Thermometry at the SCF_Lab

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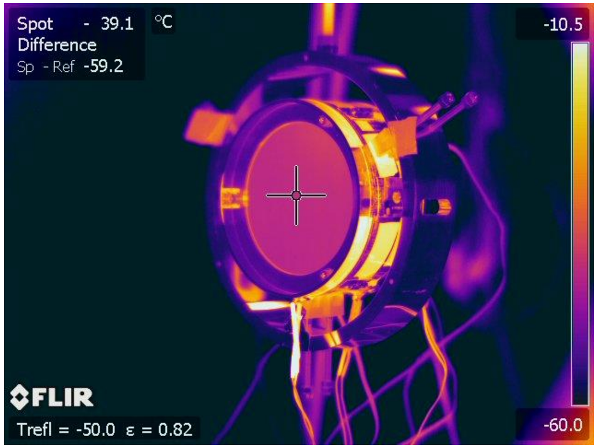

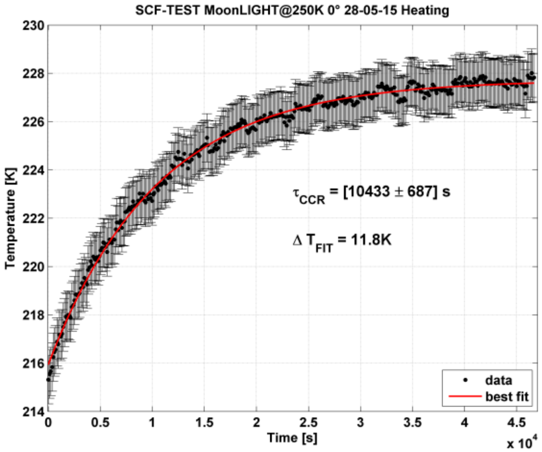

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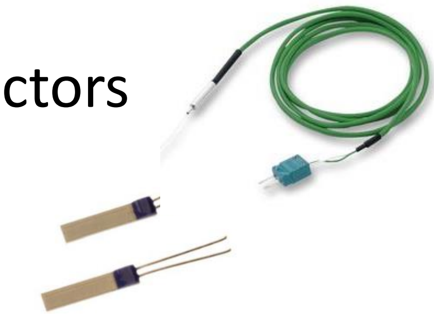
Outline

- Thermometers and thermal detectors
  - Thermocouple
  - Resistance Temperature Detector
  - Pyranometer



- Solar Simulator

- IR camera

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Thermometers and thermal detectors

Thermometers are defined by:

- Temperature Operative range:
  - Maximum value (range)
  - Minimum value (threshold)
- Readiness:
  - Time within the instrument reacts to temperature change
- Sensibility: $S = \Delta R / \Delta G$
  - ΔR = instrument response variation
  - ΔG = variation of the physical quantity measured
- Resolution
  - Depends on the instrument sensibility and quantifies the minimum variation measurable by the instrument
- Precision:
  - How much the instrument response depends only from the physical quantity measured

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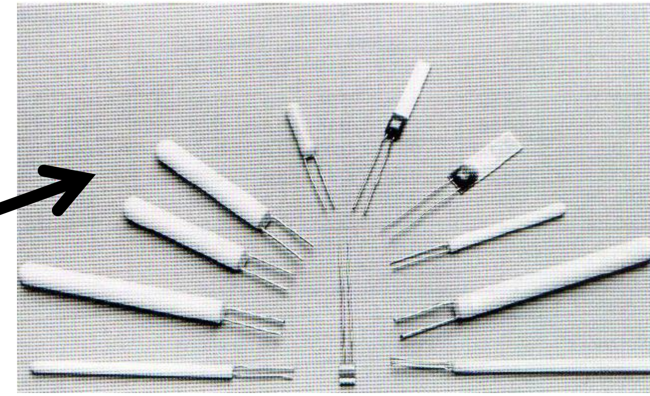
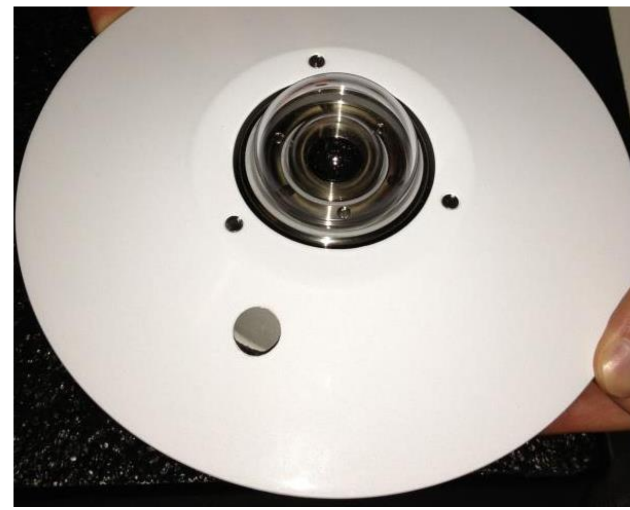
Thermometers and thermal detectors

Some thermometers type:

- Liquid thermometer
- Thermocouple
- Resistance Temperature Detector (RTD)
  - ➢ PT100, used in the SCF_Lab to acquire the temperatures from shroud and payload
- Pyranometer
  - ➢ Used to calibrate the Solar Simulator
- IR camera for thermography
  - ➢ Used for the IR thermal measurements

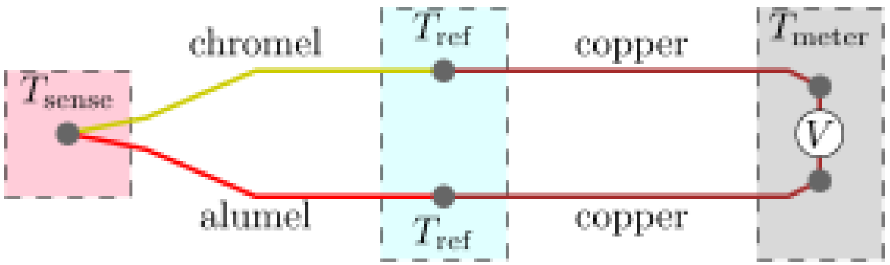




Thermocouple

$$\nabla V = -S(T)\nabla T$$

- 2 dissimilar conductors or semiconductors that contact each other at one or more points.
- Produces a voltage when the 2 temperatures differ each other: thermoelectric effect (or Seeback effect).



Advantages

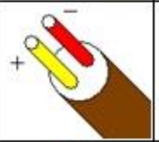
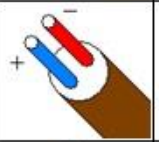
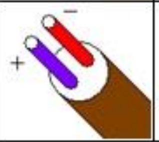
- Low mass -> High readiness
- Easy thermal coupling
- Low thermal conductivity (only if the wires are quite short)
- Useful for measure very high temperatures
- Easy communication with control devices

Disadvantages

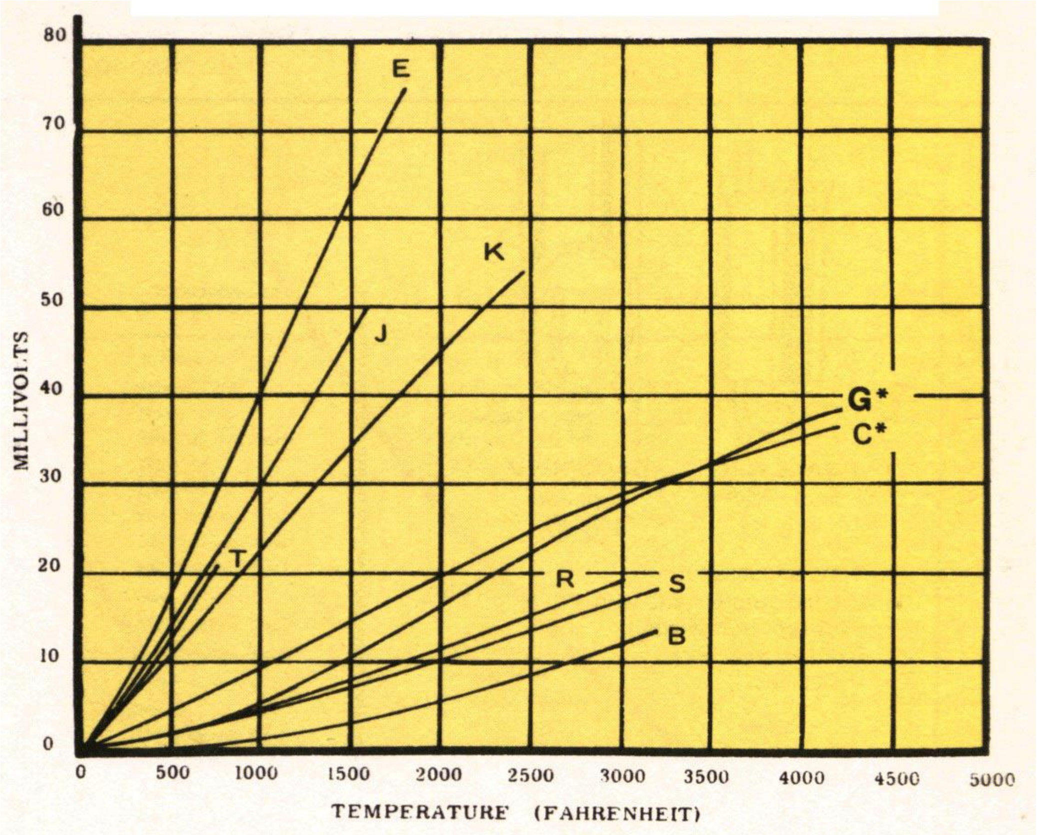
- Non linear
- Low sensitivity
- Precision depends on electromotive force reading system, usually less then 0,1K
- Sensibility depends on the material used

Thermocouple

Common Types:

Type	Material		Color Code	Range (°C)	
Thermocouple Grade	Positive Wire	Negative Wire		Minimum	Maximum
J	Iron	Constantan		0	750
K	Chromel	Alumel		-200	1250
T	Copper	Constantan		-200	350
E	Chromel	Constantan		-200	900

Non linear law:



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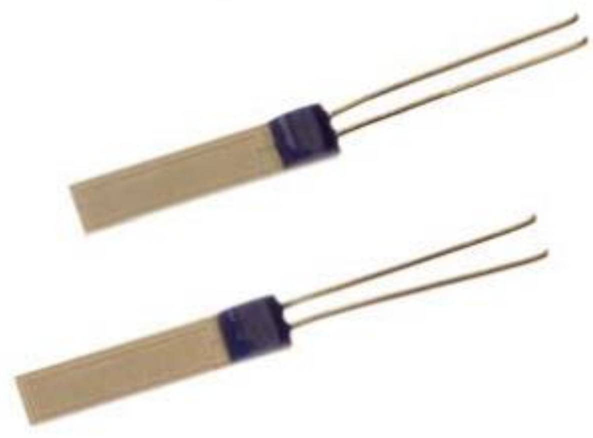
Resistance Themperature Detector

- The resistance (or better the resistivity ρ) of a metal conductor changes with its temperature
- Generally the law is: $R(T) = R_0(1 + \alpha T)$ where
  - R_0 is the Resistance at 0°C
  - α is the temperature coefficient of the material
- The temperature measurement is a measurement of a resistance made in 2 ways:
  - Volt/Ampere
  - Wheatstone bridge
- In both methods the current in the conductor must be a costant I_{Bias}



Advantages

- Useful in many T range
- Usually linear law
- Small dimensions
- Quickness
- Low-cost

Disadvantages

- Require the I_{bias} circuit
- Operative temperature lower respect to thermocouples
- Sensibility depends on the temperature because of the Joule effect

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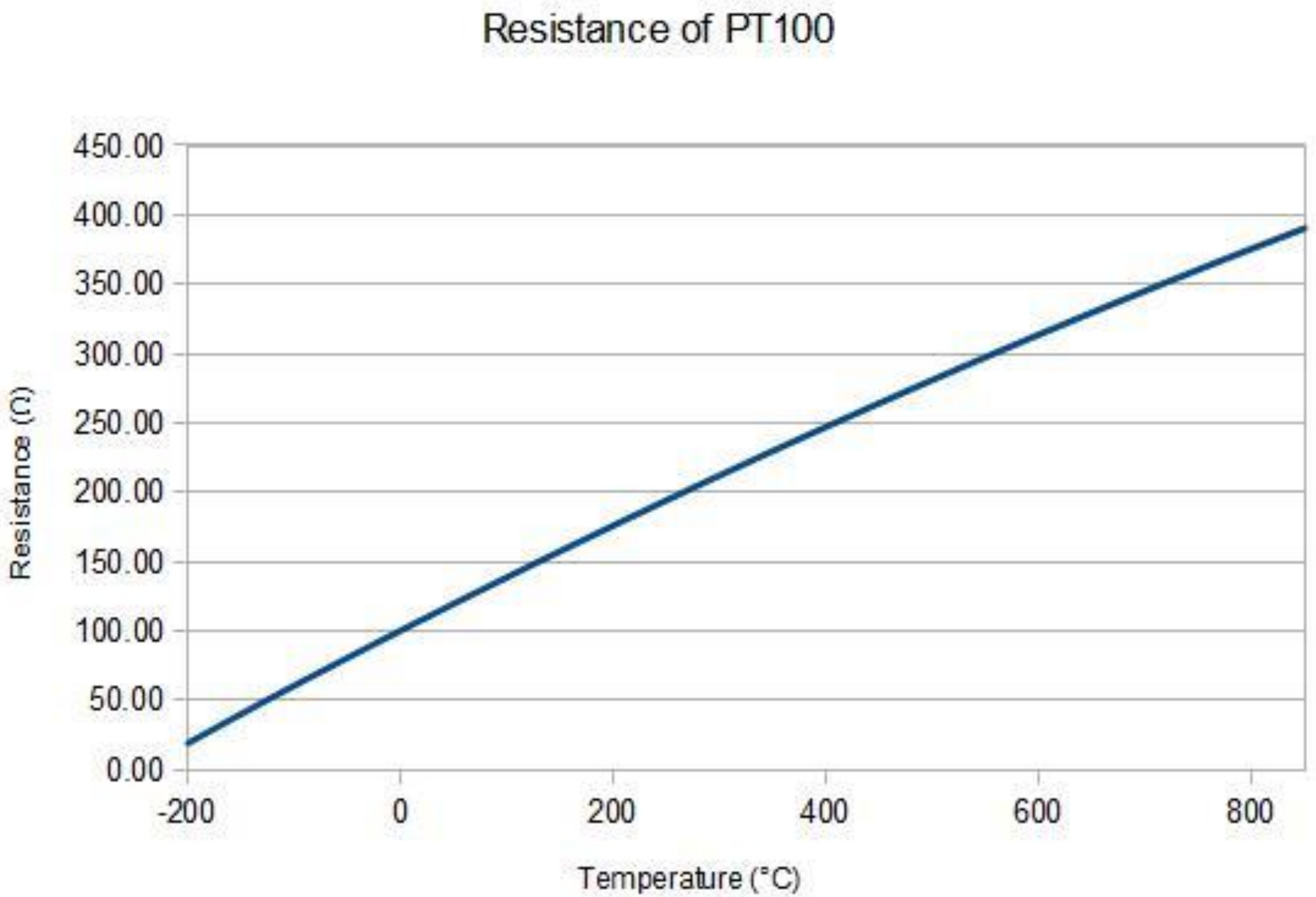
Resistance Themperature Detector



Resistance Themperature Detector

- Platinum is a common material used.
- A platinum wire can be easily realized with high pureness
- The platinum wire usually has a resistance about 100Ω with α=0.392 Ω/°C
- Work in the range of -200÷850°C

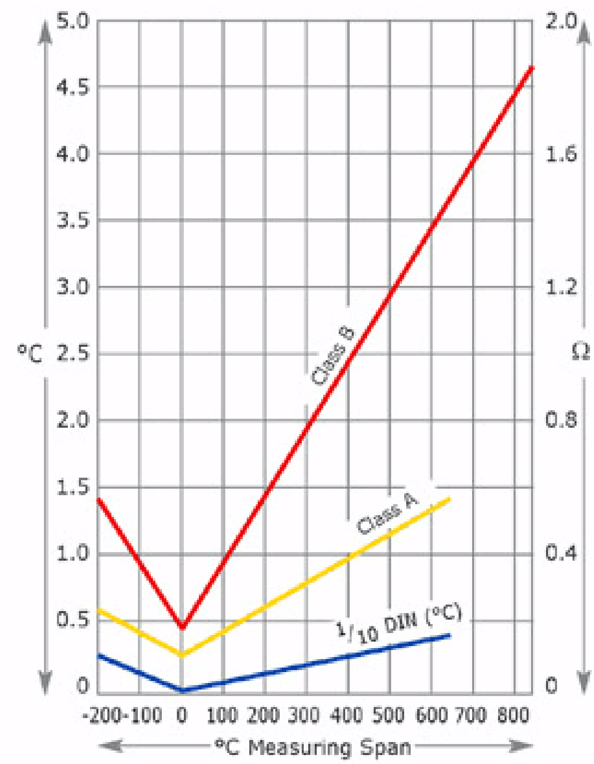
PT100 are the most used platinum resistance temperature detectors

Pt100 Elements, Thin Film (100 Ohm)

- Pt100 elements to IEC 751 Class A & B
- For use from –50°C to +550°C
- Thin film construction
- Suits surface & immersion applications where protected
- Vibration resistant

Specifications of elements

Sensor type:	Pt100 (100 Ohms @ 0°C)
Construction:	Thin film, 10mm tails
Temperature range:	-50°C to +550°C
Ice point resistance:	100Ω
Fundamental interval (0°C to 100°C)	38.5Ω (nominal)
Self heating	<005°C/mW
Thermal response	0.1s
Stability	±0.05%
Dimensions & tolerance class	2 x 5.0mm, 2 x 10mm, 2 x 2.3mm, 1.2 x 4.0mm & 1.2 x 1.6mm 1.6 x 3.2mm (surface mount - range -50°C to +150°C)



RTD used at SCF_Lab

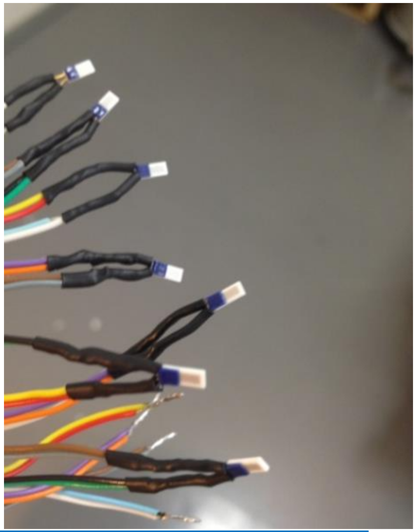
2 types of PT100

- *Wirewound*:
  - Consists of a pure platinum wire wound up and located within axial holes in a high purity alumina rod.
  - Good long term stability and a wide operative temperature range, from -200°C to 800°C.
  - Can work at cryogenic temperatures (below -50°C) with good tolerance.

  In the SCF_Lab wirewound probes are used to monitor the shroud temperature (2 circuits of 24 probes each one).

- *Flat film:*
  - Produced by a deposition of a platinum film onto a ceramic substrate, the platinum is sealed to ensure protection.
  - Small size with fast response to temperature changes
  - Very useful for surface measurement with great resistance to vibrations and shock.

  In the SCF_Lab the flat-film probes are used to monitor payloads temperature.



Resistance Themperature Detector

Resistance Temperature Detector

Resistance v temperature and tolerances for Pt100 thermometers to IEC 751

Temperature	Resistance	Tolerance Class A		Tolerance Class B		Temperature	Resistance	Tolerance Class A		Tolerance Class B	
(°C)	(Ω)	(±°C)	(±Ω)	(±°C)	(±Ω)	(°C)	(Ω)	(±°C)	(±Ω)	(±°C)	(±Ω)
–200	18.52	0.55	0.24	1.3	0.56	500	280.98	1.15	0.38	2.8	0.93
–100	60.26	0.35	0.14	0.8	0.32	600	313.71	1.35	0.43	3.3	1.06
0	100.00	0.15	0.06	0.3	0.12	650	329.74	1.45	0.46	3.6	1.13
100	138.51	0.35	0.13	0.8	0.30	700	345.28	——	——	3.8	1.17
200	175.86	0.55	0.20	1.3	0.48	800	375.70	——	——	4.3	1.28
300	212.05	0.75	0.27	1.8	0.64	850	390.48	——	——	4.6	1.34
400	247.09	0.95	0.33	2.3	0.79						

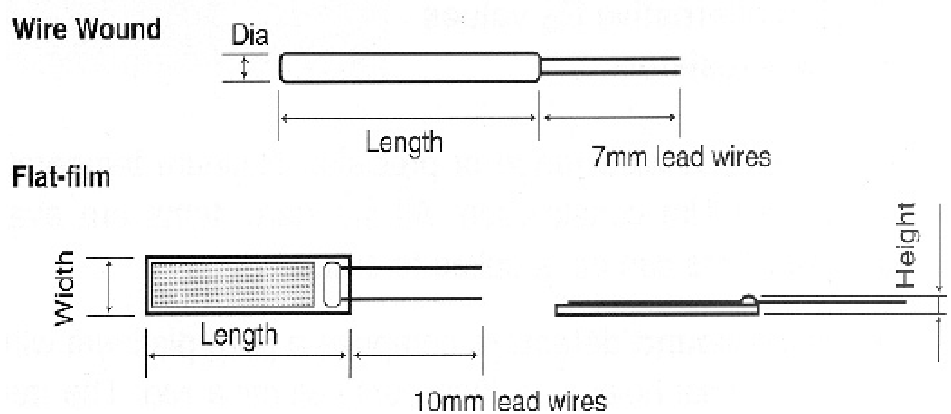
Tolerances

Class B	±(0.3°C + 0.005t)
Class A	±(0.15°C + 0.002t)
Where t is the measured temperature	
1/3 Class B	±(0.1°C at 0°C)
1/5 Class B	±(0.06°C at 0°C)
1/10 Class B	±(0.03°C at 0°C)

Note: 1/3, 1/5 and 1/10 Class B Tolerances apply at 0°C

Dimensions

Individual dimensions are given in Order Codes & Dimensions below.



Pyranometer

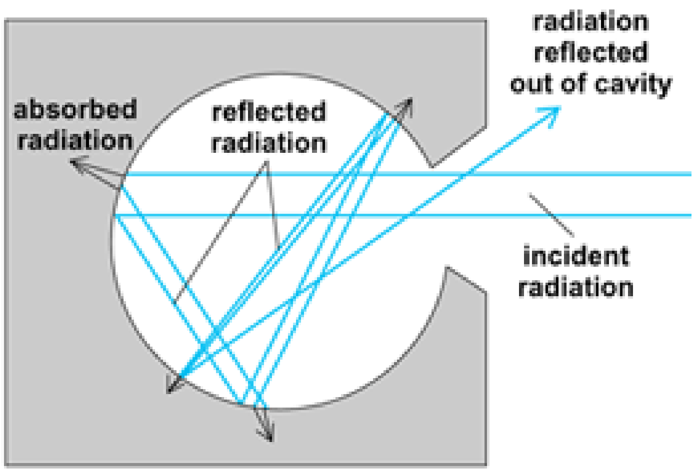
- Measures the object temperature from its irradiance
- Can be used for high temperatures (>1000K), higher than the melting point of many metals
- Can be used to measure the object irradiance (whole spectrum or only the visible)
- 2 types:
  - *Optical* = Compares the object luminosity with the luminosity of a custom lamp, at known temperature (calibration lamp). It works in the visible spectrum.
  - *Total radiation* = Measures the equilibrium temperature of an absorber element, when hit by the radiation from the object. It works in the whole spectrum, so can measure even low temperature.

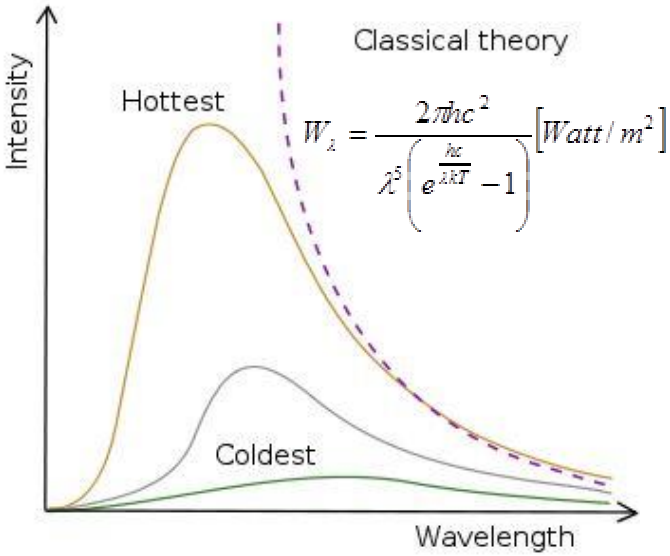
Blackbody

- A blackbody is an ideal object which absorbs all the radiation that strikes it, at any wavelength and at the same time, it is able to emit all the absorbed radiation
- It is like an isothermal cavity made of an opaque absorbing material, internally black painted
- Differentiating Planck's formula with respect to λ and finding the maximum, obtain Wien's formula:

$$\lambda_{max} = \frac{b}{T} [\mu m]$$

- Integrating Planck's formula from λ=0 to λ=+∞, it is possible to obtain the intensity of a radiation emitted by a blackbody
- Stefan-Boltzmann's law: $W = \sigma T^4 [\frac{W}{m^2}]$
- Graphically S-B represents the area below the Planck's curve for a given temperature T
- For a gray body: $W = \varepsilon\sigma T^4 [\frac{W}{m^2}]$ is the total emissive power. It is like the blackbody one, but proportionally reduced by the value ε.



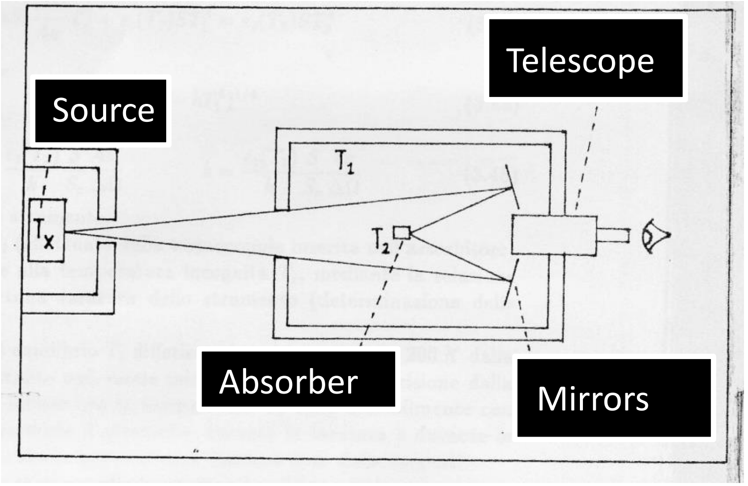


Total radiation Pyranometer

- Uses the Stefan-Boltzmann law ($W = \sigma T^4$).
- Is composed by:
  - ➢ An absorber body, black painted with inside a thermocouple/RTD/solar cell (depends on the range)
  - ➢ A set of adjustable mirrors
  - ➢ Focusing Telescope
- The telescope focuses on a specific region of the observed body
- The mirrors are oriented in a way that the irradiance hits the absorber body (it must be isolated from the instrument)
- At the equilibrium: $W_a = W_S + W_e$ where:
  - W_e = Radiation from the instrument walls
  - W_S = Radiation from the Source
  - W_a = Radiation from the absorber at the equilibrium
- In this way we can obtain:

➢ The Source temperature

➢ **The Source total radiance (over the entire spectrum)**



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Pyranometer at SCF_Lab

Total radiation Pyranometer

The measuring of Atmospheric Radiation is generally divided in to two distinct spectral regions: the solar (shortwave) region and the terrestrial (longwave) region.

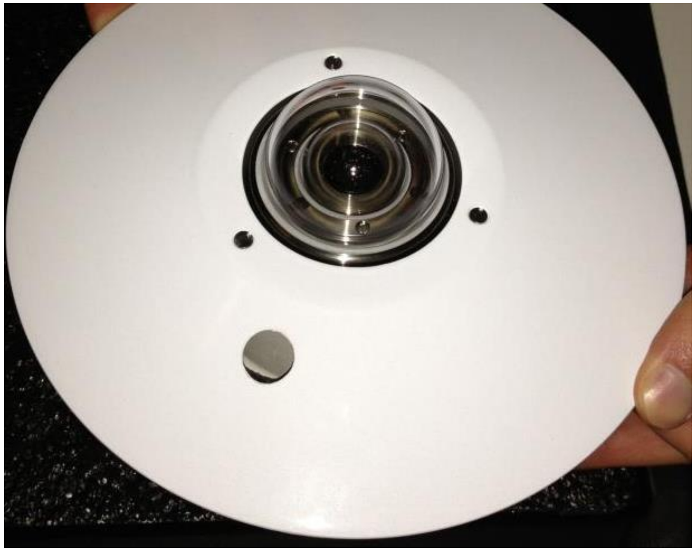
Solar radiation is a term used to describe visible and near-visible (ultraviolet and near-infrared) radiation emitted from the sun. The different regions are described by their wavelength range within the broad band range of 0.20 to 4.0 µm (microns). Terrestrial radiation is a term used to describe infrared radiation emitted from the atmosphere. The following is a list of the components of solar and terrestrial radiation and their approximate wavelength ranges:

Ultraviolet:	0.20 - 0.39 µm
Visible:	0.39 - 0.78 µm
Near-IR:	0.78 - 4.00 µm
Infrared:	4.00 - 100.00 µm

Approximately 99% of the solar radiation at the earth's surface is contained in the region from 0.3 to 3.0 µm while most of infrared radiation is contained in the region from 4.0 to 50 µm. Shortwave radiation is measured using pyranometers and pyrheliometers while longwave radiation is measured using a pyrgeometer.

$Conversion\ factor$:

$$C = 140\ \frac{1}{mV}\frac{W}{m^2}$$



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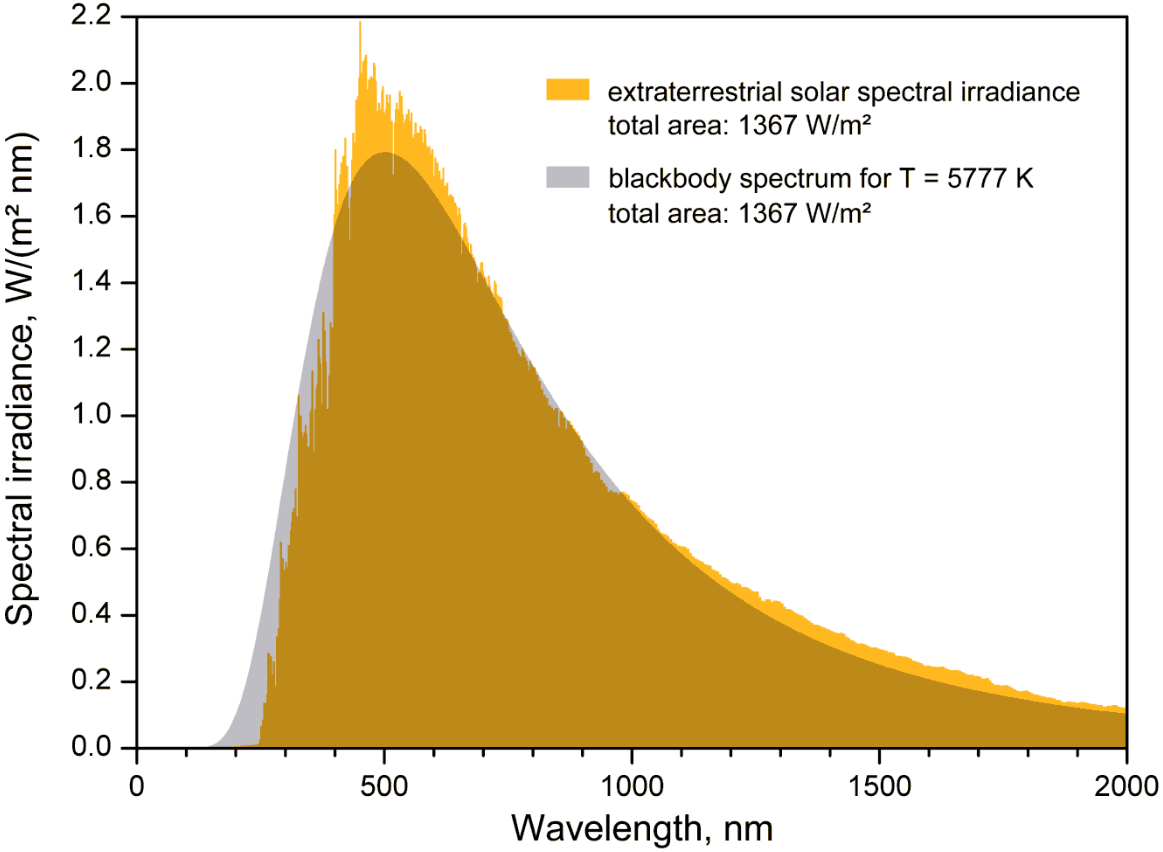
Solar Simulator

INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati

- The solar simulator is a lamp with specific filters able to reproduce the solar illumination outside the Earth Atmosphere in terms of intensity and spectrum.
- This is called AM0 spectrum.

- The instrument is housed in an enclosure of :
  L=1.6m, B=0.8m, H=2.4m
- At one end there is an aperture, through which the beam exits
- This aperture may be closed by means of a water-cooled pneumatically driven shutter
- **Within the housing, is mounted a 6kW metal halide lamp and a set of filters (49 units) which produce the Solar spectrum.**



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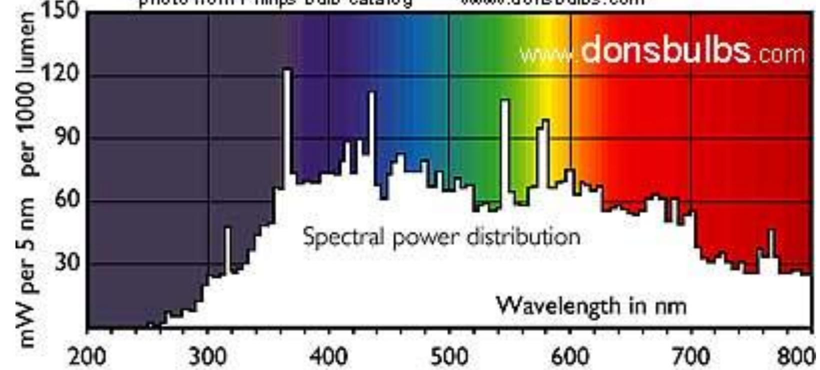
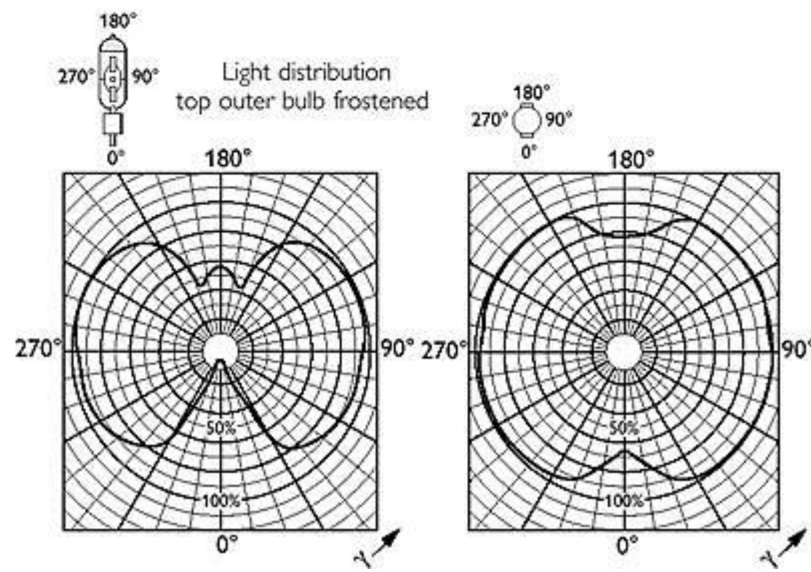
SS HMI lamp

- The **metal-halide lamp** produces light by an electric arc through a gaseous mixture of vaporized mercury and metal halides (compounds of metals with bromine or iodine).
- It is a high intensity discharge (HID) lamp.
- The most common metal halide compound used is the sodium iodide
- Once the arc tube reaches its running temperature, the sodium dissociates from the iodine, adding orange and red to the lamp's spectrum, from the sodium D line as the metal ionizes.
- Metal-halide lamps have high luminous efficiency, of around 75 - 100 lumens per watt

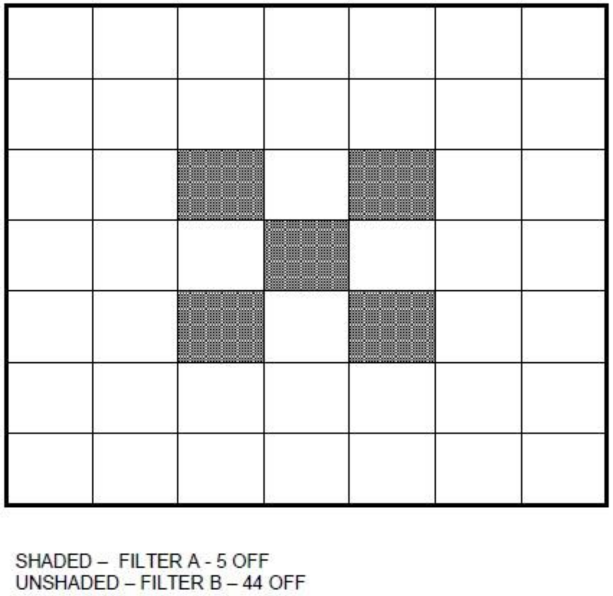
photo from Philips bulb catalog www.donsbulbs.com





SS Filters

- A mask of optical filters placed in front of the lamp, used to match the output spectrum lamp with the real solar spectrum. The mask is composed by 5 shaded and 44 unshaded filters, for 49 filters total, everyone with dimensions around 5x5cm, placed in a holder.



Solar Simulator at SCF_Lab

The distance between the lamp and the opening, along with the Simulator structure, are designed in order to obtain three different features:

- The beam divergence allows the illumination of 420 mm diameter surface.
- A close match with the AM0 (Air Mass 0) spectrum. The AM0 is defined as the Solar Spectrum outside the Earth atmosphere, in the interval 400- 3000 nm within the standard IEC 60904-9.
- The output beam uniformity is 10% inside a circle surface with 200 mm diameter.

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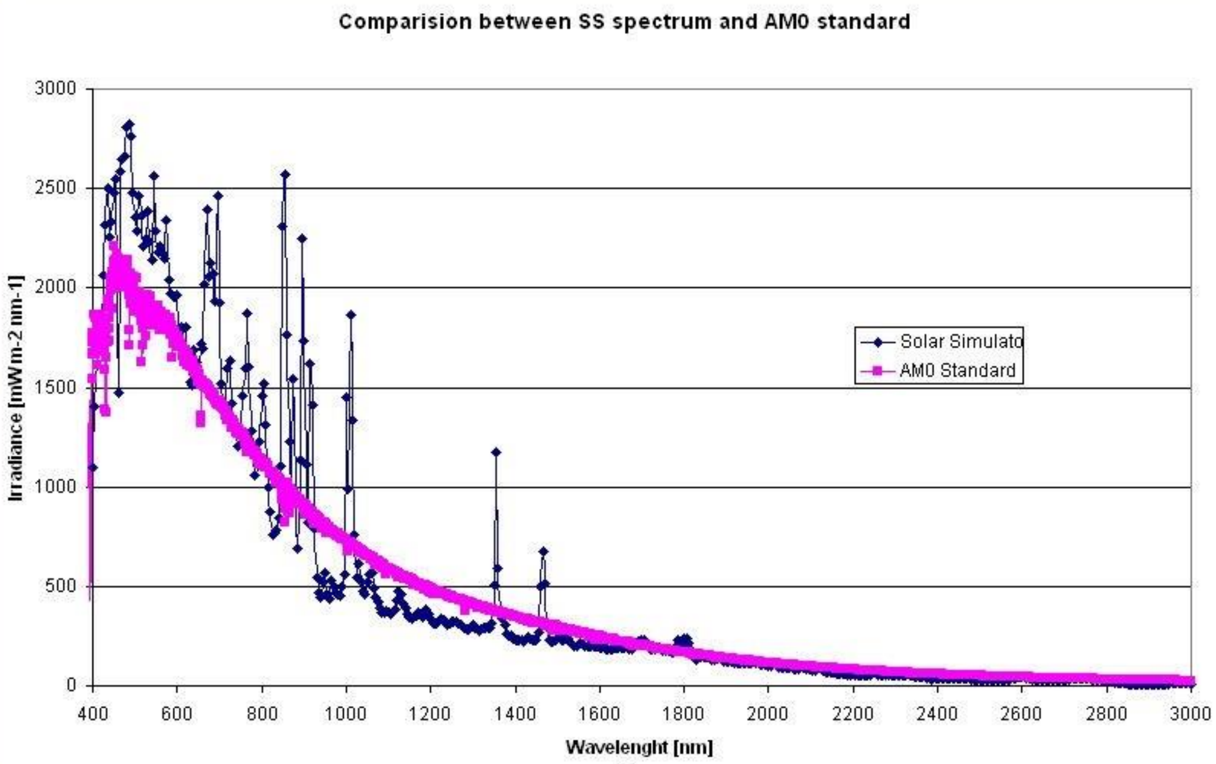
SS spectrum



According with IEC 60904-9 standard (which considers AM1.5 spectrum, there is no standard considering AMO), which relates only to the range 400 nm to 1100 nm, we applied the same percentages defined by the IEC 60904-9 standard for the AM1.5 spectrum to our AMO solar simulator

Band [nm]	AM.15 %distribution	Spectrum Integral over the range [W/m^2]	% distribution and Class Rating	Class A Upper Limit %	Class A Lower Limit %	Inside the Range
400-500	18.4	226316	21.75071768	23	13.8	Yes
500-600	19.9	221659	21.30314397	24.875	14.925	Yes
600-700	18.4	185630	17.84047846	23	13.8	Yes
700-800	14.9	140804	13.53235323	18.625	11.175	Yes
800-900	12.5	129909	12.48525948	15.625	9.375	Yes
900-1100	15.9	136179	13.08785496	19.875	11.925	Yes

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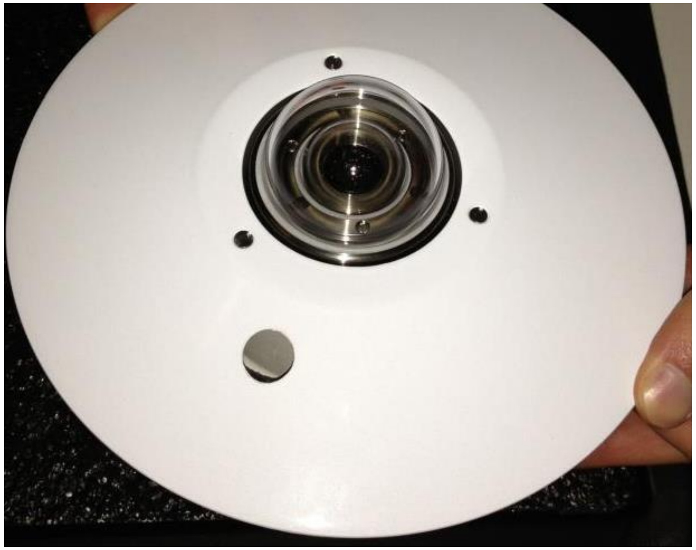
Solar Simulator measurement

Your measurement tomorrow. At 1 m from aperture:

- Intensity at center = equal to the Solar Constant within a 5%
- Uniformity = 10% inside a circle surface with 200 mm diameter.
- Instruments:

For Intensity the calibrated pyranometer

$$Conversion\ factor: \quad C = 140\ \frac{1}{mV}\frac{W}{m^2}$$



For Uniformity the Uncalibrated (but lighter) pyranometer

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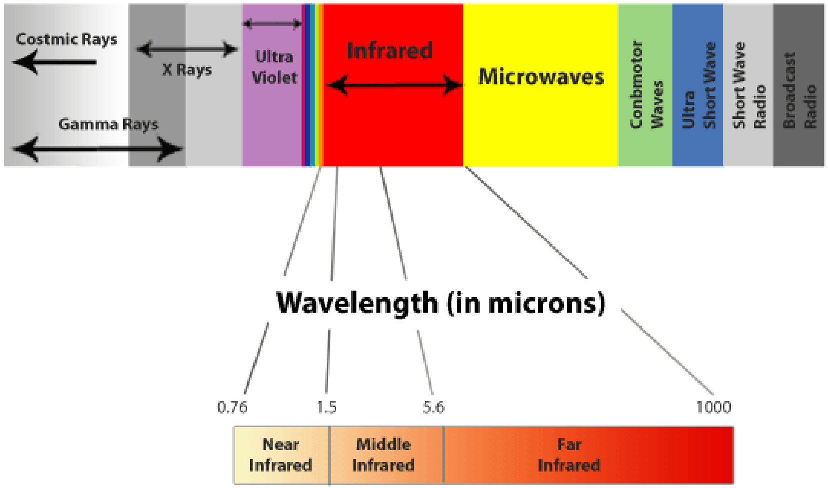
Thermography



- The Thermography is a non-invasive technique that allows to detect the temperature of an object surface without using thermal probes directly in contact with the object.
- Thermography makes possible to see an object even if it is not illuminated by a natural or an artificial source of light.
- Thermography allows to see variations in temperature and to print a thermal image known as **thermogram**.

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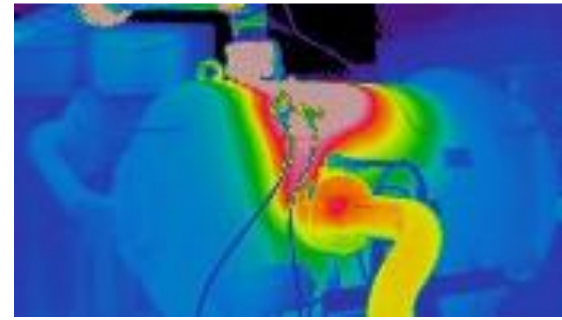
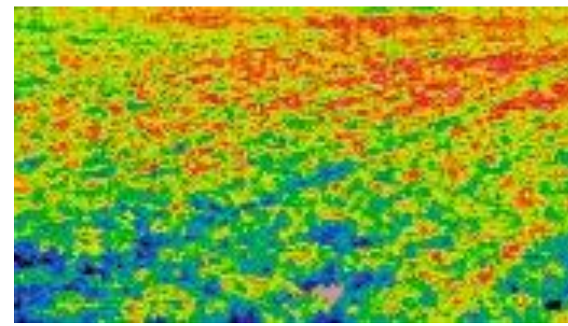
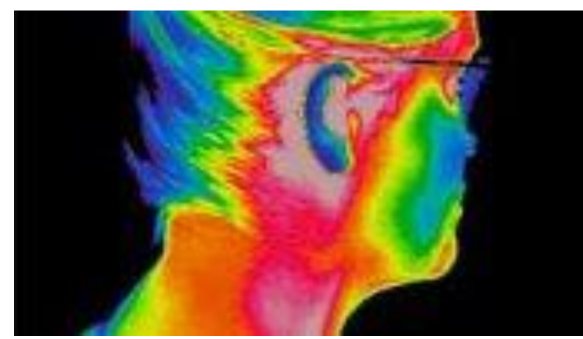
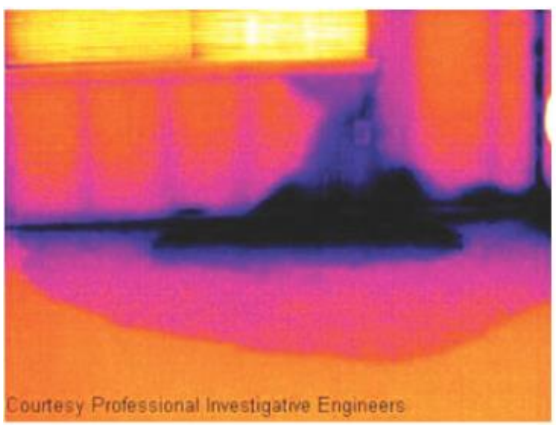
Thermography applications

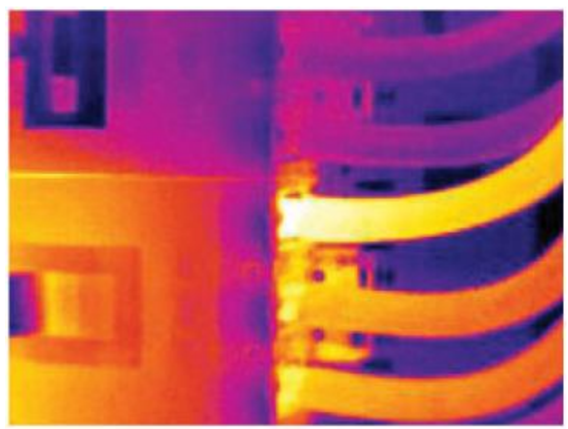
- Construction
- Electrical Systems
- Medicine
- Restoration
- Industry
- Agriculture
- Monitoring and Surveillance











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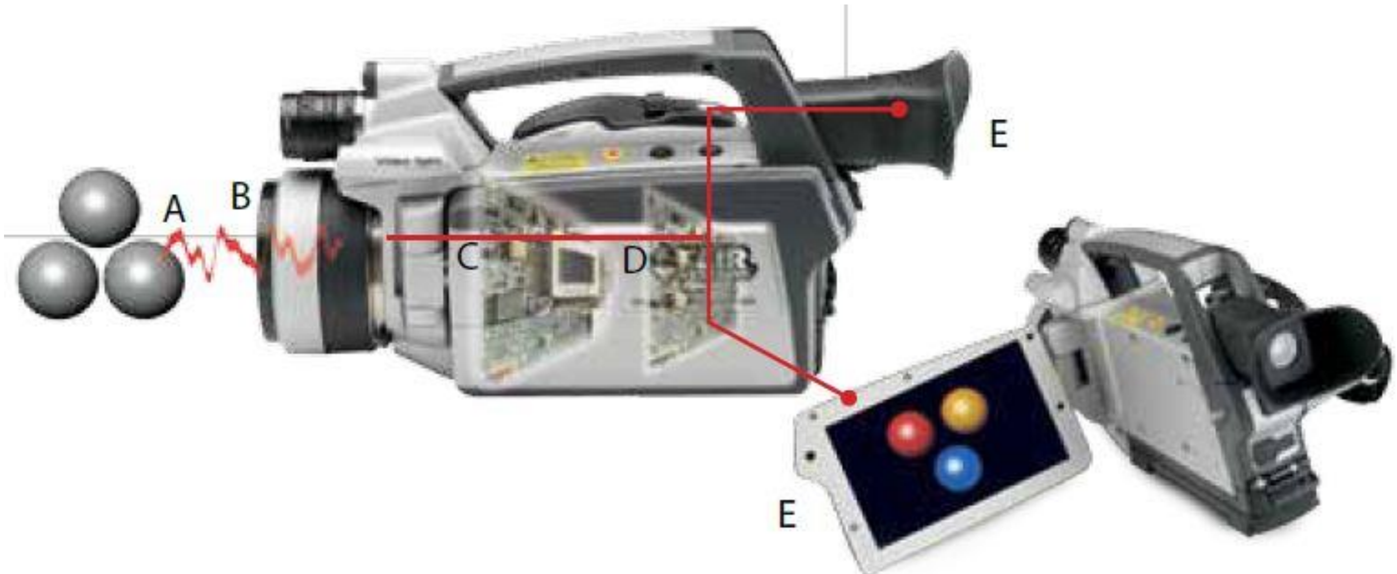
IR camera

IR camera for thermography

- IR camera measures the infrared radiation coming from an object surface that is function of the object superficial temperature
- The detector uses at the SCF_Lab measures IR radiation in the range of 7.5 µm – 13 µm and detects temperatures between -50°C and 300°C
- Behind Ge camera lens, there are different electric sensors which collect all radiation received by the IR camera and also transmit data to other components of the camera



The camera also has a laser pointer, wavelength 635 nm, max power 1 mW.

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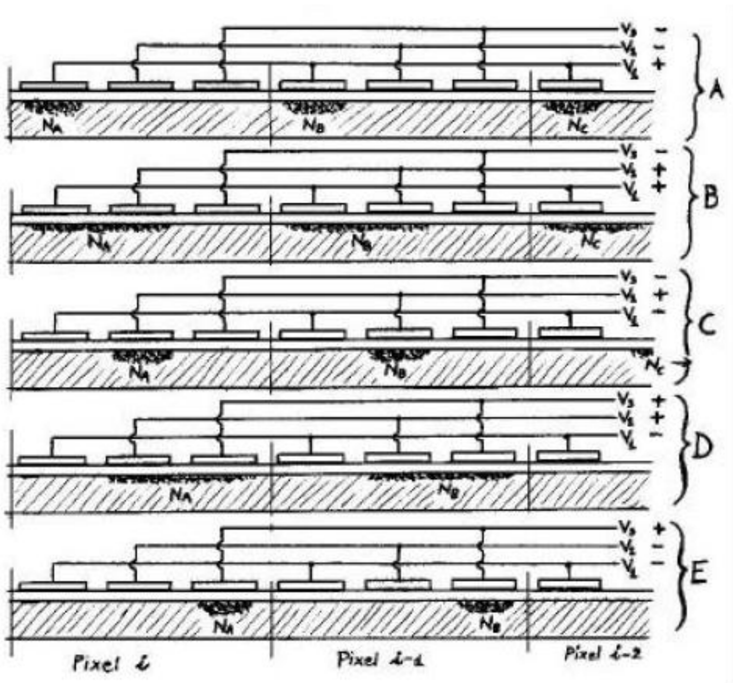
Thermal detector

IR camera for thermography



- Absorbed signal is transported in a matrix made up by photoconduction detectors, called CCD (Charge Coupled Device)
- CCD transforms light signal into electric signal

Each pixel has 3 electrodes (E_1, E_2, E_3) connected to different power lines (V_1, V_2, V_3).

1. During the measurement, E_1 collects all photoelectrons (positive voltage V_1), while E_2 and E_3 are grounded (**phase A**).
2. At the end of measurement, V_2 is brought from zero to a positive voltage, in order to allocate the charge under E_1 and E_2 equally (**phase B**).
3. After this redistribution, V_1 is gradually grounded and all charge is now under E_2 (**phase C**).
4. This operation continues between E_2 and E_3, in order to transport all charge under E_3 (**phase D**), which is connected to an output amplifier.
5. The operation is valid and continues for each pixel (**phase E**).

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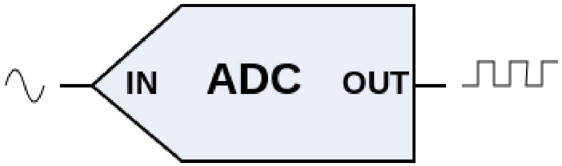
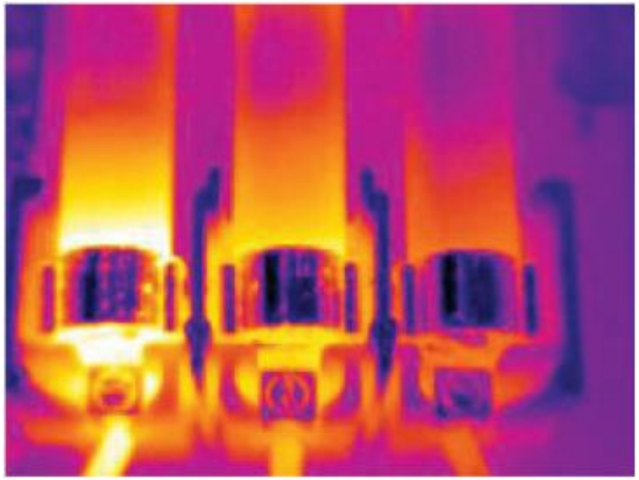
Converter

IR camera for thermography

- The processed electric signal, is still an analog signal
- In order to print an image on the IR camera LCD or on a PC display, this signal has to be converted into a digital signal
- IR camera uses a 12-bit ADC (Analog to Digital Converter), providing 4096 charge discretizations
- Elaborated images are recorded into an external memory card as a matrix of 680x460 pixels
- Each pixel corresponds to a specific color and each color corresponds to a different temperature value.





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Technical Data

IR camera for thermography

The SCF_Lab uses the IR camera SC640 by Flir in order to acquire IR payload images and investigate surface temperature profiles. Some Technical Data are shown in the figure.

Imaging performance	Accuracy	± 2.0°C (± 3.6°F) or ± 2% of reading
	Thermal sensitivity	< 0.06°C (< 0.11°F) @ +30°C (+86°F)
	Spatial resolution	▪ 40 mm lens: 0.66 mrad ▪ 19 mm: 1.3 mrad ▪ 76 mm: 0.33 mrad ▪ Close-up lens (P/N: 1196683): 50 μm
	Electronic zoom	Continuous interpolating zooming on images
	Panning	Panning over zoomed-in images
	Digital image enhance-ment	Adaptive digital noise reduction
Detector	Detector type	Focal Plane Array (FPA), uncooled microbolometer 640 × 480 pixels
	Spectral range	7.5–13 μm
Image presentation	Display	5.6 in., 1000 × 600 pixels
	Viewfinder	800 × 600 pixels
	Frame rate	30/25 Hz (PAL/NTSC)

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Parameters 1/2

The radiation detected by the IR camera consists of the properly emitted by the object and that deriving from the surrounding environment that the object reflects. In order to measure accurately the temperature, it is therefore necessary to compensate the effect due to these different radiation sources. This operation is done directly by the camera. However there are some object and environment parameters that must be set:

- Object Emissivity: thermal radiation emitted from the object with respect to that emitted by a blackbody at the same temperature
- Reflected Temperature: is defined as the apparent temperature of the objects in the environment, that are reflected by the object under investigation
- Distance: it is used to balance the absorption of the radiation due to the transmittance of the medium between the source and the detector
- Relative Humidity: it is set because the transmittance depends also by this parameter.

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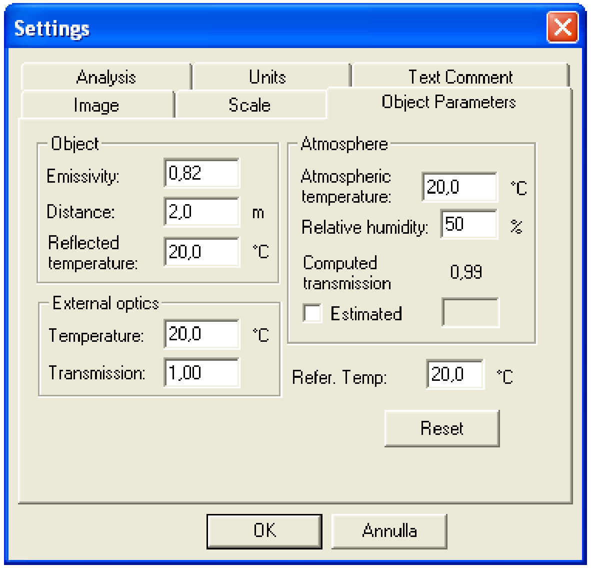
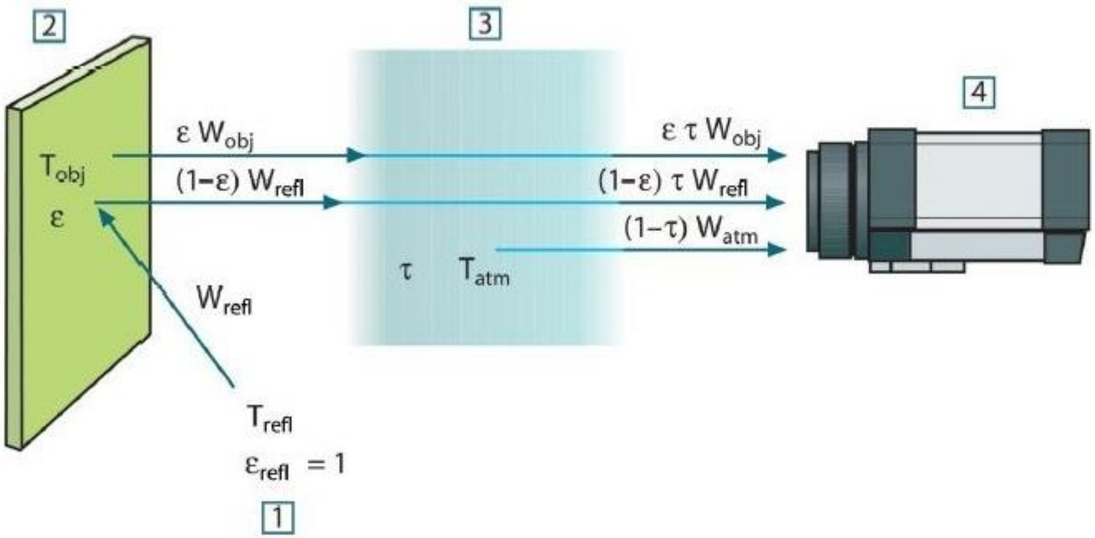
Parameters 2/2

- Atmospheric Temperature: atmospheric temperature between the camera and the object
- External Optics Temperature: temperature of external lens or window
- External Optics Transmittance: transmittance of external lens or window



Measurement Formula 1/3

Schematic description of the measurement situation, to derive a formula for the calculation of the object temperature, from the calibrated camera output:



W= radiation power

Hypothesis: Environment Emissivity ε_{refl}=1 (Kirchoff's Law)

Measurement Formula 1/3

The radiation received by the camera has three contributions:

$\varepsilon W_{obj}\,\tau$ = Object emission (τ=atmospheric transmittance)

$(1-\varepsilon)\,\tau\,W_{refl}$ = Emission reflected from the environment sources

$(1-\tau)\,W_{atm}$ = Atmospheric Emission

The total received radiation power is:

$$W_{tot} = \varepsilon W_{obj}\,\tau + (1-\varepsilon)\,\tau\,W_{refl} + (1-\tau)\,W_{atm}$$

Defining the camera output $U_{source} = C\,W_{source}$ we can write:

$$U_{tot} = \varepsilon U_{obj}\,\tau + (1-\varepsilon)\,\tau\,U_{refl} + (1-\tau)\,U_{atm}$$

$$U_{obj} = U_{tot}/(\varepsilon\tau) + (1-\varepsilon)\,U_{refl}/(\varepsilon) + (1-\tau)\,U_{atm}/(\varepsilon\tau)$$

This is the general measurement formula used in all the FLIR Systems thermographic equipment.

Measurement Formula 3/3

The voltages of the formula are:

U_{obj}	Output Voltage computed for a blackbody at T_{obj}, i.e. a voltage that can directly convert into true requested object temperature
U_{tot}	Output Voltage computed for the specific case
U_{refl}	Output Voltage for a blackbody at T_{refl} from calibration
U_{atm}	Output theoretical Voltage for a blackbody at T_{atm} from calibration

Therefore in order to obtain the correct temperature of the object, user has to set object and environment parameters as mentioned before.

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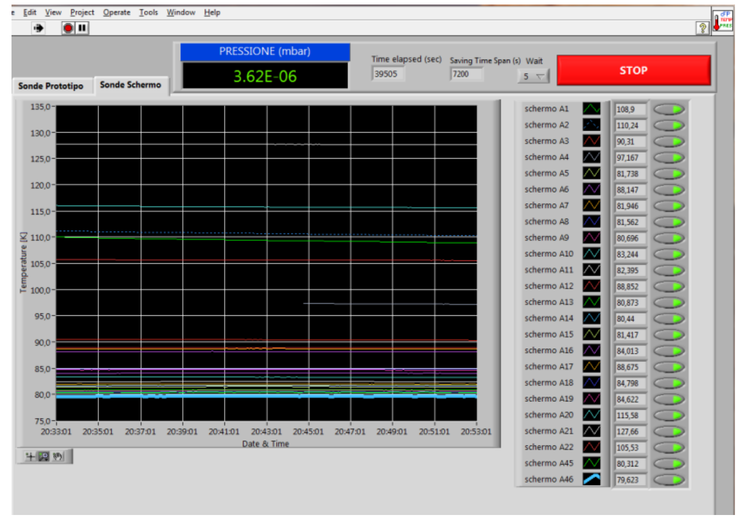
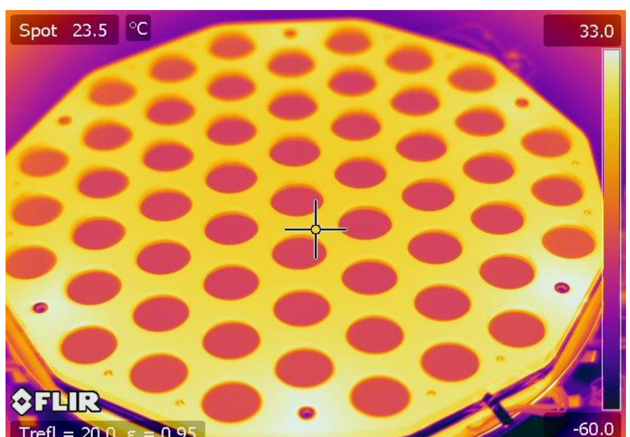
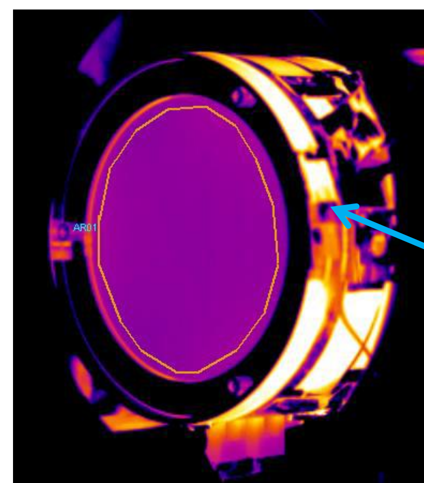
IR Acquisition

SCF-G IR Images Acquisition







Kapton tape spot
IR calibration probe

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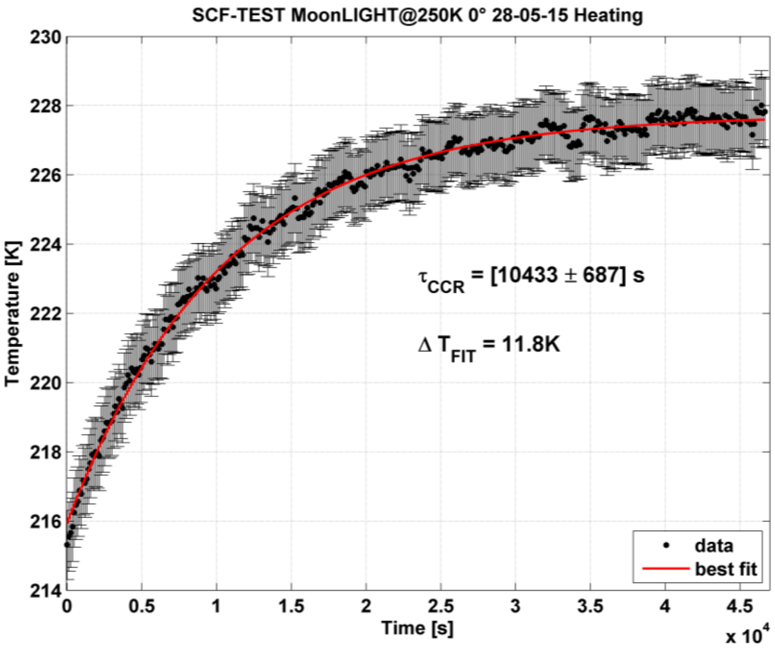
IR Thermal Analysis 1/2

In the SCF_Lab, thermal data are acquired using the IR camera Thermacam SC640 by Flir, to identify the characteristic time of CCRs and to highlight distributions and anomalous temperature gradients on CCRs front face.

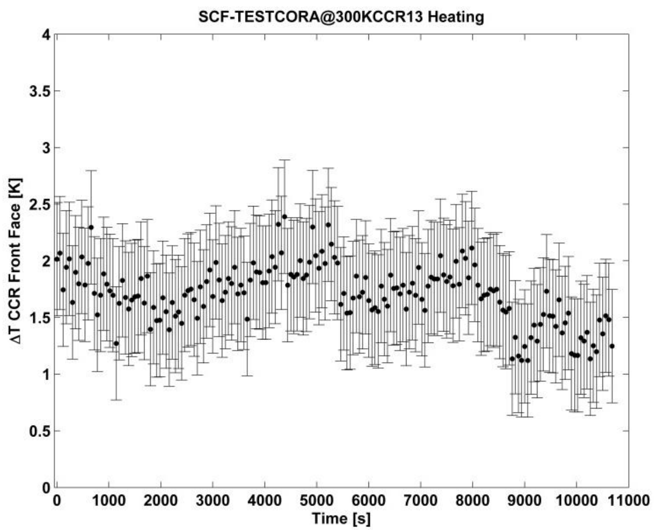
By using an own Matlab code, average temperature data are fitted exponentially to extract the information of the **characteristic heating/cooling time**, using the following law:

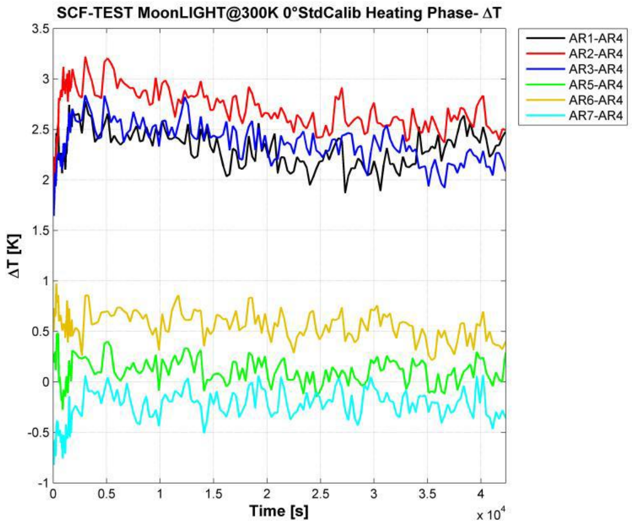
$$T_1 = T_0 \pm \Delta T (1 - e^{-t/\tau})$$

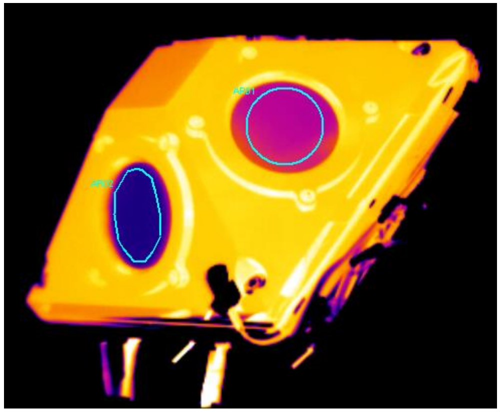


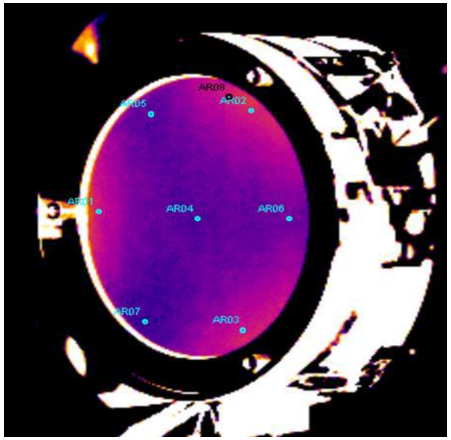
IR Thermal Analysis 2/2

We also calculate possible **thermal gradients** on the CCR front face acquiring the maximum and minimum temperature values and the temperature of some critical points . These possible gradients can be caused by a heat conduction between CCR and its housing.









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Acquisition procedure

SCF-G IR Images Acquisition Procedure

In order to acquire IR images using the ThermaCAM SC640 by FLIR System, remind these notes:

1. Place the camera in front of the IR window as close as possible
2. Check the camera power
3. Focus the image on the CCR under investigation, using button Focus or knob on the camera lens
4. Calibrate the camera setting proper Object Parameters (see Calibration procedure)
5. Use option Program by the camera menu to set the automatic acquisition time (2 minutes)
6. DO NOT MOVE the camera during acquisition phase
7. Backup data at the end of acquisition phase, copy IR images from SD card to computer for analysis.

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Calibration Procedure

SCF-G IR-camera Calibration Procedure

The thermo-camera calibration procedure for the SCF-G follows next steps:

1. Place a spot on the kapton tape (on the LRA)
2. Set the kapton Emissivity at 0.86 (from Object Parameters)
3. Set the other Object parameters

   Atmospheric Temperature=20°C Relative humidity=0%

   External Optics Temperature =19°C External Optics Transmission=0.97.

   Ignore others parameters

1. Change the Reflected Temperature up to the Temperature of the spot is the same of the temperature recorded by PT 100 probe placed on the LRA
2. Move the spot on the CCR under investigation and set its Emissivity at 0.82 (CCR emissivity)

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Thermal Analysis procedure

SCF-G Thermal Analysis Procedure

In order to perform thermal analysis of the IR images acquired follow next steps:

1. Open IR images in the ThermaCAM Researcher Professional 2.9, following this path: Image - Open - Image Directory - Add - Ok
2. Select the area you want to investigate, using the tool palette
3. Select the data temperature you want to record (average, max, min temperature)
4. Select Plot option and Add plot function
5. Press Play
6. Save the extracted temperature values
7. Create a .txt file with average temperature value on the first column, time step of acquisition in the second column, maximum temperature in the third, minimum temperature in the fourth
8. Open this file with Matlab (or write your code) and run the code to evaluate the characteristic time of CCRs

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Safety measures in the Lab

SS Safety measures

- Do not directly observe the solar beam
- When the shutter is opened, in turn off and turn on phase and when the operator is within 1m from the simulator, use the protective goggles
- Always close the shutter if the simulator is off
- Do not put your head or any other body part inside the shutter
- Do not touch the shutter when the simulator is switched on
- Do not touch the SS cover, when it is on, without protective gloves
- Do not remove any electrical cable when the simulator in powered on

SS Protection Equipment

As a DPI each operator, when operating on the solar simulator shutter and when the solar simulator is turned on, must wear protective goggles CE marked, chosen according to the wavelength used by the solar simulator, and safety work gloves.

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Safety measures in the Lab

IR camera Safety measures

- Do not directly observe laser beam.
- Do not disassemble or make changes to the battery
- Do not try to charge the battery if charging does not take place on schedule

THANKS FOR YOUR ATTENTION

ANY QUESTIONS?

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