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SPECTRAL AND POLARIMETRIC IMAGERY COLLECTION EXPERIMENT

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14. ABSTRACT
The Spectral and Polarimetric Imagery Collection Experiment (SPICE) is a collaborative effort between the U.S. Army Armament Research, Development and Engineering Center (ARDEC) and the U.S. Army Research Laboratory that is focused on the collection of mid-wave and long-wave infrared imagery using hyperspectral, polarimetric, and broadband sensors.
The objective of the program is to collect a comprehensive database of the different modalities over the course of 1 to 2 yrs to capture sensor performance over a wide variety of adverse weather conditions, diurnal, and seasonal changes inherent to ARDEC's northern New Jersey location.
Using the Precision Armaments Laboratory tower at ARDEC, the sensors will autonomously collect the desired data around the clock at different ranges where surrogate 2S3 self-propelled howitzer targets will be positioned at different viewing perspectives in an open field at 549 and 1280 m from the sensor location. As a result, this database will allow for (1) evaluation of hyperspectral and polarimetric technologies, (2) development of new sensors, (3) development of robust algorithms, (4) understanding of signature variability under the different weather conditions, and (5) evaluation of fusing the different sensor modalities.
In this report, we will present the SPICE data collection objectives, the ongoing effort, the sensors that are currently deployed, and how this work will assist researches on the development and evaluation of sensors, algorithm, and fusion applications.

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Spectral and polarimetric imagery collection experiment (SPICE), Mid and long-wave infrared imagery (MWIR and LWIR), Hyperspectral, Polarimetric, Data, Collection, Imagery, and Experiment

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INTRODUCTION

Hyperspectral and polarimetric imagery have been researched by many organizations due to their ability in distinguishing potential targets from complex backgrounds. Over recent years, such technologies have made significant improvements in hardware, algorithm development, and modeling and simulation. However, to continue the vast improvements seen in recent years, databases comprised of challenging conditions need to be collected in order to (1) understand the limitations of the technology under a variety of operational circumstances, (2) advance hardware development, (3) development of robust algorithms, and (4) improved modeling and simulation fidelity.

In order to measure performance of algorithms under adverse weather conditions, long-term data collections need to be carried out in order to capture intended weather variability. Capturing such variability can be problematic and very costly when having key personnel on-call ready to collect signal measurements for long periods of time. Furthermore, measurement opportunities may be missed during non-working hours (holidays, weekends, etc...) when desired conditions may occur.

Due to the prohibited cost of conducting long term manned data collections and the need to collect such a database for the scientific and Department of Defense community, the U.S. Army Armament Research, Development and Engineering Center (ARDEC), Picatinny Arsenal, New Jersey in collaboration with the Army Research Laboratory (ARL), Adelphi, Maryland have assembled a new data collection effort to collect mid-wave (MW) and long-wave (LW) infrared (IR) imagery using hyperspectral, polarimetric, and broadband sensors.

The objective of the spectral and polarimetric imagery collection experiment (SPICE), is to collect a comprehensive database of calibrated and qualitative measurements of hyperspectral, polarimetric, and broadband images during adverse weather events. Such measured information can be used to develop and validate sensors, algorithms, and modeling and simulation programs. The SPICE data collection distinguishes from previous efforts by offering autonomous data acquisition, storage, and sensor calibration of two target sites. The program uses dedicated, static targets year round at the different target range sites allowing scientists and engineers to compare target signatures at different ranges, viewing perspective, and weather conditions.

By collecting such a comprehensive database, it is our intent that such effort will allow the scientific community to (1) understand signature variability under the different weather patterns, (2) develop robust algorithms, (3) develop new sensors, (4) improve the fidelity of modeling and simulation programs, (5) evaluate the different technologies (hyperspectral and polarimetric) under adverse weather conditions, and (6) evaluate the possible fusion of the different sensor systems.

This report describes the location and facility where the SPICE collection will be performed, the hyperspectral sensors, the polarimetric sensors, the type of targets that will be used, the autonomous data collection, the resulting information from the data collection system, and the conclusions.

PRECISION ARMAMENT LABORATORY

The Precision Armaments Laboratory (PAL), located at ARDEC, Picatinny Arsenal, New Jersey is specifically dedicated to the testing of sensors under adverse weather conditions. The laboratory consist of a base building and a 65-m tower with two external elevators capable of serving as test beds for radars, electro-optic, or other sensors under test (fig. 1). The tower overlooks three instrumented target site areas (46, 549, and 1280 m from base), as well as a mid-range meteorological instrumentation site (642 m from base). The facility has automated collection of ground truth information to accurately determine and characterize meteorological conditions, measure the propagation path attenuation, perform the required measurements, and characterize the clutter background and target effects.



Figure 1
PAL 65-m tower

The effective height of the PAL tower is 126 m, as it was specifically positioned atop a 61-m ridge, thus providing access to a vast portion of Picatinny Arsenal. Accordingly, longer ranges (up to 5.85 km) can be accommodated, if required.

Standard meteorological measurement instrumentation includes wind speed, wind direction, temperature, humidity, and barometric sensors (table 1). Humidity and temperature are an indication of the moisture in the air that affects the propagation attenuation.

Table 1
PAL basic meteorological instrumentation types

Sensor	Measures	Comments
Anemometer	Wind speed	
Wind vane	Wind direction	
Thermometer	Temperature	
Humidity sensor	Humidity	
Barometer	Barometric pressure	
Snow/rain tipping bucket	Rain rate	Also melted snow liquid rate
Optical rain gauge	Rain rate	Possibly snow rate
Visibility meter	Visibility	Smoke, fog, haze
Pyranometer	Sun and sky radiation	
Pryheliometer	Solar radiation direction	Required tracking mount
Distrometer(s)	Drop sizing	Haze, fog, mist, drizzle, rain
Snow depth gauge	Snow depth	
Soil block	Soil moisture	
Ceileometer	Cloud range and thickness	Range and thickness of up to four layers of clouds

Other standard instrumentation includes rain gauges, a heated tipping bucket type that provides information on the liquid water content of the snow, as well as that for rain. By connecting the meteorological instrumentation to a network data logger located at the base building, meteorological information is autonomously collected and stored for further analysis.

Advanced meteorological sensors available at the PAL include an optical rain gauge, distrometers, snow depth gauge, soil moisture blocks, and a ceileometer. Optical rain gauges have the capability of performing more precise measurements at low rain rates and at extremely high rain rates. Distrometers provide measurement of precipitation sizes. Solar radiation can potentially affect the performance of the IR imagery due to thermal effect or possible inversion layer effects. Pyranometers measure total sun and sky radiation. If the direction of the solar radiation is an important factor, then use of a normal incidence pryheliometer along with a solar tracking mount will provide the required information. The ceileometer provides range and thickness information up to four cloud layers and up to a distance of 30,000 ft. Such information is crucial since low cloud ceilings adversely affect polarimetric and hyperspectral IR imagery.

HYPERSPPECTRAL SENSORS

The hyper-cam is a lightweight and compact imaging radiometric spectrometer. The spectral measurements are performed using a Fourier-transform spectrometer (FTS), which incorporates a 320 by 256 focal plane array (FPA) detector that can be windowed and formatted to fit the desired image size and to decrease the acquisition time. The LWIR hyper-cam uses a mercury cadmium telluride FPA to provide a spectral response from 8 to 12 μm ; whereas, an indium antimonide FPA having a spectral response from 3 to 5 μm is present in the MWIR hyper-cam (table 2). Spectral resolution is user selectable and ranges from 0.25 to 150 cm^{-1} . This instrument generates a complete spectrum of each pixel in the image (called a data cube), with each pixel having an instantaneous field-of-view (FOV) of 0.35 mrad. This field-portable sensor is shown in figure 2.

Table 2
Specification of the Telops MWIR and LWIR hyperspectral sensors

	MWIR	LWIR
Region of spectrum (μm)	3 to 5	7.7 to 11.5
Focal length (mm)	86	
Cooled FPA	320 by 256	
Pixel size (μm)	30	
Instantaneous FOV (mrad)	0.35	
Spectral resolution (cm^{-1})	0.25 to 150	
Black body	Internal (2)	



Figure 2
LWIR hyper-cam sensor

The instrument features two internal calibration blackbodies used to perform an end-to-end radiometric calibration of the IR measurements. The sensor also has advanced acquisition and processing electronics, including 4 GB of high speed double data rate-synchronous dynamic random access memory, with the capability to convert the raw interferograms into spectra using a real-time discrete Fourier-transform, as well as performing the radiometric calibration in real time.

The measurements from the hyper-cam are outputted on a high-speed CameraLink interface and consist of interferograms, raw spectra, or calibrated spectra along with a header that contains all configuration parameters and monitored values. A video camera bore sighted to the IR FOV allows for simultaneous recording of visible images. The configuration, monitoring, and real-time housekeeping data are transferred to the computer by a dedicated Ethernet link.

The control software has a user friendly interface and provides real-time feedback to the operator. A screen shot of the control software (named RevealPro) is presented in figure 3. On the right, the non-uniformity corrected broadband IR image is displayed with a grayscale code where black indicates low radiance levels and white indicates high radiance levels. The un-calibrated raw spectrum (or the interferogram as selected by the operator) of a selected pixel in the image is displayed in real time on the left of the screen.



Figure 3
RevealPro

The sensor has the capability to change the focus of the IR image to produce a clear image from 3 m up to infinity.

POLARIMETRIC SENSORS

A schematic of a division-of-aperture (DOA) MidIR imaging polarimeter architecture is illustrated in figure 4. A picture of the actual system is shown in figure 5. The system is based on a DOA lens technology developed by Polaris Sensor Technologies. The first element of the lens system (fig. 4) is a standard MidIR objective lens, which forms an image of the target on the field stop. The second set of optics shown inside the cryogenic chamber is the DOA optics. The collimation optic collimates the image from the field stop and forms an image of the objective lens aperture onto a 2 by 2 array of mini-lenses. The mini-lenses are in quasi-collimated space. The mini-lens set forms for identical images of the field stop onto four quadrants of the sensor FPA. When the DOA system operates as an imaging polarimeter, each mini-lens is followed by a linear polarizer at a different orientation. The DOA system can also be operated as a multi-spectral imager if each mini-lens is followed by a band-pass filter. For this system, a set of four linear wire-grid polarizers are used, oriented at angles 0, 90, 45, and 135 deg. Thus, the FPA captures four images simultaneously of the object at these four different polarization states. The images are precisely registered to within 1/10 pixel in software, and weighted subtractions are done to compute the Stokes images of the scene. The actual DOA lens set is much more complex than the schematic shown here and involves nine lenses, but this illustrates the concept. Note that the image of the Saturn V rocket located at the Space and Rocket Center, Huntsville, Alabama shown in figure 4 is an actual image taken with the system from the air. The DOA output image shown to the right in the figure is actual output from the DOA lens set. Table 3 gives the optical specifications for the DOA MidIR imaging polarimeter.

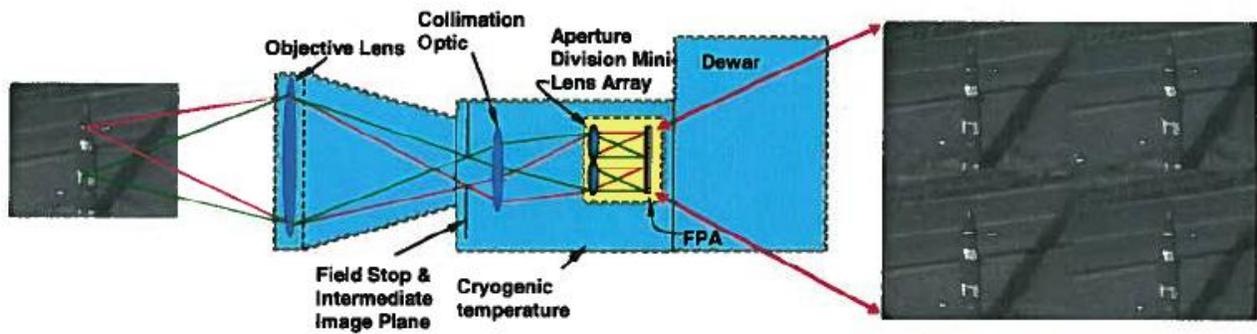


Figure 4
ARL MidIR DOA imaging polarimeter

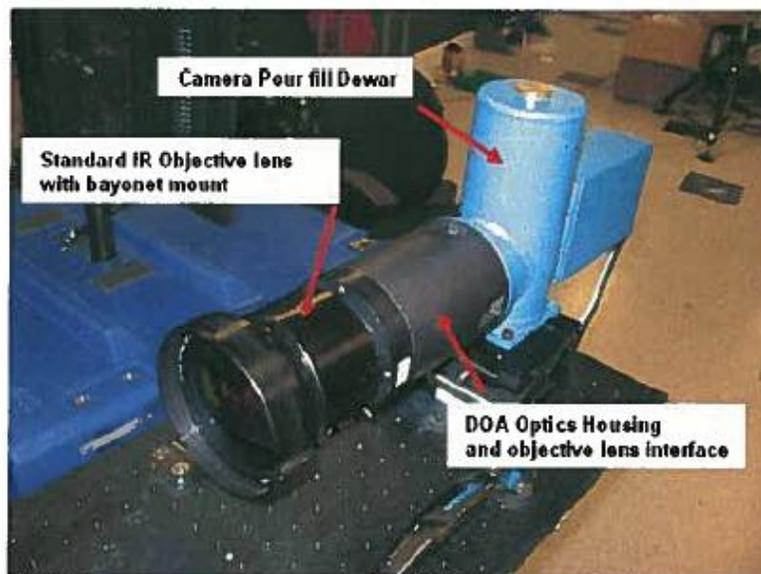


Figure 5
ARL MidIR imaging polarimeter with DOA optics

Table 3
Specification of the MidIR polarimetric sensor

Parameter	Value
FOV	5.5 deg
Objective focal length	100 mm
f/#	2.3
Total FPA pixels	640 by 512
Pixel size	24 by 24 μm
Quadrant aperture usable pixels	220 by 220
Maximum frame rate (stream to disk)	87 fps (640 by 512)
Sensor dimensions (mm)	420 L by 90 W by 210 H
Sensor weight	11 lb
System noise equivalent radiance	$1\text{e-}7 \text{ W.cm}^{-2}\text{-sr}$

The LWIR imaging polarimeter is a microbolometer-based, rotating retarder imaging polarimeter developed by Polaris Sensor Technologies, Inc., Huntsville, Alabama (fig. 6). It operates by capturing up to 12 images sequentially in time, each at a different orientation of the rotating retarder. Together, the retarder and linear polarizer act as a polarization state analyzer for the light forming the image. Using the data reduction matrix method, the Stokes vectors are calculated, which completely characterizes the polarization states of the light from the scene. Table 4 lists the sensor specifications.

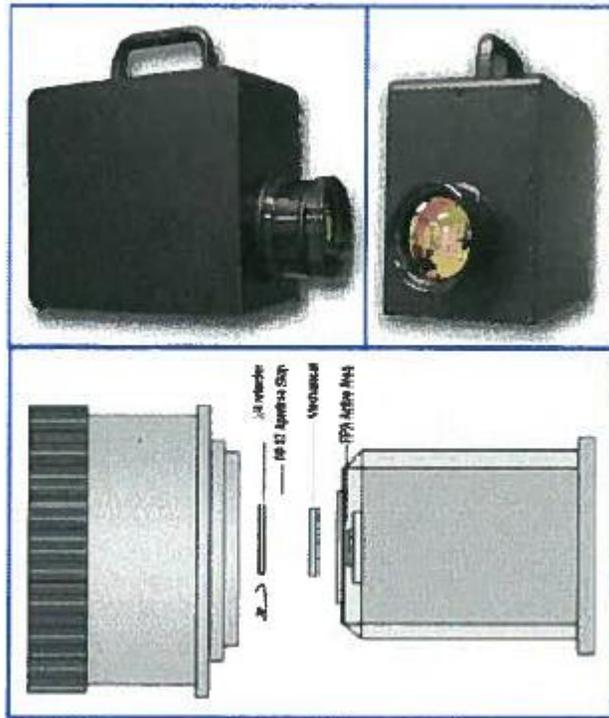


Figure 6
Polarimetric sensor and optical layout of the spinning retarder microbolometer-based sensor

Table 4
Specifications for the LWIR imaging polarimeter

Parameter	Value
FOV	13.7 by 11.0 deg
Objective focal length	50 mm
f/#	0.87
Total FPA pixels	324 by 256
Pixel size	38 by 38 μm
Maximum frame rate (stream to disk)	30 fps
Sensor dimensions (in.)	10 L by 6 W by 7.5 H
Sensor weight	12 lb
Power	15 V, 1.2 A

TARGETS

The use of actual operational military vehicles as targets to support the continuous and automatic nature of data collection at the PAL proved to be unaffordable. Thus, an alternative target approach had to be found. The solution came in the form of a surrogate foreign military vehicle. The surrogate found is that of a 2S3 howitzer that was developed and produced for an ARDEC smart munitions program (Sense and Destroy Armor - SADARM). The PAL currently possesses seven of these targets.

The surrogates (fig. 7) provide validated vehicle signatures in the 35-GHz radio frequency (RF) and MWIR regions of the electromagnetic spectrum. This was accomplished by producing a physical replication of the actual vehicle (RF region), by its metallic construction (RF and IR region), and the use of supplemental heated surfaces (IR region). In the IR region, the metallic construction properly produces the correct solar loading characteristics. The supplemental heated areas provide the correct characteristics for an operational vehicle. The heated areas are shown in figure 8.



Figure 7
2S3 surrogate target

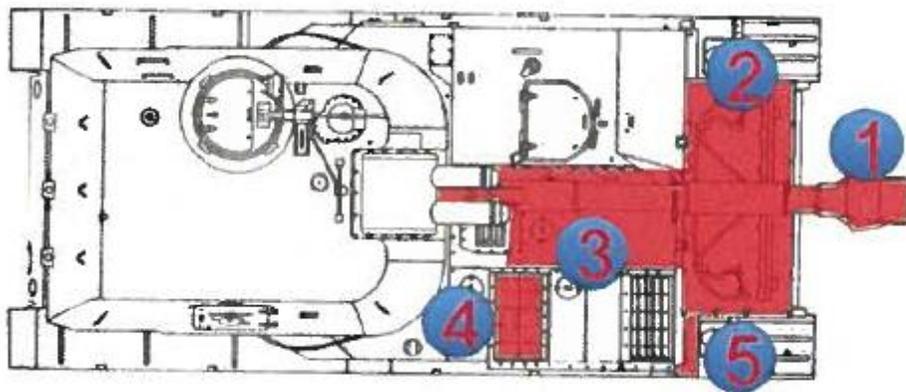


Figure 8
Surfaces heated at different temperatures per user needs

As can be seen, the engine area, exhaust areas, gun barrel, and replica road wheels can be independently heated and controlled. Table 5 identifies the temperature range available for each heated element. All target heating elements are programmable and can be automatically controlled, which lends itself perfectly to the PAL's automated data collection capability.

Table 5
Maximum temperature values for different parts of the 2S3

No.	Area	Maximum Δt (Celsius from ambient)
1	Gun tube	70
2	Front T	30
3	Back T	30
4	Overhead compartment	40
5	Exhaust (not used)	--
6	Wheels (not shown)	30

AUTONOMOUS DATA COLLECTION SYSTEM

Collection of imagery during adverse weather can be a hit or miss event. The use of test personnel for a long-term effort can be quite expensive and unproductive, if waiting for a certain weather event to occur. Furthermore, what may be construed at first as the required weather events needed for algorithm development, other events may be required long after the data collection effort has ended. Obviously, to pre-plan a list of events that is required for a complete data analysis, algorithm development, and technology evaluation can be quite difficult as one needs to predict which important factors are needed for such activities. In addition, prediction of when such events may occur in order to have the right personnel on-site is not only difficult, but also quite expensive to maintain.

To answer the difficulties in collecting a comprehensive database of a variety of weather patterns, ARDEC has assembled a selection of polarimetric, hyperspectral, and broadband sensors into an autonomous data collection effort to collect a database of calibrated and qualitative measurements during adverse weather events. By using an autonomous data collection system, ARDEC is able to collect the necessary data while keeping the data collection cost at a manageable level.

To accomplish the autonomous polarimetric data collection where the sensors need to collect images from the mid and long range target sites at pre-defined time periods and be able to self-calibrate, required a collaborative effort between Invoke, Polaris, ARDEC, and ARL.

The hyperspectral and polarimetric sensors were placed inside the PAL laboratory elevator on top of a Quickset QTP-500 Pan and Tilt positioner (fig. 9). The QTP-500 can handle payloads up to 500 ft-lb of torque, and the rugged design allows it to be in direct contact with the elements.



Shown in the image is the Mikron blackbody M350 (1), Quickset QTP-500 series (2), MWIR hyperspectral Telops camera (3), LWIR hyperspectral Telops camera (4), LWIR and MWIR polarimetric cameras from Polaris (5), and blower to protect sensors from rain and snow (6).

Figure 9
SPICE setup inside the PAL elevator

The Pan and Tilt system positions the sensors to collect data of the mid and long range target sites, and two background-only sites by receiving positioning instructions through the network by using controlling software by Invoke Corp. The positioned software reads a user defined Excel spreadsheet (script file), which is divided into five columns (time, position x, position y, blackbody temperature) that is used by the program to send position instructions to QTP-500 at a specified time. The Pan and Tilt system script positions the sensors to view the mid and long range every 5 min for the first 50 min of each hour, and clutter-only locations for the remainder of the hour. This cycle is repeated every hour, only interrupting when the polarimetric sensors need to be calibrated. The positioner software communicates with a Mikron blackbody source when calibration is needed, placing the Mikron blackbody on standby mode or automatic mode, and designating the temperature that the Mikron blackbody is to be set when in automatic mode.

To be able to capture data and calibrate the Telops hyperspectral cameras in a fully autonomous mode, where user interaction is kept at a minimum. Telops in collaboration with ARL and ARDEC has developed the Reveal Automate Suite. The Reveal Automate software allows a user to define key data collection parameters and schedule them throughout the day. The software is divided into two sections, acquisition and calibration. Each of the sections allows for 32 independent user defined segments for a 24-hr period, where a segment is defined as a start and end time in which a user-defined acquisition/calibration operation is to take place. Tables 6 and 7 demonstrate the variables that can be modified by the user in each acquisition and calibration segment.

Table 6
Reveal Automate user defined fields for data acquisition

Name	Unit	Minimum	Maximum
Start time	Time	00:00	23:59
Stop time	Time	00:00	23:59
Data cube acquisition interval	Minutes	1	1440
No. of data cubes per acquisition		1	1000
Integration time	Microseconds	5	1200

Table 7
Reveal Automate user defined fields for adaptive and user-set blackbody calibration

Name	Unit	Minimum	Maximum
Start time	Time	00:00	23:59
BB1 temperature vector	Celsius	Sensor dependent	
BB2 temperature vector	Celsius	Sensor dependent	
No. of datacubes per acquisition		1	1000
Integration time	Microseconds	5	1200
Temperature Δ	Celsius	0	20

During any given acquisition segment, a number of data cubes for a given integration time at a specified interval will be collected until the end of the current segment is reached. If a new segment is available, the software will collect the data as per the segment instructions pre-defined by the user. Once the day is completed, the system will then repeat all the segments until the user stops the Reveal program.

For the calibration section, the software supports up to 32 segments, and it uses the same logic as the acquisition section where the software repeats the segments every day. The calibration segments are defined by a start time, two vectors of blackbody temperatures, and the number of data cubes acquired per blackbody temperature. The software sends signals to the sensors for each temperature value in BB1 and BB2 vector, acquiring the blackbody calibration file(s) for all pre-defined values. To make calibration autonomous, a temperature Δ is used to check the instrument beam splitter temperature since the last calibration segment. If the temperature Δ is above the user-defined threshold, the system stops acquiring data and recalibrates again. A temperature Δ equal to 0 is considered a forced calibration by the user.

The reason behind using Δ temperature threshold for the beam splitter is because in order to ensure accurate calibration of the data, it is imperative that the beam splitter temperature does not deviate too much from the last time the sensor calibrated itself. If it does, then the calibration files will not be suitable for that specific data set.

As such, by using a beam splitter temperature threshold, the sensor calibrates itself when the beam splitter temperature is lower or higher than user specified threshold from last calibration segment.

To minimize power consumption inside the elevator, the Telops acquisition computers were placed on the sixth floor of the tower. The signals needed to communicate and collect data from Telops sensors are (1) real time visible video through a fire-wire cable, (2) two-way communication via an Ethernet cable, and (3) hyperspectral data sent through a data link cable. To accomplish communication and data transfer from a remote location, the sensors were connected directly to fiber optic cables

existent at the PAL facility. By using connection adapter (fire-wire - fiber optic, data link - fiber optic, and Ethernet - fiber optic) transceivers, the computers were placed in a remote location outside the elevator area with fast, high bandwidth, lossless connection. By doing such, the elevator is able to move up and down in order to collect data at different heights while still maintaining a perfect connection between the sensors and the computers.

The polarimetric sensor autonomous acquisition program was developed in conjunction with Polaris. Both the MWIR and LWIR use a weekly or monthly script with the fields shown in table 8. The script used is an Excel sheet for dating purposes and it is broken down by hour from 00:00 to 23:00. At each hour the user can define how many images to capture per acquisition interval. Unlike the hyper-spectral cameras, polarimetric cameras have a faster acquisition time and therefore can capture images more frequently. As such, data is being captured every minute instead of the 5 min intervals for hyperspectral.

Table 8
User defined fields for data acquisition using EXCEL files as inputs to the MWIR and LWIR polarimetric cameras

Name	Unit	Minimum	Maximum
Start time	Time	00:00	23:59
End time	Time	00:00	23:59
Interval	Time(s)	1	3600
No. of images per acquisition		1	100

Sensor calibration is accomplished during specified time intervals throughout the day, by turning the cameras to the Mikron blackbody and calibrating them at various blackbody temperatures. By calibrating the sensors with a variety of temperatures, it will allow researchers to calibrate the images by choosing the best temperature files that fit a particular image, by taking into consideration the available MET and target temperature that is collected at the PAL facility.

In order to collect the massive database that this effort is anticipating, the data collected by the computers is immediately transferred from the sensors directly to networked storage devices. Due to the fact that each data cube being transmitted from each Telops sensor is above 1 GB in size, fiber optic gigabit switches are being used to minimize congestion of data streams from the sensors to the computer. However, in order to store such massive amounts of information from the sensor to the network storage devices, dedicated localized gigabit local areas networks were setup to connect each computer to their respective storage servers to minimize congestion of data flow.

DATA COLLECTION PRODUCTS

In order to evaluate sensor technology and algorithm performance and fusion under adverse weather conditions, the instrumentation must record the necessary data from the sensor under test, the meteorological data, video, and any clutter and propagation data measured concurrently. Since the data is obtained from different instrumentation and is recorded separately in different locations, accurate time tagging of the data is essential in order to enable correlation of the data on a post-mission basis. To accomplish such, the inter-range instrumentation group time synchronization is used to minimize drift errors of all instrumentation during the data collection.

The hyperspectral data is recorded in its most basic format, as an interferometer data cube, and it can be opened and calibrated using Telops commercial off-the-shelf software. Calibration of the data is accomplished as follows: the sensors collect two vectors of different high and low blackbody temperatures for each calibration event. During the data calibration procedure, the user chooses the high and low calibration temperatures that best fit the target and background temperature values (air and ground) from the MET data for a particular date and time, ensuring that the data is properly calibrated. The calibrated data can then be opened up using Telops view, ENVI, or Matlab.

Similarly, the polarimetric data is also recorded in its most basic format and can be opened and calibrated using Polaris calibration software. Calibration of the data is accomplished by selecting a high and low calibration temperature from the calibration temperatures collected during sensor calibration. The calibrated data may be opened as a text image using Imagej, Matlab, or any other program that can read test images for further processing and image analysis. The PAL metrological database can also be opened and plotted using Excel or Matlab.

CONCLUSIONS

Hyperspectral and polarimetric sensor and algorithm development and evaluation require databases that include adverse weather variability to understand the impact that meteorological events have in detecting and discriminating targets from background clutter. As weather is often unpredictable, collecting such databases can be a hit or miss opportunity. Moreover, such data collections can become prohibitively expensive to maintain if test crews need to be on hand to collect such events. Therefore, having a system that can autonomously collect the necessary data under a variety of meteorological conditions 24 hrs a day allows for the collection of the necessary variability.

In order to address the development and qualification of sensors and algorithms under such adverse weather measurements, the U.S. Army Armament Research, Development and Engineering Center (ARDEC) and Army Research Laboratory (ARL) have put up a system that specifically addresses such adverse weather measurements in an autonomous mode. The system will allow ARDEC and ARL to collect data from hyperspectral and polarimetric sensors systematically 24/7 with minimal employee involvement. This makes the system very affordable to maintain, and collecting the necessary data can benefit the community in the development, testing, and evaluation of algorithm, sensors, and technology for warfighter applications.

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