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CELiS (Compact Eyesafe Lidar System): A Portable 1.5 µm Elastic Lidar System for Rapid Aerosol Concentration Measurement

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ABSTRACT

CELiS (Compact Eyesafe Lidar System) is a tactical elastic lidar system commissioned by the Strategic Environmental Research and Development Program (SERDP) for the purpose of air quality environmental compliance issues surrounding the offroad use of wheeled and tracked vehicles. A complete CELiS instrument weighs less than 300 lbs., is less than 2 cubic meters in volume and uses 700 W of 120V AC power. CELiS has a working range of better than 2km and a range resolution of 5m.

Keywords: Lidar, eye-Safe, aerosol, air quality, fugitive dust

1. INTRODUCTION

The Compact Eyesafe Lidar System (CELiS) is a prototype instrument development to demonstrate the ability of a small, low power, eye-safe lidar system capable of monitoring the PM fence-line concentration of fugitive dust from off-road vehicle activity as part of the SERDP Measurement and Modeling of Fugitive Dust Emission from Off-Road Department of Defense Activities program.

Lidar has a long heritage of aerosol sensing, finding uses from agricultural emission monitoring[1-3] to national security[4]. CELiS is a small, lightweight and easily transportable for quick setup and measurement of PM emissions, Figure 1. The instrument measures 35"x24"x8" and weighs <45kg. The instrument is mounted onto a Moog Quickset pan and tilt positioner which is mounted on a tri-pod. Ground support equipment (GSE) includes a portable rack with laser power supply and cooler, Lidar and Moog power supply, readout electronics and computer.

Table 1. CELiS size, weight and power

	Size	Weight
Lidar	35" x 24" x 8" (0.1 m^3)	<100 lbs (45 kg)
Moog Quickset (QPT 90)	12.5" x 12.5" x 9" (0.02 m^3)	37 lbs
Tri-Pod		27 lbs
GSE	14U rack (0.15 m^3)TBD	TBD
Power	700 W of 120V AC power (1 kW max rating for components)	

Figure 1. CELiS instrument concept with cover mounted on Moog pan and tilt positioner.

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CELiS operates in a biaxial configuration at the 1.5µm eyesafe wavelength, Figure 2. The receiver is an off-axis parabolic (OAP) telescope, aft-optics and alignment assembly and InGaAs APD detector readout. The transmitter is a Quantel 1.574µm laser with a commercially purchased 20X beam expander. Both the receiver and transmitter are mounted on a carbon fiber optical breadboard with a custom mounting solution to minimize misalignment due to thermal operating range and varying pointing vectors. Commercial components were chosen where possible except where their use negatively affected the overall system performance.

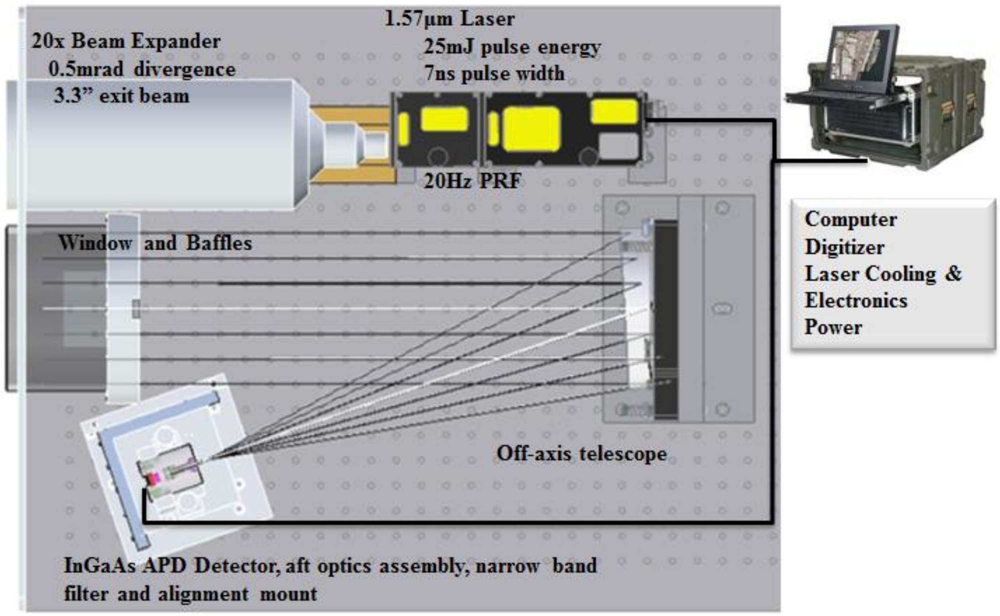

Figure 2. CELiS optical bench with transmitter and receiver. The receiver uses an off-axis parabolic (OAP) mirror, aft-optical assembly and InGaAs APD detector. The transmitter is a Quantel 1.574µm laser with a Special Optics 20X beam expander.

1.1 Laser Transmitter

The laser is a Quantel Q-Switched neodymium doped yttrium aluminum garnet (Nd:YAG) with optical parametric oscillator (OPO) operating at the eye-safe wavelength of 1.574µm, Table 2. The selected beam expander is a 20x large output beam expander design that can accept the 4mm beam from the Quantel laser. A 20x expansion ratio achieves 0.5mrad beam divergence and 3.3" exit beam.

Table 2. Quantel Ultra 100 specifications

Laser Source	Nd:Yag with OPO
Wavelength	1.574 µm
Maximum Energy	25mJ (measured)
Pulse Width (FWHM)	7ns
Energy Stability	<2%
Divergence	10mrad (measured)
Beam Diameter	4.2mm (measured)

Table 3. Beam expander specifications

Expansion Ratio	20X
Input Aperture	5mm
Output Aperture	100mm
Wavefront Distortion	< 1/2 Wave
Useable Spectral Range	400-1650 nm
Maximum Energy	25mJ (measured)
Transmission	> 92%
Coating Damage Threshold	500 MW/CM^2

Any lidar system that will be used to monitor fence-line PM emissions related to off-road training activities will be subject to a strict eye-safety requirement to protect both troops and wildlife. CELiS achieves eyesafe operation at the output aperture. Table 4 gives results using Easy Haz Industrial LSO software in accordance with ANSI Z136.1 American National Standard for Safe Use of Lasers[5].

Table 4. Laser safety results

Laser Safety Results	
Intrabeam Exposure	
Small Source Ocular MPE:	0.1 W/cm^2
Worst Case Optical Density	1.72 OD
OD at Intrabeam Obsr. Range	0 OD
Skin MPE	0.1 W/cm^2
Time Skin MPE	520
NOHD/NHZ Values	
Intrabeam Eye NOHD	0m
Diffuse Reflection NHZ	1.26cm

1.2 Receiver

The receiver consists of an off-axis parabolic (OAP) telescope, aft-optics and alignment assembly and InGaAs APD detector readout.

1.2.1 Optical design

The CELiS optical design uses a 6” OAP mirror with 18” effective focal length. The OAP is mounted to a custom mount that is designed to achieve high mechanical stability over the environmental condition.

The ray-trace is shown in Figure 3. The backscatter signal is collected by the 6” OAP mirror then focused onto a spatial aperture at the focus of the OAP. The backscatter signal is collimated by a single lens then passed through narrow band interference filters. The collimated signal is then focused onto the InGaAs APD detector active area.

The APD active detector area is a limiting design factor and driver all parameters including maintaining alignment over the environmental operating conditions. The optical design achieves a 1.2 mrad field of view. The aft-optics are designed to achieve maximum encircled energy. Figure 3 shows the encircled energy and a spot diagram at 20°C operating temperature. The design achieves better than 90% encircled energy over the environmental operating conditions.

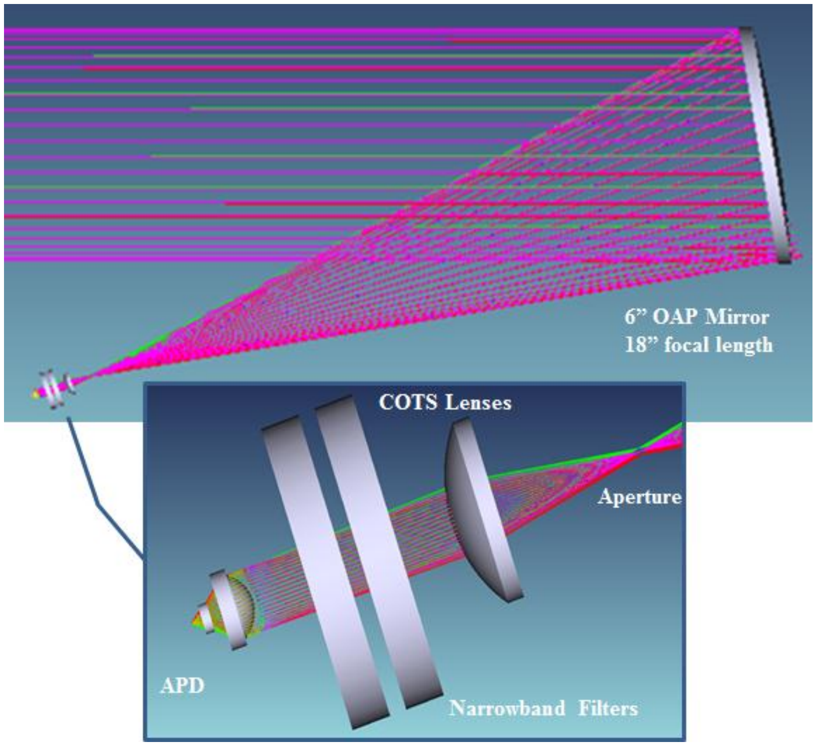

Figure 3. CELiS optical design raytrace

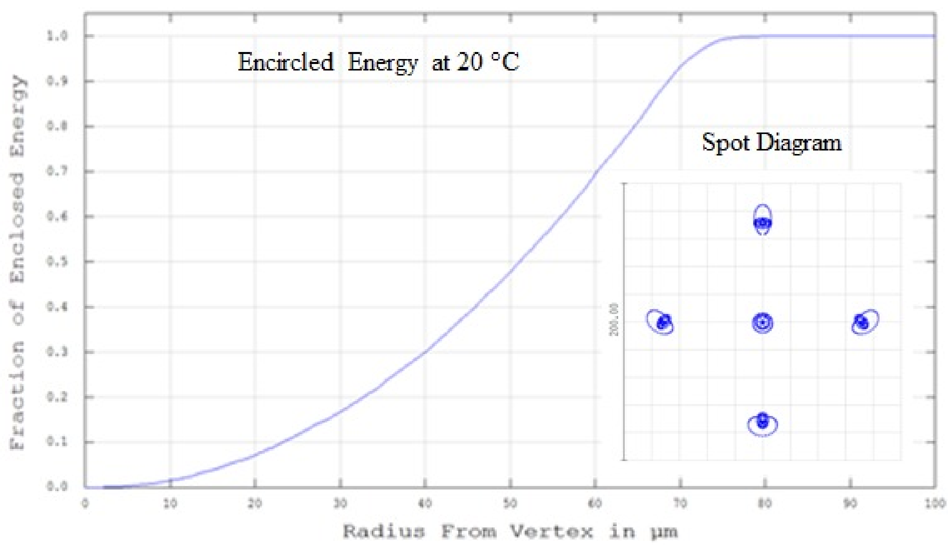

Figure 4. Encircled energy and spot diagram at 20ºC

1.2.2 Detector Readout

The detector readout uses a high sensitivity InGaAs APD detector, with an integrated ultra-low noise transimpedance amplifier (TIA) and internal thermo-electric cooler (TEC) and temperature sensor. The detector is mounted to the aft-optics assembly with an alignment fixture. An interface card is the mounted to the detector that provides power and signal connections. A custom board will supply the APD bias, APD high voltage and TEC control.

Figure 5. InGaAS APD detector module

The output signal is digitized with a 14bit A/D card running at sample rates up to 200MS/s. The card can be set at lower sample rates with target of 25MS/s, which results in a 6m range bin. The GaGe card has input voltage ranges that can be set to match the Lidar signal and maximize the dynamic range.

1.3 Control, Electronic, and Embedded Control Systems

Figure 6 shows a block diagram of the CELiS control system. A computer is used to interface to the laser, digitizer, APD control, Moog positioner, Metrology station and a wireless OPC. The computer is running custom control software with real-time plotting of the return signal.

The positioner is commanded to an azimuth and elevation pointing angle. The laser is controlled to desired operating conditions. The output pulse from the laser flashlamp triggers a data collection start on the digitizer. The digitizer is run for a desired time to collect full waveform including background signal for each laser pulse. The full waveform data is saved, including time stamp, and displayed on a real-time plot. Several waveforms can be averaged and displayed on the plot screen. Metrology and OPC data are collected, time stamped and saved with waveform data.

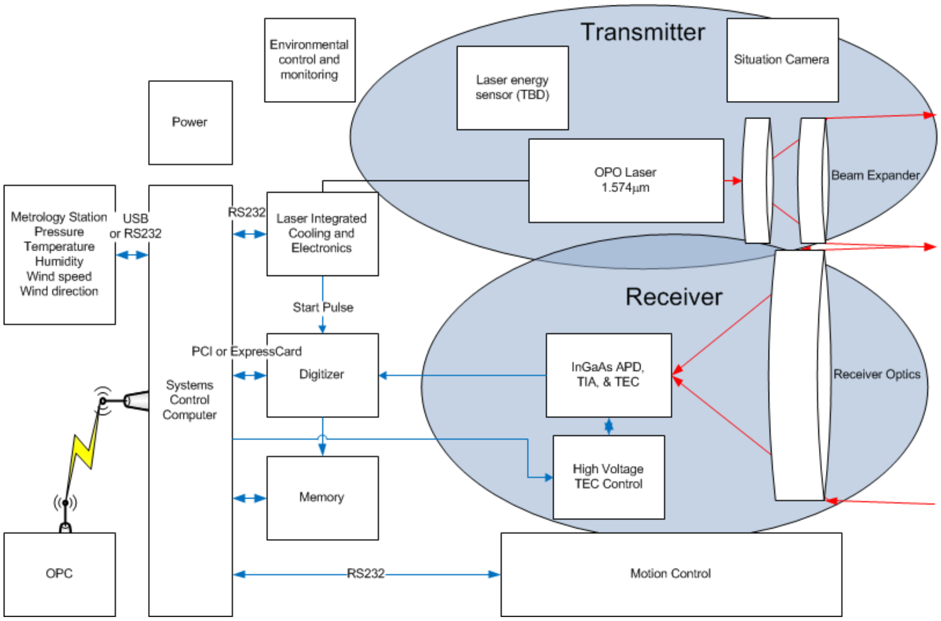

Figure 6. CELiS control system block diagram

2. MODELED SYSTEM AND PERFOMENCE PREDICTIONS

A Lidar system model has been developed to predict performance and help in design trades. The model includes a complete system design including Lidar range equation, geometrical form factor, receive and transmit optics, detector, background, and noise.

The Lidar equation for a homogeneous[6] atmosphere is given as:

$$P(R,\lambda) = P_0 \frac{c\eta}{2} \frac{q(R)}{R^2} T_{sys}(\lambda)\beta(R,\lambda)\exp\left[-2\sigma(R,\lambda)R\right]$$

where, Po is the transmitted laser power, c is the speed of light, η is the time between digitizer measurements, q(R) is the overlap function corrected area, $T_{sys}(\lambda)$ is the system (transmitted and received) efficiently, β(R, λ) is the backscatter coefficient and σ(R, λ) is the extinction coefficient. The backscatter and extinction coefficient are assumed constant and were estimated using Mie and Rayleigh scatter models. The overlap function was modeled using Measures[7] equations. Modtran data is used to estimate solar background inputs for background estimates.

The overlap function is a major consideration in development of Lidar transmitter and receiver optics. The overlap function corrected area prediction and is estimating at better than 95% full overlap at 500m, Figure 7.

Signal to noise (SNR) estimates at operating ranges were estimated for Continental clean, Continental polluted and Urban atmospheric conditions with 50% humidity. We predict operating ranges in Continental clean atmospheric conditions out to 2km for an SNR of 1for a single laser shot.

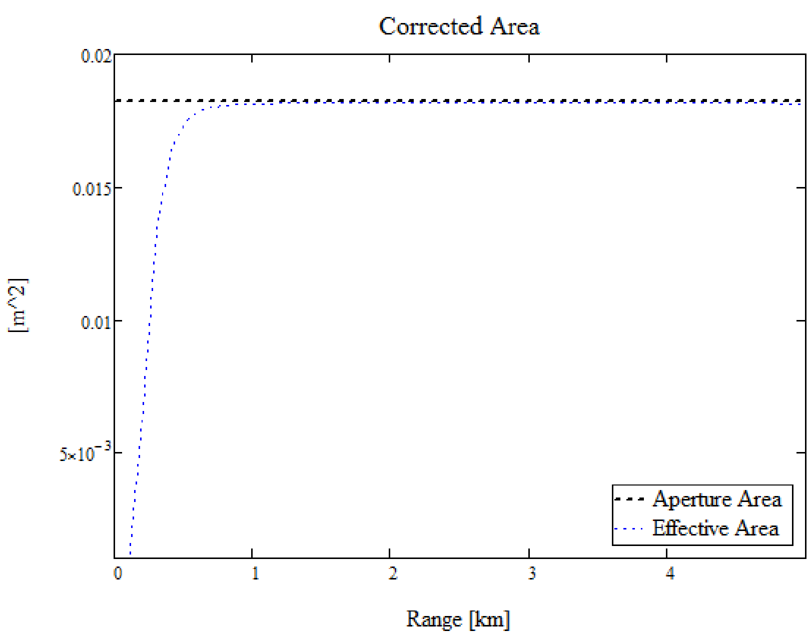

Figure 7. Overlap function corrected area

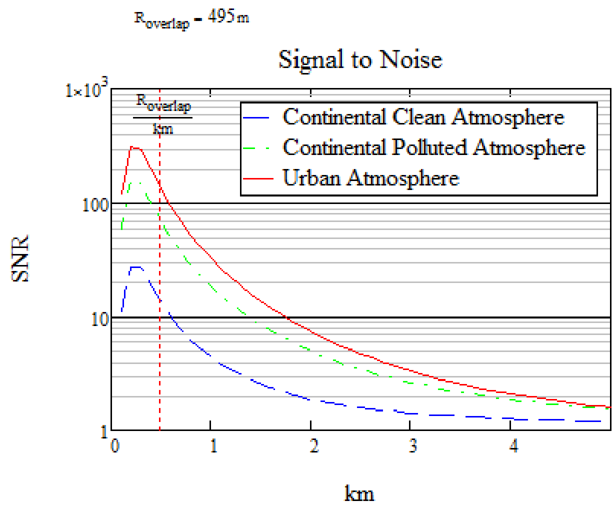

Figure 8. Performance predictions for

3. CONCLUSION

CELiS is a small, low power, eye-safe lidar system capable of monitoring the PM fence-line concentration utilizing proven calibration and retrieval algorithms including the use of optical particle counters and Meteorological measurements. The system specifications are given in Table 1.

Table 5. CELiS Specifications

Transmitter	
Wavelength	1.547 µm
Pulse Energy	25 mJ
Pulse Rate	20 Hz
Beam Diameter	3.3" (84 mm)
Beam Divergence	0.5 mrad
Receiver	
Telescope Diameter	6" (152.4 mm)
Full Field of View	1.2 mrad
Detector	InGaAs APD
Digitizer	
Dynamics Range	14 bit
Rate	200 MS/s to 1 kS/s
Input Voltage Range	±100 mV, ±200 mV, ±500 mV
Performance Predictions	
Sensing Range	>2 km
Range Bin (25MS/s)	6 m

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