PERFORMANCE AND EXAMPLES OF MEASUREMENTS OF A MID INFRARED INTERFEROMETRIC HYPERSPECTRAL IMAGER

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ABSTRACT:

Spectral imagers rely mainly on two techniques for collection of spectral information: gratings and interferometers. The former type needs cooling of the optics to avoid background signals which significantly limit the dynamic range of the measurement. The latter type, in its present commercial configurations, is not suitable for pushbroom operation in an airborne situation. A recent spectral imager configuration based on a shearing interferometer has been shown to be suitable for pushbroom operation[1,2] without the need for cooling the optics[2,3]. In a previous paper[4] we have described the design of a new spectral imager for the 3-5 μ range, where the interferometer is a specially designed single prism. The advantages of this interferometer configuration are: i) compact optics, ii) high S/N ratio in the 3-5 μ range with small optical collection diameter, and iii) enhanced mechanical stability. The instrument has now been constructed and has been shown to perform very closely to the planned specifications. 320x240 pixels are in the image with a spectral resolution close to 50 cm^{-1} and an NESR (Noise Equivalent Spectral Radiance) of 2.5×10^{-9} W/(cm^2.sr.cm^{-1}). The spectrum is calibrated in units of Watt/(steradian.cm^2.μ). If used in an airborne pushbroom mode it provides a swath width of 240 pixels in a ~6.9 degree transverse field of view. If used in a horizon scanning configuration, it has a vertical field of ~6.9^0 and a horizontal field up to 300 degrees. The IFOV is 0.5 milliradians. In this paper the major performance results and some examples of measurements are given.

1. INTRODUCTION

During the last decade the field of "Hyperspectral Imaging" has grown in leaps and bounds. The number and variety of hyperspectral imagers that have been built and deployed, and the number of papers that have been published in remote sensing conferences and journals about them are very large. The reader can learn about the existing hardware and applications by referring for example to papers published in the Optical Engineering journal and SPIE conference proceedings[5,6]. In particular, references 5 and 6 carry an exhaustive list and comparison among the various technologies used for this type of instrumentation over the years. In addition, a large amount of results and knowledge on the capabilities of hyperspectral imaging has been accumulated over those years on both the airborne and space-borne applications: see for example the papers presented at the Remote Sensing SPIE conference held in Gran Canaria on 13-16 September 2004, and the OSA conference held in Alexandria, Virginia on January 31-February 3, 2005, on Hyperspectral Imaging and Sounding of the Environment. For a review of a large number of applications of spectral imaging, see reference 7. For a review of comparison of étendue in different spectral imaging designs, see reference 8.

In this paper we announce the completion of the building of the system as presented in reference 4 and we give the values of the important performance parameters as measured on the first prototype. Some examples of measurements taken with the instrument are shown including blackbody measurements and regions of atmospheric emissions in the vicinity of refineries and fertilizer production facilities in the Haifa bay.

2. THE IR PUSHBROOM CONFIGURATION (SI 5000)

As explained in reference 4, there are two basic modes of use for a fixed interferometer pushbroom type instrument using a shearing type interferometer like or similar to the one of figure 3 of reference 9: i) scanning the horizon by rotating the optical head around a nearly vertical direction, and ii) scanning a strip of earth surface by translating the optical head along with the aircraft in the flight direction.

Figure 1 shows the optical head mounted on a tripod for horizon scanning designed for 3 to 5 μ operation. Combined with a PC, special software and a stage controller, the system is called SI 5000.

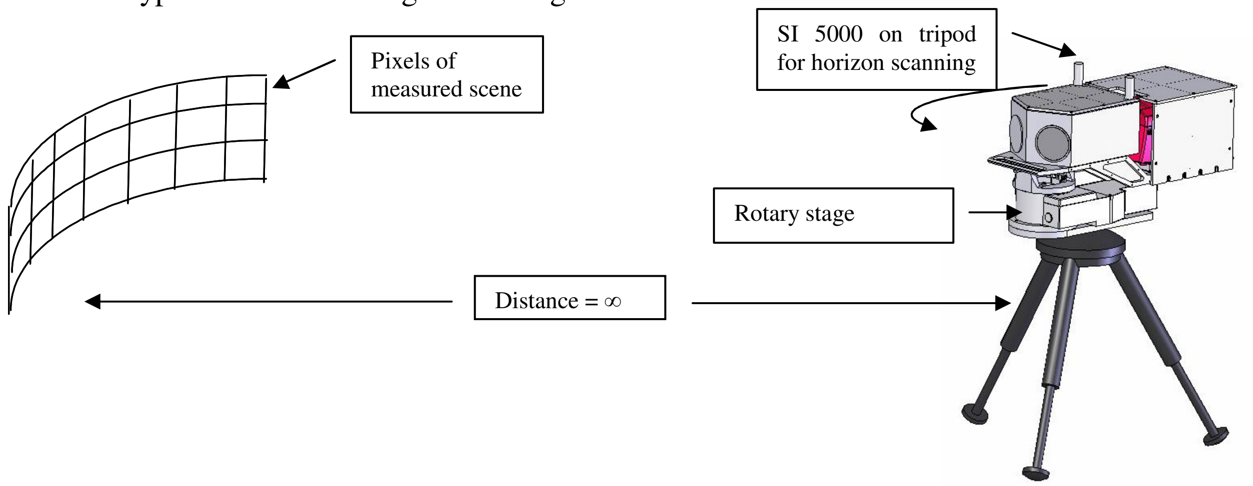

Figure 1: The SI 5000 is mounted on a horizontally rotating stage on a sturdy tripod. The instrument measures the IR self emission of each pixel of a horizon strip as function of wavelength, in a pushbroom configuration in the range 3 to 5μ. Vertical field is 6.9^0 and horizontal field is up to 300^0. The computer, stage controller and cables are not shown.

In this mode the instrument is controlled and operated by a PC and special software package with a rotation stage and stage controller for precise Field of View (FOV) scanning. The user first selects in the software the limits of FOV to be scanned in the horizontal direction (for an FOV width up to 300^0 selected for convenience reasons) and then gives a “Start measurement” command by the click of a button. The SI 5000 then captures a sequence of IR frames at precise angular intervals in synchronization with the stage movement until the whole defined FOV is scanned. These frames carry all the information which will be sorted out by the software to construct the interferograms of each pixel of the selected FOV. These interferograms are then Fourier transformed and calibrated (using a previously measured blackbody spectrum at known temperature) to yield each pixel’s intensity spectrum as function of wavelength in units of radiance. Additional software packages such as ENVI by ESRI and ITT can also be used with the system to implement further useful analysis, such as display of grey level images at different wavelengths, false color mapping according to spectral classification, statistical calculations on regions of interest, etc.

In the airborne mode the scanning for data collection is provided by the flight of the aircraft. As a result in this case the stage is not used but positioning instrumentation (GPS) and position correction software is provided to compensate for the effects of random aircraft movement.

Figure 2 shows the SI 5000 operational in a horizon scanning mode as in figure 1, acquiring spectral cubes in the region of the

Haifa bay refineries and fertilizer industry in Israel.

Figure 2: The operational SI 5000 shown mounted on a tripod (under the umbrella), and measuring the gas emissions from the Haifa refineries and fertilizer producers' smoke stacks. The author of this paper is at the system controls.

2.1 Expected performance

The instrument design as described in reference 4 is expected to give the following system performance in the 3-5 μ range:

PARAMETER	VALUE
IFOV	0.5 milliradians
Spectral range	3 to 5 μ
Spectral resolution	50 cm^{-1} or better
Number of pixels	320x240
Noise Equivalent Spectral Radiance	2.5 x 10^{-9} Watt/(cm^2.sr.cm^{-1}), at 4.8 microns and uniform blackbody source at 25C over the field of view.
Data acquisition time for $9.1x6.9^0$ FOV	~5 seconds
Working environment temperature	-10 to 40 C in the shade and no precipitation

Table 1: Performance of the SI 5000 hyperspectral imager.

2.2 Calibration in spectral radiance units

The SI 5000 is a spectral imager, sensitive in the spectral region of 3-5μ, whose output is a spectral radiance function for every pixel of the scanned region of space. The scan is done in a pushbroom fashion either by rotating or translating the optical head of the system. This radiance function is displayed in units of Watt/(sr.cm^2.μ). During the pushbroom scan an intensity function in units of volts is acquired for every pixel as function of the OPD (optical path difference) so that the radiation from that pixel goes through the interferometer. This function is then transformed into the calibrated spectrum by a mathematical algorithm. The specific mathematical algorithm which transforms the intensity curve collected in volts for each pixel of the cube into its spectrum, calibrated in units of Watt/(sr.cm^2.μ) is described in reference 4. Figure 3 shows the system being calibrated in units of radiance by measuring an extended area blackbody surface at known temperature.

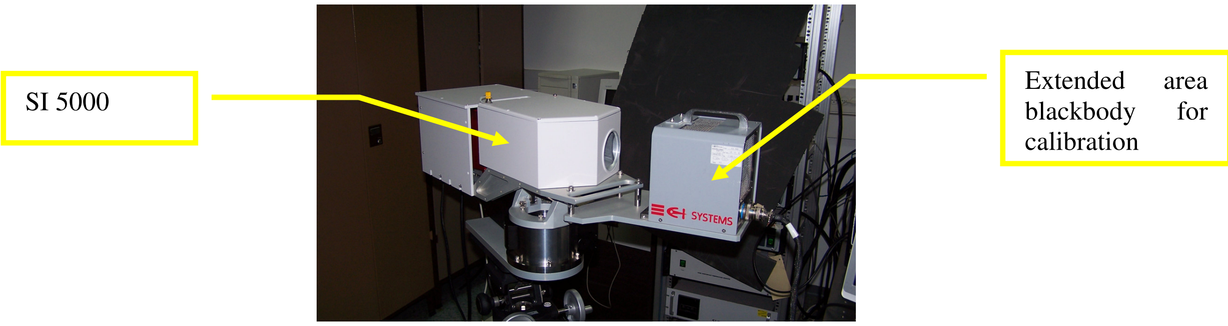

Figure 3: The SI 5000 being calibrated against an extended area blackbody source at known temperature.

3. RESULTS OF THE PRESENTLY BUILT PROTOTYPE

3.1 Spectral resolution

The instrument was originally planned to yield basically one-sided interferograms to reach larger maximum Optical Path Difference (OPD_{max}) between the two split beams in the interferometer at one side of the camera image. This requires the alignment of the collection optics (made of the objective and the relay[4]) with its optical axis rotated about 4 degrees horizontally with respect to the interferometer optical axis. As it turned out, when we tried this alignment, some spurious reflections of the internal walls of the collection optics emission by the beamsplitter cause an unwanted background in the image data. This background is avoided if these two optical axes are made to coincide. In this case the OPD_{max} reached is smaller than planned and the spectral resolution is slightly worse than planned. The average spectral resolution actually reached in this prototype is approximately 58 cm^{-1}. This value is obtained by measuring the Full Width at Half Maximum (FWHM) of the spectra of five different filters in the range of 3 to 5 microns and subtracting from them the known FWHM of the respective filters (known at much higher resolution from the manufacturer). These five values are then averaged. In order to improve this spectral resolution, in the field stop at the intermediate focal plane may be cooled with a small thermoelectric cooler: this will allow us to return to the original off-axis alignment of the collection optics with respect to the interferometer without introducing an appreciable unwanted background and recovering the higher OPD_{max} and spectral resolution. With this improvement the expected spectral resolution to be reached is estimated to be approximately 40 cm^{-1} in the whole range.

3.2 NESR

The NESR is estimated by calculating the standard deviation of the spatial variation of the spectral radiance in units of Watts/($sr.cm^2.cm^{-1}$) at 4.8 microns when measuring a uniform extended area blackbody at 25C. This measured NESR value is close to the calculated one, or 2.5 x 10^{-9} Watt/(cm^2.sr .cm^{-1}).

3.3 Examples of measurements

Figure 4 is a linearity check, showing the measured spectrum of a 50C blackbody superimposed on the 50C Planck function: the SI 5000 had been calibrated using an extended area blackbody at 30C. In general, the Planck function curve shown in the figure proves good system linearity but the signal is quite poor below 3.7 microns. Nonetheless, we expect that this signal at low wavelengths can be significantly improved by averaging over several calibration measurements. In fact, as shown in reference 4, in the resulting spectrum of equation (13) there, the calibration spectrum appears in the denominator. In a wavelength region where the values of this denominator are small and noisy the resulting measurement is expected to be also very noisy.

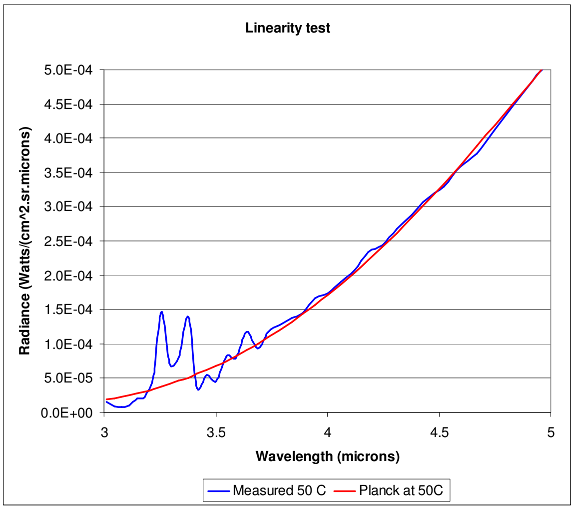

Figure 4: The Planck function at 50C is superimposed here on an extended area blackbody spectrum measured with the SI 5000, calibrated at 30C. Good agreement between the two shows a good instrument calibration accuracy and linearity. The signal below 3.7 microns is quite poor at these temperatures.

Figure 5 is a Haifa bay region as seen from the roof in figure 2 above, showing several chimneys of refineries and other industries. The image is a grey level image at 4.6 microns.

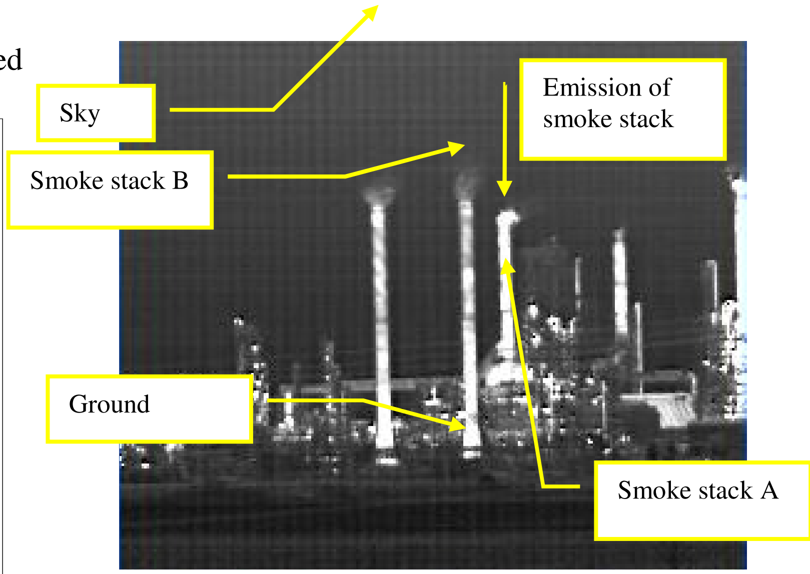

Figure 5: Chimneys of Haifa bay area in a grey level image at 4.6 microns.

Figure 6 shows the five calibrated spectra of the pixels marked on figure 5 on the same scale with some added Planck spectra for reference. The Planck spectra are multiplied by a constant 0.8 to simulate atmospheric transmittance.

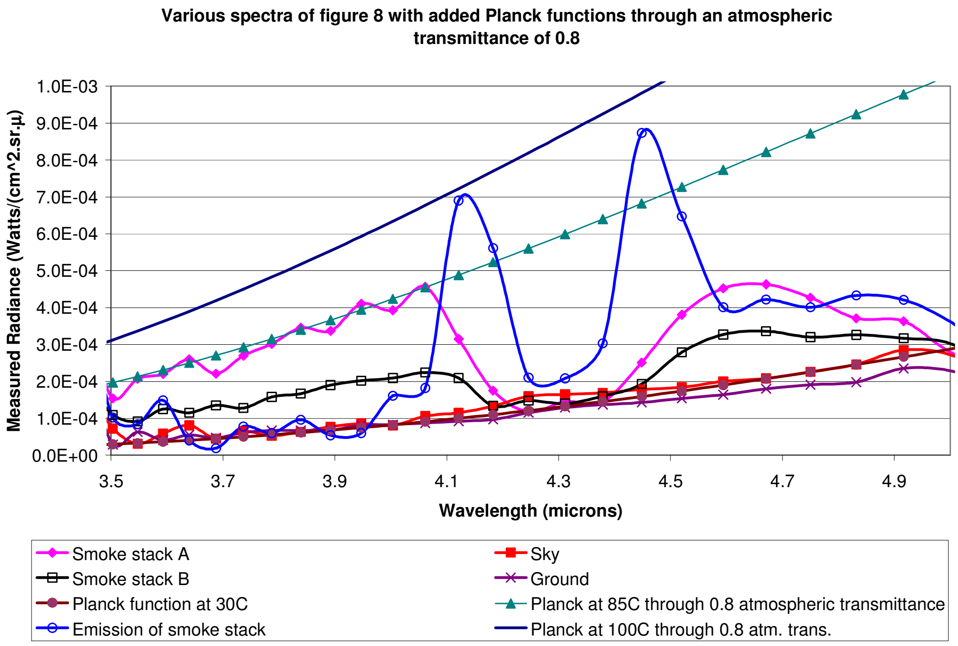

Figure 6: Five representative measured spectra of the marked pixels of figure 5 are plotted here on the same scale. Some Planck curves are plotted for reference. As can be seen from the graphs, i) the ground and sky are well fit by a 30C Planck curve, ii) the smoke stack A is well fit by a Planck function at 85C with atmospheric transmittance of 0.8 below 4.1 microns and less than 0.5 above

4.6 microns, with large CO_2 absorption at 4.3 microns, iii) smoke stack B is cooler than smoke stack A, and finally iv) the emission of smoke stack is mostly 100C CO_2 emission superimposed on a 30C sky background.

Figure 7 shows a small cloud of methane gas being blown out of a gas container: the classification is done by ENVI using a transmittance feature at about 3.3 to 3.4 microns. The measurement is from about 20 meters distance.

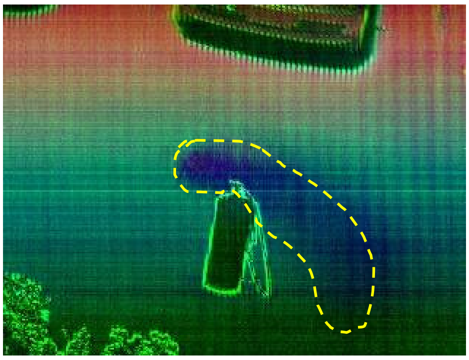

Figure 7: A methane cloud (blue, enclosed in the yellow dashed line) being detected by the SI 5000. Classification is done by ENVI using a transmittance feature at about 3.3 to 3.4 microns against the warm asphalt of the parking lot in the hot afternoon.

4. CONCLUSION

In this paper we have presented the actual performance results of a new recently completed 3 to 5 μ spectral imager, the SI 5000, which turns out to show performance very close to its design. In reference 4 we showed how an interferometric design can be used for spectral imaging in a pushbroom horizon or airborne earth surface scanning configuration. We also showed there how such system is calibrated in units of Watts/(cm^2.sr.μ). The most important characteristics are: no optics cooling and convenient system operation in a commercially available package. Here we show some examples of measurements done with the instrument, including a linearity check and several gas and smoke stacks emissions. When compared with the Planck function at different temperatures the different spectra of chimneys and their gaseous emissions can be interpreted as a sum of contributions of the chimney itself or CO_2 emission and sky background combined with atmospheric attenuation. These interpretations at this stage are conjectures derived from the shape of the spectra and have not been checked for accuracy or confirmed by more detailed analysis.

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