The LINUS UV Imaging Spectrometer

D. Scott Davis\textsuperscript{a}, Richard M. Harkins\textsuperscript{b}, Richard C. Olsen\textsuperscript{c}
Department of Physics, Naval Postgraduate School, Monterey, California 93943

ABSTRACT

We present an overview of the Naval Postgraduate School's new LINUS instrument. This is a spectral imager designed to observe atmospheric gas plumes by means of absorption spectroscopy, using background Rayleigh-scattered daylight as an illumination source. It is a pushbroom instrument, incorporating a UV-intensified digital camera, interchangeable gratings and filters, and a DC servo-controlled image scanning system. LINUS has been developed to operate across both the near-ultraviolet and the short visible wavelength portions of the spectrum in overlapping passbands. This paper provides an outline of LINUS's design, operation and capabilities, and it summarizes results from initial laboratory and field trials.

Keywords: Spectroscopy, spectral imaging, remote sensing, atmospheric gases

1. INTRODUCTION

Within the Department of Physics of the Naval Postgraduate School we have developed a new system for ultraviolet imaging spectroscopy, called LINUS (Lineate Imaging Near-ultraviolet Spectrometer). It is a successor to the earlier NUVIS device developed at the same institution by D. D. Cleary during the late 1990s. Unlike its predecessor, LINUS is a very versatile and adaptable instrument, with a broad range of spectral tuning capability, user-selectable spatial and spectral resolutions, and a fully integrated digital control and data acquisition system. It is intended to exploit available Rayleigh-scattered sunlight as an illumination source for backlighting otherwise invisible atmospheric gas plumes and to characterize those plumes by means of imaging absorption spectroscopy. Provided that the distance between LINUS and the target plume is less than approximately one scattering mean free path length (typically several kilometers), the instrument is designed to be capable of providing accurate chemical column abundances and spatial morphologies for a variety of candidate molecules. It is expected that this technology will contribute significantly to remote-sensing studies of geophysical/volcanic sources as well as man-made emitters of trace gases.

It was decided at the outset that LINUS would be a pushbroom-type imaging spectrometer\textsuperscript{1}. In this configuration, a standard dispersive spectrometer is coupled with a two dimensional image detector so that one spatial dimension across the detector records spectral information while the orthogonal dimension encodes one of the target field's spatial characteristics. Information for the other target spatial dimension is then incorporated by sweeping or stepping an image of the scene of interest across the spectrometer's entrance slit in a direction orthogonal to the slit's long dimension. Our instrument is configured so that its entrance slit is nominally vertical, with spectral dispersion in the horizontal dimension. Its foreoptical system uses a scanning mirror on a vertical axle to complete the spectral imaging operation.

2. OPTICAL CONFIGURATION

When LINUS was first conceived, it was planned to be all-reflecting. Such instruments offer several advantages, particularly their ease of tuning for different spectral passbands. We undertook an extensive design study which resulted in several compact, novel optical layouts. Those studies were roughed out by first using the Optica\textsuperscript{2} geometric optics analysis software package running under Mathematica\textsuperscript{3}, followed by refinements using OSLO\textsuperscript{4}. After weighing the results of those studies, all of which would have required the manufacture of one or more custom anamorphic UV mirrors, it was decided to bow to the project's time and fiscal constraints and to adopt a much simpler approach that would permit the use of commercially available off-the-shelf components. The final design, then, incorporates both reflecting and refracting optical elements. The resulting instrument is capable of acquiring
spectral images throughout the 200 - 500 nm spectral region. However, it must do so in overlapping, comparatively narrow spectral passbands because of the inevitable chromatic aberrations introduced by our use of lenses in the final design.

LINUS's optical layout is that of a conventional stigmatic plane grating spectrometer. The spectrometer's foreoptics are comprised of just three optical elements: an azimuthal scanning unit, a bandpass filter and an f/25 aplanatic primary lens system, which focuses target scenes at infinity onto the spectrometer's entrance slit. A schematic of the optical system is displayed in Figure 1, which represents a top view of the layout.

![Figure 1: Schematic of LINUS's optical layout.](image)

The entrance aperture of the system consists of a vertical slit whose width and height are independently adjustable. The slit is followed by an f/12.5 aplanatic collimating lens system, a plane reflection grating, and another f/12.5 aplanat which serves as the objective for an intensified focal plane camera. The various aplanats are proprietary designs of CVI Laser, Inc., and were manufactured by them from low-fluorescence material. All three lens systems are mounted on micropositioning stages to permit easy focusing and compensation for chromatic aberrations as different filter passbands are selected. Similarly, the grating holder is supported by a standard rotation stage with micrometer adjustments and can accommodate a wide variety of gratings.

The focal plane detector consists of a low-noise, thermoelectrically cooled 512 × 512 pixel CCD array that is optically coupled to an integrated image intensifier enhanced for UV sensitivity. The camera system is a Pentamax unit manufactured by Princeton Instruments, Inc. Because of the camera's cooling needs, it is mounted externally to LINUS's enclosure. It is mechanically registered onto a custom-made kinematic mount, compensated to first order for thermal expansion effects. This ensures that the camera unit can be quickly mounted and removed as often as necessary while maintaining the reproducibility of its position to accuracy of a few microns over a wide range of temperatures.

All optical and opto-mechanical components are securely attached to a standard honeycomb steel optical breadboard. Surrounding all of the optics except the camera is a light-tight enclosure made from black ABS plastic, supported by an internal aluminum skeleton. The entire unit can be supported by either a standard tabletop for laboratory measurements or by a heavy-duty tripod for field observations.
3. OPTO-MECHANICAL SCANNER SYSTEM

The opto-mechanical scanner is responsible for sending the collimated optical beam from a distant target toward the entrance slit and for steering the field of view in azimuth. It must be highly stable and conduct its positioning tasks in a reproducible manner. Because of our desire to make LINUS as versatile as possible, we chose to design our scanner around a DC servo-controlled pointing system rather than using the more conventional stepping motor approach. The moving components of our design are an armature that supports the plane scanning mirror, a DC servomotor, and a precision angular shaft encoder. The scanner is at all times under control of a closed-loop proportional-integral-derivative (PID) DC servosystem which is, in turn, directed by a set of LabVIEW® routines. The camera is also under LabVIEW control. The armature that holds the mirror is mechanically balanced so that the instrument may be tilted through a wide range of elevation angles without upsetting the servo loop's tuning. The mechanical torque for the scanner is provided by a Kollmorgen pancake-style anticogging DC servomotor, which delivers high torque at low angular velocity. The angular position of the mirror is sensed by a Teledyne Gurley ultrafine precision optical shaft encoder that produces 144,000 quadrature pulses per mechanical revolution. Under normal operating conditions the scanner servosystem keeps its pointing accuracy to within ±4.5 arcseconds, although if the need should arise, it can be easily reconfigured for coarser or finer performance. The servomotor, mirror armature and encoder are interconnected by stiff null-backlash bellows couplings. The entire unit is housed in a compact, customized support structure that has been mechanically tuned so that its vibrational resonances lie well outside the normal band of frequencies at which the scanner servosystem operates.

Figure 2: Support electronics and portable computer system.
4. COMPUTER CONTROL AND DATA ACQUISITION SYSTEM

As stated above, LINUS's various subsystems operate under real time control of a set of LabVIEW virtual instrument (VI) routines. These VIs constitute an extensive library of interrelated control and data acquisition functions that permit easy operation of the instrument and efficient use of available observation time. There are three broad classes of routines: (1) scanner servosystem control and scanner operation; (2) camera setup, configuration and operation; (3) data acquisition, instrument status monitoring, and real time "quick look" capabilities. All of the software is run on a field-ruggedized computer connected to the hardware interfaces and drivers for the camera and scanner control hardware. The entire ensemble is mounted in a pair of portable racks, as shown in Figure 2. Each operational or functional need is addressed by a LabVIEW VI which consists of two parts, a graphical program module and its associated virtual control panel. Examples are displayed in Figures 3 and 4.

![Figure 3: A portion of the main control program.](image)

Under normal operating conditions the various graphical program displays, of which Figure 3 is one example, are suppressed, as are auxiliary routines and control panels. Only the operating panels of interest, such as the one in Figure 4, appear as windows on the operator's screen. If the additional windows are needed, they are available almost instantaneously with a click of the mouse. The operator may call up additional functions at will to reset various operating parameters, display image frames as they are acquired, and so forth. This provides an efficient and uncluttered operating environment.
Figure 4: The virtual control panel user interface for the main control program.

Figures 5 and 6 illustrate some of the additional features that are readily accessible by using this approach to instrument interfacing and control. Figure 5 shows a virtual control panel used for setting the camera's operating parameters. Figure 6 illustrates a real-time display of the focal plane image as it is recorded.
5. INITIAL PERFORMANCE TESTS

LINUS's primary objective is to observe gas plumes in the atmosphere and to provide accurate remote measurements of the abundances of the various molecular species that such plumes contain. The instrument must be capable of performing highly reliable spectrochemical measurements, both in a remote field setting and in the laboratory environment. Therefore, before any detailed observations were attempted, LINUS was put through an extensive set of laboratory calibration and alignment tests, and any problems revealed by those exercises were addressed in turn.

Accurate spectrochemical column abundance measurements require detailed knowledge of the spectra being observed. This mandates careful laboratory observations of those spectra, so that the wavelengths of various molecular band systems and their respective abundance curves-of-growth are available for comparison with subsequent field measurements. Hence, as part of the LINUS project, we are equipped to perform basic UV laboratory spectroscopy using a variety of gas absorption cells and ultraviolet illumination sources. A database of such spectra then form a fiducial underpinning for the accurate analysis of field data.

For LINUS's initial applications, we have chosen to concentrate on observations of sulfur dioxide, $SO_2$. This species is of considerable interest to both the geophysical community and to those responsible for monitoring man-made pollutant plumes in the atmosphere. The $SO_2$ molecule exhibits a strong set of absorption bands across much of the near-ultraviolet spectral region. We have chosen to concentrate on a portion of the well known $SO_2 \ A \leftarrow \ X$ band system centered at about $\lambda=300$nm.

Figure 7 shows a composite of several $SO_2$ laboratory spectra recorded by LINUS over a wide range of gas partial pressures, using a single-pass quartz absorption cell illuminated by a deuterium discharge lamp. In addition to producing and analyzing gas absorption spectra like those in Figure 7, we also routinely calibrate LINUS's wavelength scale using a conventional platinum hollow cathode discharge lamp in conjunction with published Pt emission line characteristic data from a variety of sources.

Initial field trials have been conducted at both the Naval Postgraduate School campus in Monterey, where any atmospheric $SO_2$ is expected to negligible, and at Lassen Volcanic National Park in northern California, where natural volcanic vents and fumaroles are known to produce sulfurous compounds. Figure 8 displays one band of a spectral image recorded at the Naval Postgraduate School, showing a clear sky background with the crowns of some trees in the foreground. The chlorophyll in the vegetation is highly absorptive in the 300 nm region where these observations were made.
Figure 7: Laboratory measurements of $SO_2$, diluted in dry $N_2$, at various column abundances.

Figure 8: Image of sky with trees in foreground (not corrected for distorted aspect ratio effects).

Figure 9 is a plot of the measured spectral characteristics of the sky and trees in Figure 8, uncorrected for the effects of instrumental sensitivity variations or filter passband effects.
Figure 9: Spectra of representative sky and tree areas of data from Figure 8.

Two field expeditions were made to Lassen Volcanic National Park Lassen during the fall of 2002. Figure 10 is a photo of one of the fumarole vents at the Sulfur Works area, on the southern slope of Mt. Lassen. Figure 11 shows LINUS and its support equipment set up at that location. For such field deployment, the instrument and its support systems are carried by van or small truck and are powered by a portable AC generator. At the time of this writing, some of the field data have been analyzed, and more remains to be investigated. We also plan to conduct additional field observations during the summer of 2003 at Mt. Lassen and elsewhere.

Figure 10: Fumarole at Sulfur Works, Lassen Volcanic National Park.
6. SUMMARY AND ACKNOWLEDGMENTS

The development phase of LINUS is now essentially completed, although, as with any unique research instrument, small improvements and modifications will be made as needed in the future. In its present configuration, LINUS's operating capabilities may be summarized as follows:

- Spectral coverage: 200 -- 500 nm, in overlapping segments approximately 30 nm wide.
- Spectral resolution: variable with different gratings and slit settings, typically about 0.1 nm.
- Field of view: adjustable, up to 0.5° vertical; up to 2.5° horizontal.
- Spatial resolution: approximately 4 arcseconds both horizontal and vertical.
- Per frame integration time: 0.1 second -- several minutes, as dictated by noise statistics of application.
- Computer system: Windows-based PC running application-specific software under LabVIEW

The authors would like to express their thanks to the U. S. National Park Service for their cooperation in permitting us to conduct observations at Lassen Volcanic National Park. This project is supported by the United States Air Force.
REFERENCES

2. Optica and Mathematica are registered trademarks of Wolfram Research, Inc.
3. OSLO is a registered trademark of Sinclair Optics and Lambda Research, Inc.
4. Pentamax is a registered trademark of Princeton Instruments and Roper Scientific.
5. LabVIEW is a registered trademark of National Instruments.

aEmail: dsdavis@nps.navy.mil; telephone: 831-656-2877
bEmail: rharkins@nps.navy.mil; telephone: 831-656-2828
cEmail: olsen@nps.navy.mil; telephone: 831-656-2019