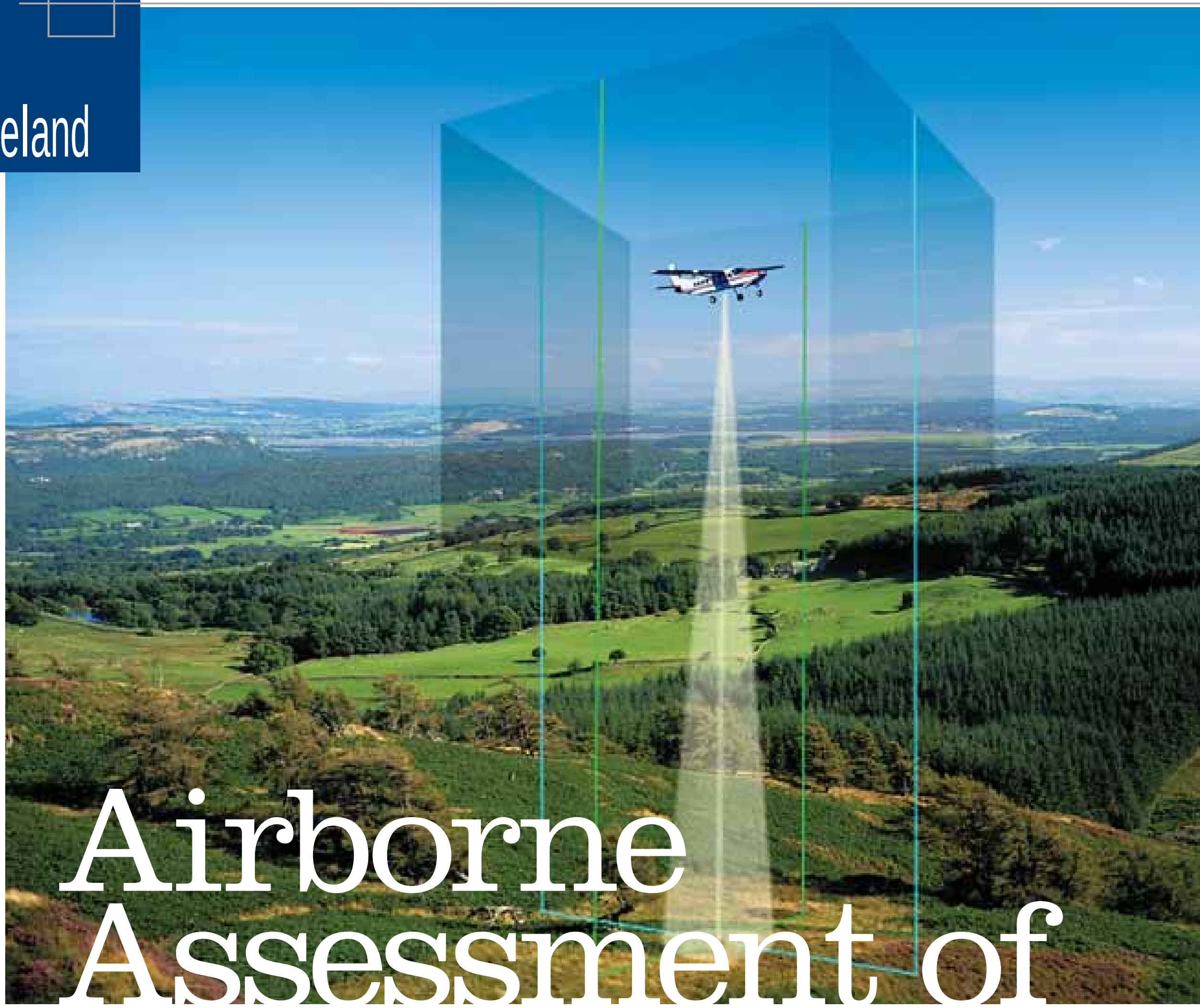

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Airborne Assessment of Pipeline Integrity

A cooperative research agreement has yielded an airborne sensor system capable of detecting and locating gas leaks from a quarter-mile high while cruising at 150 miles per hour.

STEVEN V. STEARNS

When ITT Industries Space Systems Division set out to develop the Airborne Natural Gas Emission LIDAR (light detection and ranging) system, also known as ANGEL, its goal was to provide remote detection of natural-gas leaks from transmission pipelines. Developed and tested under a cooperative agreement with the U.S. Department of Energy's (DOE's) National Energy Technical Laboratory (NETL) and the U.S. Department of Transportation's (DOT's) Research and Special Programs Administration (RSPA), the ANGEL system demonstrated its ability to do so during extensive test flights conducted in September 2004.

Specifically, during its first test flights at the Rocky Mountain Oilfield Testing Center (RMOTC), the service used advanced optical remote sensing tech-

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nology to inspect natural-gas transmission pipelines — detecting, quantifying, and reporting the precise locations of leaks from a quarter mile overhead while traveling at speeds of 150 miles per hour. The ANGEL system detected leaks from the greatest distance, at the fastest speed, with the largest detection swath, and the highest sample rate compared with other systems being tested.

Some of ANGEL's capabilities actually exceeded expectations, and the overall results yielded valuable data that will allow us to further enhance the system's future performance. With calibration, for instance, we believe that the system could detect other types of hazardous gas emissions. In an era in which monitoring and safeguarding critical infrastructure has become a top national priority, ANGEL's demonstrated and potential future capabilities could help meet a variety of key homeland-security requirements.

Anatomy of an ANGEL

ANGEL is an integrated system comprising data collection from airborne sensors, as well as ground-based data processing and analysis. The ANGEL service delivers preflight mission planning, airborne survey for emissions, postflight data processing and analysis, and both standardized and customized reports.

The system's airborne component includes a differential absorption LIDAR (DIAL) sensor, imaging camera, computing hardware and software, and a navigation package that uses an integrated Global Positioning System (GPS) and inertial measurement unit (IMU). The ground portion, developed in conjunction with ITT Industries' subsidiary RSI (Research Systems, Inc.), consists of a set of networked computer servers and workstations that provide the mission planning data required to perform the airborne survey. This same system is then used to process, analyze, archive, display, and distribute the survey results to customers.

We employed the DIAL sensor because it delivers superior sensitivity, which translates into more accurate detection of very small leaks and a low frequency of false positives. The system's tuned lasers can detect, quantify, and discriminate both methane and ethane. To geolocate the leaks, DIAL measures the time-of-flight for the emitted laser pulse to strike a point on the surface of the Earth and return. The GPS/IMU subsystem provides the precise time and location at which the pulse returns. These two pieces of information can be used to determine the absolute position of the gas. The data collected by the system is used to create a three-dimensional digital elevation model of the pipeline and any leaks detected.

In addition to the emitter/detector, the sensor system incorporates active pointing and scanning subsystems. The pointing subsystem tracks the lasers to the pipeline right-of-way (ROW) according to the preloaded mission-planning data. This enables the system to precisely track the pipeline without human intervention, automatically compensating for aircraft motion (position, pitch, yaw, and roll) based on the integrated GPS/IMU. The scanning subsystem paints the ROW with a series of laser pulses, acquiring as many as 6,000 individual surface measurements per second.

As the DIAL sensor searches for leaks, the system simultaneously collects continuous, high-resolution images of pipeline routes. Georeferenced, color imagery more fully identifies pipeline threats and risks, giving context to the leak-detection data.

Mission Profile

Each flight begins with the creation of a mission plan. Using GIS, a mission planner creates a target file consisting of a set of GIS points that define the position of the pipeline ROW in *x*, *y*, *z* space. Precise GIS data are essential to directing the pointing and scanning subsystem and accurately flying the pipeline. Thus, before the mission-planning process can be complete, any pipeline position data with unknown or insufficient accuracy must be field verified using GPS or other standard field-survey techniques.

For a typical flight, an operations center delivers the mission-planning data for a selected pipeline to the flight crew. These data are loaded into the airborne system. The pilot then flies the preselected route while the payload ingests and records real-time position and attitude data produced by the onboard GPS/IMU. This positional information ensures the continuous collection of raw sensor data along the route.

This flight-deck view shows the ANGEL test aircraft in flight.

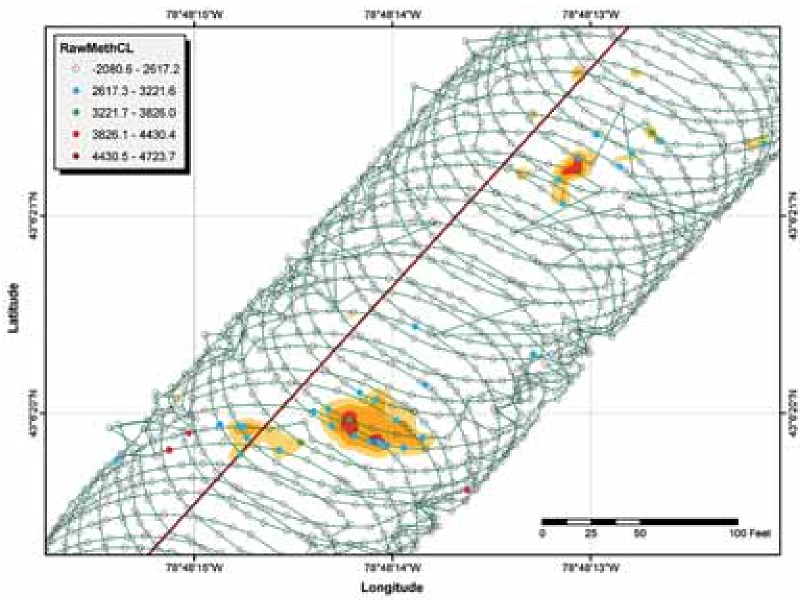
Meanwhile, the DIAL sensor collects spectroscopic measurements along the pipeline corridor. Each individual sample consists of three laser pulses, called *pulse triplet sets* (PTS), which are transmitted to the ground and then reflected back to the payload where they are detected.

When the ANGEL system was tested at RMOTC, these PTSs were generated at a pulse-repetition frequency (PRF) rate of 1,000 Hz. The PRF of the sensor is adjustable between 1,000 and 2,000 Hz. The desired information is collected along the pipeline corridor by combining the PRF with the linear motion of the aircraft and by targeting the pipelines with the pointing mechanism and the conical scanning of the laser beams (see Figure 1).

At the end of a flight, the DIAL data, continuous aircraft positional data (including yaw, pitch, and roll from the GPS/IMU), sensor performance data, and such metadata as atmospheric pressure and temperature, are taken from the aircraft on a removable hard drive. On-board digital camera data used to record imagery of the survey route in real time is transferred to a writeable DVD as a separate dataset. The complete data package is removed from the airborne system and delivered to the operations center for processing and analysis.

Postflight Deliverables

In the operations center, data are transferred from the removable hard drive and archived to ground storage disks. The sensor data are processed using a proprietary DIAL/LIDAR algorithm set.



▲ **FIGURE 1.** Conical scan display. Points are color-coded to reflect the measured concentration wavelength values for methane and ethane.

During initial processing, data points are geolocated and assessed for the presence of the natural gas. The level of gas detected is computed as a concentration path length, which is a concentration multiplied by a slant range distance measured between the sensor and the target.

Two products result from the processing:

- GIS (geographic information system) shapefiles that are analyzed to create customer reports
- Engineering data that detail sensor and related subsystem performance.

The engineering information is used to assess data quality and to compensate for various environmental, surface, and operational variables that can affect data interpretation.

The GIS shapefiles are used to create geolocated graphical and tabular reports using proprietary ANGEL Pipeline Visual Inspection and Analysis Software (APVIAS). Based on RSI's ENVI and IDL software platforms, APVIAS was customized specifically to analyze and interpret ANGEL data. With this custom program, the ANGEL data are fully georeferenced, allowing analysts to overlay the data on other georeferenced images or digital elevation models to aid in interpretation.

Maps of concentration path lengths can be used to create a graphic that can be interpreted visually, or the data can be run through additional algorithms to identify the presence and quantity of natural gas (see Figure 2).

ANGEL Takes Wing

The September 2004 DOE/DOT field testing was organized and run by the Southwest Research Institute in cooperation with NETL, RSPA, RMOTC, pipeline industry advisors, and various providers of remote sensing systems. Six industry and government groups also tested their solutions for remote gas-leak detection during the September event. Participants fielded a range of sensors operated from ground vehicles, fixed-wing aircraft, helicopters, and unmanned aerial-vehicle platforms.

The field test site is a 10,000-acre operating oil field featuring some 1,200 well bores and approximately 600 producing oil and gas wells in nine reservoirs ranging in depth from 500 to 5,000 feet. The test organizers set up a virtual pipeline route 7.55 miles long and created a series of leak sites along the route to simulate pipeline leaks ranging in size from 1 to 5,000 standard cubic foot per hour (scfh). With the exception of a known calibration leak on the southern end of the test course, the size and location of each of the leak sites for this blind test were hidden until after the test participants submitted a final leak-detection report. Further adding to the challenge were windy condi-

◀ **FIGURE 2.** Among the products generated from the pipeline survey is an online report of natural-gas emissions detected.

tions and the daily changing of leak rates and locations.

The ANGEL system was flown at every opportunity throughout the week long test period, accumulating a total of 11 flights and 58 field passes. Data were collected during every flight, averaging about 80 GB of data per day. The test aircraft was able to inspect the entire 7.55-mile virtual pipeline route in approximately five minutes. The ANGEL aircraft typically made seven complete passes over the route in each 50-minute window. Although the virtual pipeline contained several relatively sharp turns, the ANGEL sensor's intelligent pointing and scanning system and pilot guidance system enabled successful coverage of 100 percent of the pipeline route.

During each pass, the sensor measured the amount of methane more than 250,000 times, which made it possible to create a methane map for the entire length of the pipeline. Emissions were detected at various locations along the virtual pipeline on four separate days. Results were reported as "high confidence" when signals indicating high concentration path lengths were detected on multiple passes.

Following submission of the final report, test managers gave participants the actual location and size of the leaks. The data in Figure 3 summarizes leaks detected and reported by ANGEL during the course of the week, combined with the actual number of leaks created and detected overall. In addition to the larger leaks discussed in the table, ANGEL detected elevated amounts of methane at a lower level of confidence.

Building on a Solid Performance

Overall, ANGEL's performance was very good. In spite of some known limitations going into the testing — all of which have been addressed — the system successfully demonstrated its ability to point, scan, detect, quantify, geolocate, and ultimately provide a comprehensive visualization of pipeline gas emissions in a rugged, natural environment.

ANGEL was the only system tested to autonomously point the detection lasers via GIS/GPS data, autonomously scan the detection lasers in a 100-foot

GLOSSARY

ANGEL: Airborne Natural Gas Emission LIDAR

APVIAS: ANGEL Pipeline Visual Inspection and Analysis Software

DIAL: Differential Absorption LIDAR

DOE: Department of Energy

DOT: Department of Transportation

GIS: Geographic Information System

GPS: Global Positioning System

IMU: Inertial Measurement Unit

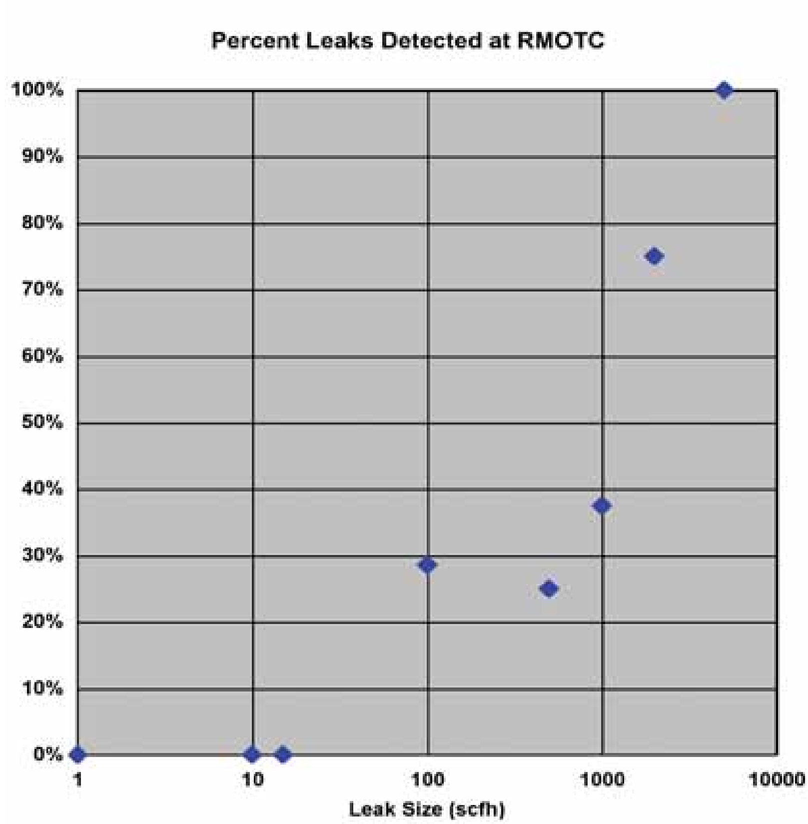
LIDAR: Light Detection and Ranging

PRF: Pulse Repetition Frequency

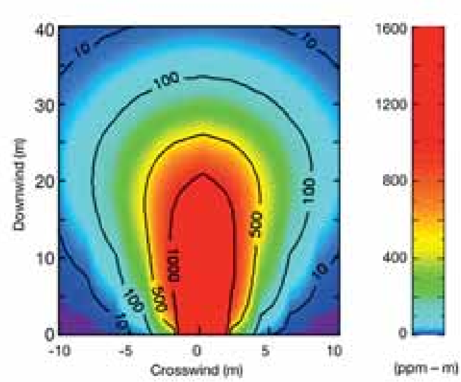
PTS: Pulse Triplet Sets

RMOTC: Rocky Mountain Oilfield Testing Center

ROW: Right of Way



▲ FIGURE 3. A four-day summary of the preliminary RMOTC field-trial results.



▶ FIGURE 4. The ANGEL system detects, quantifies, images, and maps concentrations of both methane and ethane.

swath, collect high-resolution imagery of each mission, provide detailed visualization of detected gas plumes, and provide a comprehensive customer report of results (see Figure 4). Despite the relatively windy conditions, the ANGEL sensor successfully detected more than half the leaks of 500 scfh and higher.

On completion of the testing, the ANGEL system was returned to our lab where improvements were made to address the limitations uncovered in the testing. The improvements made include

- More than doubling of the laser output operating power to enhance detection of low-end gas,
- Enabling the system to be tuned to different absorption frequencies to detect other substances. Detection of ethane with methane is a telltale sign of natural gas and significantly reduces the potential of false alarms caused by various and abundant natural sources of methane.
- Improvements to the performance of scanner optics to improve signal to noise performance.

Based on these and other improvements, we believe that ANGEL could replace existing leak-detection methodologies.

Future Uses of the Technology

The DIAL technology used in the ANGEL system has a variety of uses beyond inspecting natural-gas transmission pipelines. Potential uses include inspecting natural-gas gathering fields, gas-storage facilities, and detecting emissions of natural gas associated with coal-bed methane resource development. Another possibility is detecting and mapping natural-gas seepage that is indicative of undiscovered oil and gas reservoirs.

In October 2004, the DOT/Office of Pipeline Safety RSPA awarded ITT with funding to explore the possibility of using the ANGEL system to detect leaks from hazardous liquid pipelines. During the next year, the ANGEL system will be flown over a variety of simulated leaks of hazardous liquids, such as propane, gasoline, and diesel fuel. As part of this effort, ITT scientists and engineers will use the resulting data to explore ways to create a remote sensing system optimized for the detection of various hazardous liquid pipeline leaks.

Manufacturers

Developed by **ITT Industries Space Systems Division,** ANGEL's airborne component uses a DIAL unit from **Coherent Technologies, Inc.,** with inertial and position measurements provided by an **Applanix** POS/AV, which in its current version contains a **Trimble** BD950 GPS L1/L2 receiver. The ground portion of the system was configured by ITT Industries' subsidiary **RSI–Research Systems, Inc.** Data interpretation relies on APVIAS, which RSI developed based on its ENVI and IDL software platform. Mission planning and postflight analysis uses ArcGIS from **ESRI.** ⊕