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Feasibility of Microwave Interferometry and Fourier-Transform Spectrometry for High-Spectral-Resolution Sensing

Sig Gerstl*, Bradley Cooke, Abram Jacobson, Steven Love, and Andrew Zardecki

Abstract

This is the final report of a one-year, Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). The primary objective of this project was to perform the necessary research and development to determine the feasibility of new ideas that, if successful, could lead to the development of future new programs in high-spectral resolution remote sensing. In active remote sensing systems, the solar illumination of a scene is replaced by a man-made source, preferably a laser beam. However, when laser beams are propagated through a scattering medium, like air, random optical path fluctuations comparable to the optical wavelength are generated giving rise to the speckle effect, which is the most severe perturbation in active remote sensing systems. The limitations introduced by the speckle effect degrade or negate the data interpretation. We sought to introduce better physical models of beam scattering that allow a more realistic simulation environment to be developed that, when applied to experimental data sets, improve their interpretability and increase the information content. Improved beam propagation models require improved knowledge of the spatio-temporal distribution of the scattering and absorbing medium. In the free atmosphere the largest contributor is water vapor in the lower troposphere. We tested the feasibility of using microwave interferometry to measure water-vapor irregularities in the boundary layer. Knowledge of these distributions enable much improved atmospheric correction algorithms for satellite imagery of the earth's surface to be developed. For hyperspectral active remote sensing systems it is necessary to perform very high-resolution spectral measurements of the reflected laser light. Such measurements are possible with optical interferometers.

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1. Background and Research Objectives

Natural gaseous constituents in the atmosphere as well as gases from anthropogenic and natural emissions are a topic of growing importance in environmental and global change science. World population growth and increasing industrialization are increasing the concentrations of atmospheric pollutants such as NO_x , SO_x , O_3 , etc., while natural sources such as volcanoes, the biosphere, and forest fires contribute significantly to the overall gas concentration balance and must be considered in how they influence the global radiative energy balance.

Most gases of interest have distinctive absorption features in the mid- to long-wave infrared, making it possible to identify and quantitatively detect their concentrations by spectroscopic means. We have demonstrated the feasibility of a high-spectral-resolution, Fourier-transform interferometer (FTIR) to make such measurements with the desired accuracy. Such passive detection and identification of atmospheric gases using non-imaging spectrometers is a relatively straightforward and well-established, but also somewhat limited, technique. Within the last few years, however, infrared (IR) detector technology has advanced to the point that imaging spectrometers capable of mapping large areas of the Earth's surface are now becoming practical.

2. Importance to LANL's Science and Technology Base and National R&D Needs

This project supports Los Alamos core competencies in earth and environmental systems as well as complex experimentation and measurement. This work has broad applications to Los Alamos programs including nonproliferation, defense, arms control verification, environmental sciences, and geophysics.

3. Scientific Approach and Results to Date

In this feasibility study, we performed field experiments with an FTIR that characterized the sensitivity requirements, signal-to-noise levels, and temperature dependencies of the detectability of gases within controlled plumes from various observation distances. High-resolution gaseous absorption spectra were measured for ethylene, 1-butanol, carbon tetrachloride, and others at a stand-off distance of 500 m. The critical parameter that determines the contrast of the gas spectra versus the ambient background was the temperature difference between the plume and its background, which ranged between 15 K and 4 K. These

FTIR measurements proved the feasibility of quantitatively detecting the presence and amount of gases in a defined plume when there exists a significant temperature difference between the plume and the ambient atmosphere.

In the free atmosphere, the largest contributor to scattering and absorption of radiation in the atmosphere is water vapor in the lower troposphere. Water vapor irregularities in the atmospheric boundary layer and the troposphere play a significant role in the dynamics of vertical energy transport and coupling and a disturbing role for satellite remote sensing, making atmospheric corrections a necessity for most satellite imagery. Knowledge of these water vapor distributions enables much improved atmospheric correction algorithms for remotely sensed surface images. We have tested the feasibility of using microwave interferometry to determine the existence and extent of these water-vapor irregularities in the atmospheric boundary layer.

The National Radio Astronomy Observatory (NRAO) has provided us access to an unparalleled database of about 200 hours of zenithal point-source observations at 5 and 15 GHz. This dataset has been used in our feasibility study to describe the horizontal structure function of column water vapor. Present indications are that the technique works and that it is likely more accurate than other presently employed methods.

In active remote sensing systems, the solar illumination of a scene is replaced by a man-made source, preferably a laser beam. However, when laser beams are propagated through a scattering medium, like air, random optical path fluctuations comparable to the optical wavelength are generated, giving rise to the speckle effect, which is the most severe perturbation in active remote sensing systems. The limitations introduced by the speckle effect degrade or negate the data interpretation. In an attempt to identify remedies for this perturbation, we have developed a new concept that might allow the detection of phase shifts in laser return signals. The technique is based on imaging coherent (laser) light by measuring not only the magnitude of the signal wave front, but also its phase. A theoretical concept has been developed so far, with model calculations that indicate the feasibility of the idea.