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TO:

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SUBJECT: Wide-area Hyperspectral Motion Imaging

# Introduction

Wide-area motion imaging (WAMI) has received increased attention in defense and commercial space due to the importance of wide-area persistent surveillance for homeland protection, battlefield situational awareness, ISR of denied areas, and environmental monitoring. Recently developed systems such as Argus-IS have the capability to surveil up to 100km$^2$ at over a gigapixel resolution from an airborne platform. This huge amount of visual data requires algorithms for automated detection and tracking of targets of interest. However, traditional kinematic data based tracking algorithms have challenges in wide area motion imagery due to a relatively low-sampling rate, low spatial resolution, occlusions, changes in lighting, and multiple confusers. Recent studies have shown that incorporating hyperspectral data can boost probability of detection, reduce false alarms and improve performance in vehicle tracking and dismount detection [1].

Currently fielded imaging spectrometers use either dispersive or interferometric techniques. A dispersive spectrometer uses a grating or prism to disperse the spectrum along one axis of a focal plane array (FPA) while the other axis is used to measure a single spatial dimension. An interferometric spectrometer reconstructs the spectrum from multiple interferograms measured at the FPA by splitting the incident light into two optical paths and varying the optical path distance of one of the paths with a moveable mirror. Both approaches are not suitable for motion imaging a large area on the ground. For example, to cover 64 km$^2$ at a ground sampling distance of 0.5m, an update rate of 1Hz, and up to 256 spectral bands, a dispersive grating spectrometer must sacrifice SNR (<4us dwell time per pixel). An interferometric spectrometer is not even capable of imaging at a 1Hz update rate as it would require it's mirror to move an order of magnitude faster (65000 steps/sec) than what is typically available (2000 steps/sec) . Given these constraints, it is not surprising that no military or commercial WAMI platform has a hyperspectral sensing capability. Therefore, today's systems must choose between area coverage and spectral bandwidth. Time-encoded multiplexed imaging has the potential to enable wide area hyperspectral motion imaging as it has greater throughput than a dispersive imager and a faster scan rate than an interferometric imager.

# Time-encoded Multiplexed Imaging

The key idea behind time-encoded multiplexing is mapping spectral features in the scene to orthogonal temporal codes. To illustrate this concept, consider a single spatial pixel with the understanding that each pixel operates independently, thus this technique can scale to any size

array of pixels. In Figure 1 (top), a single spatial pixel contains three spectral colors: red, green, and blue. These colors will be assigned the orthogonal codes {0,1,1}, {1,0,1}, and {1,1,0}. The light is dispersed through a first prism onto three pixels on a spatial light modulator then recombined and measured at a single pixel detector. During the integration period, the three codes are sequenced and three measurements taken. During the first time sequence ($t_1$), the spatial light modulator is set to the first code {0,1,1} which blocks the red light so the measurement $m_1$ is a sum of green and blue. This is repeated for the subsequent codes for a total of three measurements. An estimate of the amount of red, green, and blue light within the pixel can be calculated by addition or subtraction of the measurements. For example, the blue channel is the addition of the first two measurements and subtraction of the third measurement.
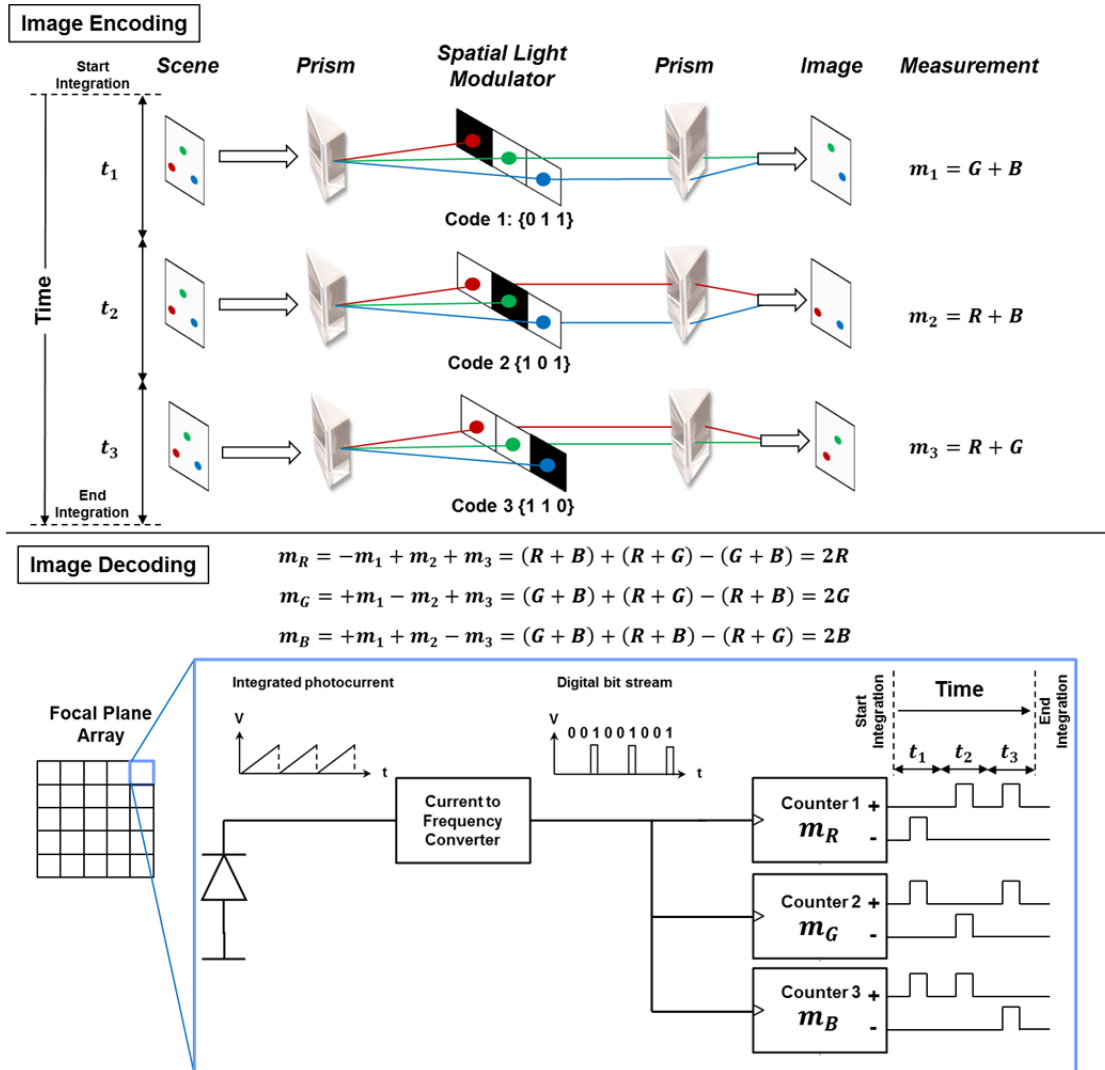


**Figure 1 Image encoding with a spatial light modulator (top) and decoding with a digital focal plane array (bottom).**

The image decoding can be performed independent from the measurement by reading out an image frame for each time sequence, however, the frame rate of the imager will limit the image decoding rate, which will limit the hyperspectral data (hypercube) acquisition rate. For example, at 100 frames/sec and 200 spectral channels, the acquisition rate is 0.5Hz.

Implementing decoding with a digital focal plane array (DFPA) enables much faster hypercube acquisition rate because the decoding can be performed in parallel and at the same time as the measurement. In a digital focal plane array (bottom of Figure 1), each pixel has an analog-to-digital converter (ADC). The ADC converts the input photocurrent into a digital pulse stream, and a counter counts the number of pulses within a given integration period [2]. The magnitude of the count is proportional to the incident photon flux. The counter can be controlled to count up, down, or not at all such that a duobinary {-1,0,+1} modulation signal can be applied. In addition, multiple counters can be connected to the digital bit stream output of the ADC.

To decode the three channel example, each of the counters is set to count up or down during the time sequences. For example, to implement the first code at $t_1$, the first counter is set to count down, and the second and third counters to count up. At the end of the integration period, each counter has an estimate of the respective color channel. This in-pixel decoding can occur at MHz rates. At a rate of 1MHz, 200 spectral channels can be acquired at a rate of 5kHz (10,000 times greater than a 100 frames/sec imager).

Mathematically, the encoded light ($g$) can be represented as a product of an encoding matrix ($W_E$) and a feature vector ($f$): $g = W_E f$, where $f$ is an Nx1 vector of the spectral channels, $W_E$ is an NxN matrix with each row corresponding to an orthogonal code, and N is the number of spectral channels. In order to recover the original spectral information, $g$ is multiplied by a decoding matrix ($W_D$): $s\hat{f} = W_D g$ such that $sI = W_E W_D$ where $I$ is the identity matrix and $s$ a scalar constant. For example, for a vector of length N, a Hadamard matrix of rank N can be used for both $W_E$ and $W_D$, and $s = N$. In practice, it is not practical to use a Hadamard matrix for $W_E$ since it is not possible to apply a negative amplitude modulation to light. Instead the S-matrix is used, which contains only binary values (0,+1) and is rank N-1. To convert a Hadamard matrix to a S-matrix: $W_E = S = (1 - H)/2$ [3].

## Technology Comparison

Table 1 summarizes a technology comparison between using a dispersive, interferometric, or time-encoded technique to acquire 256 spectral channels for a 64 km$^2$ area at 0.5m resolution at a 1Hz update rate. Using a hyperspectral system model, we estimate an SNR>250 is needed for 90% detection at a manageable false alarm rate using the adaptive coherence estimator algorithm. A radiance spectrum was calculated with MODTRAN at 5km altitude, 0.4 to 2.5um at 10nm resolution. SNR calculations were calculated assuming 10cm optical aperture, 100urad IFOV, 50% overall optical system throughput, 1000x1000 focal plane array, and detectors with 85% quantum efficiency and 1500e-/sec dark current.

Given that area coverage, SNR, and frame rate are interrelated, the dispersive line scanner can only meet the requirement for two out of these three figures of merit. In order to scan an area of 64 km$^2$ at 1Hz update rate, the per-pixel dwell time is limited to <5us which yields a SNR <10. In order to achieve better SNR, the dwell time needs to be increased. To simultaneously achieve sufficient SNR and area coverage, the update rate is reduced below mission relevance to <1mHz. In order to meet SNR and update rate, the area coverage is reduced to less than the size of a football stadium.

An interferometer has orders of magnitude increase in throughput, however the scan time is limited by the rate at which the optical path differencing mirror can move. At a maximum rate of 2000 steps/s, the minimum dwell time to acquire the full hyperspectral datacube is 128ms. It is not possible for the interferometer to meet the requirements for update rate and area coverage

because the dwell time needs to be <5ms. At 128ms dwell time, the interferometer can meet the area coverage and SNR at an update rate of <0.1 Hz or meet update rate and SNR with area coverage of <5km$^2$.

In contrast to the dispersive and interferometric approaches, the time-encoded approach is capable of imaging at 1Hz update rate, 25 km$^2$ area with SNR=400, which is greater than the modeled SNR=250. The additional margin can be used to increase the update rate to >2Hz or increase the area coverage to >100 km$^2$. In addition to the high-throughput fast scanning capability, the time-encoded approach is capable of flexible encoding and decoding, which enables multi-mode operation that can be programmed through software.

**Table 1 Hyperspectral imaging technology comparison.**

| | Grating | | | Interferometer | | | Time-encoded | | |
|---|---|---|---|---|---|---|---|---|---|
| Update Rate | 1 Hz | <1 mHz | 1Hz | 1 Hz | <0.1 Hz | 1Hz | 1Hz | >2 Hz | 1Hz |
| SNR | <10 | 250 | 250 | 0 | 2300 | 2300 | 400 | 250 | 250 |
| Area Coverage | 64 km² | 64 km² | <0.1 km² | 64 km² | 64 km² | <5 km² | 64 km² | 64 km² | >100 km² |
| Requires Precision Alignment | No | | | Yes | | | No | | |
| Macro Moving Parts | No | | | Yes | | | No | | |
| Image Post Processing | Image formatting | | | Per-pixel FFT image reconstruction | | | Image formatting | | |

# Programmable Hyperspectral Imaging

The time-encoded multiplexed approach enables flexible encoding and decoding. At the spatial light modulator, panchromatic operation can be enabled by fixing the mirrors, and hyperspectral resolution can be decreased to increase hypercube acquisition. At the DFPA, selected codes or linear combinations of codes can be decoded. This capability can be useful for decoding only spectral bands of interest or combinations of spectral bands for spectral matched filtering. For example, for 256 spectral bands approximately half are ignored due to overlap with atmospheric water absorption bands. The DFPA can selectively decode the good bands, whereas both the dispersive and interferometric methods need to measure the entire spectrum.

In FY16 using internal funding, we built a proof-of-concept prototype to demonstrate the flexible encoding and decoding in a laboratory environment. The left image in Figure 2 shows the prototype test setup, which uses commercial of the shelf (COTS) optical elements, a digital micromirror device (DMD) spatial light modulator (SLM) from Texas Instruments, and a custom MIT Lincoln Laboratory 32x32 8-channel digital focal plane array. The right image shows an image of a 1300nm LED and a 1450nm LED, both having a spectral width of 100nm. The plot shows the decoded spectrum of two pixels of the image with 10nm spectral resolution; 128 codes are used which required acquiring 16 frames, 8 codes at a time. The SLM is operating at 10kHz modulation frequency.
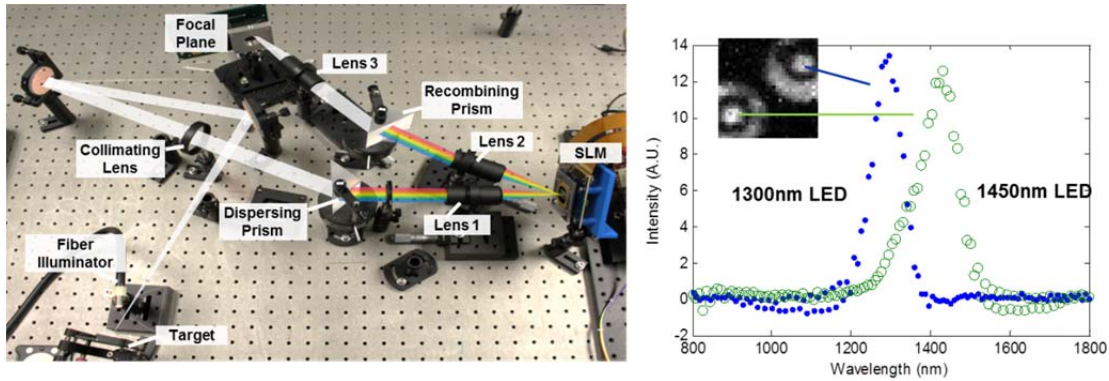
**Figure 2 Table-top proof-of-concept prototype (left) and 128 channel spectrum of two pixels from an image of two LEDs with center wavelengths of 1300nm and 1450nm (right) and FWHM of 100nm.**

Figure 3 shows the capability of flexible encoding and the tradeoff between hypercube acquisition rate and spectral resolution. In this experiment, each frame read out from the DFPA contains eight spectral channels. Since the SLM is operating at 10kHz, the total integration time is Nx100µs where N is the number of spectral channels or codes. The hypercube acquisition rate is the frame rate divided by the number of frames needed to acquire the full hypercube. For example, to acquire 128 spectral channels, sixteen frames are required where eight spectral channels are acquired per frame. Decreasing the number of spectral channels decoded increases the overall hypercube rate.
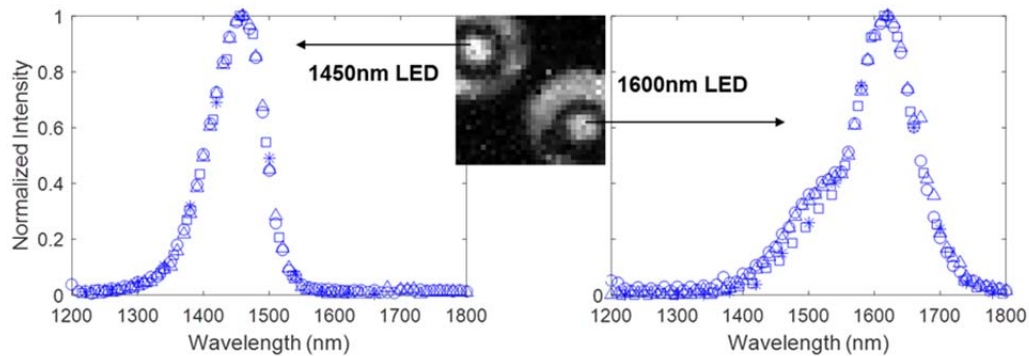


| | Codes | Frames | Frame Rate (Hz) | Hypercube Rate (Hz) | Spectral Resolution (nm) |
|---|---|---|---|---|---|
| ○ | 128 | 16 | 78 | 4.9 | 10 |
| △ | 64 | 8 | 156 | 19.5 | 10 |
| □ | 32 | 4 | 312 | 78 | 20 |
| ✳ | 16 | 2 | 625 | 312.5 | 40 |

**Figure 3 Flexible encoding enabled with a spatial light modulator.**

Figure 4 shows an example of the flexible decoding that could be enabled with a suitable DFPA. In this simulation, the DFPA decodes the top eight principal components and this data is read out in a single frame. The reconstructed spectrum shows good agreement with data acquired through fully decoding the spectrum (Figure 3). By decoding the principal components, the hypercube acquisition rate can be increased to the frame rate. For example, 64 spectral channels can be

acquired at 156 Hz instead of 19.5 Hz. Furthermore, this method can be used to implement spectral matched filtering.
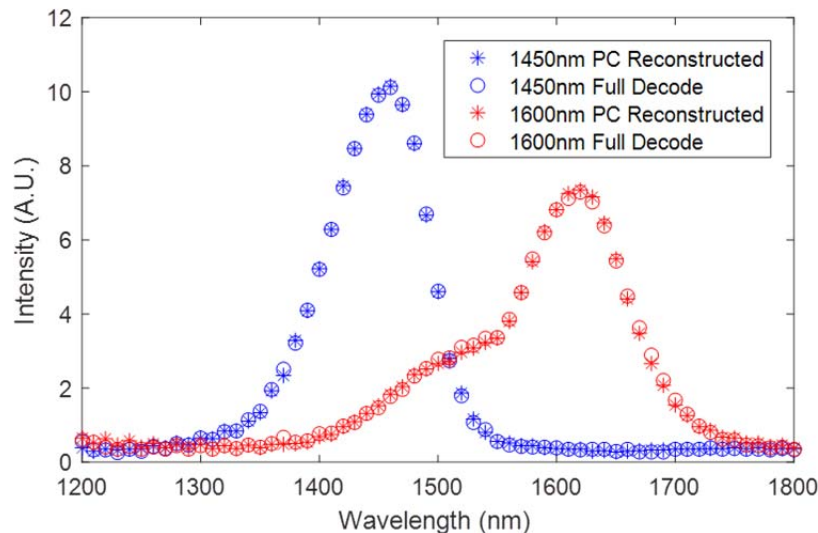


**Figure 4 Simulated decoding of principal components with the digital focal plane array.**

## Path Forward

The example used for the technology comparison was for wide-area motion imaging from an aerial platform, however the time-encoded multiplexed imaging technique is applicable to other applications involving wide area imaging such as hyperspectral imaging from a spaceborne platform. To fully realize the potential of this technology, there are still several areas in need of development. The digital focal plane array (DFPA) that was used in the tabletop proof-of-concept prototype was not designed for multiplexed imaging, and there are several modifications that can be made that can improve functionality. For example, the control of the in-pixel counters is currently global; per-column control would enable the ability to do on-chip spectral matched filtering. The new architecture of this DFPA need to be validated in a test chip and eventually scaled up to an appropriate array size. To enable wide-area scanning, a fast steering mirror needs to be synchronized to the spatial light modulator (SLM) and DFPA. Finally, a real-world demonstration is needed with data collected from realistic targets of interest.

## References

[1]     J. Blackburn, M. Mendenhall, A. Rice, P. Shelnutt, N. Soliman, and J. Vasquez, "Feature aided tracking with hyperspectral imagery," presented at the Optical Engineering + Applications, 2007, p. 66990S–66990S–12.

[2]     Schultz, Kenneth I., Michael W. Kelly, Justin J. Baker, Megan H. Blackwell, Matthew G. Brown, Curtis B. Colonero, Christopher L. David, Brian M. Tyrrell, and James R. Wey. "Digital-pixel focal plane array technology." *Lincoln Laboratory Journal* 20, no. 2 (2014): 36-51.

[3]     Harwit, Martin. *Hadamard transform optics*. Elsevier, 2012.