Appendix D

INFRARED/HYPERSPECTRAL METHODS (PAPER II)

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BASIC PHYSICAL PRINCIPLES

This appendix addresses landmine detection performance for infrared (IR) and hyperspectral (HS) sensors, which include broadband, multispectral (2–20 bands), and hyperspectral (more than 20 bands). Bands include the VNIR, SWIR, MWIR (both reflective and thermal), and LWIR.[2] It also considers the use of polarization information within these bands.

Figure D.1 displays the myriad of conditions under which mine detection must be accomplished. Indeed, one of the factors determining the success of a sensor is its ability to cover this variety of conditions within the environment, ground cover, soil, and mine.

Broadband IR mine detection operates in the thermal domain, measuring the apparent temperature difference between the target and background. Here, the target can be either a mine on the surface of the ground or the area over a buried mine. The presence of a mine leads to a difference in the rate of heating or cooling of the area over the mine, producing a diurnal cycle to the signature and a contrast reversal of the mine area versus the background that occurs over the daily cycle.

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[1] The author acknowledges the assistance of Jack Cederquist, Robert Horvath, and Craig Kenton in preparing this work. Originally published by Veridian International, 2001. Reprinted with permission.

[2] VNIR, SWIR, MWIR, and LWIR are visible/near, short-wave, mid-wave, and long-wave infrared, respectively.

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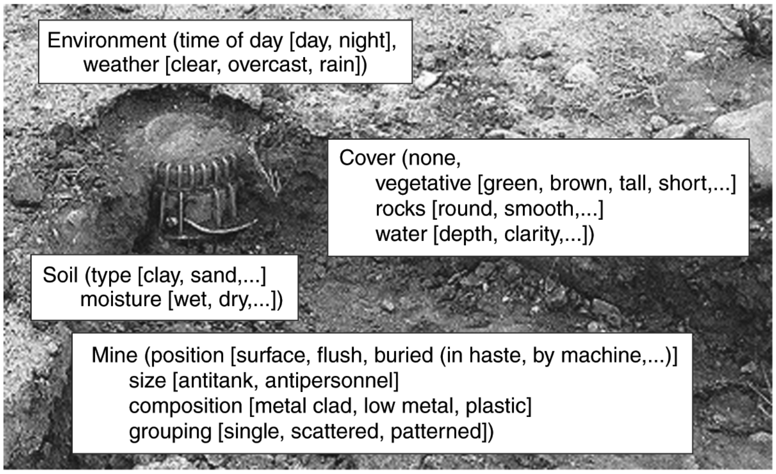

Figure D.1—Successful IR/HS Mine Detection Must Accommodate a Wide Variety of Conditions

Spectral mine detection either examines the apparent temperature difference in more detail (because multiple bands are used instead of one) or detects reflective color difference of mines or their covering material with respect to their backgrounds. Spectral detection depends on detecting the effect on soil or vegetation as a result of burying the mine, not the buried mine itself. Upon burying the mine in bare soil, the placement or presence of the mine will change the observables of a small region around it. Immediately upon placement, particle size, texture, or moisture differences can be detected by broadband IR or spectral methods. However, most prominent effects weather away with time.

The largest bare-soil effect is the result of a change in the distribution of particle sizes of the soil upon disturbance for mine burial. Soils consist of a range of particle sizes, and small particles (e.g., 2 μm) are much more mobile than larger particles. Spectral behavior depends on the soil particle size relative to the wavelength of light. Freshly disturbed soil has more fine particles that cover larger particles. This covering effect suppresses or smooths out the spectral features of the large particles in recently disturbed areas. Undisturbed areas tend to display spectral characteristics of the bulk (larger particles) of the soil. Examples include the quartz doublet feature centered at 8.5 μm and 8.9 μm—fine particles of recently disturbed soil suppress this feature, but undisturbed soils display it more strongly.

Other spectral measurements detecting disturbance are based on color changes in vegetation—VNIR and SWIR spectra can show change in chlorophyll and water spectral features. Disturbances of soils high in organic materials may be detected in SWIR by observing features from lignin and cellulose. Mine burial may permanently alter the vigor of overlying vegetation if the root zone is greatly disturbed. Excavating other minerals during burial may also provide spectral feature evidence of disturbance.

Polarimetric effects are useful for detecting surface mines. Passive polarimetry either uses the sun or sky for illumination, or uses thermal emissions. Active polarization uses a probe light, generally from a laser, and looks at polarization of the returned light. Natural materials tend to depolarize the radiation that is returned, while manmade materials, which are smoother, tend to preserve the polarization of incident radiation upon reflection, attributed to specular surfaces, or emit polarized light in accordance with the Fresnel equations. By supplying the illumination, active polarization establishes a known geometry (position and polarization of the light source) and is more reliable than passive polarization (for which the light source, such as the sun, varies in location).

STATE OF DEVELOPMENT

The maturity of IR/HS mine detection techniques is determined more by algorithm capability (i.e., the ability to transform the observed sensor outputs into decisions on the presence or absence of mines or minefields) rather than sensor maturity. All three techniques (broadband, spectral, and polarimetric) have been the subject of recent field tests. These are considered in order of decreasing maturity.

Work in broadband IR detection of mines has been conducted by Northrop Grumman, TRW, BAE Systems, and the government organizations of the U.S. Army Night Vision and Electronic Sensors Directorate (NVESD) and the UK Defence Evaluation and Research

Agency (DERA). Broadband IR sensors are commercially available, and such sensors have been used in handheld, vehicle-based, and airborne field tests. However, the processing algorithms have not been able to detect mines with sufficient accuracy, or to discriminate mines from other mine-like objects, to meet requirements.

Spectral mine detection has been carried out by companies that include Aerospace Corp., BAE Systems, Raytheon, Space Computer Corporation, SAIC, the University of Hawaii, and Veridian. Active government organizations include the Defense Advanced Research Projects Agency (DARPA), the Navy's Coastal Systems Station (CSS), and NVESD.

The market for spectral sensors is extremely limited, becoming smaller as both the number of bands and the wavelength increase. Commercial off-the-shelf sensors are restricted to multispectral sensors in the VNIR range, such as those sold by Xybion. As the wavelength increases to LWIR, the technology becomes more complex, requiring more expensive focal plane detector arrays and cooling. However, successful one-of-a-kind hyperspectral LWIR sensors have been built, and some current U.S. government programs are directed to building LWIR hyperspectral sensors with a form factor compatible with unmanned aerial vehicles (e.g., BAE Systems, Long Island, N.Y.; Raytheon, Plano, Tex.). VNIR multispectral minefield detection has been proven to work in the littoral zone under the Coastal Battlefield Reconnaissance and Analysis (COBRA) program of CSS and Veridian, meeting the operational minefield detection requirements set by this advanced technology demonstration. The basic phenomenology of hyperspectral minefield detection has been studied to identify those observables that may be sensed to detect mines (NVESD, Veridian, MTL, and SAIC). STI is now flying a prototype visible HS sensor ("LASH-MCM"). A limited field test of hyperspectral mine detection was conducted as part of the Airborne Standoff Minefield Detection System (ASTAMIDS) test, with DARPA using the LWIR HS sensor of the University of Hawaii ("AHI").

Polarimetric minefield detection activity has been conducted by Lockheed Martin (Orlando), Raytheon, TRW, and Veridian, with government activity by the British DERA and the U.S. NVESD and Army Waterways Experiment Station (WES). A polarimetric active sensor with an additional thermal IR channel was built for the

Remote Minefield Detection System (REMIDS) program of WES, and again for the ASTAMIDS of NVESD. These sensors were extremely fragile. Another such sensor is now under development for NVESD's Lightweight Airborne Minefield Detection program by Lockheed Martin. In cooperation with the Central Measurement and Signatures Intelligence (MASINT) Office and Air Force Research Laboratory, Veridian and Aerospace have built an LWIR spectral-polarimetric sensor and shown its usefulness in camouflage, concealment, and deception target detection. It has not been tested on mines. Field tests have used active polarimetric and thermal IR for both human-aided minefield recognition (REMIDS) and fully automated detection (ASTAMIDS/Raytheon).

Two types of field tests are considered—data collection (for algorithm development) and performance testing (by an independent agent against requirements, often compounding detection performance with constraints upon processing time or the size of the system). All airborne tests to date have focused on the antiarmor mines (about 12 inches in diameter), and have not yet been including the smaller antipersonnel mine (about 4 inches in diameter). Typical data collection (planning, laying mines or using an existing mined site, integrating available sensor with aircraft, collecting data, truthing it, and post-processing it) can range from $400,000 to $800,000 for each site. Independent performance testing of an established system, involving a greater range of locations, more conditions at each location, and use of an independent test organization, would approximately double the cost to $800,000 to $1.6 million. Collection of minefield data (large orderly arrays of mines placed as representatives of tactical deployment) is perhaps 30 percent more expensive than individual mine detection experiments.

CURRENT CAPABILITIES AND OPERATING CHARACTERISTICS

Table D.1 summarizes the current field-tested performance of these technologies. The ASTAMIDS tests (index numbers 1, 5, 7, and 8 of the table) were conducted at Fort Huachuca, Ariz., over an arid ground with vegetation cover of sparse grass, low bushes, scrub oak, and cactus, with soil that was a reddish mixture of clay and rocks.

Table D.1

ROC Curve and References for HS/IR Mine Detection Field Tests

Mode	#	System	Condition	PD (minefield)	PFA or FAR	Search Rate	Processing Time	Ref.
Broad-band IR	1	ASTAMIDS, Northrop Grumman	500 minefield encounters, vegetation/rocks	0.35	9.85/sq km	10.9 sq km/hr	Post-mission (45× real time)	[1]
Spectral	2	VNIR MS–COBRA ATD (Veridian)	6-band VNIR spectral sensor, littoral zone surface minefields (white sandy beach)	0.86 (patterned) 0.94 (scattered)	0.02 (PFA) (patterned) 0.07 (PFA) (scattered)	9 sq km/hr	Post-mission (14–44× real time—no requirement)	[2]
	3		Littoral/inland surface minefields (rocky beach)	> 0.8	< 1.5/sq km	6.5 sq km/hr	Post-mission (14–44× real time—no requirement)	[3]
	4	Navy MDP and ALRT (Veridian)	Tunable filter polarimetric 3-band VNIR multispectral; ground and air tests	> 0.8 (better than COBRA ATD)	N/A (< COBRA with limited data sets)	N/A	N/A	[11]
	5	LWIR HS – ASTAMIDS (DARPA)	LWIR HS sensor; buried roadmines (6 mines only)	0.67	471/sq km	2 sq km/hr	Post-mission	[1]
Polari-metric (with LWIR)	6	REMIDS (WES, Veridian)	Polarimetric and thermal IR; aids human	0.989 (patterned) 0.663 (scatterable)	N/A N/A	1.44 sq km/hr	24 hr; also achieved PD of 0.92 (patterned) within 2 hr	[4]

Table D.1—continued

Mode	#	System	Condition	PD (minefield)	PFA or FAR	Search Rate	Processing Time	Ref.
	7	ASTAMIDS, Raytheon	Polarimetric and thermal IR; automated	0.13	2.49 FA/sq km	10.9 sq km/hr	Post-mission, 2.5× real time	[1]
	8		Postprocessed (after test completion)—removed bad data due to sensor registration errors	0.2 (surface pattern with bad data) 0.57 (surface pattern, good data, night only)	N/A	10.9 sq km/hr	N/A	[5]

The tests involved over 500 minefield encounters for numbers 1 and 7, while 5 used *extremely* limited data from which no conclusions can be drawn. All tests except 8 were conducted independently, i.e., by an agent other than the developing organization. The COBRA spectral sensor tests (2) were for surface minefields under excellent conditions of white sandy beaches at Eglin Air Force Base, Fla.; the other tests (3) were conducted over more realistic littoral and land regions in Newfoundland, Canada. The REMIDS program (6) used human interpreters to make minefield decisions by inspecting the sensor data.

KNOWN OR SUSPECTED LIMITATIONS OR RESTRICTIONS ON APPLICABILITY

The best performance for broadband IR is for mines buried under uniform bare soil. Thermal IR performance for surface mines is better at night than at day. It also performs best when the time of observation can be chosen and/or multiple observations can be made at different times of day. Poorest performance occurs with nonuniform soil and soil covered with vegetation (which blocks thermal IR). Overall broadband IR is not as useful as a stand-alone sensor compared with the other sensors considered here. Its performance is limited by the diurnal cycle characteristic and by the high degree of mine-like clutter, with insufficient information available in the broadband IR to allow discrimination. Progress in the study of spectral phenomenology has led to better understanding of the origins of the broadband LWIR signature, as exploited by the Northrop Grumman ASTAMIDS, and now single or multispectral IR bands can be tailored to improve broadband IR performance.

Spectral detection performance is the best of these three sensors but is at the expense of a more complex sensor design. Detailed experiments on the physics of disturbed soil indicate that with a sufficient number of pixels on target, statistically significant discrimination ability between mine target signatures and their local backgrounds occurred within all bands (VNIR, SWIR, MWIR, and LWIR) [6,7]. Joint use of spectral bands has been shown to further improve performance [9,10]. This detector excels in detecting recently buried minefields (less than four weeks old); it is also excellent at surface minefield detection on relatively clear ground (e.g., littoral region [2]). Spectral methods perform most poorly for long-buried mines, over which the soil has returned to its natural state. The performance for buried mines is limited by the fact that buried mines are detected indirectly, through the associated disturbance of surrounding earth, which weathers away. Performance for surface minefield detection is limited by vegetative clutter that covers the mines.

Active polarimetry excels in the detection of surface mines upon uncovered ground, especially when mines are placed in regular patterns. Polarimetry combined with spectral sensing offers the possibility of excellent performance for both surface and buried mines (e.g., spectral/polarimetric sensing). Polarimetry has limited ability to detect buried mines—no specific phenomenology effect has been identified yet. Passive polarimetry is of limited utility because of the wide variation of illumination/receiver geometries and uncertain polarization of the illuminator, yet progress here has been shown.

ESTIMATED POTENTIAL FOR IMPROVING TECHNOLOGY OVER TWO TO SEVEN YEARS

Performance of IR/HS sensing is more limited by the detection algorithms than by the sensors. Sensor challenges include the engineering of robust, production-quality versions of the research prototypes used in field tests. Finer spatial resolution is believed necessary for accurate mine/clutter discrimination, especially for smaller mines.

For broadband IR, an example of the power of algorithm improvements provides an improvement in detection rate by more than a factor of two [5]. Improvements to pursue for this sensor include: (1) automatic compensation for time of day, thermal heating history, terrain (and confuser) type; (2) use of higher spatial resolution to exploit shape and within-silhouette information (e.g., texture) to aid discrimination against false alarms (FAs); and (3) leverage of minefield detection algorithms to aggregate incomplete mine detections into a more accurate field declaration. While broadband IR is unlikely to meet operational requirements of greater than 0.8 probability of detection (PD) for minefield detection, less than 1.0 FA per square kilometer on its own, an IR sensor may be combined with a complementary sensor.

Spectral limitations include the requirement to use higher-order decision statistics to achieve target/clutter discrimination (e.g., covariance rather than mean). This requires more pixels on target and more spectra needed to set detection thresholds. Spectral sensing also is limited in its ability to discriminate spectral anomalies due to soil disturbance from mine placement from other spectral anomalies, which increases false alarm rates. The understanding of possible false alarms due to burial of other objects has not been explored. Promising evidence of the far-reaching applicability of the disturbed soil phenomenology was obtained by tests that went to six locations around the world, carefully chosen for diversity, and including real minefields in Bosnia and Jordan [7,8,9], yet some additional confirmation is needed. The understanding and ability to model or explain effects of weathering, which gradually erases the effects of mine burial, is limited. Other limits, imposed by perhaps temporary needs to limit sensor complexity (size), include the choice of which multispectral bands to use if full HS capability is not possible, how to adapt these with terrain, and the limits of VNIR spectral sensors to daytime. All these limits, except perhaps solving the weathering effect, can be addressed successfully in a five-to-seven-year program, resulting in a spectral-based mine detection system capable of detecting nearly all recently laid minefields (PD greater than 0.8) at acceptable false alarm rates (less than 1.0 FA per square kilometer). Focus is recommended on reliably designing HS sensors accompanied by adaptive band-subsetting (i.e., adaptively and intelligently combining 100s of bands to 10s of bands for subsequent processing), as opposed to building ever-more-complicated multispectral sensors based on filter wheels or tunable filter cameras.

Polarimetry is most successful for, but limited to, detection of surface mines and minefields. Sensor complexity, in particular achieving multiple pixels on a mine-sized target while achieving the necessary subpixel registration accuracy between the polarization channels, sets the limits on surface minefield detection performance for this sensor.

OUTLINE OF A SENSIBLE RESEARCH AND DEVELOPMENT PROGRAM

Several points anchor a general philosophy on which a research and development program would be based:

- Harvest existing data that has already been collected to bolster phenomenology understanding and pattern recognition algorithm performance.
- Collect HS data across all bands (VNIR–LWIR), using the HS testing to determine the ultimate band count that is needed and whether these needs can be met with a multispectral sensor or even an agile (adaptively tuned wavelength) sensor. Seek to understand the utility of joint spectral bands that have shown improved performance [10] (e.g., VNIR with SWIR, MWIR and LWIR). Study the effects of aging over several months, and examine both passive and active polarimetry.
- Conduct ground-based tower-mounted data collections to understand phenomenology, and then collect data using a helicopter test bed with a stabilized sensor cavity and the same sensor suite to improve false-alarm and minefield ROCs.
- Do not encumber these data collections with expectations of a performance test, e.g., with sensor size or real-time constraints (but do not ignore their importance for realism—e.g., resolution/aperture).
- Datamine any field test with after-test improvements as exemplified by Radzelovage and Maksymonko [5] to realize full gain from all information obtained.

Table D.2 presents a sequential program based on the above precepts that would be a reasonable, five-to-seven-year, $31 million approach to achieving satisfactory IR/HS minefield detection. It places about a third of the effort on physics and phenomenology, a third on sensor design, and another third on a final performance validation test.

Table D.2

Outline of Five to Seven Year, $31 Million Program Leading to Robust, Satisfactory IR/HS Minefield Detection

#	Action	Objective	Cost
1	Conduct post-collection analyses on existing data from REMIDS, ASTAMIDS, Hyperspectral Mine Detection Phenomenology, …	Determine domains of success, reasons for failure, and improved processing algorithms	$1,500K (3 programs at $500K each)
2	Careful analysis of performance of various combinations of 10–20 spectral bands of 50–200 nm width	Understanding of ultimate need for hyperspectral vs. adaptive multispectral vs. fixed multispectral sensor	$1,000K (2 programs at $500K each)
3	Tower-based collections over VNIR through LWIR bands with HS imaging sensors, with and without active/passive polarimetry	Exploit joint band detection, examine aging effects over several months to determine factors and time constant of erasing burial effects	$1,600K, including cost of multiple spectral instruments
4	Collection with sensor suite of #3 in helicopter with stabilized sensor cavity, at two diverse U.S. locations over minefields, wide area	Measure false alarm rate and determine/optimize gain afforded by minefields rather than mines only; explore feature clustering minefield algorithms	$3,000K (two locations at $1,500K each, including platform rental and sensors)
5	Basic algorithm research—begin with probability density functions (PDFs) of hyperspectral features; seek appropriate subsettting methods (e.g., principal components analysis), seek to increase target/clutter distribution separation	Statistical pattern matching/decision theoretic-driven optimization of information across bands; adaptive band selection; data-driven PDFs to ROC curve; aggregation to minefields	$1,500K (2 programs at $750K each)
6	Spectral data compression	Process to transmit data down limited bandwidth link	$500K

Table D.2—continued

#	Action	Objective	Cost
7	Spatial/spectral integration of information	Determine best joint use of spectral information with high-resolution spatial information (shape, texture)	$1,000K (2 programs at $500K each)
8	Spectral libraries	Supplementing anomaly detection with matching of signatures of mines or clutter to known spectra to reduce false alarm rate	$1,000K (2 programs at $500K each)
9	Reliable spectral sensor development	Use above phenomenological and algorithm understanding to design and build minimal-complexity, maximum-performing sensors for handheld, vehicle, and airborne application	$10,000K (3 platforms, leveraging past work at about $2M–$4M each)
10	Final field test (hand, vehicle, and air platforms)	Demonstrates performance with final sensors	$10,000K (3 demos)

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