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PROGRAMMABLE ADAPTIVE SPECTRAL IMAGERS FOR MISSION-SPECIFIC APPLICATION IN CHEMICAL/BIOLOGICAL SENSING

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An innovative passive standoff system for the detection of chemical/biological agents is described. The spectral, temporal and spatial resolution of the data collected are all adjustable in real time, making it possible to keep the tradeoff between the sensor operating parameters at optimum at all times. The instrument contains no macro-scale moving parts and is therefore an excellent candidate for the development of a robust, compact, lightweight and low-power-consumption sensor. The design can also serve as a basis for a wide variety of spectral instruments operating in the visible, NIR, MWIR, and LWIR to be used for surveillance, process control, and biomedical applications.

Keywords: chemical/biological; spectral imaging; remote sensing.

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1. Introduction

There is a long-standing need for standoff sensors capable to detect, identify and quantify chemical and biological warfare agents and other hazardous species. Currently dominant Fourier transform infrared spectrometers (FTIR) are based on interferometry, and are therefore mechanically complex, expensive, and susceptible to mechanical disturbances. Adaptive multispectral sensors, based on mathematical transforms other than Fourier's which do not require macroscopic moving parts to provide the same spectral multiplexing capability (Felgett's advantage) as FTIR instruments is described. The technology combines a unique on-the-fly spectral adaptability with data acquisition and processing speeds high above those of its FTIR counterparts. The transition from a traditional nonimaging sensor to a multispectral imaging spectrometer is conceptually and technologically simple with adaptive multispectral sensors.

The adaptive spectrometer described in this paper produces either nonimaging, one-dimensional or two-dimensional multispectral radiance datasets ("datacube" in the case of two-dimensional spectral mapping) for gas or aerosol discrimination and classification. The spectral, temporal and spatial resolution of the data collected by the instrument are adjustable in real time, making it possible to keep the tradeoff between sensor parameters at optimum at all times. The instrument contains no macro-scale moving parts making it an excellent candidate for the development of a robust, compact, lightweight and low-power-consumption device suitable for field operation.

Potential uses of the AS include early standoff detection of chemical/biological agents. Extensive research into both passive remote chemical/biological sensors and active laser-based (LIDAR) systems has been carried out over the past several decades in government, academic and commercial research institutions.[1,2] Challenges in building a lightweight, compact and rugged standoff sensing system include the complexity of the optical system, alignment sensitivity when moving parts are involved (e.g. interferometer of a FTIR instrument) and complexity of data interpretation for the passive system, and laser tuning, energy and pulse rate requirements of the laser source in active systems.

The key innovation in passive dispersive (as opposed to interferometric) spectrometers introduced recently is the use of a programmable digital spatial light modulator (SLM) to encode spectral information.[3,4,5,6] The most advanced version of SLM currently is a reflective digital micromirror array (DMA).[7,8] The feasibility of DMA-based multiplexed spectrometers has been experimentally demonstrated recently.[9,10,11]

2. Instrument Concept

The principles of operation of the Adaptive Spectral Imager are illustrated on Fig. 1.[11,12,13] The instrument uses two polychromators (or a single polychromator in two passes) and a spatial light modulator (SLM) placed in the intermediate focal plane between them. The first polychromator disperses the image into spectral components and images them onto the SLM. The SLM spectrally encodes the image by modulating the intensity of selected spectral bands in the dispersed image. The encoded image is then spectrally recombined by the second polychromator and imaged onto a photodetector (Fig. 1).

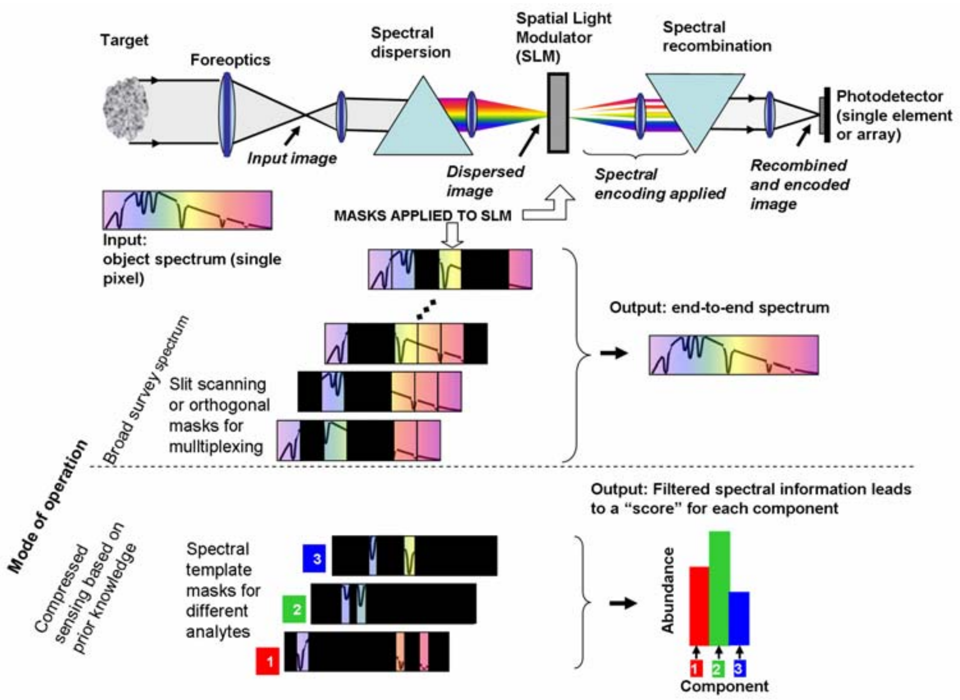

Fig. 1. Adaptive spectrograph concept: light from a standoff spectral scene is dispersed, dynamically encoded with a series of masks, and recombined on the detector.

Spectral encoding is achieved by transmission, rejection or intensity modulation of particular bands. This operation can be easily accomplished with a programmable digitally controlled two-dimensional SLM. Spectral encoding of this sort can be seen as equivalent to applying a certain mathematical transform to the spectrally resolved image. The transform can be the extraction of a value within a fixed window (spectral filter), a single sliding window (a scanning slit), a number of simultaneously applied slits conforming to the Hadamard transform in order to achieve multiplexed channel acquisition, an application-specific matched filter based on the prior knowledge about the analyte and the background, etc. In any case, the two-dimensional SLM whose pixels are individually addressable (and small relative to the resolution element) is programmed to generate a dynamic series of spatial patterns (masks) that implement the transform functions. Certain transform functions, such as matched filters, principal component analysis, and similar, can simplify data processing. Rather than indiscriminately collecting raw spectral information for post- processing, these techniques use programmable hardware to select distinctive meaningful components of the total available spectral signal and reject the spurious or information-lacking components. In this sense, the technique described performs in-hardware compressed spectral sensing. The consequences of the approach include better signal-to-noise ratio (SNR) and better economy of data acquisition, storing and processing. The latter is of no small importance for hyperspectral and multispectral imaging.

The adaptive spectrometer described here uses a DMA to spectrally encode the signal. For chemical/biological sensing, the spectrometer operates in the long wavelength infrared (LWIR) spectral range (8-12μm). A single-element detector, a linear array or a two-dimensional focal plane array (FPA) may be used to acquire the signal, leading to different functionalitities described below.

In the case of an unknown analyte and an unknown background, survey "end-to-end" spectra need to be acquired. This mode of operation is efficiently implemented with adaptive spectral imagers by using an orthogonal set of DMA masks that perform Hadamard transform of the spectrum.[14] For Hadamard transform, the DMA is programmed with a series of binary masks based on Simplex (S) matrices, where elements 0 and 1 translate into on-off modulation of individual micromirror pixels of the DMA.[3,4] Recording a *N*-channel spectrum in this way requires *N* masks based on a set of *N* matrices resulting in $N^{1/2}/2$ multiplex (Felgett's) advantage in the signal to noise ratio (SNR) relative to the simple slit-scanning approach. A Hadamard-transform spectrometer collects the light contained in approximately half of all the wavelength channels simultaneously at any point in time, thereby providing the much needed photon collection efficiency in the LWIR. The recorded images are decoded by the inverse Hadamard transform to provide the spectrum for each individual pixel (Fig. 1).

For chemical/biological detection it is common to have prior knowledge of the spectral features to be detected, at least on the part of the analyte. An adaptive spectrometer can use this information to achieve fast and sensitive detection by applying target-specific and background-specific matched-filter masks to the DMA spectral modulator. Such masks can provide analyte-specific spectral selectivity for a single column within a two-dimensional image. An adaptive spectrometer can be programmed with matched filters directly on the DMA to detect substances on which prior knowledge of spectral signatures exists. Furthermore, the spectrometer can be programmed so that successive DMA masks match different analytes to be monitored virtually simultaneously. Due to its high modulation bandwidth, the spectrometer can easily cycle through thousands of masks per second and provide rapid multi-analyte screening. Detection and identification is achieved when the integrated intensity of the signal through a given mask exceeds a threshold. The use of a single matched filter per analyte in the receiver hardware rather than time-consuming end-to-end spectrum acquisition also reduces the signal susceptibility to artifacts caused by source fluctuation or motion and vibration of the sensor platform. The data collection time per image frame is pushed to the millisecond and sub-millisecond scale with the DMA frame rate in the 10kHz-40kHz range, currently available.[15] Cycling through DMA masks at such high speed and using compressed sensing provides a critical advantage for the Adaptive Spectral Imager relative to other imaging spectrometers for applications aboard moving instrument platforms or against moving targets.

3. Instrument Design for a Passive Sensor Based on Adaptive Spectral Imager with a Two-Dimensional Focal Plane Array

Fig. 2 shows a schematic representation of an optical system for the Adaptive Imaging Spectrometer containing a core spectrograph and foreoptics. The foreoptics, which may be a standard IR camera lens or telescope, forms an image of the scene at the entrance of the core spectrograph. The spectrometer uses a novel dual-pass spectrometer design with a single concave grating to both disperse and recombine the light. We have found that we can achieve near-diffraction limited image quality with this arrangement.[16] The image delivered to the input of the spectrograph is dispersed and reimaged onto the DMA spectral modulator. The DMA consists of an array (typically 1024 x 768)[15] of addressable micromirrors. The grating subsequently also spectrally recombines the light and re-images it on a two-dimensional FPA detector.

The spatial light modulator used in our system is a modified DMA chip by Texas Instruments (DMD 0.7 XGA 12° DDR).[15] The array consists of 1024 x 768 aluminum coated individual micromirrors of 14μm x 14μm each, capable of ±12° tilt relative to the diagonal. Mirrors are individually addressable through a driver circuit available from the manufacturer. For IR applications, the original glass window needs to be replaced with an IR-transparent window. We have developed the technology to mount coated ZnSe windows on Texas Instruments DMA chips and preserve long lifetime of the chip.

Our preliminary analysis indicates that we can build an adaptive imaging spectrometer with superb imaging properties and high sensitivity towards chemical/biological agents with 180mm diameter of the primary mirror in the Offner design, with an effective F-number of F/2.8. The input field of this staring spectrometer is 8 x 8 mm in the object plane, with diffraction limited performance achieved over the entire field. This results in approximately 100 spectral resolution units and 10,000 spatial resolution units. Assuming that the image generated on the FPA fills a detector pixel, and a typical LWIR FPA sensitivity, radiometric calculations for our LWIR adaptive spectral imager suggest the signal-to-noise ratio (SNR) around 25dB per collected spectrum, high enough to characterize a distant chemical/biological agent cloud.

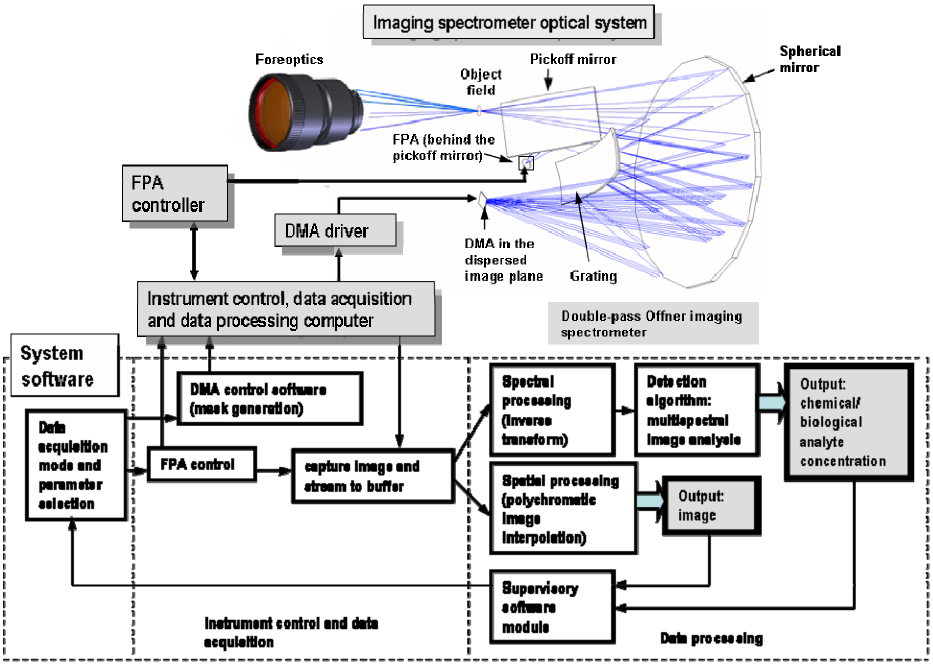

Fig. 2. System design.

The conceptual block diagram of the software package that controls the instrument, collects data, and delivers spatial and spectral information to higher-level external programs is presented on Fig. 2. The data stream captured by the FPA is routed to parallel spatial and spectral processing. The spatial image is based on the integrated intensity of all open spectral channels (about half of the total for the Hadamard transform). In order to make this image close as much as possible to the panchromatic image, additional simple processing can be applied in the form of interpolation and fitting pixel intensities. The output of this procedure is a high quality real time two-dimensional imagery.

In the case of collecting wide end-to-end spectra with the Hadamard transform-based modulation, the spectral processing software starts with pixel-by-pixel processing of the data. The reduction of Hadamard encodegrams into spectra is accomplished by applying the inverse Hadamard transform.[13] While this operation in a general case could be rather time-consuming due to the large number of matrix inversions involved, the inversion of binary square cyclic S-matrices is extremely efficient and fast (actually, orders of magnitude faster than Fast Fourier Transform (FFT) calculations). The resulting datacubes are arranged in a band-sequential format, standard for processing multispectral and hyperspectral imagery.

4. Experimental Verification

A feasibility prototype of the adaptive spectral imager has been demonstrated in the visible/near infrared 600nm – 1,050nm spectral region, and in the shortwave infrared region 1,300-1,600nm. No experimental demonstration of this instrument has yet been done in the LWIR. For the experiments described here a silicon CCD camera and a single element InGaAs detector were used, respectively. An optical system based on refractive and transmissive components was assembled for the purpose. Data acquisition and processing software was developed for the control of the DMA, capturing data from the photodetectors, and for data reduction. Spectral calibration with known input wavelength(s) produced the instrument calibration factor of 0.41nm per micromirror of the DMA array.

Fig. 3 shows a simple optical setup used to test the collection of Hadamard spectra and spectrally filtered radiation in a manner analogous to that used in a chemical-biological detection system. Note that it uses only a single detector, and relies on the programmable DMA to provide both spectral and spatial resolution. Each column of the DMA corresponds to a wavelength band, and each row of the DMA corresponds to a one-dimensional spatial element. A set of optical fibers is placed at the input to provide three unique spectral signals, which can be differentiated by selecting rows of the DMA. Fig. 4 shows the spectra of each of the fibers. The top fiber contains narrow radiation obtained from a laser diode, the bottom fiber contains light from a hot black-body lamp which is passed through a water absorption cell. The middle fiber contains lamp radiation and laser diode radiation.

Fig. 5 compares spectra and the standard deviation of the spectra (STD) obtained by Hadamard modulation spectroscopy with that obtained by scanning a slit. The spectra are identical, but the noise level is reduced in the Hadamard spectrum due to the higher light collection efficiency (multiplex advantage). In each case, the data is obtained by scanning a slit pattern on the DMA through 127 positions. In the slit-scan case, each exposure contains light from a single spectral band, while in the case of the Hadamard spectra, each exposure contains light collected from 64 spectral bands. After decoding, the Hadamard spectrum shows the expected signal to noise improvement of $(m/2)^{1/2}=6$, where m=127 is the number of resolution units in the spectrum.13

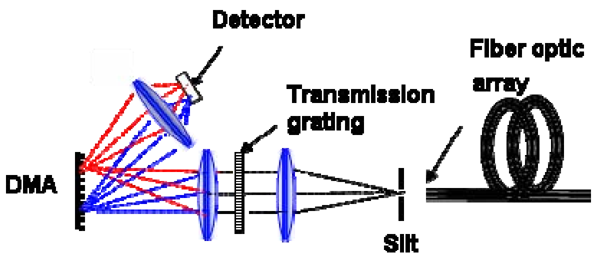

Fig. 3. Experimental setup for single-detector experiments.

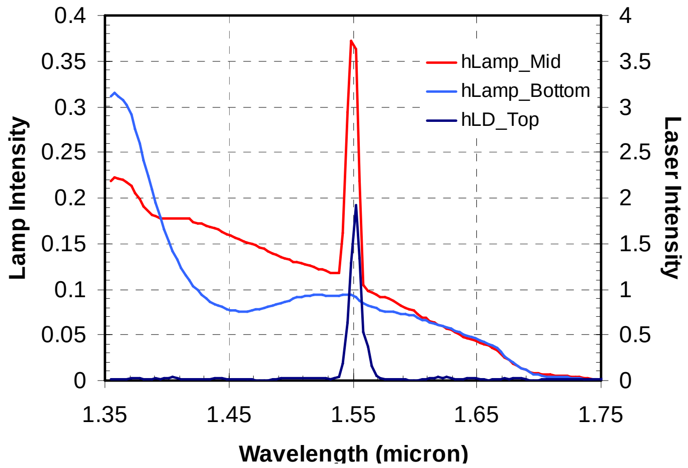

Fig. 4. Hadamard spectra of three spatial regions: top, (dark blue), middle, (red), and bottom, (light blue).

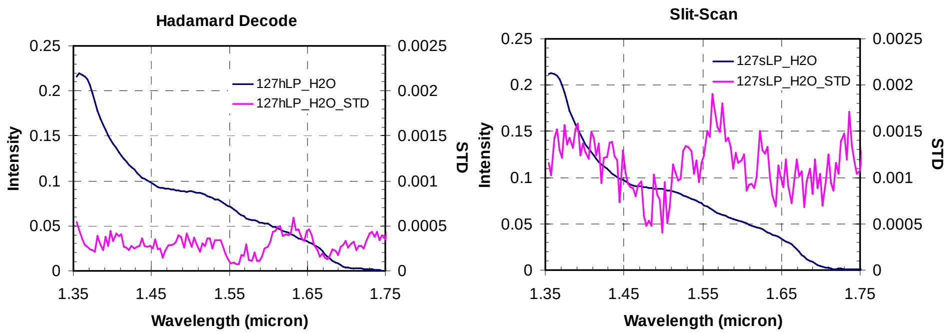

Fig. 5. Comparison of slit-scan and Hadamard spectra.

The same system was used to record temporal data from a H_2/air flame using spectral band-pass filters.[17] Fig. 6 shows water flame spectra obtained under two different flame conditions: a near stoichiometric flame and a lean flame. The spectral data match the known theoretical spectra of water. The width of the spectral band is an indicator of water temperature. Thus, we can determine the density and temperature of the water vapor within the flame using a set of three spectral bands corresponding to the center and wing of the water band, and a null band outside of the water radiation band.

Fig. 7 shows how the detected intensity in each band changes with the condition of the flame. The intensity of both the center and wing band follow the water density and temperature. The ratio of the two bands follows the water temperature. Comparing the two bands yields the column density and temperature of water as a function of fuel flow rate.

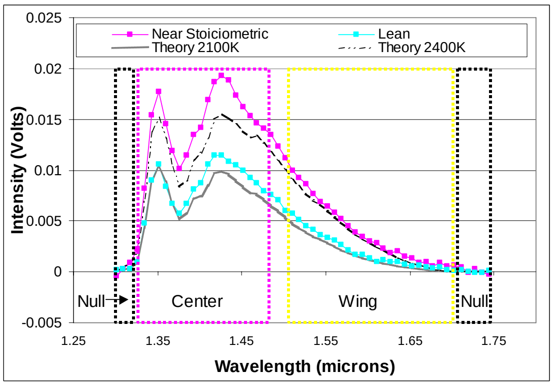

Fig. 6. Spectral of H^2/air flame showing spectral bands used for spectrally selected monitoring.

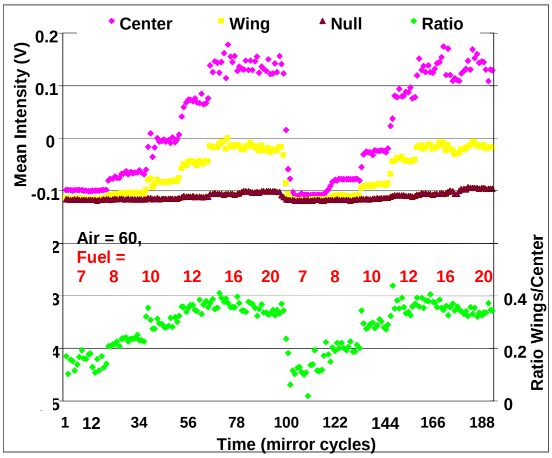

Fig. 7. Time resolved data for each spectral band.

A similar setup was used to demonstrate full two-dimensional imaging. The single detector was replaced with a second spectrograph and a CCD camera, which recorded data in the spectral range of 600-1050 nm. The imaging spectral capability of the prototype was investigated by using three blackbody objects at different temperatures placed into the instrument's field of view (Fig. 8). The blackbodies were represented by electrically heated resistors kept at constant temperature. One of the sources used (Object 1, Fig. 8) was a calibrated 1250K blackbody source. A seven-element Hadamard mask was used to produce seven-band spectra of each object with adequate spectral resolution for temperature measurement at a fast update rate. Fig. 8 shows a dynamic sequence of data collected with our adaptive spectral imager. The left-hand side shows the time sequence of spatial (spectrally combined) images, as generated after each Hadamard transform mask was applied to the DMA. Since half of all the spectral channels are open at any moment in time, and since the FPA readout is updated after every mask, the spectrally recombined image on the FPA shows a near-panchromatic view of the objects. The right-hand side of Fig. 8 shows the raw (instrument function included) Hadamard-decoded spectra of three objects, updated partially after each mask, and updated fully after each complete cycle of 7 masks. Data are scaled by an approximate instrument function, to compensate for the detector falloff at wavelengths greater than 900 nm. Fig. 9 shows the same data along with a fit to the Planck function that reveals the approximate temperature of the object. Note that the vertical (signal intensity) scale does not represent the radiance of the object, since the solid angle has not been calibrated. Based on this approach we found the approximate temperatures of the three objects to be 1400K, 1600K and 1900K (Fig. 9).

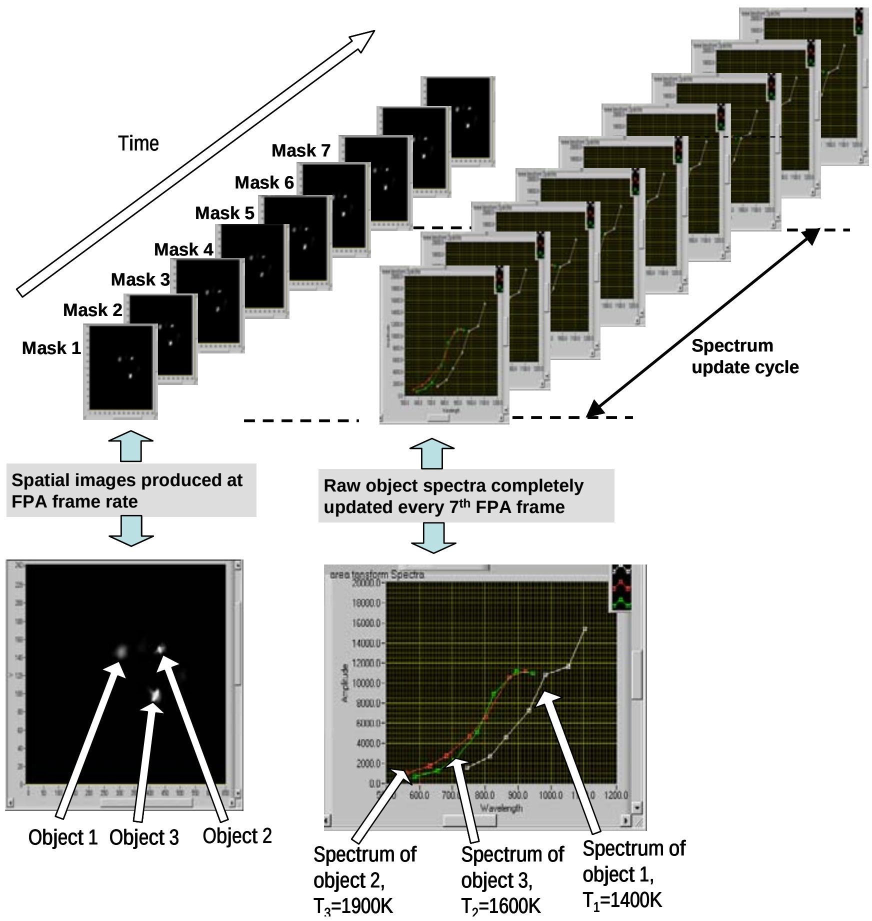

Fig. 8. Data acquisition dynamics for adaptive imaging spectrometer as demonstrated by spectral imaging objects at different temperatures within the field of view of the instrument.

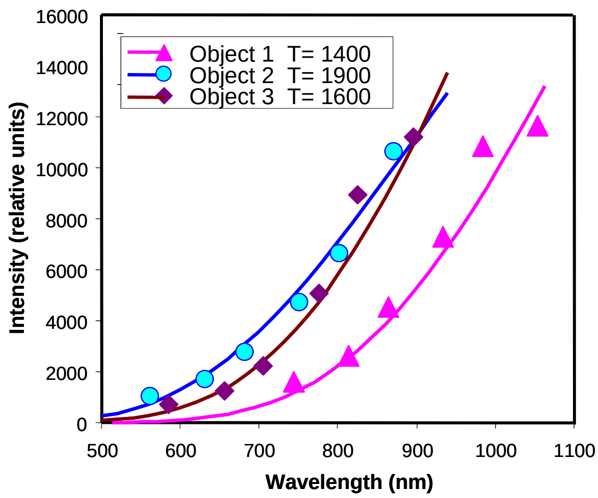

Fig. 9. The spectra of three objects in the field of view of the imaging spectrometer, together with blackbody curves fitted to the temperatures indicated.

5. Conclusions

A class of adaptive spectrometers or multispectral imagers capable of performing a variety of spectral transforms with real-time adjustment of data acquisition parameters is described. Fast adaptive spectral imagers based on this approach can greatly improve the performance of standoff chemical/biological sensors by allowing real-time optimization based on prior information, the amount and type of the information required, and the data rate. The instrument's hardware architecture appears superior to FTIR technology, since no macroscopic moving parts are needed. The technology is also applicable to spectrometers and spectral imagers in diverse areas such as surveillance, process control, and biomedical imaging, and can be adapted for use in any spectral domain from the ultraviolet (UV) to the LWIR region.

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