

**PlastiCircle**

**Grant Agreement No 730292**



## **Sorting system definition**



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# Factsheet

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## Dissemination level

<b>CO</b>	PU = Public
	PP = Restricted to other programme participants (including the EC)
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## Abstract

One of the objectives of the Plasticircle project is to improve the sorting of post-consumer packaging. Near Infrared (NIR) sorting is used commonly in the waste industry to recover materials of value from mixed streams. A high level review of the waste composition in the three pilot cities has been carried out, along with specification of the sorted product requirements and an initial study into the sorting efficiency of the Picvisa NIR unit.

## Abbreviations

HDPE	High density polyethylene
LDPE	Low density polyethylene
MRF	Materials recovery facility
NIR	Near Infrared
PET	Polyethylene terephthalate
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl chloride

## Partners short names

1. ITENE: INSTITUTO TECNOLÓGICO DEL EMBALAJE, TRANSPORTE Y LOGÍSTICA
2. SINTEF: STIFTELSEN SINTEF
3. PICVISA: PICVISA OPTICAL SORTING
4. AXION : AXION RECYCLING
5. CRF : CENTRO RICERCHE FIAT
6. UTRECHT : GEMEENTE UTRECHT
7. INNDEA : FUNDACION DE LA COMUNITAT VALENCIANA PARA LA PROMOCION ESTRATEGICA EL DESARROLLO Y LA INNOVACION URBANA
8. ALBA: PRIMARIA MUNICIPIULUI ALBA IULIA
9. MOV: MESTNA OBCINA VELENJE
10. SAV: SOCIEDAD ANONIMA AGRICULTORES DE LAVEGA DE VALENCIA Spain
11. POLARIS: POLARIS M HOLDING
12. INTERVAL: INDUSTRIAS TERMOPLÁSTICAS VALENCIANAS
13. ARMACELL : ARMACELL Benelux S.A.
14. DERBIGUM : DERBIGUM N.V.
15. PROPLAST : CONSORZIO PER LA PROMOZIONE DELLA CULTURA PLASTICA PROPLAST
16. HAHN : HAHN PLASTICS Ltd.

17. ECOEMBES : ECOEMBALAJES ESPAÑA S.A.

18. KIMbcn : FUNDACIÓ KNOWLEDGE INNOVATION MARKET BARCELONA

19. PLAST-EU: PLASTICS EUROPE

20. ICLEI: ICLEI EUROPASEKRETARIAT GMBH

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## Publishable summary

One of the objectives of the Plasticircle project is to improve the sorting of post-consumer packaging.

Near Infrared (NIR) sorting is used commonly in the waste industry to recover materials of value from mixed streams. The technology uses differences in the wavelengths of infrared light that is reflected by polymers with different chemical structures. The wavelengths of light that are reflected depend upon the covalent bonds in the polymer structure.

Using infrared spectroscopy means that pure streams of different polymers can be sorted for recycling. NIR does have its limits however and is unable to detect low levels of contamination and very thin coatings.

In these early stages of the project, the requirements for the NIR sorting of post-consumer household packaging in order to maximize the value for the Plasticircle industrial partners has been established.

In addition, it has been demonstrated that the purity of pre-sorted material collected in Spain can be increased.

Further work will be required throughout the project to achieve the quality and recovery rates set out in the Plasticircle project, however initial studies are very positive.

# Introduction

The objective of this phase of the project is to improve the classification of post-consumer packaging. Specifically in the first task of this work package the separation requirements to be achieved in the project are defined. These requirements can be summarized in the following points:

- Separation of 5 fractions of plastic:
  - PET Bottle.
  - PET Tray mono-layer.
  - HDPE Bottle.
  - PP rigid and flexible.
  - LDPE film.
- Loss of material <20%, classification purity >95%.
- PE Film and PP film with contaminants <5%.
- Final rejection fraction with presence of <7% PET, <6% rigid PE, and <8% PP-PE films.
- Presence of biodegradables materials and PVC <0,3% in the classified fractions.

In order to achieve these objectives, the first step is to study the state of the art of technologies applicable to the classification of plastic materials in order to check whether the technology currently used in PICVISA's optical separators is the most appropriate at the moment. In parallel, a series of improvements will be made to the current separator system. Efforts will focus on two distinct areas, the improvement in the equipment software and the improvement in the classification databases used.

## IPR Strategy

The PLASTICIRCLE solution corresponds to two main conceptual components: (i) a machine-vision sorter of plastic packaging issued from municipal solid waste, (ii) a pre-treatment process technology to be applied in plastic sorting facilities, including mechanical separation of materials and optical sorting at the end of the process line.

PICVISA intends to develop the IPR strategy, referred to the PLASTICIRCLE developments in material sorting, in terms of Patent and Industrial Design applications.

On the other hand, Industrial and Trade Secrecy measures are currently being carried out by the company.

Furthermore, reliable evidence will be established for a first registration in the Intellectual Property Registry of Spain and the use of the symbol ©, including software (source code, object code, algorithms, software architecture), the preparatory documentation and technical documentation concerning the methodology of material sorting, as well as the user manuals and original technical documentation of drawings, designs, graphics, procedures.

In this aim, PICVISA has identified and classified the confidential information being developed during the PLASTICIRCLE project, and has implemented an internal procedure considering the accumulated knowledge as business secrecy. Information and documentation, which is the subject of industrial secrecy, correspond to drawings, mechanical, electrical, electronic, pneumatics and hardware specifications, as well as the technical information related to the software of both the optical sorting equipment and the process line of the PLASTICIRCLE project.

Likewise, all PLASTICIRCLE improvements obtained in machine-vision and materials sorting, with applications to other materials than plastics, are also considered by the company as part of its expertise and a matter of industrial secrecy.

PICVISA already includes in its product and service contracts a regime of industrial and intellectual property rights, as well as the corresponding clauses of confidentiality according to the model of design and exploitation that are determined by the PLASTICIRCLE solution.

# 1 Technological analysis

The Ainia technology centre has carried out a study that consists of an analysis of the main advanced imaging technologies for the detection and classification of plastic waste. Other technologies of interest that allow materials to be differentiated according to their composition will also be evaluated in the study.

## 1.1 Applicable technologies

Polyethylene terephthalate (PET), Polypropylene (PP), Polyethylene (PE), Polystyrene (PS) and Polyvinyl chloride (PVC) are the most common types of plastics that can be found as waste. There are subgroups within them, such as, among others, Low Density Polyethylene (LDPE) and High Density Polyethylene (HDPE), both PEs, which is also interesting to differentiate.

Due to legal requirements and the incompatibility of different types of plastic, the proper separation of these is required in order to produce quality recycled material and it is also important to waste the minimum amount of valuable material possible from an environmental and financial point of view.

Some of the methods that have been used so far for the separation and classification of plastics include: Separation by magnetic density, flotation, triboelectric effect, artificial vision. Below, we will explore each one briefly:

### 1.1.1 Separation by flotation

The technique consists of the separation using a liquid medium. The plastic to be separated will sink or float, depending on the density of this liquid. This technique has some drawbacks: a liquid of a certain density allows only the separation of a single flow of material, and the separation time is long. It is a system that depends on the temperature and struggles to separate plastics when they are from the same family.

### 1.1.2 Separation by magnetic density

This technique is based on the use of a liquid medium to perform the separation of different plastics according to their densities. The particularity of this method is that it manages for the liquid to have a density gradient depending on the depth. To this end, iron oxide particles of an approximate size of 10-20 nm are added to the separation liquid. When a magnetic field is applied to this liquid medium, a density gradient is achieved in the liquid. This density variation will cause the different polymers to float at different depths, depending on their density. As in the previous case, this technique struggles to separate plastics from the same family.

### 1.1.3 Separation by triboelectric effect

The triboelectric effect is based on the electrostatic charge properties of materials. When two materials are rubbed together, there is a circulation of electrons between the two surfaces that have come into contact, whereby one of them is negatively charged and the other is positively charged. Tables have been created based on the tendency of the material to be negatively or positively charged (Davies, 1969). If we want to separate a material within a certain set of known materials, we can make all the materials in the set rub against another test material. It involves correctly selecting the test material so that all the materials are charged in one polarity, minus one of them which must be charged in the opposite polarity.

The triboelectric effect is only capable of separating two types of plastic at once in binary form, with the added problem that when they contain contaminants or are very similar, it does not perform the separation correctly.

### 1.1.4 Separation by artificial vision

There are several artificial vision techniques based on spectroscopy that have been used to identify the type of material and composition of the plastic without the need for contact: X-ray spectroscopy, laser-induced plasma spectroscopy, Raman spectroscopy and near/mid/far infrared spectroscopy.

The methods and techniques that have been carried out with X-ray vision have largely differentiated plastics such as PET and PVC (thanks to the chlorine atom present in the latter), which can generate hydrochloric gas if they are processed together due to erroneous classification. This system has not yet been able to correctly identify and classify the rest of the main plastics, but studies are being carried out for their use in the identification of traces of different atomic elements (XRT).

Laser-induced plasma spectroscopy (LIBS) consists of aiming a high-power laser at a specific object, which will cause a small evaporation of the material of this object and will generate plasma. In a certain moment of time after firing, this plasma ends up emitting light, whereby it is possible to identify characteristic emission lines of the atoms that compose it and thus identify the material. This technique is limited in that it can only analyze one point at a time. Studies have been conducted that validate its use for the classification of the different types of plastic, in addition to having the advantage that it is not affected by their colour, allowing the analysis of black plastics. Currently, projects are being carried out to achieve its implementation online, although it would appear that this will still take several years.

Raman spectroscopy is a technique based on the phenomenon of inelastic dispersion or Raman scattering. A sample is lit using a laser light in a range between the near ultraviolet and the near infrared. The light interacts with the material to be identified and a change in the energy levels of the photons of the

laser light occurs. This change in energy levels generates a very weak light that provides information about the structure of the material to be identified, and allows the characterization of samples at the molecular level.

This technique offers some more information in some bands regarding other spectroscopy techniques, but it requires a very sensitive and optimized instrumentation, since the signal to be analyzed is very weak. It is already used in some areas along with other types of spectroscopy, such as infrared, although it is still expensive for use in the classification of waste.

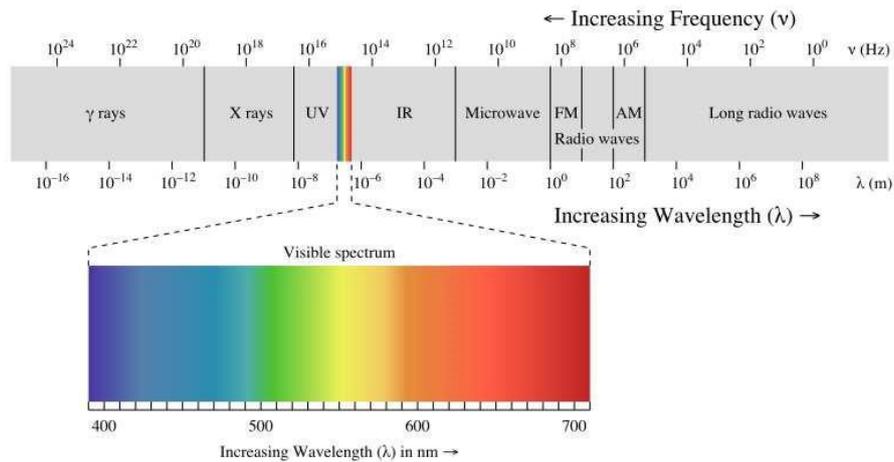
Infrared spectroscopy makes it possible to detect the spectrum returned by objects in certain frequencies between the 750 nm and 1 mm bands, which are invisible to the human eye.

The visible spectrum is approximately between the 400 nm and 750 nm bands, bordering the ultraviolet and the infrared. In turn, the infrared spectrum is divided into several subgroups:

- Near infrared (NIR | 0.75-1.4  $\mu\text{m}$ )
- Shortwave infrared (SWIR | 1.4-3  $\mu\text{m}$ )
- Medium wave infrared (MWIR | 3-8  $\mu\text{m}$ )
- Long wave infrared (LWIR | 8-15  $\mu\text{m}$ )
- Far infrared (LIR | 15-1000  $\mu\text{m}$ )

The near infrared (NIR) has a penetration rate between 3 and 5 mm, which is useful in determining the internal chemical composition of elements. SWIR is able to penetrate somewhat less, up to 2 mm, but receives the spectral response of other elements that can facilitate sample identification. The 1450, 1900 and 2800 nm bands are the so-called water absorption frequencies, so little information is extracted from wet or organic samples with high water content. The penetration of MWIR and LWIR is only 0.1 mm and they are usually used to capture the temperature of objects, since the heat released by a body can be detected in these frequencies.

Within the far infrared, the frequencies are between 100 and 1000  $\mu\text{m}$ , also called terahertz radiation. These frequencies are just before the start of microwave bands and are able to slightly penetrate tissues and plastics, but not metal or water. It can be used to perform chemometric analyses of some samples, as well as to detect differences in the water content or density of an object.



*Figure 1 - Electromagnetic spectrum*

Sensors can be found on the market that capture the spectra emitted along the different frequencies, but even on the highest MWIR, LWIR or LIR bands, the samples react to light in a more intensive way; acquiring data can take longer and have less penetration.

The sensors that are able to capture and separate the frequencies within the NIR and SWIR ranges are the most used for identifying the chemical composition of an object, both internally and externally, depending on the degree of penetration.

There are other techniques and technologies that are able to identify the chemical composition of an element, but they tend to require direct contact or even the element's partial or total destruction.

That is why, of all the studied options, the infrared spectroscopy is the most popular nowadays. It is able to take fast and safe chemometric measurements at a distance with strong signal intensity, which is also strong enough so that the noise does not affect it too much. It also has penetration capacity so the need for aggressive pre-treatments is avoided and it can provide the internal composition of some objects, even passing through very fine ones.

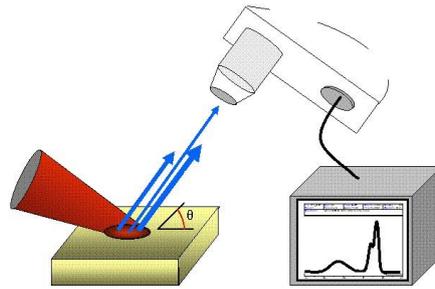
Further to this, due to its widespread use, there are more sensors and devices available, which means that the price is lower and there is more variety and more availability.

One of the disadvantages that the spectroscopy classification systems have in comparison with others is that they are affected by edges and shadows, which reduce the signal. Depending on the sensor's resolution, the size of the object could also be a problem if it is too small. Elements that are underneath others are impossible to detect.

Finally, a disadvantage that is unique to the infrared spectroscopy is that it is difficult to obtain valid information about carbon-based plastics with black pigment because the outputs are very weak in this range.

## 1.2 Infrared spectroscopy

Spectroscopy is the study of light as the length of a wave that has been emitted, reflected or dispersed in a solid, liquid or gas. Spectrometry is technology that is able to measure the intensity of optical radiation (UV, VIS and IR) at independent and adjacent intervals (bands).



*Figure 2 - Spectrometry system*

A spectrometry system is made up of the different elements that are required in order to capture a scene properly, which are:

- A sensor
- A radiation emitter
- An element that manages the captured information

In the project stage, the different elements of this system will be analysed with the aim of improving the performance and/or cost of the elements that are currently part of the system.

### 1.2.1 Sensors

A spectrometry sensor is one that is able to measure the intensity of optical radiation at independent and adjacent intervals.

There are different types of spectrometry sensors depending on the way that they capture the scene and the amount of information they obtain from it: point spectrometers and multi-point spectrometers.

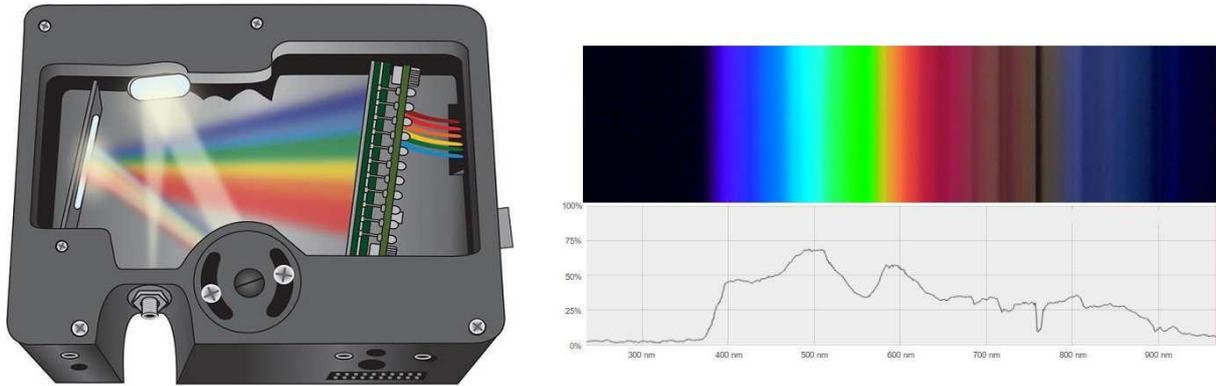
#### 1.2.1.1 Point spectrometers

This type of spectrometer records the intensity of light at a single point in space. A spectrometer is able to measure the amount of light on a limited spectral band, which is the band that it is sensitive to. The spectrometers divide this band into narrower portions, the size of these portions is closely related to their resolution. They give us the measurement of the light intensity for each of the portions, which makes it possible to then obtain the spectral response across the entire sensitive

band.

### **Dispersive spectrometer**

It is a measuring instrument that captures the spectrometry information of just one point. It has a monochromator that disperses the light into different spectra and a linear sensor. Each of the sensor's cells, which are positioned to form a line, will measure the intensity of a different band.



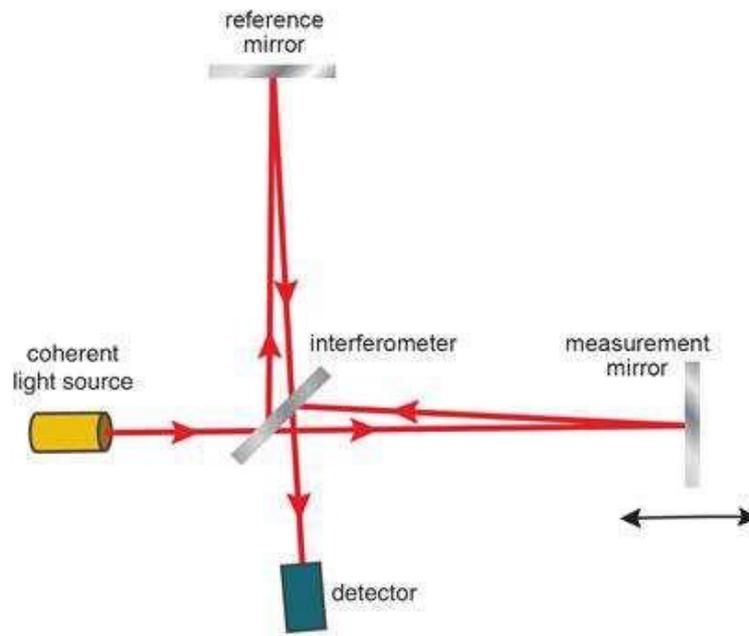
*Figure 3 - Dispersive spectrometer and an illustration of a measurement of the electromagnetic spectrum.*

This instrument is normally used to acquire information on the radiation emitted by a solid, liquid or gas, so that it's chemical composition can be known.

Due to a surface not necessarily having a uniform chemical composition, it is good practice to take several samples from it at several different points.

### **Fourier-transform infrared spectrometer (FTIR)**

Unlike a traditional spectrometer, which uses a monochromator to disperse the light along different beams, this type of spectrometer uses the Michelson interferometer principle, which generates an interferogram of the radiation that it captures through mirrors (one of which is movable).



*Figure 4 - Acquisition mechanism of the interferogram in an FTIR spectrometer.*

The Fourier transform of this interferogram allows the multi-band spectrum to be obtained, like in conventional spectrometers.

Nowadays, this type of spectrum is the most used for isolated sample-taking because it gives greater resolution due to it being able to capture them all at the same time. It also gives greater signal intensity because the interferometer does not have the same limitations as the monochromator. It is also much more precise to calibrate it by using a laser of a known frequency.

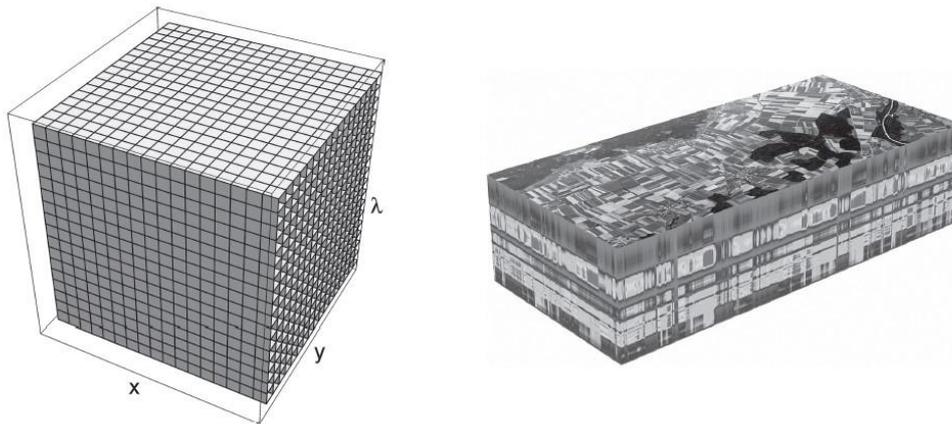
Initially it was designed to analyse the far infrared (FIR), but nowadays it can be used to analyse the entire infrared spectrum. There are already different studies which have managed to classify the different characteristic types of plastic with this type of spectrometer.

### **1.2.1.2 Multi-point spectrometers**

This type of spectrometer returns the spectral information from different points on a scene at the same time; normally the points are next to one another. The information returned contains an intrinsic spatial component between the measured points. This allows for the measured scene to be recreated by putting the data in order and they can be used to carry out more complex analyses.

The term “hyperspectral” usually refers to a set made up of a large number of spectral bands.

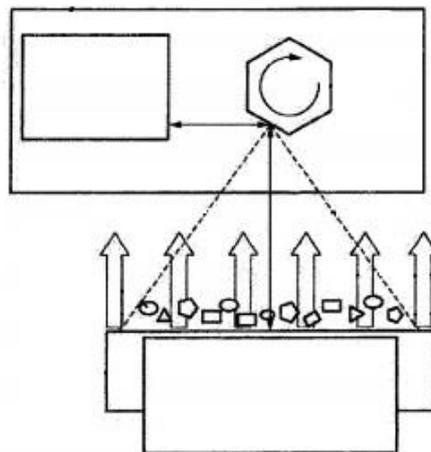
A “hypercube” is the most common way of representing the captured information using a hyperspectral vision system. This cube has three dimensions. Two of them represent an image in two dimensions of the captured scene. The third dimension represents the different bands that have been acquired from that scene.



*Figure 5 - Illustration of a hypercube.*

## **Whiskbroom spectrometer**

A spectrometer that has a mechanical part, which turns or rotates in order to change the point that is being observed. The movable part can be the sensor itself or a mirror.



*Figure 6 - Operating mechanism of a whiskbroom spectrometer.*

This sensor collects the information of the scene point-by-point in a linear way, acquiring as many samples as the rotation and acquisition speeds allow for.

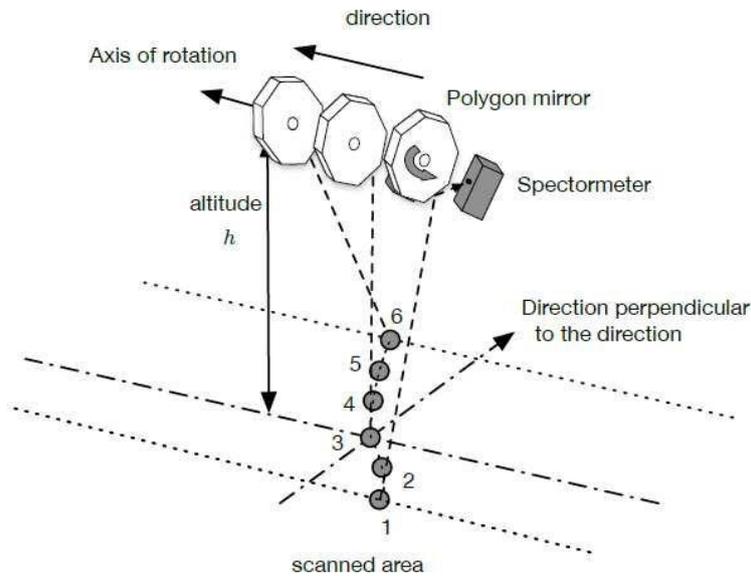
This type of linear spectrometer generates a hypercube with a length of 1 on one of its dimensions at each iteration. ( $1 \times n \text{ Pixels} \times n \text{ Bands}$ ).

If there are several iterations, they can be added to the hypercube to extend the image. ( $n \text{ Iterations} \times n \text{ Pixels} \times n \text{ Bands}$ ).

This type of spectrometer is usually used to capture wide scenes whilst the scene is changing due to the apparatus or the scene itself moving. An example is that of a spectrometer which analyses the elements that go along a conveyor belt or a spectrometer installed on a plane which captures what is happening underneath.

This type of spectrometer may be less precise than others given that it contains the movable part that controls the part of the scene that is being observed, which requires perfect calibration. Further to this, the distance from the sensor to

the point of the scene being observed is not always the same, which could cause distortion. If the scene is moved, not all of the corresponding pixels on the same line in the hypercube will be parallel in spatial terms when compared to the real scene. To correct this, the moving part is turned or rotated as quickly as possible, leading to a shorter sample acquisition time and resulting in a reduction in the intensity.

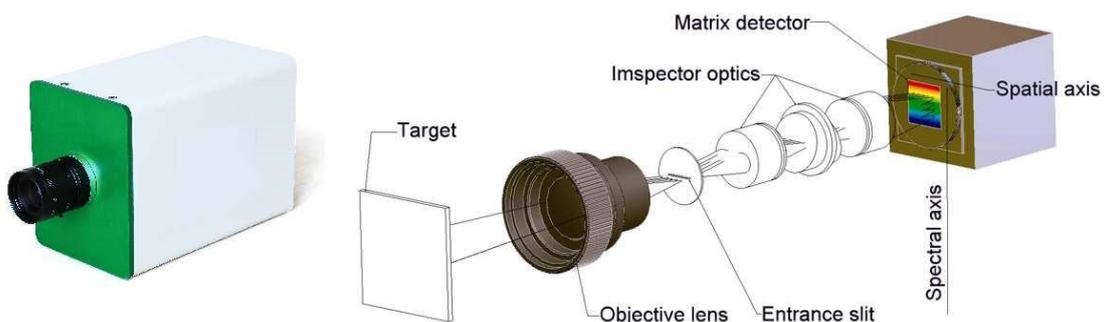


*Figure 7 - Recording of points of a whiskbroom spectrometer.*

However, all points are measured using the same linear sensor, making them more uniform than when scanned with a matrix sensor. In addition, this configuration allows the spectrometer to be equipped with a sensor with a larger number of cells for bands than that accepted by a matrix sensor, achieving a higher spectral resolution. Another advantage when calibrating the unit using the black and white references is associated with the fact that these references only need to have a single point size, making them more economical and flexible to use. In addition, this type of spectrometer is usually quite economical.

### **Pushbroom spectrometer**

This spectrometer features a matrix sensor instead of a linear sensor, allowing the spectra to be captured from the entire point line at the same time.

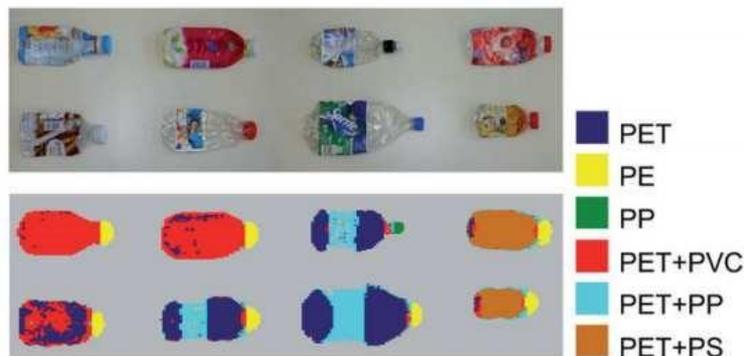


*Figure 8 - Pushbroom spectrometer and capturing the visible spectrum with a matrix sensor.*

The hypercube formed by this type of sensor during the capture process will have a length of 1 in one of its dimensions (1xnPixelsxnBands), as in the case of the whiskbroom spectrometer.

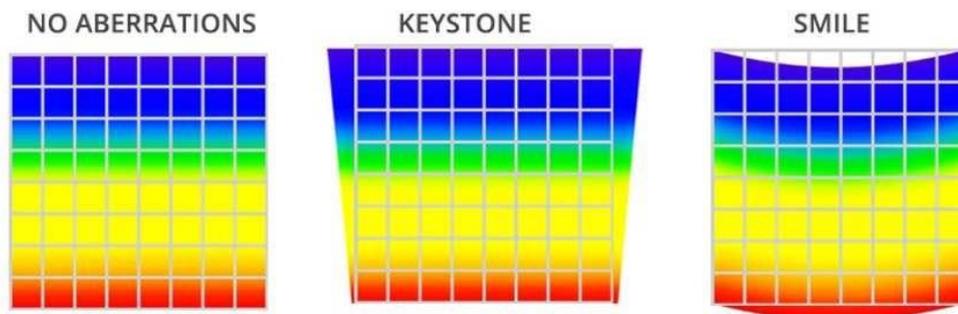
If iterations are repeated while the sensor or scene moves, these will be added to the hypercube. (nIterationsxnPixelsxnBands).

Capturing all information from a line of points at the same time means that the integration time will be higher, this translates into a higher intensity of the captured signal. In addition, it features no mechanical parts, increasing the robustness and reliability of the measurement.



*Figure 9 - Plastic classification example with a pushbroom spectrometer.*

However, they are very hard to calibrate and can suffer from different types of deformation that manufacturers try to correct, due to the use of the flat monochromator to disperse the beam on the matrix. Keystone and smile are the most commonly used.

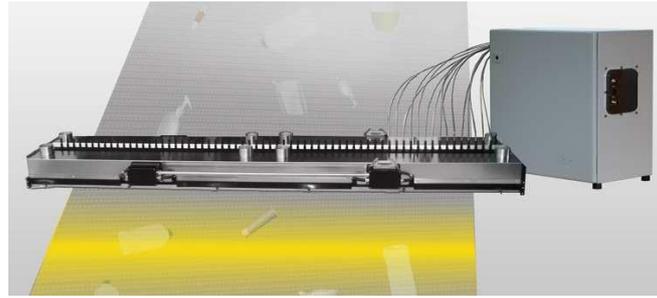


*Figure 10 - Possible deformations caused by the lenses of a pushbroom spectrometer sensor.*

Its special features make this the most common sensor used to inspect industrial production lines in which different elements are moved with a conveyor. Its only disadvantages are that its matrix sensor usually features a larger number of pixels than linear sensors, reducing the spectral resolution. They are also usually more expensive.

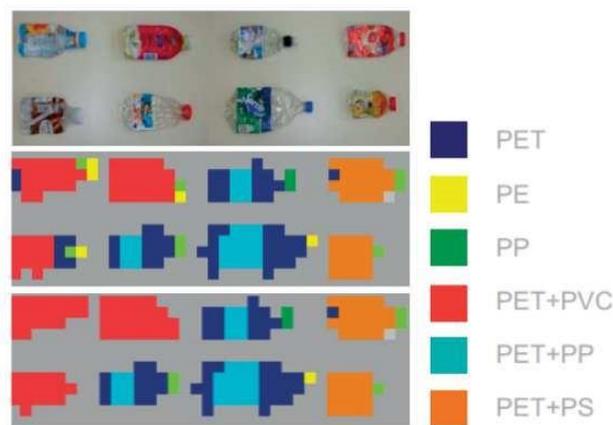
## **Spectrometer multiplexers**

This solution is similar to the pushbroom spectrometer, but it uses optical fibre probes that acquire an individual point from a scene instead of using a lens to acquire a linear scene.



*Figure 11 - Spectrometer multiplexer.*

The spectrometer features a matrix sensor, which assigns a line to each probe. However, the spatial resolution is poor, due to the placement and diameter of the probes. In some cases, small elements passing between them are not detected.



*Figure 12 - Plastic classification process using a system with spectrometer multiplexers.*

## Camera with replaceable filter

This type of camera is similar to a conventional camera, in which the sensor scans the light received to form the image of the scene, captured in two dimensions. This sensor must be sensitive to the spectrum bands of interest. If no filter is placed between the lens and sensor, the radiation reaching the latter will be a set of unclassified bands of the spectrum.

Band-pass filters must be used to capture different independent spectra, which only allow the spectrum of a band to reach the sensor.



*Figure 13 - Cameras with replaceable filter.*

Capturing a scene in two dimensions without having to move the sensor or scene

is an advantage, but a new capture is required for each band from which information needs to be captured. This depends on the filter replacement speed, which can make the process slower than when using a linear spectrometer.

The hypercube generated in this case with a capture has the dimensions of bands with a length of 1. (HeightxWidthx1). The dimensions of the hypercube will increase as additional captures are made when the filter is replaced. (HeightxWidthxnBands).

It is harder to synchronise this type of capture of a camera in production lines in which the product is not controlled. The conveyor does not usually stop, so the delay in changing the filter must be taken into account to make sure no information is lost.

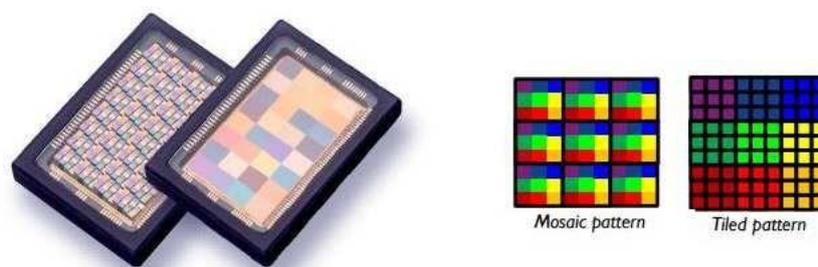
Another disadvantage is that there are a limited number of replaceable filters, so information can only be obtained from a few bands. Another solution to this involves using tuneable filters, which can change the band they allow to pass in dynamic terms. Another disadvantage of this method when compared to spectrometers with a linear or matrix sensor is that they must illuminate the entire scene uniformly and intensely, which is less economical and will produce worse results, due to the generation of shadows, heat and loss of intensity.

The lighting intensity will be lower, so the exposure time must increase, resulting in a slower acquisition process in each band.

This can be an interesting option if information is only required from a few bands. Otherwise, it is advisable to use one of the spectrometers described above.

## **Snapshot camera**

They use lenses and filters to divide the spectrum and capture the scene in the RGB spectra, as in the case of conventional cameras, each using a different sensor. Snapshot cameras operate in a very similar fashion. These cameras separate each pixel of the captured scene in pre-defined spectra and these are recorded by a sensor with a specific cell arrangement that allows all bands to be read in a single capture.



*Figure 14 - Types of sensor for snapshot cameras.*

There are two types of sensor, depending on how the spectra fall upon their cells:

- The “Tiled” pattern requires a captured scene to be duplicated internally, so each image can be captured from a section of the sensor later on. This

type of pattern provides a higher spectral resolution.

- The “Mosaic” pattern does not duplicate the scene, but rather it divides it in a similar way as a spectrometer would, structure the sensor so that all pixel bands form a square. This type of pattern achieves a higher spatial resolution.

The main advantage of this system is that it is faster than cameras with replaceable filters when capturing an entire scene, since it captures the spectrum of all bands at the same time.

The hypercube generated by this type of sensor in a single capture is the only element with three-dimensional information. (HeightxWidthxnBands).

The main disadvantage is that there is a limited number of bands and these cannot be configured, so these must be previously selected and it must be established whether there are enough or not. In addition, it shares one of the disadvantages of cameras with replaceable filters, since the entire scene must be lit with enough intensity and in a uniform manner.

Nowadays, much progress has been made in terms of this type of technology, allowing a higher spectral and spatial resolution to be achieved at a lower cost.

## 1.2.2 Illumination

The scene must emit radiation that can be detected by the sensor for the sensor of the hyper-spectral system to be capable of acquiring information from the scene. The scene might need to receive an external source of radiation, according to the spectral bands that need to be captured.

In the case of X-rays and ultraviolet rays, such as in the visible, infrared or terahertz spectrum, it is advisable to use an external source that emits in a known frequency of interest.

When radiation falls on an element, it interacts with its particles and some of the spectra can be absorbed or reflected more easily than others. The portion of radiation that is not absorbed and ends up reflected out of the body is the portion that can be measured.

To find out the internal chemical composition of the element we are radiating, the rays that have bounced off the highest possible number of particles and which have left the surface must be measured.

Different acquisition techniques exist, which are classified by the radiation path.

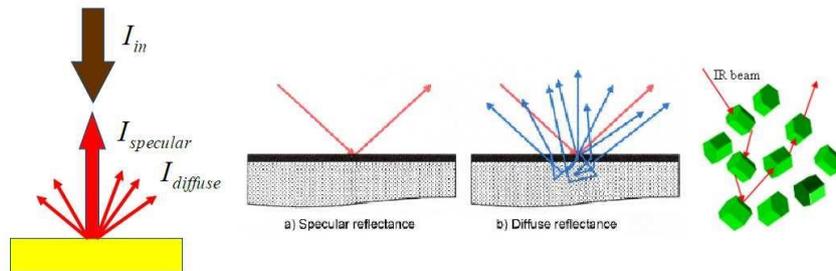
### 1.2.2.1 Illumination techniques

#### **Reflectance**

This technique is also known as diffuse reflectance and it is used to learn about the composition of a sample using rays that have radiated the surface and been reflected out of the surface at a specific departing angle.

This allows us to measure the rays that have interacted with at least one particle on the surface or those that have managed to penetrate the sample and have interacted with various samples, the information of the latter being the most valuable.

To maximise the intensity of the signal reaching the sensor, the radiation emitter and sensor must be pointing at the same point.



*Figure 15 - Direction of illumination when a reflection occurs on a sample.*

This technique is usually used on samples with a low degree of penetration and in classification lines, since they are very easy to use and flexible in different scenarios.

It only measures a small percentage of reflected rays, so illumination must be powerful enough and the integration time long enough to obtain a measurement that is as intense as possible.

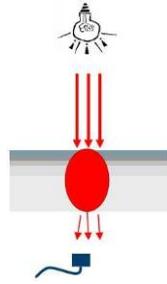
Therefore, the sensor must be placed in a position in which it cannot capture specular reflection information, since it contains very poor but much more intense information, which could mask the diffuse reflection data and even saturate the sensor. When measuring flat surfaces, the sensor and radiation emitter should form a 45-degree angle to avoid this problem.

However, this is not the perfect solution to measure plastic on a conveyor belt, since these are not completely flat surfaces and specular reflection can occur directly on the sensor. Another problem is associated with the uneven surfaces of some samples, causing them to generate shades on other samples, reducing the radiation level on the sample.

Both cases can be partly corrected by reducing the relative angle between the sensor and source of radiation. This reduces the number of shades, but increases the specular reflection received by the sensor, which leads to a reduction in the integration time and loss of information about the internal chemical composition of the sample. This last point might not be critical, since irregular samples will be used.

## **Transmittance**

This technique measures the rays passing through the sample, which provides information about its internal chemical composition.



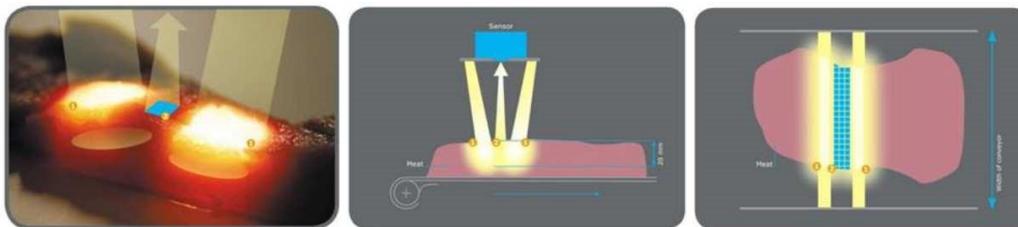
*Figure 16 - Path of light using the transmittance technique.*

This type of measurement can provide very valuable information. Unfortunately, not all materials allow light to pass through, and the light that manages to pass through and reach the sensor is very weak. This is due to the fact that the sample absorbs all radiation before it reaches the other side.

This technique is used in controlled environments, partly due to the complexity associated with implementing it, since the transport method of the sample must not interfere with the measurement and the environment must guarantee that the light of the emitter cannot reach the sensor after being reflected from other elements.

## **Interactance**

Interactance lies halfway between reflectance and transmittance. This technique seeks to measure the rays that have penetrated the sample, but which have not passed through it, as in the case of transmittance.



*Figure 17 - Direction of light when interactance occurs on a sample.*

In this case, the emitter and sensor are not pointing at the same point, avoiding the problems associated with specular reflectance.

In addition, since light does not have to pass through the sample, the intensity of the signal is much higher than that in the transmittance technique, although the internal chemical information of the full sample cannot be obtained. Moreover, the intensity level is much lower than when using the reflection technique, but the internal composition information is much more valuable.

This technique might not be suitable for all types of sample, depending on the type of material and its degree of absorption. In the case of plastics, these have irregular surfaces and the materials have different levels of opacity, so the lighting levels would not be uniform for all samples, potentially causing problems in relation to the intensity of the measurement.

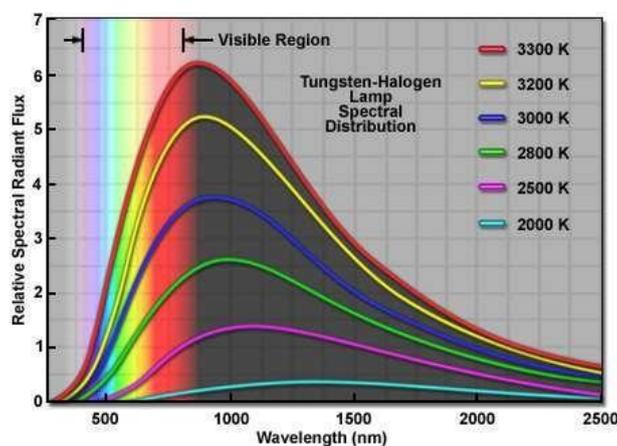
## 1.2.2.2 Sources of radiation

This study focuses on identifying plastics with infrared spectrometry methods. In this case, there are different types of sources of light in this spectrum that are of interest.

Different studies indicate that near infrared (NIR) and short-wavelength infrared (SWIR) can be used to classify different types of the most common plastics, so we will focus on the sources of radiation that can emit radiation at these frequencies.

### Halogen illumination

Halogen lamps produce a continuous light spectrum, which ranges from near ultraviolet to short-wavelength infrared. (200–3000 nm). These lamps generate radiation when they heat the tungsten filament contained inside. The higher the temperature, the more intense the radiation generated.



*Figure 18 - Spectrum of a halogen lighting source.*

A characteristic aspect is that the highest intensity peak moves throughout the spectrum, according to the temperature of the filament. The maximum temperature it can reach is 3550 degrees Kelvin.

The lighting power of a halogen lamp drops throughout its service life. High-power lamps used to illuminate the scene usually have a 2000-hour service life, after which they will have lost close to 5% of their lighting power.

The disadvantages of using this type of illumination method are a higher consumption of energy when compared to other sources and more heat generated, requiring the use of a cooling system in most cases.

Halogen lamps that have been prepared to direct radiation, which emit to a specific point or diffuse light can be found on the market.



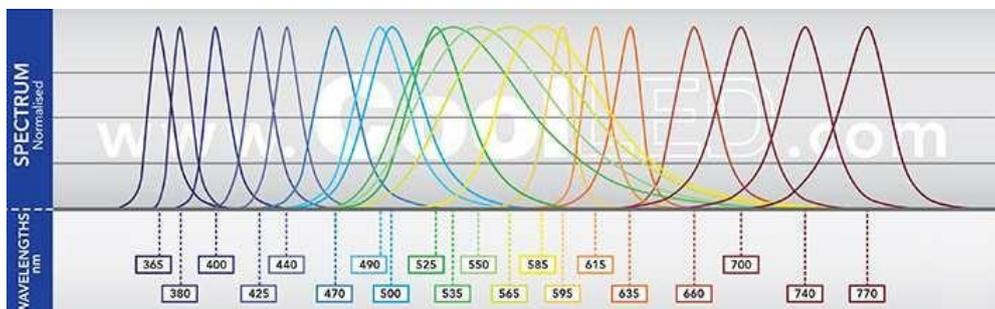
*Figure 19 - Capsule, spotlight and linear halogen lamps.*

In the case of capsule lamps, light is generated from one point, so the radiation can be concentrated in a single beam and directed to the sample to be measured. This type of lighting system is enough for point spectrometers.

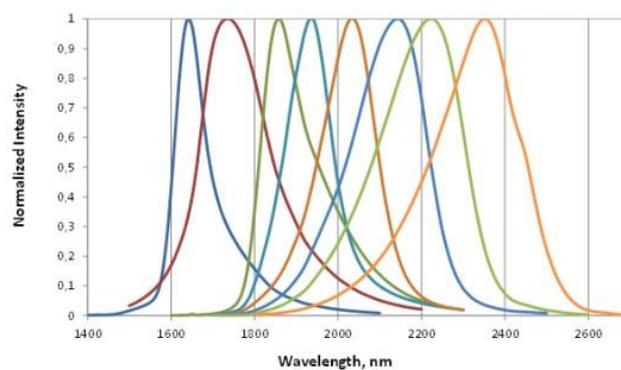
In the case of multi-point spectrometers, this type of lighting system can cause differences in intensity in different measurement areas. If a good diffuser is not available, it is best to use linear halogen lamps, since these generate the same amount of light throughout the scene, except on the edges. An external reflection system that collects the generated radiation and moves it to the points that will be inspected must be used.

## **LED Illumination**

LEDs have replaced halogen lamps in many cases, mainly due to their higher energy efficiency. This is due to the fact that the spectral range of a single LED is very small and only includes a few bands.



*Figure 20 - Electromagnetic spectra of different types of LEDs in the visible range.*



*Figure 21 - Electromagnetic spectra of different types of LEDs in the SWIR range.*

The spectral response will be different depending on the material your semiconductor is made of.

Color	Wavelength [nm]	Semiconductor material
Infrared	$\lambda > 760$	Gallium arsenide (GaAs) Aluminium gallium arsenide (AlGaAs)
Red	$610 < \lambda < 760$	Aluminium gallium arsenide (AlGaAs) Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
Orange	$590 < \lambda < 610$	Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
Yellow	$570 < \lambda < 590$	Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
Green	$500 < \lambda < 570$	<b>Traditional green:</b> Gallium(III) phosphide (GaP) Aluminium gallium indium phosphide (AlGaInP) Aluminium gallium phosphide (AlGaP) <b>Pure green:</b> Indium gallium nitride (InGaN) / Gallium(III) nitride (GaN)
Blue	$450 < \lambda < 500$	Zinc selenide (ZnSe) Indium gallium nitride (InGaN) Silicon carbide (SiC) as substrate Silicon (Si) as substrate—under development
Violet	$400 < \lambda < 450$	Indium gallium nitride (InGaN)
Ultraviolet	$\lambda < 400$	Diamond (235 nm) Boron nitride (215 nm) Aluminium nitride (AlN) (210 nm) Aluminium gallium nitride (AlGaN) Aluminium gallium indium nitride (AlGaInN)—down to 210 nm

Figure 22 - Materials for the manufacture of LED devices.

Due to the narrowness of the spectral band of LED devices, there are techniques for widening it. The simplest technique is to use several LEDs together to cover a larger spectral range. This is already applied in the production of screens. With the combination of three types of LED, red, green and blue, and playing with the intensity of each of them, a wide range of colours can be produced, including white. Another of the most commonly-used techniques is the coating of the LED with phosphors of different colours (PCLED). A fraction of the light undergoes the Stokes shift that transforms the shorter wavelengths into longer ones. Different phosphor colours can be used to further broaden the LED spectrum.

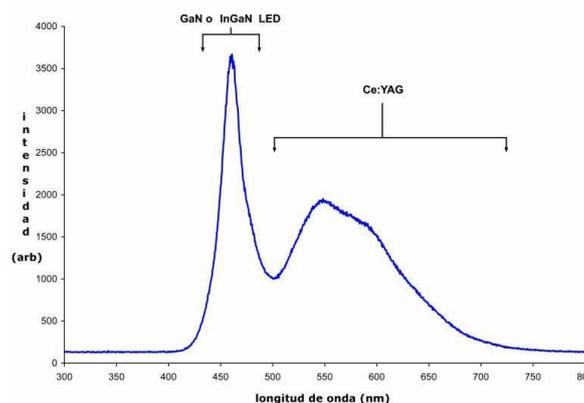
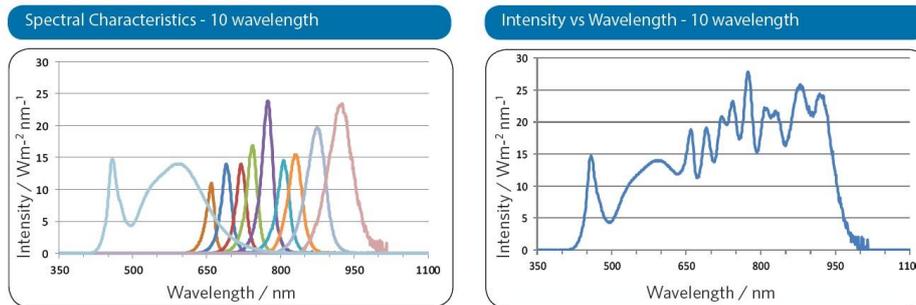


Figure 23 - Spectral response of a blue LED with yellow phosphor coating.

A blue LED and yellow phosphor are commonly used to produce light that we identify as white. Because the radiation is spread over a wider spectrum, this type of LED produces a lower intensity than pure LED devices.

Both techniques can be used to manufacture LED panels that allow a spectral response in the desired ranges.



*Figure 24 - Combination of different LEDs to obtain a continuous spectral response.*

Unlike halogen lighting, the spectral response is discontinuous. The selection of LEDs should be based on the bands that are of the greatest interest for us, since the rest will have a lower resolution.

One of the biggest advantages of the use of LED lighting compared to halogen is greater energy and light efficiency, since it is possible to avoid emitting in non-relevant spectra. This helps generate less heat.

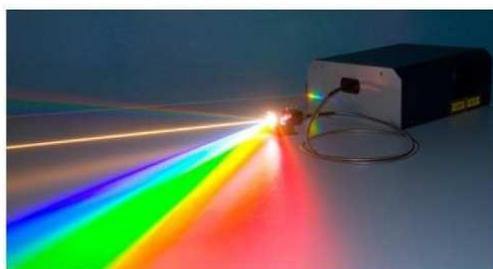
Another advantage of the LED is that its activation is very fast, being able to reach its maximum brightness in less than a microsecond. This is especially relevant if we do not need the source to always be in operation, since it is possible to turn it on only when we are going to take a measurement, helping to reduce consumption and temperature. This allows the possibility of increasing the intensity of radiation produced by applying a nominal voltage higher than that specified during a short interval of time, at the cost of reducing its useful life. It is inadvisable to use this tactic continuously as it would end up melting the circuit.

The useful life of a LED with normal use is between 35,000 and 50,000 hours, in which the intensity decreases with time. Higher than normal operating voltages or temperatures could shorten it.

Part of the energy that the LED receives is lost in the form of heat through its base which, depending on its power and operating time, may require measures to disperse that heat. It is advisable to place the LEDs on a dissipating base.

## **Supercontinuous laser**

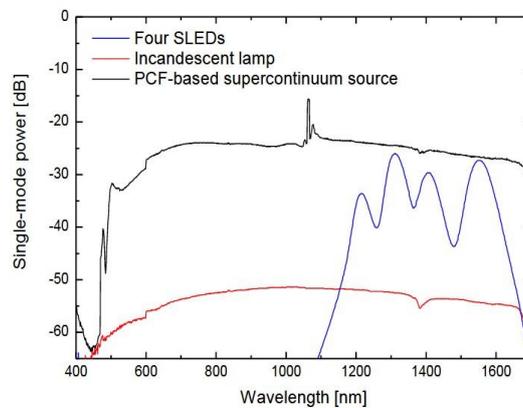
Supercontinuous light sources are very broad spectrum sources with a uniform intensity similar to that of the sun.



*Figure 25 - Supercontinuum laser.*

Commonly the light of a laser is characterised by being monochromatic with a spectral band of very narrow but very intense emission, with it being necessary for

several of them to be at different frequencies in order to emit a wide spectrum. A supercontinuum laser manages to produce a spectrally broad spectrum with the intensity of a laser.



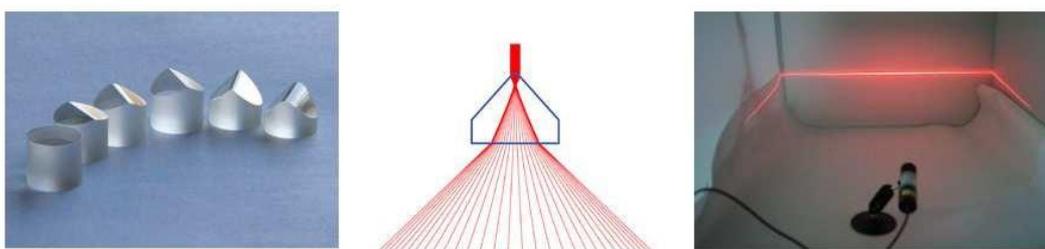
*Figure 26 - Spectra comparison: Superluminescent LEDs, halogen light and supercontinuum laser.*

Commercially there are supercontinuum lasers capable of emitting beams of various ranges, some reaching up to 4000 nm.

The main disadvantage of this technology is that it is still very expensive and research continues to improve its efficiency and lower costs.

The supercontinuum laser, like all lasers, is a point source of radiation. For use in a plastic waste identification line, some kind of technique should be used to expand the beam.

In the case of using a point spectrometer, the point of measurement of the sample and that of the laser must coincide. If a multipoint system is chosen, the direction of the beam must be modified, either with a mirror that rotates to expand it along a whole line or with the use of lenses that produce the same effect, which can cause a loss of intensity.



*Figure 27 - Linear dispersion of light from a red laser.*

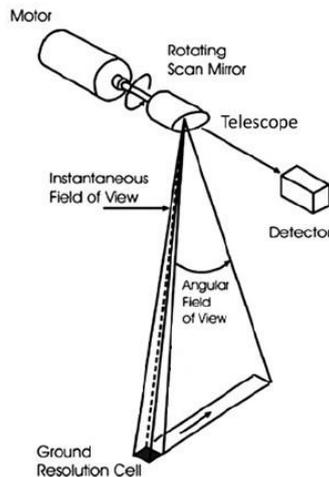
## 1.3 Whiskbroom spectrometer

After the initial study on applicable technologies and infrared spectroscopy, it has been concluded that for the time being the best alternatives for the classification of plastic would be either Pushbroom spectroscopy with hyperspectral cameras (which is the technology that is already being used in our systems), or Whiskbroom spectroscopy, which raises some doubts over whether it could reach the resolutions of hyperspectral cameras at a reasonable price. The aim was to study

the latter option in greater depth in order to try to answer the doubts it raises.

### 1.3.1 Whiskbroom scanner

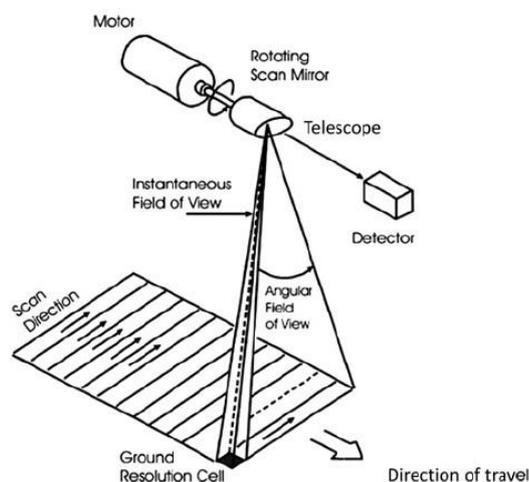
Whiskbroom scanners are typically point spectrometric sensors that cover the area of interest through the machined angular motion of a mirror or the machined rotation of the sensor itself.



*Figure 28 - Whiskbroom scanner with angular movement of a mirror.*

The sensor extracts spectrometric information from a single point at a time (Instantaneous Field of View, IFOV), but thanks to the angular motion of the mirror or sensor, the inspection point advances along a line (Angular Field of View, AFOV).

If a linear movement is added to the sensor itself or to its area of interest, for example by installing it in a vehicle or on a conveyor belt, it is possible to acquire samples throughout a scene by concatenating the processed lines.



*Figure 29 - Whiskbroom scanner with linear movement added to the angular movement.*

The hypercube will be created from the spectrum of each pixel that is acquired. The information stored will be the same or similar to that which can be captured using other types of scanner, such as Pushbroom or hyperspectral cameras.

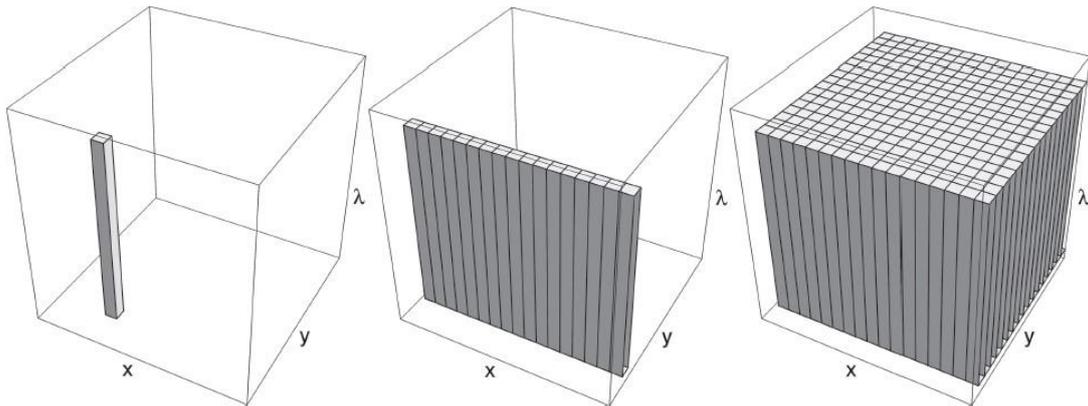


Figure 30 - Representation of the construction sequence of the hypercube.

However, the internal or interlaced structure of the hypercube data will be different due to the order in which it is acquired. In the case of the hypercube created by a Whiskbroom scanner, the structure will be of the “beep” type.

Interlaced “beep”: The hypercube is formed by the succession of the spectra of each pixel that is taken. This structure is typical of Whiskbroom linear spectrometers.

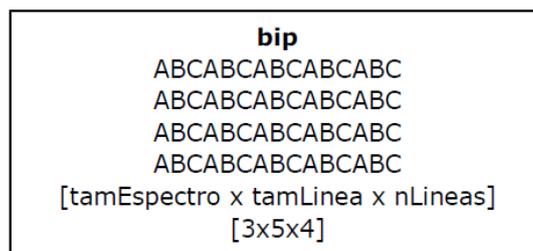


Figure 31 - Interlaced “beep”.

Pushbroom spectrometers and hyperspectral cameras use other types of interlacing such as “bil” and “bsq” respectively, as their capture sequence is different.

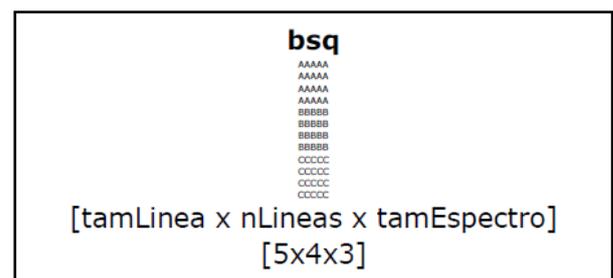
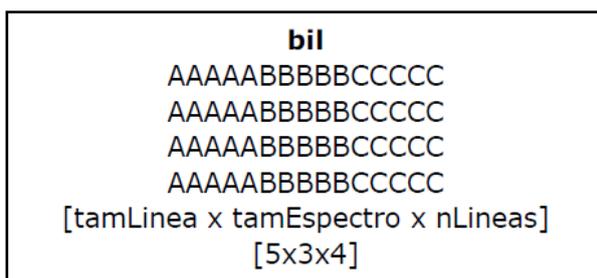


Figure 32 - Interlaced “bil” and “bsq”.

One of the main advantages of Whiskbroom scanners in the field of spectrometry is the uniformity of the data obtained, since the same linear sensor is used for the measurement of all pixels. This configuration allows sensors with a larger pixel size to be used, which translates into greater sensitivity to light, i.e. it requires less exposure time and the signal contains less noise or, on the contrary, sensors with a larger number of pixels can be used, allowing the spectral resolution to be increased.

At the time of performing the calibration, we find another of its advantages: the white and black references only need to be the size of a pixel. This makes calibration much more economical, accurate, flexible and easy to implement.



*Figure 33 - White reference.*

In addition, when using a linear sensor, this type of spectrometer is usually cheaper than the Pushbroom type.

However, this design has some disadvantages, the main one being the presence of a mechanical element, which may require occasional or periodic maintenance and calibration.

Unlike Pushbroom sensors that measure a whole point line simultaneously, Whiskbroom devices must capture each pixel of the line individually. This is another disadvantage of this type of sensor because, with a sensor of a similar size and equal illumination, more time will have to be spent on acquiring the information from a single line.

In these conditions, a longer measurement time and the particularity of taking the points sequentially in a changing scene causes a lower spatial resolution between lines compared to a Pushbroom sensor.

Also, depending on the exposure time, the mirror geometry and/or the rotation speed of the mechanical element will allow a line to be formed by more or fewer points. Depending on whether the mechanical element continues to rotate or not while the captures are made, a pixel drag effect may occur.

If we want to increase the spatial resolution and/or decrease the drag effect, we need to reduce the integration time, causing increased noise and a loss of signal intensity. An increase in the light intensity generated by the light source, an increase in mirror size or a larger pixel size could reduce this problem.

## **1.3.2 Elements of the system**

A Whiskbroom hyperspectral scanning system consists of the following three basic components: A point spectrometer, a moving mirror and a lighting system.

### **1.3.2.1 Point spectrometer**

This type of spectrometer records the intensity of light at a single point in space. A spectrometer is able to measure the amount of light on a limited spectral band, which is the band that it is sensitive to. The spectrometers divide this band into narrower portions, the size of these portions is closely related to their resolution. They give us the measurement of the light intensity for each of the portions, which

makes it possible to then obtain the spectral response across the entire sensitive band.

As already mentioned in a previous section, the ones most commonly used in the industry have a monochromator that disperses light in different bands and a linear sensor. Each of the sensor's cells, which are positioned to form a line, will measure the intensity of a different band.

Fourier Transform spectrometers are also available, but because they require longer exposure times they are not often used for online systems.

There are several features to consider when choosing a point spectrometer. The most important are the following:

- **Spectral range:** Range of spectra between which the spectrometer is able to separate and measure the different electromagnetic bands. This range usually depends on the type of monochromator and linear sensor.
- **Spectral resolution:** The separation space between two contiguous bands so that the spectrometer is able to correctly separate the information. Such band separation may vary along the spectrum. Sensors with a higher number of pixels usually have a better spectral resolution.
- **Sensitivity:** Sensor cells will excite more or less quickly in certain bands, depending on the type of linear sensor the spectrometer has and the amount of light reaching it. Higher sensitivity allows a higher quality response to be obtained with a shorter exposure time.

Those scientific articles that have achieved the best results when classifying plastics have been those where spectrometers with a spectral range between 1000 and 2500 nm (SWIR) have been used.

Below is a table with different models of spectrometers with different characteristics. Due to the high cost of equipment with a higher spectral range, data from spectrometers offering a lower range are also included in the table. The prices are just indicative for buying a unit and may vary at the time of purchase.

Model	Manufacturer	Spectral range (nm)	Spectral resolution FWHM (nm)	Price (€)
C11482GA	Hamamatsu	900-1700	7	7.000-8.000
C9913GC	Hamamatsu	900-1700	7	11.000-12.000
C9914GB	Hamamatsu	1100-2200	8	16.000-17.000
C11118GA	Hamamatsu	900-2550	20	16.000-17.000
UV VIS /H	Insion	350-850	10	900-1.000
UV VIS SENS HR /H	Insion	350-850	5	1.000-1.500
UV 2 NIR /H	Insion	200-1000	10	1.000-1.500
NIR 1.7 /H	Insion	900-1700	16	4.500-5.500
NIR 2.0 /H	Insion	940-2000	16	4.500-5.500
NIR 1.7 NT /H	Insion	900-1700	10	3.000-4.000
NIR 2.0 NT /H	Insion	940-2000	10	3.500-4.500
ROCK NIR	Ibsen	900-1700	3	7.000-10.000
ROCK XNIR	Ibsen	1175-2185	3	7.000-10.000

*Figure 34 - Spectrometers.*

Each brand carries out its tests in different environments, so in order to correctly compare some of its specifications, such as sensitivity or even the spectral range, refer to each manufacturer's catalogue.

For the carrying out of a Whiskbroom spectrometer test, look for one with greater sensitivity since it will permit the reduction in exposure time of each point and, consequently, increase the spatial resolution.

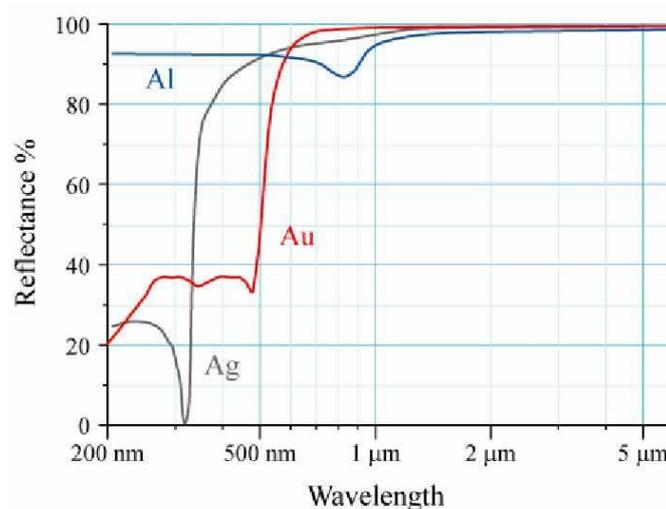
### **1.3.2.2 Mobile mirror**

Most scanner systems based on the use of a laser beam use a mobile mirror to direct it to the different points of interest. Some of the most common equipment that uses this system is laser printers, 3D printers, barcode readers, laser engraving machines, laser lighting for events, etc.

Performing the opposite action, moving or rotating the spectrometer probe or lighting, is a major challenge when implementing the system and can be affected by the physical limitations of the probe, the lighting or the mechanical system itself. In our case, the application is very similar, as we need to direct the point of interest of the spectrometer to the different points of the recycling tape that we want to scan/measure and, in the case of using point lighting, also the light source.

The direction the beam can take can be one-dimensional, as in a laser printer, or two-dimensional, as in laser lighting at events. As our objective is to measure line by line the band that transports the material to be recycled, a mobile mirror that allows the direction to be modified in only one direction will be sufficient.

Normally they are built from aluminium, due to its low cost and high reflectivity in most of the bands, although mirrors made from other materials can also be found.

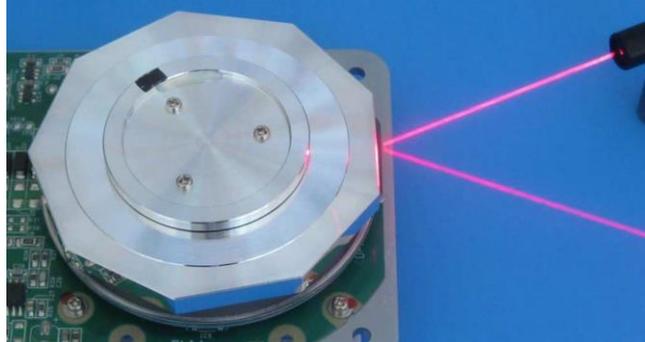


*Figure 35 - Reflectivity of the aluminium (blue), gold (red) and silver (grey).*

The most commonly used mobile mirrors in the industry that would allow this change of direction of both the point of interest of the spectrometer and the illumination source are the following:

## **Polygonal mirrors**

Polygonal mirrors rotate at great speeds on their central axis, allowing a fast scan of the line they reflect.



*Figure 36 - Polygonal mirror reflecting a laser beam.*

To control the scanning motion, a rotary encoder is required to communicate the position and speed of the mirror, and an electronic control circuit to manage the current supplied to the motor.

This type of mirror is popular because it can maintain a constant speed, its angle of vision can reach up to 120° in polygonal mirrors on three sides, and the speed it can reach is very high, being able to perform up to 70,000 sweeps per second.

Polygonal mirrors are often used for the construction of LIDAR devices, barcode readers, laser printers, Whiskbroom scanning in drones, etc.

Depending on the height at which we place the mirror, it should have a greater or lesser opening angle when making the measurements so that it can cover the entire conveyor belt. There are mirrors with angled faces to concentrate the area of interest to a greater or lesser extent. It is also important that the size of the faces is as large as possible, since this makes it possible to collect more light from the scene, allowing a reduction in the exposure time of the spectrometer.

This type of instrument is designed for devices with high acquisition rates, and therefore, it is usually configured to rotate at very high speeds. If we want to acquire several points from a single line, the mirror must rotate at lower speeds. Even at low speed, the mirror is never still, so the measurement taken is likely to comprise a set of points on the line.

The following companies market polygonal mirrors with a controller, offering some equipped with the features we need (low speed, high reflectivity, sampling angle etc.) for about €1000:

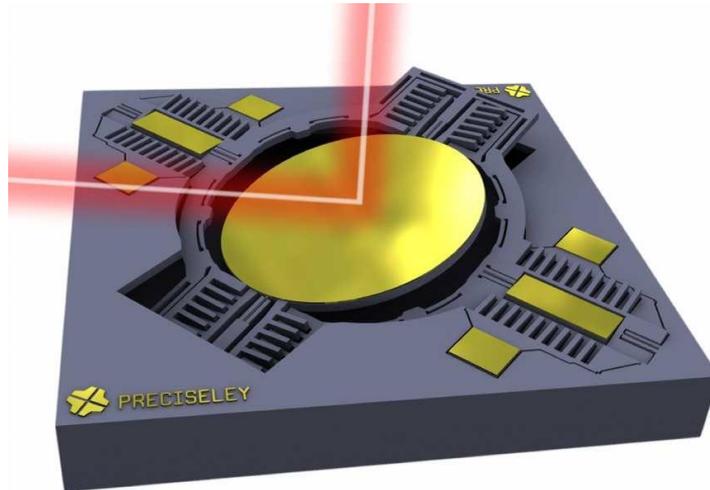
<https://precisionlaserscanning.com/>

<https://www.eminebea.com/>

On the manufacturers' websites, the models they offer and their specifications can be consulted.

## **MEMS mirrors**

A MEMS (Micro-ElectroMechanical System) mirror is an optical device that allows the direction of a beam to be modified along one or two dimensions.



*Figure 37 - Representation of a MEMS mirror reflecting a laser beam.*

This type of mirror uses different physical principles to change its orientation. These principles can be electromagnetic, electrostatic, thermoelectric or piezoelectric, among others.

Non-resonant MEMS mirrors are those that, via the use of a controller, can orient the mirror almost instantaneously to the desired position, which is ideal for scanning or illuminating only certain points of interest on the line for as long as it is necessary, avoiding the pixel drag that occurs in polygonal mirrors.

Quasi-static MEMS mirrors enter a state of equilibrium similar to that of a pendulum, being able to perform high-speed sweeps of up to 50,000 lines per second. Their way of acting on the scene would be similar to a polygonal mirror, apart from the ability to vary its direction.

Commercial firms usually offer mirrors of up to 7.5 mm in diameter, and it is possible to find some which are a little larger. Depending on their size, they will be able to reflect more or less light towards the spectrometer.

As with the polygonal mirror, the MEMS mirror also has a limited opening angle, being possible to find up to 45°. Depending on the height at which it is placed, it will be necessary to take this aspect into account so that it can cover the whole scene.

At first, it was expected that this type of mirror would be used for the Whiskbroom scanners of UAVs to take photographs of the Earth, but it has become evident that the vibrations that occur in that environment, as well as in other classes of vehicles, interfere with the mirror positioning system. Thus, the use of MEMS mirrors has been relegated to environments where they are not affected by vibrations.

MEMS mirrors are often used for microscopic analysis, object recognition and measurement, 3D cameras, triangulation, laser marking, imaging, spectroscopy, etc.

The following companies market MEMS mirrors with a controller, some of them offering a wide variability of configuration options, for a price of around €900-€1500:

<https://precisionlaserscanning.com/>

<https://www.preciseley.com/>

<https://www.hamamatsu.com/>

<http://www.opusmicro.com/>

On the manufacturers' websites you can consult the models they offer and their specifications.

### **1.3.2.3 Lighting system.**

The scene must be lit with sufficient intensity across all the electromagnetic frequencies it is wished to study so that all the measurements taken will be of adequate quality and allow for better identification of the plastics. Greater lighting intensity and quality may lead to less exposure time being required for each measurement, allowing the spatial resolution to be increased.

As the measurement area of a Whiskbroom scanner is a point, the lighting may be synchronised with it and be focused on solely lighting up that point, preventing the light from being dispersed along an entire line. This may improve the system's energy effectiveness and efficiency and also open up new lighting options. However, synchronising the measurement point with the lighting may require the use of techniques that may be more costly to implement than a simpler system that evenly lights up the entire scanning line with greater intensity.

Thus, the two lighting systems deemed most effective shall be presented: linear halogen lighting and pinpoint lighting with a Supercontinuum laser. These were already discussed in previous sections so we shall only add some information relating to the solution we are seeking.

#### **Halogen lamps**

Halogen lamps produce a continuous spectrum of light that can cover from near ultraviolet up to shortwave infrared (200–3000 nm). There are different types of halogen lamps (capsule, spotlight, linear). Depending on how the measurement is to be made it may be appropriate to use one kind or another.

If measurements are going to be made at fixed points on the belt (using a MEMS mirror for example), the use of capsule or spotlight type halogen lamps may be justified, as only the points to be measured have to be lit up. On the other hand, if several samples are taken on a line but the measurement point changes while the capture is being made (using a polygon mirror for example), the lighting must be even along all the points, so it is recommended to use linear halogen lamps.

As it is desired to give priority to reducing the spectrometer's exposure time in order to take more points per line, one must seek that the lighting system based on halogen lamps, produces the greatest possible intensity.

It should be taken into account that over the past few years, different legislation has been enacted, obliging manufacturers to cease making some types of halogen lights. A type of lamp should be chosen with a technical application that can hardly be affected by the future regulations of halogen lamps.

### **Supercontinuum laser**

The radiation beam produced by supercontinuum lasers is usually very intense and covers a very wide spectral range (400-2400 nm), illuminating the entire band more or less evenly. The beam of light emitted by the supercontinuum laser has the qualities typical of any laser such as directionality, a well-defined emission frequency (in this case the spectrum is much wider than with a normal laser), a capacity for emitting in pulses and coherence.

In this case, the coherence and the capacity to emit pulses is irrelevant, as although we are using a pulsed supercontinuum laser, the pulses are so close together that a single measurement of the spectrometer would capture hundreds of them. The directionality quality means that the output of the laser will emit the spectral radiation as a ray, causing the entire intensity of the beam to be focused on a point of the scene. This point has a certain diameter, which will get larger as the point of origin gets further away from that of the end.

Due to the pinpoint nature of the beam of a supercontinuum laser, it is necessary that the spectrometer's observation point and the laser's target must coincide, with the technical difficulties this entails.

There is the possibility of transforming the laser's point into a line and simplifying the device, thus encountering a scenario similar to that of using linear halogen lamps. There are several techniques to attain the conversion:

- The use of a dispersing lens: With the lens one can transform a pinpoint beam into a line. However, each spectrum the beam is made up of diverges at a different angle. This would result in a non-homogeneous line, with segments at the ends where some spectrums would not reach. Moreover, the light's intensity would be spread out along the entire line, leading to an increase in the exposure time.
- The use of a polygon or MEMS mirror: Using one of these mirrors, rotating or gyrating at great speed, it is possible to move the beam through the scene so quickly that if we were to measure the intensity of the spectrums at each point of it, it would be equivalent. However, as when using the dispersing lens, the light intensity would be lower as it would be spread out along the entire line. Thus, creating a line with a supercontinuum laser could be less effective and more expensive than using halogen sources.

If it is decided to use this type of lighting in its pinpoint variant, one must find the way of synchronising the spectrometer points and the beam. This is possible by using polygon or MEMS mirrors.

One of the main disadvantages of using this technology is its high price.

Depending on the application, another disadvantage is that the point struck by the beam gets very hot and may burn or melt certain materials if it strikes for enough time. In our case, as the belt is moving the latter should not be a concern, as long as pertinent safety measures were taken.

Some of the companies that sell this type of equipment are:

<http://www.fyla.com/>

<https://www.thorlabs.com/>

In the case of the FYLA Company, they have the following supercontinuum laser models that could be of interest for our needs. The prices are approximations.

Modelo	Rango espectral (nm)	Precio (€)
SCT500	500-2200	19.000
SCT1000	450-2400	23.500

*Figure 38 - Supercontinuum lasers by the Fyla Company.*

According to the specifications of the lasers, model SCT500 is the one of most interest as it has the highest light intensity in the infrared spectrum, which is the one most used for sorting plastics. The details and specifications of the available models offered by both manufacturers are explained on their websites.

### 1.3.3 System configuration.

To implement a Whiskbroom scanning system with the task of the in-line identification of the different types of plastic that comprise the different objects that travel along a conveyor belt, several designs have been devised using the different elements discussed in the previous section.

#### 1.3.3.1 Spectrometer.

On one hand, the scanning element must be a spectrometer. The model to be purchased will depend on the price and on the bands it is finally wished to use for identifying plastics. It must be highly sensitive to light to fulfil the aim of equalling the efficiency of the current system, which uses a hyperspectral Pushbroom camera as a capturing system. On seeking a spectrometer that is highly sensitive to light, it is sought to capture the maximum possible number of points per line and the maximum number of lines per second, to attempt to not lose too much spatial resolution in comparison to the previous system.

To reach similar levels of spatial resolution to those of a Pushbroom scanner using a Whiskbroom scanner, would probably require a greater number of spectrometers or use a system with a matrix sensor (multiplexing). These solutions for increasing the spatial resolution do not fulfil the aim of reducing costs, as they are probably more expensive than the current solution of using a Pushbroom hyperspectral camera.

There are spectrometers, such as model C11118GA from Hamamatsu that are capable of taking a measurement in 6µs. In an ideal scenario in which the lighting

were sufficient to take a measurement with sufficient signal, for example it could take a line of 500 points every 3ms approximately.

### 1.3.3.2 Mirror.

Due to the pinpoint nature of the spectrometer, a system must be used to manage its observation area. For our case, the most usual is to use a polygon or MEMS mirror and by rotating them or changing their orientation, perform scans in one dimension.

The polygon mirrors on the market are conceived for scanning laser beams at high speeds, of about at least 1000 lines per second. It is possible that a slower one could be found or a customised one could be built with a motor and a controller.

If a polygon mirror is used, it would rotate continuously so that each measurement would be the result of all the points through which the area of interest passes during the exposure time of the spectrometer. Depending on the rotation speed and the integration time, more or less points could be taken per line or even a single point for every so many lines.

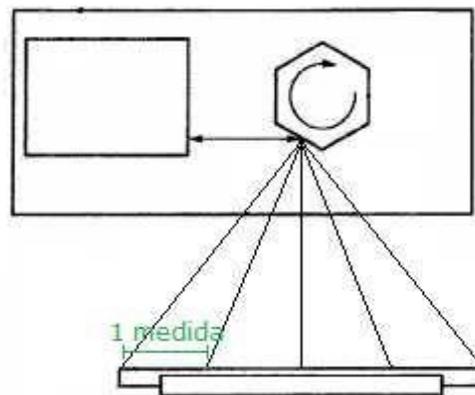


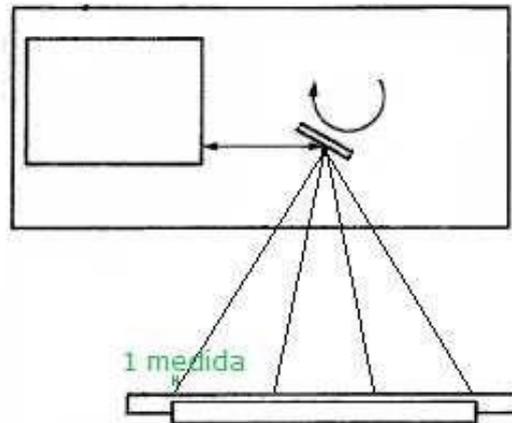
Figure 39- Distance travelled for taking a measurement with a polygon mirror.

In the example of diagram 12, four points are being taken per line. However, each one of the points covers a quarter of the belt, so that in this space several types of plastics may be encountered in addition to foreign objects or those pertaining to the belt itself. The measurement will be a grouping of the objects encountered, giving mixed results. In the case being studied this would lead to a problem, so that if a polygon mirror were used, a number of lines would have to be decided on, for the spatial resolution to be sufficient for the sorting.

A non-resonating MEMS mirror can adopt a certain orientation almost instantly, also being capable of catering for lines, just like a polygon mirror or a quasistatic MEMS mirror and even though it is at a somewhat slower speed, it is perfectly adequate.

With this type of mirror one can specify the exact position on the line towards which we wish to orientate the spectrometer's point of interest and during how much time before passing onto the next one. This possibility prevents us from

scanning different objects in a single measurement, allowing for knowing the position of these on the belt with greater accuracy.

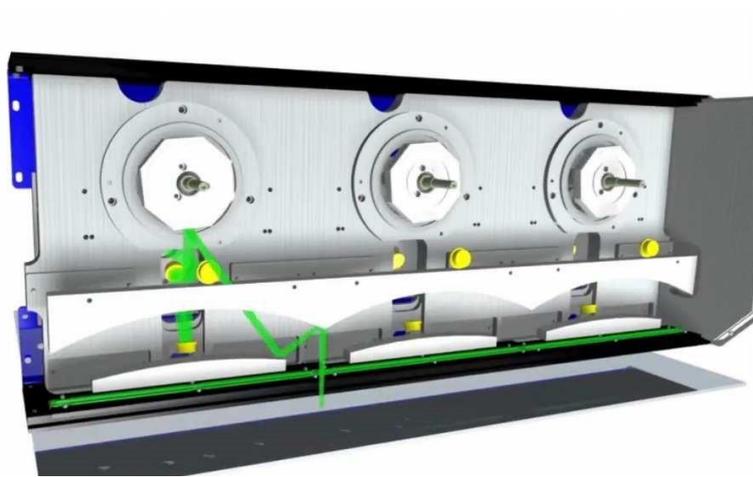


*Figure 40 - Measurement point on the belt with a MEMS mirror.*

Another aspect to be taken into account is the angle limit by which the direction of the spectrometer's observation point can be modified. Whereas in the polygon mirrors there are models that allow angles of up to  $\pm 60^\circ$ , the MEMS mirrors are somewhat more limited and on the market one can find models that reach up to  $\pm 40^\circ$ , such as for example the DC0400CG model from Opus Microsystems. The specification that indicates the maximum orientation angle of a mirror limits the height at which the mirror must be set with respect to the belt, so that it is able to cover it entirely. For example, to cover a belt one metre wide with a MEMS mirror that allows a change in the orientation of  $\pm 40^\circ$ , it must be fitted some 60 centimetres above the belt.

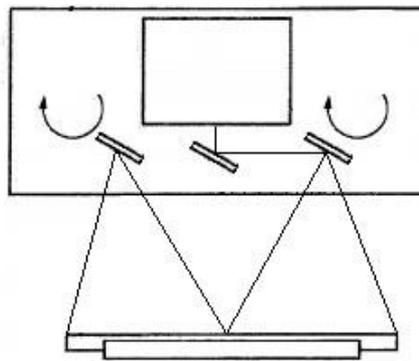
The distance between the spectrometer's sensor and the sample is crucial for ascertaining the required exposure time, as the closer it is, the more light it will be able to receive and require less time. This also means that we shall receive a signal with greater intensity from the centre of the belt than from its ends.

Several of the possible solutions for this case are to increase the lighting intensity of the light source or to use collimator lenses to concentrate the light that reaches the sensor. Another would be to use several spectrometers or mirrors.



*Figure 41 - Whiskbroom scanner with several mirrors and spectrometers.*

A similar solution that would keep the cost low and increase the signal quality would use several mirrors to aim the spectrometer's observation point at the different points on the belt.



*Figure 42 - Diagram of the Whiskbroom scanner with two MEMS mirrors.*

This solution is both for use with polygon and MEMS mirrors. Even so, to reduce the distance and the scanning time per line even more, it would be preferable to use one spectrometer per belt section, as we avoid the signal from having to travel between mirrors and the small attenuation that this may cause.

### **1.3.3.3 Lighting**

Good lighting of the scene is essential to obtain data with useful information that allows for identifying the type of plastic being analysed. The radiation that excites the scene must contain the range of spectrums it is being attempted to capture with the spectrometer.

The lighting must be even on all the bands and at all the measurement points to increase the accuracy of the sorting model. Sufficient intensity must be sought to reduce to the spectrometer's exposure time to the minimum.

On one hand, using a halogen lighting system is the cheapest option, it can cover the range of spectrums we wish to measure (NIR and the beginning of SWIR) and offers options for trying to increase the intensity it produces, either at a point or a line.

The second lighting option being considered is the use of a supercontinuum laser. These lasers focus all the intensity of the spectral radiation that they produce on a single point. As the spectrometer also measures in pinpoint form, both systems can be used if the target point is synchronised. Said synchronisation can be performed by making the spectrometer and the lighting use the same mirror system, managing to make both follow the same path. This system is the one used by laser scanners due to its implementation simplicity and as it is not costly. A barcode reader is an example of this kind of system.

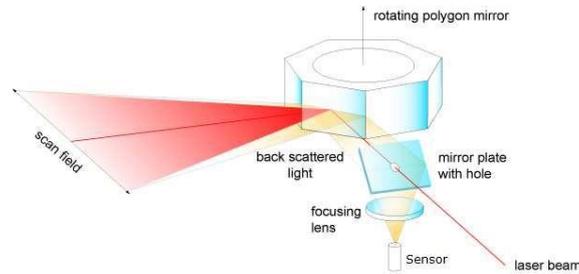


Figure 43 - Diagram of a barcode reader.

### 1.3.3.4 Scanbox.

This same system is the one used in the SCB equipment from the FYLA Company, also known as the SCANBOX. The spectrometer and the light source are sold separately.

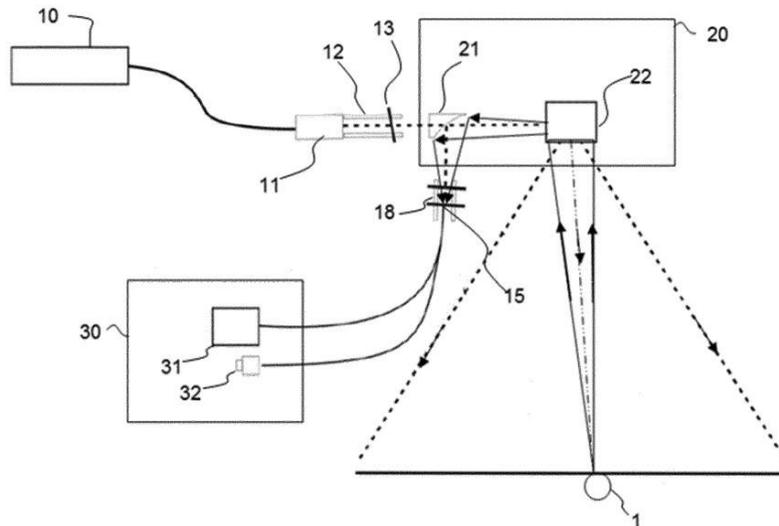


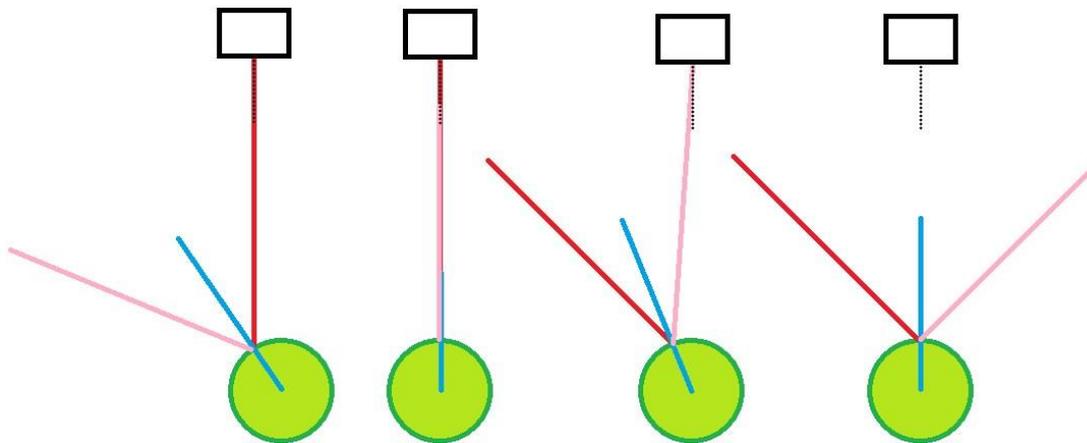
Figure 44 - Diagram of the SCB system from FYLA.

This SCB system (20) uses a supercontinuum laser as the light source (10), the beam of which hits a polygon or MEMS mirror (22) and is aimed at a point of the scene (1). In turn, the spectrometer (31) is observing it and measures the spectrums that are returned from the point on the scene (1) to the mirror (22). The supercontinuum laser and the spectrometer are capable of observing the same point on the scene thanks to a parabolic mirror with a hole.

The SCB system by FYLA has a cost of approximately €12,000 in its version using MEMS mirrors and of €16,000 in its version with polygon mirrors. The minimum speed

of the polygon mirror version travels a line in 1ms. This may be too fast for the spectrometer. The MEMS version allows the speed and the position of the measurement points to be programmed. Some of the system's technical specifications can be found on the manufacturer's website.

As already discussed in previous sections, there were three techniques to light up a scene in spectroscopy: reflectance, transmittance and interactance. Due to the irregular and random nature of the elements that travel along the belt, it was recommended to use reflectance, which consists in lighting up the scene and measuring the beams that have interacted with the material at the same point in order to know the original radiation spectrums absorbed by it. It was also seen that the best light incidence angle is of  $45^\circ$  with respect to the spectrometer's sensor. Nevertheless, said angle is the optimal one for scenes with a relatively flat surface and that are perpendicular to the observation axis. In the case of identifying plastics for recycling, these are going to have irregular shapes and specular reflective angles that hit the sensor.



*Figura 45 - Direction of specular reflection after a light beam strikes a cylindrical object.*

Supposing that a perfectly cylindrical plastic bottle laying down passes along the belt and that the beam of the supercontinuum laser only hits one point, for bottles 1 and 2 of Figure 45 it would occur that the radiation beam and the spectrometer's sensor would form an angle of  $0^\circ$ . For 3 and 4, the angle they would form would be of  $45^\circ$ . In both cases there is some condition in which the specular light will reach the sensor.

Moreover, the incidence angle on the scene varies depending on its position. The incidence angle of the light on an object at the central point of the belt would be of  $0^\circ$  but at the ends it would be of  $40^\circ$  (assuming that we use a mirror with  $\pm 40^\circ$  of rotation and the distance is not far).

On the other hand, the pinpoint of the supercontinuum laser is not of one pixel but has a diameter that varies depending on the distance. This means that the number of measurements affected by the specular reflection may be greater.

One must study the morphology of the most common plastics that will be encountered on a recycling belt and their position in order to optimise the lighting angle with respect to the spectrometer's sensor to minimise beams coming from

the specular reflection from reaching the latter.

Finally, it is important to point out that the spectrometer and the lighting's target points will not coincide if their mutual orientation is other than  $0^\circ$  and the morphology of the material is irregular. When the height of the material to be measured varies, the laser will move out of the field of vision. It may also occur that there are obstructions by other objects that will have the same effect.

In the event of a scenario with an even height of the samples, if it is wished to use lighting that strikes at an angle of  $45^\circ$  (for example) with respect to the spectrometer, two similar mirror systems must be built, one for the spectrometer and another for the lighting and to synchronise both of them so that they aim at the same point at all times. This method may be more complicated to implement due to the synchronisation issue and the cost will be higher.

### **1.3.3.5 Market.**

There are hardly any companies on the market that offer commercial Whiskbroom scanning systems for in-line use, with most of the solutions being focused on the ambit of aerial hyperspectral image acquisition.

Álava Ingenieros, Photon Lines and the BaySpec Company, among others, have in the past implemented Whiskbroom equipment units for in-line installation.

From BaySpec it is considered that the use of the Whiskbroom technology for in-line scanning has the advantages of a superior spectral and spatial resolution to those that can be offered by a Pushbroom camera, in addition to a spectrometer that reaches the 2500nm band being much cheaper than a Pushbroom camera. Its slow speed should be pointed out as an important disadvantage. The same company mentions that it is only worth using a Whiskbroom scanning system for systems that need to reach far bands such as that of 2500nm, as a matrix sensor which reaches that band is much more expensive, making the Pushbroom hyperspectral equipment units much more expensive.

## **1.3.4 Emerging technologies.**

Today, the sorting of plastic waste using infrared spectrometry continues to be expensive due to both the prices of the sensors and that of the lighting it is necessary to use, although not as much as some years ago.

New ongoing research will bring down the costs of the technologies currently on the market even more in the future.

The black pigment in plastics continues to be a problem when it comes to sorting them properly, although it appears that in the near future this will no longer be the case. Companies in the industry are developing plastics with alternative black pigments to carbon that are visible in the near infrared, which in the near future will allow them to be sorted using NIR spectrometry.

Companies such as Bertin Technologies are developing an in-line black plastics identification system by means of laser induced plasma spectrometry. The project deals with the identification of the black plastic of monitors and screens on a controlled belt.

<http://www.libs-quantom.com/life-project/>

Just at the end of the infrared range, in the far infrared band we encounter the waves called terahertz radiation, this type of waves are capable of penetrating non-conductive materials such as cloth and plastics. It can be used for the chemometric analysis of materials and to detect differences in the water content or the thickness of the materials.

Several optical systems capable of transforming shortwave infrared (SWIR) waves into the visible spectrum have recently been patented and they may possibly be found on the market some years from now. These systems could lower the cost of infrared vision systems.

- PATENT US2017094199 (A1) - SWIR TO VISIBLE IMAGE UP-CONVERSION INTEGRATED DEVICE (30/03/2017)
- PATENT WO2017006307 (A1) - SWIR TO VISIBLE UP-CONVERSION OPTICAL SYSTEM (12/01/2017)

The use of halogen lights may cease to be feasible some years from now. Many companies are changing from halogen lighting to LEDs due to their lower cost and greater effectiveness, which may lead to a drop in supply as demand falls, making prices rise.

### 1.3.4.1 Terahertz.

Within the framework of the project and after evaluating the technologies applicable to the selection of plastics, we have decided to enter into greater depth on the knowledge of this technology and on the options it can offer.

Terahertz radiation, also known as submillimetre radiation, covers the electromagnetic wavelength at the end of the far infrared, just before the microwave band (0.1-1.0 mm / 3 THz-0.3 THz approx.). This radiation is not ionising, which means that, in contrast to X-Rays, it is not harmful to the human body, greatly facilitating its implantation and use (Ashish Y. Pawar, 2013).

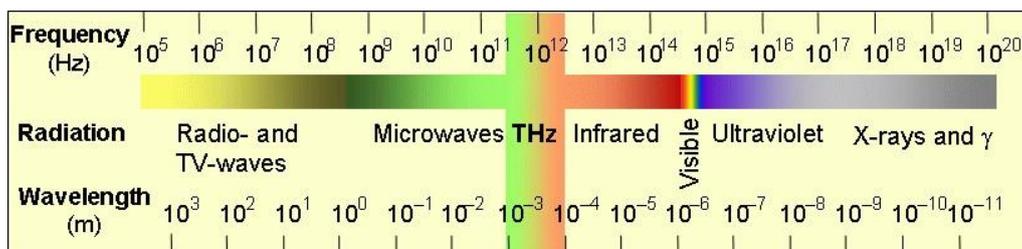


Figure 46 - Terahertz radiation in the electromagnetic spectrum.

Said radiation has the capacity to penetrate a wide range of non-conductive material such as clothes, paper, cardboard, wood, plastic and ceramics, while it cannot pass through water or metal. However, if the sample is very thin or has low

absorption, it is difficult to detect significant changes between the source and the radiation returned by the piece.

The method for measuring the dimensions is equivalent to that used in infrared spectrometry. A source of terahertz radiation is required to stimulate the sample and measure the radiation that it does not absorb.

Acquisition can be carried out with any of the acquisition techniques already noted in infrared spectrometry: Reflectance, Transmittance and Interactance (Tyler Bowman, 2016).

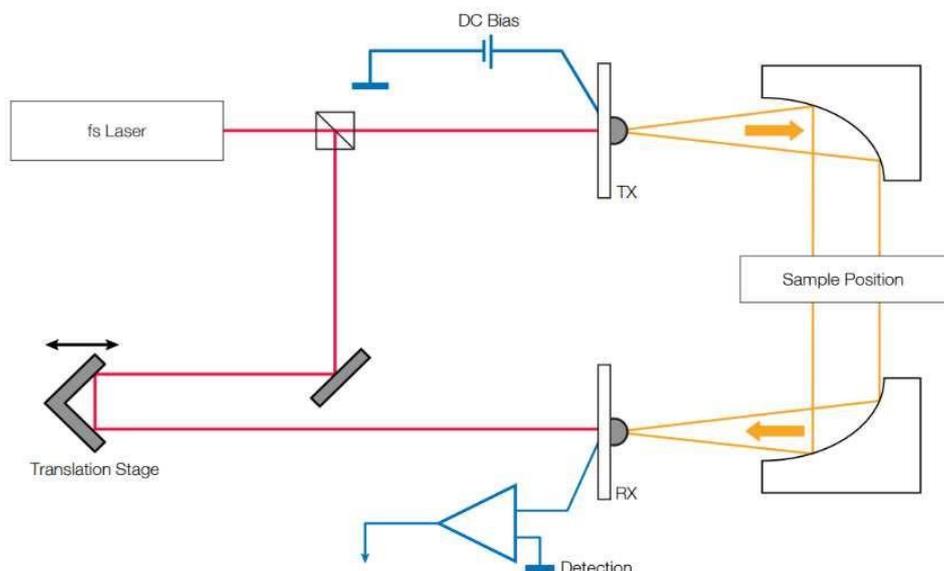
There is a wide variety of sources of radiation in the terahertz frequency, from diodes which emit a very narrow range of the spectrum, to devices based on organic crystals which cover much wider ranges.

Two types of terahertz systems are to be found on the market: those based on the time domain, and those based on the frequency domain.

### 1.3.4.2 Terahertz, time domain.

The terahertz system based on the time domain normally uses ultra-short pulses (in the order of femtoseconds), generated by a laser. Each pulse of the laser is divided in two. One part goes to the emitter and the other to the receiver.

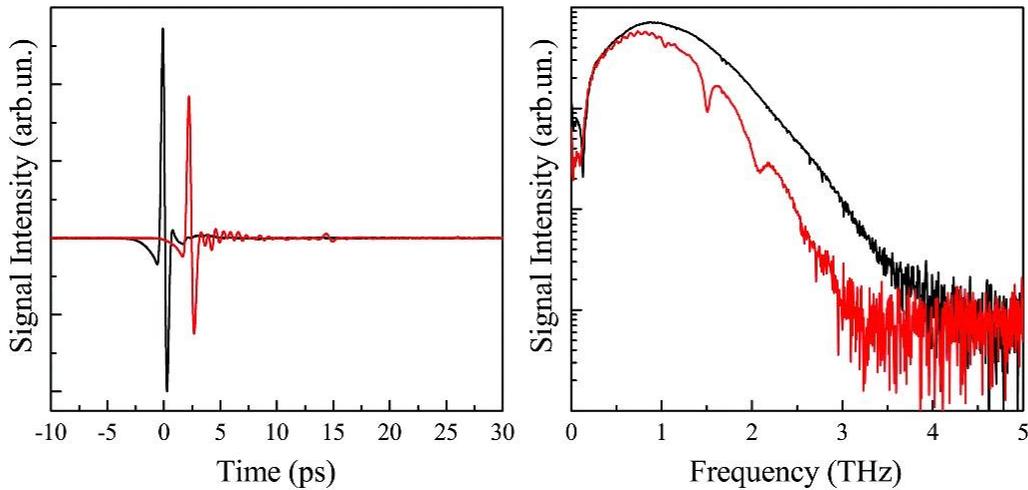
The part which goes to the emitter produces a current, which in turn generates a set of electromagnetic waves in the terahertz range of the spectrum. Said electromagnetic waves interact with the sample and arrive at the receiver, modifying its properties (for example, conductivity). The second part of the laser pulse arrives at the receiver and is used to examine the effect of the electromagnetic waves on this at a given moment.



*Figure 47 - Plan of a time-domain based terahertz system.*

Different pulses with different delays are used to examine said effect at different moments in time. Once the effect of the whole set of electromagnetic waves on

the sensor has been measured, the Fourier transform will be used to reproduce the spectrum.



*Figure 48 - Effect of two waves in the time range, and their spectrum by applying the Fourier transform.*

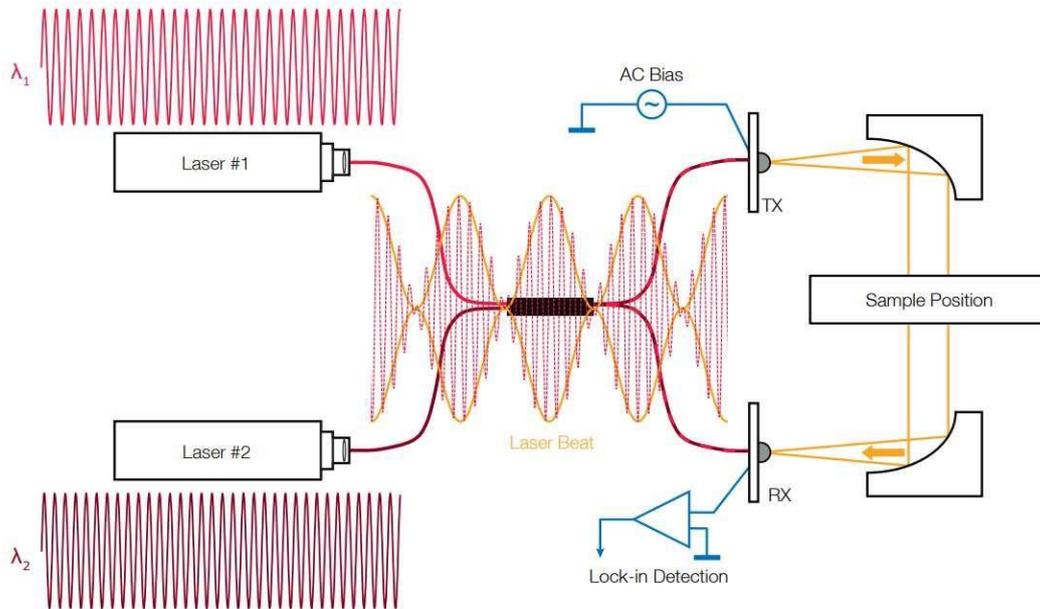
The time taken to carry out a measurement of a single point with this technology may be around 20 milliseconds. This could cause a problem when placed on the production line, depending on the speed of the conveyor belt, as it could cause resolution problems.

The company "TOPTICA Photonics" has various devices on sale capable of carrying out this type of measurement, as well as systems based on the frequency domain, which we will see as follows.

### **1.3.4.3 Terahertz, frequency domain**

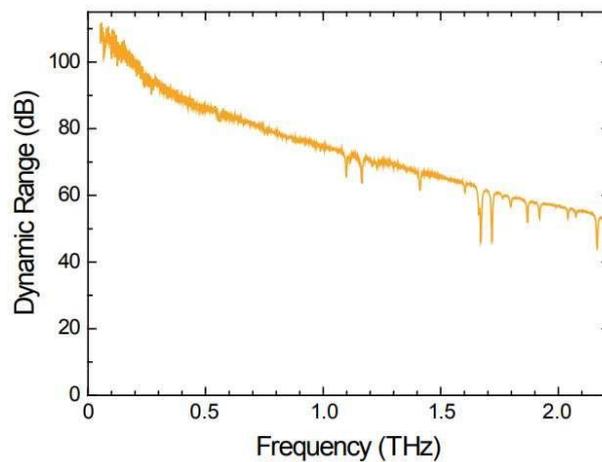
The terahertz system based on the frequency domain uses continuous wave terahertz radiation. Said radiation is generated by combining a semiconductor at the exit of two continuous wave lasers which operate at very similar frequencies. The difference between their frequencies is the frequency of the terahertz electromagnetic wave obtained.

The sensor receives the radiation that has interacted with the sample as well as the original wave, which allows a measurable photoelectric current to be generated.



*Figure 49 - Frequency-domain based terahertz system.*

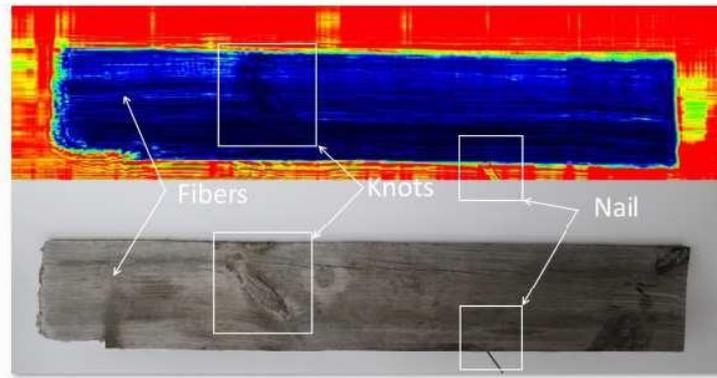
By varying the frequency of one of the continuous wave lasers, it is possible to modify the frequency generated in the terahertz range, making it possible to take measurements of different bands of the spectrum.



*Figure 50 - Measurement of the spectrum using different frequencies.*

These systems need around 15 seconds to cover all frequencies at a single point. However, if only one frequency or a small range of them is required, the acquisition time is reduced proportionally.

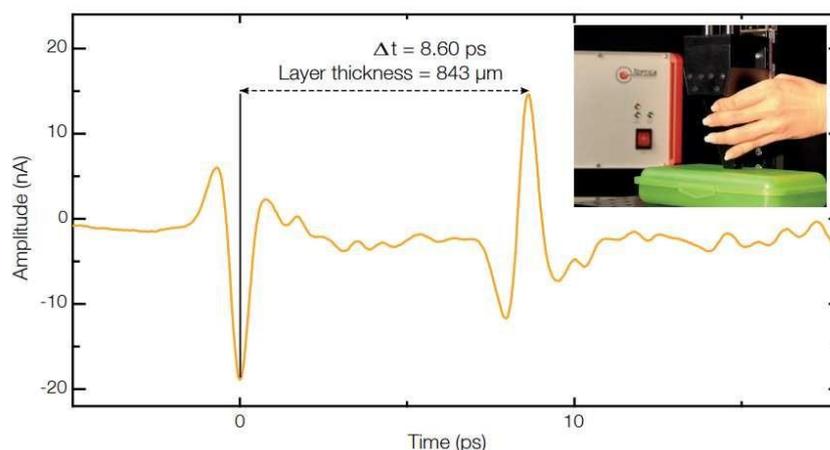
Systems can be found on the market which emits only one frequency, as well as receivers without frequency sweeping, in linear and matrix configurations, which are being used in industry in the field of product safety and surveillance. One of the companies selling equipment with these features is "TeraSense".



*Figure 51 - Example of industrial application of terahertz vision.*

### 1.3.4.4 Applications.

The terahertz frequency has the quality of passing through plastics and other non-conductive materials, and is capable of calculating their thickness by measuring the times of the echoes produced as they enter and leave these materials.



*Figure 52 - Example of application to measure thickness of plastic.*

Different echoes are produced depending on the different layers that the material has, making it possible to measure strata of different materials and the distance between them (Gyeongsik Ok, 2014).

Radiation which falls on a conductive material such as water or metal will not pass through, or will only do so very weakly, greatly reducing the information on the objects behind it. Due to this characteristic, if used for plastics, these should be dry.

Another very frequently used function in terahertz spectroscopy is the possibility of investigating the physical properties of certain materials (Chung-Hyeon Ryu, 2016). Changes in the refraction index are observed in the polymers at different temperatures. This can reveal slight structural changes (S.Wietzke, 2011).

However, while terahertz spectroscopy can be used for the spectral analysis of materials (Josette El Haddad, 2013), its use in certain fields is not so well developed or effective as other technologies such as NIR spectroscopy and X-rays, particularly in the classification of plastics due to their practical transparency

in terahertz frequencies.

## 1.4 Conclusions.

The conclusion which can be reached after analysing the state of art of the existing technologies is that infrared spectroscopy is the most suitable alternative for the application under study in terms of cost and properties.

Within the field of infrared spectroscopy, there are still some doubts as to which range is the most suitable to use: the 900-1700 nm range is somewhat cheaper, while the 1000-2500 nm range appears to be the most suitable, although it is a good deal more expensive than the aforementioned.

At this point in the project we are waiting to be able to carry out tests with a hyperspectral system in the SWIR range extended to 2500 nm in order to verify whether or not this type of equipment can offer better properties than the lower range. Depending on the results obtained in these tests, the option of implementing a whiskbroom spectrometer with halogen lighting may be proposed, although it seems that it will be difficult to reach the resolutions which are being used with a hyperspectral pushbroom device.

