ENVIRONMENTAL REMOTE SENSING FOR MONITORING PLANT HEALTH

TECHNOLOGY DESCRIPTION

This project tests many different types of remote sensors, in parallel, and collects optical signatures on populations of plants grown and stressed under controlled conditions to identify the best sensor, or combination of sensors, for detecting the presence of contamination in soil and/or groundwater. Classical as well as novel methods are used for data collection and data analysis (in an effort to make the best use of all the raw data obtained). Data analysis methods include neural net analysis, higher-order derivative analysis, analyzing fluorescence ratios, etc. To understand the entire plant stress picture more completely, the experimental stressed-plant populations are analyzed biochemically, anatomically, and morphologically. In addition to using passive reflectance as a baseline, laser-based technology is being developed as a more chemically sensitive optical probe; new state-of-the-art passive hyperspectral imagers (developed by other laboratories are being tested here) have produced good results.

Laser induced fluorescence (LIF) techniques (hardware, software, methodology, and data analysis) represent the primary part of the technology being developed at Special Technologies Laboratory (STL), but the complete technology being investigated in this project is the remote sensing of plants for underlying contamination. For the LIF techniques, a pulsed ultraviolet laser (normally eye-safe) is used to excite fluorescence in the vegetation being surveyed. The fluorescence is collected spectrally in the 400- to 800-nm region. Data can be collected in full daylight. Sensor standoff can be anywhere from a few feet to hundreds of feet; the sensor system could even be used on a low-altitude airborne platform (it has already been mounted on aircraft more than once).

The data collected are analyzed for indications of stress in the plants that may signify an environmental problem (change detection) such as subsurface contamination. While the experiments of this project concentrate primarily on greenhouse-grown plants, leveraging through contracts with other agencies plus cooperation with other laboratories has already led to several field tests of the LIF techniques developed, and additional field measurements are planned under outside support. The ultimate goal is field deployment of a remote sensing instrument suite for contamination detection, be it identification of problem areas, containment verification, monitoring of phytoremediators, or whatever, through signatures from plants.

TECHNOLOGY NEED

No comparable baseline technology currently exists for surveying large areas for minor to moderately severe subsurface contamination. Passive remote sensing technologies currently in use can see only very severe problems, usually involving dead or dying vegetation. Unless the contamination is extremely heavy, surveys for subsurface contamination most often rely on spot checks using groundwater or soil sampling techniques that generally require laboratory analyses; this makes large-area ground surveys very labor intensive and, therefore, difficult and expensive. A faster, cheaper technique is needed.

Because of the large areas of land involved, some of which are not easily accessible, monitoring based on remote sensing will, in most cases, be the safest and most cost-effective monitoring method. Remote sensing data coupled with ground truth data have been shown to be a cost-effective way to eliminate the need for detailed point sampling of large areas of land. Remote sensing, however, has been limited by the lack of data available for using vegetation cover as an indicator of subsurface and surface contamination. This work is focused on understanding the phenomenological origins of the changes in vegetation that is exposed to contamination. To understand the causes of the observed changes as well as to establish the best remote sensing methods to measure them, more than the traditional remote sensing tools have been used to collect the data needed to develop an understanding of plant health changes. Laser-induced fluorescence was chosen to complement existing passive techniques because fluorescence from plants has been shown to be altered by stresses such as metal contamination.

Collaboration with others has allowed evaluation of state-of-the-art passive hyperspectral imagers alongside the laser-based techniques. The approach of the work is to identify, compare, and develop the most effective vegetation remote sensing technologies for the detection of subsurface contamination at U.S. Department of Energy (DOE) sites emphasizing, but not limiting, the investigations of LIF techniques. In parallel, stressed plants are measured anatomically, biochemically, and physiologically for a better understanding of the complete problem.

The present and future needs for monitoring DOE sites are:

- To detect changes for very long term monitoring of contained sites and stewardship of lands.
- To pinpoint existing contamination in soil/groundwater for later cleanup.
- To periodically monitor contained sites for possible leakage.
- To demonstrate cleanliness of remediated sites.
- To monitor phytoremediators.

Examples of Site Technology Coordination Group (STCG) needs for FY 2000 are:

<u>Long Term Monitoring Needs & Opportunities</u>
SR00-3027 - Long Term Monitoring Technologies
ORBW-08 - Long-Term Performance Assessments
AL-09-02-01-SC - Long-Term Site Monitoring System

<u>Performance Monitoring Needs & Opportunities</u>
AL-07-09-02-SC - Hydrologic Performance Monitoring of Engineered Covers
SR00-3025 - Verification Technologies for *In Situ* Solidification and Stabilization Closure Actions
ORHY-21 - Real Time Performance Assessment Monitoring
OH-F048 - Long-Term Monitoring of Caps and Covers

<u>Characterization Needs</u>
SR00-3023 - Methods for Locating and Stabilizing Buried Solid Waste
RL-SS15 - Improved, *In Situ* Characterization to Determine the Extent of Soil Contamination of One or More of the Following Heavy Metals: Hexavalent Chromium, Mercury, and Lead
ORHY-03 - Noninvasive Technologies to Identify Leaking Utilities
OH-F049 - Non-Intrusive Location of Buried Wastes and Fill Material
OH-AB-007 - Characterization and Management of Mixed Waste from Areas C-Lower/C-West

<u>Science Needs</u>
RL-SS37-S - Monitoring of Contaminants - Chemical Sensor Principles
NV18-0001-07S - Optimized Monitoring of Contaminant Transport and Subsidence in the Vadose Zone of Low-Level Radioactive Waste Sites
ID-S.1.04 - Real-Time Field Instrumentation for Characterization and Monitoring Soils and Groundwater.
AL-09-01-03-SC-S - Succession and Long-Term Performance of Landfill Covers

STL has worked with the Savannah River Site (SRS) on this project and SRS has expressed considerable interest in pursuing remote sensing techniques. STL is currently looking at some of their existing passive multispectral flyover data. The SRS is where we plan to make our first field measurements of stressed versus unstressed plants growing *in situ* at a DOE site. This year, using some of the technology developed in this project, field measurements are planned at the Fort Irwin, California military training center.

BENEFITS

This technology will allow faster, cheaper, and less labor-intensive surveys of large areas (by ground or air) with more complete ground coverage. The new remote sensing methodology being developed will also make it feasible to monitor contained sites regularly at reasonable costs, and will make it possible in many cases to detect contamination problems earlier (than with currently used remote sensing techniques), before the problems manifest as visible dead or dying vegetation. Remote sensing allows better access for certain difficult-to-reach areas (e.g., swampy areas), and reduces or eliminates the time that must be spent by workers in dangerous and/or contaminated zones. This technology also eliminates the need to handle soil or water samples (perhaps contaminated with other things than the expected contaminants) unless indicated for ground truth verification. In fact, unlike water/soil sampling techniques, the remote sensing techniques per se produce *no* waste; it is 100 percent non-intrusive. In summary, the technology being developed will be faster, lower cost, lower risk, than point sampling techniques. It will allow surveys of areas not easily accessible and provide more complete coverage data than point sampling. The technology being developed will also become the baseline technology for environmental surveys where no comparable baseline technology presently exists, and will be especially valuable and applicable in long term site monitoring requirements. The recent increased interest in phytoremediation techniques offers an especially good match for our detection technologies; since a single species is normally used, the complication due to signatures from multi-species plots is eliminated. The technology could be used on phytoremediators for barrier monitoring, contaminant mapping, uptake monitoring, etc. A byproduct benefit will be the stressed/unstressed plant fluorescence data (from LIF methods) which will be available to other researchers in a searchable database.

Group data taken at Epcot Center on two species of plants grown under five different concentrations of stressor chemical. During a one-week period, multiple measurements are made by various researchers. The Laser-Induced Fluorescence Imaging (LIFI)/Laser-Induced Fluorescence Spectroscopy (LIFS) system is under and to the left of the white umbrella, and to the right is the hyperspectral imaging system. Far left and front are where respiration and chlorophyll measurements are taken. Other measurements are not shown (reflectance spectra, excitation-emission spectra, three-dimensional matrix (EEM), plant weight, size, etc., destructive testing for various chemicals, and other measurements), but are performed in this same time period. This DOE work is on view to the general public; e.g., see green-topped tour boat passing by in background.

CAPABILITIES/LIMITATIONS

The primary limitations of the techniques being developed are (1) the lack of actively-induced (laser or otherwise) fluorescence reflecting the plant health and stress data needed to identify contaminant stress in plants; (2) the lack of field experience/data with both laser-induced and passive-hyperspectral techniques. It is not currently known what the techniques can be expected to do in the field, since tests to date have been limited primarily to the laboratory and, at this time, not all comparison data (active versus passive systems) that STL has collected have yet been analyzed, nor have the new data analysis techniques been fully refined. This technology should be effective in soils to depths limited only by the penetration depth of roots. It is not currently known how specific the technique can be made, but it should not be expected to be capable of differentiating between specific contaminants; rather, its primary value will be in (pre visual) change detection. This will depend partly on the results of current investigations of several data-analysis methodologies as well as the outcome of new research indicating that it may be possible to code plants to be responsive to specific contaminants.

COLLABORATION/TECHNOLOGY TRANSFER

Current collaborations are:

- Walt Disney World/Epcot Center: Collaboration and in-kind support including greenhouse space, office space, temperature-controlled labs and chambers, laboratory equipment, consumables budget, and 5 to 10 percent time-use of a plant nutritionist, entomologist, pathologist, technician, horticulturist, engineer, and secretary.
- National Aeronautics and Space Administration (NASA)/Kennedy Space Center and Dynamac Corp.: Collaboration and in-kind support including laboratory space and use of equipment high performance liquid chromatograph, spectroradiometer, pyranometer, microscopes, histology microtome and staining system, balances, etc.), consumables budget, and some personnel support (leaf histology and biochemistry).
- NASA/Stennis, Louisanna: Hyperspectral imaging equipment brought to group data-takes for measurements, with subsequent sharing of information.
- Georgia State University: Visible/near infrared (NIR) imaging system brought to group data-takes at Walt Disney World/Epcot Center with subsequent sharing of information.
- Kansas State University: Plant physiology and leaf biochemistry.
- Florida Institute of Technology: Advanced data analysis.
- Citrus Research Education Center (University of Florida): Plant viruses and tagging plants with green fluorescent protein.
- Strategic Environmental Research and Development Program (SERDP): Funding to test these technologies for measuring stress in desert plant species at Fort Irwin, California.
- Army Corps of Engineers, Topographic Engineering Center, Virginia: Hyperspectral and fluorescence data fusion studies; assisting in putting our measurements in a database usable by anyone.

The SRS has also expressed an interest, and STL is planning an on-site demonstration there. Thus far, Interest about commercial applications has been expressed only through inquiries. There has been no concrete action so far. Interested commercial entities include:

- Walt Disney World Company: Measuring stress in transplanted mature trees.
- Weyerhauser Corporation: Monitoring of timber producing forests.
- Schwartz Electro-Optics: Sensors for agricultural spraying.

ACCOMPLISHMENTS AND ONGOING WORK

A Memorandum of Understanding was initially signed between DOE and Walt Disney World and following this, a plant measurement laboratory was established at The Land in Epcot Center, with a full-time on-site plant scientist (contracted by STL through Dynamac Corp.) and technical support. The laboratory has been outfitted with much state-of-the-art instrumentation, plus custom instrumentation built by STL. A laser-induced fluorescence imaging (LIFI) system was modified for plant measurements and a laser-induced fluorescence spectroscopy (LIFS) system was built and added to it; this portable system is used at Epcot Center and other field locations by STL. With the customized and evolving instrumentation, the on-site plant expertise, and the collaborators from government and academia, the facility at Epcot Center is a one-of-a-kind plant measurement facility, a facility that is specifically operated in support of finding remote sensing solutions for certain DOE problems.

Over the past few years the project has been growing various plant species (specifically those relevant to DOE sites) under controlled conditions and stressing them with various levels of several different metals. While fluorescence is emphasized, these plants are measured with various sensors, both active and passive, and the results are compared to evaluate sensor performance for stress measurement. Baseline natural variation (plant age, season, time of day) has also been collected, as has biochemical, anatomical, and structural changes, in an attempt to correlate what is happening in the stressed plant with changes in the sensed optical signatures.

Specific Accomplishments for the Past Few Years

- Many group data takes, wherein sets of control and stressed plants are measured at the same time with a wide array of instrumentation including laser-induced fluorescence imaging, laser-induced fluorescence spectroscopy, excitation-emission spectra, three-dimensional matrix (EMM), classical reflectance, hyperspectral imaging (state-of-the-art instrumentation and analysis provided cost-free by collaborators) as well as subsequent destructive lab analysis (biochemistry, anatomy, and morphology) of plant tissue, and results are then compared/correlated.
- Data collection has been focused on species growing at the SRS and Oak Ridge National Laboratory; i.e., bahia grass, loblolly and slash pine, and sweetgum. Current stressors we are examining are zinc and copper.
- STL has been working with a DOE site (SRS) interested in the technology and are currently formulating an experimental plan with them for on-site work.
- Continued work with collaborators, primary being government (NASA/Kennedy Space Center and NASA/Stennis), academia (University of Georgia), and private industry (Walt Disney World and Dynamac).
- Test application of LIF technology at Fort Irwin, California under a SERDP grant to measure stress levels in desert plants due to the impact of military training maneuvers.
- Tested more sophisticated spectral data analysis techniques; neural net analysis appears the most promising and is being pursued with both fluorescence and reflectance data sets for the automated identification of stress.
- Built and demonstrated a smaller, lighter, more rugged, and more user-friendly LIFS system; the LIFI system was also miniaturized and ruggedized on another job.
- Built a laser energy and a wavelength calibration channel into the LIFS system.
- Continued collection of baseline (unstressed) plant signature database (14 plant species over a period of 2 years) to measure natural variation in plant signatures.
- Low key effort to look into green fluorescent protein technology (Used LIFI/LIFS to examine some plants with green fluorescent protein tagged virus).
- Experiments on the effects of light on remote sensing fluorescence signatures collected: light-adapted versus dark-adapted plants, plants grown under different light levels, plants measured under different light levels, including rapidly changing light levels.
- Measured fluorescence signatures as a function of laser power.

The primary emphasis this fiscal year has shifted from running experiments to organizing and analyzing collected data and writing up results for journal publication. "Organizing" includes spending considerable effort in putting experimental data into a standardized database that will be usable by anyone, and that contains all associated experimental information (metadata) as well as the LIFI/LIFS (and other) files per se. Future data collections will also have the advantage of storing data in the upcoming database, allowing for easy storage and retrieval of standardized information associated with each collection. While an analysis routine for the LIFS data has now been developed and used for all preliminary analyses, until now the analysis of LIFI images has been labor intensive and on a file-by-file basis. In an effort to streamline LIFI image analysis so that LIFI information can be combined with other measurements that are part of the plant studies at Epcot Center, STL is developing routines, based in large part on ENVI software, to aid analysis. Raw LIFI binary files are background subtracted, fluorescence band ratios are calculated for individual regions of interest (ROI), and statistics (mean, standard deviation and ratios) are calculated within the chosen ROI. Processing of the Bahia grass zinc LIFI sets is nearly completed as of this writing.

Laser-Induced Fluorescence Imaging (LIFI)/Laser-Induced Fluorescence Spectroscopy (LIFS) system, developed with CMST funding, being used at Fort Irwin, California to (successfully) measure stress in desert species. Equipment was transported in and operated from a rented sports utility vehicle. The generator (red) at left in background powers the system.

Two manuscripts have already been submitted to the Journal of Plant Physiology for review. The title of the first manuscript is: Detection of Zinc Stress in Bahia Grass (*Paspalum notatum* Flugge.) by Remote Sensing: I. Plant Biometric, Biochemical, Anatomical, and Elemental Measurements. The title of the second manuscript is: Detection of Zinc Stress in Bahia Grass (*Paspalum notatum* Flugge.) by Remote Sensing: II. Hyperspectral Imaging Measurements**.** Third and fourth manuscripts are being prepared and are currently awaiting final data analysis; they will concentrate on (1) interpreting the detailed three-diminesional excitation/emission spectra collected with the Hitachi fluorescence spectrophotometer and (2) on LIFI/LIFS measurements for bahia grass leaves grown with various levels of zinc.

Several Important Preliminary Results

- Both laser-induced fluorescence techniques and passive hyperspectral imaging technologies work efficiently in detecting metal stress in all plant species studied.
- Laser-induced fluorescence techniques have been able to detect some pre-visual optical stress signatures.
- Preliminary results indicate that laser-induced fluorescence data, unlike any passive system, can be collected and appear valid over a wide range of light conditions, from full sun to darkness.

TECHNICAL TASK PLAN/TECHNOLOGY MANAGEMENT SYSTEM INFORMATION

TTP No./Title: NVO5C221 - Environmental Remote Sensing for Monitoring Plant Health
Related TTP No./Title: NVO-5-C2-53 - Portable Laser-Induced Fluorescence Imaging System
Tech ID/Title: 1900 - Environmental Remote Sensing for Monitoring Plant Health

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