to modulate with just an AC waveform showed an output non-linear response when crossing through the turn-off point of the SLED. A FFT analysis of the waveform showed better noise characteristics associated with sine wave modulation than with either square or triangular wave modulation. Throughout the remainder of the laboratory testing, all modulation of the source was done using an applied sine wave.

Without any optical surfaces in the optical path and driving the diode current with a modulating waveform, the spectral waveform continued to resemble a well behaved Gaussian source. The next step was to determine the impact of adding the necessary optics in the beam path to allow for the diverging fiber coupled output to be focused and guided onto the active areas of the two detectors. The immediate impacts on the beam output power, shape and spectral content can be summarized as follows:

- The spectral qualities of the beam were degraded from the Gaussian looking waveform due to the presence of unwanted back reflections. This departure from the ideal waveform introduces potential degradation of available energy at the detector, which will negatively impact the system SNR.

- The addition of gas cells into the system produced a 70 % loss in the overall energy at the detectors due to the normal transmission losses through glass surfaces. The gas cells were originally built with AR coated windows, which were optimized for wavelengths near 3.3 µm. These windows worked poorly when transmitting light near 1.63 µm. The gas cells were disassembled and higher transmissive sapphire windows were installed. The transmission losses through all the window surfaces were reduced to 25%.
- Beam positioning was highly dependent on the pressure within the gas cells. For the balanced detector system to work properly over different gas concentrations, the beam spot could not wander across the detectors. Changing the pressure within the sample gas cell produced a slight movement in the beam, which changed the location of the beam spot on both of the detectors. This may have been caused from slight refractive index changes within the gas medium, or may have been due to slight bulging of the windows due to the pressure changes.

In addition to a change in the absorbance of the gas cell, the balanced detector differencing technique also had spatial sensitivity and was sensitive to optical alignment changes between the signal and reference arms. Consequently an optical design requirement for the breadboard optical system was to make sure the observed change in signal was due to changes in sample cell optical depth, and not due to variations in optical alignment with sample gas pressure. This design requirement was achieved by integrating the light spatial profile after the gas sample cell to eliminate possible extraneous signal variations with pressure.

Light entering and exiting the gas sample cell is collimated. A degree of spatial integration at the expense of system light loss was accomplished by adding a scotch-tape diffuser at the gas sample cell exit. An additional short focal length lens was added after the diffuser to collect and re-collimate light from the diffusing screen.

After incorporating the scotch tape diffuser into the breadboard optical system Ophir tested this beam integration concept by observing the balanced signal as a function of pressure using dry nitrogen gas in the sample cell. After a sudden change in nitrogen gas pressure, a transient was observed that represented a small percentage change in steady state signal voltage. The steady state voltage from the balanced detector was independent of the nitrogen gas pressure. From these results, Ophir inferred that the steady state signals observed from the methane absorption experiments are due to light absorption only. A scotch tape diffuser introduces an unacceptable light loss into a practical optical system. During upcoming work, Ophir will investigate other spatial integrating optical elements with a light loss more suitable for the airborne optical system, such as a spatial integrator consisting of two lenslet arrays separated by a single-element focusing lens.

3.7.1.1. Evaluation of Balanced Detector and System Noise Reduction

The balanced detector circuit theoretically is capable of eliminating nearly all sources of common mode noise. Of course, the results that are achieved will depend upon the type of light source used and the background noise present on the source output. The noise reduction seen by Ophir for the balanced detector and the SLED source was somewhat less at about 20 dB. Ophir performed the noise reduction experiments by looking at the "Balanced Output" of the Nirvana into an FFT plot displayed upon the digital oscilloscope. The noise floor of the FFT plot indicated a 20 dBV decrease in noise, when the detector was placed into the balanced mode. The laboratory experiment was tightly controlled and other sources of common mode broadband noise such as background sunlight noise and atmospheric perturbations were absent from the setup. It is likely that with the addition of these and other "real world" noise sources, that the noise cancellation would be greater. Ophir also believes that the SLED light source may contain less noise sources than comparable laser diodes, where the vendor noise data was measured.

Vibration within the setup in Figure 1 was definitely a problem. Tapping the table, walking around the table, and even a pump motor in the next room caused transients within the balanced detector output. This is a major concern when operating in a high vibration environment such as an airborne platform. Ophir was able to remove some of these troublesome vibrations by better securing the cables to the balanced detector and by removing all the test measurement equipment from the optical table. In the future airborne sensor, Ophir will implement some of the following measures to minimize vibration-induced transients:

- Experiment with methods of reducing signal output changes due to optical beam wander. One source of error seen with photodiodes is that photodiodes have varying sensitivity across their active area. Interestingly enough photodiodes typically have less sensitivity in the middle and greater sensitivity towards the edges. If the optical beam hitting the detector is similar in size to the detector active area, any small movement of the beam will be seen as a change in the output. This is undesirable, since the only change in output one wants to see is that associated with the changing absorption through the sample gas cell. Besides totally eliminating optical beam movement, one solution may be to flood the photodiode with an optical beam that is larger than the active area. Any small beam movement will not likely be seen by the photodiode. Of course, the immediate drawback to this solution is the hit taken in the total optical return. The modeled results shown earlier in the report do not account for these less than ideal losses. Perhaps a better solution is to look at using larger active area photodiodes. Small movements of the optical beam would be limited to the relatively larger center of the diode thus limiting the area sensitivity fluctuations.
- Use vibration sensitive fiber optical connections. Index matching gel will be used to help minimize fiber-to-fiber connections.
- The receiver optical path will be tightly controlled to the balanced detector. Each of the optical components will need to be rigidly mounted and not subject to independent movements. Perhaps a single receiver stack is required, where all the optics and the balanced detector move equally together.

The lock in amplifier measured noise floor for the laboratory setup, when the balanced detector was placed in "Balanced" mode, was higher than expected at 1 – 2 mV. The anticipated noise floor was expected to be significantly less than 1 mV. The unexpected higher noise level created an SNR that was lower than expected. The primary reason for the increased system noise was due to the inability of the balanced detector to completely balance out the two optical inputs. Theoretically, the balanced output should be zeroed completely out and contain only the balanced detector circuit electrical and optical shot noise. When adjusting the variable attenuator, the balanced output should be capable of being tuned to the circuit noise floor. Figures 8 and 9 illustrate what in reality was seen at the balanced detector output for two different SLED tuning temperatures. The SLED was current modulated with a 500 Hz sine wave.

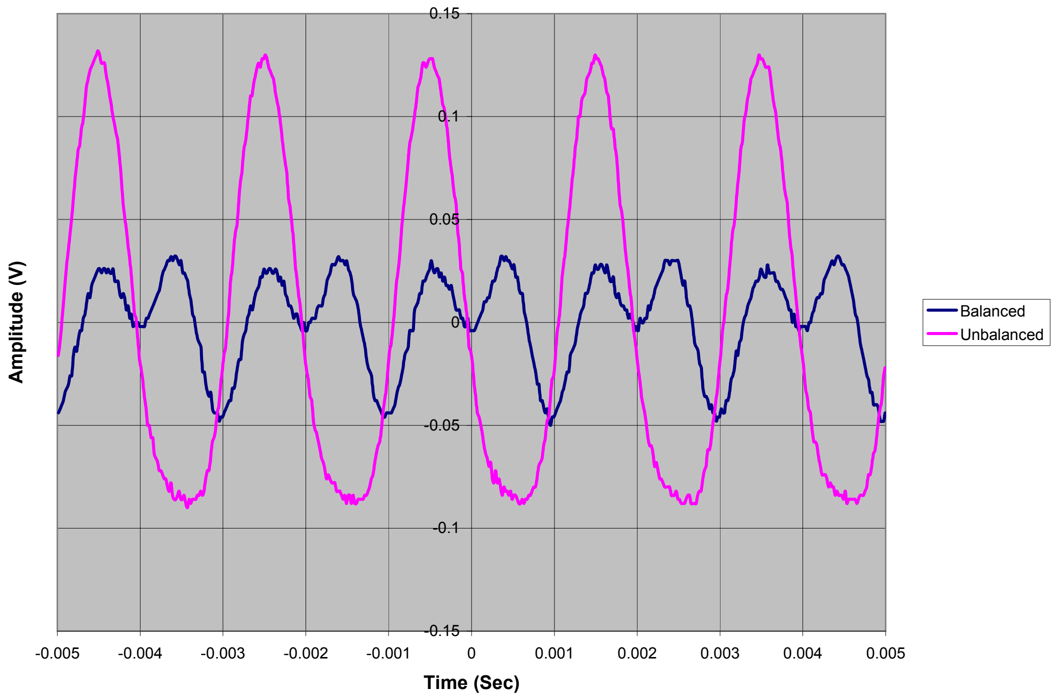

Figure 8. Balanced Detector Output For Balanced and Unbalanced Conditions at SLED Tuned Temperature of 20°C

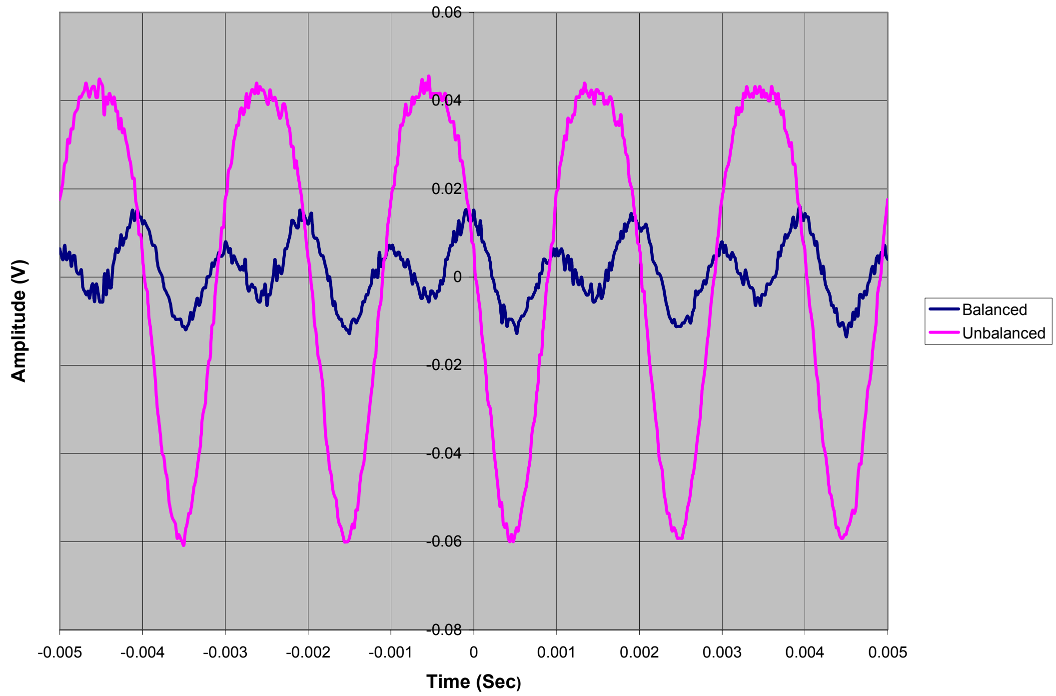

Figure 9. Balanced Detector Output For Balanced and Unbalanced Conditions at SLED Tuned Temperature of 35°C

The reference gas cell contained 99.9% methane and the sample gas cell contained 9.9% methane and they were both at atmospheric pressure. The dark trace (blue) shown in the Figures was the optimally adjusted balanced output. The lighter trace (magenta) shown in the Figures was the slightly unbalanced output. The optical balancing of the circuit was performed by manually adjusting the variable attenuator. Remembering that the theoretical balanced output should be limited to the background shot and circuit noise, one would expect to see a much smaller zeroed out signal. Figures 8 and 9 are shown for display purposes only, and during the experiments Ophir was able to reduce the actual rms voltage amplitude at times below what is shown. At no time though was Ophir able to eliminate the peak-to-peak excursions. Second order harmonics were also evident in the balanced detector output but absent in the unbalanced mode. These harmonics only appeared near where the optimal balanced output occurred. When the optical attenuator was adjusted further to attempt to zero the output, the signal would change to a similar signal containing second order harmonics only at a different balanced polarity.

The second order harmonics were not expected and Ophir is trying to better understand their presence in the balanced output. The first assumption is that this problem may be exaggerated by the broadband nature of the light source. Secondly, the hypothesis was given that a slight phase shift was occurring between the two optical path signals, and that this phase shift was showing up in the output. A model was created to simulate the balanced output harmonic content. Interestingly, the results for this model matched nearly exactly what was seen at the balanced output. Very small phase shifts of 1° between the two input signals into the model were able to replicate the system balanced detector output harmonics. It is obvious that from these results the two optical inputs need to be optically nearly identical, absent of differential phase shifts and polarization shifts. Practically speaking this is probably not possible in the real world, so some method should exist at the balanced detector to electrically balance out the two optical inputs. Different techniques for summing the inputs within the detector may yield better canceling of the optical inputs. This will require some electrical simulation at Ophir and may ultimately lead Ophir to redesign the balanced detector circuit.

It must be noted that the present Nirvana Balanced Detector was not optimized with extended range photodetectors. The detectors rolled off in sensitivity rapidly above wavelengths of 1620 nm. It is anticipated that a new design using the balanced detector method would include the implementation of well-controlled TECC cooled extended range photodetectors. This would result in better system SNR due to better responsivity and lowered noise.

3.7.2. Methane Gas Absorption Results

One major goal of the laboratory experiment was to provide quantitative data showing signal absorption for different methane and ethane gas concentrations using a broadband light source. Unfortunately, the SLED wavelength was less than optimal for both methane and especially ethane absorption. While methane showed measurable signal absorption, the absorption signal for ethane was very near the noise level of the system. A very small signal deflection was measured at the balanced detector, when a high concentration of ethane gas was introduced into the sample gas cell but varying the concentration produced no further changes in the signal (an indication that the signal was buried in the noise). These results compare favorably with the absorption model, which indicate little absorption at this wavelength.

Figure 10 shows a plot of the balanced detector signal vs. the methane absorbance in ppm*m using the laboratory setup with a 1.63 µm light source. The solid line shows the relationship between the approximate slope of the data and the noise floor. The noise floor is indicated by the dotted line and was measured at the detector output into a lock-in amplifier. This noise represents the minimal detector rms signal output produced when the optical paths were optimally balanced (as demonstrated in Figure 9). Methane concentration in the cell was controlled starting with methane at an over-pressure of 1 atmosphere and then gradually reducing the pressure. It appeared that the thin gas cell window suddenly relaxed (in shape or flatness) at an absorbance near 27,000 ppm*m and caused a spatial shift in the optical beam to impact the ratio between the two optical detectors. The signal absorption data can be viewed as fairly linear with respect to varying methane concentration. More data points between 10,000 ppm*m and zero concentration are required to better determine overall sensitivity of the system at smaller concentrations. Ophir hopes to gather more data in the future to determine the minimal detectable concentration of the system.

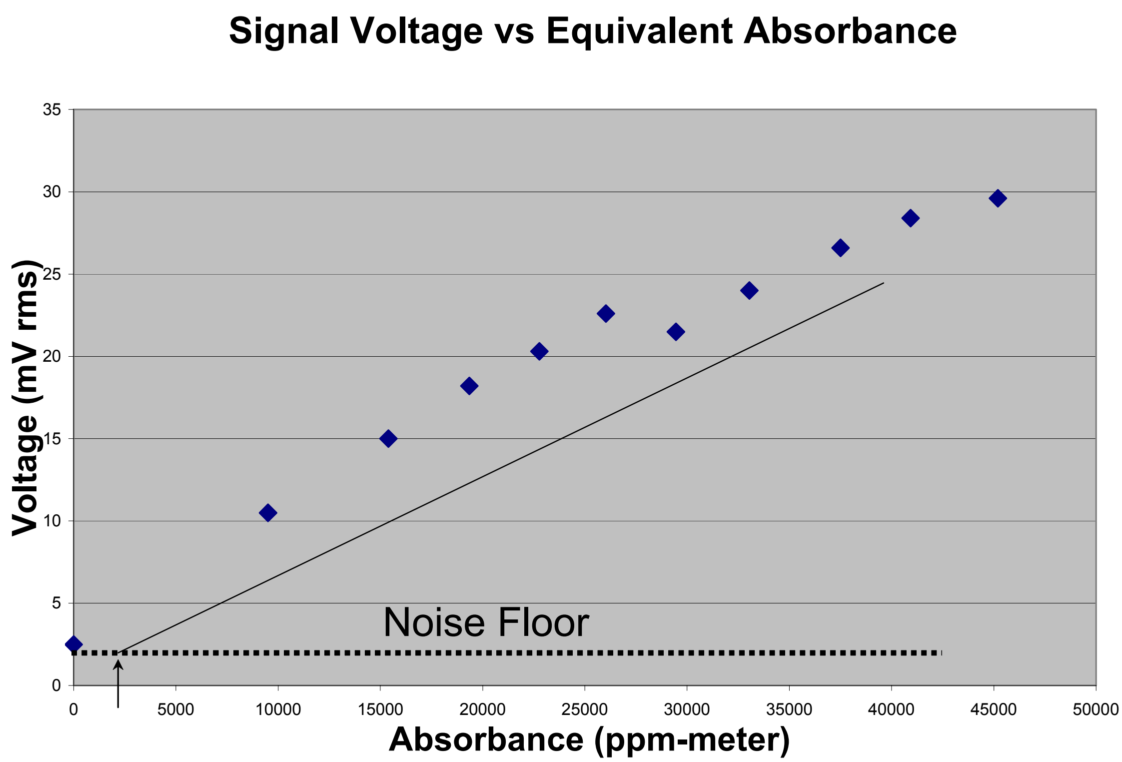

Figure 10. Methane Signal Absorption vs. Concentration Using 1.63 µm SLED Light Source

4. Project Issues

4.1. Cost and Availability of Seed Light Source and Amplifier for Airborne Sensor

Ophir has contacted numerous companies concerning the availability of broadband light sources greater than 1.63 µm. After further screening, Ophir has determined that three vendors are capable of developing and building the light source to Ophir's specifications. One vendor has given us a quote for developing and building a fiber amplifier capable of 25 dB of gain. They have delivered some simulations that show great promise in meeting the specifications. The amplifier still requires the development and fabrication of an extended wavelength seed source. To Ophir's knowledge, no one has yet developed a broadband source at this required wavelength. Ophir has contacted the SLED vendor chosen for the laboratory testing and requested a quote for the higher wavelength SLED. The vendor has stated that the higher wavelength SLED is certainly achievable and has submitted a quote to cover the non-recurring engineering cost, fabrication cost and minimum quantity build of 30 units. The total preliminary cost for the complete amplifier $167,000. It needs to be stressed that $70,000 of this total cost is associated with a required minimum buy of 30 seed light sources distributed and payable over a one-year period of time.

Ophir has been in contact with a second vendor that has proposed a parametric amplifier design to meet the specifications. The initial simulations from the vendor look quite promising in that they meet the peak center wavelength and the FWHM of the Ophir specifications. A telecon will be scheduled soon to discuss some questions on the recommended technology and to discuss future costs and lead times for the technology development.

The spectrally beam combined diode source is the last technology discussed with vendors. An estimate to proceed with this development was $120,000. Ophir will request from all of the proposing vendors a Firm Fixed Price (FFP) quote for the design and development of one light source.

4.2. Lack of Noise Cancellation in Laboratory Balanced Detector

The balanced detector circuit that Ophir used for the laboratory testing had a flat responsivity out to 1620 nm, and then experienced a sharp roll-off. Therefore, the detector would have an inadequate response at the higher wavelength required by the airborne sensor to sense both methane and ethane. Noise cancellation in the balanced detector was less than expected. The ability to sense very small quantities of methane was hampered by the low SNR of the system, limited by the higher than anticipated noise floor. The inability for the detector to properly zero out the two differential optical inputs was discovered to be the root of the problem. Modeling showed that the two optical inputs likely had a small differential phase shift, which was unable to be subtracted within the balanced detector circuit. This showed up as a small non-linear waveform on the output.

Ophir believes that the balanced detector approach will lead to reduced SNR in the final system and is committed towards the concept. The following changes will be incorporated into a new design of a balanced detector circuit:

- Installation of extended range photodetectors
- Phase subtraction circuitry on the input summing junction
- Diffusing optics on the optical inputs

4.3. Lack of Ethane Absorption at Less Than Ideal Light Source Wavelength of 1.63 μm

The laboratory testing failed to show measurable amounts of ethane absorption using the 1.63 μm SLED light source. In order to more closely reach the optimal ethane absorption wavelength, the suggestion was made to try and parallel the outputs of several small 1.65 μm LED sources that Ophir has in stock. Ophir has contacted a company that specializes in fiber coupling of discrete semiconductor packages. Ophir is waiting on their reply. Ophir is not expecting to commit any new resources, outside of what has been described, towards the short-term lab measurement of ethane absorption.

5. Conclusions

Ophir has completed the proposed first three critical schedule milestones including:

- Ground Based Co-Located Transceiver Testing With Targets
- Signal to Noise Modeling Using 3.3 µm and 1.6 µm Sources
- System Hardware Requirements Definition

Much of the experience gained in the laboratory will be utilized in the final design of the airborne transceiver. The transceiver design has been delayed pending the results of the testing and pending the identification of the selected light source vendor. Complicating the selection of the light source vendor is the unexpected cost associated with the development of the light source. No commercial products presently exist that will meet the specified requirements. Ophir has identified three potential sources and will request Firm Fixed Price (FFP) quotes for the development and fabrication of the light source. Preliminary estimates from two vendors have shown the cost to be out of the scope of the contract. Ophir will continue to investigate other sources of funding such as venture capital, available government resources, and Ophir internal research and development.

The transceiver design will continue with the redesign of the balanced detector circuit. Some laboratory testing will continue in order to isolate the source of the output imbalance. The new design will be optimized for peak sensitivity at higher wavelengths using extended range, TECC cooled photodetectors. Special attention will be given to using photodetectors with large active areas (up to 3.00 mm) to help eliminate beam response non-uniformities and to sense the maximum possible beam input. The layout and physical format of the balanced detector will be designed to seamlessly integrate into the transceiver fixture.

Once the light source cost and lead-time issues have been resolved, the design, development, and assembly of the airborne transceiver will begin on an accelerated schedule in order to complete ground testing by January 2004. Resource management at Ophir will be critical to the integration of the system hardware, software and testing. Ophir has broad experience in the development airborne sensor prototypes and while the schedule cushion has evaporated somewhat, seven to eight months of development time is still sufficient to prepare for airborne testing next year.

6. References

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7. Attachment 1 – Gas Industry Data Survey Results

Ophir sent the following list of informational questions to WBI Holdings, Inc. in Bismarck, ND and El Paso Pipeline Group in El Paso, TX:

1.) Recently, Ophir took some data with the fence-line monitoring sensor next to a pipeline near Glendive, MT. Gas distribution company personnel simulated some typical Class 1, 2 and 3 natural gas leaks. Do you have any information on what the Flame Ionization Detector (FID) gas concentration is of these leaks (Class 1, 2 and 3) at the source?
2.) Do you have any data or information illustrating the quantitative impact of wind on pipeline natural gas leak leaks (gas plume movement and concentration)? This will impact the pointing of the airborne optical sensor. Does the sensor need to be scanned over a broad region or can the sensor be pointed in just a single downwind position from the pipeline?
3.) Does the natural gas pipeline industry have any need for detecting gas concentrations smaller than class 1, 2 or 3 leaks?
4.) Do you have any input on the desired aircraft speed or flight altitude? This might depend upon your preferred airborne platform i.e. helicopter or small propeller driven airplane.
5.) What kind of ground surface resolution do you require for the location of the natural gas leaks? How would you like these gas leak locations to be specified? We envision the flight path of the air vehicle to be monitored and recorded by saving appropriate GPS coordinates. How about other information that needs to be time tagged to the flight such as time of day, date, known weather conditions, etc.? Ultimately, how would you like the final flight survey to look and what kind of data should it contain?
6.) A related question is how do we determine the location of the pipeline from the air? Are there any visual features that closely identify the pipeline location? This is important since the sensor beam size may be as small as a few feet hitting the ground. Do we know the exact GPS coordinates along the pipeline, so that they could be pre-programmed into the computer? Perhaps a computer display of flight path vs. pipeline location would be useful for both real time and post-flight analysis. Finally, do you think that having a visual recording of the ground terrain would be helpful during the post-processing of the data? Does this add any useful information to the pipeline leak surveys?
7.) Do you have any input as to the desired size, weight, and cost of the airborne sensor? Would you purchase airborne sensors or would you more likely hire service bureaus to perform the inspections? What target cost per mile for pipeline inspection would the industry support?
8.) Would you be interested in accessing airborne pipeline leak reports via the Internet? One method of delivering and reporting airborne pipeline surveys would be to download the survey results to a central website. Each customer would have a secure and company-specific series of web pages that show the

current survey status (which pipeline sections were surveyed, which were still scheduled for survey, leak detection results, etc.) Would this be beneficial for your company's operations?

9.) A significant fraction of the U.S. pipeline network is available on Global Positioning System/Geographical Information System (GPS/GIS) databases. Would you be interested in receiving pipeline survey results overlaid on a GPS/GIS map of their pipelines? (This could be provided either via the Internet or on a CD deliverable with the survey final report).

10.) Currently, Ophir plans to provide the measured methane and ethane concentrations along the length of the pipeline section surveyed as the primary data product. These measurements could also be roughly classified as "zero," "low," "medium," and "high," providing a general indication of the probability of a leak occurring at a reported location. Is this the best format and method for reporting of the survey data? Is there additional information or an alternate format that your company would prefer?

Table 6 summarizes the responses from these companies to the questionnaire.

Ophir Directed Question	**WBI Holdings, Inc. Response**	**El Paso Pipeline Group Response**	**Design Impacts for System**
Any known gas concentrations of Class 1, 2 and 3 leaks?	Leaks are not classified by concentration but by potential danger	Leaks are not classified by concentrations but by potential danger, detect smallest leak possible	It seems as if Ophir should design system to detect minimal or ambient levels of methane and ethane gases
Are you aware of any wind impact data on natural gas leak dispersion?	WBI has no data on this	They know of no data. Most companies have max. wind speed limits when performing surveys.	No help here in determining the minimal detectable concentration in the presence of wind
Does the natural gas industry have any need for detecting gas leaks smaller than Class 1, 2 or 3?	They would like to know whenever there is a leak of any size	A leak is a leak. They have detected leaks once the pipes are exposed.	Design goals here are to detect at least Class 3 leaks and let companies decide what to do with the data.
Do you have any input on the desired aircraft speed or flight altitude?	Whatever works the best	Best answered by the pilots. Company has flight restrictions on aircraft. Helicopters might disrupt the gas plume.	Design around existing airspace rules and regulations. Helicopter designs need to take into account the rotor downdrafts.
What kind of ground location resolution do you require for the location of natural gas leaks?	No input on resolution. Person will go out to confirm leak and then classify it for potential danger.	Leaks are currently specified by mileposts. Time, date tagging, and weather conditions would be useful. Progressing towards GPS in future.	Design of system around GPS coordinates with location specified as to nearest milepost marker.
How do we determine location of the pipeline for aerial survey? Is visual recording of the pipeline useful?	Some pipelines have visible markers but not all. Pipeline database moving towards GPS. Visual recording would be useful.	Visually locating pipelines is tough. Location in future with GPS is a solution. One solution is to have an employee present with surveyors.	This is going to be a problem since there are no standardized GPS coordinates for most pipelines. Can't see some pipelines visually from air.
Input as to the desired weight, size, and cost of the sensor? Would you purchase a unit or hire out to bureau?	No input on this subject.	Smaller the better. They would hire a service bureau before purchasing the sensor (less capital and maintenance).	Basically, no input on size, weight and cost. They would rather not purchase the sensors.
Would you be interested in accessing the airborne leak reports via the Internet?	Yes	This sounds like a great idea. The data should be at least Internet capable, possibly on CDs.	They like the accessibility of the Internet.
Would you be interested in receiving pipeline survey data overlaid on a GPS/GIS map of their pipelines?	This would be helpful in that we are in the process of inputting data to GIS now.	This might be useful for trend analysis, seasonal leak analysis, verifying fixed leaks.	Everyone seems to like this although the GIS data available on pipelines is minimal.
Do you want classification of leaks? Any additional info required for leak data?	No classification of leaks, they will determine upon site survey the amount and type of leak.	They don't want classification label put on leaks. They would classify by percent gas or ppm.	We would just give them leak in ppm-m.

Table 6. Response to Ophir Corporation Questionnaire Requesting Input on the Design Requirements for an Airborne, Optical Remote Sensor from WBI Holdings, Inc. and El Paso Pipeline Group