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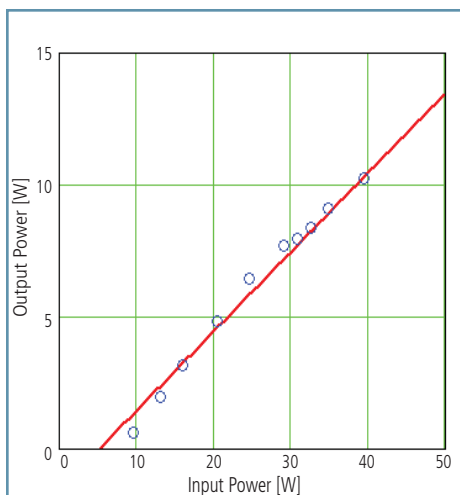
Raytheon's Sensing Technologies

Featuring innovative electro-optical
and radio frequency systems

Raytheon

Customer Success Is Our Mission

Raytheon Achieves Advanced Radar Functionality at Optical Wavelengths via Coherent Ladar



1645nm Er:YAG laser pumped at 1534nm
CW Operation: 32% slope efficiency with
respect to incident power (57% with
respect to absorbed power)

Figure 5. Resonantly pumped ErYAG laser results showing high efficiencies

transmitter/system — especially when implemented in conjunction with the PWG gain architecture/geometry.

Summary

Advanced active EO systems will be critical to providing a competitive advantage to our forces for the foreseeable future. To maintain its position as a leading provider of these systems, Raytheon is actively maintaining a leadership position in the development of the next-generation lasers that power these active EO systems. Development of advanced laser architectures, such as fiber and planar waveguide lasers, along with advances in laser diode technology and gain medium materials, will fuel Raytheon's growth in this expanding market segment. ●

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Prior to the discovery of the laser in 1960, optical range measurements depended on the use of incoherent spark sources that suffered from large pulse widths and high-beam divergence. The laser's narrow, high-energy pulses and highly collimated monochromatic beam made for an ideal source and revolutionized rangefinder accuracy and functionality. It was soon realized that these narrow-linewidth sources would make heterodyne detection possible in the infrared (IR) and optical spectral range.

Laser radar (or ladar — laser detection and ranging) is an extension of conventional microwave radar techniques to much shorter wavelengths (by a factor of 100,000). Like microwave radar, ladar can simultaneously measure range, velocity, reflectivity, and azimuth and elevation angles. Ladar is well suited for precise measurements useful in target classification and recognition, but ill suited for wide-area search because of the time and energy required.

Laser radars, with their optical wavelengths and active sensing, behave like forward-looking infrared sensors in terms of angular resolution, and like microwave radars in terms of range and velocity measuring capability. However, coherent effects and extreme wavelength differences give rise to phenomena not seen in these more traditional sensors.

For example, coherence of the laser transmitter causes speckle in the return from optically rough target surfaces. The apparent brightness of individual scene pixels may fluctuate wildly, giving visually poor intensity imagery unless considerable scene averaging is applied, which requires more time on target and more consumed energy. Often, ladar images are better displayed as range rather than intensity images.

The extremely short wavelengths typical of ladars move the noise floors well into the quantum dominated regime. Thermal noise is the driving limit in sensitivity in radars, however, in ladars the quantized photon energy in the signal and background light drive the noise floor sensitivity. As the wavelengths approach visible light, the signal itself becomes noise-like and the detection threshold becomes roughly one photon. In addition, the short wavelengths give rise to huge Doppler shifts that may require processing bandwidths far greater than needed in conventional radar.

Coherent Ladar Capabilities at Raytheon

Coherent ladar became viable in the early 1980s with the development of frequency stable CO₂ laser transmitters. Raytheon (then Hughes Aircraft) was in the forefront of the technology development, flying the first frequency modulated (FM) ladars in 1981–86. Radar waveforms such as Linear FM Chirps were used. In the late 1980s, diode-pumped solid-state lasers replaced the CO₂ gas lasers as the preferred transmitters for ladar, due to their simpler and more robust designs.

Inverse Synthetic Aperture Ladar

During the mid-1990s, Raytheon developed and demonstrated one of the first flyable coherent ladar systems to measure space object microdynamics for discrimination between precision decoys and RVs for the Exo-atmospheric Kill Vehicle (EKV). The Advanced Discriminating Ladar Transceiver (ADLT) sensor used a short wavelength, coherent mode-locked, solid-state transceiver and inverse synthetic aperture ladar processing to provide range-resolved Doppler imagery of the target. The laser transmitter used a fiber-optic laser waveform generator, which produced the coherent, high-bandwidth waveform and amplified this signal within a multi-stage diode-pumped, solid-state

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amplifier with extremely high efficiency and high gain. The challenges that were overcome during the demonstration phase of the ADLT program included development of a fiber-based waveform generator, wide-bandwidth signal processing (~1 GHz), and a high laser amplifier gain (~3,000) requiring a new laser material (Nd:YVO₄). The success of the ADLT demonstration proved that coherent ladar has a much higher pay-off than simpler direct detection systems, by allowing a multitude of waveforms to extract subtle discriminating target features.

Synthetic Aperture Ladar

In January 2003, Raytheon was awarded DARPA's Synthetic Aperture Ladar for Tactical Imaging (SALTI) Program. The program culminated on Feb. 17, 2006, with production of the world's first synthetic aperture ladar image from an airborne platform. This success dramatically advanced state-of-the-art ladar research by transitioning ladar technology from the lab to actual flight demonstrations.

SALTI is an imaging synthetic aperture ladar that operates at optical wavelengths. Traditional radar components, such as exciters, antennas and waveguides, have all been replaced by their optical equivalents:

lenses, mirrors, and beam splitters to enable control of optical waveforms. Optical ladars exploit platform motion to synthesize a synthetic aperture in exactly the same manner as RF radars; significant differences include dwell-time and beam-footprint on the ground. The result is a narrow field-of-view imaging sensor capable of producing ultra-high resolution 2-D and 3-D images of the target.

SALTI's success is built on several years of intense work overcoming many difficult problems confronting optical ladars: atmospheric, vibration and motion compensation, Doppler processing and laser phase noise. The random nature of the atmosphere introduces phase-noise into signals, resulting in degraded pulse compression. Slow-time image compression requires Doppler knowledge beyond that obtainable via inertial navigation systems and inertial measurement unit instrumentation; new motion compensation techniques had to be invented. Modern radars employ state-of-the-art, sub-Hz clock oscillators. In comparison, the best 1.55 μm laser sources have kHz-level linewidths — again, new solutions had to be invented to surmount these problems.

After flying 30-plus successful missions over land and water, SALTI has demonstrated the imaging capabilities achievable through optical SAR. In conjunction with modern

radars, optical SAR offers very powerful capabilities to augment persistent track and assured ID mission requirements. With the upcoming SALTI Phase IV & V programs, Raytheon Space and Airborne Systems (SAS) is preparing to transition the SALTI technology toward a deliverable long-range sensor system for our customers.

Vibration Ladar

Using the ladar technology base developed under the SALTI imaging ladar program, Raytheon SAS has embarked into the vibrometric sensor market.

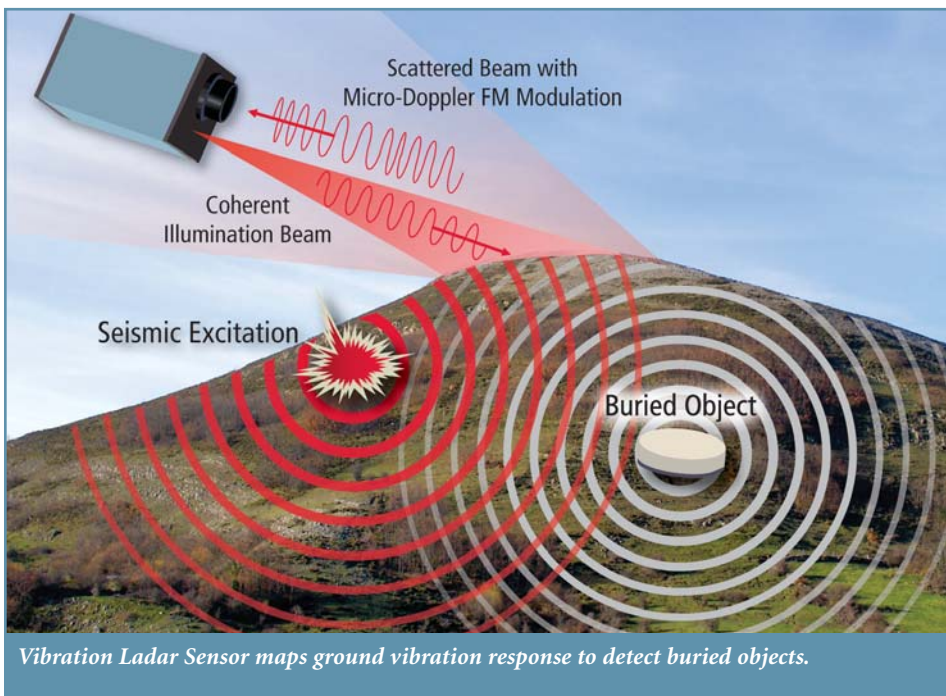
Our goal is to develop an instrument capable of watching the surface of the Earth vibrate, similar to high-speed photography of a drum head, or the resultant waves of a water drop rippling across the surface of a mill pond. Specialized signal processing will enable the warfighter to isolate and detect vibrations from objects buried in the Earth.

Vibrometric sensing contains a number of unique and interesting scientific challenges to overcome. First and foremost is the issue of platform motion: How can signal processing detect faint vibrations on the ground's surface while driving over a rocky, gravel road that induces massive random vibrations into the gimbaled optical sensor?

Raytheon researchers working on SALTI had begun to investigate this question, focusing on the goal of augmenting SALTI's already impressive imaging capabilities with vibrometry. Our research team designed and built a table-top laser Doppler vibrometer and began testing platform motion detection and compensation algorithms. A successful Independent Research and Development (IR&D) project in fiscal year 2007 led to patentable intellectual property and patent applications are underway.

Ongoing and Future IR&D Efforts: Receivers

Raytheon SAS ladar researchers quickly realized that ladar sensors generate raw data streams comparable to modern active electronically scanned array radars. Consequently, ladar and radar architects and signal processing specialists collaborated, resulting in a



Vibration Ladar Sensor maps ground vibration response to detect buried objects.

significant transfer of knowledge. Specifics include radar pulse compression, phase compensation (“pre-warp”), Hilbert transforms, and Chirp-Z transforms, just to name a few.

Doppler centroiding is one of the most serious issues confronting ladars operating in the near-infrared eyesafe wavelength band (1.55 μm). This effect arises from the Doppler relationship between platform velocity and optical wavelength. Thus, ladars demand very stringent timing requirements between wideband sensor data and narrowband line-of-sight (LOS) servo-control mechanisms. Traditional passive IR LOS mechanisms think in two dimensions, known as angle–angle space. In comparison, ladar LOS mechanisms must

think in three dimensions: angle–angle and range. As a result, ladar receivers are evolving rapidly, incorporating commonly used real-time radar processing techniques, including in-phase and quadrature processing, digital filtering and decimation.

These demands have led to the concept of a fully integrated ladar LOS servo controller, exciter and receiver, which is similar in concept to active electronically scanned array (AESA) radars but with appropriate modifications for ladar. Currently, ladar and radar technologists across Raytheon are sharing information on architectures, wideband data formats, data transmission and data storage techniques. As ladar receivers continue to evolve and incorporate radar

technology lessons learned, Raytheon SAS is well positioned to provide this blending of RF and photonics technologies into an integrated active sensor system capable of significant stand-off ranges with remarkable synthetic aperture image clarity. The enhanced sensing capability afforded by Raytheon’s coherent ladar systems will allow the sensing platforms to perform their critical target detection, identification and handoff missions while remaining out of harm’s way. ●

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ENGINEERING PROFILE



Jéan-Paul Bulot

Principal Multi-Disciplined Engineer
Raytheon Space and Airborne Systems

Jéan-Paul Bulot is an architect and research scientist working on several coherent ladar programs led by Space and Airborne Systems’ Advanced Concepts and Technology: SALT, SAVi and NSEP. He is also the principal investigator and a part-time member of multiple internal research and development teams working on ultra-high bandwidth coherent waveforms, advanced ladar speckle noise reduction techniques, laser doppler vibrometry and vibrometric algorithms.

“My job is to stretch the boundary of what’s possible, to illuminate the path of new scientific discoveries enabling my customer goals,” according to Bulot.

Bulot believes his drive to become an engineer began early. “There’s this famous family photo of me spinning a soup can at the age of three,” he recalled. “By sixteen I knew I was going to be an engineer of some sort.”

His career at Raytheon began in 2000, when Maurice Halmos, senior ladar scientist, and Lou Klaras, senior laser electronics engineer, were looking for creative minds to tackle difficult multi-disciplinary problems in ladar. A good friend and fellow Georgia Tech engineer already working at Raytheon sent Bulot’s resume to Klaras and, according to Bulot, “It’s been a nonstop rollercoaster ever since.”

Bulot cites many reasons for the success he has found in his career. “I grew up without TV in a family that encouraged independence, creativity, self-reliance and

the idea of being able to self-educate,” he said. “I am particularly grateful that my parents instilled the idea that there is always positive learning to be discovered, even in failures.”

“My engineering is akin to my big-wave surfing: I seek the path of balance in a rapidly and dynamically changing environment. Failure is my friend and feedback mechanism that tells me if my intuition is correct. I trust my team — I champion their successes. Where I perceive shortcomings, I lend a hand, and if I don’t know the answer I find someone who does.”

This collaborative approach is seen in Bulot’s commitment to teaching and mentoring junior engineers, a commitment he sees as mutually beneficial. “Explaining an idea empowers the student to grow in skill and progress forward in life and career, while offering the teacher a fresh viewpoint and opportunity to further probe and improve the true understanding of how something works.”

His work at Raytheon allows Bulot to continually learn and grow by interacting with a diverse group of employees committed to success. “I enjoy working with individuals who exhibit excellence in all manner of their professional and personal lives; it’s fascinating and inspiring to have the opportunity to discuss a broad spectrum of ideas and I appreciate differing points of view. I believe life offers the opportunity to be both a student and a teacher everyday; as the famous woodworker George Nakashima once said, ‘work can be a form of yoga for the mind.’”

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