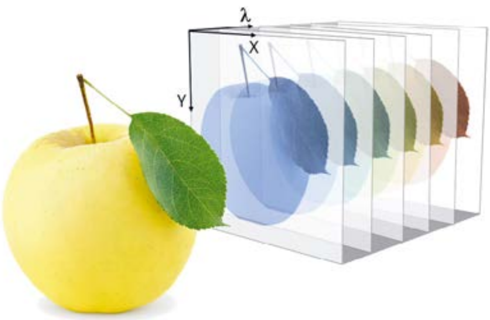
VIS-NIR HYPERSPECTRAL CAMERAS

Stéphane Tisserand
SILIOS Technologies, 13790 Peynier, France
***stephane.tisserand@silios.fr**



Hyperspectral and multispectral imaging can record a single scene across a range of spectral bands. The resulting three-dimensional dataset is called a "hypercube". A spectrum is available for each point of the image. This makes it possible to analyse, quantify or differentiate the elements and materials constituting the scene. This article presents the existing technologies on the market and their main characteristics in the VIS/NIR spectral domain (400–1000 nm). It then focuses on a specific multispectral technology called *snapshot* multispectral imaging, combining CMOS sensors and pixelated multispectral filters (filtering at the pixel level).

https://doi.org/10.1051/photon/202111058

Hyperspectral imaging is usually distinguished from multispectral imaging based on the number of spectral bands captured by the instrument. As a general rule, hyperspectral cameras can record over 100 spectral bands, while multispectral cameras typically capture fewer than 25. This article covers products providing at least 8 spectral bands. The commercially available hyper/multispectral cameras on the market are based on a wide range of different technologies. Their respective performance levels, advantages and disadvantages suit them for a variety of uses and markets.

In the first part of this article, we propose to review the main technologies available and prepare a table listing their characteristics to guide users in their choice. The second part of the article emphasizes on one of these technologies: *pixelated filter snapshot* multispectral cameras. This section presents the performance levels of the cameras available on the market.

The technologies described below on the VIS/NIR domain (400-1000nm) have equivalents in the SWIR, LWIR and MWIR ranges. The main advantage of the VIS/NIR range is the use of silicon-based sensors (i.e. CMOS technology), which are simple to implement at a low cost as they are produced in large volumes. Prices of equivalent systems in the SWIR, LWIR and MWIR regions, using more "exotic" sensors (InGaAs, HgCdTe, etc.) are much higher (2 to 20 times).

A WIDE RANGE OF TECHNOLOGIES

Hyper/multispectral camera technologies can be divided into three categories: *pushbroom* technologies, *snapshot* technologies and intermediate technologies. The main characteristics of these technologies are summarized in table 1.

PUSHBROOM TECHNOLOGIES (EXTERNAL SCANNING)

Like filter wheel technology (which is not covered in this article), pushbroom is a long-established technology. Its best-known application is probably multispectral Earth observation from satellites. Conventional pushbroom technology involves a 2D sensor that records spatial data along one dimension of the sensor (y) and spectral data along the other (x). The wavelength dispersion of the signal (or separation of different spectral components) is obtained with either a diffraction grating or a one-dimensional band filter. The second spatial dimension is

Category	Technology	Number of bands	Spectral Resolution	Spatial Resolution per band	Volume of data	Hypercube registering time	Optical system complexity	Footprint	Robustness	Level of price	Industrialization scalability
Push-broom with external 1D scanning	Grating	100 to 400	2 to 6 nm	up to 3000 px (1D)	High	Long	Specific	Medium/ large	"Sensible (fine aligment)"	Medium to high	Low
	1D Filter	100 to 150	10 to 15 nm	2048 px (1D)	High	Long	Specific	Very low	Robust	Low	Very High
Push-broom with internal 1D scanning	1D Filter	100 to 200	7 to 15 nm	0.25 to 7.5 Mpx	High	Medium-long	Specific	Very low	"Sensible (moving parts)"	Medium	Medium
Snapshot 2D with spectral scanning	Tunable filter	300 to 600	5 nm	2.3 Mpx	High	Medium-long	Standard	Medium	"Sensible (tunable parts)"	Medium	Medium
Snapshot 2D with sub-images	"2D filter (sub-images)"	150 to 200	10 nm	0.17 Mpx	Medium	Short	Specific	Low/ Medium	Robust	Medium	High
Snapshot 2D with macro-pixels	2D filter (macro-pixels)	8 to 25	10 to 40 nm	0.07 to 0.5 Mpx	Low	Short	Standard	Very low	Robust	Low	Very High

Table 1: Key features of hyper/multispectral technologies in the VIS/NIR range.

obtained by displacing the sensor relative to the scene, in the direction perpendicular to the indicatrix of the grating or to the filter bands (figure 1). This displacement can be achieved by moving the camera (mounted on a drone or a satellite, for example) or by moving the object below the camera (objects on a conveyor belt, for example). This case can be described as *external* pushbroom scanning.

The main advantage of push-broom technology is its capacity to generate a hypercube with a very high spatial and spectral resolution. Spectral resolutions below 10nm can be obtained in the 400–1000nm range. From a spatial viewpoint, these systems ●●●

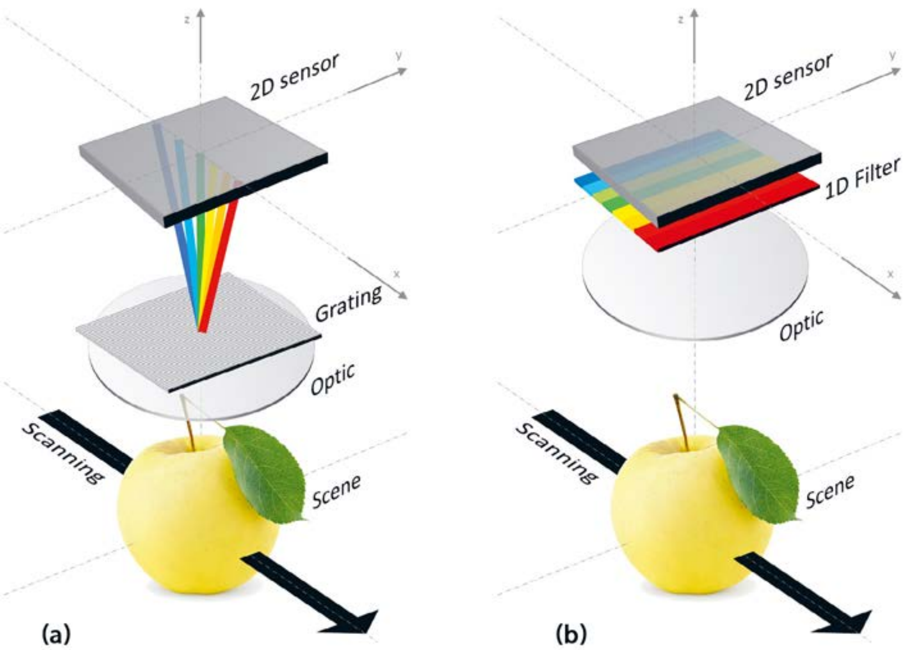


Figure 1. Hyper/multispectral pushbroom technologies based on a grating (a) or on a 1D multiband filter (b). The scanning is external (either the camera or the scene is moving).

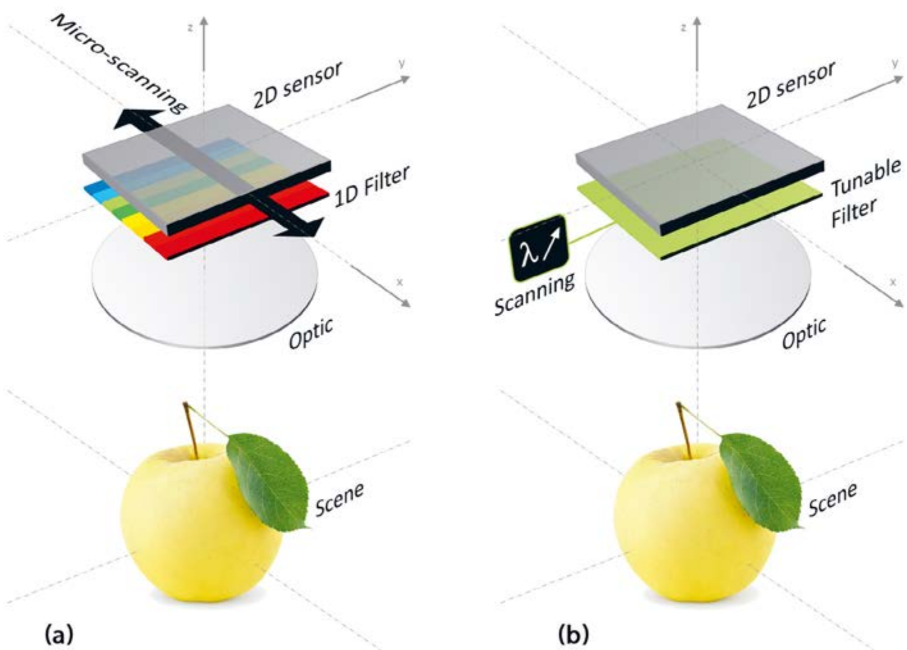


Figure 2. Intermediate hyper/multispectral technologies based on the scanning of a 1D multiband filter (a) or the λ scanning of a tunable filter (b). The scanning is internal.

use sensors that frequently offer over 2,000 pixels in their largest dimension. The resolution of the second spatial dimension depends on the speed of the camera's movement relative to the object and the rate of image capture. This wealth of information comes at a price: the amount of the data. The resulting hypercube is extremely large. Consequently, these high-performance systems, whether fixed or embedded, are often used as laboratory tools. They are designed for advanced scientific research and are frequently deployed in preliminary studies to determine the reduced set of spectral bands that is essential to address a sorting, discrimination or quantification problem that will then be performed industrially by systems with a lower spectral resolution (see snapshot technologies).

The main disadvantage of pushbroom technology arises from its image recording principle. Unlike snapshot technologies, the image is captured sequentially. The whole 2D scene is not recorded instantaneously; it is captured by scanning. Only static scenes or scenes in which the kinetics of the movement are negligible compared with the time taken to capture the image are suitable for these systems. This limits the scope of possible applications.

The number of manufacturers of hyperspectral cameras based on this principle is quite large. Here is a non-exhaustive list: *Brimrose, Bruker Corporation, Corning, Headwall, Hyspex, Itres, Middleton Spectral Vision, Norsk Elecktro Optikk, Resonon, Senop, Specim, Spectral Engine, Surface Optics, Telops* (see table 3).

INTERMEDIATE TECHNOLOGIES (INTERNAL SCANNING)

To mitigate the complexity of traditional pushbroom systems, newer technologies have emerged. These attempts to move towards a more conventional snapshot-type capture mode. The principle involves performing the scanning inside the camera itself. Moving the sensor on a miniaturised plate makes it possible to sweep the scene and recover the missing second spatial dimension (figure 2). This means there is no longer any need to move the camera relative to the scene. Another approach involves sweeping through the spectral

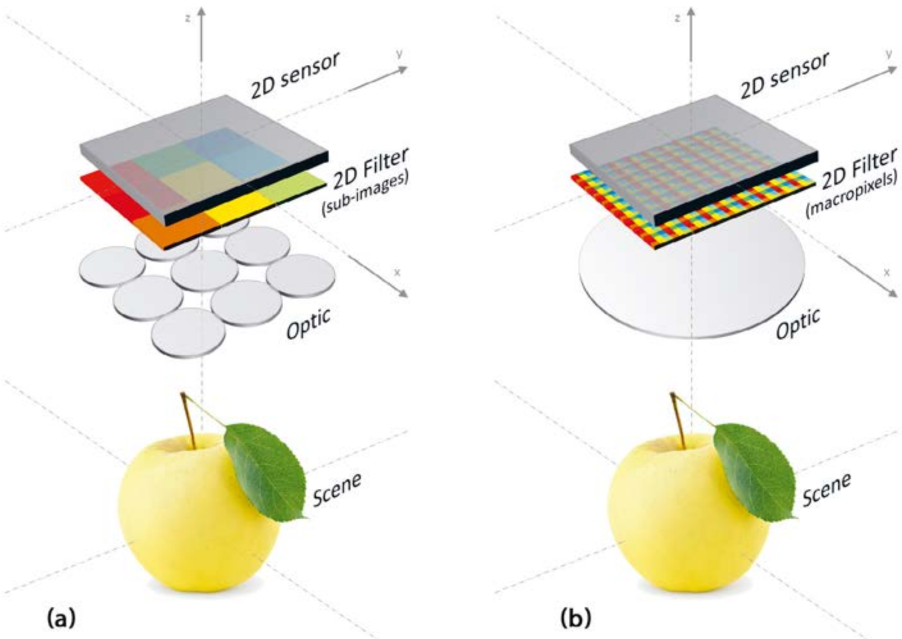


Figure 3. Multispectral snapshot technologies based on a sub-image 2D filter (a) or a pixelated 2D filter (b). There is no scanning.

dimension, using a tunable filter in front of the sensor for example.

The capture is then similar to a snapshot approach, greatly simplifying its implementation. However, the recording of the hypercube is still based on capturing a sequence of images over time. In other words, the hypercube is not acquired in a single shot. Consequently, most of the disadvantages of the capture method described in section 1.1 remain. Like conventional pushbroom systems, these systems can achieve high performance levels in terms of spatial and spectral resolution. As a result, the hypercube is again very large.

These intermediate technologies produce less bulky systems than most traditional pushbroom systems, while still providing high levels of performance and also simplifying the data capture mode for the user. To our knowledge, the main manufacturers of products based on these intermediate technologies are: *IMEC (Snapscan technology), HINALEA, PHOTON etc and SPECIM (IQ camera)* (see table 3). This list is probably not exhaustive.

SNAPSHOT TECHNOLOGIES (NO SCANNING)

The so-called snapshot technology allows the hypercube to be captured in one single shot, without any scanning. The principle is based on capturing all the spectral and spatial data at the same time. The 2D sensor is partitioned with a 2D spectral filter (figure 3), filtering by sub-images (or thumbnails) or at a pixel level (macropixel organization). We note that sub-image filtering is fairly uncommon due to the complexity of the multi-optic system required to capture the scene. Filtering at the pixel level, on the other hand, allows standard optics to be used (mounting type C or CS, for example). In terms of advantages, these snapshot systems are particularly compact, robust and often more affordable. Their manufacturing methods, derived from the semiconductor and microtechnology sectors, make them suitable for low-cost, high-volume production (see section 2). The major disadvantage of these systems is the loss of performance compared to the hyperspectral systems presented in sections 1.1 and 1.2. The numbers of spectral bands and/or ● ● ●

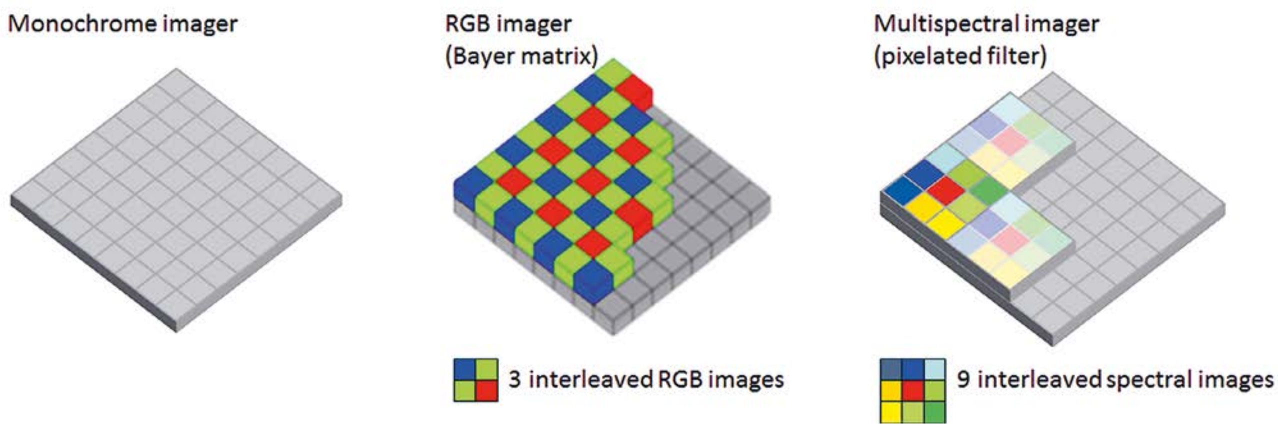


Figure 4. Bayer filter principle and example of a 3×3 multispectral macropixel.

the spatial resolution are significantly lower. The spatial resolution of each spectral image falls to less than 0.5 Mpx (between 0.07 and 0.47 Mpx) compared to 1 to several Mpx for the above technologies. However, if the application is able to accommodate this level of performance, the snapshot solution is the best choice on the basis of price, robustness, compactness, integrability, volume manufacturing etc.

To our knowledge, the manufacturers of snapshot cameras are for the thumbnails filtering: Cubert and for macropixel filtering: *XIMEA (with IMEC sensors), Photon Focus (with IMEC sensors), Spectral Devices and SILIOS Technologies* (see table 3).

PIXELATED FILTER SNAPSHOT MULTISPECTRAL CAMERAS

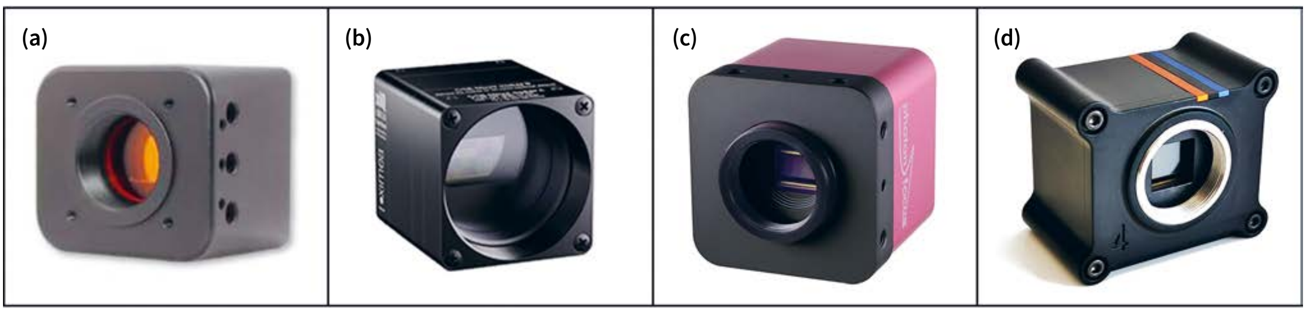
This multispectral technology is based on the well-known principle of the Bayer filter mosaic, which is used to convert monochrome sensors into colour sensors. The Bayer filter consists of a macropixel (or kernel) of 2×2 pixels as shown in figure 4. Snapshot multispectral cameras use more complex macropixels of 3×3, 4×4 or even 5×5 pixels. Each pixel in the macropixel filters a specific band, offering a breakdown into 9, 16 or 25 bands. Several technologies have emerged, each offering specific abilities. The pixelated mosaic filter is either applied to the sensor itself (the CMOS sensor wafer for IMEC, or individual sensors for Spectral Devices), or produced on a separate substrate that is then cut up and assembled (hybrid transfer) on the sensor in its commercial housing (COLOR SHADES® technology from SILIOS Technologies). The IMEC technology, based on semiconductor tools and processes, offers high-volume production capacity, while the technologies developed by Spectral Devices and SILIOS have the unique ability to adapt to any commercial sensor and any multispectral configuration the customer may require and this starting from a very low volume of production. This means both companies can produce custom multispectral cameras at very affordable prices in addition to their catalogue cameras.

Other differences relating to the production technologies for the bandpass filters used provide to the cameras distinct characteristics.

SPECTRAL BANDWIDTHS

The width of the spectral bands depends on the technology used. An analysis of the commercial

Figure 5. Snapshot multispectral cameras. (a) Spectral Devices (MSC-VIS8/MSC-NIR8), (b) Ximea (MQ022HG-IM-SM4X4-VIS/ MQ022HG-IM-SM5X5-NIR) – IMEC sensor, (c) Photon Focus (MV1-D2048x1088-HS02-96-G2/MV1-D2048x1088-HS03-96-G2) – IMEC sensor, (d) SILIOS Technologies (CMS/CMS4/TOUCAN).



products reveals two families of cameras (see table 2, column 6): narrowband cameras, *i.e.* cameras with FWHM widths between 10 and 15 nm (XIMEA and Photon Focus – IMEC sensor), and wider bandwidth cameras, with FWHM widths between 20 and 45nm (Spectral Devices and SILIOS). The formers offer the advantage of a significant spectral finesse. This makes it possible to have a larger number of spectral bands within a given spectral region. Cameras based on IMEC sensors can offer 16 or 25 spectral bands. This means the sampling of the spectrum is relatively high. Spectral Devices and SILIOS cameras are limited to a maximum of 16 bands to avoid too much overlap between bands. However, wider bands offer other advantages compared with narrower bands. (i) They offer a lower level of attenuation, allowing more flow to pass through. (ii) These broad filters also have much greater tolerance in terms of angular incidence (lower angular sensitivity) than narrow filters. A wide range of apertures can thus be used with these cameras without the need for dedicated calibration in advance.

SPATIAL RESOLUTION - NUMBER OF BANDS.

The spatial resolution of each spectral sub-image in the hypercube depends on the native resolution of the sensor (table 2, column 7) and the number of spectral bands being measured (number of pixels in the macropixel - table 2, column 3). The native resolutions of the sensors range from 1 to 4Mpx. The resolution of the spectral sub-images is equal to this native resolution divided by the number of bands. The highest spatial resolution per sub-image is obtained with SILIOS CMS4 cameras using a 4Mpx sensor and a macropixel of 3×3 pixels (8 bands + 1 PAN), *i.e.* 682×682px^2. With Spectral Devices, the same conditions (4Mpx and a macropixel of 3×3 pixels) result in a resolution per sub-image of only 256×256px^2. This is because Spectral Devices considers only alternate lines and columns of the sensor to space out the pixels of the macropixel and to reduce the effects of crosstalk. The raw signal from each pixel becomes less sensitive to crosstalk pollution but at a price of a weaker spatial resolution. Digital crosstalk correction methods based on a spectral calibration of the camera can also be applied but these are beyond the scope of this article.

SPECTRAL EXCURSION RANGE

Unlike products based on internal or external scanning technologies, none of the Bayer-type snapshot cameras fully covers the VIS/NIR spectral domain (400–1000 nm). Rejection thin film filters in a domain of 600nm are complex and their structure at the pixel level (a few microns) is difficult to reach with conventional fabrication technologies. Preference is thus given to simpler filter structures that restrict the spectral excursion range. Analysing all the cameras on the market shows that this excursion is limited to below 300 nm (see table 2, column 5). This width allows the visible (400–700nm), the near infra-red (700–1000nm) or any other intermediate domain to be addressed separately. Only one commercial camera (the TOUCAN model recently launched by SILIOS) gives access to an excursion of 450 nm, covering the visible and part of the near infra-red (420–870nm).

PAN PIXEL

Finally, some cameras (CMS and CMS4 from SILIOS) include a panchromatic (PAN) or neutral pixel in the macropixel. This pixel is not selective in terms of wavelength. Its optical density prevents neighbouring pixels being blown out by too high a signal level (reprendre). It provides a simple broadband photometric reference for the scene. An equivalent can of course be obtained on all cameras without panchromatic pixels by summing the responses of all the pixels.

PRICE

The cheapest cameras on the market are available in the €5k to €7k range while the cost of the most performant cameras ranges between €12k and €18k. ●

Camera manufacturer	Camera ref.	Number of bands	Spectral range (nm)	Spectral range width (nm)	Bandwith (nm)	Sensor (native resolution)	Spatial résolution (HxV)	Web site
SPECTRAL DEVICE	MSC-VIS8-1-A	8	474 to 640	166	20 to 35	CMV4000 (4.2Mpx)	256 x 256	www.spectraldevices.com
	MSC-NIR8-1-A		720 to 980	260	18			
XIMEA/PHOTON FOCUS (IMEC HSI sensor)	MQ022HG-IM-SM4X4-VIS3 (XIMEA) / MV1-D2048x1088-HS03-96-G2 (PHOTON FOCUS)	16	460 to 600	140	10 to 15	CMV2000 (2.2 Mp)	512 x 272	"www.ximea.com www.photonfocus.com"
	MQ022HG-IM-SM4X4-RN2 (XIMEA) /	15	600 to 860	260	10 to 15		512 x 272	
	MQ022HG-IM-SM5X5-NIR2 (XIMEA) / MV1-D2048x1088-HS02-96-G2 (PHOTON FOCUS)	24	665 to 960	295	10 to 15		409 x 217	
SILIOS TECHNOLOGIES	CMS-C	"8 + 1 PAN"	430 to 700	270	25 to 45	RUBY (1.3 Mpx)	426 x 341	www.silios.com
	CMS-V		550 to 830	280	25 to 35			
	CMS-S		650 to 930	280	25 to 35			
	CMS4-C	"8 + 1 PAN"	430 to 700	270	25 to 45	CMV4000 (4.2Mpx)	682 x 682	
	CMS4-V		550 to 830	280	25 to 35			
	CMS4-S		650 to 930	280	25 to 35			
	TOUCAN	10	420 to 870	450	25 to 45	CMV4000 (4.2Mpx)	512 x 512	

Table 2: Main characteristics of commercial snapshot multispectral cameras (above 8 bands)

Manufacturer	Web Site	Technology
BRIMROSE	www.brimrose.com/ aotf-hyperspectral-imaging-system	Pushbroom
BRUKER CORP.	www.bruker.com (see : HI90)	Pushbroom
CORNING	www.corning.com (see : spectral sensing)	Pushbroom
HEADWALL	www.headwallphotonics.com	Pushbroom
HYSPEX	www.hyspex.com	Pushbroom
ITRES	www.itres.com	Pushbroom
MIDDLETON SPACTRAL VISION	www.middletonspectral.com	Pushbroom
NORSK ELECKTRO OPTIKK	www.neo.no	Pushbroom
RESONON	www.resonon.com	Pushbroom
SENOP	www.senop.com	Pushbroom
SPECIM	www.specim.com	Pushbroom
SURFACE OPTICS CORP.	www.surfaceoptics.com	Pushbroom
TELOPS	www.telops.com	Pushbroom
IMEC	www.imechyperspectral.com	Internal Scanning
HINALEA	www.hinaleaimaging.com	Internal Scanning
PHOTON Etc	www.photonetc.com	Internal Scanning
SPECIM	www.specim.com	Internal Scanning
CUBERT	www.cubert-gmbh.com	Snapshot (Thumbnails)
PHOTON FOCUS	www.photonfocus.com	Snapshot (macropixels)
SILIOS TECHNOLOGIES	www.silios.com	Snapshot (macropixels)
SPECTRAL DEVICES	www.spectraldevices.com	Snapshot (macropixels)
XIMEA	www.ximea.com	Snapshot (macropixels)

Table 3: Main manufacturers in the field of hyper/multispectral imaging systems (non-exhaustive list).