Development of Coherent Laser Radar at Lincoln Laboratory

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The invention of the laser in 1960 created the possibility of using a source of coherent light as a transmitter for a laser radar. Coherent laser radars share many of the basic features of more common microwave radars. However, it is the extremely short operating wavelength of lasers that introduces new military applications, especially in the area of target identification and missile guidance. This article traces laser-radar development at Lincoln Laboratory from 1967 to 1994. This development involved the construction, testing, and demonstration of two laser-radar systems—the high-power, long-range Firepond laser-radar system and the compact short-range Infrared Airborne Radar (IRAR) system. Firepond addressed strategic military applications such as space-object surveillance and ballistic missile defense, while IRAR was used as a test bed for airborne detection and identification of tactical targets.

The history of radar development reveals that radar advances and innovations are often driven by the availability and quality of high-power signal sources. The British invention of the high-power microwave magnetron allowed scientists and engineers at the MIT Radiation Laboratory, in Cambridge, Massachusetts, to develop airborne microwave radar during World War II. As the temporal coherence of signal sources improved, new signal processing techniques became available. Finally, with the development of computers and high-speed digital signal processing, new ways to detect targets and extract target information surfaced. The development of the laser radar mirrors this paradigm.

The laser's high operating frequency plus temporal and spatial coherence properties provided the basis for developing unique laser radars at Lincoln Laboratory from 1967 to 1994. This article discusses two Laboratory laser-radar systems developed by the Optics division. The long-range Firepond laser-radar system, operating at wavelengths of 10.59 μm and 11.17 μm for the carbon-dioxide (CO_2) laser and 1.064 μm for the neodymium-doped yttrium-aluminum-garnet (Nd:YAG) laser, was used to develop strategic military applications of laser radars. The compact Infrared Airborne Radar (IRAR) system, operating at wavelengths of 10.59 μm for the CO_2 laser, 0.85 μm for the gallium-arsenide (GaAs) laser, and 1.064 μm for the Nd:YAG laser, was used to develop tactical military applications of laser radars.

Coherent Laser Radars at Lincoln Laboratory: 1967 to 1971

The CO_2 laser, invented in 1964 by C.K.N. Patel, operated in the infrared spectrum at wavelengths with minimal absorption [1]. The CO_2 laser rapidly gained efficiency and power compared to other laser systems. In 1966, using the construction techniques of MIT professor Ali Javan, who pioneered the helium-neon laser, Charles Freed at Lincoln Laboratory built a CO_2 laser with a temporal coherence that exceeded any previously reported CO_2 laser by a factor of at least 100 [2]. This development set the stage for Lincoln Laboratory to demonstrate the first coherent CO_2 laser radar in 1967. Yet another hundredfold improvement in laser frequency stability was demonstrated in 1968. That same year, researchers in Lincoln Laboratory's Solid State division had developed a

FIGURE 1. The Lincoln Laboratory Millstone Hill radar site in Westford, Massachusetts. The Firepond Optical Research Facility is located in the left foreground.

wide-bandwidth (1.5 GHz) copper-doped germanium photoconductor for use as a photomixer with a laser-radar receiver that could observe Doppler frequency shifts in satellite echoes.

In parallel with Lincoln Laboratory's efforts, Raytheon built a 1000-W, continuous-wave (CW) CO_2 laser oscillator with funding from the Defense Advanced Research Projects Agency (DARPA) and the Office of Naval Research. The oscillator was given to the Laboratory for laser-radar experiments after Raytheon evaluated it. The Firepond Optical Research Facility (shown in Figure 1), near the Millstone Hill radar site in Westford, Massachusetts, was completed by the Laboratory in late 1968 to permit long-range laser-radar measurements on terrestrial targets, aircraft, and satellites (the name Firepond derives from the adjacent pond that serves as a source of water in case of fire). By the end of 1971, a 1.2-m-diameter telescope had been installed at Firepond and angle-resolved images of various targets were collected with a flying-spot scanner. The results of these early measurements encouraged researchers to examine military applications of laser radar.

Laser Radars for Strategic Defense at Firepond: 1972 to 1993

In 1972, Robert S. Cooper of Lincoln Laboratory investigated the utility of a wideband, high-power, range-Doppler laser radar for space surveillance. The study, seen as the start of a ten-year effort, generated specifications for a 200-kW laser amplifier with a bandwidth of 1 GHz, the most powerful coherent laser radar yet conceived. Many critical components had to be invented. Although key technologies and significant milestones were achieved, the work ended without successfully developing an imaging laser radar. The main shortfall was the failure to achieve the 200-kW high-power amplifier with a continuously circulating CO_2 medium.

Advances continued at Lincoln Laboratory during this ten-year period in laser-radar component development. David Spears built wideband mercury-cadmium-telluride (HgCdTe) photodiode photomixers for monopulse laser angle tracking [3]. Charles Freed continued basic research in laser physics and eventually cataloged the lasing frequencies of nine out of eighteen possible CO_2 laser isotopic combinations [4]. In 1976, because optical modulators were required to incorporate the wideband FM waveform on the laser beam, Lincoln Laboratory developed a wideband, double-sideband, GaAs electro-optic modulator that was used to form the first CO_2 laser-radar range-Doppler images of a pair of moving retroreflectors on a ground range.

Although the radar power goal of 200 kW was not achieved, the laser amplifier still was among the most powerful in the world. When driven by the original 1-kW narrowband laser amplifier, it had a maximum peak pulse power close to 11 kW. Without an efficient wideband electro-optic modulator or a wideband laser preamp, however, the power was available only in the narrowband mode.

In 1977, narrowband monopulse laser tracking was demonstrated in experiments on aircraft and satellites. The monopulse experiments resulted in tracking errors of approximately 1 μrad root mean square (rms) for targets equipped with retroreflectors [5]. Other experiments included the light detection and ranging (lidar) measurement of high-altitude winds in 1978.

In 1981 the high-power laser-radar amplifier system was installed in the Firepond Optical Research Facility. The laser-radar power amplifier (LRPA) filled a large room. The pond adjacent to the facility was used to cool the LRPA. Figure 2 shows the Firepond

high-power, narrowband, coherent laser-radar system in 1981. The 10.59-μm wavelength and 1.2-m aperture produced a beamwidth of about 10 μrad.

Many modifications were required to achieve reliable operation at typical peak powers of 4 to 5 kW in 4-msec pulses. For example, contamination of the laser gas during operation of LRPA required continuous replacement of the laser gas.

The sharp Doppler-frequency resolution allowed researchers to collect Doppler time intensity (DTI) measurements of satellites. In 1981, Lincoln Laboratory successfully generated a detailed DTI plot of a slowly tumbling space object—an Agena D rocket booster, at a slant range of 1350 km. Figure 3 illustrates three Doppler spectra obtained with the Firepond laser radar from an orbiting Agena D rocket booster. The laser radar demonstrated a capability for acquiring and monopulse-angle-tracking unenhanced targets in low- and medium-altitude earth orbits. Space objects were automatically tracked in frequency while Doppler data were recorded, and DTI plots were generated on a wide variety of targets. However, the failure to produce high-resolution, range-Doppler images and meet the average-power goal led to an interruption of the radar program in the early 1980s.

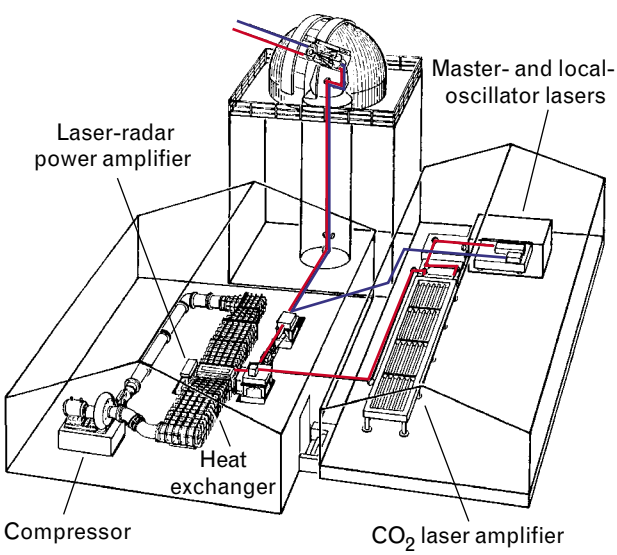

FIGURE 2. Firepond high-power, narrowband, coherent laser-radar system in 1981. The building on the left housed the laser-radar power amplifier (LRPA) and its supporting equipment; the building on the right housed the carbon dioxide (CO_2) laser amplifier.

In 1984 the Strategic Defense Initiative Organization (SDIO) recommended the use of an orbiting laser-radar sensor to discriminate warheads from decoys during the post-boost phase of an ICBM's flight. Lincoln Laboratory responded with the Optical Discrimination Study, funded by DARPA, to further define the requirements for laser radars for ballistic missile defense. Completed in January 1985, this study led to the Optical Discrimination Technology program in February 1985. The Laboratory resumed the high-power laser-radar effort with a reinforced emphasis on high-resolution, range-Doppler imaging.

Because atmospheric CO_2 (principally the common isotope $^{12}C^{16}O_2$) has some narrowband absorption at 10.59 μm, models of atmospheric propagation predicted a significant nonlinear frequency dispersion and, therefore, a distortion of the wideband laser-radar signal. In the new laser radar, all of the lasers used a rare form of carbon dioxide ($^{13}C^{16}O_2$) and thus had to operate in a sealed-off mode to conserve the gas. The resultant output wavelength, 11.17 μm, was not

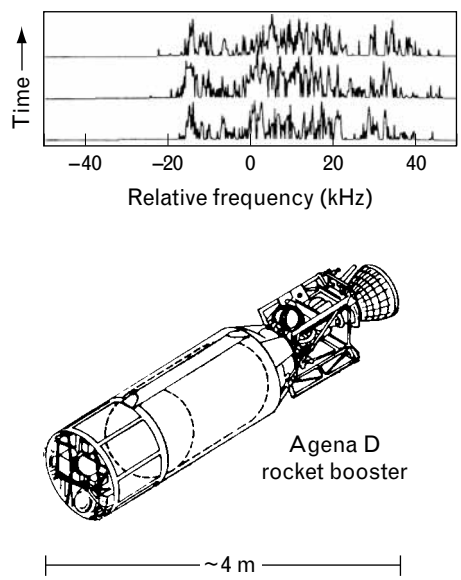

FIGURE 3. Three successive single-pulse Doppler spectra of a tumbling Agena D rocket booster (object 3892) collected by the Firepond CO_2 laser radar (10.59 μm) in 1981. The orbiting booster is at a slant range of 1350 km. The Doppler frequency resolution of the narrowband laser radar is 250 Hz, which corresponds to a Doppler velocity resolution of approximately 1.5 mm/sec. This resolution is due to the extremely high operating frequency (approximately 28,200 GHz) of the laser radar.

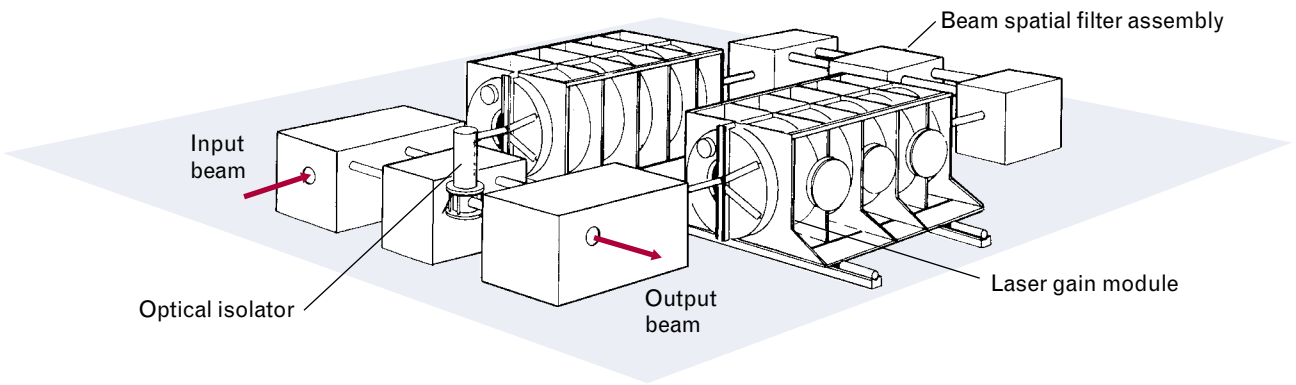

FIGURE 4. High-power, wideband, coherent laser-radar amplifier. The electron-beam-sustained, electric-discharge, isotopic-CO_2 laser amplifier had a bandwidth of over 2 GHz with pulse energies of up to 100 J. The amplifier was developed by Rockwell International and Spectra Technologies.

significantly absorbed or distorted by propagation through the atmosphere.

A master-oscillator/power-amplifier (MOPA) configuration was chosen for the wideband laser radar; however, a short-pulse design was used to maximize the laser-amplifier gain. Lincoln Laboratory developed major components for this radar: the programmable wideband waveform generator (which made the wideband linear-FM multiple-chirp waveform), and the wideband laser receiver and analog stretch processor. A wideband, efficient, single-sideband electro-optic modulator was finally developed [6].

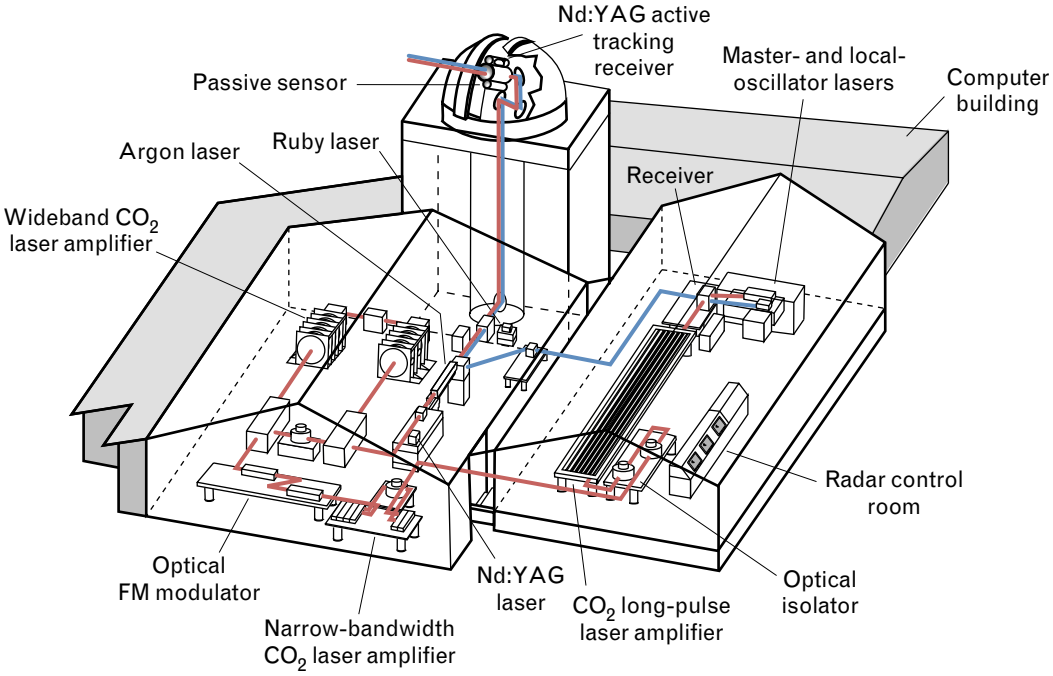

FIGURE 5. The Firepond high-power, wideband, coherent laser-radar system and other electro-optic subsystems in 1992. Several laser radars are indicated, including the high-power, wideband imaging CO_2 laser radar (11.17 μm); the long-pulse, narrowband CO_2 laser radar (10.59 μm); the photon-counting frequency-doubled neodymium-doped yttrium-aluminum-garnet (Nd:YAG) laser radar (0.532 μm); and the argon-ion-laser (0.514 μm) and ruby-laser (0.694 μm) illuminators. The optical path of the imaging-laser-radar transmitter signal is traced in red and the receiver signal path is traced in blue.

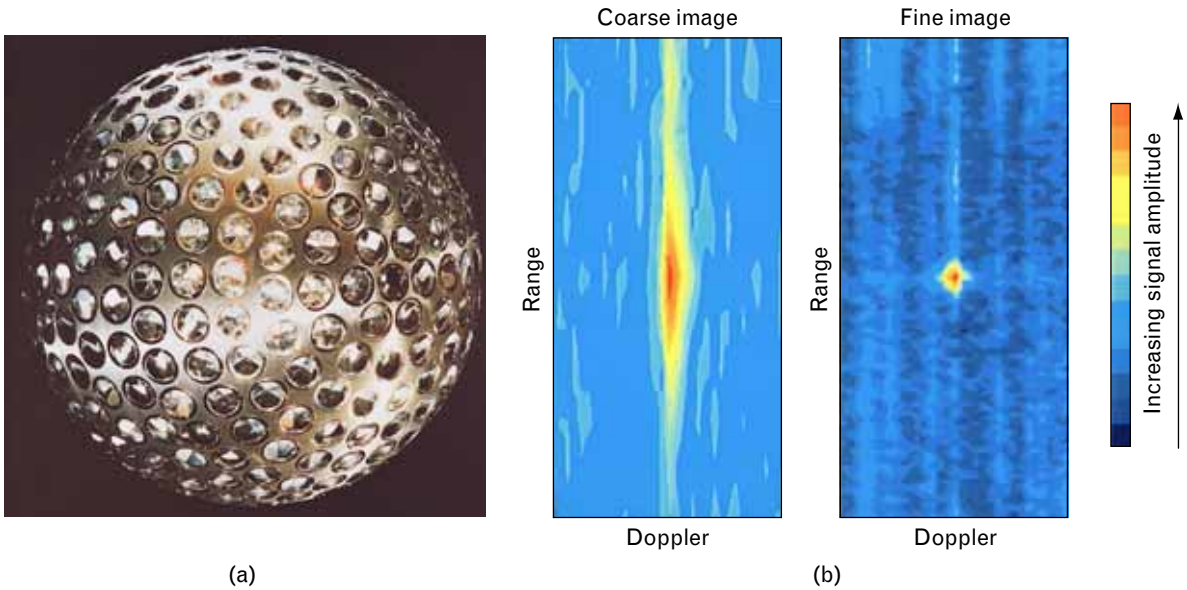

FIGURE 6. (a) The Laser Geodynamics Satellite (LAGEOS), a 60-cm aluminum sphere with a brass core. The satellite has a total mass of 406 kg and is in a near circular orbit at an altitude of approximately 5900 km. LAGEOS has 426 silica retroreflectors and 4 germanium retroreflectors to serve as a laser-radar target. (b) Range-Doppler image of the LAGEOS satellite collected by the wideband CO_2 laser radar at Firepond. The coarse image was made with a signal bandwidth of 150 MHz, while the fine image was made with a bandwidth of 1 GHz. Doppler velocity resolution is approximately 30 cm/sec. Color in the image represents relative signal amplitude. The range and Doppler sidelobes are better than 20 dB below the main lobe. The range-Doppler images are the point-target responses of the imaging laser radar produced by different bandwidths.

The wideband imaging laser radar had a pulse-repetition frequency of 8 Hz with a pulse duration of 32 μsec. The laser waveform consisted of multiple linear-FM chirps, each with a bandwidth of 1 GHz. The maximum output energy achieved with the wideband, coherent radar amplifier was 100 J/pulse (3.1 MW peak power). The laser radar initially operated at an energy of 24 J/pulse, then at an energy of 40 to 60 J/pulse during typical imaging experiments [7]. Figure 4 illustrates the high-power wideband coherent laser-radar amplifier; Figure 5 illustrates the Firepond high-power, wideband, coherent laser-radar system and other electro-optic subsystems in 1992.

On 4 March 1990, the wideband laser radar successfully collected the first range-Doppler images of an orbiting satellite. Laser-radar images of Sea Satellite (Seasat) were collected at 800 to 1000 km while a visible-light tracker performed precision angle tracking. The plan to build a laser radar for space-object surveillance, originally developed in the 1972 study, was fulfilled eighteen years later.

For the next two years, wideband range-Doppler images of satellites at ranges up to 1500 km were collected. Although most range-Doppler images of satellites are classified, Figure 6 shows a photograph and two range-Doppler images of the retroreflector-equipped Laser Geodynamics Satellite (LAGEOS). The range-Doppler images of a single scatterer were collected with two different waveforms. The high-resolution waveform relied on a 1-GHz-bandwidth linear-FM chirp, while the low-resolution image used a waveform with a bandwidth of 150 MHz.

Only twenty-five days after the laser radar first began imaging operations, the Firefly sounding-rocket experiment for the SDIO was successfully completed. This exercise involved sounding-rocket launches from the NASA Wallops Island Space Flight Facility in Virginia, on 29 March 1990 (Firefly I), and 20 October 1990 (Firefly II). In both tests, the flight path, aimed toward the east, was projected to reach an apogee of 460 km at an elevation angle of 36° from Millstone Hill, resulting in a range of 700 km. The actual apogee and range were 462 km and 743 km, respectively, for the Firefly I test, and 456 km and 724 km

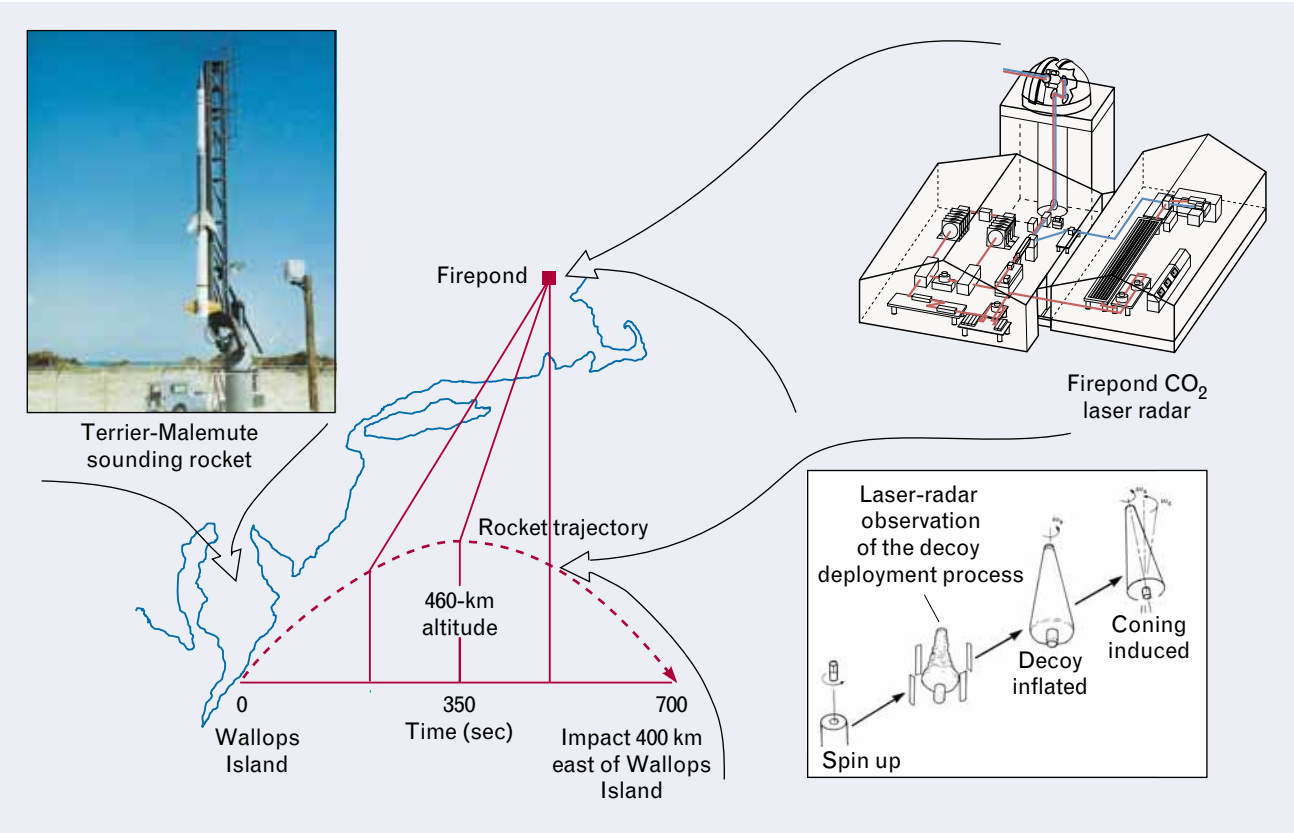

FIGURE 7. The Firefly CO_2 imaging-laser-radar experiment. This experiment successfully demonstrated that an imaging laser radar could observe the deployment and inflation of a replica reentry-vehicle decoy at a range of over 700 km. The Firefly tests, held on 29 March and 20 October 1990, utilized a Terrier-Malemute sounding rocket equipped with an inflatable conical balloon. The rocket was launched from NASA Wallops Island Space Flight Facility in Virginia and observed by the Firepond CO_2 laser radar in Westford, Massachusetts. The decoy was ejected as a spinning canister that inflated into a 2-m-long cone.

for the Firefly II test. By utilizing angle-tracking data for initial acquisition from the NASA C-band and Haystack X-band radars, the Firepond laser radar angle tracked the deployed target to sub-μrad precision. The laser radar collected real-time, high-resolution, range-Doppler images of the ejection and inflation of the replica decoy [8]. Figure 7 illustrates the planned trajectory of the Firefly experiment.

After the first Firefly experiment, satellite measurements continued with the Raytheon narrowband, 1-kW CO_2 laser radar. These experiments focused on the measurement of vibrations of the boom structure of the Laser Atmospheric Compensation Experiment (LACE) satellite for the Naval Research Laboratory. Lincoln Laboratory researchers were able to measure the extremely low-frequency vibrations of this retroreflector-equipped satellite.

With the success of the Firefly experiments, the U.S. Air Force Brilliant Eyes program office wanted to investigate the use of a low-power, diode-laser-pumped Nd:YAG laser radar for ranging on rocket boosters and post-boost vehicles. This concept involved the use of photon-counting ranging on the target, which is discussed in the sidebar entitled "Photon-Counting Optical Receivers." The Laboratory developed a 30-mJ/pulse diode-laser-pumped, Nd:YAG laser transmitter, and the associated laser-radar tracker.

A second series of flight tests designated Firebird (for Firepond bus imaging radar demonstration) demonstrated sophisticated laser-radar discrimination techniques and laser-radar countermeasures. In these tests, the Millstone and Haystack radars were operated to support the Firepond laser radar in ac-

PHOTON-COUNTING OPTICAL RECEIVERS

IN ADDITION TO performing coherent detection and conventional energy (direct) detection, special optical receivers can also detect individual photons under certain circumstances. This form of detection is the ultimate in optical-receiver sensitivity. A photon-counting detector typically has extremely high gain associated with the photoelectron-generation process. Examples of this type of photodetector include very high-gain photomultipliers and very high-gain avalanche photodiodes. Photomultiplier tubes have the added advantage of a minimal noise figure associated with the gain process.

The conditions for photon counting require a minimal optical background level and minimal photocathode dark current; essentially, the mean number of background photoelectrons and thermally generated electrons must be much less than one during the period of observation. A photomultiplier gain of 10^6 is not unusual and is required to overcome noise associated with the amplifier following the photomultiplier. A single photoelectron can produce 10^6 signal electrons. A high receiver threshold is set such that the current pulse representing an individual photon or a rare thermally generated noise electron originating in the photocathode easily crosses the threshold, while amplifier noise currents are orders of magnitude less than the threshold. Thus individual photons are detected.

Using very short laser pulses with range gating allows this type of detection to be used to perform range measurements. Assuming a unity conversion of photons to photoelectrons and a nonfading target, the probability of detecting at least one or more photons out of three photons received is almost 95%. Three photons of green light correspond to a received energy of approximately 10^{-18} J. The false-alarm rate would depend on background and dark-current levels. A conventional radar having a 3-dB noise figure and requiring a single-pulse IF signal-to-noise ratio of 13 dB (P_d = 95%, P_{fa} = 1.25×10^{-5}) would require about 1.66×10^{-19} J per Hz of receiver bandwidth. For a microwave radar receiver with a 1-MHz bandwidth and no additional processing, 1.66×10^{-13} J of energy would be required for a single measurement. The performance of a coherent laser radar operating at a green wavelength (0.5 μm) would require an additional factor of 90 in energy (the ratio of photon to phonon energies, $h\nu/kT$) above the requirements for the microwave radar.

quiring and tracking the targets. The Firebird experiments used a high-performance Talos-Minuteman I Stage II guided booster to deploy a dozen targets to be acquired by the Millstone Hill sensors and other airborne and ground-based sensors scattered along the U.S. east coast. Test objectives for Firebird 1 included laser-radar deployment discrimination based on the rocket-plume interaction of the bus with decoys and other deployment dynamics. Firebird 1B added countermeasure-complex surface signatures, photon-counting Nd:YAG laser-radar bus tracking, and passive stereo tracking by using dispersed ground and airborne sensors.

The Firebird 1 rocket was launched on 12 April 1991. During the Firebird 1 experiment, the Firepond, Haystack, and Millstone Hill radars plus the Cobra Eye aircraft sensor and infrared sensors at NASA Goddard collected data. Firebird 1B was launched on 13 April 1992. The following sensors also collected data during the flight: Utah State University's infrared sensor located at Firepond and the SDIO Airborne Surveillance Testbed (AST) infrared-sensor aircraft, the Position and Velocity Extraction (PAVE) Phased Array Warning System (PAWS) UHF radars in Massachusetts and Georgia, and optical sensors at Malabar, Florida. Figure 8 shows the

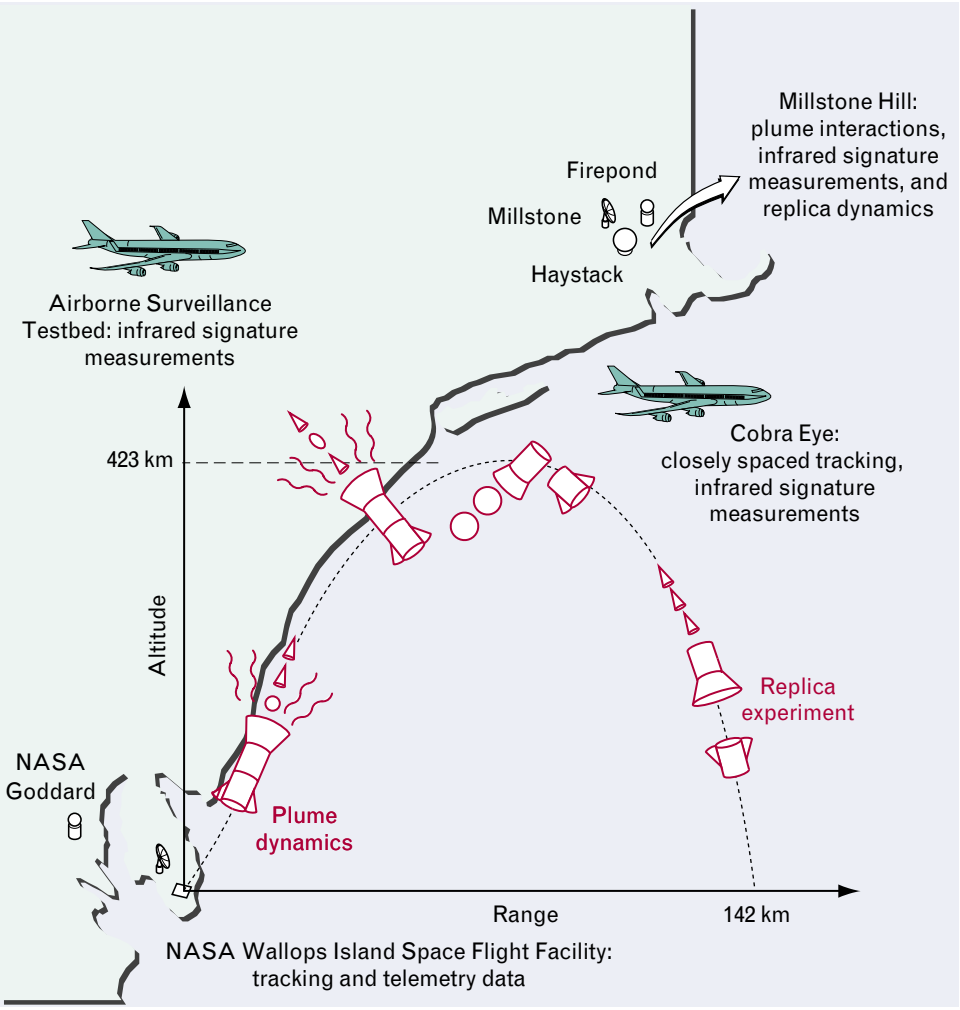

FIGURE 8. Firebird (Firepond bus imaging radar demonstration) 1B flight-test scenario. The Firebird test involved deployment of numerous passive infrared, laser-radar, and microwave-radar decoys and calibration spheres. It is noteworthy that the favorable weather along the entire east coast of the United States permitted the collection of optical, infrared, and laser-radar data from Florida to Massachusetts, and from high above West Virginia to high above the Atlantic Ocean south of Rhode Island. UHF and microwave data were collected at sites in Massachusetts, Virginia, and Georgia. Data were successfully collected on the deployment dynamics and signatures of several classes of reentry-vehicle decoys.

Firebird 1B flight-test scenario. Although the Firebird test data remain classified, the flight tests gave excellent results and completed the experimental investigation of the laser-radar discrimination techniques described in the 1984 SDIO study and other optical-discrimination studies [9]. In October 1993, high-power laser-radar research at Lincoln Laboratory ended with the completion of the Optical Discrimination Technology program.

Tactical Laser Radars—The Infrared Airborne Radar System: 1975 to 1994

In 1975, Robert J. Keyes of Lincoln Laboratory led a study of the potential utility of a coherent CO_2 laser radar for ground-target surveillance, acquisition, and fire control. It was envisioned that a ground-attack aircraft such as the A-10 would use this system, night or day, for very low-altitude (100 m or less) attack, to

insure that the laser radar would be below clouds and most weather. The extreme low-altitude environment for the platform would also frustrate certain classes of air-defense systems. The system was sized for a 10-W transmitter developed by Stephen Marcus [7] and a 15-cm aperture. The follow-on study by Richard J. Becherer [10] added further refinements and requirements. An internal research program on tactical lasers began in 1976.

A number of singular technologies developed in the course of the program include coherent detector arrays, binary optics that provided local-oscillator beams with the proper phase and amplitude on the coherent detector arrays [11], and surface-acoustic-wave devices for Doppler processing. In addition, image-processing schemes automated the understanding of the multiple data returns available from a laser radar, especially when operated in synchronism with a passive infrared detection system that provides a measurement of target and background temperatures.

A development goal to increase the image frame rate led to the specification of a twelve-element, coherent HgCdTe detector array to provide sufficient autonomous search and identification capability for the laser radar. Subsequently, a passive infrared array was placed in the same dewar with the active array, sharing the same optics train so that near simultaneous measurements could be made of target and background temperatures to assist in target detection and identification, as described in a report by Robert C. Harney [12].

Under the technical direction of Robert J. Hull and Theodore M. Quist, the Infrared Airborne Radar (IRAR) development proceeded through several phases: technology development and laboratory demonstration, operation of the laboratory system in a truck from which targets of interest could be observed at various military locations, and, finally, flight test [13]. The truck-transportable system involving a laser radar and passive infrared sensors is shown in Figure 9. The laser-radar and passive infrared systems were boresighted and pixel-registered with the data streams digitally recorded. Figures 10 and 11 show images from the transportable system. Figure 10 displays laser-radar range images of a tank and truck at a range

FIGURE 9. Transportable multisensor measurement system consisting of a coherent CO_2 laser radar with a boresighted and pixel-registered 8-to-12-μm passive infrared sensor and digital recording system.

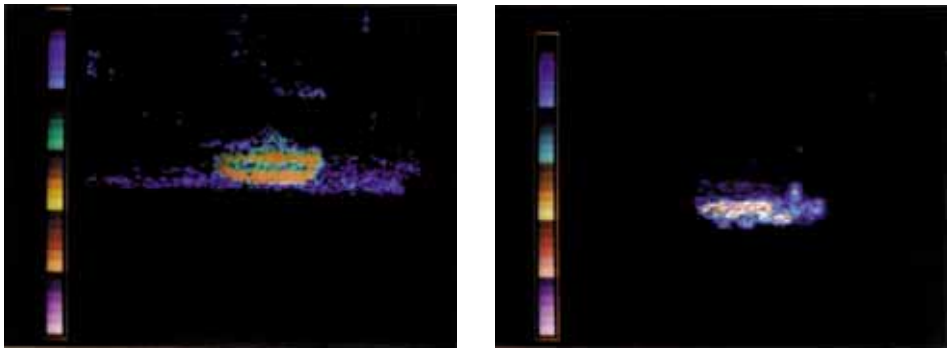

FIGURE 10. Coherent laser-radar, color-coded intensity images of tank (left) and truck (right) taken with the transportable system at a range of 2.7 km.

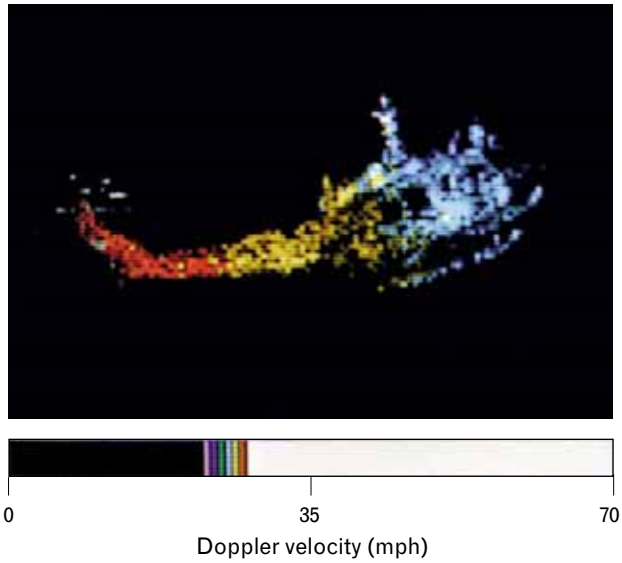

FIGURE 11. Doppler-velocity image of a UH-1 helicopter executing a rotational maneuver. The image is an angle-angle-Doppler-intensity image collected by the truck-transportable CO_2 laser radar. The Doppler shift of each of the approximately 16,000 pixels in the image was extracted by a surface-acoustic-wave processor at a frame rate of 1 Hz. Velocity is mapped into color as shown. Laser radars, by virtue of their very short wavelengths, simultaneously permit high angular resolution (equivalent to human vision in this image) and high Doppler resolution (approximately 1 m/sec in this image). The ability to sense moving parts on a vehicle provides a powerful means to discriminate targets from clutter.

of 2.7 km. Figure 11 is a Doppler-velocity image of a helicopter executing a rotational maneuver. The Gulfstream G-1 airborne multisensor aircraft, which carries the IRAR, is shown in Figure 12. All of the systems utilized an optical turret attached to the underside of the aircraft for beam scanning with the major electronic and recording systems within the aircraft fuselage. In Figure 13 hangars with aircraft and other buildings and fences in the foreground are imaged in passive infrared, laser range, and laser intensity. These images were taken from the airborne system during early ground tests. In the passive infrared image, white is warm and black is cold. In the laser-range image, objects farthest away are in yellow and nearest in blue. In the laser-intensity image, black and white denote the absence or presence, respectively, of strong signals. In Figure 14, IRAR measurements of the Bourne Bridge by the forward-looking laser radar are shown in color to denote the relative ranges of bridge

FIGURE 12. Gulfstream G-1 aircraft with the Infrared Airborne Radar (IRAR) optical aperture located in the ventral fairing on the aircraft. The IRAR test bed carried a wide variety of active and passive sensors over a ten-year period.

components. The inset image shows that, since absolute range is being measured, the laser-radar range image can be transformed to views other than the one at which the image was taken. Laser-radar range data also allow similar transformations on the passive infrared image. This experiment was a seminal investigation of what later was to be called multidimensional image processing. The Doppler-image capability of the airborne forward-looking laser radar is demonstrated in Figure 15, which shows cars traveling on Interstate 495 near Boston.

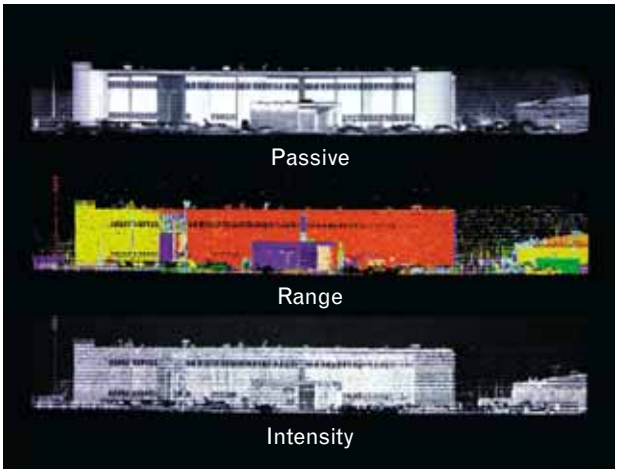

FIGURE 13. Simultaneous passive infrared, CO_2 laser-range, and laser-intensity images of Hanscom Air Force Base hangars and buildings, collected by the IRAR system. The range accuracy of the range image is 1 m.

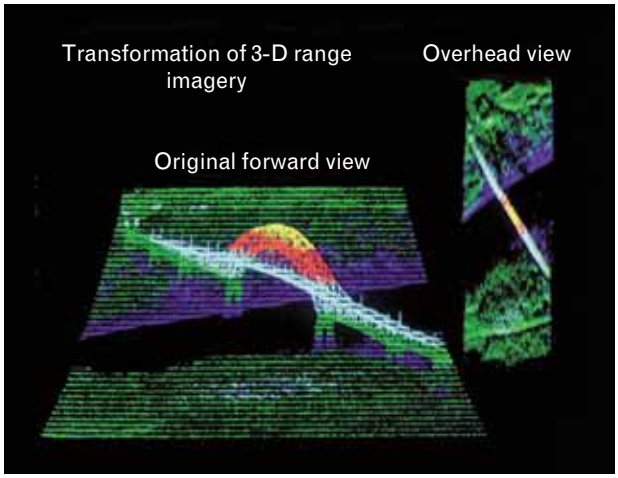

FIGURE 14. IRAR CO_2 (10.59 μm) laser-radar images of the Bourne Bridge, which spans Cape Cod Canal in Massachusetts. Range to each picture element is coded in color. The data collected in the original oblique view are transformed into an overhead view, as shown in the inset image. This view may be useful for missile seekers that use terrain features for targeting.

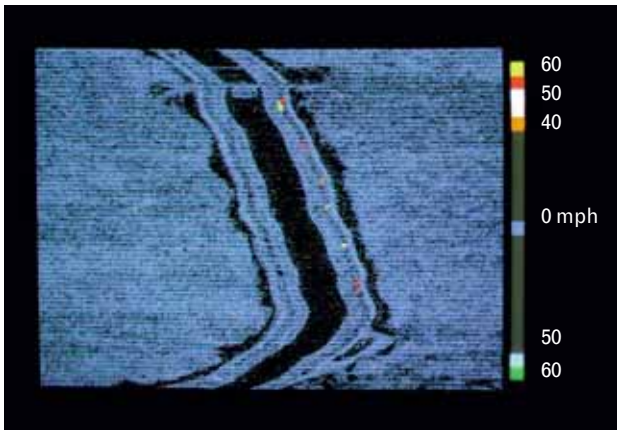

FIGURE 15. Angle-angle-Doppler image taken with the IRAR in flight over Interstate 495 near Boston, Massachusetts. Velocity is represented by color. Automobiles are clearly visible on the highway. The background can be suppressed by simple velocity thresholding.

After a decade of research, development, and testing of a forward-looking multidimensional laser radar based on a CO_2 laser and active and passive HgCdTe detector arrays, sponsors at DARPA and other groups became interested in laser-radar operation at vertical or near vertical viewing conditions relative to the ground. Two potential applications were to use high angle and range resolution to penetrate foliage and camouflage and to use laser radars as acquisition and guidance sensors for vertical attack by smart weapons. The forward-looking sensor suite was augmented by a high-range-resolution millimeter-wave radar boresighted to the optics for further multidimensional investigations. Downlooking GaAs and Nd:YAG laser radars were developed that could operate at a downlooking range of about 100 m and have a cross-range spatial resolution of 15 cm combined with a range precision of 15 cm. The first high-resolution downlooking sensor, developed by Perkin Elmer, used

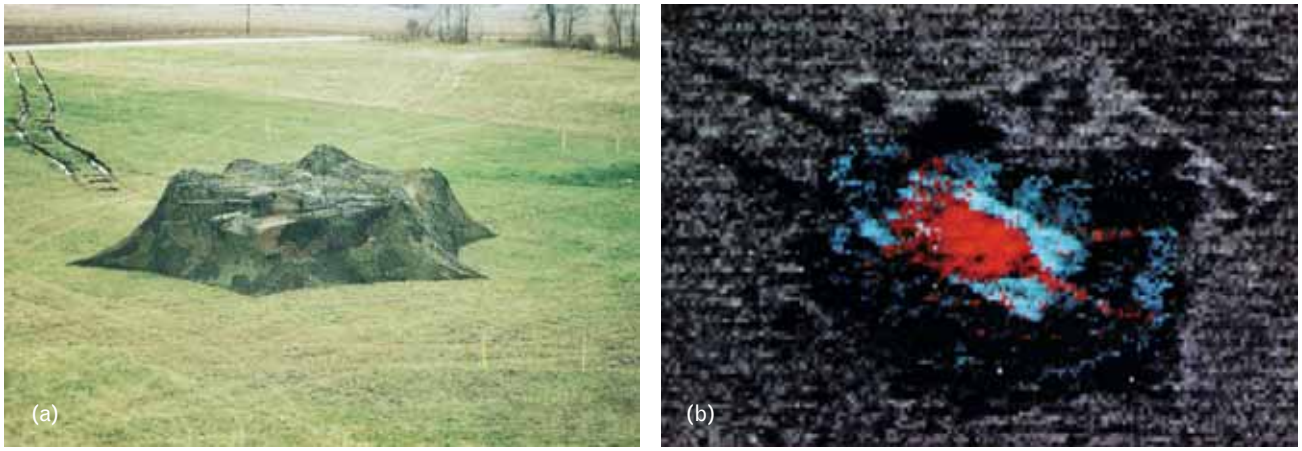

FIGURE 16. (a) Visible-light photograph and (b) GaAs (0.85 μm) laser-radar angle-angle-range image of a tank concealed by a camouflage net. The laser radar utilizes a high-accuracy, sinusoidal, amplitude-modulated waveform while observing the tank in a downlooking scenario. The camouflage net was readily gated out of the image to leave the tank image. The tracks left by the tank in the soil are also visible in the laser-radar image.

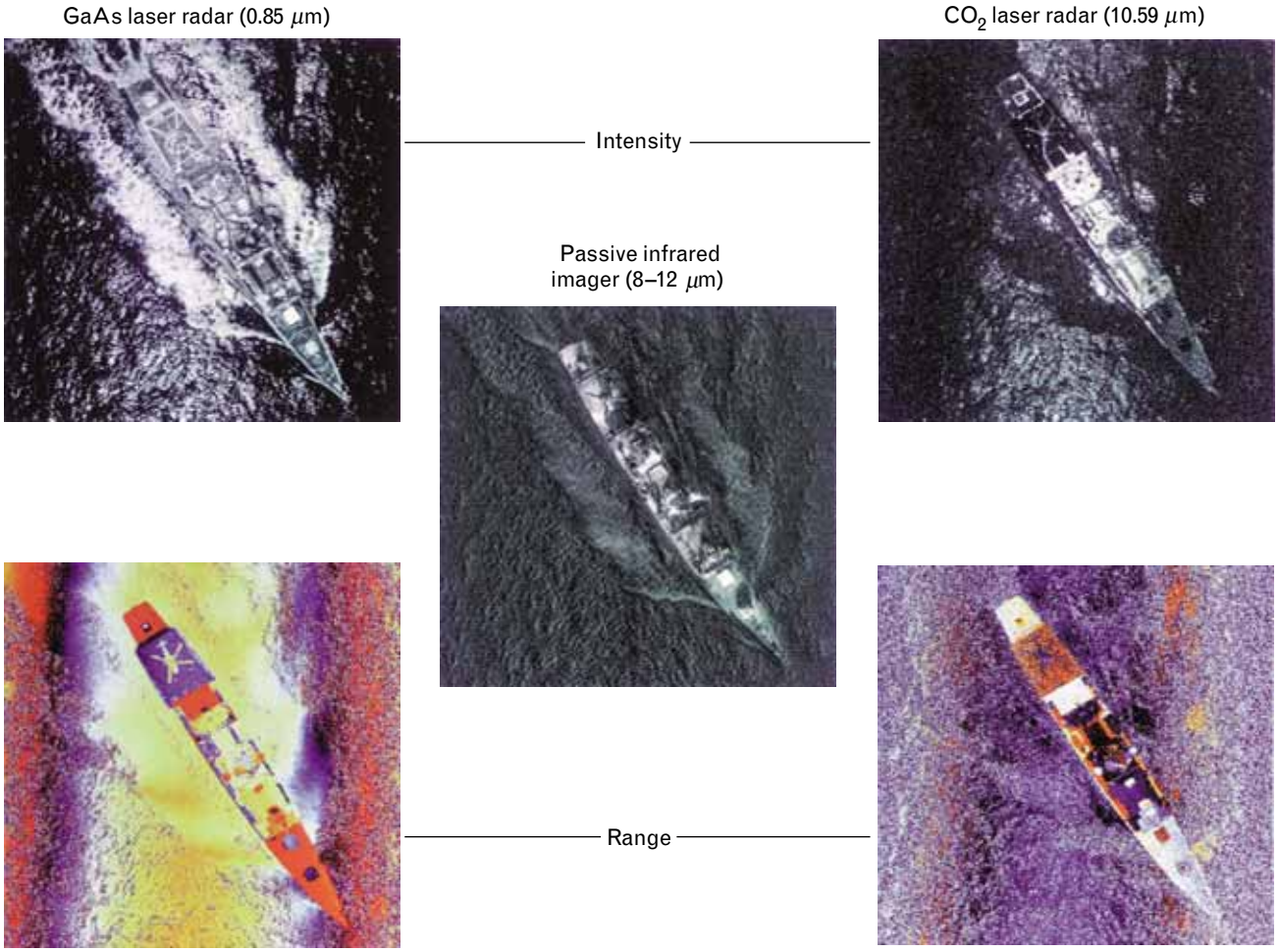

FIGURE 17. Multiple, simultaneous downlooking images of the fast frigate USS *Connole* (FF-1056) collected by using the Multispectral Active/Passive Sensor (MAPS) system. The MAPS system includes a GaAs laser radar (0.85 μm), a coherent CO_2 laser radar (10.59 μm), and an infrared imager (8-to-12 μm) mounted in a Gulfstream G-1 aircraft. Registered image pixel range, scene reflectivity at 10.59 μm and 0.85 μm, and apparent temperature provide unique data for target classifier algorithms.

GaAs laser-diode technology that resulted in a relative range precision of 15 cm and a range-ambiguity interval of 30 m. The capability of this system is demonstrated in Figure 16, in which a tank can be seen clearly under a visible-light camouflage net. A Lincoln Laboratory sensor system called the Multispectral Active/Passive Sensor (MAPS) was subsequently developed that also incorporated a 10.59-μm-wavelength relative range-measuring laser radar and an 8-to-12-μm passive infrared imager. These sensors were all boresighted to provide near simultaneous measurements of targets and backgrounds. Figure 17 shows an example of the data obtained by using a ship as a target.

As noted previously, the GaAs system had high relative range precision, but the range-ambiguity interval presented difficulties in areas where it was required to look down through tall trees. An absolute-ranging laser radar based on the Lincoln Laboratory Nd:YAG microchip laser was developed to replace the GaAs radar in the MAPS. With a range precision of 15 cm, development of a real-time processor was the pacing technology. Preliminary processing has demonstrated that height thresholding with this system can be used to search for objects hidden under trees where there are holes in the tree cover.

In 1994, near the termination of the program, laboratory investigations were also made of the use of

the microchip laser for development of an optical synthetic aperture. This technology holds promise for space-based surveillance of space objects, where spatial resolution would be independent of range.

Summary

The CO_2 laser-radar research that took place from 1966 to 1994 developed many novel technologies, components, and techniques that have yet to be fully utilized by the Department of Defense. Other programs at the Laboratory have focused on the use of ruby and Nd:YAG solid state lasers, and new applications for CO_2 and solid state lasers continue to be investigated for a number of applications. However, the overall goal of the Laboratory program was to encourage the Department of Defense to exploit the great value of coherent laser radar for a variety of applications, and this goal was successfully realized. Many technical firsts were achieved during this time. The work stands as a tribute to the ingenuity, hard work, and dedication of the people at Lincoln Laboratory who defined the field of laser radar.

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