HI-CLASS on AEOS: A Large Aperture Laser Radar for Space Surveillance/ Situational Awareness Investigations

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ABSTRACT

The Air Force Research Laboratory/Directed Energy Directorate (AFRL/DE) via the ALVA (Applications of Lidars for Vehicles with Analysis) program installed in late 2000 a wideband, 12J, 15Hz CO_2 laser radar (ladar) on the 3.67 meter aperture AEOS (Advanced Electro-Optics System) telescope at the Maui Space Surveillance System (MSSS), located on the summit of Haleakala, Maui, HI. This ladar adopts the technology successfully demonstrated by the HI-CLASS (HIgh Performance CO_2 Ladar Surveillance Sensor) operating on the nearby 0.6 meter aperture Laser Beam Director (LBD) and developed under the Field Ladar Demonstration program jointly sponsored by the Air Force Research Laboratory and the Army's Space and Missile Defense Command.

The moderate power (~180watts) HI-CLASS/AEOS system will generate multiple, coherent waveforms for precision satellite tracking and characterization of space objects for 1 m^2 targets at ranges out to 10,000 km. This paper will discuss the operating characteristics and innovative features of the new system. The paper will also review recent results in support of AF needs, demonstrations, experiments, as well as planned activities.

INTRODUCTION

This paper describes the development, overview, operating concepts, representative data, and current status of pulsed high-power coherent CO_2 laser radar systems at MSSS. The paper reviews the first generation kilowatt class ladar/lidar HI-CLASS/LBD system as the foundation for a second-generation ladar system that was developed under the AFRL/DE ALVA program for integration on the new AEOS 3.67m telescope. The layout and projected capabilities of the new HI-CLASS/AEOS system and differences from HI-CLASS/LBD are specifically addressed. This new system, operational in late 2000, takes full advantage of the large AEOS aperture to substantially improve the ladar range and sensitivity. These improvements make the HI-CLASS/AEOS system suitable for precision tracking and characterization of space objects. Recent results from experiments and demonstrations will be presented. The document concludes with a summary.

The HI-CLASS program and its two system capabilities can support the following types of efforts:

1) Space Situational Awareness (high accuracy ladar measurements (range, range-rate, angles) for precision satellite orbit maintenance
2) Sensor ranging data to calibrate operational radar and optical sensors
3) Small satellites/objects (< 30 cm) tracking
4) Satellite identification, orientation, stability, and structure data with its range-resolved Doppler data
5) Chemical-biological detection, such as Doppler Shift Scanning Differential Absorption Lidar (DSS DIAL) and remote sensing data
6) Field Ladar tactical demonstrations
7) Automatic Target Recognition (ATR) technology development to support Theater Surveillance, and
8) Support of compact ladar systems applications for airborne and spaceborne surveillance platforms.

HI-CLASS SYSTEM DESIGN

The original HI-CLASS system was integrated with the 0.6m LBD by 1997. The system was designed with a dual function capability to conduct both Ladar and Lidar measurements. It serves as a test bed for Ladar measurements of orbiting targets and Lidar detection of chemical vapors using natural terrain returns at three designated ground sites with ranges of 20-60km. The ladar mode is designed for long range high precision hard-body acquisition, tracking, and imaging.

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14. ABSTRACT
From the earliest days of space exploration, space has been used for military purposes. This use has ranged from imagery for reconnaissance, such as the recently declassified Project Corona1, weather, and terrain mapping to long range communications and the more recent innovations from precision navigation. Over the past few decades, space has proven itself a superior force multiplier. America?s extensive investments in military space systems paid off demonstrably in OPERATION DESERT STORM2 and OPERATION ALLIED FORCE. The Department of Defense Space Policy calls space a ?strategic enabler? and calls it a necessary precursor to the way we fight wars on land, at sea, and in the air. We have, perhaps, reached the point where we take the need for space support in battle as a given. But if it is so obvious to us that we need space to fight, what must the rest of the world be thinking? There is nothing uniquely American about space that prevents the rest of the world from learning from our example.

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The system is designed to acquire sun-illuminated orbiting targets in (approximately) known nominal trajectories using a CCD or intensified CCD-acquisition sensor with sufficient angular resolution to boresight the laser radar. The associated angle track is then upgraded to a trajectory track using a pulse-tone waveform (Figure 1) to establish precise range and range rate. The HI-CLASS/LBD (AEOS) systems have range and range rate search windows which can accommodate targets with nominal trajectory uncertainties up to: 8(16) km in range and 100 (200) m/s in range rate. The high fidelity, pulse-burst waveform (Figure 1) consisting of a coherent train of micropulses (FWHM < 1.5 ns) separated by 40 ns and extending over an interval from 5 (AEOS) to 16 (LBD) µs is then used to image the target. Spinning targets (using standard inverse synthetic aperture (i.e., ISAR concepts) generate range-Doppler images while non-spinning target produce range amplitude images. The pulse-burst waveform produces images with the nominal resolutions: 20 cm range resolution for both systems and 0.4 (1.6) m/s range rate resolution for the LBD and AEOS systems, respectively. Furthermore, when the signal-to-noise levels are high, one may, in principle, improve on this by de-convolving the return signal with the transmitted waveform that is recorded for every pulse on each system.

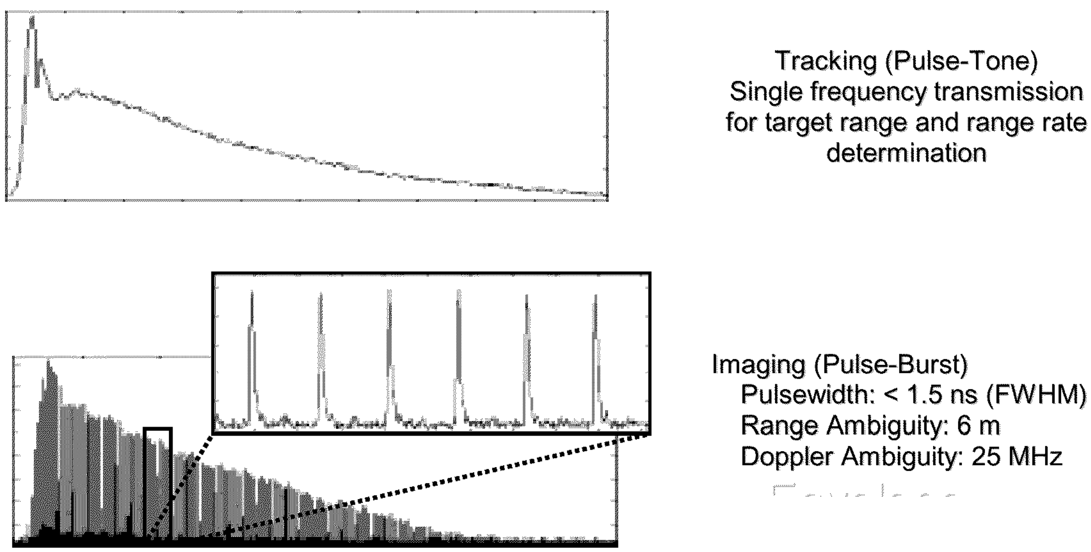

Figure 1: Pulse-tone and pulseburst waveform envelopes

The HI-CLASS ladars share a common ladar architecture: transmitter (power oscillator/ amplifier for LBD and power oscillator only for AEOS system), heterodyne receiver, microwave receiver, digital processor and display. In the HI-CLASS/LBD ladar, the transmitter consists of two similar modules serving as the power oscillator and amplifier. The oscillator power of 300 watts is boosted to 1000 watts in a simple Power Oscillator-Power Amplifier (POPA) configuration. The HI-CLASS/AEOS system incorporates a single module, power oscillator producing approximately 180 watts as the transmitter. Both transmitters can switch from pulse-tone to pulse-burst waveforms at their respective system repetition rates, i.e., 30 Hz (LBD) and 15 Hz (AEOS). In addition, both transmitters are equipped with an Output Pulse Monitor (OPM) that uses coherent detection to capture the output waveform phase and amplitude to assist in signal processing. Transmitter coupling to the respective beam directors incorporates a transmit/receive (T/R) switch to effect isolation between the high output power and the extremely sensitive, heterodyne receiver. The HI-CLASS/LBD employs polarization selection to achieve transmit/receive (T/R) isolation; the HI-CLASS/AEOS employs a mirror with a small central aperture as the T/R switch by taking advantage of the "point-ahead" angular offset between the transmitted and return beams.

The heterodyne receiver employs a wideband, quad-element, Hg:Cd:Te detector illuminated with a local oscillator to functionally achieve a photon counting capability as well as to extract the Doppler shift of the target.

The microwave receiver amplifies, band limits and "Doppler tracks" the return signal, i.e., it utilizes a variable frequency microwave oscillator to shift the return signal to baseband. The nominal bandwidth for the pulse-tone waveform is 20 (40) MHz for the LBD and AEOS systems, respectively and 750 MHz for the pulse-burst waveform in both systems. The microwave receiver generates in-phase and quadrature outputs to facilitate processing.

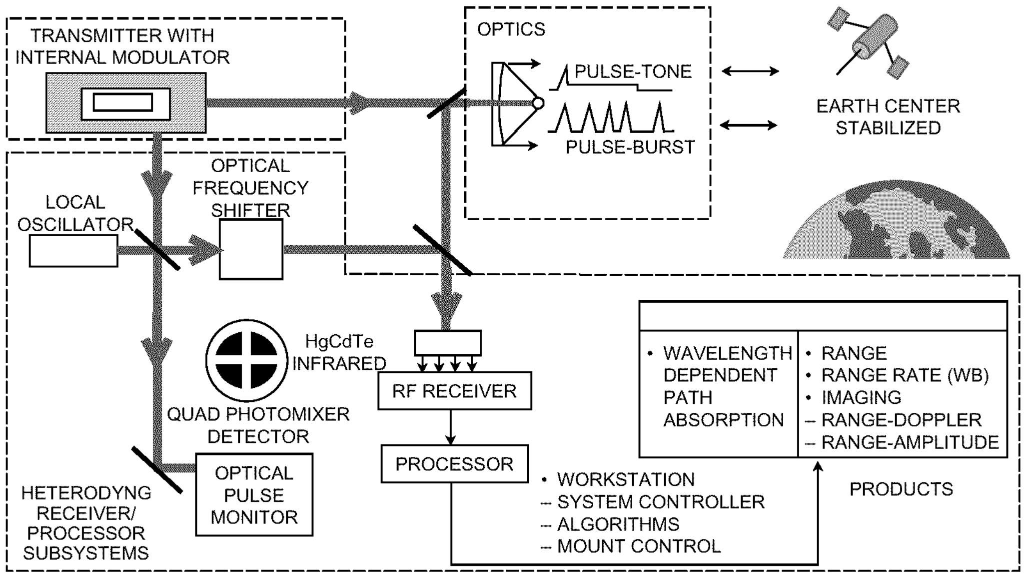

Figure 2: Functional block diagram of HI-CLASS system

The digital processor digitizes and records the narrow and wideband waveforms at the full system repetition rates. In addition, it captures the output pulse monitor signals along with all system operating and status parameters (more than 100) at the respective system repetition rates. The LBD system can generate real time range, range rate and range-Doppler images at 30 Hz; by mid-2000, the AEOS system will generate real-time range and range rate estimates at 15 Hz. The processor has a graphical user interface (GUI) to set all system parameters and to monitor return signals and system performance (Figure 3).

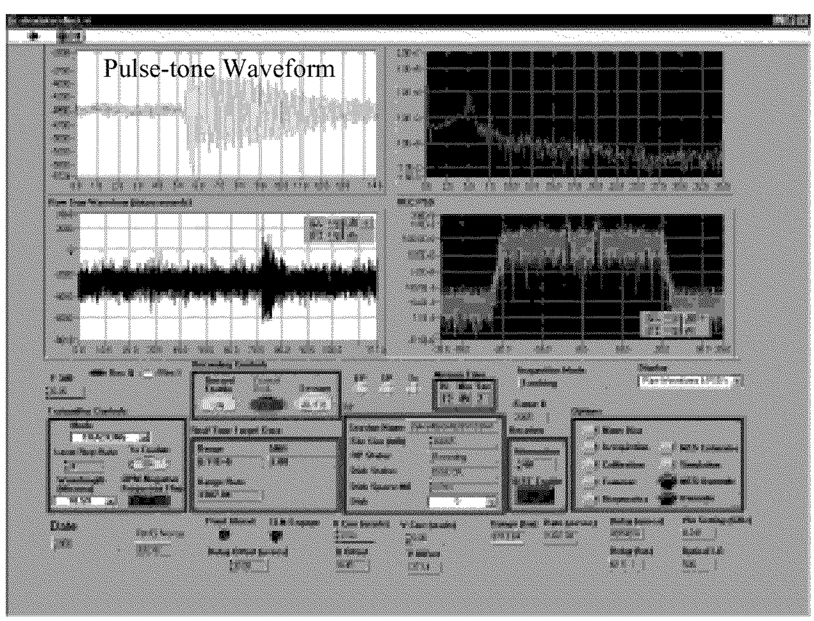

Figure 3: GUI showing first return from LAGEOS II satellite on November 10, 2000

HI-CLASS/AEOS CAPABILITIES

Substantial performance enhancements are achievable with the HI-CLASS/AEOS system, as compared with the HI-CLASS/LBD system as shown in Figure 4. The CNR at fixed range and transmitter energy scales as (diameter)^4.

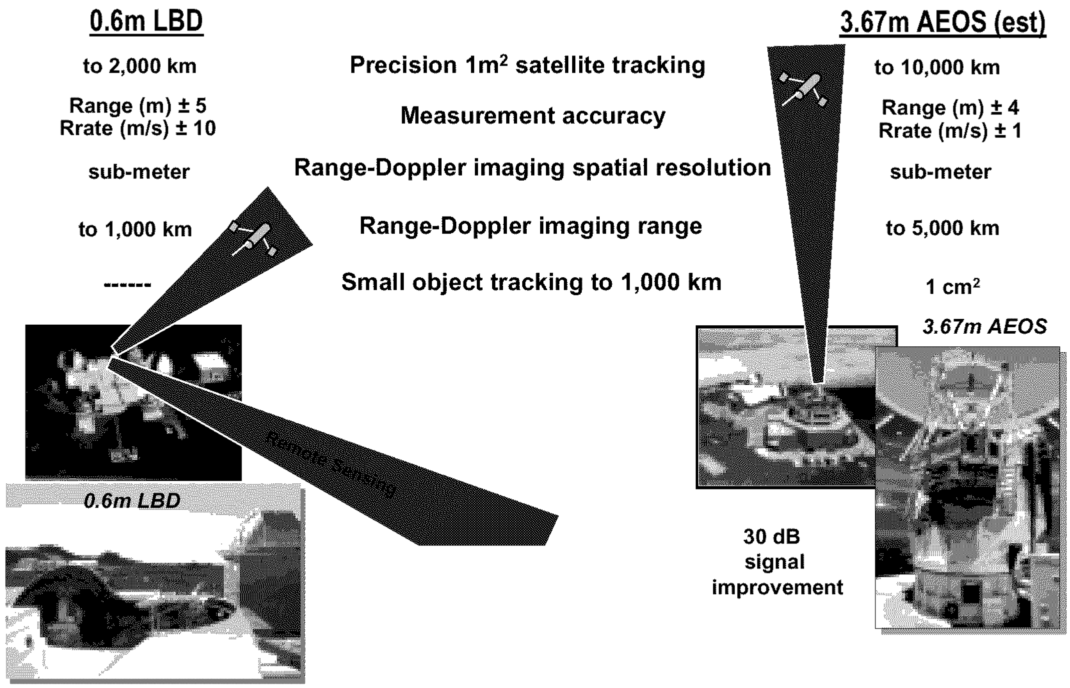

Figure 4: Comparison of HI-CLASS LBD and AEOS systems

The HI-CLASS/AEOS system will provide precision metrics and range-amplitude images of LEO and MEO objects. HI-CLASS/AEOS, unlike HI-CLASS/LBD, operates purely as a tracking and imaging Ladar at a (fixed) wavelength of 11.13μm. Since orbiting objects are not generally amenable to ISAR type imaging, the waveforms were simplified to provide a tracking and range-amplitude imaging capability only. These capabilities are derived from a 5μs injection-seeded (acquisition) pulse-tone waveform and a mode-locked pulse-burst imaging waveform with the same 5μs envelope duration. The transmitter will provide average powers of ~ 180w (12J at 15Hz) in an oscillator configuration:

Some receiver upgrades have been incorporated in the new system. A dual Bragg shifter provides electronically selectable (plus and minus 500 MHz) LO shifted outputs. Complex relay optics were used with a single shifter in the HICLASS/LBD to effectively implement the required positive and negative frequency offsets. The processor uses state-of-the-art quad C60 arrays rather than the (now obsolete) quad C40's on HICLASS. The C-60 processors are programmed to perform the required fast FFT functions and this dispenses with the frequency domain array processors (FDAP) used in the HI-CLASS/LBD system. The range and Doppler search windows have also been expanded by a factor of two to accommodate larger range/Doppler hand-off uncertainties.

The various simplifications/upgrades addressed above are being implemented to reduce cost and improve system reliability, with the objective of obtaining a near turn-key capability; in particular, the forfeiture of the wavelength agility option and restriction of the waveform duration to ~ 5μs represents major system simplifications as compared with HI-CLASS/LBD. Operator control workstations can be easily modified through GUI interfaces as shown in Figure 3 above.

The AEOS facility, a description of its capabilities to support multiple users, and the location of the HI-CLASS system within AEOS are shown in Figure 5. The layout of the 3.67m experiment room and optical system are illustrated in Figures 6 and 7

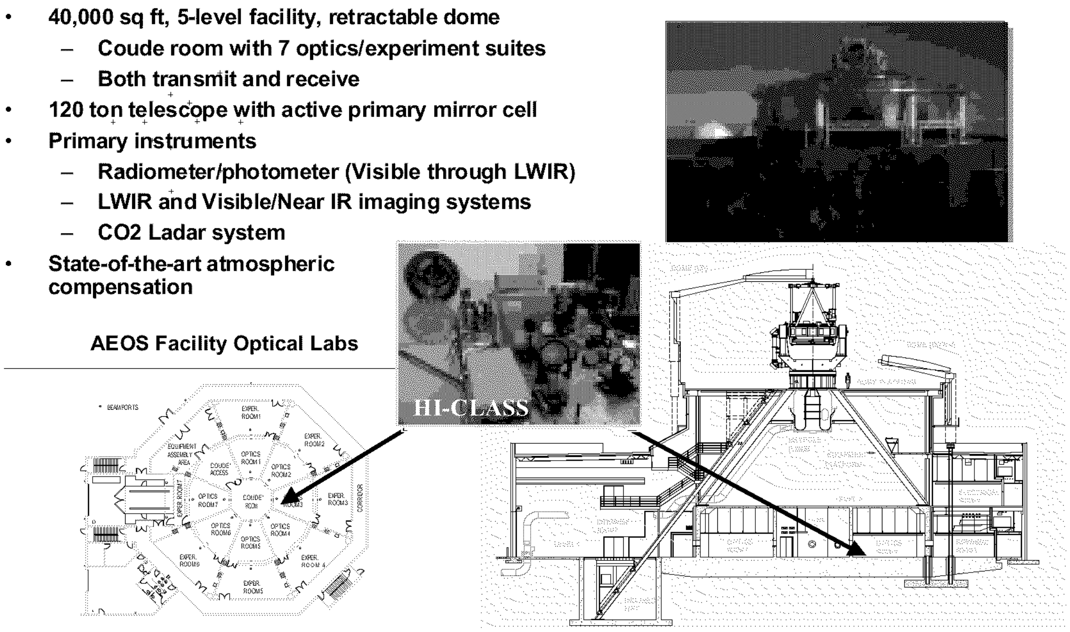

Figure 5: AEOS facility with HI-CLASS system

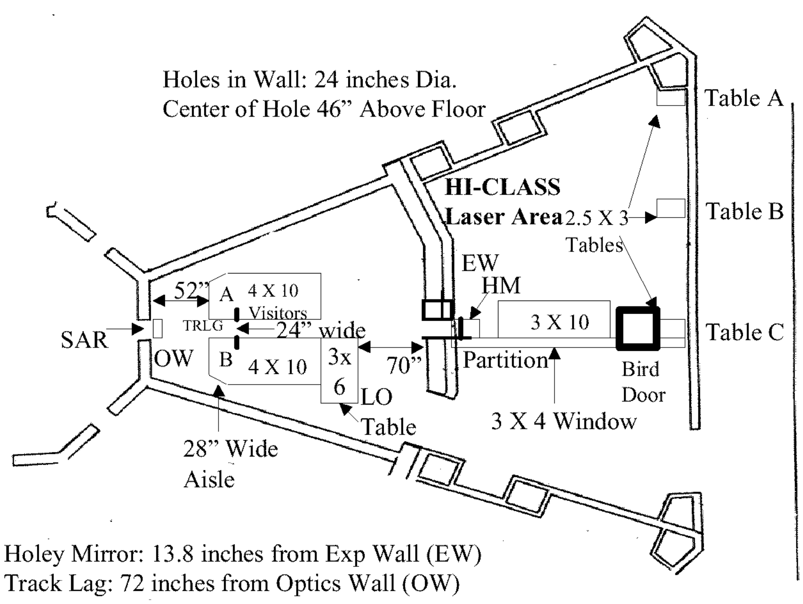

Figure 6: HI-CLASS/AEOS Experiment room layout

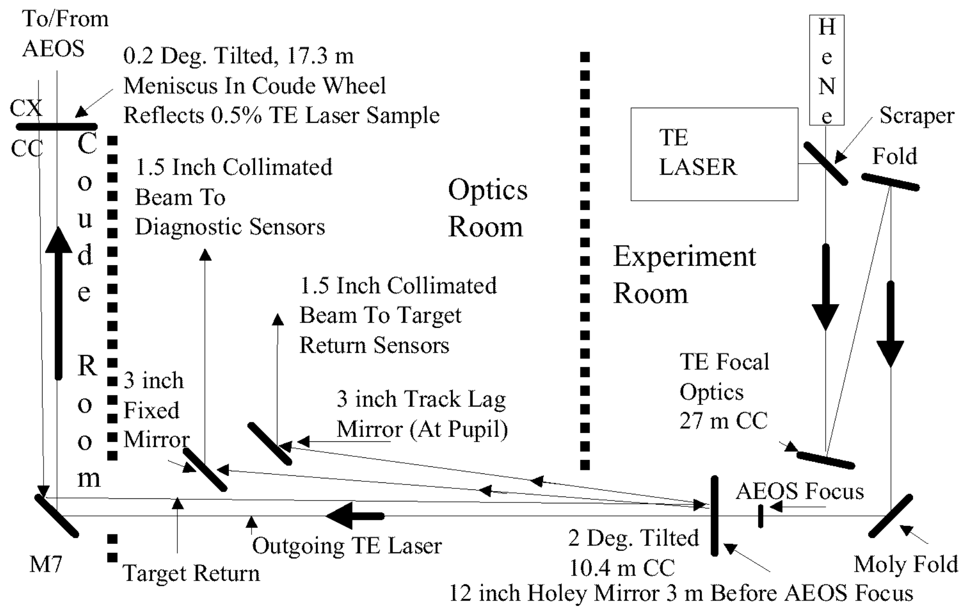

Figure 7: Beam train for HI-CLASS/AEOS system

RECENT RESULTS

The HI-CLASS/AEOS system obtained its first return signals from LAGEOS II on November 10, 2000 with the satellite at a range of approximately 6,100 km. LAGEOS II has four 3.75 cm diameter, infrared retro-reflectors located at the corners of a tetrahedron which yielded signals of approximately 35 dB. Between November 10 and December 15, 2000, the HI-CLASS/AEOS system obtained returns from nine additional missions including both cooperative (retro-reflector-equipped) and non-cooperative satellites. Figure 8 shows representative traces from two of these missions. In one 35-minute period, the HI-CLASS/AEOS system acquired, tracked and obtained returns from three uncooperative targets at ranges from 800 to 1800 km indicating that this sensor could contribute to a Space Object Catalog maintenance function.

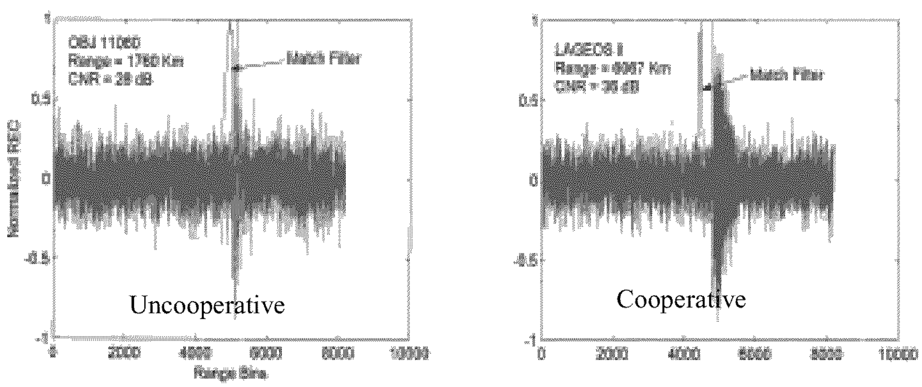

Figure 8: Unprocessed (40 MHz bandwidth) and match-filtered return signals from uncooperative and cooperative targets

Data from these missions are currently being analyzed. Figure 9 shows a preliminary estimate of range, range rate, and CNR measured by the HI-CLASS/AEOS system from object 11060 on November 30th, 2000. The limitation of the fraction of trajectory estimated derives from an FAA regulation precluding laser operations at target elevations less than 25° and periods of predictive avoidance (when other satellites are in the space being lazed).

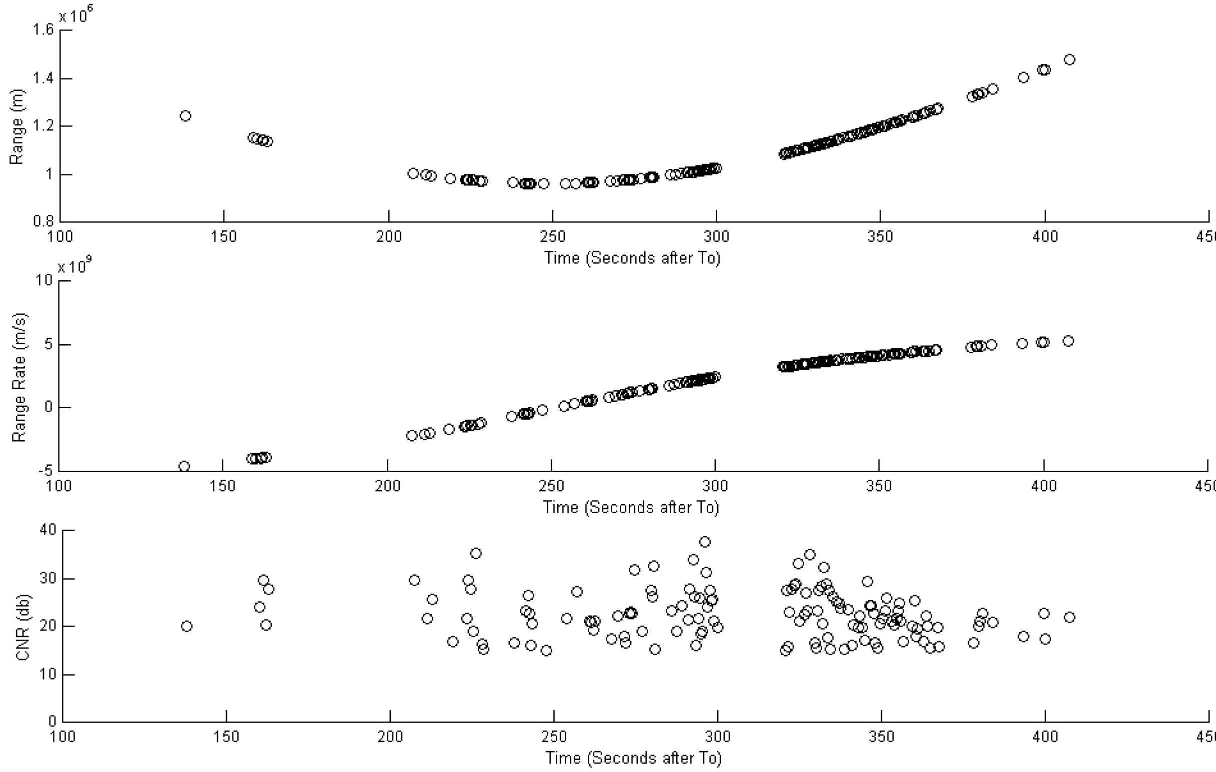

Figure 9: Return signal strength, estimated target range and range rate for target 11060.

CURRENT PROGRAM ACTIVITIES

An additional experiment taking place at the Air Force Research Laboratory is Reflective Tomography imaging techniques for Automatic Target Recognition. The HI-CLASS data contain information about the range-resolved reflectivities and the Doppler spectrum of a target. For earth-stabilized satellites, the cross range motion is insufficient to produce Doppler images, but reflective tomography can be used to reconstruct an image of the satellite. The HI-CLASS system will provide data in support of algorithm development for this technique.

Textron, AFRL/DE and NASA (Marshall) are investigating what would be required for a proof-of-principle small sphere calibration experiment to determine the viability of the HI-CLASS/AEOS (and possibly other MSSS assets) to acquire/re-acquire and track small targets deployed in LEO by the shuttle. Selected appropriately sized trackable targets will be deployed to validate the HI-CLASS/AEOS capability to re-acquire the targets establish accurate trajectories and possibly to provide a “sizing” filter using the pulse-burst waveform.

The current HI-CLASS/AEOS system located in Suite 4 has available a large optical table suitable for other visiting experiments. This table has access to the AEOS and HI-CLASS beam trains via a remotely controlled mirror assembly.

SUMMARY

This paper has summarized the capabilities and designs of two long range CO_2 laser radar systems at the MSSS site. The paper highlights the upgrades and projected capabilities of the HI-CLASS/AEOS system, with a particular emphasis on a projected auxiliary capability to track and size small objects in LEO orbits. The paper discussed recent results and future activities. The success of the recent results shows that HI-CLASS systems are well suited for space situational awareness support such as precision tracking and remote sensing.

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