Development of Coherent Laser Radar for Space Situational Awareness Applications

Narasimha S. Prasad[*] **and Albert DiMarcantonio,**
NASA Langley Research Center, 5 N. Dryden St., MS 468, Hampton VA, 23681
Van Rudd,
135 S. Taylor Ave., Lockheed Martin Coherent Technologies, Inc., Louisville, CO 80027

ABSTRACT

NASA Langley Research Center (LaRC) is working on an innovative and high performance mobile coherent laser radar (ladar) system known as ExoSPEAR for space situational awareness applications in LEO and beyond. Based on continuously agile pulse doublet technology, the 100 W, nanosecond class, near-IR laser based coherent ladar is being developed for short dwell time measurements of resident space objects (RSOs). ExoSPEAR system is designed to provide rapid and precision tracking of RSOs over very long ranges. The goal is to demonstrate mm-class range resolution, mm/s class velocity resolution and microrad angular resolution with significantly reduced error-covariance in track accuracy. Precise orbit determination would help in advancing functionality of early warning systems for tracking uncooperative targets for planetary defense applications. Furthermore, improvements in resolution of micromotion measurements would enhance our understanding of astrodynamical properties of resident space objects.

In this paper, the current experimental status of the ExoSPEAR ladar architecture will be reviewed. Performance simulations illustrating the dependence of range and velocity precision in LEO orbits on ladar power aperture product will be presented.

1. INTRODUCTION

The threat of orbital debris not more than five years ago might be characterized as 'critically remote'. Today, given the increasing numbers of space-faring nations, orbital systems and unwanted conjunctions, it would be characterized as 'critically imminent' [1, 2]. The assessment of possible conjunctions with other resident space objects (RSOs) is critical to protection of commercial, civil and Department of Defense (DoD) space assets. This is entirely dependent on the orbit determination (OD) accuracy and the ability to predict drag and solar radiation pressure effects on the RSOs accurately. While precise ranging to an RSO using radar or singlet pulse based laser systems can be limited by the effects of tumbling, extremely accurate Doppler measurement is possible using a doublet coherent laser tracking system. Addition of such tracking to the OD processing can significantly improve the accuracy of these orbits for possible conjunctors, allowing more accurate event forecasting.

Existing technologies used to identify and track RSOs primarily include X-Band and Ka-Band radars [3], and passive or optical telescopes [4]. These systems are limited in their abilities to simultaneously and accurately range, track and characterize RSOs. Typical conjunction predictions are based on statistical models and mathematical analysis, and can only estimate the probability of a collision between orbiting objects. Advanced sensors with improved track accuracies would help improve conjunction predictions analyses.

NASA LaRC is advancing a novel long range ladar technology known as 'ExoSPEAR' for space surveillance applications. ExoSPEAR is a technically innovative and operationally unique ground-based LADAR system for aerospace observation and measurement. The ExoSPEAR ladar system architecture was developed by Lockheed Martin Coherent Technologies (LMCT) (previously known as Coherent Technologies, Inc., CTI) under funding from AFRL, Kirtland AFB, Albuquerque, NM for long range tracking of fast moving objects under the program known as Range Acquisition and Tracking Laser-Radar (RATLR) (Contract # FA9451-07-C-0220). NASA

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[*] narasimha.s.prasad@nasa.gov; Phone 757-864-9403; Fax 757-864-8828.

acquired this prototype system under an interagency agreement and has now re-purposed it for space exploration and science applications. The ExoSPEAR ladar technology will enable precision measurements to accurately search, detect, identify, classify, characterize, target, localize, and track specific resident space objects (RSO) to facilitate removal or evasion operations.

ExoSPEAR is specifically designed to provide very high precision, short-dwell-time measurements of RSOs in LEO and beyond. Currently, LaRC is expanding its utility and scope for space situational awareness, astrophysics and atmospheric sensing applications from its initial objectives. Its technical capabilities include rapid RSO track acquisition, micro-motion or vibrometry and imagery. This system had been ground tested at White Sands Missile Range using static targets, spinning cones returns for testing speckle decorrelation, and retro returns suitable for satellite tracking. With precision ranging and tracking and hence precision OD, this evolving technology enables reducing conjunction prediction regions for ranges LEO and beyond. The proposed technology confidently challenges traditional systems for space debris detection and monitoring, space object identification, space situational awareness, and sub-millimeter range tracking of RSOs for solar physics, general relativity, precision navigation.

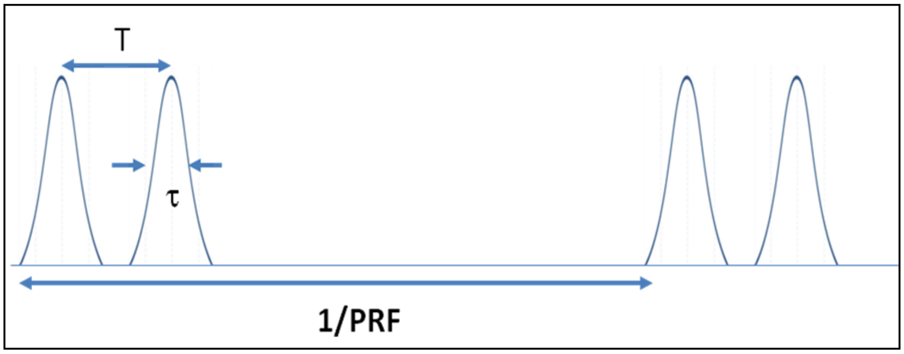
Exo-SPEAR ladar is based on an innovative, first-in-class, patented doublet-pulse technology for very high precision, rapid acquisition, and day-night space observation. **Doublet pulse based Coherent Detection architecture provides highly sensitive and precise tracking measurements (US Patent # 5,815,250)**. The predicted performance of the baseline ladar architecture includes mm-class range resolution, mm/s class velocity resolution and microrad angular resolution with an estimated error-covariance of ~ 1m x 5m and maximum iso-planatic patch. The current system employs unique innovative technologies that can easily lend themselves to orbital debris detection, characterization, and tracking. Plans are underway to demonstrate tracking less than 10 m^2 optical cross-section (OCS) targets in LEO. With energy scaled version of this ExoSPEAR technology combined with improved receiver electronics and large diameter telescopes, tracking near Earth objects (NEOs) such as meteoroids, asteroids and comets may well be possible. In this paper, the current status of the ExoSPEAR system architecture and near-term plans are discussed.

2. DOUBLET PULSE BASED COHERENT DETECTION

The heart of the ExoSPEAR coherent laser radar (ladar) system is the doublet-pulse technique. Generally, for sensing soft targets the term lidar is used where as for hard targets, the term ladar is often employed. The theory of coherent ladar is well described in literature [5-8]. Normally, singlet laser pulse based ladars (or lidars) are used for various applications including wind sensing, trace gas detection, and hard-target imaging. However, the doublet-pulse ladar technique provides several advantages over singlet pulsed ladars and radars for precision ranging of fast moving targets.

The doublet-pulse waveform, shown in Figure 1, is a high time-bandwidth product (TBP) waveform, which can be employed to achieve simultaneous high-range and high-velocity precision measurements. The doublet waveform consists of a pair of short laser pulses from a single longitudinal mode laser of pulsewidth, t (full width at half-maximum (FWHM) = t) separated by a time duration T and is as shown as Figure 1. The duration, T >> t can be precisely varied and set for measurements. Figure 2 illustrates the doublet pulse operation for ranging and velocity measurements. Range is estimated from the time-of-flight of each individual pulselet. Velocity is estimated by measuring the distance the target moved during the pulse separation time, T. The velocity precision is proportional to the inverse of T. The range precision is proportional to t. The time bandwidth product (TBP) is approximately T/t. Accordingly, with a doublet-pulse waveform significantly increased precision in range and velocity resolution is obtained simultaneously. Besides precision ranging, other applications of this concept include vibrometery and 3D coherent imaging.

There are several benefits of using doublet pulses in a coherent ladar operation as determined from the total velocity estimate variance relations shown in Figure 5. These relations are for the finite contrast-to-noise ratio (CNR) limit; where m_s = number of pulse energy (PE) signals per coherent waveform, M_v = diversity; δt_v = velocity waveform duration ($T_D/2$ for doublet pulse). The last relation shows the saturation limit due to speckle coherence or frequency/velocity spread. Since the velocity measurement precision improves linearly with the waveform coherence time, it is advantageous to have the waveform span the coherence time of the target.



$$\boxed{\sigma_V^2 = \sigma_{V_{sat}}^2 + \sigma_{V_{cnr}}^2 + \ldots}$$

$$\boxed{\sigma_{\mathrm{v}} \geq \frac{\lambda}{2\pi\sqrt{8}\delta_{t\mathrm{v}}} \frac{\sqrt{(m_s+1)}}{\sqrt{M_{\mathrm{v}}}\,m_s}}$$

$$\boxed{\sigma_{v,shot} \geq \frac{\lambda\sqrt{\ln(2)}}{2\pi\tau} \frac{\sqrt{1+CNR}}{\sqrt{M}\,CNR}}$$

$$\boxed{\sigma_{\mathrm{v}_{sat}} = \frac{\lambda}{4\pi\tau_c\sqrt{M_{\mathrm{v}}}} = \frac{\lambda}{2}\frac{\delta_f}{\sqrt{2M_{\mathrm{v}}}}}$$

Figure 1. The doublet pulse waveform. (Left) The FWHM of each pulse is t and two pulses are separated by time duration, T. Each doublet waveform is separated by 1/PRF. (Right) Total velocity estimate variance relations.

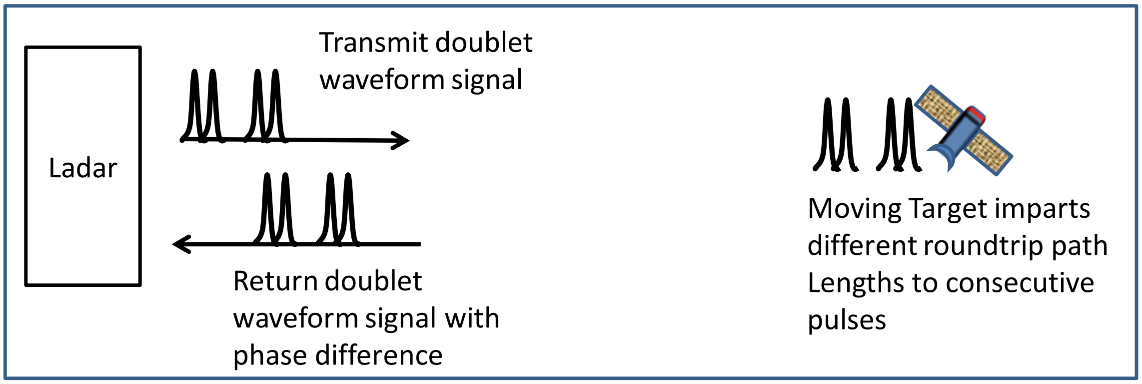


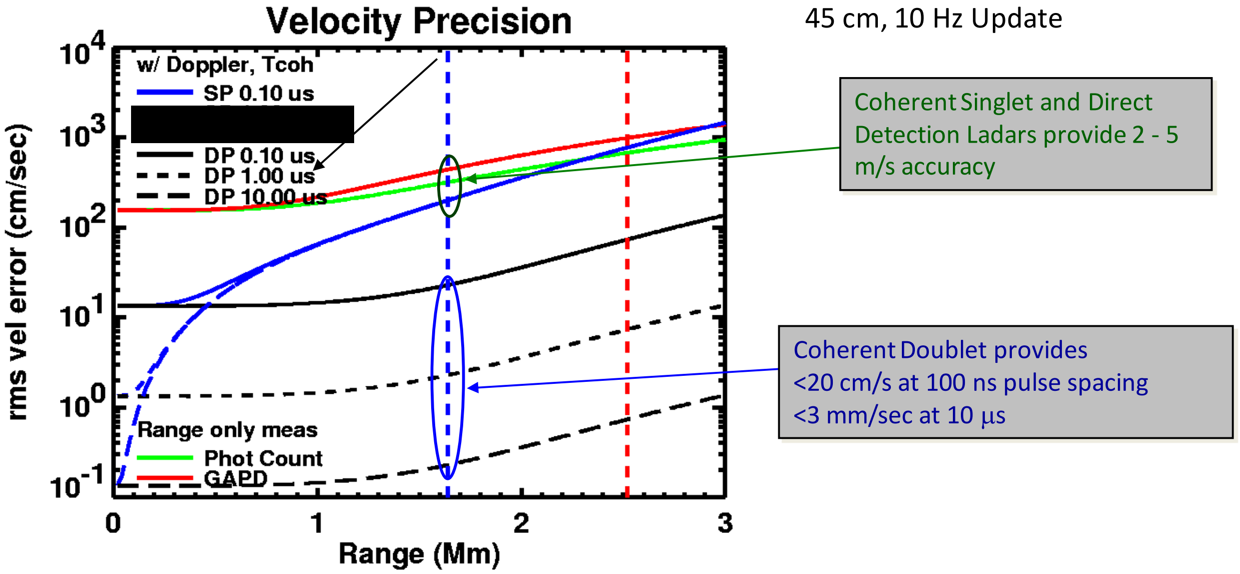
Figure 2. The doublet waveform based velocity measurement scheme. Each pulse of the doublet waveform reflects off from the moving target at different times and consequently induces path difference and hence, phase difference in the received pulses.

There are measurement limitations of a coherent singlet-pulse ladar. Shorter pulsewidths increase range precision but decrease velocity resolution. In contrast, longer pulsewidths provide poor range resolution but good velocity resolution. With a single transform-limited pulse, one must trade-off between range and velocity resolution. This implies large time-bandwidth pulses are required to overcome the single pulse limit. Pulse modulation schemes such as frequency modulated continuous wave (FM-CW) or use of multiple pulses increases the time-bandwidth product. Consequently, the doublet pulse technique offers significantly increased TBP.

Coherent detection provides several advantages over direct detection. First, coherent detection provides robust shot-noise-limited detection. Specific advantages in this case include (a) Immunity to detector dark counts or amplifier noise, (b) Immunity to background light, solar illumination, and other interference, and (c) resistance to countermeasures. Secondly, the coherent scheme provides retention of signal phase (frequency) information. In this case, direct measurements of target velocity (not derived from range rate) allow significant improvement in velocity and acceleration measurements. Increased range resolution is limited only by the signal bandwidth – phase modulation in addition to amplitude only modulation. Range Doppler Imaging (RDI) provides for additional discriminants. Synthetic aperture ladar measurements allows for spatial resolution below the diffraction limit of the physical aperture. Co-phasing of multiple smaller apertures allows for improved size, weight, and power (SWAP).

Figure 2 illustrates the doublet waveform scheme used for precision range and velocity measurements. The transmit waveform consists of two narrow pulses separated by an adjustable delay between them. These two pulses reflect off from a moving target. Since the two pulses of the doublet intercept the target at different times, they experience different round-trip path lengths which create a phase difference between the two waveforms at the detector. This phase difference is measured by the coherent receiver and interpreted as a target velocity. The range is simultaneously determined by measuring the time-of-flight for each pulse independently. The precision of the velocity measurement is tied to the separation in time between the two pulses of the doublet. Extremely precise measurements, in the cm/s range, can be achieved with separations on the order of one microsecond (assuming a one micron laser wavelength). Even finer measurements with mm/sec accuracy are possible with wider doublet separations. Simultaneously, the range resolution is determined by the short width of each pulse. It is this characteristic of the doublet-pulse waveform, the ability to simultaneously obtain high accuracy range and velocity, makes it very attractive for precision target tracking applications.

Performance models to understand the advantages offered by coherent doublet versus direct detection have been carried out. For a nominal operation, rms velocity error in cm/s is plotted against range in Mm. Figure 3 illustrates a typical scenario of coherent vs. direct detection performance and the results can be summarized as follows. Coherent doublet waveform provides 10-1000x improvement in line-of-sight (LOS) velocity precision over direct detection. Coherent doublet waveform ladar allows >10x decrease in time required to detect LOS acceleration. Coherent Singlet or Direct Detection need 5 - 8 sec whereas coherent doublet requires <0.2 s for >1 ms pulse spacings.



45 cm, 10 Hz Update

Coherent Singlet and Direct Detection Ladars provide 2 - 5 m/s accuracy

Coherent Doublet provides
<20 cm/s at 100 ns pulse spacing
<3 mm/sec at 10 µs

Figure 3. Advantages of coherent detection over direct detection schemes. Vertical lines indicate maximum range for 95% Pd at 1% PFA for different aperture sizes. Blue: 20 cm Red: 45 cm. All systems are 400 Hz, 125 mJ/waveform, and assume a 10 Hz update rate of the target track.

Contrary to a singlet pulse, the doublet-pulse waveform offers ambiguity in the velocity measurement. Hence, the measurement process must start with a singlet pulse with no velocity ambiguity. One needs to “zoom in” on the velocity as a track is developed. When track data allows, processing mode switches to doublet waveform with narrow pulse separation. When track data allows, doublet separation increased. First doublet spacing must have wide enough ambiguity to accept inaccuracy of singlet velocity. Note that maximum accuracy is limited by speckle decorrelation of the target. Variable Spacing allows one to zoom in obtain accurate velocity.

Figure 5 illustrates velocity and acceleration precision estimates. For our current 100 W system, using a 50 cm aperture and 10 Hz update, performance modeling indicates a velocity precision of ~1 cm/s to 2 mega meters (Mm) and acceleration precision of <0.1 m/s^2 to 2 Mm. With existing ExoSPEAR hardware parameters, performance simulations have indicated that RSO tracking of optical cross-sections (OCS) of 10 m^2 in LEO, and feasibility studies of long range vibrometry measurements can be performed. With upgrades (i.e., higher energy and/or multipixel coherent focal plane receivers), it is possible to perform 1 m^2 and down to 10 cm^2 OCS debris tracking along with significantly improved vibrometry and 3D imaging measurements. vibrometry provides for RSO status analysis including failure prediction and 3-D imaging provides for real-time dynamic orientation and hence the state vector of an RSO. Theoretical analyses of its performance have been carried out and the associated Kalman-based tracking system has been vetted in a laboratory setting.

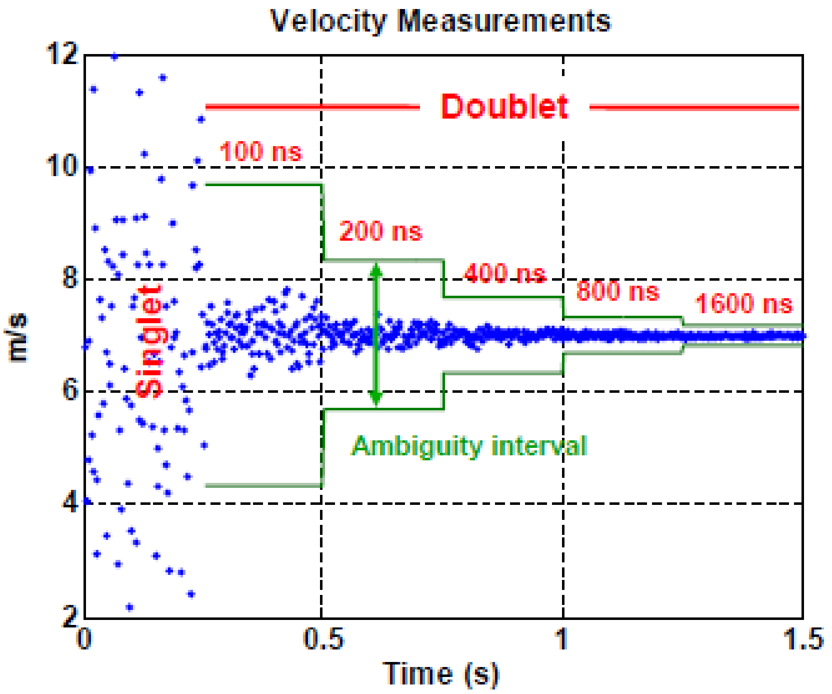


Figure 4. For precision velocity measurements, variable zooming allows one to "zoom" into an accurate velocity value.

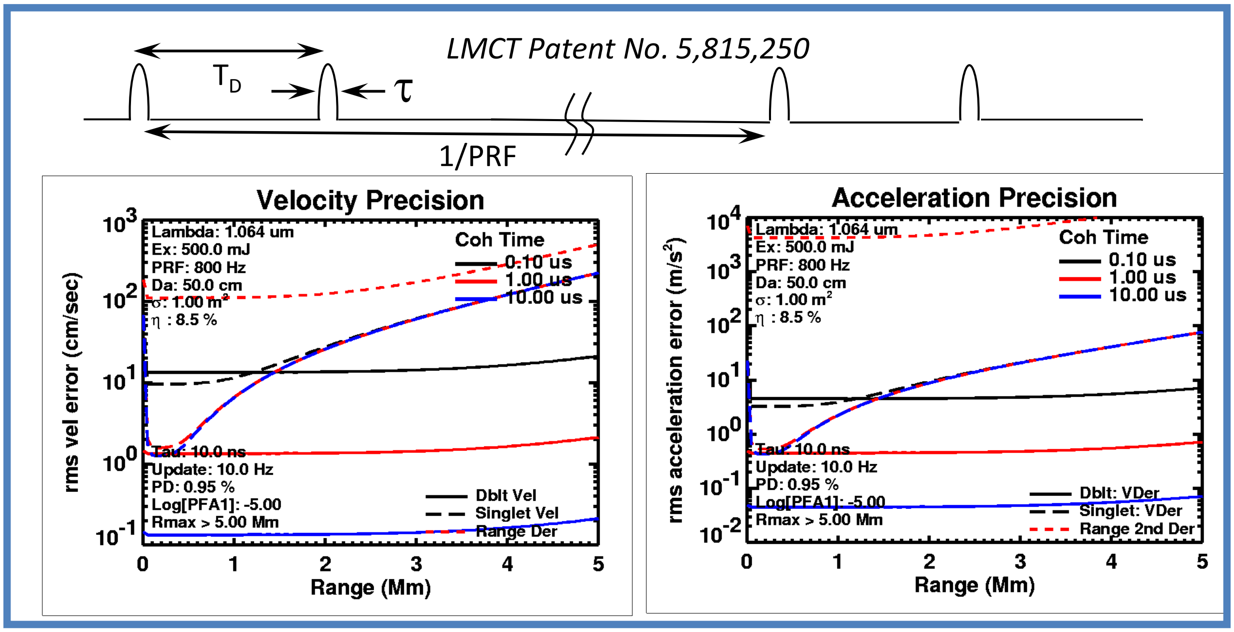


Figure 5. Velocity and acceleration precision estimates using typical system parameters.

3. EXOSPEAR SYSTEM ARCHITECTURE

Figure 6 shows the schematic of the ExoSPEAR ladar architecture to achieve enhanced velocity and range resolution. It comprises of two diode pumped single longitudinal mode laser systems known as miniature Slave Oscillators (MiSO) known as MiSO1 and MiSO2 configured in master oscillator power amplifier (MOPA) architecture. Table 1 shows specifications of each laser transmitter.

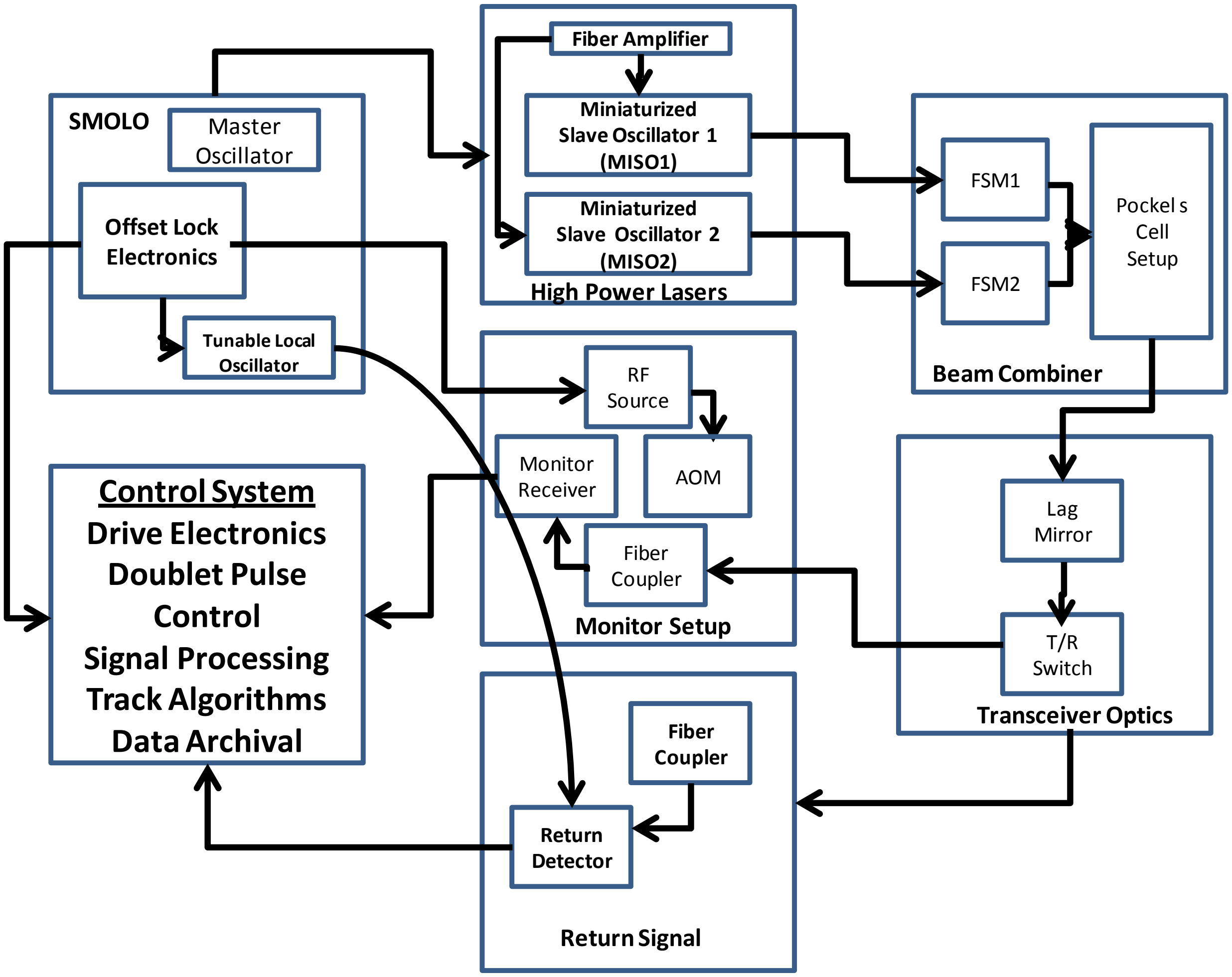


Figure 6: The ExoSPEAR ladar System architecture.

In each case, commercially available seed lasers are used to configure an arrangement known as stable master oscillator local oscillator (SMOLO). The output is fiber coupled to a MiSO consisting of slab amplifier layout to achieve up to 60 mJ/pulse. The output from these two laser systems is combined using a Pockels cell arrangement in combination with two Free Scanning Mirrors (FSMs) to achieve adaptive pulse separation. Monitor setup consisting of acousto-optic modulator and receiver components are used to observe laser beam characteristics for proper alignments. The

Table 1: Laser transmitter specifications

Parameters	Specifications
Wavelength	1.064 µm
PRF	800 Hz, (two Lasers each running at 400 Hz)
Transceiver output power	> 50 W
Pulse energy	> 60 mJ/pulse, 2 pulses/waveform
Pulse width	< 11 ns
Pulse spacing utilized	20 ns to 1 ms
Beam quality	1.2 times Diff. Limited; PITB > 0.5
Beam Divergence (full angle)	< 0.3 mrad
Spectral Transform Limited Pulse	<10%
Centroid Beam Pointing Stability	<1/10th Diffraction Limited
Ladar system efficiency	Laser #1: 3% and Laser #2: 6%

transceiver optics arrangement with lag mirror and Transmit/Receive (T/R) switch will simultaneously transmit as well as receive the return beam. The return laser beam, collected by a telescope, will be coherently detected using a single pixel detector after mixing it with the local oscillator. The corresponding electronic signal will be directed for further processing. The two electronics racks consists of Data Acquisition Computer with software for streaming data and basic processing, Internal Alignment (IA) computer with software routine for aligning laser beams, and PXI computer with software for controlling laser operation. A closed-loop tracking-and-control loop is utilized to resolve ambiguity and optimize track performance. The current algorithm provides real-time range, velocity, and acceleration tracks as well as a number of other diagnostic signals. Acceleration jolts at the target turn-around points can be captured. Figure 7 shows the current ExoSPEAR prototype system operational at NASA LaRC. The entire fits into a conex container of 20 ft. x 8 ft. in length. The graphical user interface illustrating various components of track information is shown in Figure 8.

The concept of operation (Conops) for consists of a spectrally and spatially coherent laser beam that is cued and directed towards the object of interest. The scattered laser light from the object is collected by a telescope where the photons are detected and processed. In a bistatic arrangement, the incident and backscattered light utilize the same optical telescope. Improved precision over existing sensor systems combined with mobility could benefit space surveillance network operations. For our current ExoSPEAR lab system, performance models indicate the achievable velocity resolution (10 ms pulse spacing) is < 1 cm/s, and the range resolution with a 10 ns pulsewidth is ~1.5 m. Plans are underway to carry out proof-of-concept experiments for ranging and tracking in a progressive manner using weather ballons, UAV, aircraft, and International Space Station.

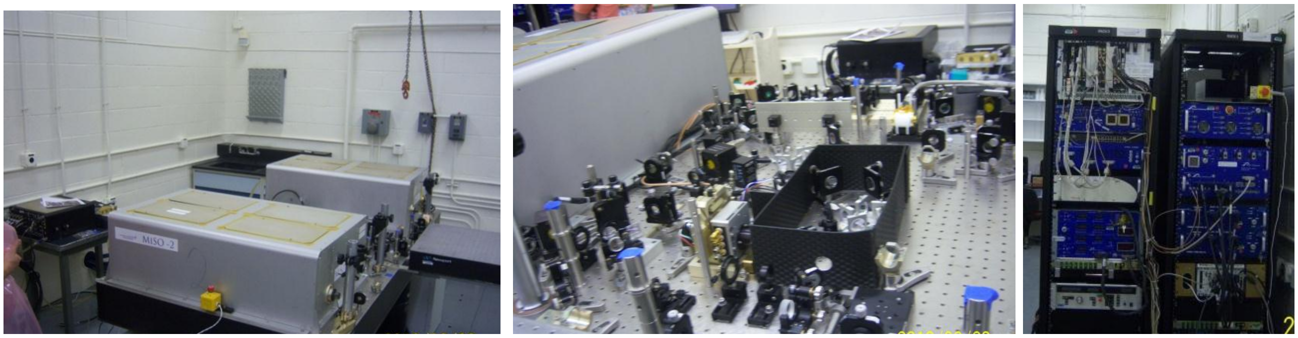


Figure 7. Left Picture: The ExoSPEAR laser transmitters, MiSO1 and MiSO2. Middle Picture: Pockels Cell arrangement for beam combining and adaptive doublet formation. Right Picture: The electronics rack consisting of drive electronics and signal processing computers.

Range: 33.52m
Mean: 33.4m
Std. Dev.: 199.68mm
Velocity: 299.86mm
Mean: 299.45mm
Std. Dev.: 2.77mm/s
Acceleration: -123.72um.
Y-Max (m): 100
Y-Min (m): -100
Num. Pts.: 4000
☑ Raw Pts.
☑ Kalman Est.
Y-Max (m/s): 2
Y-Min (m/s): -2
☑ Raw Pts.
☑ Kalman Est.
Y-Max (m/s^2): 20
Y-Min (m/s^2): -20
Commanded: 0 s
Measured: 9.914 us
Directory:
☐ Reprocess
Pulses Averaged: 4
IRIG-B: 20090226 21:43:35
Db. Angle Mean: -127.942 de
Connection Status: GUI

```
21:43:23 DQ: AArchive: opened file C:\DATA/20090226/20090226_214323.raw for writing.
21:43:24 DQ: 9430000 signals armed and retrieved. (8671)
21:43:28 DQ: 9470000 monitors armed and retrieved. (1328)
21:43:49 IStructClientBase: Invalid record ID 0x2!
```

Figure 8. The coherent lidar system user interface illustrating track information. The ladar algorithm provides real-time range, velocity, and acceleration tracks as well as a number of other diagnostic signals. Note its ability to see acceleration jolts at the target turn-around points.

4. SUMMARY, CONCLUSIONS AND PROGNOSIS

ExoSPEAR is an innovative waveform (pulse-doublet) coherent detection laser radar technology that enables tracking of RSOs for unambiguous subsequent conjunction management and/or mitigation, and an architecture that provides capabilities which have been difficult or impossible to achieve with existing passive or active sensors, and offers unprecedented precise orbit determination, day or night. It offers a technology path for demonstrations in long range precision ranging, tracking, vibrometry, and 3D imaging. The ExoSPEAR system, integrated with the derivatives of the large space optics would provide for the rapid and precise detection and tracking, and offer unprecedented remote sensing capability for a variety of exploration, science and technology demonstration operations. The technology discriminator is the coherence pulse doublet for achieving improved track accuracies with simultaneous mm class range precision, and mm/s class velocity precision. The operational discriminator would be global mobility for ubiquitous orbital coverage LEO and beyond. Programmatically, operationally and technologically, ExoSPEAR is as an integrated system of coherent doublet pulse ladar, coude-path optics, telescope, ground and space operations compatible platforms, and logistics vehicles that ushers in a new spectral dimension for space situational awareness measurements.

The current prototype provides a framework and a test bed for precision ranging and tracking experiments of RSOs in LEO. Preliminary models have indicated that the current ExoSPEAR system parameters could provide tracking of targets in LEO. The ongoing planning emphasizes a conex based mobile based remote sensing system to utilize established telescope sites data collection. The current system is suitable for ground-based tests at telescope facilities including ISTEF facility located in NASA's KSC and AMOS facility on Mt. Haleakala in Hawaii. The ladar capability would provide for tracking, identification, classifying, characterizing and dynamically orienting

RSOs and eventually NEO's with unprecedented speed of acquisition, accuracy and resolution. ExoSPEAR could operate independently and interdependently as a build-out of the Space Surveillance Network architecture. Finally, the proposed ExoSPEAR technology would populate remote sensing space situational awareness architecture to monitor space operations, conduct discriminating science, and advance new technology.

ACKNOWLEDGEMENTS

The authors wish to acknowledge David B. Founds, AFRL/RDTP Chief, Systems Support Office, Kirtland AFB, Dr. Duane Smith, (currently at Raytheon), Stephen Sandford, Director, STED, NASA LaRC, Robert Kerns, Manager, Commercial Space Projects Office, NASA LaRC , William C. Edwards, ED, NASA LaRC for valuable contributions in setting up the ExoSPEAR system.

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