Doublet pulse coherent laser radar for tracking of resident space objects

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ABSTRACT

In this paper, the development of a long range ladar system known as ExoSPEAR at NASA Langley Research Center for tracking rapidly moving resident space objects is discussed. Based on 100 W, nanosecond class, near-IR laser, this ladar system with coherent detection technique is currently being investigated for short dwell time measurements of resident space objects (RSOs) in LEO and beyond for space surveillance applications. This unique ladar architecture is configured using a continuously agile doublet-pulse waveform scheme coupled to a closed-loop tracking and control loop approach to simultaneously achieve mm class range precision and mm/s velocity precision and hence obtain unprecedented track accuracies. Salient features of the design architecture followed by performance modeling and engagement simulations illustrating the dependence of range and velocity precision in LEO orbits on ladar parameters are presented. Estimated limits on detectable optical cross sections of RSOs in LEO orbits are discussed.

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 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

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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. This system can provide rapid RSO track acquisition, RSO micro-motion or vibrometry, 3D-imagery, and precision, navigation, and timing (PNT). 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 10 cm^2 cross section targets in LEO as well as tracking near Earth objects (NEOs) such as meteoroids, and asteroids may well be possible.

The basic concepts of doublet pulse based coherent ladar scheme and its advantages over direct detection scheme along with velocity and acceleration precision estimates using typical operational parameters are described in the reference [5]. Coherent Singlet-Pulse ladar has measurement limitations. In the case of short pulse operation, reasonable good range resolution can be obtained but will provide poor velocity resolution and hence cannot provide precision tracking. However, range resolution reduces for long pulse operation but velocity resolution increases. With a single transform-limited pulse one must trade-off between range and velocity resolution. To overcome the single-pulse limit, large time-bandwidth pulses have to be utilized. With a doublet-pulse waveform range and velocity resolution is obtained simultaneously. Figure 1 illustrates simultaneous measurement of range and velocity by a doublet pulse waveform based ladar.

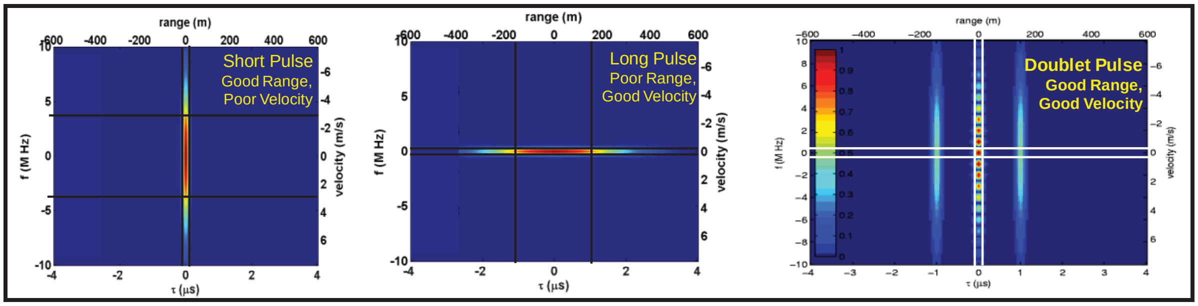


Figure 1. Left: Good range resolution with single short pulses. Middle: Good velocity resolution with longer pulsewidth operation. Right: Doublet pulse operation provides good range and velocities.

The simultaneous measurement of range and velocity using short pulsewidth doublet pulse coherent ladar technique offers a means for precision tracking. The technique offers best of both worlds; precise range measurements from narrow pulses, precise velocity from Doppler shift over long dwell time. The pulse separation is adjusted in real-time to provide best possible measurement. The pulse separation cannot be too small due to poorer velocity precision as well as too large to avoid speckle decorrelation.

Precision requirements drive system requirements. With pulsewidths of 10 ns or less, range resolution < 1 m or one part in 10^6 can be achieved. For velocity measurements of < 1 cm/sec (need to hit the Cramer-Rao Lower Bound), one part in 10^5 precision, doublet-pulse spacings has to be >1 msec. The agile doublet-pulse waveform forming setup in ExoSPEAR meets all of these performance requirements. Accordingly, the overall performance goal of the current ExoSPEAR system is to achieve high-accuracy tracking of long-range, fast-moving objects in LEO. In this paper, the performance modeling and engagement simulation results of the ExoSPEAR system are discussed.

2. EXOSPEAR SYSTEM ARCHITECTURE

Theory and experimentation techniques of coherent and other ladar techniques are discussed in references [6-8]. Figure 2 shows the schematic of the ExoSPEAR ladar architecture based on doublet pulse coherent ladar technique 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. 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 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 is directed for further processing.

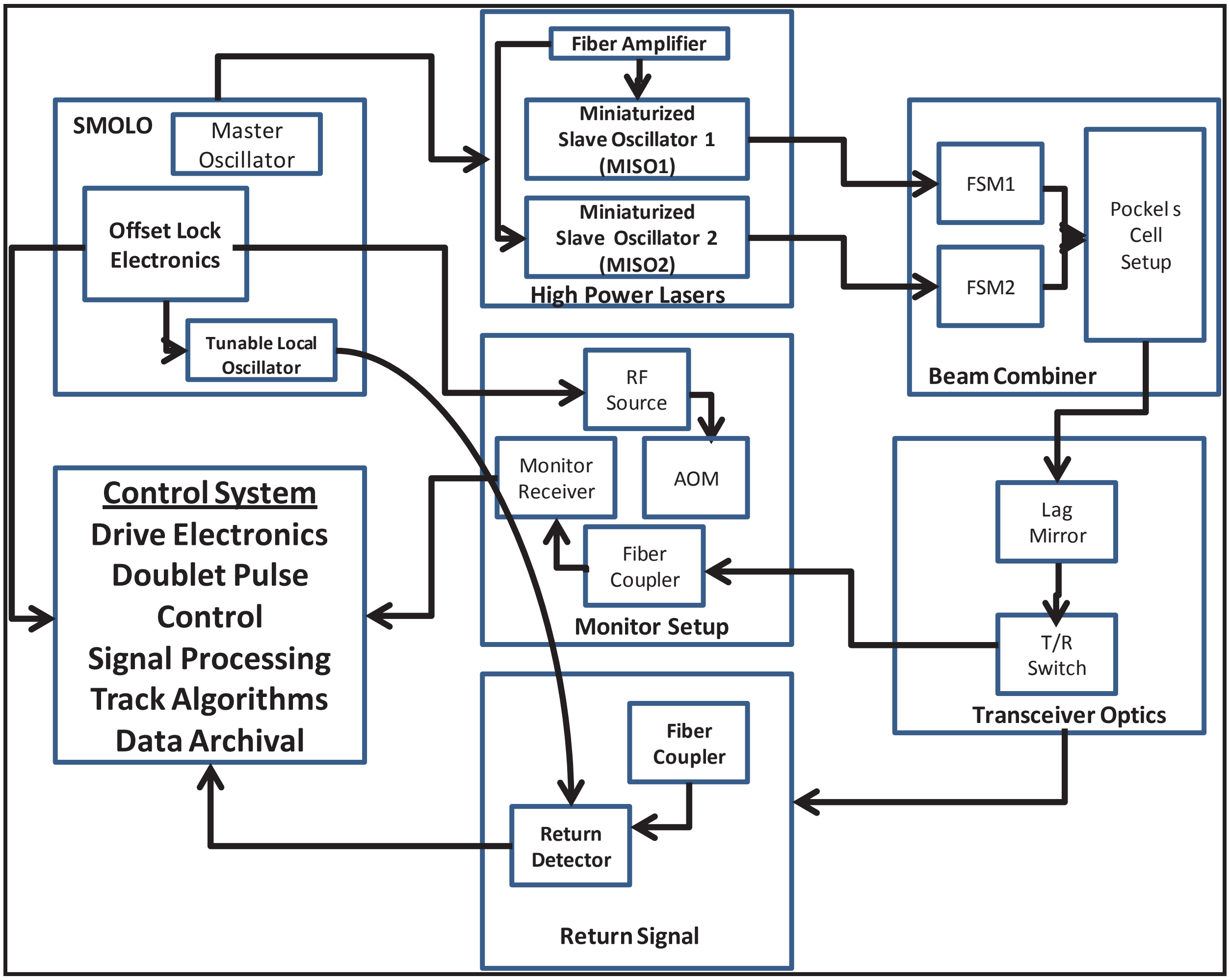


Figure 2: The ExoSPEAR ladar System architecture.

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%

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. Figure 3 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 4.

Figure 3. 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
Y-Max (m): 100
Y-Min (m): 100
Auto Scale On
Num. Pts.: 4000
☑ Raw Pts.
☑ Kalman Est.
Commanded: 0 s
Measured: 9.914 us
Directory:
☐ Reprocess
Velocity: 299.86mm
Mean: 299.45mm
Std. Dev.: 2.77mm/s
Y-Max (m/s): 2
Y-Min (m/s): -2
Auto Scale On
☑ Raw Pts.
☑ Kalman Est.
Pulses Averaged: 4
IRIG-B: 20090226 21:43:35
Db. Angle Mean: -127.942 de
Acceleration: -123.72um
Y-Max (m/s^2): 20
Y-Min (m/s^2): -20
Auto Scale On
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 4. 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.

The LRL system is designed to precisely track satellites from a ground site. The system consists of a coherent, doublet pulse lidar, a Kalman filter target tracker, and a feedback control system. The system has been thoroughly tested in the lab environment. Key capabilities such as obtain high-accuracy tracks quickly and obtain real-time processing and feedback control have been established. They include feedback control of processing mode, pulse separation, pulse averaging, and data acquisition capabilities. The current algorithm provides real-time range, velocity, and acceleration tracks as well as a number of other diagnostic signals. It has the ability to see acceleration jolts at the target turn-around points. The prototype system was successfully tested at White Sands Missile Range with static and spinning cone targets. Efforts are underway to carry out proof-of-concept experiments for ranging and tracking of potential fast moving targets including International Space Station.

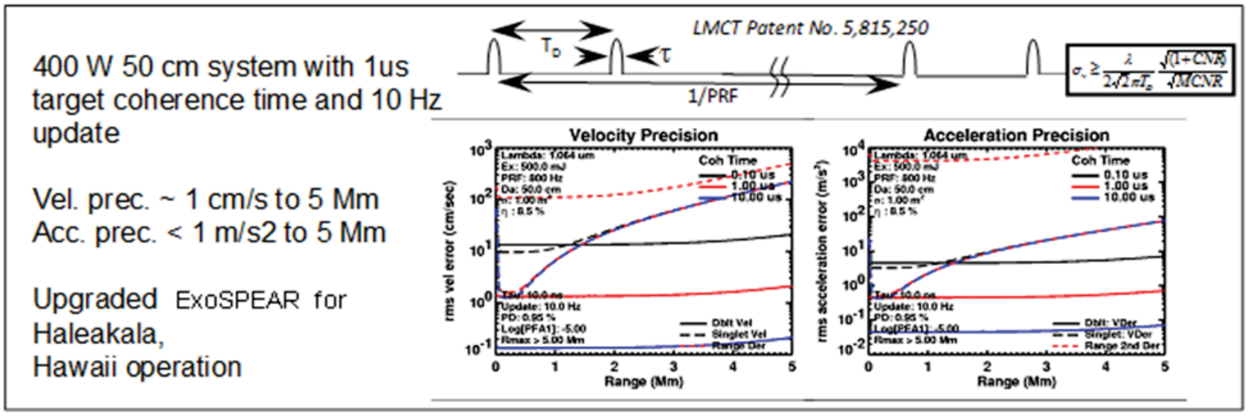
The concept of operation (Conops) for consists of a spectrally and spatially coherent laser beam that is cued and directed towards the object of interest. The scattered laser light from the object is collected by a telescope where the photons are detected and processed. In a bistatic arrangement, the 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.

3. PERFORMANCE MODELING

Using typical transceiver parameters, extensive performance modeling has been carried out. To illustrate the anticipated velocity and acceleration precisions for ISTEF telescope facility located in NASA's Kennedy Space Center, Florida and AMOS telescope facility located in Mt. Haleakala, Maui, Hawaii were carried. In the case of The ISTEF Site is located at the Kennedy Space Center, Florida. ISTEF is a Navy SSC PAC facility operated by CSC. For ISTEF demonstration with a telescope aperture of 22 cm, a 100 W system with 10 Hz update provides a velocity precision of ~1 cm/s upto a range of 2 megameters (Mm) and an acceleration precision of 0.1 m/s^2 to 2 Mm. Similarly for Mt. Haleakala demonstration, using 400 W 50 cm system with 1 ms target coherence time and 10

Hz update, a velocity precision of 1 cm/s and an acceleration precision of <0.1 cm/s^2, both upto 5 Mm is predicted. Figure 5 illustrates rms velocity and ecceleration errors for Mt. Haleakala operation using typical parameters.

Figure 6 shows the clutter to noise ratio (CNR) estimation in dB versus range in Mm for various target sizes. The current system is predicted to detect 10 m^2 targets such as SeaSat & Okean beyond 1 Mm. With averaging of 100, one needs about -1 dB for reliable detection. The detection curve takes into account the automatic adjustment of averaging level done by the system. The system will be able to detect 1 m^2 targets within 500 km. Depending on target altitude there should be ample signal to detect LAGEOS 1 (10^6 m^2) by incorporating appropriate pointing stability with no passive track.



400 W 50 cm system with 1us target coherence time and 10 Hz update

Vel. prec. ~ 1 cm/s to 5 Mm
Acc. prec. < 1 m/s2 to 5 Mm

Upgraded ExoSPEAR for Haleakala, Hawaii operation

LMCT Patent No. 5,815,250

$$\sigma_v \geq \frac{\lambda}{2\sqrt{2}\pi T_c} \frac{\sqrt{(1+CNR)}}{\sqrt{M}CNR}$$

Figure 5. Rms velocity and acceleration error predictions for Mt. Haleakala operation. Doublet pulse waveform allows maintenance of range resolution and precision while significantly improving the velocity and acceleration measurement.

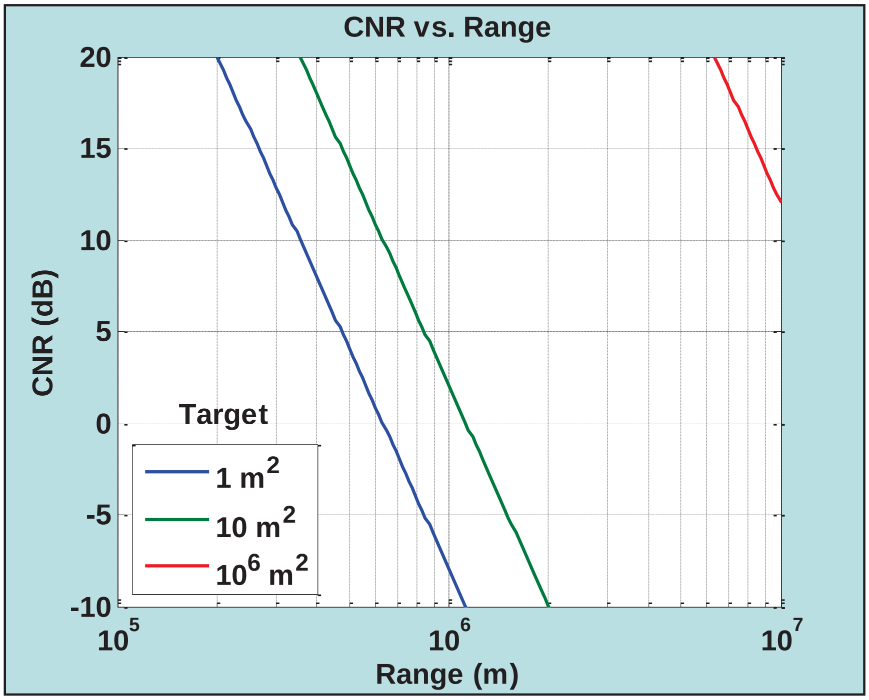


Figure 6. Satellite CNR Predictions.

4. ENGAGEMENT SIMULATION STUDIES

A system simulation has been developed to test processing and tracking algorithms. Real-time code was used wherever possible. Realistic representation of total system has been developed. The key component to complete the simulator is the signal generator. Accordingly, a signal simulator for realistic coherent data was successfully developed. This signal simulator faithfully models speckle effects, including temporal correlation of phase and intensity. The simulation allows for evaluation of tracking performance in various scenarios. For simulation noise sources, local oscillator (LO) shot noise was included in signal simulator. Speckle effects were included in signal simulator (and specification of target rotation rate). Accurate representation of amplitude modulation and velocity spread were accomplished. However, TLO frequency drift, detector dark current, pointing errors and transmit pulse phase and amplitude variations were not included. The engagement simulation uses a signal simulator to create realistic coherent signals, models targets as collection of point scatterers and tracks each scatterer position and velocity. Speckle effects were faithfully created. The output of signal simulator is simulated digitizer data which includes shot noise effects. Figure 7 illustrates the top level tracking architecture. The signal generator produces realistic raw data to simulate the DAQ subsystem

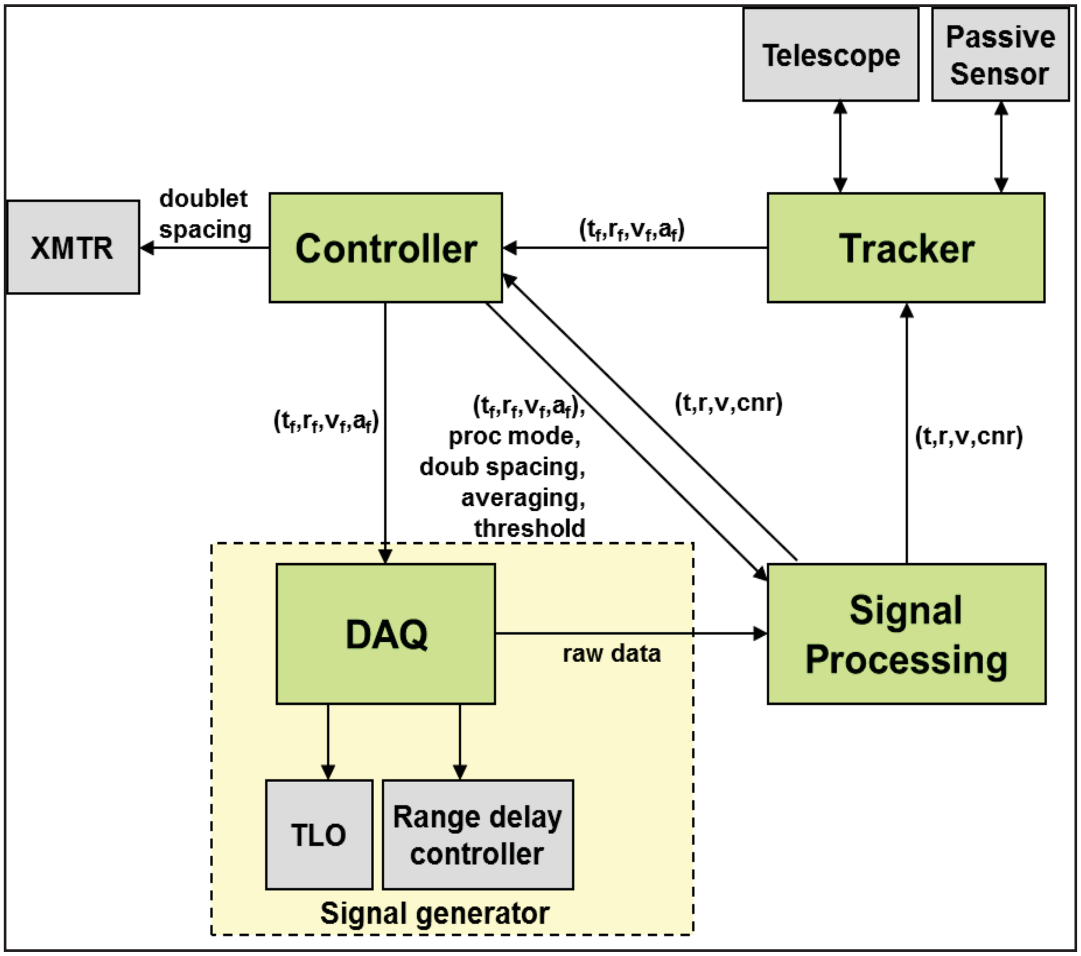


Figure 7. Top Level Tracking Architecture. The simulator includes all of the major subsystems.

Several scenarios were investigated. In one test case, the typical simulation parameters were as follows: Engagement duration is equal to 100 sec. Lambertian sphere target of diameter of 4 m is considered. The LRCS of 10 m^2 representing a more realistic target was considered. Rotation rate is equal to 100 mrad/s. High rotation rates are considered to decrease speckle decorrelation time. Estimate decorrelation time is on the order of 6 μs. In this case, angular scan pattern was implemented. A pointing jitter of 1 μrad, 1 σ on each axis was introduced. This was independent between transmit and receive (due to time-of-flight). Figure 8 shows the simulation results. We see good tracking in range, velocity, and acceleration, at least, at gross levels. The system chooses pulse separation as large as possible without causing too much speckle noise. Initially sees too much speckle noise at ~40 s with a spacing of 1280 ns. It held this level for over 20 seconds until it decided it produced too much noise. The system reduces spacing and then uses smaller steps to increase doublet spacing and settles on 1134 ns as optimal spacing.

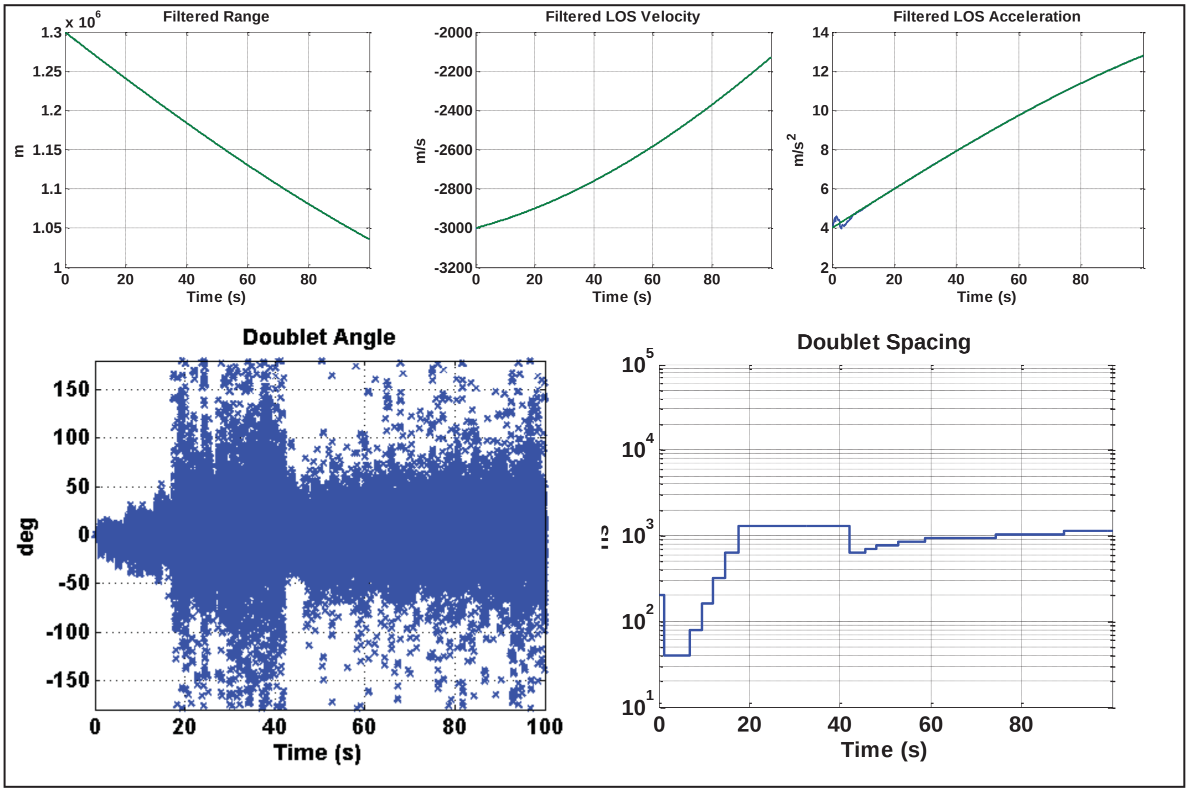


Figure 8. Simulation Results: Estimated Range, Velocity, Acceleration, Doublet Spacing and Doublet Angle.

Figure 9 illustrates simulation results of velocity and acceleration errors and scan pattern. The tracker produces velocity estimates within ~2 cm/s of truth. This is an excellent performance since speckle is limiting the doublet pulse spacing. Furthermore, acceleration is also tracked very well. In this case, better than 0.02 m/s^2 is predicted. Note that there is no direct measurement of acceleration, but derived from velocity measurements. In the case of scan pattern simulation results, the coarse scan completes one petal before initial detection. The plot shows commanded pointing angles, not actual achieved pointing angles. Jitter corrupts actual angle. Even in the presence of jitter, the system finds the target and maintains pointing. Similar results in the other parameters, as well, have been obtained.

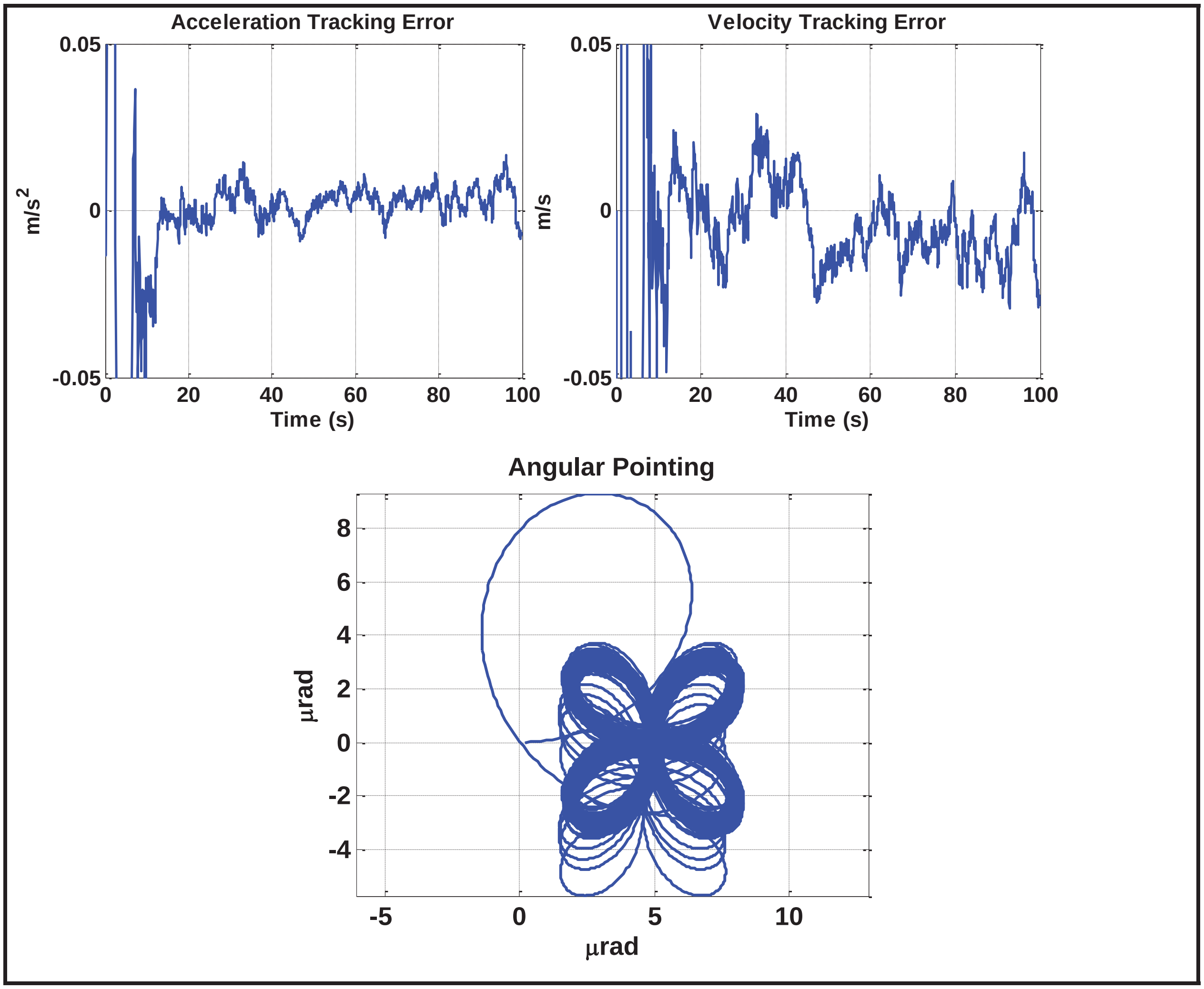


Figure 9. Simulation results of velocity and acceleration tracking errors (top) and scan pattern (bottom).

5. 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.

Modeling and simulation results are very promising. Actual algorithms used throughout simulation, except for signal simulator. Excellent velocity track (~1 cm/s). Simulated system is able to effectively decide on processing parameters in real-time. Various scenarios including singlet vs. doublet, averaging levels, and doublet spacing have been investigated. System maintains the correct velocity ambiguity interval even as the waveform zooms in to 5 cm/s intervals and the target velocity is changing by 2 km/s.

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 with unprecedented speed of acquisition, accuracy and resolution. ExoSPEAR could operate independently and interdependently as a build-out of the Space Surveillance Network architecture. Field campaigns are being planned. 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), 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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