<u>Technology Status Report</u>

on

Active Remote Detection of Natural Gas Pipeline Leaks

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U.S. Department of Energy
National Energy Technology Laboratory
3610 Collins Ferry Road, P.O. Box 880
Morgantown, WV 26507-0880

Steven V. Stearns and Raymond T. Lines
Eastman Kodak Company
Commercial and Government Systems
1447 St. Paul Street
Rochester, NY 14653
steven.stearns@kodak.com

Christian J. Grund
Coherent Technologies Inc.
135 S. Taylor Avenue
Louisville, CO 80027
chris.grund@ctilidar.com

and

C. Russell Philbrick
Penn State University
Department of Electrical Engineering
University Park, PA 16802
crp3@psu.edu

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ABSTRACT

Active remote sensing technology and hardware is now becoming sufficiently advanced for true commercial implementation beyond the purely laboratory R&D applications that have been developed over the past two decades. Optical remote sensing technologies using active techniques for the detection of natural gas leaks have recently attracted a great deal of attention throughout the natural gas pipeline industry. Funding over the past several years from both private industry and various government agencies has supported the development of a range of active remote sensing techniques for a variety of applications including the measurement of weather parameters, measurement of chemical species, and remote sensing techniques which involve mapping of terrain. Active sensing techniques provide a number of advantages in the areas of sensitivity, specificity, rapid response, large area coverage, and efficiency, combined with the ability to achieve extremely low false alarm rates. Here we provide a brief overview of the science behind the various active sensor technologies, and discuss the additional hardware components required to create an integrated system designed to monitor leaks in natural gas pipelines to meet the requirements for pipeline integrity, safety, and security.

INTRODUCTION

Over the past several years a number of studies have been funded to examine the advantages and disadvantages of active and passive remote sensing approaches for the remote detection of natural gas pipeline leaks [1,2]. These studies clearly indicate the limitations of using passive techniques to detect small pipeline leaks. Here we will limit the scope of our work to a discussion of the numerous active techniques which could be applied in the detection of natural gas pipeline leaks and discuss other critical components which would likely be required in the construction of a commercially viable pipeline leak detection system.

SPECTRAL OVERVIEW

The most effective signatures available for discrimination and identification of chemical species are found in their infrared spectra. The infrared spectra provide unique signatures because of the range of various vibration frequencies and rotation modes caused by their different mass components, moments of inertia, and molecular bond types and strengths. Because of the many unique energy levels existing within the molecular dynamical states, the optical wavelengths can be used for remote detection of chemical species in the presence of most other chemicals, and the remote detection can be used in a wide range of environmental conditions.

The spectral regions available for active remote sensing are limited to the windows of the optical spectrum. Several regions of the spectrum are not useful because of the strong absorption of radiation by the molecular species that are normally present in the atmosphere. Figure 1 shows the transmission ‘windows’ of the optical spectrum in the near and mid-infrared regions that can be used for identifying chemical species. The subject of remote detection of chemical species has been discussed in many references that demonstrate the use of both passive and active instruments for detection of the presence of chemical vapors and for mapping the image of their spatial distribution [3 – 8]. In some cases, the quantitative measurements of concentration of chemical species have also been demonstrated.

The important hydrogen bonds associated with CH stretching vibration in hydrocarbon species are responsible for the spectral features in the 3 to 3.5 µm (3400 – 2700 cm^{-1}) region that are most useful for measuring the methane and ethane components in natural gas. The methane spectrum for natural background levels is shown if Figure 1 and the primary absorption features associated with a variety of functional groups are shown in Figure 1.

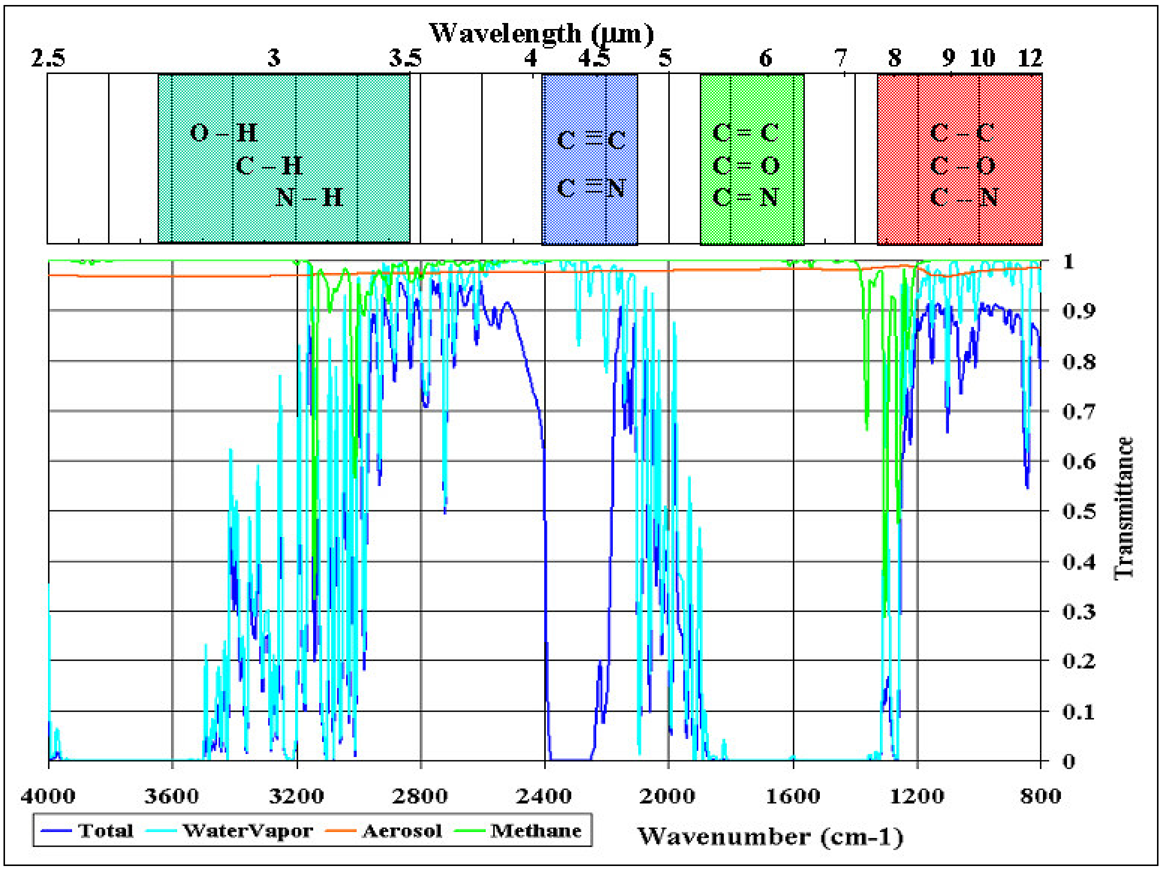


Figure 1. The transmission windows of the optical spectrum between 0.5 µm and 10 µm from calculations using the MODTRAN model show the principal useful windows of the optical spectrum; visible wavelengths below 1.4 µm, 1.5-1.8 µm, 2-2.5 µm, 3-5 µm, and 8-16 µm. The most important spectral range for the hydrocarbons (C-H) and a variety of other functional groups are shown at the top of the figure.

DETECTION OF NATURAL GAS PIPELINE LEAKS

The leak from a buried gas pipeline can range from minute concentrations to levels that can cause explosions. The need to monitor leaks and maintain pipeline integrity and safety, as well as prevent loss of product, places an emphasis on the development of new detection capabilities. The typical composition of natural gas pipelines is about 96 % methane, 3% ethane and 1% from many other components. The concentration of methane in a leak plume are well above the levels of ~1.7 ppm that is typical in the background atmosphere. The methane background concentration can vary by up to an order of magnitude when local sources of animal feedlots and active swamp-gas sources are considered [9]. The ethane levels may vary by a percent or two in the pipeline concentrations, but the background sources of ethane are insignificant.

The plumes that are formed by leaks can appear quite differently depending upon the soil characteristics where the pipeline is buried. The voids and porosity of the ground can result in point source or distributed source features at the surface, and the location of the source can be shifted several meters from the actual location of the leak. Plumes from pipeline leaks may occur at various leak rates and under a range of atmospheric conditions that may require sensors to perform in situations corresponding to leak rates ranging from 1 – 10,000 standard cubic feet per hour (scfh). Methane plumes from natural gas leaks are expected to create elongated ground-hugging plumes that extend 10s of meters downwind from the leak site. Models indicate that natural gas plumes created from buried pipeline leaks are relatively stable and that even moderate wind conditions (<10 mph) do not appear to rapidly dissipate the gas plume.

Weather is an important consideration for monitoring the vapor plumes which result from pipeline leaks. Plume modeling has demonstrated that winds below 10 mph do not have a major effect on detection of plumes from leaks larger than 100 scfh. Therefore, light wind is not a major consideration in system performance. Table 1 lists some additional atmospheric conditions that may affect the measurement, such as haze, dust, drizzle, snow, and fog. With the exception of fog, none of these conditions reduce the reflected signal by more than a factor of two and, therefore, will have little impact on the measurement. Fog, on the other hand, can have a serious impact, and will severely limit sensor performance of all active optical remote sensing techniques.

Table 1. Atmospheric weather conditions effect on optical transmission [11].

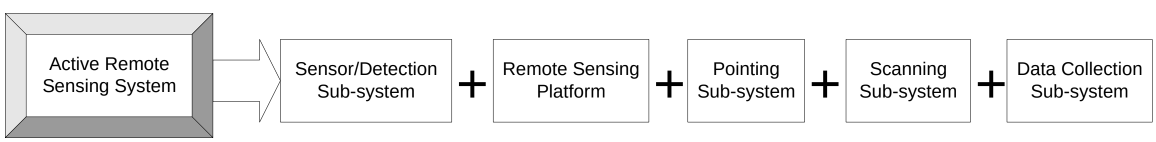
Environment Conditions	Two-way transmittance (from 500m altitude)
Desert haze	96%
Maritime haze (IC=10)	95%
Heavy dust	75%
Smoke	75%
Drizzle (2 mm/hr)	50%
Snow (0.01 g/m3)	65%
Fog (1 km vis.)	1%

Background reflectance is a critical value in the system design because of the need to take advantage of the sensitivity gains from using a hard target return. There is no need for range resolved analysis of the gas leak plume because the plume is expected to be near the ground and analysis to quantify the leak rate will use the integrated path concentration (ppm-m). Table 2 lists reflectance values for various surfaces in units of inverse steradians. The values in the figure vary from 0.004 to 0.071. Green grass is one of the least reflective of common background materials. If the system can work with a grass background, it should work with any of the backgrounds listed

Table 2. Nonconventional Exploitation Factors Data System (NEFDS) database values for reflectance (in units of inverse steradians) [10].

Material (NEFDS ID)	NADIR Reflectance (near 3000 nm)
Clay soil (0105)	0.071
Sandy loam soil (0128)	0.016
Sand soil (0145)	0.058
Volcanic rock (0534)	0.15
Frost (9004)	0.004
Coarse snow (9007)	0.01
Green Grass (9010)	0.0046

OVERVIEW: ACTIVE REMOTE SENSING SYSTEM



An active remote sensing system must incorporate and integrate a number of critical sub-systems beyond the sensor/detection components. A traditional systems engineering approach should be taken to understand these various sub-systems and their importance in the overall effectiveness of the complete system.

1 – SENSOR/DETECTOR SUBSYSTEM

Optimal design of a remote sensing system involves a thorough understanding of the collection requirements and trade-offs of many inter-related parameters. Size of the target, distance from sensor to target, sensitivity, detector integration times, and environmental constraints must all be considered among other parameters. Many types of active sensors can be applied to the problem of remote natural gas detection. A brief description of these types and how they address major issues of collection follows.

Radar Imaging is an attractive remote sensing technology because of its all-weather capability and because existing weather radar systems can be leveraged [9-10]. Radar can be designed to perform detections over large distances; however, radar cannot directly detect natural gas. Instead, the radar measures fluctuations in the atmospheric refractive index due to the presence of the plume. Since these fluctuations can be created or modulated by other factors, there is a high probability of false alarms [11-12]. Thus radar imaging may suffer poorer sensitivity.

Backscatter Absorption Gas Imaging **(BAGI)** is another promising technique[13-14]. It is similar to DIAL but only uses one wavelength. An area is imaged which may contain the target gas. Where the gas exists, the image is dark. This technique is good because it directly detects the gas. However, without an additional reference BAGI technique does not quantify concentrations. BAGI techniques also have trouble distinguishing between deep shadows and actual methane gas detection. Low reflectivity pixels are also a problem for detection. These problem areas make detection of smaller plumes difficult. The need for wide area illumination will limit sensor to target range.

Active Gas Correlation Spectroscopy **(AGCS)** has been investigated as a solution to gas and vapor detection. Gas correlation spectroscopy has been used to detect gases from ground [15-17] and space platforms[18]. By adding an intense broadband light source, the sensitivity of the technique is increased. Broadband illumination is somewhat limited because the transmitted energy is necessarily spread over both peaks and valleys of the absorption spectrum, significantly reducing the observed gas contrast. The broader bandwidth also raises the potential for interferences from other species

Differential Absorption Lidar (DIAL) Remote sensing based on the differential absorption lidar (DIAL) technique offers high sensitivity, particularly for the surface reflectance DIAL. .[19-24] This technique uses two closely spaced wavelengths, which are selected so that one matches a prominent absorption line and the other lies off the absorption feature. Both wavelengths are transmitted simultaneously, or nearly so, to essentially freeze any variations in the atmospheric path, the signal plume distribution, and the surface reflectance. The DIAL technique requires lasers tuned to individual narrow spectral bands, adding complexity. However, modern high power tunable laser systems make this technique practical with low integration times and high sensitivity.

Raman Lidar Techniques make use of the signals resulting from a change in the wavelength of the scattered photon that leaves the molecule in a higher energy state (Stokes), or takes energy from the molecule (anti-Stokes). The Raman scatter signals from vibrational scattering can be used to measure the concentration of a molecular species and rotational scattering signals can be used to profile the temperature. A laser pulse scattered from a volume can be used to simultaneously measure the profiles of water vapor, ozone, temperature, and optical extinction [19,25-27]. The Raman technique is the most robust for measurements of species concentrations because only one laser is used and the results are obtained directly from simultaneously measured signals at Raman shifted wavelengths. However, the smaller Raman scattering cross-sections result in lower sensitivity. Analysis techniques use ratios of the signals to remove any dependence on transmitted power, transmitter and receiver efficiencies, and optical path.

Laser Induced Fluorescence (LIF) instruments have important capabilities for detection of certain chemical species, such as the aromatic hydrocarbons, but are less able to quantify the concentration [19, 28]. The LIF techniques have been successfully used to measure the distribution and relative concentration of oil spills on the surface of water. LIF techniques often use UV excitation which may limit sensor effectiveness in areas with organic material on the ground as many organic substances tend to fluoresce in the UV.

2 - REMOTE SENSING PLATFORM

A number of active remote sensing natural gas detection systems have been built in the last few years or are currently under development. These include hand-held single point systems, tripod mounted sensors, truck mounted sensors, and sensors designed to be mounted in aircraft. The selection of the appropriate platform is largely dependant on the size, weight, power, and other requirements of the sensor. The choice of the platform in turn is a major component of the ultimate utility of the sensor system as a whole. Over the past decade, active remote sensing systems have become light and powerful enough that they can be designed to be mounted in a number of lightweight rotary wing or fixed wing aircraft.

The greatest strength of rotary wing aircraft is their maneuverability and ability to closely follow a twisting pipeline right of way (ROW) at relatively low altitude (20-100 feet if required). In addition, when a leak is detected, the helicopter can hover over and even land on the pipeline ROW to effect repair if necessary. Rotary wing aircraft would be the platform of choice for sensors requiring a long integration time or lower powered sensors with a limited range. The disadvantages of using a helicopter for a commercial leak detection system are that helicopters are slower than fixed wing aircraft and thus less efficient, they are more susceptible to mechanical failure, significantly more expensive to purchase, operate, and repair, are more difficult to operate in hazardous weather conditions, and, in general, have a poorer safety record than fixed wing aircraft. Although the background levels of methane in the atmosphere severely limit the detection of small leaks from altitudes of greater than a few thousand feet, flying a helicopter too close to the ground significantly increases pilot workload and is risky.

For higher powered sensors with more range, a fixed wing aircraft may be a better solution. One major advantage of selecting a light, fixed wing aircraft as a platform is economics. Light fixed-wing aircraft are significantly cheaper to own and operate than helicopters. As a general rule the smaller the aircraft the more economical. Fixed wing aircraft can also operate at over twice the speed of rotary wing aircraft. Though survey speed has some advantages, it should be noted that not all sensor techniques are photon-efficient to simultaneously satisfy the required survey speeds and leak sensitivity for methane detection, and some would be impractical for ethane detection at high speed. Ferrying a fixed-wing aircraft from job to job and day-to-day operation of the system would be significantly easier and safer due to the ability of fixed wing aircraft to fly in a wider range of hazardous weather conditions including icing conditions.

3 - POINTING SUBSYSTEM

An active remote sensing system would be further strengthened by the inclusion of a real time "intelligent pointing system" which could continually point the sensor at the pipeline ROW and guide the pilot. A pointing system provides several advantages. The first is that advanced pointing systems loaded with a 3-dimensional digital map (GIS) of the pipeline route would allow the pilot to efficiently fly pipelines in areas where the pipeline ROW is difficult or impossible to locate from the air. Natural gas pipelines are typically buried and even well marked pipeline right-of-ways (ROWs) can be difficult to accurately follow from the air. Pipeline ROWs in urban areas, agricultural, or arid regions are particularly difficult to follow as they often lack a well-defined ROW. A second major advantage of a pointing system is that an aircraft so equipped could be designed to effectively operate at elevations of over 1200 feet AGL and thus allow the pilot to avoid much of the turbulence of the air in the near-ground boundary layer. In addition, over areas of land with relatively flat terrain, a combined active sensor pointing system and pilot guidance system may even allow a pipeline to be flown at night. Due to generally lower wind speeds and atmospheric turbulence at night, night flying may allow the detection of very small leaks which would be difficult to detect in the daytime.

4 - SCANNING SUBSYSTEM

Combining a sensor with a scanning or flood illumination system with a wide swath width will greatly improve the performance of the system by allowing broad ROW coverage. Pipelines in the US are generally buried in the middle of a 50 to 250 foot wide ROW. Gas from a leaking pipeline can at times migrate underground some distance from the pipe so sensing for the presence of leaks across the entire width of the ROW will reduce the chance of missing the plume. In addition, changes in the wind speed and direction will change the size, shape, and orientation of the plume within the ROW.

Scanning a pulsed laser back and forth or flood illuminating a wide swath as the aircraft flies along the ROW would allow the creation of a digital image of a leak plume. Imaging the plume should significantly reduce the false alarm rate by providing information of plume size, shape, and location in addition to the concentration path length of the plume. The resolution and sensitivity of such an active imaging system would be largely dependant on the power available to the sensor system. More power to the sensor would allow the creation of a wider swath as the aircraft flies along the ROW. A higher pulse repetition rate will also allow a higher resolution sampling of the ROW when using a pulsed laser source.

5 - DATA STORAGE SUBSYSTEM

The ability to collect and store sensor readings and positional data as the aircraft flies along the pipeline will allow post-processing of data and creation of a geo-referenced digital images of natural gas leaks along the length of the pipeline. Accurate collection and archiving of high resolution digital leak data from many miles of pipeline will allow the possibility of change detections for the pipeline as the pipeline is flown year after year. Sensors providing broad ROW coverage will be collecting data at the rate of 10s of gigabytes/hour and will also require significant onboard sensor data storage.

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