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ENGINE SUPERFICIAL TEMPERATURE AND INFRARED SIGNATURE

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ABSTRACT

A system calibration and data processing method has been set up to provide spatial information on temperature and a spatially accurate radiant intensity map under different angles.
The methodology has been developed to evaluate the thermal exchange between engine and engine-cowling and their infrared signature in the 1 - 6 micrometer range in order to evaluate special infrared treatment to reduce infrared emission.
The infrared imagery camera has been coupled to an analogic/digital data acquisition system.
Calibration studies have been conducted in our infrared laboratory to provide the absolute calibration on the thermograph in the previously defined spectral range.
The results are presented in profiles of temperature and radiance.

1. Introduction

The objects of this research may be summed up as follows:

1) Study of the surface temperature distribution of: exhaust pipe, exhaust gas plume and engine cowling.

2) Study of the integral infrared signature of some portions of the airplane under different angulations.

3) Development of an accurate and easily repeatable methodology to meet both the above mentioned aims.

An AGA Thermovision System 780 S.W. has been selected for this kind of research.
This system makes it possible to obtain the temperature spatial distribution of the object by fairly simple data processing.

In order to have the integral infrared signature we had to calibrate the system to establish a relationship between the output of the thermograph and the radiant energy impinging on it.
The thermograph has been calibrated in our infrared laboratory by a technique that will be explained in the following paragraphs.
The main advantage of this technique is the possibility to use an instrument capable of producing, with a single measurement, significant data both on the surface temperature distribution and on the infrared signature.
As the AGA thermograph gives a visual representation of the phenomenon it is possible to immediately locate the more significant areas.
A further advantage is that the integral spatial signature may be easily obtainted from the same set of data.
There are indeed some inaccuracies due to differences in spectral energy distribution between the object being studied and the infrared source used for system calibration.
It is also necessary to calculate the configuration factor of the object relative to the thermal imaging system.
The readings were taken with an AGA Thermovision provided by AGA ITALIA. The Oscar System and Data Recording have been provided by I.C.I.T.E. while the conventional temperature systems by I.A.M. Rinaldo Piaggio and I.C.I.T.E..
The calibration was carried out in the infrared laboratory of I.A.M. Rinaldo Piaggio. Data were processed in the Data Processing Centers of I.A.M. Rinaldo Piaggio and I.C.I.T.E.
We wish to thank Mr. Roberto Ricca of AGA ITALIA for his suggestions and helpfulness and Mr. Edoardo Janis (I.A.M. Rinaldo Piaggio) and Mr. Italo Meroni (I.C.I.T.E.) for their collaboration.

2. Studied objects and their configuration

The power plant which was subject to our research is the Lycoming Turboprop LTP-101-2 which powers the Piaggio P.166 DL3 aircraft.
This installation places the exhaust pipe above the engine, gases being discharged rearwards through the disc of the pusher-type propeller. This causes the exhaust gases to become mixed with the ambient air in a relative short space by the suction of the propeller and the relative speed of the airplane.
This particular powerplant configuration limited our studies to the exhaust pipe, to the gas plume between the pipe outlet and the propeller disc, (as we observed that mixing, between the exhaust gases and the ambient air behind the propeller, is practically complete) and to the engine cowling; all these studied under various angles of observation.
As surface temperature and infrared emission are dependent on airspeed, in flight measurements of these quantities were also made on the aircraft.

Fig. 2-1 Piaggio P.166-DL3 Aircraft

3. Materials

The outlet pipe is of AISI 321 stainless steel passivated in an acqueous solution of nitric acid.
The coverings of the intake aperture of the oil cooler and feeding engine ducts are also of AISI 321 steel.
The engine cowling is of an aluminium clad alloy 2024 T3 which has been chemically treated (Alodine 1000), and painted with epoxidic and poliurethane varnish.

Symbols

W	Radiant Emittance	$W\ cm^{-2}$
W_λ	Spectral Radiant Emittance	$W\ \mu m^{-1}\ cm^{-2}$
J_λ	Spectral Radiant Intensity	$W\ Sr^{-1}\ \mu m^{-1}$
J	Radiant Intensity	$W\ Sr^{-1}$
P	Radiant Flux	W
ε	Emittance	-
τ	Transmittance	-

Abbreviations

I.U. = Isotherm Unit

T.L. = Thermal Level

T.R. = Thermal Range

Tr = Throughput

Te = Temperature

F.C. = Configuration Factor

4. Surface Temperature

The thermal imaging system was used in the more conventional way to appreciate the surface temperature pattern. Special care was taken however to optimize the accuracy and clarity of pictures which were also meant to yield informations of the infrared signature.
Readings were taken before dawn to abolish the effects of solar infrared radiation. We also verified the absence of artificial infrared radiation sources. Atmospheric conditions were ideal: lack of wind, clear sky, low humidity, low temperature .
We instrumented the engine with a set of thermocouples to establish a reference and to appreciate the accuracy of temperature and emittance measurements.
We took pictures and digitized images under various angles, engine regimes, distances, also with different settings of the typical relief parameters of the thermograph (Thermal Level, Thermal Range, F/Number, Filter).

5. Data Processing

The digitized data stored on tape have been processed by specialized computer programs.
These computer programs can be used to reproduce:

1) The image (digitized by the Oscar) corresponding to a matrix of pixels, matrix dimension being 128x128 (frame mode) or 128x64 (field mode) with 8 bit resolution.

2) The black and white images of the isoradiant and isothermal areas with the superimposition of alphanumeric characters for a good number of thresholds chosen by the operator.

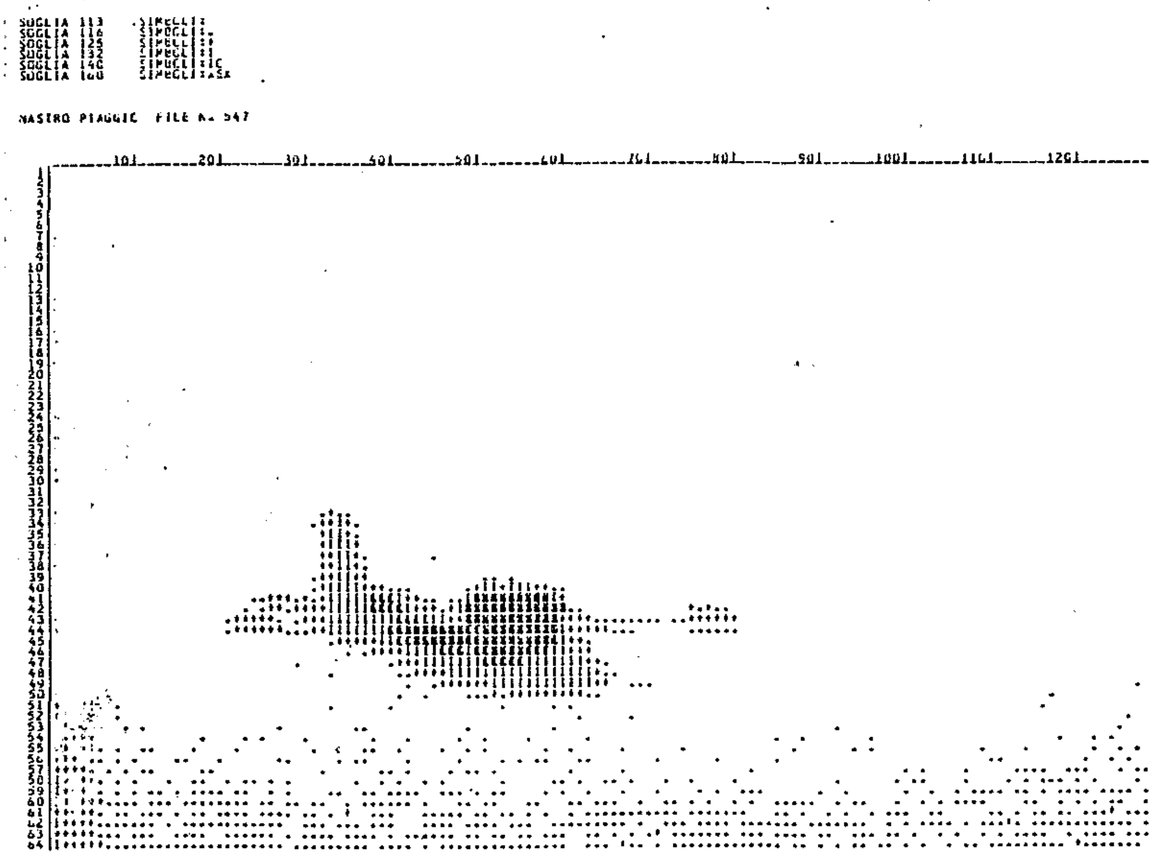


Fig. 5-1 Isoradiant image of P.166-DL3 in flight

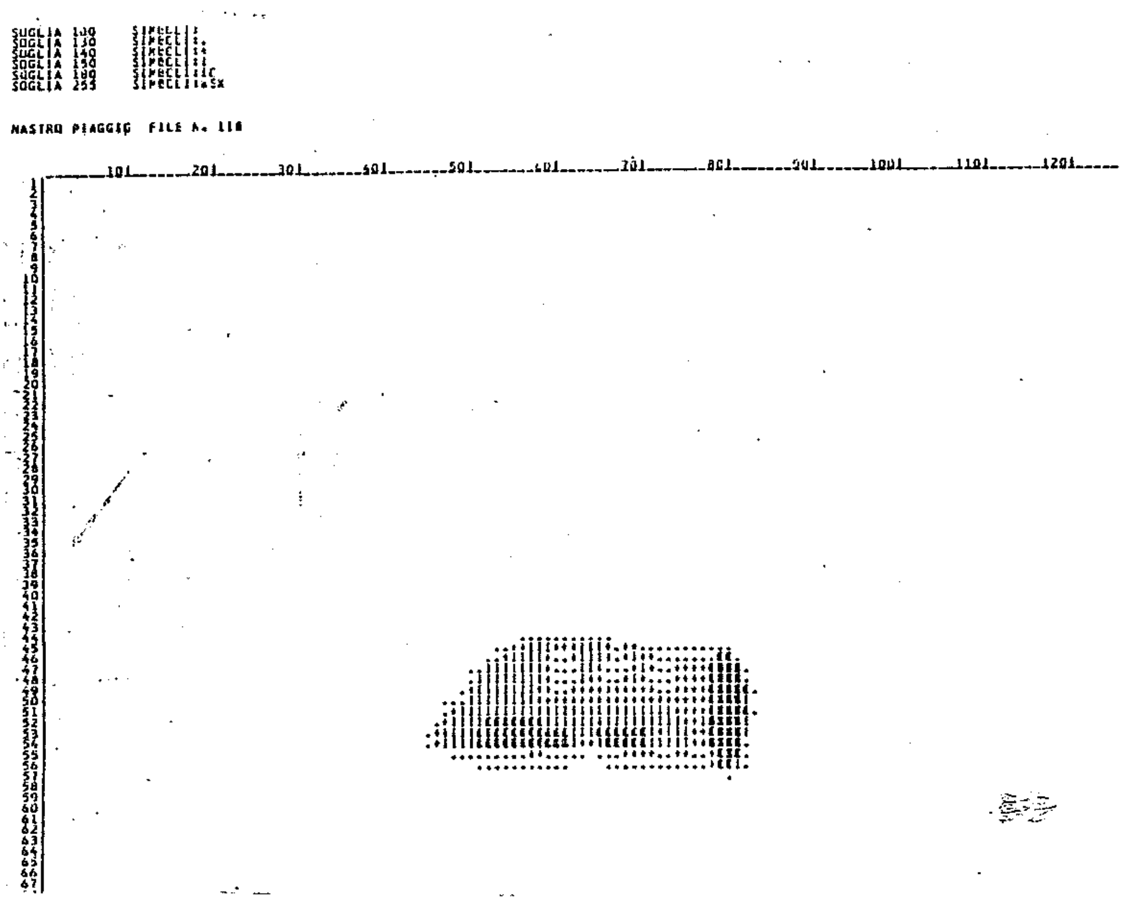


Fig. 5-2 Isothermal computer printout displaying the exhaust gas pipe

3) The map of surface temperatures for all the 16,384 points forming the image. The temperature is obtained, after correcting the instrument value to account for the atmospheric transmittance over the distance between AGA camera and object and the emittance of the object, using the following relationship:

$$T(\,^{o}C) = \frac{B}{\ln\left(\frac{A+I.U.}{I.U.xC}\right)} - 273$$

where:
A, B, C are characteristic constants of instrument depending on F/Number.
I.U. (Isotherm Unit) is the absolute instrument value.

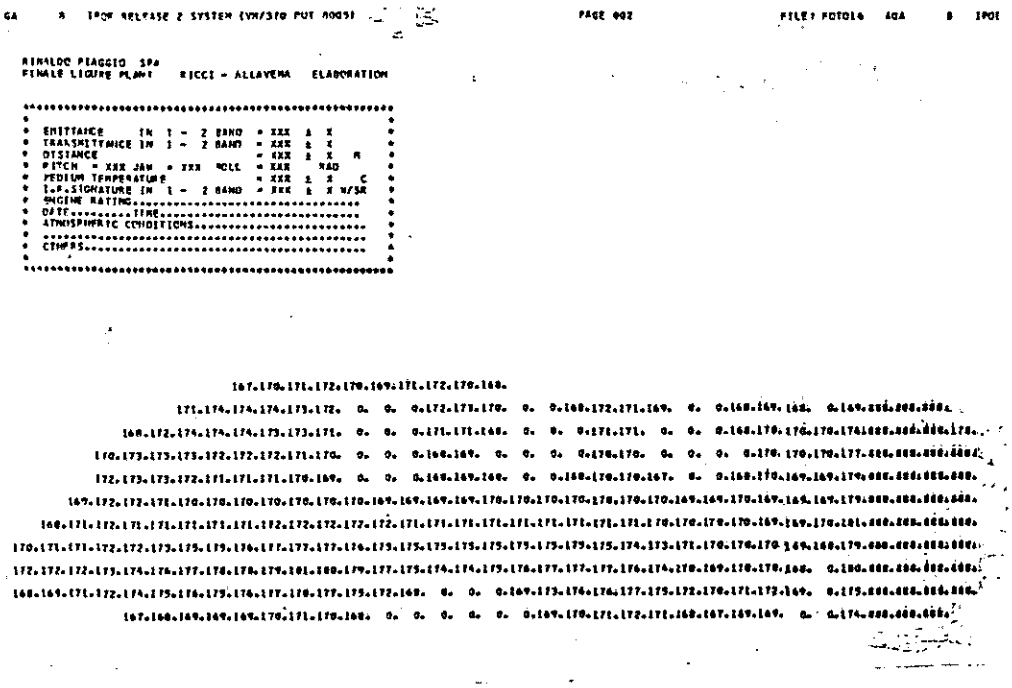


Fig. 5-3 Processed thermal image showing the exhaust gas pipe. Numbers represent temperatures. (Values shown here are not real).
The spots in the upper half are pieces of 3M low emittance tape. Note the saturated values at the right hand of the image which correspond to a visible portion of the jet pipe inner surface.

4) The average value of temperatures within given thresholds or a geometrically defined area.

6. Infrared Signature

The experimental signature was compared with results obtained by theoretical calculations performed with our computer programs.

6.1 Apparatus

1) AGA Thermovision Mod. 780 S.W.

2) Oscar

3) Black body

4) Monochromator

5) Thermocouples

6) Variable slit

7) Ancillary equipment

6.1.1 Description and Features

1) The thermal imaging system used in this research was equipped with an InSb photovoltaic detector and a lens with 20° field of view. The spectral range is 1.4 - 5.8 micrometer with low sensitivity in the 2 - 3.4 micrometer range.

2) Data were digitized with Oscar (off line system computer access and recording) and then recorded using a digital tape recorder.

3) The infrared calibration source (Barnes mod. 11-210) has the following characteristics:
   - Aperture diameter — 7 inch
   - Temperature range — 50 - 1000 °C
   - Absolute calibration accuracy — ±5 °C
   - Simulator emittance (ε) — .99 ± 1%

4) The monochromator has the following characteristics:
   - Wavelength region approx.1-16 μm (in 3 gratings)
   - Resolving power: dependent on aperture slit and grating
   - Configuration: off-axis Ebert
   - Gratings: ruled type.

6.2 AGA System Calibration

The calibration procedure developed consisted in plotting a family of energy versus I.U. (Isotherm Unit) curves at preset F/Numbers with and without CO_2 filter.

6.3 Strumental Set-up

Fig. 6.3-1 Strumental set-up in I.R. laboratory

1) The black body source was aligned so that the image of its aperture was in the center of picture.

2) The distance between the black body source and the thermograph was kept fixed for the whole time of the calibration and was chosen to keep the black body aperture within the T.F.O.V (Total Field of View) of the thermograph.

6.4 Procedure

The temperature of the black body was increased and kept constant until an isoflux was observed. Then the image of the black body aperture was digitally acquired selecting the Thermal Level and Thermal Range in such a way that digital data output were neither saturated nor suppressed.
In this way we acquired several images of the black body aperture at different temperatures (within 50-600 °C range) with different combinations of F/Number, Thermal Level, Thermal Range and Filter (at a fixed distance).
The magnetic tapes of calibration data were processed on the IBM 4331 computer.
The calibration procedure consisted of:

1) Individually correcting (using T.L., T.R. and τ) the digital number corresponding to one pixel referring to black body aperture image to have the I.U. (Isotherm Unit, i.e. absolute instrument value).

2) Adding all the corrected I.U..

3) Afterwards black body energy emitted and impinging on AGA thermograph were calculated. Such an energy is a function of the following parameters:

$$P = P\,(\tau\,,\,\varepsilon\,,\,Tr,\,Te,\Delta\lambda)$$

The radiant power into the camera is the radiant intensity times the solid angle that is subtended by the camera to the black body aperture.

τ = transmittance of atmosphere between AGA and black body
ε = emittance of the black body

To appreciate the radiant flux available to the camera for a selected F/Number we used the relationship:

$$P = \frac{\varepsilon\,\tau}{\pi}\int_{\lambda_1}^{\lambda_2} W_\lambda\,d\lambda \iint \frac{dAs\,\cos\alpha\,dAr\,\cos\beta}{R^2}$$

Where:

$$W_\lambda = \frac{C1}{\lambda^5 \left(e^{\frac{C2}{\lambda Te}} - 1\right)}$$

and

$\lambda 1 - \lambda 2$ = spectral band of AGA

$C1 = 3.745 \cdot 10^4$ W cm^{-2} μm^4

$C2 = 1.4387 \cdot 10^4$ μm ^oK

Te = ^oK

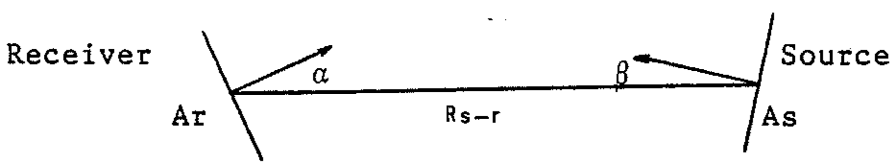
λ = μm

ε = Emittance of black body

τ = Transmittance of the atmosphere between the AGA and the black body

As = Lambertian gray surface

We assumed ε and τ constants on the spectral band and W_λ not dependent on the surface of black body.
The double integral in the formula is defined throughput (Tr) and the subscripts are illustrated in the following schema:



It is also useful to define the configuration factor (F.C.) which is directly related to the Tr and is generally computed by various computer programs :

$$Tr = Fs\text{-}r \times As \times \pi$$

In our calculation we have estimated Tr using a computer program (finite difference method) which computed the F.C.. It is possible however, when the separation Rs-r is about 10 or 20 times the maximum transverse dimensions of As or Ar, to use the formula:

$$Tr = \frac{As \times Ar}{R^2}$$

The accuracy of the Tr is about 99%.
W_λ has been integrated using the pocket calculator HP-34C and comparing the results obtained with an infrared slide-rule.
We then calculated the energy available to AGA for every temperature of the black body and traced out a series of calibration curves (best fitting method) of the kind here illustrated for every F/Number:

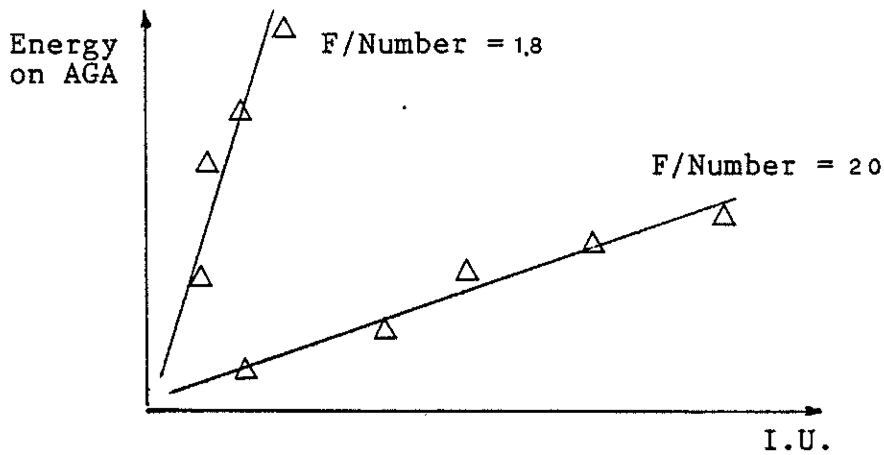


Fig. 6.4-1 Calibration curves

6.5 I.R. Signature Evalutation

After obtaining the proper calibration curve for every F/Number we calculated the integral I.R. signature of portions of the P.166-DL3 by the following procedure:

1) The digitized image was elaborated and corrected to eliminate infrared atmospheric absorption for the AGA-object distance.

2) We executed the summations of the absolute values on each of the investigated areas (it is possible to isolate the investigated area by selecting proper thresholds or tracing its geometrical boundary).

3) Having these summations we appreciated the radiant flux P impinging into the camera and select the appropriate calibration curve.

4) The integral infrared signature (J) of the object was finally calculated by the following relationship:

$$J = \frac{P}{\pi x F.C.}$$

7. Emittance Measurement

Measurements of the spectral and normal emittance of materials and coatings at fixed temperatures were made in the infrared laboratory.
In practice we compared the spectral radiant emittance of the black body and of the specimens at the same temperature.
Processed results are comparable with those obtained indirectly with the thermograph and with the values reported by specialized publications.

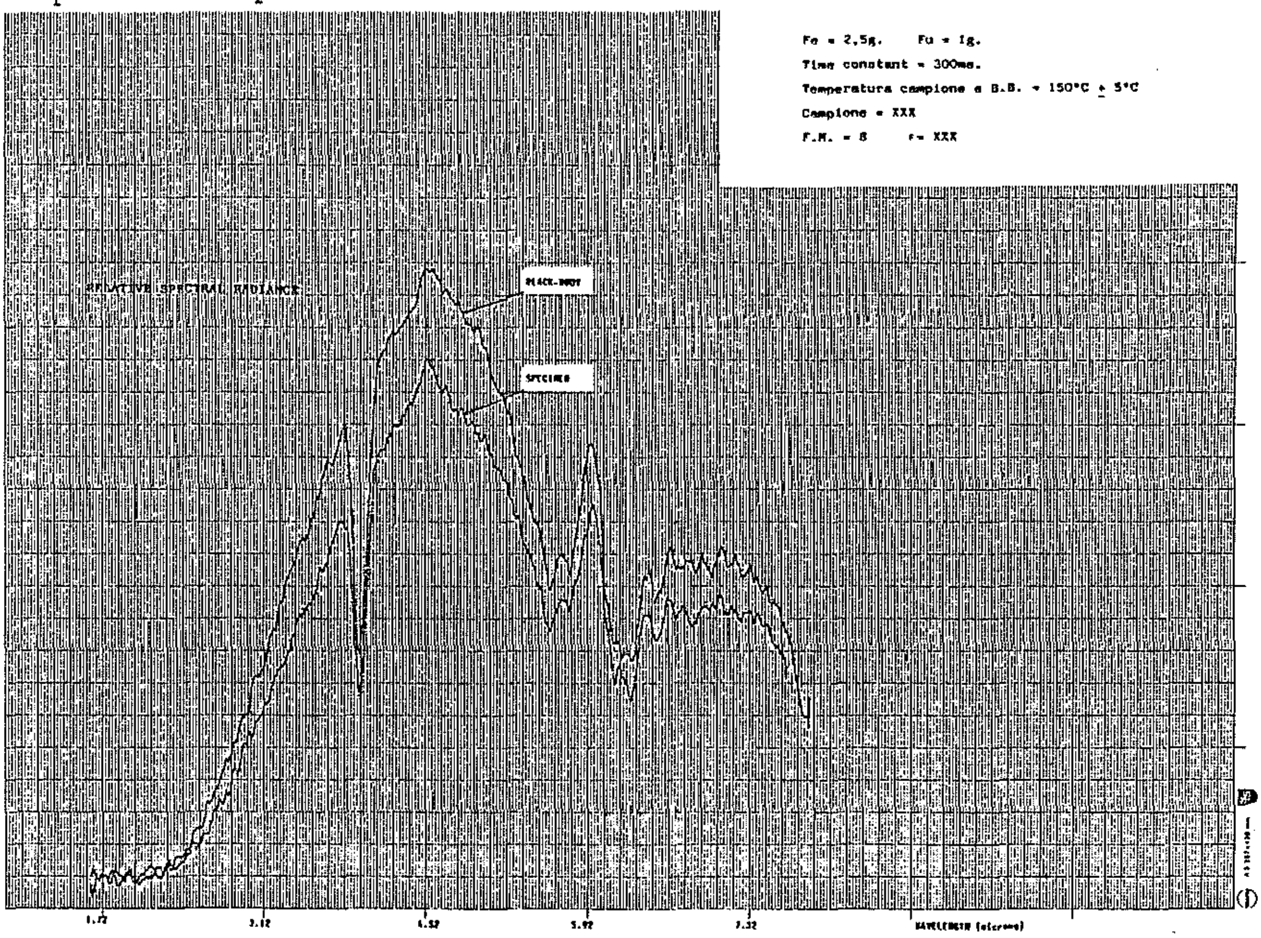


Fig. 7-1 Example of relative spectral radiant emittances of black body and specimen.
Note the absorption bands of CO_2 and H_2O.

8. Atmospheric Transmittance

To appreciate the atmospheric transmittance in the spectral range of interest for the distance and the peculiar atmospheric conditions, we used the computer code LOWTRAN 4 and transmittance curves supplied by the AGA Corporation.

9. Spectral Response of the Thermograph and the Filter

We used a monochromator to check the spectral response of the thermograph and of the filter (convoluted with the thermograph).
The thermograph and filter spectral response are convoluted with the black body and monochromator. The atmosphere between AGA and black body has not been purged.
The spectral limits are quite well defined in spite of the absorption bands of carbon dioxide and water .
The 1-2μm band was also analyzed but the CO_2 band falling within this range prevented an accurate evaluation of the phenomenon.

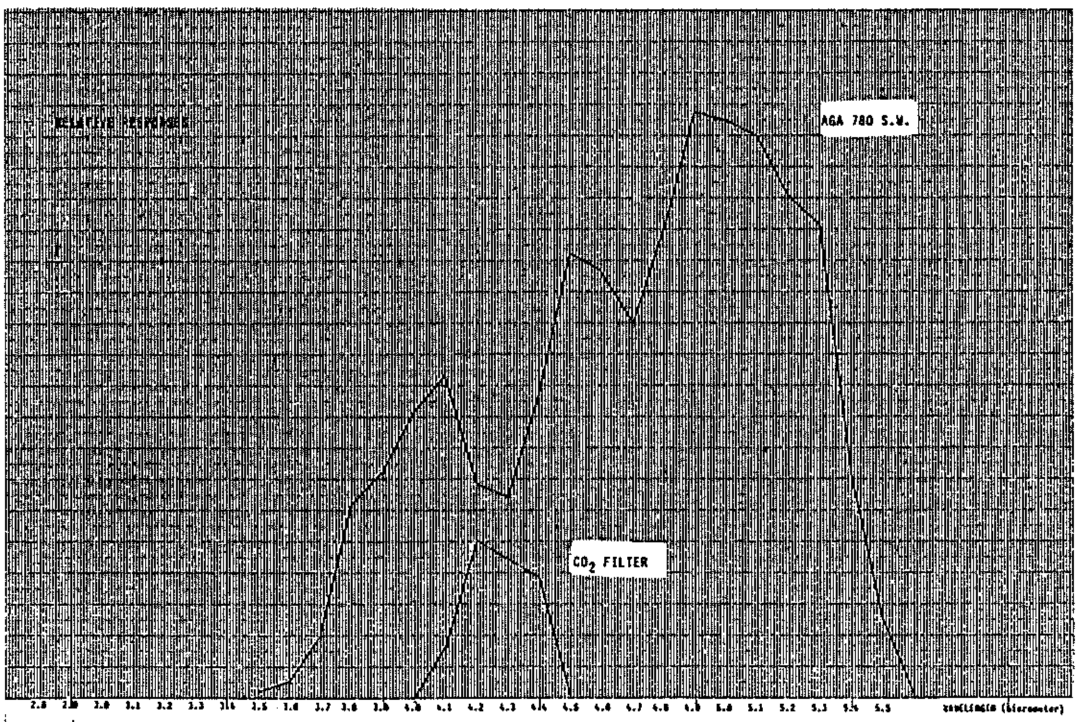


Fig. 9-1 Spectral response of the thermograph and the filter.
Note the absorption bands of H_2O and CO_2.

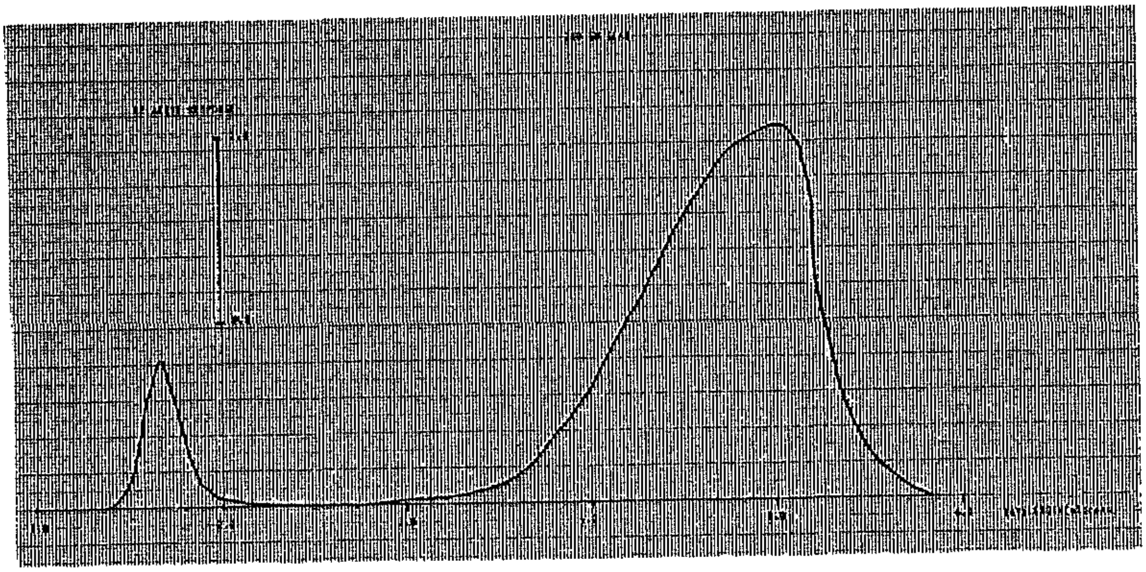


Fig. 9-2 Spectral response of the thermograph.
(By courtesy of AGA Italia)

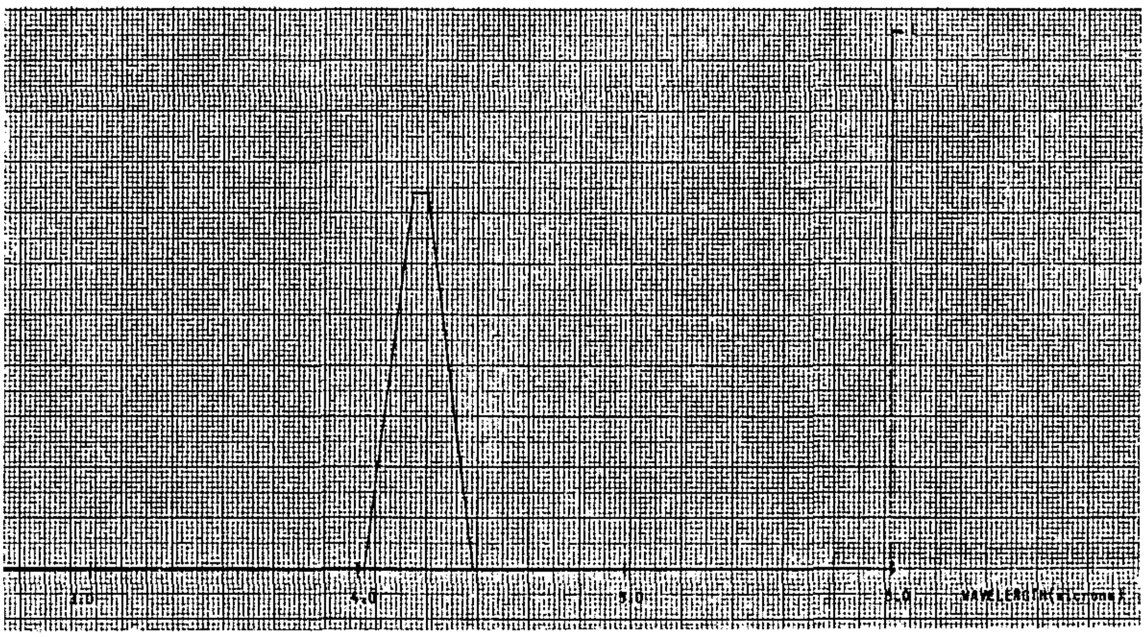


Fig. 9-3 Spectral response of the carbon dioxide filter.
(By courtesy of AGA Italia)

<u>10. Evaluation of I.F.O.V. and T.F.O.V. (Instantaneous and Total Field Of View)</u>

To correctly evaluate the energy emitted by an object it is necessary that the angle subtended by the object be equal or bigger than the T.F.O.V. of the thermograph.
It is possible to evaluate such a value in a simple way using a variable micrometric slit and a reference infrared source.

10.1 Strumental Set-up

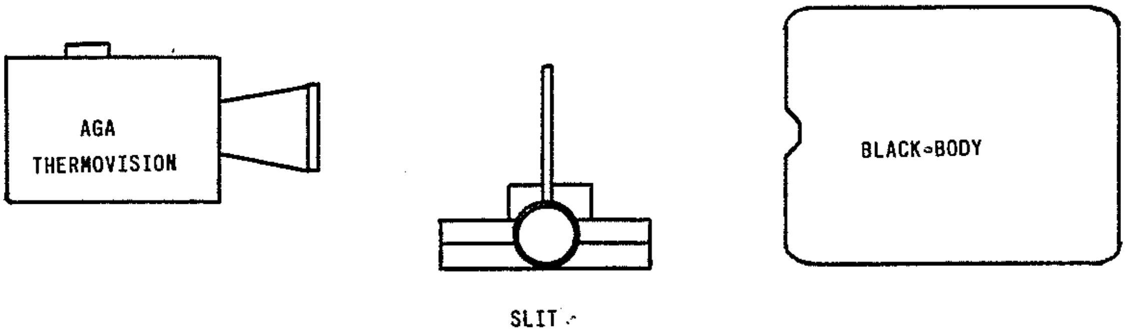


Fig. 10.1-1 Strumental set-up in I.R. laboratory.

10.2 Operation

After optimizing the black body image we put the variable slit at full aperture in front of the black body, then we began to slowly close it until the signal began to decrease in intensity: the angle subtended by the slit to the thermograph is the T.F.O.V..
By further closing the slit until signal amplitude is reduced to half of its initial value we then found the I.F.O.V..
There is a difference between the horizontal and vertical T.F.O.V. and I.F.O.V..

11. Errors

11.1 Errors Affecting Temperature Evaluation

The relationship used to calculate the temperature (see page 19-6) is the following:

$$Te = \frac{B}{\ln\left(\frac{A + I.U.}{C \times I.U.}\right)} - 273$$

where :

$$I.U. = \frac{I.U.'}{\tau \times \varepsilon}$$

Assuming that single parameters are affected by the following absolute errors:

$$\begin{array}{ll} A & \pm\Delta A \\ B & \pm\Delta B \\ C & \pm\Delta C \\ \varepsilon & \pm\Delta\varepsilon \\ \tau & \pm\Delta\tau \end{array}$$

The absolute error which afflicts the temperature will be:

$$\Delta T = \left|\frac{\partial f}{\partial A}\right| |\Delta A| + \left|\frac{\partial f}{\partial B}\right| |\Delta B| + \left|\frac{\partial f}{\partial C}\right| |\Delta C| + \left|\frac{\partial f}{\partial \varepsilon}\right| |\Delta\varepsilon| + \left|\frac{\partial f}{\partial \tau}\right| |\Delta\tau|$$

11.2 Errors Affecting Infrared Signature Evaluation

Assuming J function of the following parameters:

$$J = J(\varepsilon, \tau, Tr, Te)$$

The absolute error will be:

$$\Delta J = \left|\frac{\partial J}{\partial \varepsilon}\right| |\Delta\varepsilon| + \left|\frac{\partial J}{\partial \tau}\right| |\Delta\tau| + \left|\frac{\partial J}{\partial Tr}\right| |\Delta Tr| + \left|\frac{\partial J}{\partial Te}\right| |\Delta Te|$$

12. Conclusions

The infrared signature measurements were compared to those predicted with our computer programs and found to be in good accordance.
The inherent inaccuracy with this kind of experimentation is that the spectral energy distribution of the studied objects is not that of a black body (used for the calibration), so that it would be necessary to take informations on the spectral energy distribution of the object investigated.
It is possible, however, to increase the accuracy of these measurements by using a series of interferential filters, to calibrate the whole system and by studying the investigated object energy over a narrower band.
All this, of course, requires a more laborious calibration and data processing.
The proposed methodology allows us to make a simultaneous study of the temperature and signature with a good accuracy that can be improved by a good knowledge of spectral energy distribution (obtained with a set of filters) and by improving the emittance and transmittance measurements.
The operator who is going to repeat this kind of research has to study, with a particular accuracy the emittance and transmittance values in the spectral range of interest.
It would be advisable to take some conventional temperature measurements of points of interest on the object.
This research, of course, has to be carried out in fine weather conditions and without the presence of artificial infrared sources.