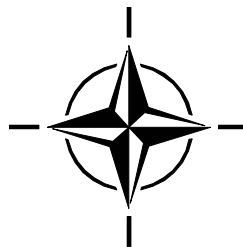**NATO OTAN**

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RTO TECHNICAL REPORT

TR-SET-065-P3

Survey of Hyperspectral and Multispectral Imaging Technologies

(Etude sur les technologies d'imagerie hyperspectrale et multispectrale)

This Report forms part of RTG-33's activities in assessing
multispectral/multiband infrared imaging systems.

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by

Fabrizio Vagni

The Research and Technology Organisation (RTO) of NATO

RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote co-operative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective co-ordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also co-ordinates RTO's co-operation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of co-operation.

The total spectrum of R&T activities is covered by the following 7 bodies:

- AVT   Applied Vehicle Technology Panel
- HFM   Human Factors and Medicine Panel
- IST   Information Systems Technology Panel
- NMSG   NATO Modelling and Simulation Group
- SAS   System Analysis and Studies Panel
- SCI   Systems Concepts and Integration Panel
- SET   Sensors and Electronics Technology Panel

These bodies are made up of national representatives as well as generally recognised 'world class' scientists. They also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

RTO builds upon earlier co-operation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

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Survey of Hyperspectral and Multispectral Imaging Technologies

(RTO-TR-SET-065-P3)

Executive Summary

Hyperspectral (HSI) and multispectral or multiband imaging (MSI) systems are powerful tools in the field of remote sensing. While HSI systems collect at least 100 spectral bands of 10 – 20 nm width, MSI sensors are systems collecting less than 20, generally non contiguous, spectral bands.

HSI systems have a very wide capability of spectral discrimination, while MSI systems are designed to support applications by providing bands that detect information in specific combinations of desirable regions of the spectrum. The number and position of bands in each system provide a unique combination of spectral information and are tailored to the requirements the sensor was designed to support.

Promising or well developed military applications of multispectral and hyperspectral technologies are:

- Gathering information about battlespace;

- Discrimination between targets and decoys;

- Defeating camouflage;

- Early warning for long range missiles and space surveillance;

- Detection of weapons of mass destruction; and

- Detection of landmines.

The paper reviews today's technologies that are applied in hyperspectral, multispectral and multiband imaging systems and lists commercially available sensors for airborne, spaceborne and ground based applications. Although not exhaustive, the survey does provide a fairly complete picture of all current and emerging technologies and deployed imaging systems. The information provided is unclassified and publicly available on the World Wide Web and in the open literature.

Most HSI and MSI systems work in a wavelength range from the visible to the infrared. This survey is dedicated to the technologies involved in the domain of the infrared, commonly divided in bands called NIR (Near Infrared, λ: 0.7 – 1.1 μm), SWIR (Short Wavelength Infrared, λ: 1.1 – 3.0 μm), MWIR (Medium Wavelength Infrared, λ: 3.0 – 5.5 μm), LWIR (Long Wavelength Infrared, λ: 7.7 – 14 μm).

This paper is part of RTG-33's (SET-065) activities in assessing multispectral/multiband infrared imaging systems. The information in this report is considered valid to a date of September 2005.

Etude sur les technologies d'imagerie hyperspectrale et multispectrale

(RTO-TR-SET-065-P3)

Synthèse

Les systèmes d'imagerie hyperspectrale (HSI) et multispectrale ou multibande (MSI) sont des outils puissants dans le domaine de la télédétection. Alors que les systèmes HSI recueillent au moins 100 bandes spectrales d'une largeur de 10 à 20 nm, les capteurs MSI sont des systèmes qui recueillent moins de 20 bandes spectrales, généralement non contiguës.

Les systèmes HSI ont une très grande capacité de discrimination spectrale alors que les systèmes MSI sont conçus pour supporter des applications en fournissant des bandes qui détectent des informations dans des combinaisons spécifiques de régions souhaitées du spectre. Le nombre de bandes et leur position dans chaque système offrent une combinaison unique d'informations spectrales et sont adaptées aux exigences pour lesquelles le capteur a été conçu.

Voici quelques applications militaires prometteuses ou bien développées de technologies multispectrales et hyperspectrales :

- Collecte d'informations du champ de bataille ;
- Discrimination entre cibles réelles et leurres ;
- Neutralisation du camouflage ;
- Alerte lointaine pour des missiles de longue portée et la surveillance de l'espace ;
- Détection d'armes de destruction de masse ;
- Détection de mines terrestres.

Ce document rappelle les technologies actuelles utilisées par des systèmes d'imagerie hyperspectrale, multispectrale et multibande et répertorie les capteurs disponibles dans le commerce pour des applications aériennes, spatiales et terrestres. Bien que cette étude ne soit pas exhaustive, elle permet néanmoins d'offrir une vue d'ensemble relativement complète de l'ensemble des technologies actuelles et émergentes ainsi que des systèmes d'imagerie déployés. Les informations fournies sont non classifiées et publiquement disponibles sur Internet ainsi que dans la documentation non classifiée.

La plupart des systèmes HSI et MSI fonctionnent dans une gamme de longueurs d'onde allant du visible à l'infrarouge. Cette étude est consacrée aux technologies utilisées dans le domaine de l'infrarouge, généralement divisé en bandes appelées NIR (proche infrarouge, λ : 0,7 à 1,1 μm), SWIR (infrarouge de courte longueur d'onde, λ : 1,1 à 3,0 μm), MWIR (infrarouge de moyenne longueur d'onde , λ : 3,0 à 5,5 μm) et LWIR (infrarouge de grande longueur d'onde, λ : 7,7 à 14 μm).

Ce document fait partie des activités du RTG-33 (SET-065) dans l'évaluation des systèmes d'imagerie multispectrale/multibande infrarouge. Les informations contenues dans ce rapport sont considérées comme valides à une date de septembre 2005.

INTRODUCTORY NOTE

In the year 2003, RTG-33 of the SET Panel initiated a technical survey on hyperspectral and multispectral/ multiband imaging systems operating in the thermal infrared. The objectives of the survey were

- To collect technical data of such imagers, whether existing, under development or planned;

- To understand the motivation for developing such imagers; and

- To collect information on performance characterization techniques used to assess these imagers.

A questionnaire entitled "Multicolor/Multiband Infrared Imager and FPA Survey" was developed to assist TG-33 in providing relevant information. Information was expected primarily from establishments and companies within NATO nations.

Although widely distributed, the response to the questionnaire was modest and no commercially or military sensitive information was provided. TG-33 decided to continue this survey on its own by collecting and assessing information available from open literature and the World Wide Web. Dr. Fabricio Vagni from Galileo Avionica, Italy, was responsible for this activity. He was assisted by other TG-33 members, especially by Dr. V.A. Hodgkin from US NVESD. TG-33 is very thankful to Dr. Vagni for conducting the survey and preparing this paper.

Chapter 1 – INTRODUCTION

Remote sensing is a natural extension of the human need to explore and understand its environment. Through advances in technologies it is now possible to extend the way we see the world to a perspective never before possible.

The ability to extract information about our world and present it in ways that our visual perception can comprehend is the ultimate goal of imaging science in remote sensing. Together with systems based on radar and laser technologies, Hyperspectral Imaging (HSI) and Multispectral Imaging (MSI) systems are the most powerful tools in the field of remote sensing.

Since the mid 1950s, some airborne sensors have recorded spectral information on the Earth surface in the wavelength region extending from 400 to 2500 nm. Starting from the early 1970s, a large number of spaceborne multispectral sensors have been launched, on board the LANDSAT, SPOT and Indian Remote Sensing (IRS) series of satellites, just to name a few.

The hyperspectral era began in the late 1970s and early 1980s, with a significant advancement when the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) was proposed to NASA in 1983. This sensor was the first to acquire image data in continuous narrow bands simultaneously in the visible to SWIR wavelength regions.

Parallel to NASA development of the AVIRIS sensor, a number of commercial ventures where hyperspectral sensors were deployed have been started. Since 1978, the Canadian company ITRES began the development of the Compact Airborne Spectrographic Imager (CASI); this sensor has been in operation since 1989 and was used not only for commercial operations in the private sector, but also for research projects. Now there are many types of HSI and MSI systems, not only on satellites or airborne platforms, but also in smaller packages, for ground based applications [1,2].

HSI and MSI systems both have the capability of producing images in which single pixels have spectral information content relevant to particulars of the scene under observation and have some common applications. However, they differ in the involved technologies, in the method of producing images and in the processing of the collected information.

The available literature contains several disparate definitions in order to give a criterion to distinguish hyperspectral sensors from multispectral ones. These definitions often include the numbers of bands, the width of each spectral band and the idea that bands are contiguous across a region rather than having numerous gaps between the bands.

A reasonable criterion, to be considered in a rather flexible way, is that an HSI system collects at least 100 spectral bands of 10-20 nm width. Because HSI sensors will only be effective in spectral regions where the atmosphere is transparent, the nature of the sensor cannot be truly contiguous and can be broken into bandwidth groupings. MSI sensors can be defined as systems collecting less than 20, generally non contiguous, spectral bands [3,4,5,6].

The basic idea involved in the HSI and MSI systems is the concept of spectral signature. In simple terms, all materials reflect, emit, transmit or absorb electromagnetic radiation based on the inherent physical structure and chemical composition of the material and the wavelength of the radiation. So, for any given material, the amount of electromagnetic radiation that is reflected, emitted, transmitted or absorbed varies with the wavelength of the radiation. If the percentage of reflectance or emissivity for a given material is plotted across a range of wavelengths, the resulting curve is referred to as the spectral signature for that material.

Because the spectral signature is different and indeed unique for each material, it should be possible to discriminate between one material and another based on differences in spectral signature of the materials.

While HSI systems have a very wide capability of spectral discrimination, MSI systems are designed to support applications by providing bands that detect information in specific combinations of desirable regions of the spectrum. The number and position of bands in each system provide a unique combination of spectral information and are tailored to the requirements the sensor was designed to support.

A good understanding of background and object spectral signatures, and their dynamic behaviour in realistic environments is essential in the interpretation of hyperspectral and multispectral imagery. Therefore the availability of good spectral libraries, i.e. collections of spectral reflectance and emissivity measured from materials of known composition, is of basic importance. Knowledge of the influence of the atmospheric conditions (temperature, pressure, humidity, haze or aerosol, wind speed and direction) and of the solar radiation is extremely important in correctly interpreting the imagery.

In fact, the ratio of the reflected to the emitted radiation from a surface changes significantly when the wavelength changes from the near infrared to the long wavelength infrared range. Moreover, a surface reflectance is strongly affected by the sun angle.

Another point that must be clarified is that the end-user of the imagery may not just be a human looking at a picture or movie. Generally, the amount of information collected by HSI and MSI systems is very large. Therefore an automated process may be performed on the imagery prior to human observation. So, the final performance of an HSI or MSI system (and the future development of these technologies) depends strongly on the quality of the processing systems (hardware and software) of the collected data.

Some HSI and MSI systems work in a wavelength range from the visible to the infrared. However, this survey is dedicated to the technologies involved in the domain of the infrared, commonly divided in bands called NIR (Near Infrared, λ: 0.7 – 1.1 μm), SWIR (Short Wavelength Infrared, λ: 1.1 – 3.0 μm), MWIR (Medium Wavelength Infrared, λ: 3.0 – 5.5 μm), LWIR (Long Wavelength Infrared, λ: 7.7 – 14 μm).

The information in this report is considered valid to a date of September 2005.

Chapter 2 – APPLICATIONS

At the beginning the multispectral and hyperspectral technologies were developed for science and research applications. The extension to the military field of the increasing capabilities of these technologies was a natural evolution. Today a number of commercial ventures are involved in the use of the multispectral and hyperspectral imagery and in the development of new kinds of applications.

Here is a list of promising or well developed fields of application of multispectral and hyperspectral technologies.

Military applications:

- Gathering information about battlespace;
- Discrimination between targets and decoys;
- Defeating camouflage;
- Early warning for long range missiles and space surveillance;
- Detection of weapons of mass destruction;
- Detection of landmines; and
- Monitoring of international treaty compliance.

Civilian applications:

- Environmental monitoring;
- Geologic mapping;
- Vegetation analysis (Agriculture, Food safety, Forestry);
- Atmospheric characterization and climate research;
- Understanding of the structure and of the functioning of ecosystems;
- Monitoring of coastal environments;
- Biological and chemical detection;
- Disaster assessment;
- Urban growth analysis; and
- Gas leak detection.

Chapter 3 – HYPERSPECTRAL TECHNOLOGIES

To understand the basic principles of HSI systems, it must be kept in mind that the data collection of these systems is a four dimensional problem, consisting of two spatial, one spectral and one time dimension. To collect HSI data cube (or hypercube, i.e. the data set with two spatial and one spectral dimension) requires either scanning (in a time interval) in the spectral or spatial domain. Commonly, for spaceborne or airborne systems using a two-dimensional detector (or focal plane array, FPA), the scan in the spatial dimension along the direction of the motion of the platform is performed through the motion of the platform itself (see Figure 1).
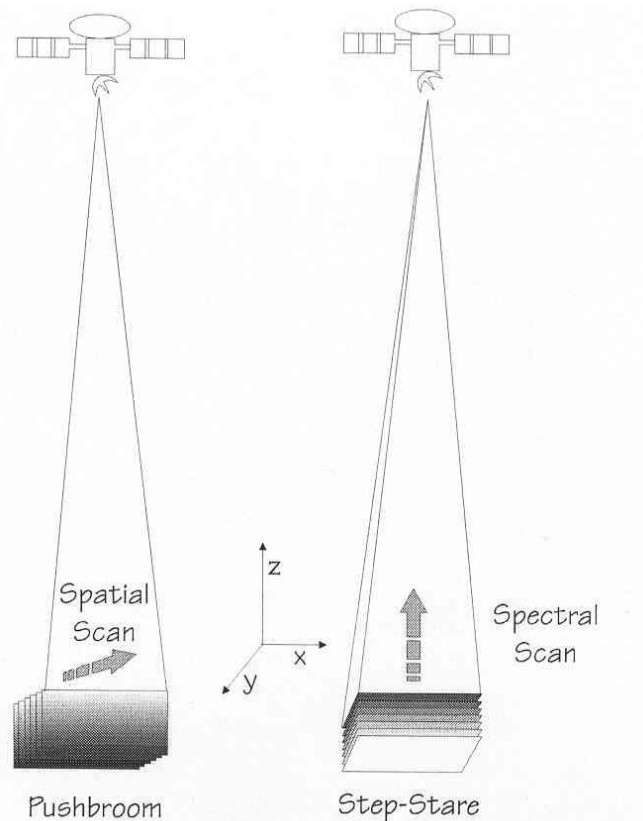
Figure 1: Hyperspectral Data Cube Collection with Scanning in Spatial or Spectral Domain.

In this technique of scan, called pushbroom, the second dimension of the detector collects simultaneously all the spectral information. A variant of this method is the whiskbroom, used when the detector of the system is a linear array. In this case an active scan mechanism is required to scan the spatial dimension orthogonal to the direction of the motion of the platform.

A different method to collect HSI is the step stare technique, in which the sensor is pointed to a fixed ground position during data cube collection then stepped to the next ground position for the next data cube. This type of method requires a gimbaled platform or a step stare mirror. In this case the (two-dimensional) detector acquires simultaneously the two spatial dimensions of the data cube and the spectral information in a time interval.

The main difference is that in the pushbroom scanning system the speed of the platform determines the dwell time for each pixel, while for the step stare system the dwell time is not controlled by the speed of

the platform, but is controlled by the length of the time the platform has a line of sight to the ground target. It is apparent that the whiskbroom technique has the least favourable dwell time.

The advantage of the step stare method is that it is possible to get, with respect to the pushbroom, longer integration time and greater signal to noise ratio.

As noted before, hand held or ground based hyperspectral systems are now in use. Their image gathering process is generally the step stare technique and the spectral information is acquired in a time interval. Or they may use a scanning mirror to recover the second spatial dimension information.

In the most schematic approach, an HSI (and MSI) system is generally composed of a lens for the collection of the radiation and of a focal plane array for the detection of the radiation: between them is interposed a device for the spectral division or selection of the incoming radiation.

There are many different types of devices for the spectral division or selection, suitable for different applications, and they can be divided in three main classes [6,7,8,9,10]:

- Dispersive spectrometers;
- Fourier Transform interferometers; and
- Narrow band adaptive filters.

Reported below are the most common present and emerging solutions for the production of these devices.

3.1 DISPERSIVE SPECTROMETERS

Dispersive imaging is the technology that was first applied to spectral imaging instruments and has been deployed both on high altitude and spaceborne platforms for many years. For a dispersive imaging spectrometer some means of dispersing the input radiation such as a grating or prism is used. By coupling the dispersing grating or prism with a two-dimensional array of detectors, a spectral image is formed such the spatial information is along one axis and spectral information is along the other(see Figure 2).
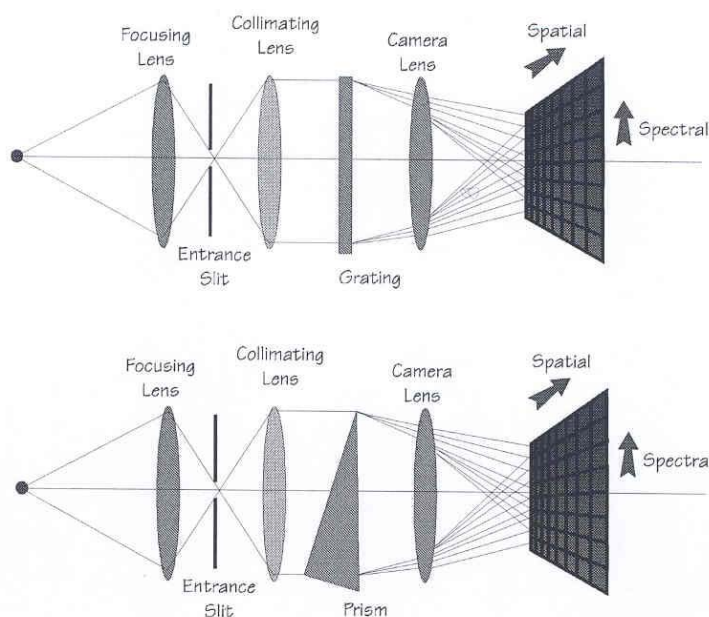

Figure 2: Grating and Prism Dispersive Imaging Spectrometer.

A typical prism or grating imaging spectrometer has input optics to focus the radiation on a slit, a collimating optic to bring parallel rays to the dispersing element, and then a focusing optic to focus the dispersed radiation on the detector array. Each detector in the array acts as the exit slit. Careful matching of the detector size and the entrance slit is necessary for optimum performance [7,8,10,11,12].

The resolving power of the prism spectrometer is proportional to the dimension of the base of the prism and to the ratio of change in refraction index with a change in wavelength. The larger the prism and the higher the dispersion of the material the finer the spectral resolving power. The disadvantage is that materials with high dispersion also have high absorption which produces as a consequence a reduction of the throughput of the system.

In a grating spectrometer the prism is replaced by either a transmissive or reflective grating. Gratings can be made to have optical power and blazed to improve the performance for a certain order of interference and for a specific wavelength region. The spectral resolution of a grating is proportional to the order and to the number of lines in the grating and is constant on the image plane for a constant incident angle of the radiation.

Generally, a prism has the advantage of uniformly high efficiency and low scatter, but optical designs based on prisms tend to be considerably more complex than their grating-based counterparts. Gratings permit the realization of all-reflective optical systems and peak efficiencies of about 85% are now achieved and the level of scatter is comparable to the level of non perfect coatings on prism surfaces.

There are two grating forms of interest, both formed on spherical substrates. The first form is the convex grating type utilized in the Offner spectrometer and its derivatives. Gratings of this type tend to be small, typically 1" in diameter.

The second form is the concave grating utilized in the Dyson spectrometer. In this case, the grating is the largest element of the spectrometer, and it can have a diameter of 3 – 4". The size difference between the two forms requires, at the present, different technologies for grating production. At this time electron-beam technology is the best choice for the convex grating production for the Offner spectrometer (see Figure 3). For larger gratings as used in the Dyson spectrometer the holographic method is preferred.
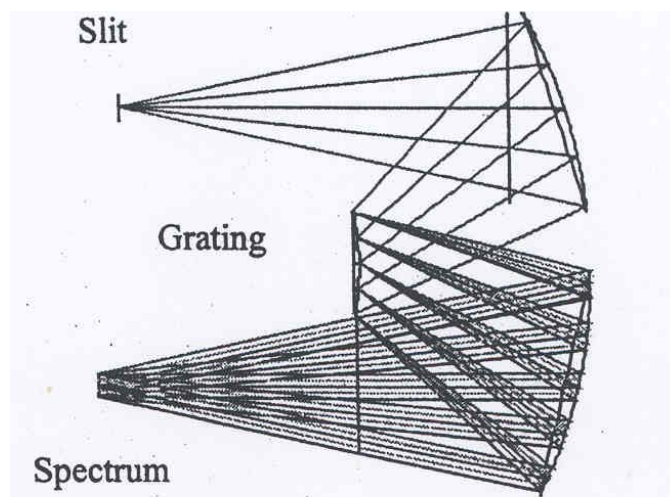

Figure 3: Offner Interferometer.

The progress in electron-beam technology has permitted fabrication of the required high performance convex gratings for the relatively difficult design of the Offner spectrometer. These gratings, due to the

all-reflective surfaces involved, can satisfy the stringent requirements of imaging spectroscopy over a broad spectral band from UV to thermal IR, with the spectral and spatial distortion reduced to a small fraction (about 1%) of a pixel.

The advantages of the Offner spectrometer are that it operates with a relatively low F-number ($\geq$f/2), it accepts a long slit while maintaining a compact size, it needs only three optical surfaces and it utilizes only spherical and centred surfaces [8,10].

It has been designed also an imaging spectrograph which associates in single optical package both the dispersing elements prism and grating. To be more precise the system Prism-Grating-Prism (PGP, see Figure 4) is composed of a specially designed volume transmission grating cemented between two almost identical prisms.
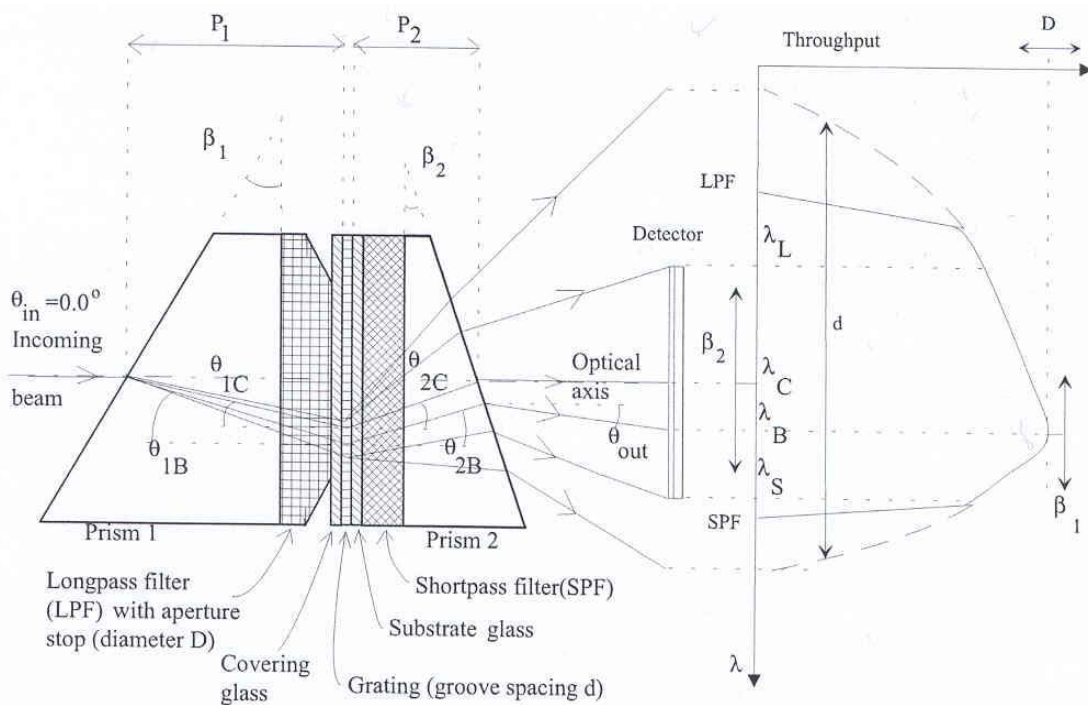

Figure 4: Prism-Grating-Prism Imaging Spectrograph.

Short and longpass filters are typically placed between the grating and the prisms, cutting off unwanted wavebands and changing the spectral response. The geometrical configuration of the prisms is such that the exit optical axis of the centre wavelength of the working (dispersed) wavelength range is parallel and centred with respect to the optical axis of the front lens collecting the broadband radiation and of the subsequent collimating lens.

So, the direct vision property, a straight optical axis of the overall system, is the most important characteristic of the PGP solution, which allows an extremely compact size of the complete spectrograph. Also in this case the two-dimensional detector collects in one direction the spatial and in the other direction the spectral information. When used on airborne platforms it requires the pushbroom imaging mode of operation.

The PGP spectrograph has been developed for different applications and with different wavelength ranges from about 320 nm to 2700 nm [8].

A recent evolution of the dispersive techniques in imaging spectrometers applications is the Image Multi-Spectral Sensing (IMSS) technology, developed and patented by Pacific Advanced Technology since 1992.The IMSS is based on the principle of diffractive optics; as such it is a combination of a diffractive imaging spectrometer and an adaptive tunable filter. Using a single lens, which is a circular blazed grating, IMSS performs both imaging and dispersion (see Figure 5). This solution enables a very small, lightweight and robust imaging spectrometer.
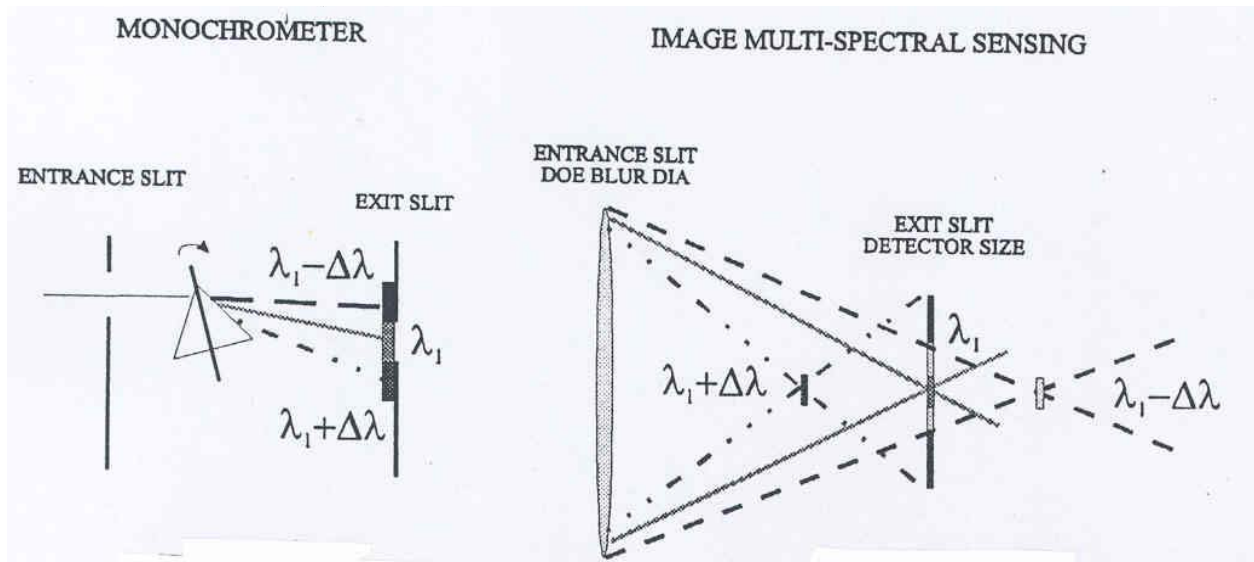

Figure 5: Basic Principle of the IMSS.

In the IMSS design the diffractive optical element disperses the light along its optical axis and the lens-detector array distance is scanned (around the medium focal length of the lens for a given wavelength range) to produce images of different colours.

The design of the lens is such that the depth of spectral focus is very shallow, so that spectral defocus takes place rapidly as the lens-detector distance is changed. In this way, for a given lens-detector distance, the image at one only wavelength (with a determinate $\Delta\lambda$) is in focus. Using suitable image processing algorithms (implemented in real time) the out-of-focus images are rejected and only the in focus component is retained.

The advantage of the IMSS design over a conventional dispersive spectrometer is that the entire input aperture collects the light as opposed to the narrow entrance slit and the throughput of the system is considerably higher than a conventional dispersive system. Moreover, the IMSS spectrometer collects spectral images in a spectral sequential mode; each frame of the camera is a spectral colour and subsequent frames can be different colours if the lens of the system is scanned along the optical axis. Or, subsequent frames can be the same colour; in this way the IMSS spectrometer is extremely adaptive and can collect only those spectral bands of interest and can dwell at a single spectral band indefinitely. The IMSS technology can be used from the ultraviolet to the far infrared wavelength range.

A point to be considered is that when changing the lens-detector distance, the effective focal length of the system changes and consequently the f-number and the magnification as a function of the wavelength. This can be compensated for by either increasing the complexity of the optical system with a zoom lens to compensate for magnification change or by re-mapping the images into the field of view of the image with highest magnification [7,13].

3.2   FOURIER TRANSFORM INTERFEROMETERS

Michelson interferometers have been in use since 1880. However, practical Fourier Transform spectroscopy began only in the early 1950s. It had a great development starting from 1965, with the introduction of the "fast" Fourier Transform and in coincidence of the first advances of the primitive electronic computers. These factors made reasonably short computation time for the Fourier Transform. Today, commercial Fourier Transform spectrometers are widely available and are common laboratory instruments, aided by fast computers which perform the algorithm in a flash.

The current Imaging Fourier Transform Spectrometers are based on two interferometer designs, Michelson or Sagnac (see Figure 6).
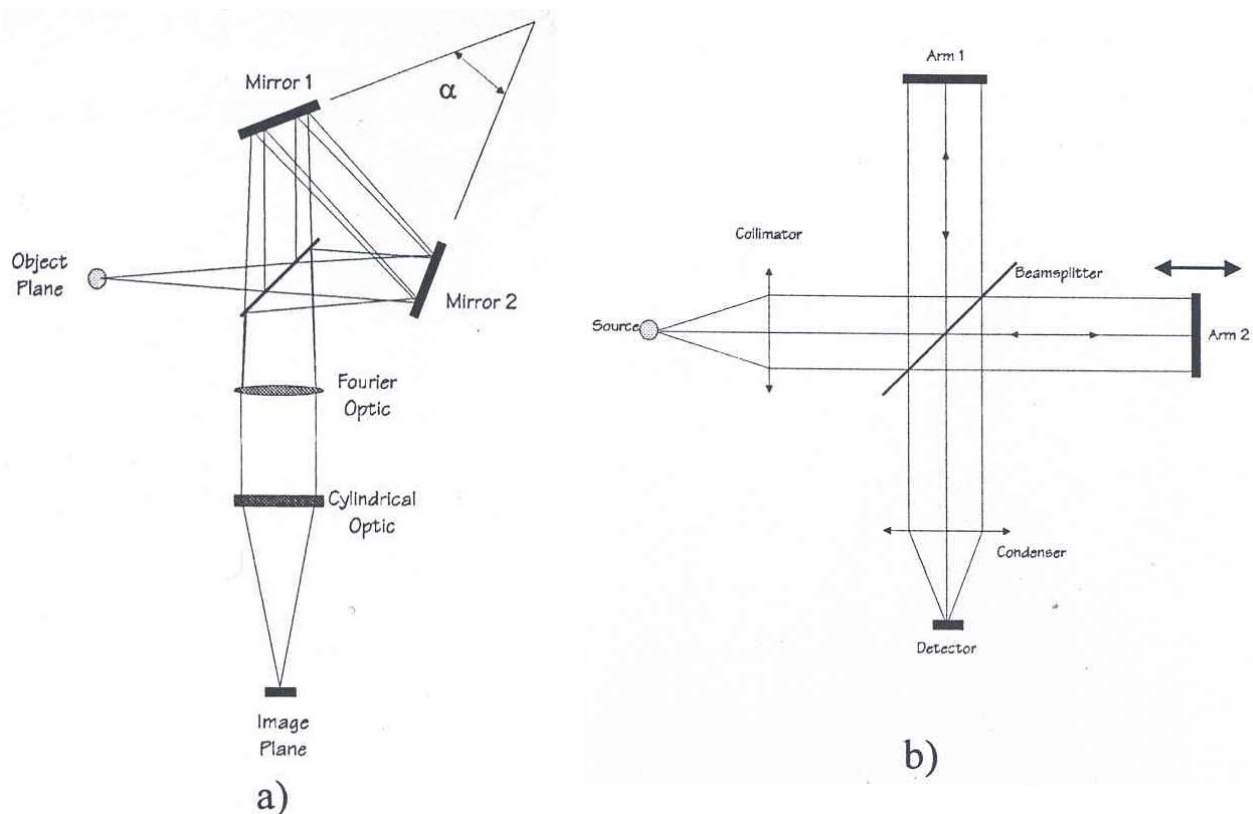

Figure 6: Optical Scheme of Sagnac (a) and Michelson (b) Imaging Spectrometer.

The common principle of these two interferometers consists in splitting the radiation from a source into two beams, introducing a controlled phase shift, and recombining them.

The wavefronts of the beams on recombination interfere by the principle of superposition. The combined beam is focused on a detector. The intensity of the light is modulated by the path difference of the two beams. The amplitude of the signal is sampled at an appropriate sample rate during the acquisition, and a Fourier Transform converts the amplitude modulated signal into a frequency spectrum.

In both types of spectrometer the division of the incoming radiation is performed through the use of a beamsplitter (a partially reflecting/ transmitting surface typically 50% / 50%). After separation the two wavetrains travel on two paths orthogonal to each other and they are reflected back by two flat mirrors for the recombination.

The main difference between the two designs is that in the Michelson spectrometer the two mirrors are orthogonal to the optical path of the respective wavetrains and the phase shift between them is introduced by moving (generally) one mirror back and forth along the optical path. In the Sagnac spectrometer the two mirrors are not orthogonal to the optical path of the respective wavetrains, but they have a fixed angle (< 90°) between them, a fixed position (no moving parts) and identical distances from the beamsplitter. The reflected and transmitted rays follow exactly the same path, but in opposite directions. In this type of spectrometer the fundamental component is the beamsplitter, which provides phase shift between the two coherent interfering rays so that the optical path difference changes linearly with variation of the angle of the entering ray with respect to the instrument optical axis.

When fabricated without moving components, the Sagnac spectrometer has relatively low resolution, but good mechanical stability and compactness. The lack of moving parts significantly reduces the sensitivity to vibrations as opposed to the moving mirror of the Michelson spectrometer. The disadvantage of the Sagnac compared to the Michelson is that spatial information is obtained in only one dimension and (generally) a combination of spherical and cylindrical optics is necessary. The second spatial dimension can be recovered by a field scanning mirror or a moving platform.

Thus with a Sagnac spectrometer the spectral information is collected in one direction and the spatial information is imaged perpendicular to that direction. A Sagnac Fourier Transform spectrometer is analogous to a dispersive spectrometer in that the spectral information is dispersed in one direction and the spatial information is collected in a single line in the perpendicular direction. The only difference is that the dispersive spectrometer measures the wavelength of the light directly and does not need the additional step of taking a Fourier Transform as does the Sagnac spectrometer.

The Michelson spectrometer, on the other hand, can be configured to allow imaging in two dimensions. It has a pixel based interferogram which when Fourier transformed gives spectral information for each pixel. However, in a Michelson spectrometer the spectrum is built up in a time interval (the time it takes to translate the moving mirror through the bandpass, or free spectral range of interest). Unlike the Sagnac spectrometer there is a trade-off between temporal and spectral resolution. The finer the spectral resolution the longer it takes to collect the interferogram and the lower the temporal resolution, however, the higher the signal to noise [7].

3.3   NARROW BAND TUNABLE FILTERS

Many of the emerging technologies developed for the HSI systems are based upon narrow band tunable filters. They have the characteristic to pass radiation through a very narrow bandpass, or spectral bin, and this can be spectrally tuned over a wide spectral range, usually in a very short time. Most HSI system based on this technologies work in step stare mode. Circular variable filters, Linear variable filters, acousto-optical tunable filters, liquid crystal tunable filters, and tuned etalons are examples of these new technologies.

3.3.1   Circular and Linear Variable Filters

Circular and Linear variable filters are interference filters that are deposited either on circular substrates, in which the transmitted wavelength changes linearly with the angular position of the substrate or on substrates in which the transmitted wavelength changes linearly with their linear position. The transmission is about 25 – 30 %.

In the case of a circular filter, a two-dimensional detector is placed (of course behind it) at a constant radius from the centre of the filter. The integration and readout of the detector is synchronized with the rotational rate of the circular filter. The detector is operated in such a way that a single band of the filter

follows the read out of each line. As the filter moves on the detector, the spectral bin covering the first line moves to the second line as that line is read out and so on. After that spectral bin has passed the full length of the detector, then the next spectral bin comes into the field of view with the first line and the operation starts over again.

The number of spectral bins is determined by the size of the circular filter and the size of the detector. For the same size of the circular filter, increasing the size of the detector will result in fewer spectral bins.

The main advantages of circular and linear variable filters are the simplicity of the optical design and the exiguity of the signal processing required.

This technology can cover the entire spectrum from the visible to the far infrared [7].

3.3.2   Acousto-Optical Tunable Filters

Basically, an acousto-optical tunable filter (AOTF) is an all-solid state electronic dispersive device which is based on the diffraction of the light in a crystal. Light is diffracted by an acoustic wave because an acoustic wave propagating in a transparent material produces a periodic modulation of the refraction index, due to photo-elastic properties of a crystal. A transmission grating can be created in a crystal by the alternating planes of compression and rarefaction produced by a travelling ultrasonic wave. The grating constant is equal to the wavelength of the sound wave in the crystal and can easily be changed by a change in frequency of the acoustic wave. So, by this technology it is possible to get an electronically tunable optical filter, with no moving parts, and which allows a very fast frequency tuning from the ultraviolet to the long wave infrared.

Generally, an AOTF is composed of an anisotropic crystal and of a piezoelectric transducer bonded to it. A radio frequency signal is applied to the transducer which, in turn, generates an acoustic wave propagating through the crystal. These propagating acoustic waves produce a periodic moving grating which diffracts the incident light beam. When broad band light is incident on the filter, it passes only a selected number of narrow bands corresponding to the applied radio frequencies. Wavelength tuning can be performed sequentially or randomly; this filtering action is notable in that a multiplicity of wavelengths may be selected simultaneously.

Several different configurations can be adopted in order to utilize the AOTFs in imaging spectrometers: the acoustic wave can be almost orthogonal to the input light beam or parallel to it and, generally, polarizers are introduced in the optical path to separate the output diffracted beam from the transmitted beam.

It must be noted that the strength of a diffracted beam (i.e. diffraction efficiency) is proportional to the strength of the acoustic beam. By controlling the strength of the acoustic beam the output intensity of the AOTF can be controlled. However, care must be used in avoiding heating of the crystal which can affect the collected spectral information.

Depending on spectral region to be analysed, different birefringent crystals are used to fabricate AOTFs. Quartz is frequently used in UV and visible region: it has good transparency in this region, but relatively low acoustic figure of merit (the ability to couple acoustic wave to the crystal). In the infrared region TeO2 crystal (0.35 – 5.0 μm) and Tl3AsSe3 (also known as TAS; 1.0 – 16 μm) are used; due to their much higher (with respect to quartz, 800 and 900 times) acoustic figure of merit. These two crystals require lower power of applied radio frequency signal.

The advantages of the AOTF are the short response time (typically microseconds) and the consequent very fast spectral band selection, the absence of moving parts, the compactness and a wide angular aperture.

The disadvantages are that the full spectral range is limited by the angular aperture (the larger the angular aperture the smaller the full spectral range), the possible heating of the crystal (with consequent shift of the diffracted wavelength) due to the radio frequency applied and a relatively complex optical design [5,14].

3.3.3 Liquid Crystal Tunable Filters

A liquid crystal tunable filter (LCTF) is an optical filter in which the centre wavelength of the narrow bandpass can be tuned by changing the voltage that is applied onto the filter. More in particular, it is based on a Lyot filter, which is a sandwich of birefringent liquid crystal, glass, quartz placed between two polarizers whose surfaces are parallel to each other (see Figure 7).
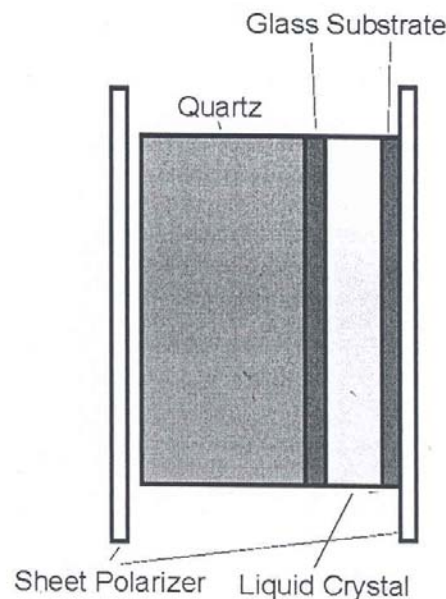

Figure 7: Scheme of a Single Lyot Stage of a Liquid Crystal Tunable Filter.

The input polarizer converts incoming unpolarized light into linearly polarized light. The polarized light then passes through the birefringent crystal where it is split into ordinary and extraordinary beams. The birefringent crystal also introduces phase delay between the two beams (and hence, it is called retarder). The birefringence $b = n_e - n_o$ (n_e, n_o are refraction indices of extraordinary and ordinary beams) leads to a time delay $\Delta t = bd/c$ where d is the thickness of the birefringent element and c is the speed of light in vacuum. Retardance R in angular units (phase difference) is expressed as $R = 2\pi bd/\lambda$ (where λ is wavelength). The intensity of the transmitted beam is proportional to the transfer function $T = \cos^2(\pi bd/\lambda)$. As a consequence, only light with a certain wavelength can be transmitted. Specifically, light with wavelength for which $bd = n\lambda$ (n integer) will have the greatest transmittance while the light for which $bd = m\lambda/2$ (m odd integer) will be extinguished. The liquid crystal plate is essentially the electrically variable retardance element in the sandwich composed of quartz, glass, polarizers and liquid crystal itself. To achieve the desired wavelength resolution in LCTF a series of these sandwiches are stacked in cascade, with relative thickness in precise proportions. The filters can be tuned to provide serial or random access through the wavelength range in time of the order of milliseconds.

Because of the limited availability of materials which possess electro-optic properties necessary for construction of LCTFs, the longest wavelength which currently available LCTFs can be spectrally tuned is 1700nm; typically a NIR LCTF can be tuned from 1000 to 1700 nm.

LCTFs have relatively large acceptance angle and apertures, good compactness, simplicity of driving and no moving parts; while the small tuning range is a limiting characteristic [5,14,15].

3.3.4   Tuned Etalon

The Fabry Perot etalon is the base of tuned etalon spectral imagers. The etalon is the core element of the Fabry Perot interferometer and is basically composed of two plane parallel partially reflecting surfaces with a given spacing between them (see Figure 8).
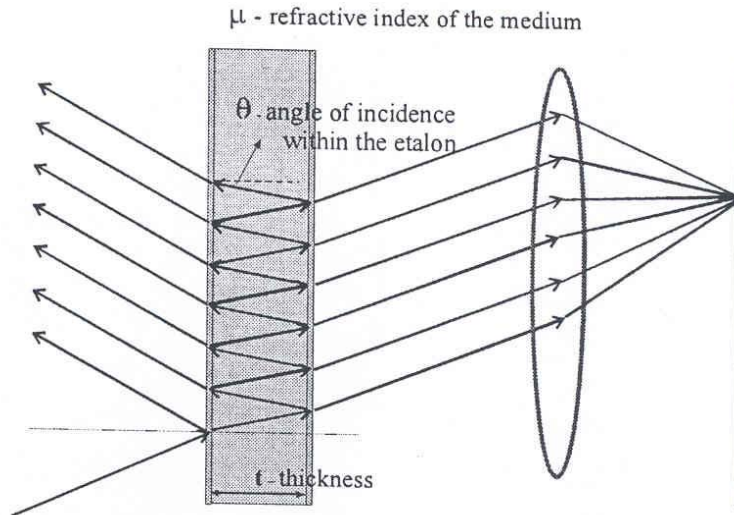

Figure 8: Reflection and Refraction of a Plane Wave in a Fabry Perot Etalon.

In practice, the etalon can be realised by a slab of glass (or other transparent material in relation with the desired wavelength range) in air or by air gap between two glass (or other) plates. A radiation beam incident on this system with a given angle with respect to the first surface leads to the creation of a number of secondary reflected and transmitted beams of decreasing intensity. Depending on their phase relation, the reflected or transmitted beams will interfere constructively or destructively. The effect of multiple beam interference is qualitatively the same as in that for grating. Maximum transmission occurs when the order (least phase shift) is equal to 1. The difference between the grating spectrometer and the Fabry Perot interferometer is the order of interference used: for the Fabry Perot it is usually large whereas for the grating spectrometer it can be as small as 1.

The free spectral range (i.e. the useful spectral range of an order where there is not superimposition of the dispersed light of contiguous orders) and the spectral resolving power of the Fabry Perot interferometer are both dependent on the order For larger free spectral range and smaller bandpass, lower orders are more desirable. However, going to lower orders requires that mirror spacing be very small and the tolerance becomes a critical factor. Also, small defects in mirror coatings can affect the overall performance of the interferometer.

The spectral tuning of this type of spectral imager can be performed rapidly by adjusting the mirror spacing or the tilt angle of the input beam with respect to etalon surface.

Limiting characteristics of the tuned etalon spectral imagers are: low throughput due to the number of optical elements of the imaging system and a consequent need of multiple frame averages to get a good signal to noise ratio, limited field of view ($< 9°$) owing to off axis wavelength shifts, and sensitivity to temperature variation [7,16,17,18].

3.4   FIGURES OF MERIT

All the previously listed technologies have been utilized in a wide variety of applications and have been developed and improved in many different configurations, by optimising parameters, by introducing new solutions taking into account a specific application.

Of course there is not an "absolutely" best technology and in order to select the most suitable technology (and its possible variant) for a given application at least the following figures of merit must be considered in search of the most satisfactory trade-off:

- Full spectral range;

- Spectral resolution ($\delta\lambda$) or spectral resolving power ($\lambda/\delta\lambda$);

- Field of view;

- Spatial resolution;

- Noise equivalent spectral irradiance;

- Throughput;

- Data cube collection time;

- Wavelength selectability;

- System complexity (optics, mechanics, signal processing, temperature sensitivity);

- Size, weight, power consumption;

- Maturity of technology; and

- Cost.

Chapter 4 – MULTISPECTRAL TECHNOLOGIES

MSI systems collect data in few and relatively wide spectral bands, typically measured in micrometers or tenths of micrometers. These spectral bands are selected to collect radiation in specifically defined parts of the spectrum and optimised for certain categories of information most evident in those bands.

In principle, some of the technologies above described for HSI systems can be used also for MSI systems, but more frequently different solutions are adopted.

A common approach is to insert in sequence in front of a broad band detector of a thermal imager a series of interference filters (up to 7 or 8), inserted in a rotating wheel. The filters divide the sensitivity range of the detector in several sub-bands of equal or different bandwidth. They can be of the type band pass, low-pass or high-pass, tailored for specific tasks; the filters can be cold or uncooled.

The flexibility is not the prevalent characteristic of this solution, but generally it is not difficult to interchange different filter wheels, with filters of different features for different tasks.

A recent and very promising technology developed to produce multispectral imagery without the need to use and manage dispersing or filtering systems is a new class of two-dimensional detectors operating at the same time in two or more separate wavelength ranges.

This new class of detectors is mainly based and in some way is an evolution of the well known technologies of Quantum-Well Infrared Photodetector (QWIP) and of Mercury Cadmium Telluride (MCT). A lot of manufacturers are developing this kind of detector and among them are: AIM (Germany), ACREO (Sweden), BAE Systems (UK), DRS (USA), ELOP (Israel), LETI (France). Most of detectors developed or in development are dual band, commonly operating in MWIR and LWIR, but also other solutions are adopted such as NIR/LWIR, MWIR/MWIR, LWIR/LWIR. QWIP detectors with three bands (MWIR/LWIR/LWIR) and with four bands (responsivity peak at 5, 9, 11, 14 µm) have been produced and successfully tested.

The structure of both types QWIP and MCT detectors can be grown by molecular beam epitaxy on GaAs substrate for QWIP and on lattice matched CdZnTe substrate for MCT. At present it seems difficult to indicate which is the most promising technology. QWIP detectors have the advantage that their spectral response is relatively narrow and so it is possible to get very little or no "spectral crosstalk" between detector elements designed for different bands. Moreover dual band QWIP detector structures present no serious material growth issues because, for the most part, the operating wavelengths are determined by the layer thicknesses, which are easily controlled with molecular beam epitaxy. The principal disadvantage of QWIPs is their low single pixel quantum efficiency relative to MCT which, on the contrary, has this parameter close to unity. However, for MCT, the material growth and device processing are much more challenging as is the reduction of material defects [19,20,21,22,23].

It is apparent that, when discussing dual band thermal imagers, the concept of spectral signature of possible targets loses most of the significance. The advantages of a dual band thermal imager with respect to a broadband one are mainly in the fact that it can operate in a wider range of ambient conditions, it can be more effective in false alarm reduction, in decoy discrimination, in defeating IR countermeasures such as smoke or camouflage, and in clutter rejection.

The last frontier of MSI and HSI systems can arise from a new generation of imaging sensors called Adaptive Focal Plane Array (AFPA), the principal characteristic of which is to be electrically tunable in the wavebands of IR spectrum on a pixel by pixel basis, thus enabling the real time reconfiguration of the

array to maximize either spectral coverage or spatial resolution. The primary objective of the development of an AFPA is the realization of a MSI or HSI system in a standard FLIR package.

One of the first attempts to produce an AFPA is based on the use of the technology of the Quantum-Dot Infrared Photodetector (QDIP) associated to new processing strategies that allow both the centre wavelength and spectral resolution to be, within certain limits, independently adjusted in the infrared range $3 - 8$ μm.

Most of the QDIPs reported so far have InAs or InGaAs dots sandwiched in a GaAs matrix. In a recent evolution of this scheme, InAs dots are placed in a thin InGaAs quantum well. The presence of the InGaAs well in this design lowers the ground state of the dots, increasing the effective barrier seen by the carriers.

By varying the thickness and composition of the InGaAs well and the surrounding barrier layers, the operating wavelength of the detector can be tuned over the MWIR to LWIR range. Once the operating wavelength is fixed, further tuning within the wave band can be accomplished by varying the bias of the detector. The spectral response at a given (tuned) wavelength is quite wide. It is only by the use of a new post-processing technique that the bias driven diversity in the spectra can be exploited to produce an approximately unimodal response that can be tuned from 5 to 8 μm and with an adjustable FWHM, down to $\Delta\lambda \sim 0.5$ μm for each centre wavelength [24,25].

Chapter 5 – OVERVIEW OF CURRENTLY AVAILABLE IMAGERS

5.1 AIRBORNE / SPACEBORNE SYSTEMS [1,9]

Name	Full Name	Manufacturer Country	Number of Bands	Spectral Range (μm)	Band Width at FWHM (nm)
AAHIS	Advanced Airborne Hyperspectral Imaging System	SETS Technology	288	0.432 – 0.832	6
AHI	Airborne Hyperspectral Imager	Hawaii Institute of Geophysics and Planetology	256	7.5 – 11.7	100
AHS	Airborne Hyperspectral Scanner	Daedalus Enterprise Inc.	48	0.433 – 12.70	
AIP	Airborne Instrument Program	Lockheed USA		2.00 – 6.40	
AIS-1	Airborne Imaging Spectrometer	NASA, JPL USA	128	0.90 – 2.10 1.20 – 2.40	9.3 10.6
AMSS	Airborne Multispectral Scanner MK-II	Geoscan Pty Ltd.	46	0.50 – 12.00	
ARES		USA	75	2.00 – 6.50	
ARIES	Australian Resource Information and Environment Satellite	Australia	128	0.40 – 2.50	
APEX	Airborne Prism Experiment		Programmable to a max of 300	0.38 – 2.50	10
CHRISS	Compact High Resolution Imaging Spectrograph Sensor	Science Applications Int. Corp. (SAIC) USA	40	0.43 – 0.87	
CIS	Chinese Imaging Spectrometer	Shanghai Institute of Technical Physics China	91	0.40 – 12.50	
DAIS 21115	Digital Airborne Imaging Spectrometer	GER Corp. Germany	211	0.40 – 12.00	
DAIS 3715	Digital Airborne Imaging Spectrometer	GER Corp. Germany	37	0.40 – 12.00	
DAIS 7915	Digital Airborne Imaging Spectrometer	GER Corp. Germany	79	0.40 – 12.00	
DAIS 16115	Digital Airborne Imaging Spectrometer	GER Corp. Germany	160	0.40 – 12.00	

Name	Full Name	Manufacturer Country	Number of Bands	Spectral Range (μm)	Band Width at FWHM (nm)
EART EXPLORER		ESA	202 (?)	(3)10 – 1000	
EO-1		USA	7	0.43 – 2.35	
EPS-A	Environmental Probe System	Germany	32	0.40 – 12.00	
EPS-H	Environmental Probe System	Germany	76 * 32 32 12	0.43 – 1.05 * 1.50 – 1.80 2.00 – 2.50 8.00 – 12.00	*Customised according user requirements
FLI/PMI	Fluorescence Line Imager / Programmable Multispectral Imager	Moniteq Ltd.	228	0.43 – 0.805	
FTVFHSI	Fourier Transform Visible Hyperspectral Imager	Kestrel Corp., FIT	256	0.44 – 1.15	
GERIS	Geophysical and Environmental Research Imaging Spectrometer	Germany	63	0.40 – 2.50	
HIRIS	High Resolution Imaging Spectrometer	USA	192	0.40 – 2.50	
HYDICE	Hyperspectral Digital Imagery Collection Experiment	USA	210	0.40 – 2.50	7.6 – 14.9
HYMAP		Integrated Spectronics Australia	126	0.45 – 2.50	15 – 20
HYPERION		TRW	220	0.40 – 2.5	10
IISRB	Infrared Imaging Spectrometer	Bomen	1720	3.50 – 5.00	
IMSS	Image Multispectral Sensing	Pacific Advanced Technology	320	2.00 – 5.00	
IRIS	Infrared Imaging Spectrometer	ERIM USA	256	2.00 – 15.00	
ISM	Imaging Spectroscopic Mapper	DESPA	128	0.80 – 3.20	
LIVTIRS 1	Livermore Imaging Fourier Imaging Spectrometer	Lawrence Livermore USA		3.00 – 5.00	

Name	Full Name	Manufacturer Country	Number of Bands	Spectral Range (µm)	Band Width at FWHM (nm)
LIVTIRS 2	Livermore Imaging Fourier Imaging Spectrometer	Lawrence Livermore USA		8.00 – 12.00	
MAIS	Modular Airborne Imaging System	Shanghai Institute of Technical Physics China	71	0.44 – 11.8	
MAS	Modis Airborne Simulator	Daedalus Enterprise Inc. USA	50	0.53 – 14.50	
MERIS	Medium Resolution Imaging Spectrometer	ESA	15	0.40 – 1.05	
MIDIS	Multiband Identification and Discrimination Imaging Spectroradiometer	Surface Optics Corp., JPL, USA	256	0.40 – 30.00	
MIVIS	Multispectral Infrared and Visible Imaging Spectrometer	Daedalus Enterprise Inc. USA	102	0.43 – 12.70	
MODIS	Moderate Resolution Imaging Spectrometer	NASA USA	36	0.41 – 14.24	
OMIS	Operative Modular Airborne Imaging Spectrometer		128	0.46 – 12.50	
PROBE-1			100 – 200	0.44 – 2.54	11 – 18
ROSIS	Reflective Optics System Imaging Spectrometer	DLR, GKSS, MBB Germany	128	0.45 – 0.85	5
SASI	Shortwave Infrared Airborne Spectrographic Sensor		160	0.85 – 2.45	10
SFSI	SWIR Full Spectrographic Imager	CCRS Canada	122	1.20 – 2.40	10.3
SMIFTS	Spatially modulated Imaging Fourier Transform	Hawaii Institute of Geophysics USA	75	1.00 – 5.00	
SSTI HSI	Small Satellite Technology Initiative Hyperspectral Imager	TRW Inc. USA	384	0.40 – 2.50	
TRWIS III	TRW Imaging Spectrometer	TRW Inc USA.	384	0.30 – 2.50	

Name	Full Name	Manufacturer Country	Number of Bands	Spectral Range (μm)	Band Width at FWHM (nm)
VIFIS	Variable Interference Filter Imaging Spectrometer	University of Dundee	60	0.44 – 0.89	10
VIMS-V	Visible Infrared Mapping Spectrometer	ASI	512	0.30 – 1.05	
WIS	Wedge Imaging Spectrometer	Hughes St. Barbara Research Center USA	170	0.40 – 2.50	
WARFIGHTER (WF-1)		Phillips Laboratory USA	280	0.45 – 5.00	

5.2 GROUND BASED / HAND HELD SYSTEMS

Name	Manufacturer Country	Number of Bands	Spectral Range (μm)	Technology
GALAAD (Prototype)	ATIS France		7.0 – 14.0	Double grating with needle mask
CTHIS LWIR (CromoTomographic Hyperspectral Imaging Spectrometer)	Solid State Scientific Corporation USA	40	6.5 – 11.0	Rotating prism
CTHIS MWIR (CromoTomographic Hyperspectral Imaging Spectrometer)	Solid State Scientific Corporation USA	64	2.7 – 5.0	Rotating prism
ImSpector N10	Spectral Imaging Ltd. (Specim) Finland	Spectral resol 5.0 nm	0.7 – 1.0	Prism-Grating-Prism (PGP)
ImSpector N17	Spectral Imaging Ltd. (Specim) Finland	Spectral resol 10.0 nm	0.9 – 1.75	Prism-Grating-Prism (PGP)
Orion IR Multispectral Imager (SWIR, MWIR, LWIR models)	CEDIP France	4 or 6 per model	SWIR MWIR LWIR customized	Filter wheel

Name	Manufacturer Country	Number of Bands	Spectral Range (μm)	Technology
Sherlock LWIR	Pacific Advanced Technology USA	Spectral resol. 3 nm at $\lambda = 3.0\mu m$	8.0 – 10.5	IMSS (Image Multi Spectral Sensing)
Sherlock MWIR	Pacific Advanced Technology USA	Spectral resol. 33 nm at $\lambda = 8.0\mu m$	3.0 – 5.0	IMSS (Image Multi Spectral Sensing)

Chapter 6 – ADDITIONAL INFORMATION

Up-to-date information about Airborne Remote Sensing Technology and Applications can be found on http://CARSTAD.gsfc.nasa.gov.

The ASTER Spectral Library is available by NASA as part of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) imaging instrument program. It includes spectral compilations from Jet Propulsion Laboratory, Johns Hopkins University and United States Geological Survey (Reston), and contains nearly 2000 spectra of minerals, rocks, soils, man-made materials, water and snow. Many of them cover the entire wavelength region from 0.4 to 14 μm. The library is accessible interactively via Worldwide Web at http://speclib.jpl.nasa.gov.

The USGS Spectral Library compiled by the United States Geological Survey Spectroscopy Lab in Denver, Colorado contains about 500 reflectance spectra of minerals and plants in the wavelength range from 0.2 to 3.0 μm.

This library is accessible at http://speclab.cr.usgs.gov/spectral-lib04.html.

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Background discrimination	Military applications	Remote sensing
Comparison	MSI (MultiSpectral Imaging)	Reviews
Data acquisition	MWIR (Medium Wave Infrared)	Signal processing
Electro-optics	NIR (Near Infrared)	SWIR (Shortwave Infrared)
Field tests	Operational effectiveness	Target acquisition
HSI (HyperSpectral Imaging)	Optical correlators	Target signatures
Hyperspectral imaging	Optical detection	Trials
Image processing	Optical processing	Urban areas
Infrared detectors	Optical sensors	Urban warfare
Infrared equipment	Pattern recognition	Warning systems
Interferometers		

14. Abstract

The primary goals for NATO SET-065/RTG-33 were to determine the benefits of multiband/ multispectral imaging and to improve and extend the existing infrared target acquisition models to include new targets and/or imaging conditions. All activities performed by the group in this context are summarised in the *Final Report*.

One main activity was a field trial at the Angers Technical Center in France in 2004. The objectives of this field trial were to collect multiband and hyperspectral imagery for investigation of spectral vehicle and human target signature characteristics in the urban environment. The paper *Collection of Hyperspectral and Multispectral Image Data in Urban Environment* gives a detailed description of this trial and of the data acquired.

The paper *Survey of Hyperspectral and Multispectral Imaging Technologies* reviews today's technologies that are applied in hyperspectral, multispectral and multiband imaging systems.

The TG-33 activities produced results that furthered the understanding of multiband sensor performance and improved performance modelling.

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