Long Range Automated Hyperspectral Target Detection

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Introduction: Intelligence, surveillance, and reconnaissance (ISR) sensors are becoming ubiquitous in military operations. In fact, many people refer to a condition known as "ISR saturation," in which the volume of still imagery and video becomes so great that it cannot be efficiently processed by decision makers on the battlefield. Hyperspectral imagers, such as the MX-20SW developed at NRL, are powerful because they collect and analyze detailed spectroscopic information for each pixel in the image and automatically cue operators to areas of interest. This avoids requiring the operator to view the entire image to identify the very small fraction that is relevant to Department of Defense operations, thereby helping to solve the problem of ISR saturation. The MX-20SW is particularly valuable because it operates in the shortwave infrared (SWIR) spectral region that yields much lower atmospheric scattering and, hence, longer range than sensors operating in the visible spectrum. In addition, many militarily relevant materials are more spectrally distinct in the SWIR than in the visible.

Why Spectral Measurements Are Useful: Computer algorithms can analyze each pixel's spectrum within the high-resolution image to cue operators to those pixels that are most likely to be of interest. For example, in a natural forest scene, much of the vegetation will have spectra that look similar. However, the spectrum of a military vehicle or important chemical compound might look quite different from the forest background. NRL has developed algorithms that can recognize those pixels either by matching their spectral signature if that is known a priori, or by recognizing those pixels that are anomalous compared to the image's background. By automatically drawing attention to those most interesting pixels, the hyperspectral imaging system significantly reduces the workload of the image analysts and increases the amount of ISR imagery the analysts can review by orders of magnitude.

NRL's Contribution: NRL is the developer and system integrator for the MX-20SW, an SWIR (900 to 1700 nm), real-time, long-range, airborne hyperspectral imaging system for target detection as well as collection of measurement and signature intelligence (Fig. 1). An imaging spectrometer is integrated into a modified MX-20 stabilized gimbal system manufactured by L-3 Wescam, which enables it to point precisely anywhere within the full hemisphere under the


FIGURE 1
The MX-20SW hyperspectral imager.

airborne platform. Previous implementations required tactical aircraft to either directly overfly or employ restrictive flight routes in order to collect hyperspectral data, whereas the MX-20SW allows for arbitrary flight routes substantially offset from the search target. While this capability presents a distinct tactical advantage for our military's aircraft, the system must address the scientific concerns associated with light propagation over long distances in the Earth's atmosphere as well as highly variable viewing geometries. Several design approaches were taken to address these scientific concerns. First, the SWIR band was chosen to mitigate atmospheric scattering, increasing long-range visibility of targets. Second, a large-aperture (12 in. diameter), long focal length (900 mm/1800 mm) lens is used to collect sufficient light at long range. These characteristics enable the system to produce high quality spectral imagery (Fig. 2). Finally, a technique called covariance equalization is used so that hyperspectral target

FIGURE 2
Example imagery taken by the MX-20SW.

FIGURE 3
The MX-20SW installed on the multisensor platform.

detection can remain effective in the oblique viewing geometry. Covariance equalization calculates a statistical transformation between the backgrounds of two different scenes and then applies this same transformation to a known target spectrum taken from one scene in order to predict what the spectrum should be in a second, different scene. Using this technique, varying atmospheric conditions and viewing angles can be normalized, such that hyperspectral target detection can remain effective for highly oblique viewing geometries and a wide variety of image backgrounds.

All the target detection algorithms are implemented on a real-time processor that cues analysts to targets of interest at the rate at which the imagery is collected by the sensor. NRL's unique algorithm architecture and processing implementation allows results to be generated in minutes, compared to the 8 to 24 hours required by other systems. This near-real-time capability, coupled with the SWIR, long-range, high-resolution, oblique viewing ability, enables the system to deploy operationally on a multisensor platform (Fig. 3). The results from each of the sensors can be fused to provide high confidence to the image analyst that the target of interest has automatically been detected by the computer system. Over the course of the MX-20SW program, we have implemented various upgrade programs and built three additional units.

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Full Element Simulator/Stimulator for the *Virginia* Class LWWAA Sonar System

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Introduction: In August 2003, the lead ship of the Navy's latest class of attack submarine, USS *Virginia*, was christened. On board was the first fiber optic sonar system to be deployed on a U.S. Navy vessel: the Light Weight Wide Aperture Array (LWWAA). The hull-mounted LWWAA sonar system is based on fiber optic sensor technology developed at the Naval Research Laboratory and transitioned to industry for production.[1] The LWWAA sensing system comprises the outboard system consisting of thousands of fiber optic hydrophones and the inboard system consisting of the lasers and receiver electronics to interrogate the sensors and extract the acoustic information from the returning light (Fig. 4).

FIGURE 4
USS *Virginia* (LWWAA panels circled) and the onboard electro-optic system.

Fiber optic sensor systems offer some unique advantages in performance, reliability, and cost, but they also present some unique challenges in simulation and integration testing. The fundamental simulation complication arises from the fact that fiber optic systems require three parts: optical source, sensor, and receiver. To simulate the sensors, an optical instrument must be built that accepts signals from the source optics and produces optical outputs appropriate for the receiver. Independent simulation of each individual channel for large-scale systems with thousands of sensors, such as the LWWAA, is not practical due to size and cost considerations. For the first ten LWWAA ship sets, array simulators and sensor stimulators (SIM/STIMs) with severely limited scope and capabilities were used for development and integration testing. These SIM/STIMs could not fully characterize the system and ultimately resulted in the Navy performing some of the LWWAA operational verification testing on deployed submarines at considerable cost and inconvenience.

In 2008, planning commenced for a technology refresh of the LWWAA launch and receive electro-optic systems; this included a task to design and build a new SIM/STIM with enhanced simulation and stimulation features that would address the missing performance test capabilities.

Capabilities: The new SIM/STIM (Fig. 5) is built to optically simulate all the LWWAA sensing elements including all the source and receiver electro-optics with a reduced set of independent channels to control cost. The optical telemetry of the SIM/STIM was designed to match that of the tactical system, thus linking the laser sources to the correct receivers with optical throughput losses and telemetry lengths matching those found in the tactical system. The range of acoustic signal simulation has been expanded to include much higher and lower frequencies to simulate interferers and flow noise. To recreate the effects of the operational environment of the tactical sensors on the optical signal path, the simulation interferometers have the ability to change their optical path length to simulate the effects that depth changes have on the sensing elements. The new SIM/STIM incorporates optical attenuators and polarization controllers that allow for full optical simulation of the sensor behavior in the tactical environment. The simulation interferometers incorporate environmental isolation, which prevents external noise interference in and above the frequency band of interest, and incorporate a sufficient number of sensor simulators to allow for rudimentary beam forming.

Utilization: The NRL-built SIM/STIM allows the Navy to test multiple performance requirements of the LWWAA system that previously could only be tested at great cost on a tactical platform or at sea. This new capability will be used to verify the design of the new electro-optic launch and receive systems being developed under the technology refresh program and to verify the performance of production units going forward.

The ability to simulate all of the source and receiver electro-optics allows the user to fully exercise the system startup procedures and verify their proper

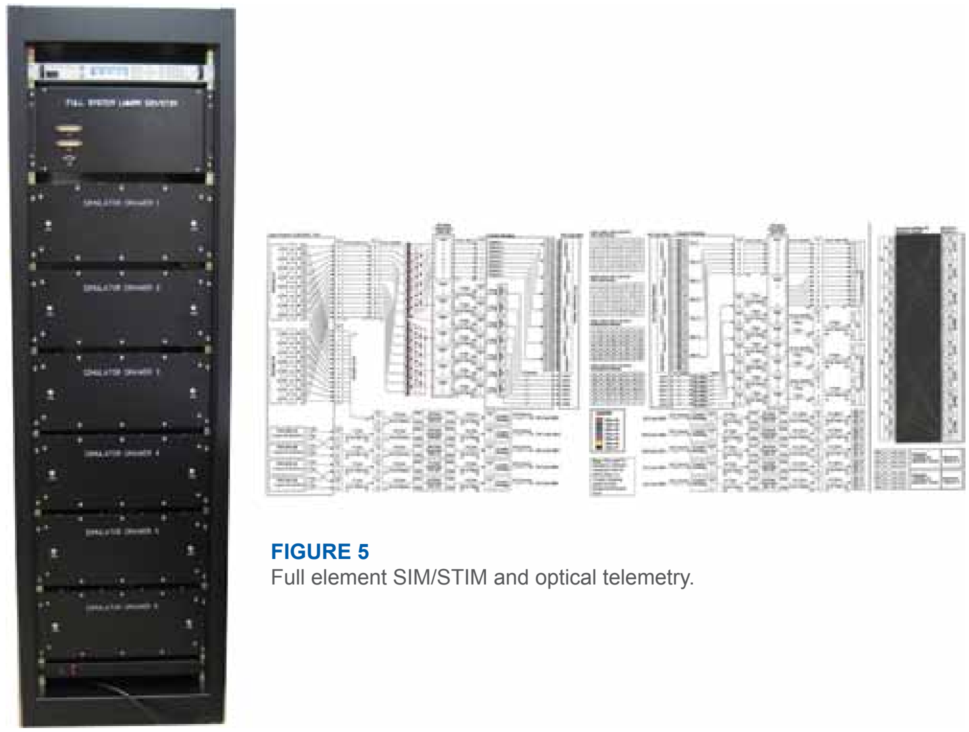

FIGURE 5
Full element SIM/STIM and optical telemetry.

operation, sequencing, and elapsed time. Having all the sensor elements available simultaneously also allows the user to verify the optical telemetry paths and exercise the system-level optical performance monitoring and fault location functions. Additionally, producing a full suite of acoustic data streams allows the user to stress-test the interface between LWWAA and the sonar processing system.

The enhanced stimulation capabilities of the new SIM/STIM test interferometer allow for a wider range of system performance requirements to be tested. The expanded frequency range allows for more complete in-band testing to be performed in the presence of realistic out-of-band acoustic signals. The ability to change the simulation interferometer's path length allows for the testing and verification of system performance as the simulated platform changes depth. These stimulation capabilities, coupled with the simulation of all elements, allow the user to verify directly the performance of all the source lasers, the telemetry path cable and connectors, and receiver channels instantaneously.

The new SIM/STIM was delivered to Lockheed Martin in October 2010, where it successfully underwent its performance verification testing. It has since been used during the *Virginia* sonar system technology insertion upgrade to identify system performance issues and verify their correction. In the summer of 2012, it will play an important part in the design verification testing of the LWWAA technology refresh project.

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[Sponsored by NAVSEA]

Reference

[1] A. Dandridge, A.B. Tveten, and C.K. Kirkendall, "Development of the Fiber Optic Wide Aperture Array: From Initial Development to Production," *2004 NRL Review* (Naval Research Laboratory, Washington, DC, 2004), pp. 177–179.

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Broadband Supercontinuum Generation

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Introduction: Supercontinuum sources are light sources that generate broadband emission within a spectral region through various nonlinear interactions in optical fiber. While supercontinuum sources based on silica fiber are commercially available spanning from ~0.4 to ~2 µm, emission beyond this wavelength region is limited by significant multiphonon absorption loss in silica. Mid-IR supercontinuum sources operating within the important 2 to 5 μm mid-IR atmospheric transmission band would have many applications in areas of chemical sensing, IR countermeasures, hardware-in-the-loop testing, and free space communications. To generate supercontinuum within the 2 to 5 μm band requires fiber materials with large transparencies in this region as well as high nonlinearities.

Chalcogenide fiber is based on the chalcogen elements sulfur (S), selenium (Se), and tellurium (Te). Fibers have high transmission in the IR out to ~12 μm depending on composition and low losses (i.e., of less than 1 dB/m). Chalcogenide fibers also have high nonlinearities, 100 to 1000 times those of silica. The large mid-IR transmission window coupled with the high intrinsic material nonlinearities make chalcogenide fibers ideal for supercontinuum generation in the mid-IR.

Supercontinuum Generation Mechanism: Typically, supercontinuum sources operate by pumping near or in the anomalous dispersion region of the nonlinear fiber. Pumping near the anomalous dispersion region allows four-wave mixing and soliton dynamics to enhance the efficiency of supercontinuum generation. Typically, microstructured photonic crystal fiber is used in supercontinuum sources as it allows one to tailor the dispersion properties of the fibers to match the pump wavelength of the source. Chalcogenide fiber material zero dispersion point is ~5 μm, and so the use of microstructured fiber structures allows one to shift the dispersion minimum closer to the near-IR, thereby enabling pumping with commercial fiber sources around 1.5 to 2 μm. However, this results in fiber structures with very small core sizes (2 to 3 μm), which can be difficult to fabricate and typically have high intrinsic losses as well as high insertion losses. Power scaling with such small core structures is also problematic, especially with suspended core microstructured fiber, in which the core is effectively thermally isolated from the cladding by an air layer. Consequently, our supercontinuum design involves operating in the normal dispersion region of the chalcogenide fiber. Operating in this region allows standard step index fiber structures to be used, which relaxes the constraints on core size dimensions, eases coupling into the fiber, and enables power scaling. The high intrinsic nonlinearity of the chalcogenide fiber material allows efficient supercontinuum generation in the normal dispersion region.

All-Fiber Mid-IR Supercontinuum Source: A high-peak-power pulsed-fiber source operating at 2.5 μm was developed for pumping the chalcogenide fiber to generate mid-IR supercontinuum. Figure 6 shows the pump source, which consists of a commercial erbium (Er) mode-locked fiber laser operating at 1.5 μm with a repetition frequency of 560 kHz. The output of the erbium fiber laser is amplified by an erbium/ytterbium (Er/Yb) fiber amplifier, Raman shifted to 2 μm, amplified in a thulium (Tm) fiber amplifier, and finally Raman shifted in highly nonlinear fiber to a wavelength of ~2.5 μm. Approximately 700 mW of power at 2.5 μm is obtained at the pump output. The peak power of the fiber pump source is estimated to be greater than 10 kW. The pump source is coupled to a 2 m length of arsenic sulfide (As_2S_3) fiber made at NRL. The As_2S_3 glass for the fiber is fabricated from highly purified precursors, leading to a minimum transmission loss of ~0.7 dB/m around 1.5 μm. Broadband mid-IR supercontinuum is generated spanning from 1.5 to 5.5 μm. More than 235 mW of power is generated with 10 dB

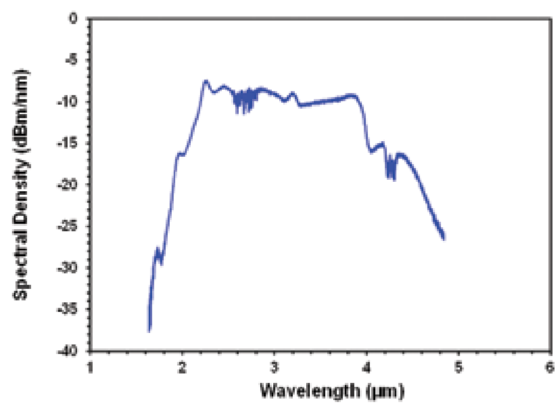

FIGURE 7
Supercontinuum source spectral output.

of spectral flatness from 1.9 to 4.4 μm and 20 dB of spectral flatness from 1.65 to 4.78 μm. Figure 7 shows the spectrum of the generated broadband mid-IR supercontinuum. These power levels are suitable for many spectroscopic applications, but some applications, such as IR countermeasures, require higher power. For these applications, power scaling of total supercontinuum power can be achieved by increasing the repetition rate of the pump laser source while maintaining the per-pulse peak-power, resulting in an increase in

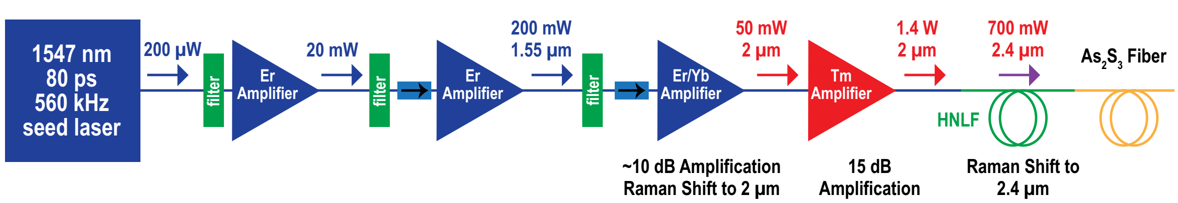

FIGURE 6
Schematic of the supercontinuum source.

average power. For example, increasing the repetition rate of the pump laser from 560 kHz to 5.6 MHz while maintaining peak power will allow a tenfold increase in mid-IR average power.

Summary: We have developed an all-fiber broadband mid-IR supercontinuum source based on chalcogenide fiber. The source exhibits high power and spectral flatness over the important 2 to 5 μm atmospheric transmission region. The source is power scalable by increasing the repetition rate and average power of the pump source.

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