Applications of real-world gas detection: Airborne Natural Gas Emission Lidar (ANGEL) system

Darryl G. Murdock,[a] Steven V. Stearns,[b] R. Todd Lines,[c] Dawn Lenz,[d] David M. Brown,[e] and C. Russell Philbrick[e]
[a] ESRI, 8615 Westwood Center Drive, Vienna, VA 22182, USA
dmurdock@esri.com
[b] ITT Corporation, Space Systems Division, 800 Lee Road, Rochester, NY 14606, USA
steven.stearns@itt.com
[c] Brigham Young University-Idaho, 525 South Center Street, Rexburg, Idaho, 83460, USA
linest@byui.edu
[d] ITT Visual Information Solutions, 4990 Pearl East Circle, Boulder, CO 80301 USA
dlenz@ittvis.com
[e] The Pennsylvania State University, Dept. of Electrical Engineering, University Park, PA 16802, USA
dmb326@psu.edu, crp3@psu.edu

Abstract. An airborne DIfferential Absorption Lidar (DIAL) system was used to detect methane, propane, and light crude gas vapors during real-world collections. A series of overflights were conducted at two separate test locations (Kingsville/Corpus Christi, TX and Spencerport, NY). DIAL, digital orthophotography, and video data were collected, processed and analyzed at both sites. A new Hydrocarbon Detection Algorithm (HHDA) was developed to detect gasses other than methane. The HHDA shows promise for detecting multiple species in a local area with uniform surface reflectance or known variability.

Keywords. Lidar, remote sensing, methane, data processing, reflectivity, optical systems

1 INTRODUCTION

In the first quarter of 2006, ITT began offering commercial airborne leak detection and imaging services to the North American natural gas transmission pipeline industry. The Airborne Natural Gas Emission Lidar (ANGEL) Service uses three separate sensors: a DIfferential Absorption Lidar (DIAL) sensor, a high-resolution mapping camera, and a color digital video camera. The ANGEL Service's system remotely detects, quantifies, and allows precise reporting of natural gas leak locations. The ANGEL sensor represents the first major commercial application of lidar using the DIAL technique. The airborne platform selected to house the ANGEL Service's system is a fixed wing aircraft that is typically flown 1000 feet over the pipeline right-of-way and inspects the pipeline at a speed of up to 150 mph [1-5]. The efforts to develop DIAL lidar technology for applications in detection of leaks in natural gas pipelines and supplies follows earlier demonstrations of infrared imaging the gas plumes, such as that demonstrated using the BAGI technique [6].

Under contract from the United States Department of Transportation Pipeline and Hazardous Materials Safety Administration (DOT/PHMSA), ITT examined the possibility of using the ANGEL Service's system to detect and image hydrocarbons other than natural gas (methane). Over the summer of 2005 ITT Space Systems Division, working together with researchers from Penn State University, successfully developed algorithms for and demonstrated the detection and imaging of a range of different hazardous liquid effluents during a series of flight tests in Texas and New York. This paper examines the algorithms and analysis from these two collection efforts.

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In addition to producing leak detection reports, the ANGEL Service also provides continuous digital imagery and digital video of the pipeline corridor and surrounding area. Geo-referenced digital still and video imagery allows customers to more fully identify pipeline threats and risks and provides context to the leak detection data. The data collection system for the ANGEL Service consists of an aircraft and an integrated sensor payload. Ground support and data processing is provided by the ITT ANGEL Service Operations Center in Rochester, NY. Staffed by a team of engineers, scientists, technicians, and business support personnel, the Operations Center provides the required mission planning data and support to perform an airborne operation. Following each data collection effort, the Operations Center computer system is used to process, analyze, archive, display, and distribute a final report to customers describing pipeline survey results.

The sensor payload is integrated into a modified Cessna Grand Caravan 208B aircraft shown in Fig. 1. The Caravan was selected as the optimal platform for ongoing commercial operation of the ANGEL Service. The aircraft is currently based out of an ITT hangar facility in Rochester, New York. This airframe was chosen because of its large payload capacity, available electrical power, and slow airspeed – all prerequisites for successful flight operations of the data collection systems.

Fig. 1. ITT Cessna Grand Caravan aircraft with the ANGEL payload.

2 SENSOR SYSTEM DESCRIPTION

The ANGEL sensor payload currently incorporates three separate sensors: a differential absorption lidar (DIAL) sensor, a high-resolution digital mapping camera, and a digital video camera. Figure 2 shows a high-level workflow of the ANGEL system planning, collection and analysis.

The ANGEL DIAL sensor shown in Fig. 3 uses three laser wavelengths to illuminate the pipeline right-of-way with mid-wave infrared (MWIR) laser pulses. These laser pulses are scattered from the ground and detected by a receiver package on the aircraft. The sensor contains three separate laser benches tuned to emit co-aligned pulses at slightly different wavelengths of MWIR laser light to create a triplet of laser pulses at a 1 kHz rate. The ANGEL sensor was designed to detect both methane and ethane - the two major components of natural gas. The methane "online" laser bench emits laser energy at a wavelength which is absorbed by methane molecules along the path. A second "online" bench emits light at a wavelength which is absorbed by ethane. The third "offline" laser bench emits light at a wavelength which is not absorbed by methane, ethane, or any common gasses in the atmosphere. Ratios of the methane and ethane online signals and the offline return energies are combined with information on the path between the aircraft and the ground, and allow the algorithmic calculations of the amount of target gas between the aircraft and the ground. This type of DIAL system measures the concentration path length (CPL) in units of parts per million per meter (ppm-m).

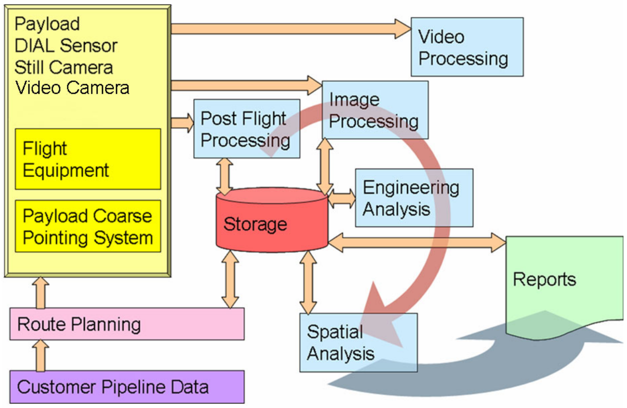


Fig. 2. View of the ANGEL Service planning, collection and analysis workflow.

The ANGEL DIAL sensor is equipped with an automated pointing system, which continuously tracks the position and orientation of the aircraft. Using either a customer-supplied or digitized file of the target pipeline location, the sensor constantly tracks the pipeline position and keeps the DIAL scan swath centered directly over the pipeline. As the aircraft flies along the pipeline utility right-of-way (ROW), the laser pulses are scanned within the ROW to build up an image swath of gas concentrations along the pipeline. Sensor settings, aircraft speed, and altitude change permits selection of the DIAL scanner swath width and spatial coverage resolution in the target region. For example, a typical collection near 650-750 feet altitude results in a swath width being approximately 100 feet. Nominal flight speeds are about 150 mph. In addition to the sensor-targeting data file, pipeline position information is also supplied to the aircrew via a customized visual display that allows the crew to verify the flight path over the intended pipeline route even in areas where the ROW is not discernable from the air.

Fig. 3. View of the ANGEL Service sensor payload integrated into a Cessna 208B aircraft (left). View of the optical port on the underside of the aircraft shows the optics for the three sensors (right) with DIAL Sensor Window, 4K x 4K Digital Camera, and 1K x 1K video camera (clockwise).

3 HAZARDOUS-LIQUID AIRBORNE LIDAR OBSERVATION STUDY (HALOS)

Under contract with the United States Department of Transportation Pipeline and Hazardous Materials Safety Administration (DOT/PHMSA), ITT and Penn State University researchers examined the ability of its ANGEL Service to detect, measure, and image a wide range of different hydrocarbons from a remote sensing airborne platform. The objectives of the HALOS contract were to: (1) develop an understanding of hazardous liquid pipeline leaks, (2) demonstrate that ITT's DIAL technology can detect and measure hazardous liquid emissions over a broad area in real world conditions, and (3) use this information to design a "next generation" airborne sensor system optimized for the detection of both natural gas and hazardous liquid emissions.

In North America, the oil and gas pipeline industry operates four major pipeline networks. The North American natural gas pipeline network consists of more than 300,000 miles of primary transmission pipelines. The ANGEL Service was originally designed to inspect this natural gas pipeline network and find leaks before significant loss of product, or hazardous conditions occur. In addition to the natural gas pipeline networks, transmission lines consist of three separate hazardous liquid pipeline networks.

One hazardous liquid network of transmission pipelines is dedicated to transport of LPG. The predominant component of LPG is propane. Propane is a liquid hydrocarbon at relatively high pressures in the pipeline, and is quickly volatized when released to the atmosphere. Because propane is a liquid in the pipe, LPG pipelines are considered hazardous liquid pipelines. Although propane gas is slightly more dense than methane, HALOS computational simulations and physical plume modeling indicate that at low concentrations, airborne propane gas plumes emitted by a leaking pipe are very similar in distribution size, shape, and overall geometry when compared with natural gas plumes.

A second major transmission network in North America is the network of refined liquid pipelines. These pipelines are used to transport a variety of liquid fuels such as automobile gasoline, aviation gas, kerosene, diesel fuel, and Jet A. Leaks from a refined liquid pipeline are extremely complex due to the number of different fuels that can be transported in the same pipeline, and the varying behavior of these hazardous liquids when released from the pipe.

Under the DOT contract, the HALOS team characterized the spectral and physical properties of a range of different refined liquids and subsequently modeled the behavior of refined liquid pipeline leaks. Liquids that reach the surface from a leaking buried pipeline evaporate, creating a plume of hydrocarbon vapor. The size and concentration of that airborne plume depends on the specific liquid, the size of the leak, and the rate of evaporation. In this study, the refined liquids were subdivided into two groups: volatile liquids like gasoline and AV gas, and less volatile liquids like diesel, kerosene, and Jet A.

The third type of liquid pipeline network is used for crude oil transmission. Unrefined crude oil is a highly variable hazardous liquid, and consists of literally dozens of different hydrocarbon components. As with refined liquids, when a buried oil pipeline leaks, the oil may sink into the ground or may pool at the surface. Volatile components of oil pooled at the surface will evaporate to form an airborne vapor plume. Although leaks from oil pipelines were not specifically studied under the HALOS contract, ITT had an opportunity to over-fly a staged release of natural gas condensates that are of a composition similar to light crude oil.

One advantage of using an airborne DIAL system is the ability to detect and quantify very small concentrations of vapor in the air between the aircraft and the ground. The ability to detect a specific gas depends on its unique spectral characteristics. As an example, propane has a major absorption spectrum in the same MWIR spectral region as methane and ethane. Modeling in the early stages of the HALOS effort indicated that the spectral line positions of the ANGEL DIAL sensor overlap broad adsorption features of propane gas. As a result of this modeling it was proposed that an overflight of a propane plume would likely be detectable in the DIAL signal, and indicated that propane plumes could be detected without system hardware modifications. Further investigation demonstrated that, although the ANGEL sensor was designed specifically to detect natural gas, leaks from other hazardous liquids are also detectable by the ANGEL Service without spectral retuning. Early HALOS modeling efforts led to a series of flight tests over different simulated hydrocarbon leaks, and those tests have demonstrated the feasibility of using a DIAL system to detect hazardous liquid leaks.

4 DATA PROCESSING AND ANALYSIS

At the end of each flight, the DIAL data, continuous aircraft position data (yaw, pitch, and roll), sensor performance data, and meta-data such as atmospheric pressure and temperature are transferred to a removable hard drive. Digital mapping camera data is recorded on a separate hard drive. Video camera data is transferred to a writeable DVD as a separate data set. The complete three-part data package is removed from the airborne system and delivered to the Operations Center for processing and analysis. Data is transferred from the removable hard-drives and archived to fault-tolerant RAID storage arrays. The DIAL sensor data is processed using software based on ITT's proprietary DIAL/Lidar algorithm set. During initial processing, data points are geo-located and analyzed for the presence of the natural gas. The signal level of gas detected is computed as a concentration path length (ppm-m).

The output of the initial data processing step includes: (1) GIS shapefiles that are used by analysts to create customer reports, and (2) engineering data that details sensor and related subsystem performance. ITT engineers use this latter information to assess data quality and to compensate for various environmental, surface and operational variables that can influence data interpretation. GIS shapefiles are used to automatically create geo-located graphical and tabular reports using the ANGEL Pipeline Analysis and Reporting System (APARS, described below). All ANGEL data is fully georeferenced so analysts can overlay the ANGEL DIAL data onto the images from digital mapping camera, or other imagery, to aid in interpretation. Mapping of concentration path lengths may be used to create graphics similar to that which is displayed in Fig. 4. This data can then be interpreted visually, and can be analyzed using algorithms to identify the presence and determine the quantity of natural gas.

Digital mapping camera imagery is processed to create a series of orthomosaic images of the pipelines inspected. Standard orthomosaics are generated and are available to analysts or customers as required. Imagery produced is GIS ready and serves as a base layer for the DIAL analysis display. An entire video record of each pipeline inspection is recorded on DVD and is viewable immediately upon landing. Georegistered video is available within a few hours of landing. Video material is used for post flight briefings and is archived for a customer-deliverable DVD set.

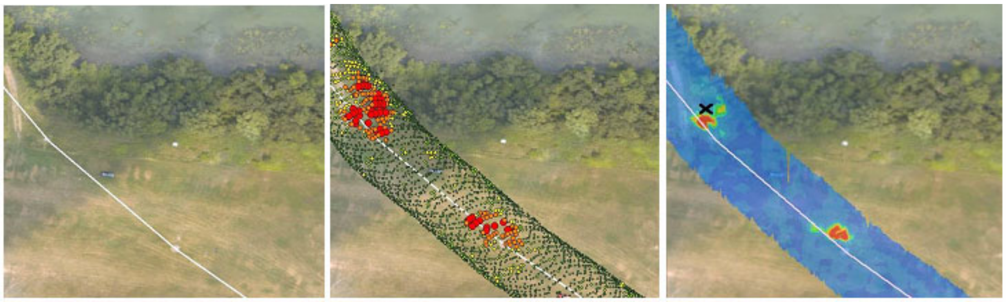

(a) **(b)** **(c)**

Fig. 4. Test Site #3, Spencerport, NY. Consecutive frames show (a) white line indicates DIAL targeting path, (b) Red and orange point locations indicate elevated methane concentrations within the laser scan pattern, (c) Red and orange polygons indicate elevated methane concentration within the scan pattern.

Immediately after initial processing is completed, and while additional data is being analyzed, reports are generated. The ANGEL Pipeline Analysis and Reporting System (APARS) is a custom suite of tools and algorithms for processing, analyzing, visualizing, and reporting the DIAL measurements and image data. Implemented with the IDL (Interactive Data Language) and ENVI (Environment for Visualizing Images) software products from ITT Visual Information Solutions, the system provides both interactive and batch-processing capabilities that are integrated with the ANGEL ground data processing system.

The application allows the user to select and import a DIAL dataset and analyze it in the context of georeferenced imagery. Interactive tools allow both qualitative and quantitative data analysis, providing visualization and statistical analysis capabilities tailored for the ANGEL data. Batch processing tools provide automated data analysis to pinpoint areas that warrant further inspection. The system produces summary reports of identified locations that are used for further analysis, field follow-up, and archiving.

5 HALOS DATA PROCESSING ALGORITHMS

A standard DIAL analysis is used as the basis for our analytical efforts. Lidars using the DIAL technique have been available for many years [7], however this three-wavelength aircraft mounted instrument represents the first significant application of DIAL in commercial use. Several different data processing algorithms were subsequently created and tested during this study. These methods include:

- First Order Algorithm – Series of standard DIAL comparisons and logic code to support the selection of the DIAL analysis approach to use for correct target analysis.
- Second Order Algorithm – HALOS Hydrocarbon Detection Algorithm (HHDA) algorithm capable of using three or more wavelength channels as data input streams.
- Scene Segmentation – Scene segmentation used in conjunction with first and second order algorithms to account for variable background reflectance.

The motivation in the development of multiple algorithmic approaches for hydrocarbon detection was to obtain the most robust and versatile algorithm to implement in future real world operational scenarios. Since the ANGEL system was designed for operation under a vast array of terrains and environmental conditions, it is essential to test the system and corresponding data processing approaches in these regimes. Approaches range from a first order technique using the standard online and offline wavelengths for the detection of primarily methane, ethane, and propane, to a multiple wavelength algorithm for the detection of many different hydrocarbon species. The multiple wavelengths HHDA is the first generation multiple species detection algorithm built for the ANGEL instrument. Several standard DIAL approaches are used to validate the result of this algorithm. Furthermore, as an improved alternative to the simple ratios of the return signal intensities for validation of the HHDA, a program using two basic DIAL algorithms governed by a logic comparison was developed. The real time logic can be used to reduce computation time by selecting one of two DIAL approaches and later demonstrate the feasibility of rapidly determining possible target species encountered throughout the scan. An initial low resolution scan of this nature provides the necessary information to set up a slower, more advanced processing algorithm (like the HHDA) capable of calculating the CPL of targeted species. The linked DIAL algorithms can also be used for incomplete or partial failure collections, when data is only available for 2 of the 3 wavelength channels. Specific examples of this approach were tested using collects made at Spencerport, NY and Corpus Christi, TX when only the primary methane on-line and off-line lasers were operational. Both the DIAL algorithms and the HHDA algorithm use spatial scene segmentation (described in section 6) to acquire an adequate number of lidar data points to make conclusions with confidence over common ground-cover subsets. For common species, both algorithmic approaches yielded similar results.

The CPL derivation for both algorithmic approaches stems from the basic lidar equation for returned power due to elastic scattering is presented by Measures [7] as,

$$P(\lambda) = \frac{A_o P_L \rho(\lambda)}{\pi} \frac{T^2(\lambda_L, R_T)}{R_T^2} \xi(\lambda) \xi(R_T) \tag{1}$$

where $\boldsymbol{P}(\lambda)$ is the return power per pulse and $\boldsymbol{T}^2(\lambda_L, R_T)$ is the transmission. The factor $\boldsymbol{R}_T$ is the range from the transceiver to the surface of the earth, $\rho(\lambda)$ is the surface reflectivity. The factors $\boldsymbol{A}_o$ and $\xi(\lambda)\xi(R_T)$ describe of the optical system. Most of the terms do not change with wavelength.

5.1 HALOS Hydrocarbon Detection Algorithm (HHDA)

The HALOS project goal was the detection of complex hydrocarbons. As part of that goal, a signal retrieval algorithm was required which would allow detection of a multi-spectral signature in the presence of additive noise. The standard DIAL approach utilizes only two wavelengths to detect a single absorption feature. The HHDA algorithm goes beyond the DIAL approach, and it can theoretically use an infinite number of discrete absorption (or reflection) features. We elected to use a statistical estimator based on the idea of maximum likelihood. This approach provided the desired multi-spectral feature discrimination with the power of a robust estimator.

Our HHDA is a statistical estimator is designed to detect the absence or presence of a target gas absorption independent of surface reflectivity changes. The algorithm is based loosely on the work of Warren [8]. We begin with a generalized lidar equation for power as shown previously. At each wavelength, the received power is the fundamental measurement and it can be represented by the signal detected,

$$N(\lambda) = \frac{\lambda}{hc} g \eta \frac{P_L \tau_d \rho(\lambda) A_o}{\pi R_T^2} \xi(\lambda) \xi(R_T) \exp\left(-2 \int_0^{R_T} \kappa(\lambda, R)\, dR\right) + w(\lambda) \tag{2}$$

where g is the gain and η is the quantum efficiency of the detector. The term $w(\lambda)$ is the detection system noise. The constants h and c are Planck's constant and the speed of light, respectively. We separate the transmission factors for the general atmosphere and the target gas using the model

$$N(\lambda) = \frac{\lambda}{hc} g \eta \frac{P_L \tau_d \rho(\lambda) A_o}{\pi R_T^2} \xi(\lambda) \xi(R_T) T_{air}^2 \exp\left(-2 \int_0^{R_T} N(R) \sigma(\lambda)\, dR\right) + w(\lambda) \tag{3}$$

where $N(R)$ is the concentration of the target gas and $\sigma(\lambda)$ is the absorption cross section of the target gas, and T_{air} is the transmission of the atmosphere without any target gas. A maximum likelihood estimation technique is employed that allows us to incorporate prior knowledge of the surface. This prior knowledge may be gleaned from nearby pixels or even prior flights. The signal model above is divided into fluctuating and non-fluctuating terms. Statistics are gathered for the null case, and applied to the estimator. The estimator produces both a CPL estimate and uncertainty.

The algorithm requires care in determining the source of absorption coefficient parameters to be used in order to ensure accurate results. A lab measured absorption coefficient for methane given in the PNNL spectral database was used for consistency reasons, because the algorithm uses an iterative processes to calculate CPL. Accordingly, using sensor determined absorption coefficients could result in an algorithm more sensitive to the absorption coefficient. The HHDA algorithm, which was originally coded and run in MatLab, uses segmented groups of normalized return energies from the ground data processing system.

We have found that the natural surfaces are composed of high spatial frequency reflectivity changes in the midwave infrared region. The transition from field to roadway and back to field, or the spatial distribution of vegetation found in southwestern forests are examples. It was also found that the surface reflectivities may vary over relatively small distances. Thus, we use knowledge of the surface characteristics to improve detection performance. To characterize the surface, each scene was first spatially segmented. Ideally, the segmentation is accomplished by using an automated classifier, where the only restraints are to ensure no segment has too few measurement points.

5.2 DIAL Verification Algorithm

The algorithms developed for the verification of the HHDA stem from two separate standard DIAL comparisons of the data acquired for each of the three wavelengths. Independent examination of these comparisons provides a way to scale wavelength effects using the overall detection results with the more advanced HHDA, or any multiple wavelength algorithm spanning a large wavelength range.

The first DIAL comparison used for the calculation of propane at Spencerport and Corpus Christi utilized the methane secondary offline and methane primary offline lasers. Note the abbreviations, Methane Primary ON-line wavelength (MPON), Methane Primary OFF-line wavelength (MPOFF), and Methane Secondary OFF-line (MSOFF) through the following derivations. The MPOFF laser was used as a propane on-line while the MSOFF was used as the propane off-line for DIAL analysis. Since the background atmospheric absorption (and hence interference) was minimal for both the methane primary and secondary off-line wavelengths, comparing the off-line channels yields a DIAL pair sensitive to fugitive propane emissions. Thus, when performing the ratio of the normalized return power, like terms cancel due to wavelength and range similarity, and the following ideal expression for concentration path length of propane evolves, which can be rewritten as,

$$CPL_{propane} = \int_0^{R_T} N_{propane}(R)\,dR = \frac{1}{2\left[\sigma^A_{propane}(\lambda_{MPOFF}) - \sigma^A_{propane}(\lambda_{MSOFF})\right]} \ln\left[\frac{P(\lambda_{MSOFF})}{P(\lambda_{MPOFF})}\right] \quad (4)$$

The second DIAL method utilized the MPON line as the propane off-line while keeping the MPOFF as the propane on-line. Knowing MPON line is a significant absorbing wavelength for methane, the amount of background atmospheric methane must be taken into account before using this DIAL pair for a propane CPL analysis. By calculating the background methane CPL for multiple flights throughout the period of testing, it was possible to account for the background methane absorption and subsequently normalize the ratio for propane analysis. Accounting for this background methane parameter modifies the simplified return power on the methane channel, and hence changes the result for the CPL of propane in the following manner.

$$\begin{aligned} CPL_{propane} = \int_0^{R_T} N_{propane}(R)\,dR = {} & \frac{1}{2\left[\sigma^A_{propane}(\lambda_{MPOFF}) - \sigma^A_{propane}(\lambda_{MPON})\right]} \quad (5) \\ & \times\left(\ln\left[\frac{P(\lambda_{MPON})}{P(\lambda_{MPOFF})}\right] - \left[2CPL_{methane}\left[\sigma^A_{methane}(\lambda_{MPON}) - \sigma^A_{methane}(\lambda_{MPOFF})\right]\right]\right) \end{aligned}$$

The average CPL can be calculated by utilizing the returns from multiple passes over a visually and spectrally uniform, non-leak site with solid return strength. For example, results from the Spencerport flights showed a high correlation with returns from an asphalt roadway. Manual area of interest selection methods were used to subset the appropriate data returns. We have conceived an automated, or semi-automated selection method, which could be implemented in future developments. By creating a histogram and averaging the methane CPLs for these regions, we determine a reliable background methane CPL parameter that can be used for the independent DIAL and HHDA analysis offsets.

5.3 DIAL Logic Code

The DIAL analysis techniques described were built into an overall code that utilized the three-line dataset to select which algorithm to execute, thus eliminating incorrectly interpreted output results. Such an error instance would occur when calculating a propane CPL measurement over a methane leak. We assume for simplicity that if there are no staged leaks in the far field, the only absorbing gas would be the methane background. To determine the type of leaks (if any), we take the correlation coefficient of the region to investigate CPL measurement between different DIAL pairs. First, we calculate the region's propane CPL using the first DIAL method described. We then calculate the propane CPL using the second DIAL method and compute the correlation coefficient between the two methods for the string of propane CPL measurements. This string of measurements corresponds to the scanning the region to derive statistics. If there are no propane or methane leaks in the far field, this coefficient will be high, since both DIAL methods would arrive at a similar propane non-detection conclusion.

Additionally, these coefficients would also be high for a propane leak, once again due to the methane background being previously accounted for in the average background. The only case when this coefficient would not be greater than zero would be in the case of a methane leak in the far field, as the second DIAL method would yield an incorrect propane CPL reading. Since our first DIAL method would be unaffected by a methane leak, the correlation between the two propane CPL calculations would fall negative. Undetected propane or methane leaks both default to the propane detection scheme in our decision code, which is good for combating the issue of false positives but will obviously increase the probability of missing small methane leaks. The flowchart in Fig. 5 describes the logic process of this algorithm, and how it could be used as a lead into more advanced multiple wavelength algorithms, such as the HHDA.

6 SCENE SEGMENTATION

Each of the retrieval techniques used is sensitive to variations in surface reflectivity. When the signal levels are low, because of lower surface reflectivity, the threshold for minimum detectable concentration rises rapidly. While developing the data processing techniques for the ANGEL system, we found that the signal returns from the reflectivity of natural surfaces often exhibit high frequency changes. The transition from field to roadway and back to field, or distributed vegetation found in southwestern forests are examples. It was also found that the surface reflectivities may change, even over relatively small wavelength ranges (10's of nanometer). As an example, a histogram of normalized return energy from the roadway for Spencerport is illustrated in Fig. 6. The histogram confirms the single mode distribution of the spectrally uniform target region, and the detection performance is enhanced by including the baseline return power offset provided by varied degrees of reflectivity.

To capitalize on the fact that similar groundcovers are largely single modal in reflectivity, each scene was first spatially segmented. Ideally, the segmentation would be accomplished by using an automated classifier where the only restraints are to ensure no segment has too few points. If there is a plume of the target gas, then the classifier would define another segment. Once a region is identified as a potential target, statistics are gathered on the surrounding area near the potential target. These statistics provide a description of the surface reflectivity in that region, and provide a starting point for statistical estimators and detection testing.

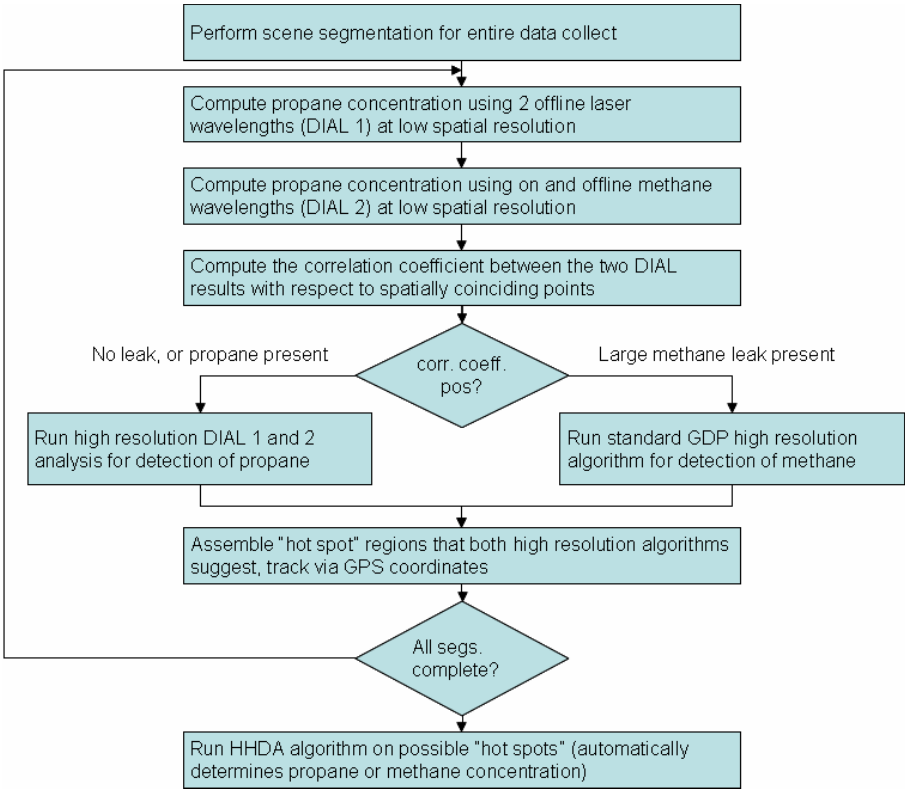


Fig. 5. DIAL logic code flowchart of operations.

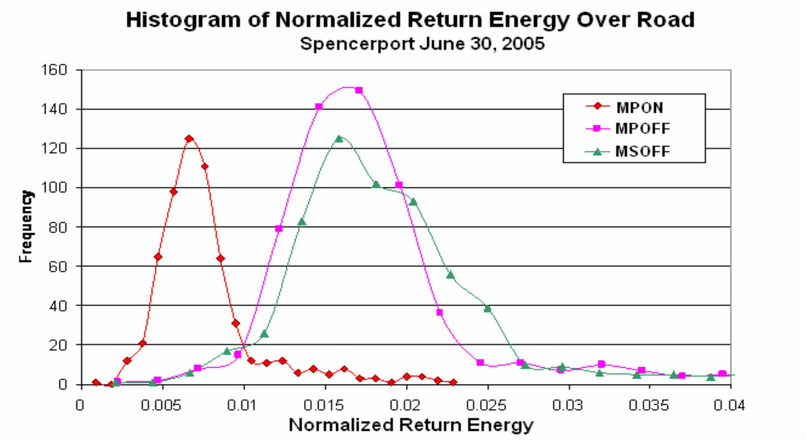


Fig. 6. Histogram of normalized return energy.

For the HALOS project, segmentation was done with simple classification routines prepared in MatLab and using ESRI GIS tools. Once segmented scenes are available, the data is processed through a series of algorithms. Within the uniform region, we define a sub-region, which is treated as the plume in the statistical estimator. The estimator gives a CPL value for the sub-region, based on the statistics over the entire uniform reflectivity region. The sub-region is scanned, yielding an estimate of the target gas CPL for the uniform reflectivity region, see Fig. 7. This is then repeated for each uniform reflectivity region in the entire scan, and thus creates 2-D CPL plots for the entire data collect.

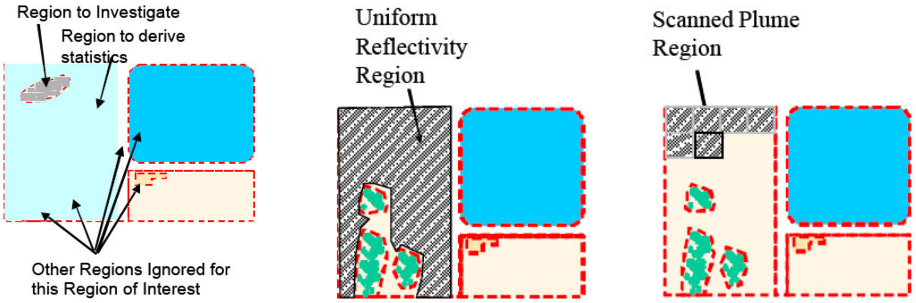


Fig. 7. Details show scene segmentation and scanning to process data points relative to groundcover.

7 FLIGHT TESTS: SETUP, FLIGHT TEST COLLECTION, AND RESULTS

A set of real-world flight test activities were conducted during the summer (17 June - 25 August 2005). All overflights were designed to test the ability of the ANGEL Service's system to detect hydrocarbons other than natural gas. Controlled releases were performed during flights conducted at Corpus Christi and Kingsville, Texas and at Spencerport, New York. For these controlled flight tests, the HALOS team used compressed cylinders of propane gas, they worked with industry partners to safely stage releases of gasoline vapors adjacent to a cooling pond in Corpus Christi, Texas, and they arranged releases of natural gas condensate vapors from an operational tank battery near Kingsville, Texas. The hydrocarbon releases at Corpus Christi and Kingsville, Texas, and the propane and methane releases at Spencerport included flights over the same site with and without the gas releases. The flights without releases provided controls, or "null" cases. Table 1 shows a summary of all data collection activities performed during these real-world flight tests.

Table 1. Data Collection Overview: Date, Location and Type of Data Collected.

Collection Date	Location	Description
17 June	Corpus Christi, TX	Propane and Gasoline releases
17 June	Kingsville, TX	Tank battery Hydrocarbon emissions
30 June	Spencerport, NY	Propane releases
17 August	Spencerport, NY	Propane releases
25 August	Kingsville, TX	Tank battery Hydrocarbon emissions

7.1 Gasoline Vapor Release (Test Site #1)

7.1.1 Test Setup

Test site #1 for the HALOS project was at the Barney Davis Power Plant in Corpus Christi, Texas. Preparation of the test site was organized in cooperation with Texas A&M University, the Corpus Christi Pollution Prevention Partnership, and with permission of Barney Davis

Power Plant management. Because of the hazardous nature of the gasoline target, and the need to leave a clean target site, this test was the most complex to organize for the HALOS effort. The test site was chosen close to Corpus Christi, but in the secure gated area of the power plant property. The test arrangement included two adjacent 100 ft^2 temporary evaporation basins to simulate a gasoline leak. The frame for the basins was constructed using 10-foot lengths of 1x10-inch lumber. The basins were lined with 50 mil inert black PVC sheeting. Before the overflights, ~80 gallons of gasoline was pumped into the basins to cover the basin area with several inches of gasoline. The test target basins were constructed and filled in the pre-dawn hours of June 17, 2005. The original intent of conducting the test at this time was to minimize the influence of wind on the gasoline plume disbursal. However, the wind speed during the test was ~15 mph and the evaporation rate of the gasoline was correspondingly high. At the end of the 1-hour test only 25 gallons of gasoline remained in the basins. Fig. 8 shows the construction and filling of the gasoline evaporation basins.

A Davis Scientific WeatherPro portable weather station was deployed to record ambient meteorlogical conditions, including wind direction and speed, temperature, humidity, and barometric pressure. A Thermo Electron Corporation TVA-1000 Toxic Vapor Analyzer using flame ionization detection (FID) was used to determine ambient levels of hydrocarbons before and during the Barney Davis Power Plant data collection.

7.1.2 Flight Test Collection and Results

The gasoline flight test included two passes using two different routes. The first overflight was a "null" run flown before the basins were filled with gasoline. The second overflight, 19 minutes later, was conducted when the basins were filled with gasoline. Table 2 shows the order of the collections and the ambient conditions at the time of each overpass. One problem with this collection site was due to limits imposed by the controlled airspace of a nearby a military flight-training airfield, and this limited the overflight opportunities to the pre-dawn period. The very early morning low light conditions negated the collection of usable video or digital imagery data at this site. The wind direction for these collections blew the plume of gasoline vapors over the Barney Davis Power Plant cooling pond.

DIAL data from Site #1 was processed and USGS False Color IR Digital Ortho Quarter Quad (DOQQ) imagery was used to provide context reference for the DIAL data analysis and reporting. After modifying the analysis software to detect gasoline vapors, the results from the gasoline runs were reported in relative units. The ANGEL sensor was not able to accurately quantify gasoline vapors at the time of this test. However, color-coded DIAL results in Fig. 9 clearly show the presence of a large plume of gasoline vapors. Very large quantities of gasoline were detected over land and over the power plant cooling pond.

Fig. 8. Ground images showing the construction (left) and filling (right) of 10 x 10' gasoline target prior to overflight at Test Site #1.

Table 2. Test Site #1 test conditions for the gasoline flight test. FID measurements downwind of the evaporation basins are expressed as parts per meter volume.

Time	Route	Winds	Hydro-carbon	FID (ppm)
0602	1804	16 mph 165°	Null	1.4
0621	1806	13 mph 180°	Gasoline	2700-3100

Fig. 9. ANGEL Service detection of gasoline vapor release over water at Corpus Christi, TX, with DOQQ imagery used as contextual backdrop.

7.2 Natural Gas Condensate Vapor Release – (Test Site #2)

7.2.1 Test setup

On June 17, 2005 real-world ANGEL Service overflights of the El Paso Production facility in Kingsville, Texas focused on the detection of natural gas condensate vapors emanating from an operational condensate tank battery. Prior to the release of hydrocarbon emissions, an overflight was performed to establish a baseline of background hydrocarbon concentrations. Figure 10 shows a ground-level photo of the condensate tank battery looking SSW. Each tank was equipped with a thief hatch on top designed to allow periodic dip sampling of the tank contents. Personnel were pre-positioned at the base of the tank ladders to facilitate rapid opening of the thief hatches between overflights. A portable meteorology station was deployed near the tank battery to record meteorological conditions during the overflight. The facility was inspected with a FID device to determine ambient levels of hydrocarbons before and during the Kingsville data collection.

7.2.2 Flight Test Collection and Results

Three different routes were flown over the Kingsville facility at approximately 850 feet Above Ground Level (AGL). First, a "null" pass was flown north to south with the vapor recovery unit (VRU) for the tank battery in normal operation to establish baseline concentrations. Following the "null" collection, the VRU was turned off for the remaining five passes in an attempt to create a slightly elevated background hydrocarbon concentration level. Data from the pass with the elevated hydrocarbon level was then used to determine sensor sensitivity. Table 3 shows the collections attempted and the ambient conditions at the time of each overpass for the flight collect at the El Paso Production Facility, Kingsville, Texas.

Fig. 10. El Paso Production Condensate Tank Battery (as viewed from the NNE, Kingsville, TX. Note: windsock orientation indicating winds out of the south.

Table 3. Actual Overflights performed at Test Site #2 – Vapor Recovery Unit (VRU) labeled as on/off.

Route	Time	Travel Dir	Winds	FID (ppm)	VRU
1800	0738	North - South	3 mph 160°	10-30	on
1801	0744	East - West	4 mph 160°		off
1802	0750	West - East	2 mph 160°		off
Route	Time	Travel Dir	Winds	FID (ppm)	VRU
1800	0755	North - South	3 mph 157°	25-600	off
1801	0759	East - West	3 mph 188°	2100	off
1802	0801	West - East	2mph 172°	200-800	off

After the first three passes were completed, the thief hatches on all of the tanks were opened, creating a large plume of condensate vapors. Figure 11 shows a closed and opened thief hatch on top of one of the tanks. ANGEL processing routines were applied to the Kingsville data from the 17 June collect. Measurements of the hydrocarbon gas level at the Kingsville site were made with the tank array closed and open, respectively. Field FID measurements indicated that even with the array hatches closed, the air in the tank area is not free of hydrocarbon vapors due to venting of condensates vapors from the tanks and pipes in the facility. Shutting down the tank battery VRU raised the background level of hydrocarbon in the air surrounding the tanks.

Fig. 11. Thief Hatches closed and opened at Kingsville, TX facility.

Point measurement of hydrocarbon concentration with a hand held FID indicated 300-ppm of background hydrocarbon-based gas. This elevated background is shown in Fig. 12 (left panel). Once the thief hatches were opened, the increased hydrocarbon vapors were clearly detected as seen in Fig. 12 (right panel). During this set of overflights, the wind was from the south and, as expected, the north area of the image shows a large plume of gas condensate vapors escaping from the tanks.

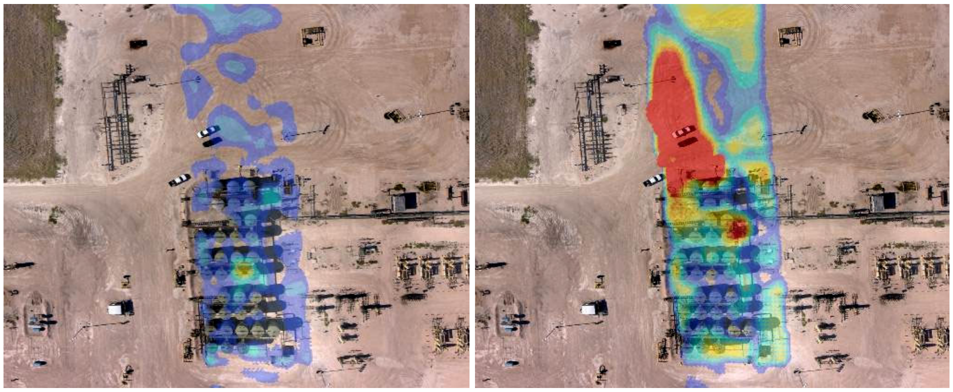


Fig. 12. Data from the 17 June ANGEL Service's system overflight of a natural gas condensate tank battery in Kingsville, Texas. ANGEL DIAL data is overlaid on the simultaneously collected high-resolution orthorectified imagery. Color-coded DIAL results clearly show the presence of localized background concentrations with the thief hatches closed (left), and higher hydrocarbon emissions with the hatches open (right).

7.3 Propane Vapor Release – (Test Site #3)

7.3.1 Test setup

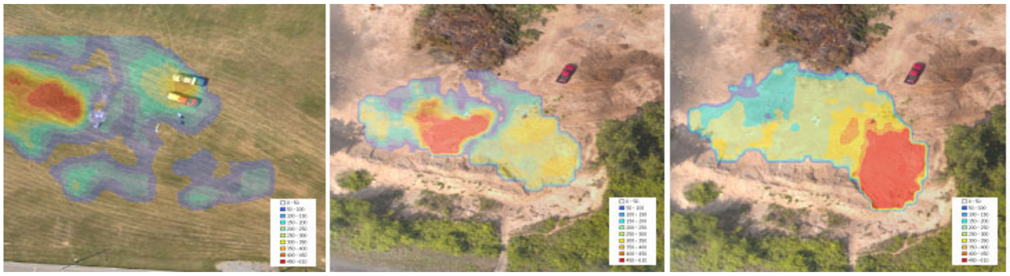
On June 30, 2005 a series of controlled releases of propane gas were staged in Spencerport, New York. At the Spencerport site, two separate propane release locations were used. One release location was located in the middle of a mowed grass field, and the second was positioned in a nearby sandpit. Two sites were selected to provide both a high reflectivity (sand) and low reflectivity (grass) background for the propane releases. The controlled gas release setup at the Spencerport site was created by routing a metered compressed cylinder gas flow through Tygon tubing to a release site marked with an aerial survey target. A pile of gravel on top of the tubing was used to diffuse the gas at the release point. Propane plumes were created for the test by opening the valves of the propane cylinder 60 seconds prior to the overflight. As with all of the HALOS flight tests, air to ground radios were used by the ITT ground team to communicate and coordinate with the flight crew on the ANGEL Service aircraft.

After each overflight the propane cylinder valves were closed and the process repeated for additional flights. Fig. 13 shows a typical propane release setup at the Spencerport test site. Portable meteorology stations were set up at each of the two Spencerport propane release locations to record wind speed, direction, and other general meteorological conditions at the time of the overflights. Winds during this collection were calm to weak from the SE.

7.3.2 Flight Test Collection and Results

On June 30, 2005 over a dozen propane releases of various sizes were overflown by the ANGEL Service at the Spencerport test site. In addition, several 'null' runs were conducted to establish a baseline condition. Data from these collects was processed and analysts prepared a variety of color-coded propane plume displays for visual examination/comparison. Examples of the propane plumes detected and imaged during this test are presented in Fig. 14.

Fig. 13. Spencerport propane gas release setup that includes a compressed propane gas cylinder in the foreground connected to a flowmeter by Tygon tubing. Aerial photography target (iron cross) was used to simplify identification of the leak point.



(a) (b) (c)

Fig. 14. Test Site #3, Spencerport, NY: (a) 24 scfm propane leak over grass; (b) 19 scfm propane leak over sandpit; (c) 34 scfm propane leak over sandpit.

In these images the color-coded plumes of propane are clearly visible as indicated by the areas above ~100 ppm-m. The lidar data under analysis in this study included data points that were collected over similar groundcover, therefore, we have processed regions with largely single modal returns independently. Figure 14(a) illustrates such processing for those returns segmented from the grass coverage region of the swath. Further down the flight line, the sandpit region was also independently processed. Ultimately, scene segmentation of this type will be automatically performed to characterize the swath for all different groundcovers. Imagery from the ANGEL high-resolution mapping camera was used as the base layer for these plume display figures. Ground crew vehicles and personnel are clearly visible in these images. Although the ANGEL DIAL sensor was not designed to detect LPG/propane leaks, the DIAL sensor proved to be quite sensitive in detecting propane leaks under a wide range of different conditions.

8 CONCLUSIONS

The goal of this study was to determine if the ANGEL sensor could be used to detect hydrocarbons other than methane. Future DIAL systems will be able to sense methane, gasoline, and propane as well as a wide variety of other hazardous liquid leaks. It is anticipated that future sensors will be lighter, require less power, and be mounted on many different types of manned and unmanned vehicles.

We have demonstrated the effective use of a multi-line DIAL sensor collection and data processing system capable of detecting a wide range of hydrocarbons. Hazardous liquids modeled and measured during the HALOS study included propane, gas condensates, crude oil, and refined hydrocarbons like gasoline, aviation gas, diesel fuel, Jet A, and kerosene. The ITT ANGEL Service’s system has demonstrated the capability of rapidly detecting, measuring, and imaging a wide range of different hydrocarbons while flying at altitudes of 1000 – 2000 feet and speeds up to 150 mph. Flight tests in New York and Texas clearly demonstrate that airborne DIAL systems are capable of detecting and imaging leaks of natural gas, propane, gasoline vapors, and natural gas condensate vapors. Results from the HALOS effort provide a high level confidence for future design of an airborne sensor optimized for the detection of leaks from both natural gas and hazardous liquid pipelines.

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Darryl G. Murdock, Ph.D., Dr. Darryl Murdock is a Remote Sensing and Geospatial Systems professional. He is currently works in Vienna, VA as an account manager for ESRI. He has previously worked as a GIS business owner, specializing in natural resource management. Dr. Murdock was Chief Technologist for the ANGEL program at ITT Space Systems Division, where he was responsible for developing test protocols and testing the various components of the ANGEL collection systems, including the lidar transceiver assembly, digital metric camera, and digital video system. He has worked across the United States and Internationally as a GIS and Remote Sensing consultant. A former Army Aviator, he received his B.S. from the U.S. Military Academy at West Point, M.S. and Ph.D. in Environmental Engineering from SUNY College of Environmental Science and Forestry.

Steven V. Stearns, Ph.D., is Senior Scientist & Principal Investigator for the Airborne Natural Gas Emission Lidar (ANGEL) Service, Space Systems Division, ITT Corporation. He has more than twelve years of experience in lidar, hyperspectral remote sensing and data exploitation. His current area of interest is the use of airborne DIAL for the detection and mapping of airborne plumes of hydrocarbon gasses. He has successfully led a number of contracts with the U.S. Air Force Research Labs, U.S. Department of Energy, and the U.S. Department of Transportation. Dr. Stearns taught undergraduate and graduate geology at the College of Charleston, in Charleston, S.C. His MS and Ph.D. are in Geology from Texas A&M University and his Bachelor

R. Todd Lines, Ph.D., completed a BS in Physics from BYU and his MS and PhD in Physics from New Mexico State University. He began his career working for the Army Research Laboratory, but spent over a decade in the defense industry working for Raytheon and ITT Space Systems Division. Past experience includes work on the National Polar-orbiting Operational Satellite System (NPOESS) and in designing experimental and commercial laser radar systems. Dr. Lines is currently on the faculty at Brigham Young University – Idaho, in the Department of Physics.

Dawn Lenz, Ph.D, received her doctoral degree in astrophysics from the University of Chicago in 1998 with a thesis on numerical modeling of physical processes in the solar atmosphere. She held a National Science Foundation postdoctoral fellowship, 1999-2000, continuing her solar physics research at the Instituto de Astrofisica de Canarias in Tenerife, Spain. She is a consulting engineer with ITT Visual Information Solutions (formerly Research Systems, Inc.), where she designs and develops custom software applications for scientific research, analysis, and data visualization. Her work spans a wide range of scientific and technical fields, including remote sensing, mineralogy, and medical research.

David M. Brown is a PhD candidate in the Department of Electrical Engineering at The Pennsylvania State University. Mr. Brown received his BS and MS degrees from the Department of Electrical Engineering at Penn State University in 2003 and 2005, respectively. He is member of the Communications and Space Science Laboratory at Penn State where his current research interests lie in remote sensing, optics, and electromagnetics. He is a registered EIT in the state of Maryland and the recipient of the Melvin P. Bloom Graduate Fellowship in Electrical Engineering for 2004-2008. Mr. Brown was also the recipient of the SPSEE Graduate Fellowship in Electrical Engineering from 2005-2007.

C. Russell Philbrick, Ph.D., earned BS 1962, MS 1964, and PhD 1966 degrees in Physics from N.C. State University while performing early laser investigations. He was with the Air Force Cambridge Research Laboratory (now AFRL) for 21 years in military and civilian positions where he developed rocket, satellite, and remote sensing techniques for investigations of the composition, structure, and dynamics of the atmosphere and ionosphere. Dr. Philbrick joined Penn State University in 1988 as Professor of Electrical Engineering and lectures in areas of optics, space physics, electromagnetics, and laser remote sensing. For the past 30 years, he has been one of the leaders in developing lidar techniques, and his research group has carried out many investigations of atmospheric properties and processes using lidar for the DoD, NSF, EPA, DOE, and other agencies. Dr. Philbrick was the principal technical advisor on lidar for the ITT group during the development of the ANGEL system. He has served as principal advisor for graduate degrees of more than 50 students, many senior honors theses, as well as faculty advisor for several student projects that prepared and launched instruments on space shuttle, rockets, and satellites.