New airborne pushbroom spectral imager for the 3-5 and 7-12 μ wavelength ranges

Dario Cabib*, R.A. Buckwald, Moshe Lavi, Amir Gil
CI Systems (Israel) Ltd., Ramat Gavriel, Migdal Haemek 10551, Israel

ABSTRACT

A large variety of airborne spectral imagers have been designed and built in recent years for environment and earth resource mapping applications. CI has developed a new design of an infrared version of such instrument, with the following advantages: i) it is appropriate for both Mid Wave (MWIR or 3-5 μ) and Long Wave (LWIR or 8-12 μ) infrared wavelength ranges, and ii) it has no moving parts, and is especially efficient in signal collection in the MWIR, where the number of photons reaching the detector from room temperature objects is low.

In this paper we show the principle of operation of a Sagnac interferometer based spectral imager, together with the most important optical parameters used in the present design. The system is mounted on a stabilization gimbal (with higher performance in pitch) to preserve signal to noise ratio and the required spatial and spectral resolution of the measurement: stabilization control is 50 microradians in pitch, and 0.5 milliradians in yaw and roll.

The system may be most suitable for airborne monitoring of environmentally unfriendly gases, such as SO_x and NO_x industrial products.

Keywords: Fourier Transform Spectral Imaging, Fourier Transform Hyperspectral Imaging, Imaging Spectroscopy

1. INTRODUCTION

During the last decade the field of "Hyperspectral Imaging" or "Imaging Spectrometry", or "Spectral Imaging", as it is sometimes called by different people, 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 is enormous. The reader can get some background on the existing hardware and applications, by referring for example to papers published in the Optical Engineering journal and SPIE conference proceedings[1,2]. In particular, references 1 and 2 carry an exhaustive list and comparison among the various technologies used in practice 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 spaceborne 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 3. For a review of comparison of étendue in different spectral imaging designs, see reference 4.

Pioneering work in Fourier Transform hyperspectral imaging was done at CI Systems in the years 1989-1990: the work established a novel and generic method of collecting and storing hyperspectral imaging data with a design based on an interferometer, combined with collecting optics and a two-dimensional detector array suitable for the visible range. This technology was named at the time SpectraCube™: it was suitable for staring imaging, and was then dedicated to microscopy research in biology by a spin-off company of CI. In subsequent years the SpectraCube™ technology, combined with a specially developed multicolor fluorescent DNA hybridization and staining technique, was the basis for a breakthrough in the analysis of chromosome abnormalities. This scientific breakthrough (named Spectral Karyotyping, or SKY™) was published in Science magazine in 1996[5]. Many other publications by a large number of researchers in this field, followed in later years.

It turns out that with a conceptually small modification of the system (described in a later section), the same interferometric design used in the SpectraCube™, can be used in a pushbroom configuration in the infrared range, suitable for airborne and spaceborne applications. The collecting optics and interferometer must be suitable for infrared, and the infrared array is preferably cooled for high signal to noise performance. For airborne requirements, a special stabilization system must be used. In this paper we review the concept of the SpectraCube™ technology and describe its

*Tel.: 972-4-6448811, Fax: 972-4-6441052, e-mail: dario.cabib@ci-systems.com

pushbroom modification, including a specific example that can be implemented in practice. Some performance parameters of this design are also mentioned.

2. REVIEW OF THE SPECTRACUBE™ TECHNOLOGY

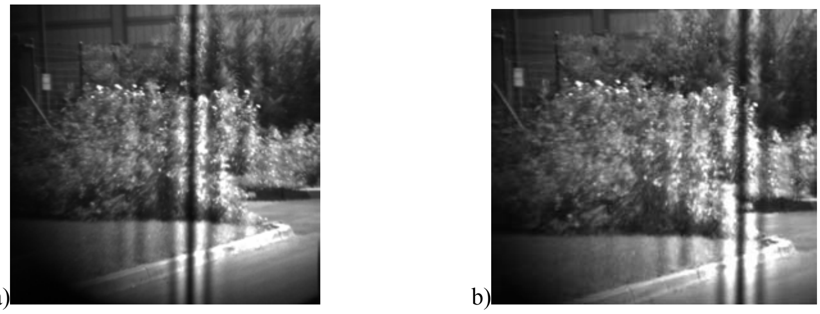
The SpectraCube™ is based on a similar design as the one described in reference 4 and is described in detail in reference 6. Figure 1 shows the SpectraCube™ combined with a fluorescence microscope for cancer genetics applications[5]. In this case the system works only in the visible range of the spectrum. The rest of the system of figure 1 is a fluorescence microscope, including special filters for excitation blocking and fluorescence detection.

Figure 1: The SpectraCube™ spectral imager, combined with a fluorescence microscope, being used for very advanced analysis and classification of genetic abnormalities in cancer genetics studies.

First the spectral cube of interferograms (one interferogram per pixel) is acquired by rotating the Sagnac interferometer around an axis parallel to the interferometer mirrors, and by storing in the memory of the computer the different images obtained from the CCD during this rotation. As the interferometer rotates, each pixel of the CCD remains the stationary image of a pixel in the FOV at all times, while the light intensity reaching it is modulated by the resulting optical path difference (OPD) scan. The instantaneous OPD depends on the interferometer position and on the horizontal position of that pixel within the Field of View (FOV) of the spectral imager. At the end of the interferometer rotational scan, the signal measured for each pixel as function of time is the interferogram corresponding to the spectrum of the pixel as function of OPD. In a second step, the interferogram of each pixel is Fourier transformed to obtain the fluorescence spectra of all the pixels of the cube. In a third step, the spectrum of each pixel is analyzed and classified according to a predetermined algorithm or look up table of stored spectra; this information is used to display the image segmented into regions of different colors. Figure 2 shows the SpectraCube™ technology, as implemented for remote sensing in an instrument called SpectraView. It is mounted on a tripod to measure the spectra of every pixel of an object in the wavelength range 400-1000 nm, and a field lens collects the light instead of the microscope. In the usual case now the illumination is from the environment, particularly sun light, so the cube is a spectral reflectance cube of the object being measured.

Figure 2: The SpectraCube™ based spectral imager (SpectraView), equipped with a telescope lens and mounted on a tripod, for remote measurements of objects in the 0.4 to 1 micron spectral range.

Figure 3 shows an example of two frames of the SpectraView, as they are seen on the computer screen of the instrument during the interferometer rotation. It is seen that vertical fringes are superimposed on the scenery of the FOV, and they are horizontally shifted, since the two frames are taken at different interferometer angular positions.

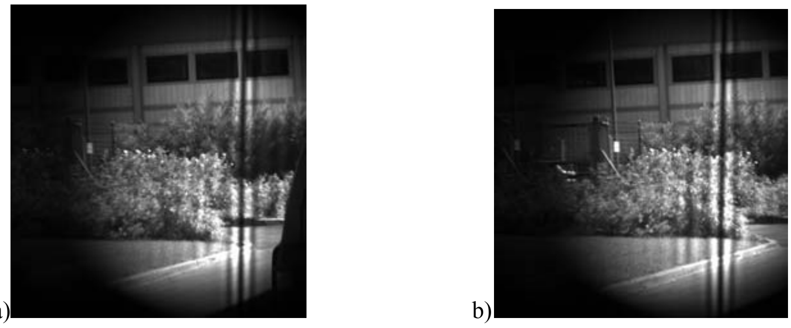


a) b)

Figure 3: a) FOV frame at the central interferometer position (the central bright fringe is the "zero OPD" fringe); b) the same FOV scene, corresponding to an interferometer off-center angular position: since the interferometer is rotated, the central fringe is not on the central pixel column.

These fringes are caused by the interferometer modulation of the radiation from the FOV. They are vertically oriented because for any interferometer angular position, the OPD between the two interferometer arms varies only in the horizontal direction: therefore, radiation from pixels on the same vertical column undergoes the same OPD. The central bright fringe is on the "zero OPD" pixels, at which all wavelengths interfere constructively. To the left of those pixels the OPD is of opposite sign as to the right of them. As the interferometer is scanned by rotation, the FOV remains stationary on the computer screen, and the fringes move with respect to the FOV to the right or to the left, depending on the direction of the interferometer scan. As mentioned above, after a complete rotational scan, all the interferograms are stored for all the pixels and all the spectra are now calculated by Fourier Transform.

Alternatively, the same interferogram information for the pixels of the FOV can be obtained if the interferometer is kept fixed and the optical head is rotated around a vertical axis (say for example by rotating the head of the tripod of figure 2 at constant speed), and the CCD frames are acquired as before. As the optical head is rotated, now the scene of the FOV moves horizontally, and the fringes remain stationary; after the head is rotated a large enough angle, the gathered information is the same. Figure 4 shows two CCD acquired images at two different optical head positions.



a) b)

Figure 4: Two CCD acquired images for two optical head angular positions, while the interferometer is stationary in the optical head. The image moves horizontally, while the fringes remain stationary. The optical head rotation is equivalent to the aircraft movement, for the purposes of this explanation.

3. THE AIRBORNE IR PUSHBROOM CONFIGURATION

As explained in reference 1, a spectral imager as in figure 1 can be classified as an "Interferometric" "Framing" type, in which the scene to be observed has the same length as the field of view of the instrument. Therefore, in this case, it is also a "staring" type. See Table 1 of reference 1, for the complete set of different types of spectral imagers.

The instrument as used in figure 4 belongs instead to the "Interferometric" "Windowing" classification of reference 1.

Suppose now that a SpectraView type instrument is mounted down-looking in an aircraft, and aligned in such a way that the fringes on the image of the FOV are perpendicular to the travel direction of the aircraft. This is a situation similar to the one described in figure 4, the only differences being that the FOV is now to nadir instead of in a horizontal direction, and the length of the measured area on the earth surface is limited only by the distance traveled by the aircraft. So, a SpectraView type instrument used in this way belongs to the "Interferometric" "Windowing" class of reference 1, like the one described in figure 4. Since in this configuration the instrument does not need a limiting slit like in dispersive systems, nor does it need a wavelength limiting filter as monochromator, the optical throughput is the largest possible, and is the reason for the highest signal achieved among all these types.

Now we will discuss the main features and challenges of a passive IR type pushbroom SpectraView type instrument for use on an aircraft. The most important challenges are: infrared sensitivity and optical Line of Sight (LOS) stability. A design of such an instrument is usually driven first and foremost by commercially available infrared detector arrays, for several reasons: export controls, cost, performance requirements, delivery times, etc. (in this order) are usually quite heavy for this type of component. As a result, any practical system solution must first be based on a viable detector array solution.

In order to give further explanations of possible IR implementations, we will refer to a specific example, based on real life situations. A typical pixel size on an infrared detector array is 50 μ, a typical aircraft altitude for measurements is 1 Km. In order for the spot spreading due to diffraction not to be larger than a detector element size, the F/no. of the collecting optics should satisfy the following condition (from Raileigh criterion):

$$F/no. < \frac{d}{2.44\lambda} \approx \frac{20}{\lambda}, \qquad (1)$$

where d is the detector size and λ is the wavelength in microns. For the wavelength ranges 3-5 (the MWIR or Mid Wavelength IR) and 7-12 μ (the LWIR or Long Wavelength IR), equation (1) gives:

$$F/no. < 5 \text{ for } \lambda = 3\text{-}5\ \mu \qquad (2)$$

$$F/no. < 2 \text{ for } \lambda = 7\text{-}12\ \mu \qquad (3)$$

For a pixel field of view (IFOV) of 1 milliradian (with a footprint on the ground of 1 meter at 1 Km. distance), a collecting optics focal length of 50 mm. is required. This means as a consequence, from equations (2) and (3), an optical collecting aperture larger than 10 mm. for 3-5 μ, and larger than 25 mm. for 7-12 μ. This small optics size results in instrument compactness and relatively low cost. The number of pixels in the array is 320 x 256, so that the total field of view in one frame is 18.3 x 14.6^0. Figure 5 shows a conceptual view of a dual band IR spectral imager according to the present design.

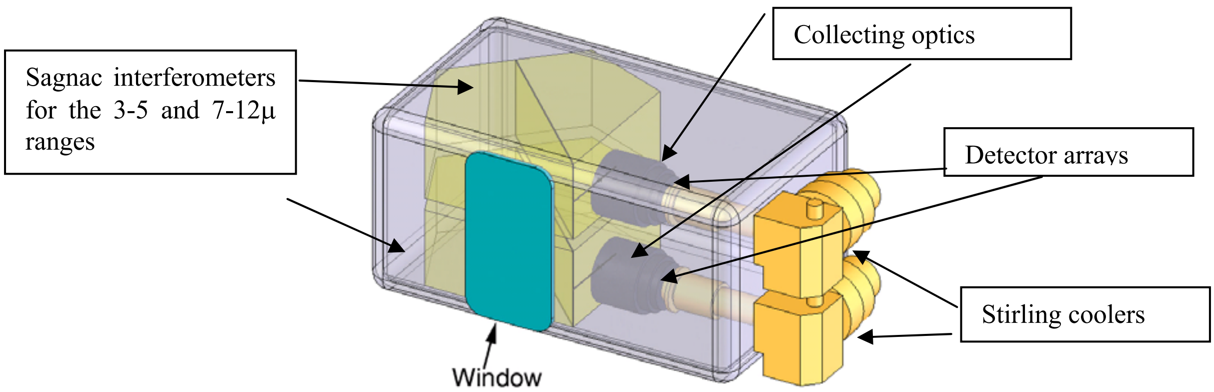


Figure 5: Conceptual view of the dual band IR spectral imager according to the present design. The small optics size and the fact that the collecting optics is made of only two units between the interferometers and the detector arrays, make the instrument especially compact and low cost.

In order to calculate the spectral resolution of the system we must remember Nyquist sampling theorem, which states that in order to avoid distortions, the sampling frequency of a signal containing a maximum frequency ν_{max}, must be at least $2.\nu_{max}$. This means that the interferometers of figure 5 must be aligned in such a way as to give at least 2 pixels per fringe at 3 and 7 μ, respectively. If aligned in such way, the number of fringes in one frame is 300/2=150 (by allowing 20 pixels for the central fringe of a one-sided interferogram) for both 3 and 7 μ: the OPD_{max} is then 450 μ at 3 μ (150x3), and 1050 μ at 7 μ (150x7), respectively. Since the spectral resolution is given by:

$$\Delta\lambda = \frac{1}{OPD_{\max}} \cdot \lambda^2(\mu), \tag{4}$$

then

$$\Delta\lambda = 0.02\mu @ 3\mu \text{, and } \Delta\lambda = 0.05\mu @ 7\mu . \tag{5}$$

This is ~<1% in both cases. Since in each range separately OPD_{max} is a constant, the resolution depends on wavelength as λ^2 (from equation 4).

Finally, we have to consider the system's mechanical stability, especially with respect to vibrations, and find the way to keep it within limits, appropriate for the required spatial and spectral resolution performance of the system. Vibrations are important for two reasons:

i) Interferometers are in general known to be sensitive to vibrations, because random movements of the interferometer optical elements affect the OPD in an uncontrolled way, thereby introducing noise in the interferogram,

ii) An aircraft has an inherent vibration regime, which may be passed on to the system and affect its signal noise ratio and resolution. In a system such as the one considered in this paper, there are two ways in which the aircraft vibrations affect resolution:

iii) By randomly changing the line of sight of the instrument, the image is blurred,

iv) By randomly changing the line of sight in the direction perpendicular to the fringes, the OPD at each pixel in each frame is blurred, and when carrying out the Fourier transform of the interferograms, the resulting spectra become more noisy and distorted, with loss of signal to noise ratio and spectral resolution.

In the present system, there are some inherent design features which eliminate or substantially reduce these deleterious vibrations effects:

The interferometer used in the system is a Sagnac interferometer, made of a monolithic block (see figure 6): this design avoids any change and misalignment in the relative positions of the beamsplitter and the two interferometer mirrors (see i) above).

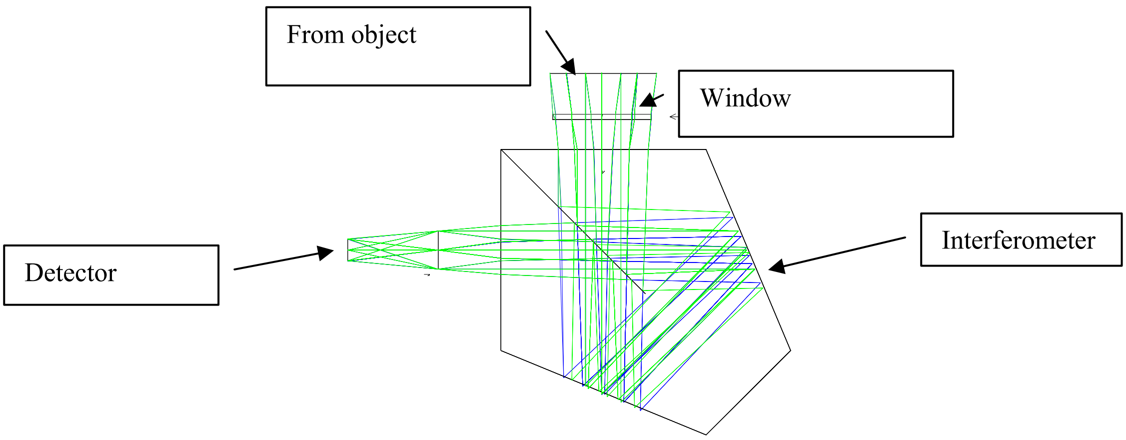


Figure 6: Monolithic interferometer design, avoiding any optical misalignment of the beamsplitter and interferometer mirrors, due to vibrations of any type.

Problems ii), iii) and iv) above are significantly reduced by mounting the spectral imager in a gyro-stabilized gimbal. The requirements on this gimbal are more severe than a standard one only in the aircraft pitch direction. This is because an uncertainty in the pitch angle causes a blurring in the OPD, which significantly affects signal to noise ratio and spectral resolution, whereas an uncertainty in the other directions only cause a small image blurring, but no significant signal noise. In order to calculate the gimbal stabilization control requirement in each direction, we carried out a mathematical simulation in which the various sources of noise due to aircraft vibration affect a known spectrum as seen by the instrument through a 1 Km. thick atmosphere in specified atmospheric conditions. We found that a 5% IFOV uncertainty in the pitch direction is the maximum tolerable, giving about 1% deviation RSS (Root Sum Square). This translates into 50 microradian stabilization in this direction. For comparison, the tolerable IFOV uncertainty in the roll and yaw directions is 500 microradians, or ten times larger. In order to satisfy this requirement, a special gimbal is supplied with the system.

4. DETECTOR ARRAY WELL FILLING AND COOLING

Since a typical scene can be assumed to be close to a blackbody at room temperature, the frame integration time of the selected detector array determines the typical number of photons reaching a detector element through the optics of the spectral imager. For typical specifications of a MWIR array: 12 million electrons at full well, 0.75 quantum efficiency, exposure time of 10 milliseconds, F# 2.5, and detector element area of 625 μ^2, we can calculate a typical well filling level of 1/2 in the brightest pixels. This shows that a typical pushbroom spectral imager based on a different design, for example a grating with a defining slit and the same detector array, would be much less efficient than a design described here, as far as well filling is concerned. In fact, such design would result in the best case in 1/2n filling, where n is the number of wavelength resolution elements. This would result in a significantly lower dynamic range.

The most sensitive IR detector arrays, InSb and HgCdTe, are cooled at liquid nitrogen temperature. This is usually done by a dedicated Stirling cooler system for each detector. However, IR emission from the internal walls of the optical enclosure may be scattered onto the detectors, and contribute to noise and spurious signals, which limit the system performance. In order to avoid these undesirable phenomena, the whole optical system is also cooled, typically to liquid nitrogen temperature. This is done by vacuum sealing the optical enclosure, built as a double wall dewar. The internal LN2 container of the dewar is filled with liquid nitrogen before the flight, so the optical elements and the internal optical enclosure are at LN2 temperature. The nitrogen is allowed to slowly evaporate, but the low temperature is satisfactorily maintained during a few hours, enough to cover the flight time, for best performance.

5. APPLICATION

As is well known[7], environmentally unfriendly gases such as SO_2 and NO_2 have absorption lines in the infrared range. Great advantage may be achieved by mapping their concentration over industrial regions, for monitoring purposes.

NO_2 bands: 750, 1617, 2898 and 2906 cm^{-1}.

SO_2 bands: 518, 1152, 1362, 2500 cm^{-1}.

6. CONCLUSIONS

In this paper we have reviewed spectral imaging technology based on interferometry, and specifically a design using a Sagnac interferometer and its advantages. The evolution of a visible staring spectral imager to an infrared pushbroom hyperspectral imager for airborne use has also been shown. Some design considerations related to diffraction limited image, achievable spectral resolution, avoidance of vibration induced loss of signal to noise ratio and photon collection efficiency, have also been discussed. One suitable application for airborne use has been proposed: mapping the concentration of environmentally unfriendly gases in the atmosphere such as SO_x and NO_x in industrial areas.

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