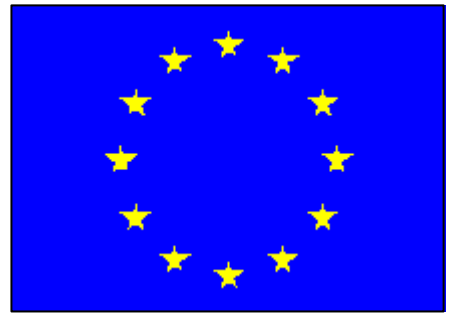




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EVR1-CT-2002-40028
D-07-04
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EUFIRELAB:
Euro-Mediterranean Wildland Fire Laboratory,
a “wall-less” Laboratory
for Wildland Fire Sciences and Technologies
in the Euro-Mediterranean Region

Deliverable D-07-04

Infrared Measurement Devices
Principles and Basic Results

Juan MELÉNDEZ, Antonio DE CASTRO, José Manuel ARANDA,
Angel LERMA, Fernando LÓPEZ.

February 2004

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SUMMARY

This document summarizes the operating principles of infrared (IR) instrumentation useful for forest fire studies, and the main results that can be obtained with them. The first chapter is a general introduction. Chapter 2 is a review of the basic concepts of IR physics necessary to understand the operation of instrumentation, including definitions on the IR spectrum, radiometry, laws of radiation, emittance and transmittance of solids and gases, and the main features of IR emission of fires. Chapter 3 classifies the different types of instrumentation according to their spatial and spectral resolution. Chapter 4 describes radiation thermometers and heat flux transducers (neither spatial nor spectral resolution). Chapter 5 explains the main types of IR spectrometers (spectral resolution but no spatial resolution). Chapter 6 deals with IR cameras (spatial resolution but no spectral resolution) and chapter 7 with imaging spectrometers (both spatial and spectral resolution). For each type of instrumentation, a table is included with the instruments used by the Eufirelab members. This information has been gathered by means of a questionnaire submitted to the Eufirelab teams in November 2003.

LIST OF ASSOCIATED DOCUMENTS

This document is related to other Eufirelab reports:

- D-07-03 Fire metrology: a state of the art
- D-07-05 Infrared cameras principles and general presentation
- D-07-07 Infra red camera: an interesting tool for wildland fire monitoring

When necessary, the text may refer to some of these documents. In addition, bibliographical references are provided in the final section.

1 INTRODUCTION

In the last years, infrared (IR) sensors have been increasingly used in forest fire-related applications.

These applications can be broadly divided in two categories:

- **Fire monitoring:** this includes fire detection and monitoring of fire propagation, but, in a broad sense, also fire risk assessing and follow-up of biomass recovery after fire
- **Fire measurements,** including all kind of experimental fire studies that provide quantitative or semi-quantitative results.

The pioneering applications of IR sensors to forest fires belong to the category of fire monitoring and were made using infrared sensors onboard satellites originally intended for meteorological purposes.

Satellite observations have proved very useful to assess fire risk and follow post-fire recovery (JUSTICE et al., 1993), in particular in isolated or unpopulated areas.

Satellites have monitored propagation of large fires but up to now they are not useful for operational fire detection.

This situation may change in the near future, when a new generation of specific fire satellites, promising early fire outbreak detection and monitoring, becomes operative (website FUEGO).

In addition to satellite based sensor, IR sensors are also increasingly used by many forest services, from airborne or ground-based platforms.

Typical ground based devices are IR cameras placed on rotary platforms on lookout towers; airborne sensors have been also used to help in fire extinction (YOUNG, 1994)

Applications of IR cameras to wildland fire monitoring are described in Deliverable D-07-07 of EUFIRELAB project: Infrared camera: an interesting tool for wildland fire monitoring.

The increasing use of IR cameras in monitoring applications has encouraged many research groups to consider their use -as well as that of other IR sensors- in fire measurements.

This report focuses on the application of IR sensors to fire measurements in experimental fires, both indoor and outdoor.

The operating principles of the different types of instrumentation useful for those measurements are described, as well as the main results they can provide.

In addition, the instruments used by the EUFIRELAB members are listed in tables throughout the document.

This information has been gathered by means of a questionnaire submitted to the EUFIRELAB teams in November 2003.

Chapter 2 reviews the basic concepts of IR physics necessary to understand the operation of instrumentation: definitions on the IR spectrum, radiometry, laws of radiation, emittance and transmittance of solids and gases, and the main features of IR emission of fires.

Chapter 3 classifies the different types of instrumentation according to their spatial and spectral resolution.

Chapter 4 describes radiation thermometers and heat flux transducers (neither spatial nor spectral resolution).

Chapter 5 explains the main types of IR spectrometers (spectral resolution but no spatial resolution).

Chapter 6 deals with IR cameras (spatial resolution but no spectral resolution).

Chapter 7 briefly describes imaging spectrometers (both spatial and spectral resolution).

The questionnaire used to gather information on the IR instrumentation used by EUFIRELAB members is included as an appendix.

2 A REVIEW OF INFRARED BASICS

2.1 THE INFRARED SPECTRUM

The infrared (IR) region covers a wide section of the electromagnetic spectrum between the visible and the radio waves.

It is customary to include into it the wavelengths from, approximately 0.75 to 1000 μm (Figure 2-1).

For reasons that will be explained later, it is common to divide the IR region further in:

- Near IR (0.75 to 3 μm),
- Medium IR (3 to 6 μm) and
- Far -or Thermal- IR (6 to 15 μm).

IR radiation, although invisible to the eye, is similar to visible radiation in its physical properties; i.e., can be considered as "optical" in its nature (unlike radiowaves or gamma rays).

There are several kinds of sensors that allow us to "see" IR radiation, but before describing them, it is necessary to explain the general concepts underlying IR measurements.

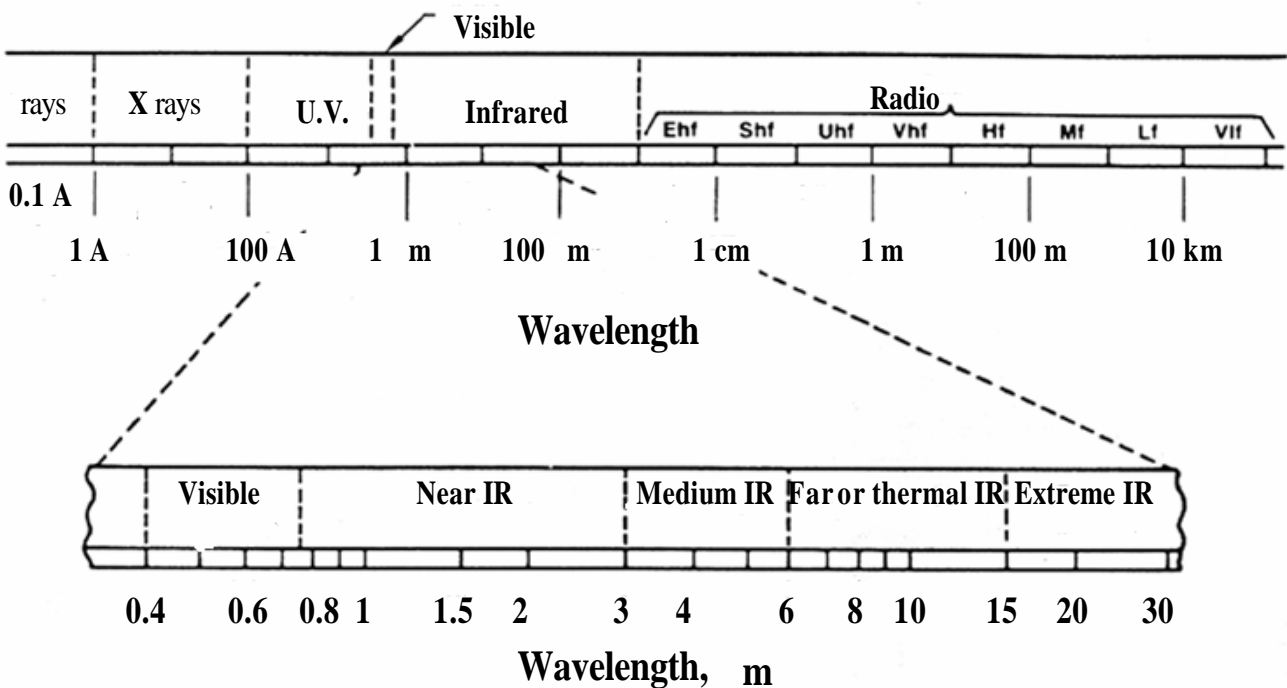


Figure 2-1: The IR portion of the electromagnetic spectrum

2.2 BASIC CONCEPTS OF RADIOMETRY

Note: this section and the two following have been adapted from reference (MELÉNDEZ ET AL, 2003)

The part of optics devoted to measurement of radiation is called radiometry.

2.2.1 Radiometric magnitudes

A preliminary step to perform any measurement is to establish the magnitudes to be measured. (MCCLUNEY, 1994)

The basic radiometric magnitude is called **radiant flux** and measures the power transported by the radiation:

- symbol: Φ
- units Watts

As a rule, the output signal of an infrared detector is proportional to the radiant flux incident on the device.

This radiant flux depends obviously on the size of the detector, and hence it may be convenient to work with the incident power per unit area.

This magnitude is called **irradiance**:

- symbol: E_e
- units: W/m^2 .

When radiation emitted, rather than incident, is considered, the magnitude is called **exitance**:

- symbol: M,
- units: W/m².

The most basic task when performing IR measurements is to estimate the exitance of a given source, knowing the irradiance it creates on a detector.

In order to solve this problem, it is convenient to use another magnitude called radiance.

In order to define it, we consider a differential of area, dA, of a source, and a differential solid angle dω (Figure 2.2).

The angle between dω and the normal vector to the surface is θ.

Flux contained in dω coming from dA is denoted as d²Φ.

Radiance at dA is defined as:

$$L = \frac{d^2\Phi}{d\omega dA \cos\theta}$$

That is to say, flux per unit area per unit of projected solid angle.

The definition, stated here for a source, is extended trivially for a detector and even for a ray, at any point along its path.

Units of radiance are Watts per square meter per stereo radian.

For a source, radiance may vary from point to point, and for a fixed point, it may vary as a function of the direction.

Thus, it provides the most complete geometric characterisation of the emitted radiation.

A simple and important case is that of a *Lambertian source*, for which emission is isotropic (L does not depend on the direction).

The importance of radiance stems mainly from the *invariance theorem* (NICODEMUS, 1963) that states that, in any optical system, the radiance along the path of a ray is invariant (if the refractive index changes, L must be divided by it).

This theorem greatly simplifies radiometric calculations.

All the radiometric magnitudes introduced here may be defined as spectral, that is to say, per unit wavelength (or, equivalently, per unit wave number)

2.2.2 Absorption, reflection and transmission

When light strikes a body, a part of it is reflected, a part is absorbed and a part is transmitted.

Three parameters are defined:

- ρ = reflectance = fraction of power reflected
- α = absorptance = fraction of power absorbed
- τ = transmittance = fraction of power transmitted

Obviously, ρ + α + τ = 1

Most solids can be regarded as opaque (τ = 0) and then α = 1 - ρ (solid)

On the other hand, gases have zero reflectance and α = 1 - τ (gas)

These parameters depend on the material, on the wavelength and, to a certain degree, on temperature.

A body for which α = 1 for all wavelengths (i.e., a body that absorbs all the radiation that strikes upon it) is called a *blackbody*.

A body for which α is constant (<1) for all the wavelengths it is called a *grey-body*.

Usually, solids can be treated as grey-bodies, whereas gases have a strong spectral structure.

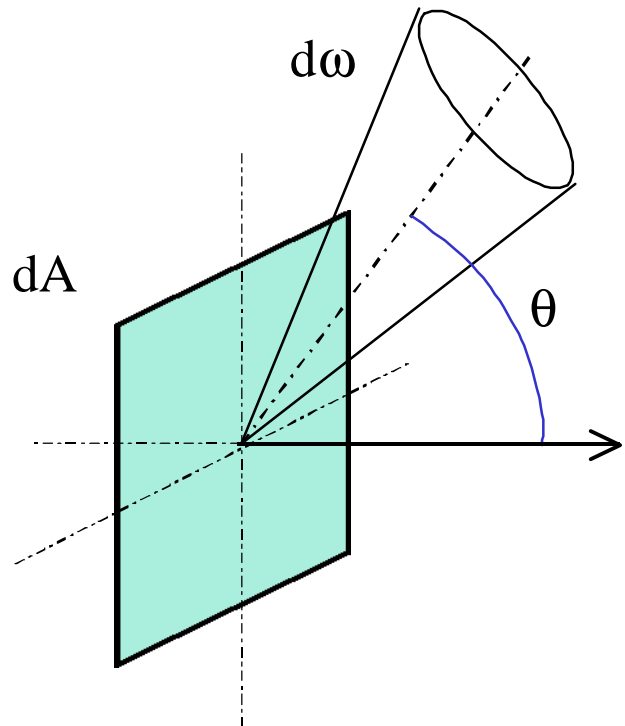


Figure 2-2: Definition of radiance

2.3 BASIC LAWS OF RADIATION

It is a well-known physics fact that all bodies emit continuously electromagnetic radiation.

This radiation emission has two very characteristic features:

- it increases very fast with temperature, and
- it is strongly wavelength-dependent.

For a *blackbody* in thermal equilibrium, these features are summarised by two laws:

- *Stefan-Boltzmann law*, stating that the total radiated power increases as T^4 (being T the absolute temperature of the body), and
- *Wien's law*, stating that the spectral distribution of the emitted radiation has a maximum at $\lambda = 2898/T$ microns.

2.3.1 Planck's law

Both Stefan-Boltzmann and Wien laws can be derived from the more general *Planck's law*, which specifies the spectral dependence of the blackbody emission, as a function of temperature.

Planck's law is illustrated, for the specific temperatures of the Sun (approx. 6000 K) and the Earth (approx. 300 K), in Figure 2.3 (SCHOWENGERDT 1997).

It is clear that most of the radiation that can be seen when looking at the earth in the visible spectrum or in the Near IR region will be reflected solar radiation, whereas in the Thermal IR spectrum (from 6 to 15 microns) the emitted radiation dominates. In the region intermediate between Near IR and Thermal IR, both reflected and emitted contributions are important. This is the main reason to separate the IR spectrum in those three regions.

2.3.2 Emittance. Kirchhoff's law

Blackbodies are idealisations, but the behaviour of a real body can be related to that of a blackbody by means of *emittance*, ϵ .

Emittance is a function of the wavelength and the temperature, although usually only the wavelength dependence is specified: $\epsilon(\lambda)$.

The spectral power emitted by a real body is: $\Phi(\lambda, T) = \Phi_{BB}(\lambda, T) \cdot \epsilon(\lambda)$

Being $\Phi_{BB}(\lambda, T)$ the spectral power emitted by a blackbody, given by Planck's law.

For a body in thermal equilibrium, emittance equals absorptance (*Kirchhoff's law*): $\alpha(\lambda) = \epsilon(\lambda)$

According to Kirchhoff's law, emission and absorption occur at the same wavelengths, and their intensities are linked: the strongest absorbing bands will be those with strongest emission

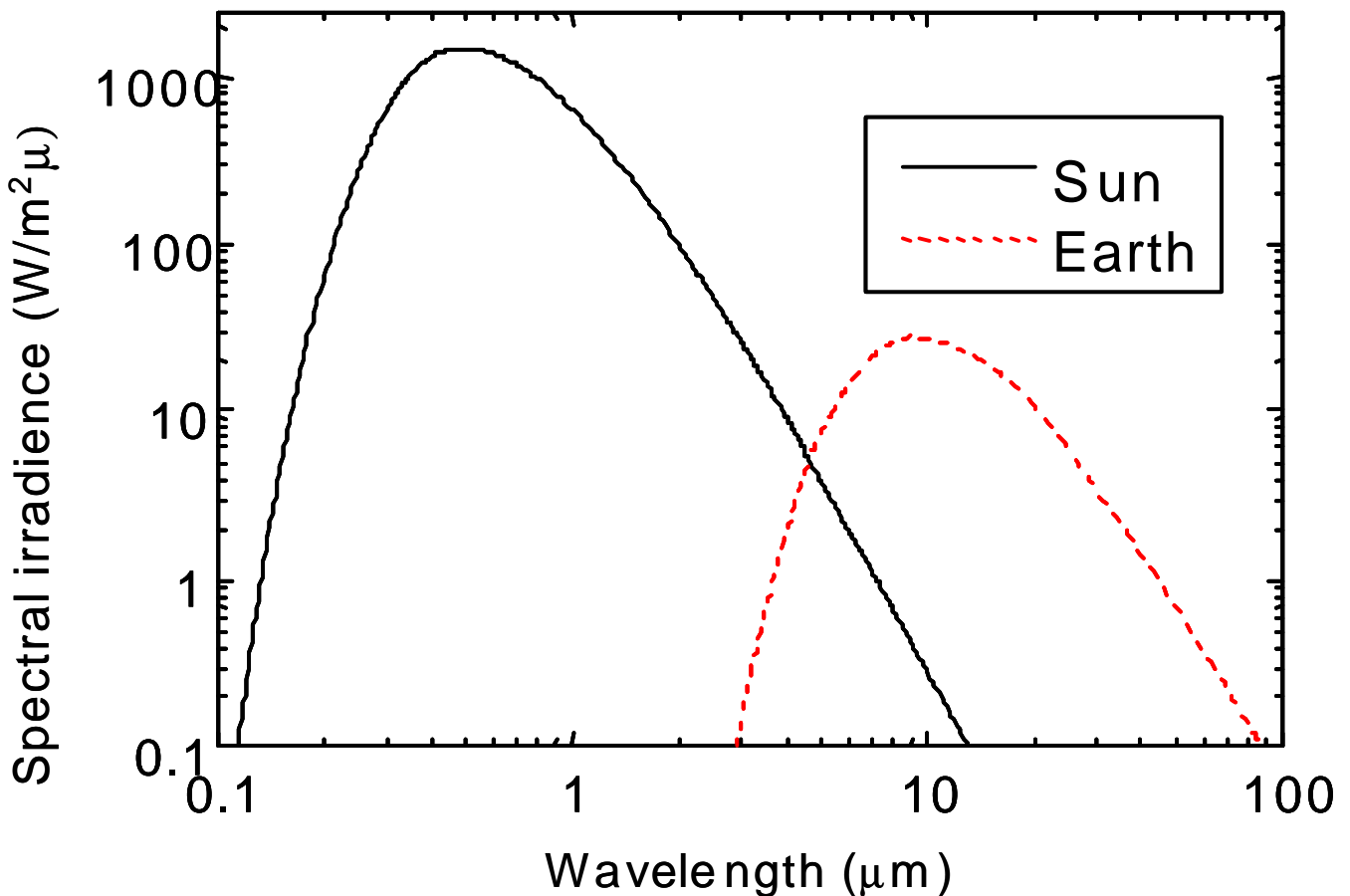


Figure 2-3: Solar spectral irradiance incident on the Earth (solid black) compared to Spectral irradiance emitted by the Earth (dashed red)

2.4 EMITTANCE OF SOLIDS AND GASES

2.4.1 Basic features

As explained before, the absorptance of solids (and therefore its emittance) has little spectral dependence.

Hence, the spectral profile of their emission is similar to that of a blackbody.

On the other hand, gases are transparent over most of the spectrum, but show absorption bands that may be very strong at specific wavelengths.

These bands are related to specific energy levels of the molecules.

In particular, all gases (except those with monatomic or diatomic homonuclear molecules, like O₂ and N₂) show IR absorption bands related to vibrational levels.

These bands are characteristic for each chemical species, constituting its "IR fingerprint".

According to Kirchhoff's law, emission and absorption occur at the same wavelengths, and their intensities are linked: the strongest absorbing bands will be those with strongest emission

2.4.2 Atmospheric transmittance

These features of IR absorption of gases can be seen clearly in the transmittance of the atmosphere, as shown in Figure 2-4 (HUDSON, 1969).

The absorption bands create wide regions in which the atmosphere is opaque.

Carbon dioxide and water vapour are the gases with strongest IR absorption bands in the atmosphere.

In contrast, there are regions, called "windows", in which the atmosphere is nearly transparent.

The most important are:

- The VIS – near IR window (0.4 to 2.5 μm)
- the Medium IR (MIR) window, from 3 to 5 μm, and
- the Thermal IR (TIR) window, from 8 to 14 μm (although we will restrict it to 8 to 12 microns).

Remote optical measurements through the atmosphere should be performed in those windows (or in visible/near IR).

2.4.3 Infrared emission of fires

What we have explained up to now permits already to sketch the main features of the IR emission of fires:

A fire has a very strong IR emission.

For solids at approx. 1000°C, the wavelength of maximum emission, according to Wien's law, is 4 μm, in the centre of the MIR band.

Furthermore, at that temperature, according to Planck's law, 31% of the radiated power is emitted in the MIR band, 16% in the TIR band, and only 2·10⁻⁷% in the visible band.

There are two contributions to the IR emission of a fire: that of the emitted gases (mainly CO₂ and H₂O at the flame) and that of the hot solids (embers and hot ashes).

The first one consists of discrete bands; the second one is a continuum.

The emission of a fire is seen always through the atmosphere.

As the atmosphere contains CO₂ and H₂O, it will absorb strongly the IR emission of those gases.

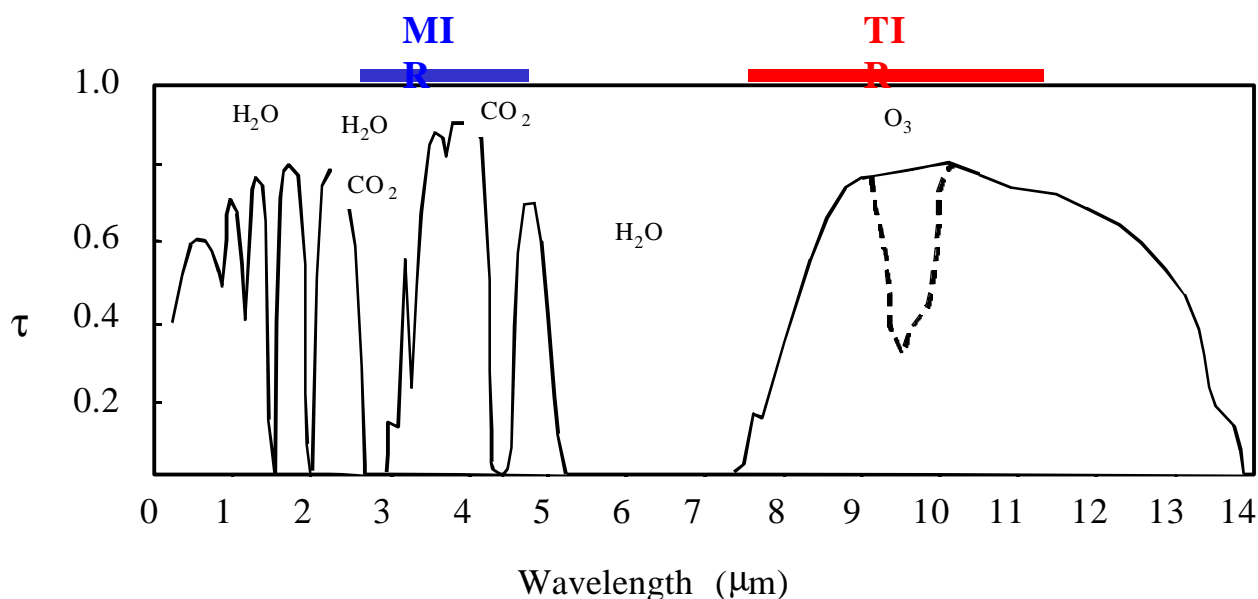


Figure 2-4: Transmittance profile of the atmosphere (vertical path). The gases responsible for the main absorption bands are indicated (O₃ refers to stratospheric ozone)

These qualitative features can be illustrated with reference to Figure 2.5 that shows, in black, an experimental emission spectrum of a small laboratory fire, compared to the theoretical emission of a blackbody at different temperatures.

Distance of observation was approximately 6 m.

The most salient feature of the fire spectrum is a double peak between 4 and 5 microns.

It is due to the emission of the hot CO₂ at the flame.

Because of the absorption of the cold atmospheric CO₂, it is divided into two "spikes":

- the narrow "blue" spike, at 4.2 μm, and
- the wide "red" spike at 4.55 μm)

As explained by Kirchhoff's law, emission and absorption by a certain gas occur at the same wavelengths, but temperature widens the bands, and therefore absorption here only affects the centre of the CO₂ band.

There are also wide H₂O emission bands at 3 μm and from 5 to 8 μm.

In those bands, also, emission from hot H₂O at the flame is mixed with absorption from cold H₂O at the atmosphere.

With careful examination of the spectrum, other minor chemical compounds like CO and hydrocarbons may be identified.

The gas-related peaks are superimposed on a continuum grey-body-like component, due to the emission of hot solids (embers)

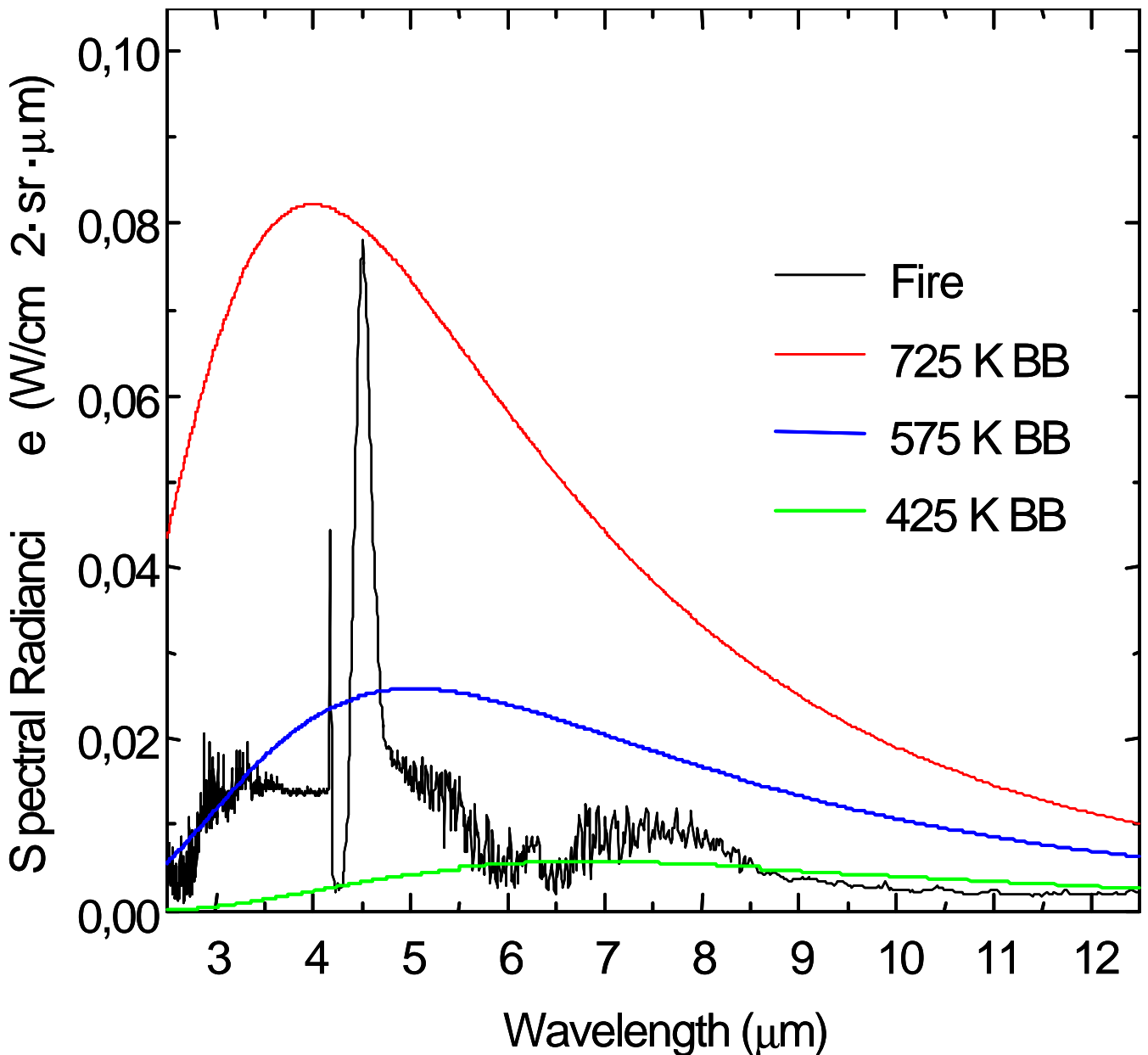


Figure 2-5: Experimental spectral radiance of a fire compared to those of three different blackbodies

3 IR INSTRUMENTATION: GENERAL CONCEPTS

An IR detector is a device that provides a signal proportional to the IR radiation that falls onto it.

We will assume the usual case in which the signal is a voltage and the radiation is defined as irradiance (power per area).

There is a large variety of IR detectors (VINCENT, 1990), that can be divided broadly into two families:

Thermal detectors (bolometers, thermopiles, pyroelectric detectors) are sensitive to the entire IR spectrum and may operate at room temperature.

Quantum detectors (usually, photodiodes or photo-conductors made of semiconductors) are much faster than thermal detectors, but they operate only in a specific spectral range, and usually require cooling at cryogenic temperatures.

Both kinds of detectors are used in IR instrumentation.

From the point of view of the user, however, the main distinction does not arise from the detector type but from the operating mode.

The two relevant variables here are spectral resolution and spatial resolution.

According to this, four types of IR instrumentation can be distinguished:

		Spectral resolution	
		No	Yes
Spatial resolution	No	Radiation thermometers	IR spectrometers
	Yes	IR cameras	Imaging spectrometers

The output of a simple IR detector without any accessories (except for the read-out and, eventually, the bias circuits) will be a voltage proportional to the irradiance that falls on the detector in the spectral band in which the detector is sensitive.

For all the applications, some kind of optics is adapted to the sensor.

In the simplest case, the optics serves only to restrict the field of view to a certain solid angle.

This simple configuration forms the basis of a **radiation thermometer** (the irradiance is related, through Planck's law, to the temperature of the object in the field of view).

Related instruments are the **heat flux transducers**.

Both kinds of devices have neither spatial nor spectral resolution, and their output is a *number*.

If a wavelength selecting device (for instance, a prism or a diffractive grating) is coupled to the optics, an instrument with *spectral resolution* can be made-up.

This is the case of **IR spectrometers**, whose output is a *spectrum*.

IR spectrometers integrate the incoming radiation over the whole field of view of the instrument.

An instrument can be conceived that discriminates between different points within the field of view, i.e., that has *spatial resolution*.

Most of these instruments do not have spectral resolution, and are called **IR cameras**.

Their output is an *image*.

Finally, the instruments that combine spectral and spatial resolution are called **imaging spectrometers**.

Their output, sometimes called a *spectral cube*, can be viewed as an image for each wavelength of the spectral range or, equivalently, as a spectrum for each point of the field of view.

In the following chapters we describe in more detail these instruments and summarise the main features of the IR instruments used by the members of the EUFIRELAB consortium.

4 RADIATION THERMOMETERS AND HEAT FLUX TRANSDUCERS

4.1 RADIATION THERMOMETERS

Radiation thermometers are also known as non-contact thermometers or as pyrometers.

In the classical pyrometer, a lamp filament with adjustable (and known) temperature was seen in front of the object of measurement.

When the eye detected a balance in brightness between the filament and the background (i.e., the object to be measured), both temperatures were the same.

In the classical pyrometer, the eye is used as a visible radiation detector that operates in null-mode.

This makes them it very sensitive devices, but limited to object temperatures above incandescence, typically above about 700°C.

Now they have been replaced in most applications by IR detector based devices (WEB TEMPERATURES)

The simplest and most common design is basically an infrared detector equipped with a simple optics that collects the radiant infrared energy in a certain field of view (FOV) and focuses it onto a single detector (usually photoconductive or photovoltaic).

The user points to an object and enters its estimated emissivity, and the device calculates a temperature on the basis of the received radiation.

This design is compact and simple to use (see Figure 4-1).

One of the simplest examples is the ear clinical thermometer.

The object must cover the whole field of view to get a significant measurement, but as well as this condition is fulfilled and atmospheric absorbance is negligible, the temperature readout is not affected by the distance to the object.

This is because the FOV area increases as the square of the distance, and the received radiance from an area differential decreases as the square of the distance.

However, a specific range of distances of operation is recommended for each model non-contact thermometer, usually to a maximum of one or two meters.

Common accessories are a thermocouple to enable contact measurements for IR surface emissivity verification, and a built-in laser pointer for better aim.

The range of measurable temperatures spans from 0°C to 2000°C, depending on the model, approximate accuracy is $\pm 1^\circ$ or $\pm 1\%$; and time response is in the ms range.

Low temperature models are usually broadband, whereas high temperature models are narrowband (i.e., they have an optical filter to select only a narrow range of wavelengths)

More sophisticated models use a dual-band approach: they use two optical filters at two neighbour wavelengths and rather than measuring radiation in one band, they compare the signals at the two wavelengths.

This is, to a first approximation, independent on emissivity for a greybody, and thus more precise in many circumstances.

Prizes range from 100-200 euro for the simplest one band models, to 1500-3000 euro for dual-band professional models.



Figure 4-1: A radiation thermometer with a laser pointer to mark the FOV (<https://www.testo.de/ZZ/en/shop/>)

4.2 HEAT FLUX TRANSDUCERS

A radiation thermometer measures the radiant heat transfer through a surface. Heat flux transducers measure the total heat transfer through a surface (including convection and/or conduction).

The two most common designs are (BRYANT ET AL, 2003):

The Schmidt-Boelter gauge

It uses a thermopile in which the elements are separated by a thin layer of a material of known thermal resistance.

If there is a heat flux through the layer, there will be a temperature gradient and the thermopile will generate a voltage.

The heat flux is proportional to this differential voltage.

The Gardon gauge:

It is a differential thermocouple measuring the temperature difference between the centre and the circumference of a thin circular disk, bonded by its periphery to a cylindrical heat sink (sometimes water refrigerated).

Heat flux induces a temperature difference between centre and periphery, which is measured by the thermocouple (DOEBELIN 1990)

Both designs can be modified to measure only radiant flux by, for instance, adapting a lens to block convective heat flux.

With this modification, the heat flux transducer becomes similar to a radiation thermometer, but with a wide FOV and calibrated in heat flux (irradiance) units instead of temperature units. (WEB VATELL)



Figure 4-2: Two designs of heat flux transducers based on the Gardon Gauge principle. One (left) is water cooled and the other (right) is conduction cooled. (<http://www.vatell.com/HF%20Sensors.htm>)

4.3 TABLE

Summary of Radiation Thermometers and Heat Flux Transducers owned by EUFIRELAB members

	Contact Person	Instrument name	Range	Response time	Operating principle
P13	ADAI Domingos Xavier VIEGAS xavier.viegas@dem.uc.pt	Heat Flux Transducer Thermogage 1000-1 Vatell www.vatell.com	Full Scale (10mV) : Low end: 0 to 5 W/cm ² High end: 0 to 5000 W/cm ²	Low end: 1 sec High end: 3 msec	Gardon Gauge, water cooled
		Heat Flux Transducer Thermogage 9000-9 Vatell www.vatell.com	Full Scale (10mV) : Low end: 0 to 10 W/cm ² High end: 0 to 7500 W/cm ²	Low end: 1 sec High end: 3 msec	Gardon Gauge with lens (radiometer), water cooled
		Radiation Thermometer Testo 860-T2 www.testo.de	-30.0 ... 900.0 °C	msec	IR detector

5 IR SPECTROMETERS

NOTE: this section has been adapted from reference (MELÉNDEZ et al, 2003)

A spectrometer is an instrument that can be used to measure the spectral positions of features of interest in the spectrum over a spectral range of interest.

Typical IR detectors integrate the energy received in a wide spectral range, and they cannot provide such a spectral information.

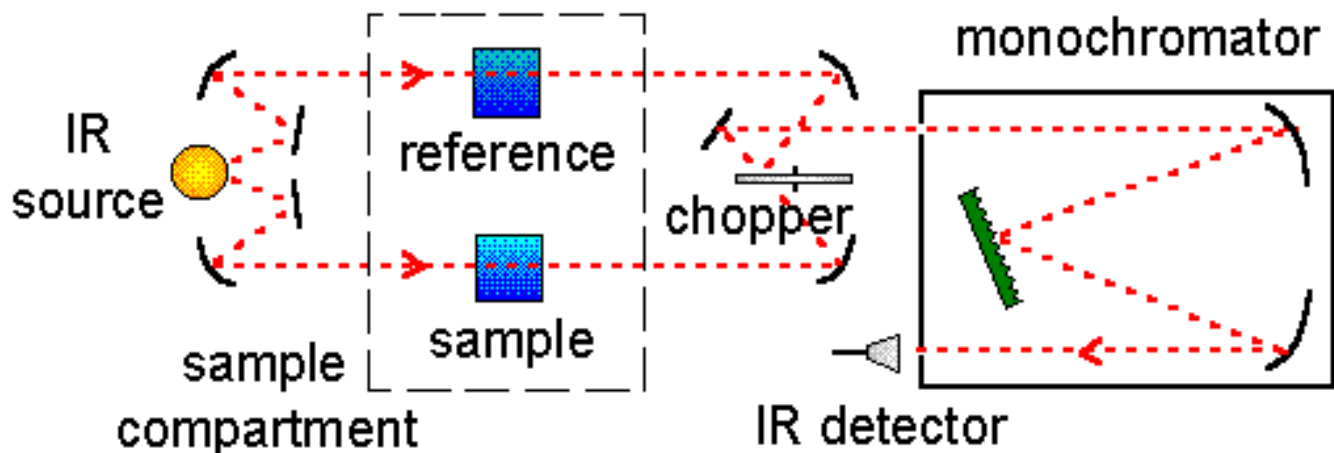
Therefore it is necessary an optical element (a monochromator) to discriminate the information in wavelengths to fabricate a spectrometer.

Usually there are two ways to obtain this spectral information; these two solutions give rise to two different families of spectrometers.

5.1 DISPERSIVE SPECTROMETERS

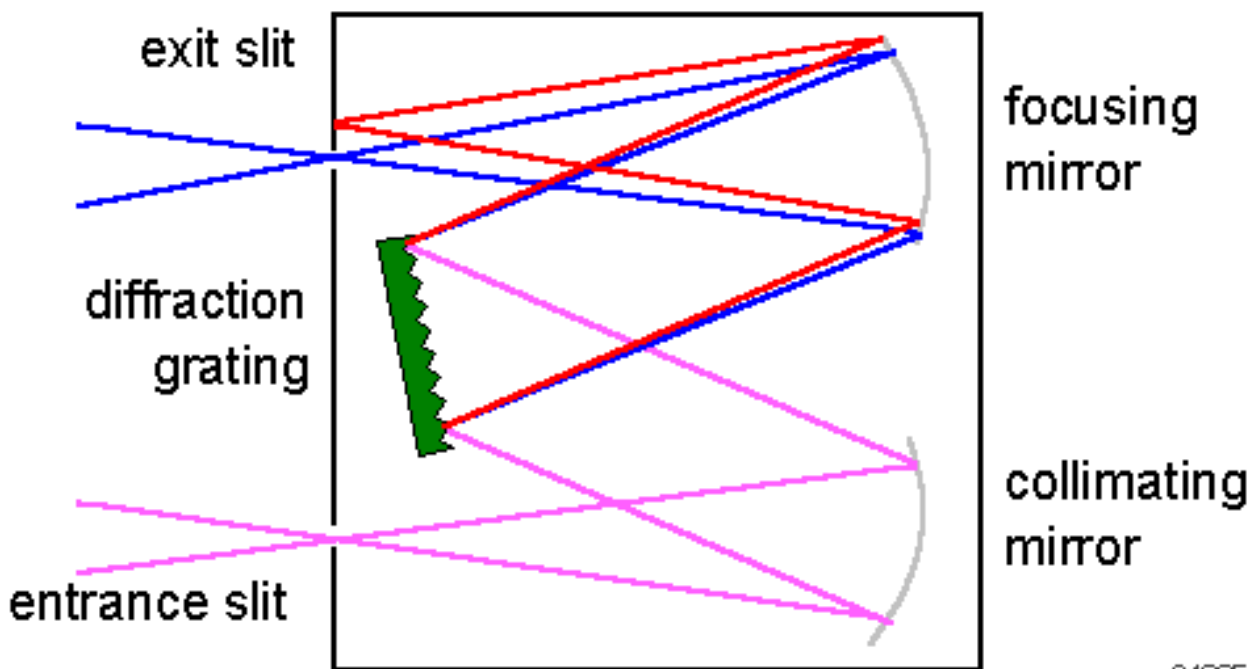
In these instruments, the monochromator is a dispersing element: a prism or a diffraction grating.

Figures 5-1 and 5-2 illustrate a schematic of a dispersive spectrometer.



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Figure 5-1: Schematic of a dispersive spectrometer (source <http://elchem.kaist.ac.kr/vt/chem-ed/analytic/ac-meths.htm>)



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Figure 5-2: Wavelength selection by using a diffraction grating. (source <http://elchem.kaist.ac.kr/vt/chem-ed/analytic/ac-meths.htm>)

5.2 FTIR SPECTROMETERS

These instruments use a Michelson interferometer as the monochromator element. (BEER, R., 1992)

The detector measures an interference pattern due to the moving mirror.

This pattern corresponds to the Fourier transform of the spectral distribution of energy.

Major advantages of FTIR spectrometers over a dispersive instrument are:

- All the wavelengths are measured at the same time (FELLGETT’S advantage)
- The simple optical path of the interferometer permits to reach the detector more energy than in the dispersive spectrometers. That means an improvement of the signal-to-noise ratio (JACQUINOT’S advantage)
- Frequencies are known very precisely, because the interferometer has a helium-neon laser as an internal frequency standard (CONNÉ’S advantage)
- The effective spectral resolution is constant over the entire spectrum.
- High acquisition speed, that permits co-adding multiple scans to improve the signal-to-noise ratio

When a spectrometer is calibrated for measurements of spectral radiant flux, the instrument is called a spectroradiometer.

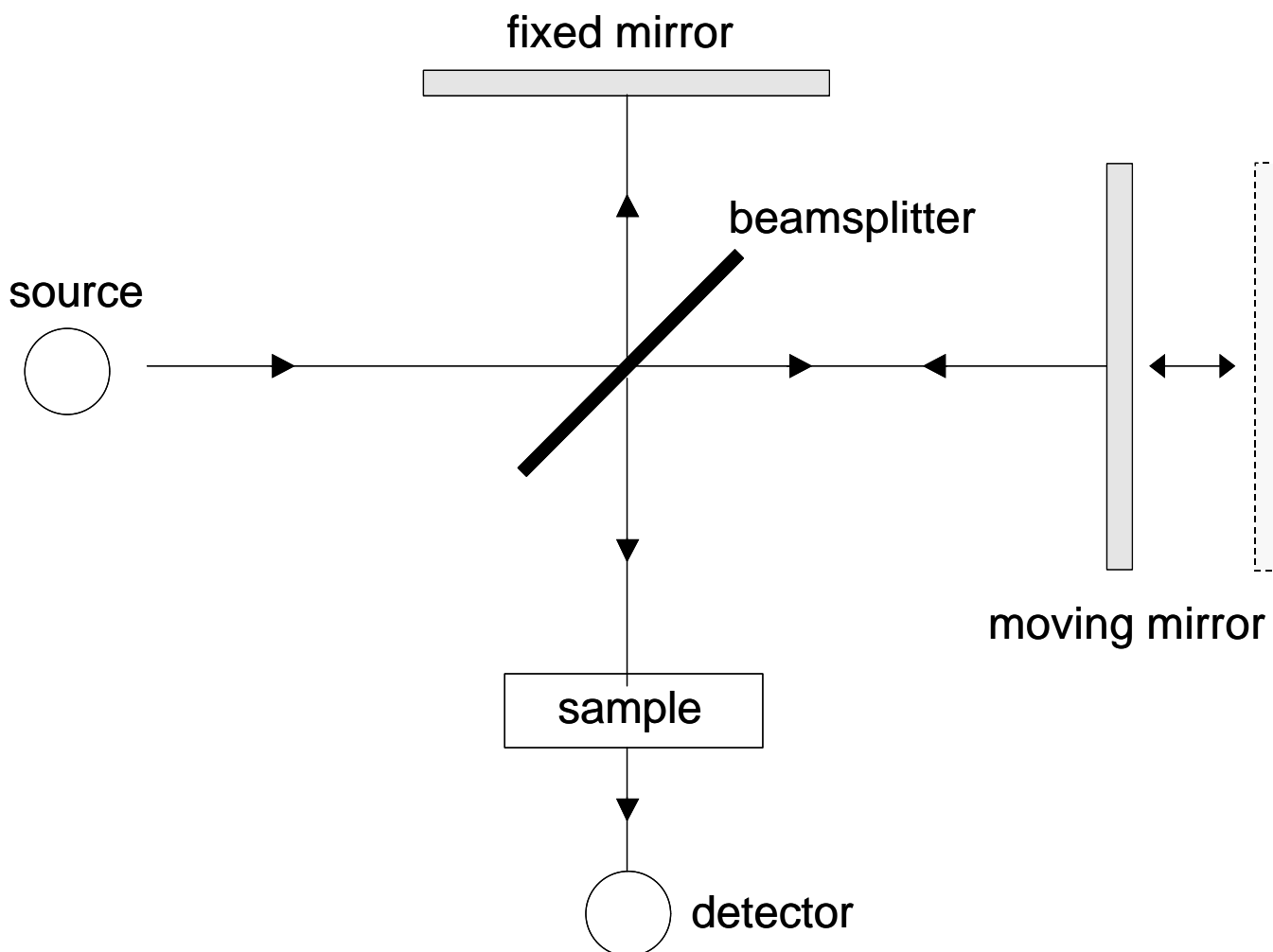


Figure 5-3: The MICHELSON interferometer

5.3 ACTIVE AND PASSIVE MEASUREMENTS.

A spectroradiometer can be used in two different configurations (SIGRIST, M.W., 1994):

The configuration is called *passive* when the spectroradiometer points directly to a hot source and measures the spectral distribution of the energy emitted by the source.

The configuration is called *active* when an artificial IR source is used as the emitter: in this case, the sample (solid or gaseous) is between the spectroradiometer and the source; then, the instrument measures the absorbed energy by the sample.

These two configurations appear to be very interesting in the study of fires.

Passive measurements can determine the spectral distribution of energy emitted during a fire, paying attention to the different phases of the burn.

Active measurements are very useful to characterise gases emitted by a biomass sample during a pyrolysis process, *in-situ* and in a non-intrusive way

Determination of these gases and its concentrations is very important to improve the knowledge of combustion chemistry.

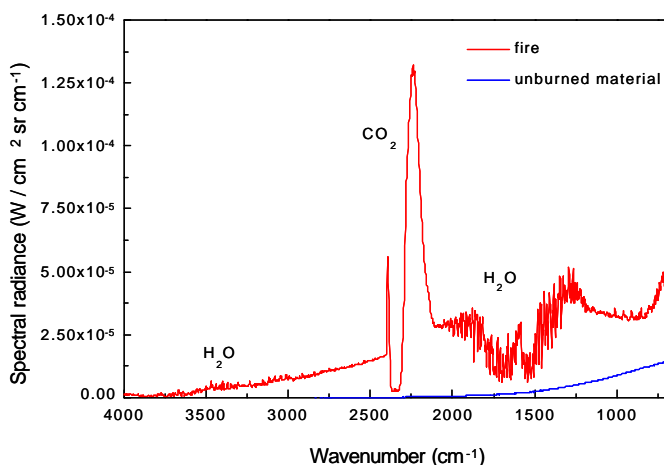


Figure 5-4: Spectral radiance measured for: blue: an unburned terrain, red: the same terrain during a straw burn.



Figure 5-5: An example of spectroradiometer (Midac Air Monitoring). On top, the interferometer module, at the bottom, a telescope.(<http://www.midac.com/>)

5.4 TABLES

Spectroradiometers owned by EUFIRELAB members

	Research Group	Contact Person	Instrument name	Spectral Range	Detector type	Operating principle /observations
P11	Universidad Carlos III de Madrid-	Juan MELÉNDEZ melendez@fis.uc3m.es	Spectroradiometer MIDAC- Air Monitoring System www.midac.com	2.2 to 16.6 μm	MCT (LN2 cooled)	FTIR
			Spectroradiometer GER www.ger.com	0.35 to 2.5 μm	Si /SPb (uncooled)	Dispersive
P30	Instituto de Economía y Geografía. CSIC	Pilar MARTÍN mpilar.martin@ieg.csic.es	Handheld Fieldspec Spectroradiometer Analytical Spectral Devices http://www.asdi.com/	0.325 to 1.075 μm	512-channel photodiode array 0.325-1.075 mm	Dispersive <i>Acquisition planned for the next future</i>

6 IR CAMERAS

NOTE: Here only a brief description of IR is presented. For more information, please consult the Eufirelab Deliverable: D-07-05, "Infrared Cameras: Principles and General Presentation" and references therein (Meléndez 2004).

6.1 SCANNING AND FPA INFRARED CAMERAS

An infrared camera (or IR imager) is an IR sensor coupled to an optical system designed to achieve spatial resolution, therefore providing an image as an output.

Cameras have also an electronics subsystem to amplify and condition the low-level output signal of the detector.

Most IR cameras have at least two outputs, a video output (for visualisation) and a digital output (for quantitative measurements).

In order to achieve spatial resolution using a single detector, the first IR cameras used a complex optical scanning module.

Scanning was synchronised with acquisition in order to reconstruct the image.

The fabrication of linear arrays of IR detectors simplified scanning, and the subsequent development of bi-dimensional (matrix) arrays has made it possible to dispense with the scanning.

The so-called "staring" Focal Plane Arrays (FPAs) have become the standard for IR cameras (Wolfe, 1999). (See Figure 6.1)

A disadvantage of FPA cameras is that they are more difficult to calibrate, because as a rule each individual detector in the array has a different response.

This lack of homogeneity must be corrected with a so-called Non Uniformity Correction (NUC) table that stores the calibration parameters for each pixel and applies them when visualising images.

IR cameras are designed to operate in one of the so-called atmospheric IR windows (Figure 2-4), in order to assure a good atmospheric transmittance, necessary for the camera to "see" at large distances.

Most cameras operate in the Medium IR (3 to 5 microns) or Thermal IR (8 to 12 microns).

The cameras that operate in the NIR window usually cover also the visible spectrum.

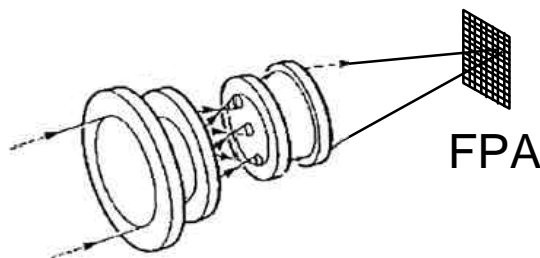


Figure 6-1: An IR camera using a focal plane array (FPA) needs no optical scanning.



Figure 6-2: An IR camera (Amber Radiance 1t)

6.2 QUANTITATIVE MEASUREMENTS WITH IR CAMERAS

Many applications of IR cameras (for instance, monitoring of wildland fire propagation) do not require a quantitative output.

Using an IR camera for those applications is not very different from using a visible camcorder.

However, IR cameras can provide also quantitative results on the IR emission of the target, and therefore on its temperature, emitted power and possibly other parameters.

One example is IR thermography, a well-established technique for non destructive testing, quality control, etc.

Most applications of IR thermography are to industrial processes where the environment can be carefully controlled.

IR cameras can be used also for quantitative outdoor measurements, but the effects of the sun, atmosphere, etc, must be taken into account by modelling the IR scene.

This topic has been highly developed by satellite remote sensing (see for instance (SCHOWENGERDT, 1997).

A summary of the main issues in this topic can be found in (MELÉNDEZ 2004).

6.3 TABLES

Summary of IR cameras owned by EUFIRELAB members (1)

	Contact Person	Instrument name	Band (μm)	Detector type
P01	INRA-PIF Jean-Luc DUPUY dupuy@avignon.inra.fr	FLIR – SC2000 FLIR www.flir.com	7 to 13.5	Microbolometers Uncooled 320x240 pixels
P02	ERT – Università di Corsica Albert SIMEONI simeoni@univ-corse.fr	JADE III CEDIP http://www.cedip-infrared.com	3-5 μm	InSb Stirling cooled 320 x 240 pixels
P07	Universidad de Sevilla-GRVC Begoña C. ARRUE barrue@cartujaue.us.es	IR-M300E Thermal Imager Mitsubishi Electric www.mitsubishielectric.com Indigo Merlin Uncooled www.indigosystems.com ContoIR 2000AS Raytheon www.raytheoninfrared.com	3 to 5 7.5 to 13.5 7 to 14	Platinum Silicide Stirling-cycle cooler 256 x 256 pixels VOx 160 x 120 pixels Amorphous Silicon Microbolometer Uncooled 160 x 120 pixels
P11	Universidad Carlos III de Madrid- Juan MELÉNEDEZ melendez@fis.uc3m.es	Indigo Merlin Uncooled www.indigosystems.com Amber Sentinel No website (company bought by raytheon) Amber Radiance 1t No website (company bought by raytheon) Thermosensorik 384M www.thermosensorik.de Raytheon 2000B www.raytheoninfrared.com Raytheon 2000AS www.raytheoninfrared.com	7.5 to 13.5 8 to 12 3 to 5 1.5 to 5 7 to 14 7 to 14	Vox, Uncooled 320x240 pixels Vox, Uncooled 320 x 240 pixels InSb Stirling Cooled 256 x 256 pixels CMT Stirling Cooled 384 x 288 pixels BST, Uncooled 320 x 240 pixels Si-a, Uncooled 160 x 120 pixels
P13	ADAI Domingos Xavier VIEGAS xavier.viegas@dem.uc.pt	Thermovision® 550 FLIR www.flir.com	3.6 to 5	FPA SiPt, Cooled Stirling 320 x 240 pixels
P17	CEREN Frederique GIROUD f.giroud@wanadoo.fr	THERMACAM PM 290 FLIR www.flir.com	3.4 to 5	FPA ,Stirling Cooled 256 x 256 pixels
P18	Xunta de Galicia-CIFAL Pedro CUIÑAS pcuinas.cifal@siam-cma.org	CYCLOPS TI 35 + Land Instruments http://www.landinst.com	3.5 to 5	12 element HgCdTe Thermoelectrically cooled
P20	Universidad de Castilla –La Mancha José M. MORENO JoseM.Moreno@uclm.es	Acquisition under study		
P31	Universidad de Córdoba Francisco RODRIGUEZ Y SILVA	Acquisition under study		

7 IMAGING SPECTROMETERS

An instrument that combines spatial and spectral resolution is an *imaging spectrometer*.

The first instruments of this kind were called *multi-spectral imagers*.

One early example was the Multi-spectral Scanner System (MSS) onboard the Landsat satellite, launched in 1972.

It acquired simultaneous images of a scene at four different spectral bands, from 0.5 to 1.1 μm .

Since then, instruments with an increasing number of bands (up to several hundreds in the *hyperspectral imagers*) have been developed (WOLFE 1997).

Complexity and high cost has confined most of them to military or satellite remote sensing applications.

However, multispectral imaging has potential uses in many other fields, such as medicine, non-destructive testing and environmental monitoring.

In general, whenever the IR emissivity or reflectance of an object has spectral structure (i.e., the object is not a greybody) multi- or hyperspectral imaging will provide a rich information that is missed by a standard IR camera.

As we pointed out in Chapter 3, the output of a spectral imager can be viewed as an image for each wavelength of the spectral range or, equivalently, as a spectrum for each point of the field of view.

In any case, it is a 3-dimensional volume of data, that is sometimes called a *spectral cube* (Figure 7.1)

In order to qualify as an imaging spectrometer, an imaging system must provide images in several spectral bands that comply with three requirements:

- *Co-registration*: the fields of view (FOV's) must be the same in both bands, not only for the whole image, but also for corresponding pixels in each image.
- *Simultaneity*: critical for the study of a dynamical phenomenon like fire.
- *Radiometric calibration* to ensure that digital numbers in each image can be compared.

If these requisites are accomplished, the whole set of images at a specific time is called a "multispectral image" and it is possible to apply to it the powerful processing techniques developed originally for remote sensing applications (SCHOWENGERDT, 1997).

Several different methods have been used to achieve spectral resolution in an IR imaging system:

- Rotating wheels with band-pass interference filters in specific wavelengths. Although images at different wavelengths are not strictly simultaneous, this quasi-simultaneity can be enough for many processes not too fast.
- Variable circular interference filters that allow to change continuously the transmitted wavelength
- Dispersive systems: germanium prisms, diffractive gratings, Fabry-Perot or Michelson interferometers, diffractive optics...

There is not a single optimum solution; rather, it must be studied for each application.

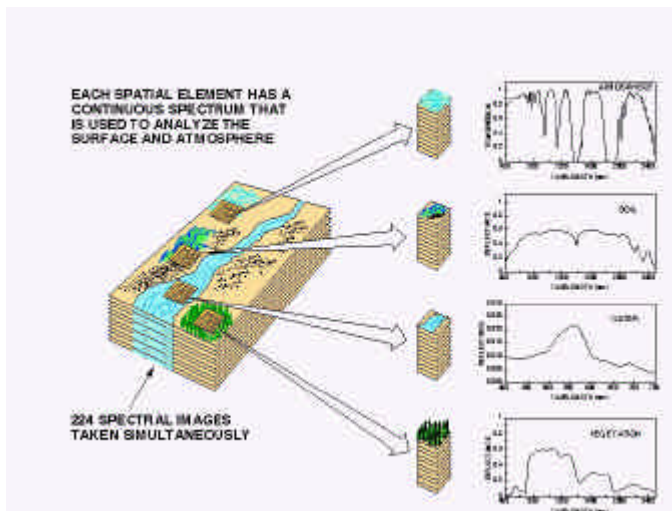


Figure 7-1.: The concept of spectral cube. Adapted from <http://aviris.jpl.nasa.gov/html/aviris.concept.html>

Summary of Imaging Spectrometers owned by EUFIRESLAB members

	Contact Person	Instrument name	Spectral Range	Detector type	Operating principle
P11	Universidad Carlos III de Madrid Juan MELÉNDEZ melendez@fis.uc3m.es	Image Multi-spectral Sensing (IMSS) Pacific Advanced Technology (PAT) http://www.patinc.com/	3 to 5 μm	No detector (operates coupled to IR camera)	Diffractive optics selects wavelength in the 3 to 5 μm band

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- WEB TT
<http://www.ttiglobal.com/Menu.asp?Param1=1&Param2=IR>
- WEB TESTO <http://www.testo.de/ZZ/en/site/information/>
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9 APPENDIX: QUESTIONNAIRE ON IR INSTRUMENTATION

9.1 IDENTIFICATION OF RESEARCH TEAM

Research group		Partner	
Contact person		E-mail	

Do you have in your lab infrared (ir) equipments ?

Yes	
No, but we have used it occasionally	
No	

Do you plan to acquire ir equipment in the next future ? (y/n)	
--	--

If yes, indicate the type and main characteristics	
--	--

9.2 IR CAMERAS

Number of equipments:

If you have more than 1 equipment, please fill the following information for each one

Model				
Company website				
Representative in your country				
Spectral range				
Detector type				
Cooling system	uncooled			
	cooled		cooling type	
Detector size	Single			
	Array		Dimensions × pixels	
	Linear		Dimensions pixels	
Outputs	Video		Type	
	Digital		Type	
				Frame rate
Lenses	50 mm			
	100 mm			
	Others			
Radiometric calibration	Yes			
			Temperature range	
	No			
Optical filterscoupled to the camera	No			
	Neutral			
	Narrow (bandpass)			
Other wavelength selector				
Acquisition system	Analog		Video type	
	Digital		Framegrabber type	
				Model
				Commercial website
Acquisition and processing software	Acqui. SW			
	Image Proc. SW			

9.3 IR SPECTROMETERS

Number of equipments

If you have more than 1 equipment, please fill the following information for each one

Model		
Company website		
Representative in your country		
Type	Lab. Equipment (spectrophotometers)	
	Field equipment (spectroradiometers)	
Spectral selectivity	Dispersive	
	Ftir	
Detector type		
Cooling system		
Spectral range		
Spectral resolution		
Field of view (semi-angle) (only for spectroradiometers)		

9.4 OPTICAL PYROMETERS

Number of equipments

If you have more than 1 equipment, please fill the following information for each one

Model	
Company website	
Representative in your country	
Temperature range	
Response time (typical) (minimum)	
Spectral range	
Associated optics	

9.5 HEAT FLUX TRANSDUCERS

Number of equipments

If you have more than 1 equipment, please fill the following information for each one

Model	
Company website	
Representative in your country	
Response time (typical) (minimum)	
Irradiance range	
Measurement principle	

9.6 OTHERS (BLACKBODIES, CALIBRATED DETECTORS,...)

Please provide the most relevant technical characteristics

9.7 EXPERIMENTAL TECHNIQUES

Please provide a brief explanation of your experimental techniques, as well as the most relevant parameters you measure with your IR equipments.