Through-canopy radiance analysis of electromagnetic waves in visible and infrared spectrum

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***Abstract* — A through-canopy radiance analysis of electromagnetic waves in the visible and infrared spectrum is presented. Through experiments, theoretical concepts concerning to aircraft canopy transmittance are presented, allowing the understanding of real phenomena observed in practical measurements. Experimental results show that the compound (acrylic) used in aircraft canopies is completely opaque to infrared over 2.2µm, presenting increasing opacity from 1.1µm to 2.2µm. Special absorption wavelength can be observed, relative to frequencies of vibration of water molecules existing in the environment. Therefore, a mapping of the acrylic transmittance is presented in the visible, Near Infrared (NIR) and Medium Infrared (MIR), allowing the planning of its use as an interface for in-flight measurements of aircrafts and flares signatures.**

***Key-words* - Infrared, Electronic Warfare, spectrometry.**

I. INTRODUCTION

For most platforms, electronic defense is not a stand-alone system but a means to improve the survivability of an isolated target or an entire battle group. The benefits of EW (Electronic Warfare) are manifest. The simple use of a decoy can, therefore, prevent massive casualties and let a missile harmless. The dramatic advances in EW technology during the past few decades have been supported by technical researches and are cloaked in security [1].

Most of the systems based on the exploitation of radiant energy use the infrared (IR) band. Because of that, IR band receives particular attention in all elements that constitute the infrared scenario (from the radiating target to the IR sensor). According to the Brazilian Ministry of Defence, this area must be studied and developed by the researchers, allowing a potential increase in our technological independence [2] [3].

One of the main interests of the Brazilian Air Force, especially of the Electronic Warfare Laboratory (LAB-GE), in ITA, is the determination and characterization of different target signatures, mainly aircrafts and decoys. Preliminary studies were done in order to measure these targets signatures still on the ground, but air measurements remain a challenge. The measuring of the radiance of flying targets allows a full fleet IR mapping and the creation of an IR library.

Depending on the distance and the existing interfaces between the target and the IR sensor, the IR transmittance can be affected, avoiding a correct detection and interpretation of the results. These parameters must be considered in order to achieve good results. Therefore, it is important to study these interfaces and to know what is the actual impact on the measurements.

Considering the medium between the target and the sensing aircraft as constituted only by the atmosphere and the aircraft canopy, it is necessary to characterize the acrylic compound of the canopy and its transmittance in different visible and IR ranges. This knowledge will allow correcting the target radiance measurements and understanding certain phenomena, generally observed during these measurements.

In this paper it will be analyzed the transmittance of an IR target through the aircraft canopy environment, in order to check the feasibility of a low cost setup for measuring the radiance of flying targets.

In section II they are presented some theoretical concepts that will allow understanding the proposed setup and the experimental results. In section III, it is proposed a setup and some experiments that lead to the understanding of the actual phenomenon and finally, in section IV, some concluding remarks are made about the experimental results.

II. THEORETICAL CONCEPTS

Radiometry is known as the measurement of the radiant energy, which is based on a system of physical measurements. Radiometers absorb some of the radiant energy from a source and convert it to another form, such as electrical, thermal or chemical energy. Radiant energy must always be converted to some other form of energy, what is done by different kinds of sensors. In practical measurements of extended sources, it is commonly used the term "radiance" to describe the radiant flux, that is, the total energy radiated measured at a specific distance of the radiating target per target unit area ($W.m^{-2}.sr^{-1}$) [4].

The concept of a blackbody is fundamental to the understanding of the thermal radiation. In 1860, Kirchoff showed that "good absorbers are always good radiators" [5]. Considering a blackbody a perfect radiator (most efficient), it is possible to have it as a standard of comparison, from which all the other radiators will be proportional to. In 1879, Stefan concluded that the total amount of energy radiated by a blackbody is proportional to the fourth power of its absolute temperature, showing a clear relationship between these two parameters. In 1884, Boltzmann reached the same conclusion, by the application of thermodynamic laws, what leads to the Stefan-Boltzmann Law. It was only in 1900 that Planck announced the derivation of his Radiation Law that surpassed all the previous and that resumes the behavior of blackbody radiators. It is expressed by

$$W_\lambda = \frac{2hc^2}{\lambda^5} \cdot \frac{1}{e^{ch/\lambda KT} - 1} \quad (1)$$

where W_λ is the spectral radiant emittance, λ is the wavelength, h is the Planck's constant, T is the absolute temperature of the black-body, K is the Boltzmann constant (K= 1.3806503 × 10^{-23} $m^2.kg.s^{-2}.K^{-1}$) and c is the velocity of light.

According to the blackbody definition, gray bodies are objects that radiate, for each one of the wavelengths, only a ratio of the total possible energy radiated by the blackbody. This radiated energy ratio is known as emissivity. Fig.1. shows the general behavior of two blackbodies at different temperatures (1075K for the red and 900K for the green dashed line) and a gray body (blue point line), with an emissivity of 0.75 and a temperature of 1075K.

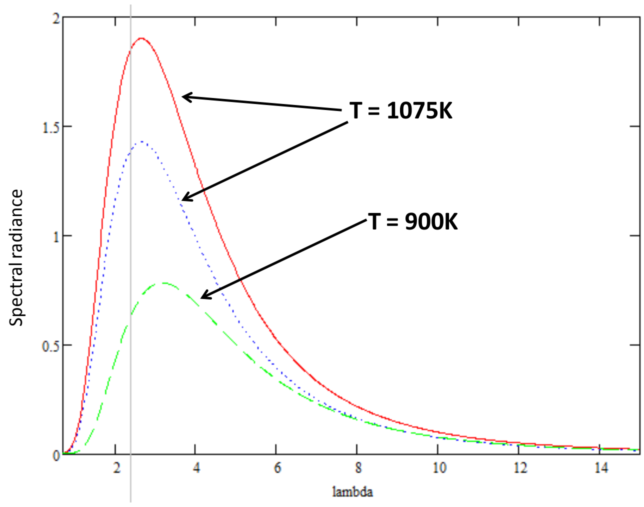


Fig. 1. Three different curves representing the blackbody behavior and the gray body behavior according to the Planck's Law.

In Fig.1. it is possible to perceive the difference between the black and the gray body at 1075K. The red and blue curves are essentially the same, with the difference of a multiplying factor of 0.75. This emissivity determines the behavior of a gray body. The green dashed line is another blackbody curve representing a temperature of 900K. It is possible to see the difference between the areas under the curves, proportional to the fourth power, as predicted by Stefan.

After considering the radiating target, it must be considered the interface between it and the IR sensor. Beyond the atmosphere, that is considered a well-known medium, the understanding of the effects of additional interfaces is fundamental, in this case, the study of the canopy interface.

An aircraft canopy is the transparent enclosure over the cockpit. Its main function is to provide a weatherproof and reasonably quiet environment for the aircraft's occupants, protecting them during flight. The canopy must be as aerodynamically shaped as possible to minimize drag and as transparent as possible to improve the outside visibility [6] [7].

Despite being transparent in the visible range, if wanted to use a portable IR camera inside the cockpit of an aircraft to characterize flight targets, some additional studies are required due to the fact that we have the canopy as additional interface. Canopies can be made of glass, acrylic or polycarbonate [8].

Glass is a very attractive material in transparency design because of its unequalled properties of durability. Chemical reinforcement provides glass with exceptional strength and superior optical quality. There is no limitation in shape or thickness and all glasses, even the thinnest, can be efficiently reinforced while the optical quality is preserved [8].

Thermoplastic polymers, acrylic materials have found large applications in aircraft and helicopters since they allow manufacturing light, clear and complex shaped transparencies. It is therefore suitable for bird proof windshields, canopies, outer cabin window panes and other transparencies for pressurized aircraft [8].

Polycarbonate features an exceptional toughness and impact resistance, making it a really attractive material in design of windshields submitted to high velocity bird strikes. It is light and shows a good temperature resistance.

Due to the fact that FAB's aircrafts use mainly acrylic canopies, this study focuses on them.

On the other side of an IR system, there is the sensor. One of the possible IR cameras is a non-cooler micro bolometer camera. It shows some advantages of being portable, the room temperature and easy operation and low price. Other kinds of camera can be found, depending on the used sensor. They will play different roles and detect in different bands. Fig. 2. shows the performance of the different sensors.

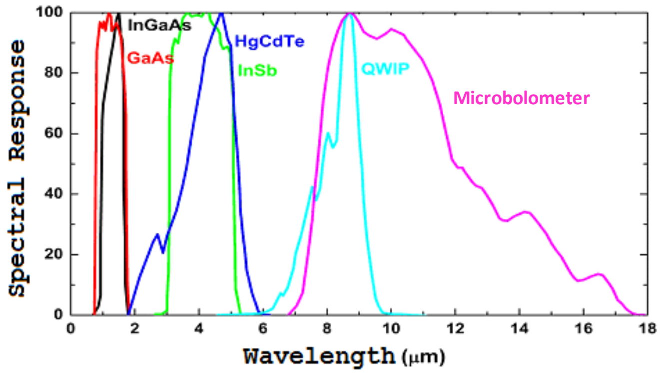


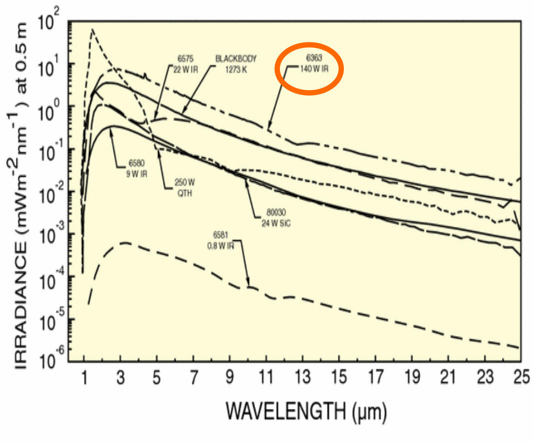
Fig. 2. Different performances of sensors, representing the detection bands of each one.

In Fig.2. it is possible to see that, for each objective, there is a special type of sensor. During the planning of the detection, the medium and the target must be considered to the optimization of the sensor performance.

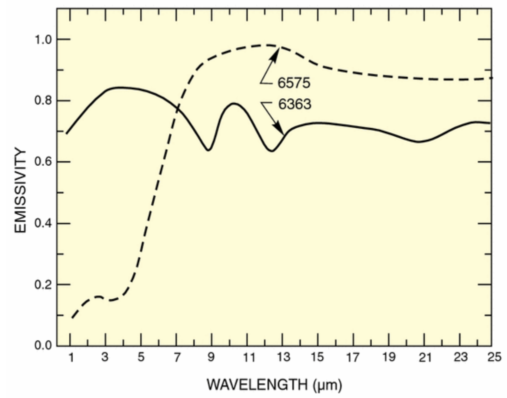
III. SETUP AND EXPERIMENTAL RESULTS

In order to determine the feasibility of a through-canopy characterization of a radiating target, it was developed a setup constituted of two parts. The first one allows proving the detectability of a specific sensor and its response when submitted to an acrylic canopy interface. The second one shows the transmittance of the acrylic canopy according to different wavelengths of the IR spectrum, what explain the previous achieved results.

As a radiating target it is chosen a silicon-carbide element, a traditional type of IR radiator. The 6363 IR Emitter of Newport is a 20mm long radiator with high and relatively uniform emissivity over the 1 to 25μm range, considered a gray body. When feed with 10V, it shows a surface temperature of about 1075K. Although it presents a standard 12V lamp voltage by the technical order, the 10V was used because it increases the lifetime, being calibrated previously. Fig. 3a) and b) shows the irradiance and emissivity of this element [9].



a)



b)

Fig. 3. a) Irradiance and b) emissivity of the 6363 IR element [9].

In Fig.3. is possible to see the relatively uniform emissivity, around 0.75, of the used gray body, what agrees with the previously showed in Fig.1.

As a first approach, the radiating element was heated to 1075K, in order to show its known characteristics. The figure can be seen in Fig.4.

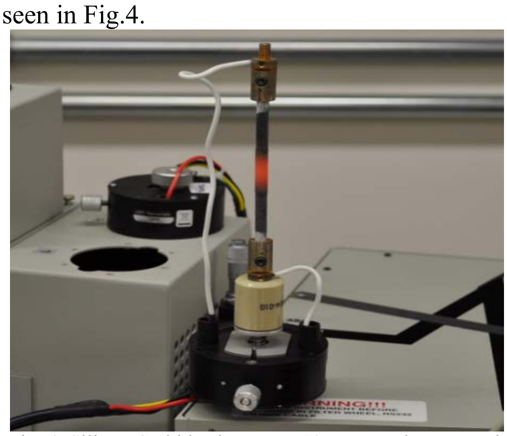


Fig. 4. Silicon Carbide element at 1075K, used as a gray bod.y

The detection in IR band was provided with the use of a FLUKE Ti32 Commercial Thermal Imager [10]. It is a micro bolometer camera FPA of 320x240 sensible elements. The results in free space (atmosphere) can be seen in Fig.5, where a maximum of 650ºC was achieved because of the camera restrictions.

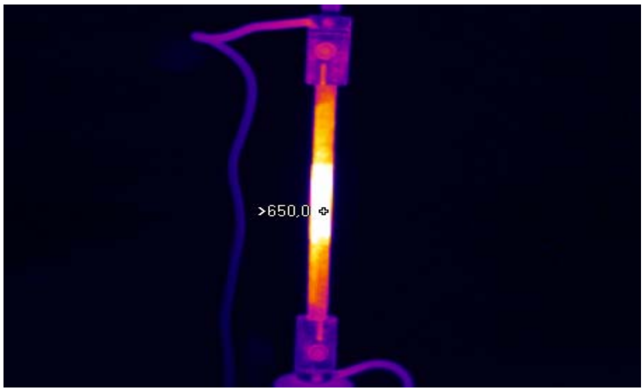


Fig. 5. IR imaging of the M-6363 gray body element.

Fig.5. shows the detection of the target through the use of the thermal camera. Beyond the detection of the hottest part, it is possible to see the detected temperatures of the other parts of the element. This image allows perfectly the understanding of the transparency of the atmosphere to the radiation in the camera IR band. As showed before, microbolometers have a detection band from 7 to 18μm. When verified the 3D graph, the profile of the image confirms the saturation of the camera, demanding, for a better detection, another kind of imager.

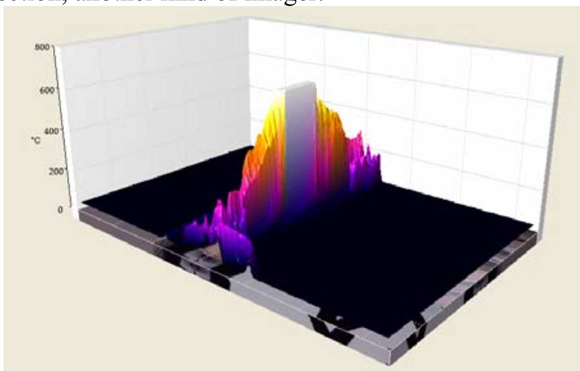


Fig. 6. 3D IR imaging of the M-6363 gray body element at 1075K.

Fig.6. shows a clear decrease of the temperature from the center of the element to the edges. The center, showed with a white color, is highly saturated, showing that the silicon carbide is heated above 650ºC, achieving, probably, the 1075K provided by the user manual.

The same steps previously done were repeated, now, with a piece of acrylic canopy as an interface, between them. Fig. 7. shows the provided setup.

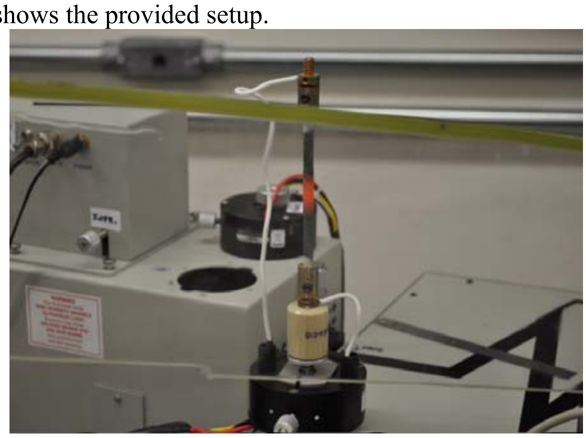


Fig. 7. Silicon Carbide element at 1075K, with an interface of acrylic canopy.

Once interposed the acrylic canopy between the target and the sensor, it could be seen the follow images, presented in Fig.8 and 9.

Fig. 8. 2D imaging of the M-6363 gray body element.

Fig. 9. 3D IR imaging of the M-6363 gray body element.

Fig.8. shows that the acrylic canopy is completely opaque to IR radiation from 7 to 18µm. The unique color, approximately at 21ºC shows that the measured temperature was the room temperature instead the radiating temperature. In Fig.9., the 3D image allows a comparison between the visible length image and the IR image. Both images allow concluding that acrylic is not a good medium for measurements with micro bolometers imagers. This activity is not possible to be made with this kind of camera.

In a second phase, after determining the impossibility of through-canopy measurements with a micro bolometer camera, it is presented an experiment in order to determine the transmittance of the acrylic. Therefore, it could be understood the reasons of the presented behavior, as well as understand possibilities to the intended detection through canopy.

For this, it was used a Spectrum™ 400 Infrared Spectrometer, what provides FT-IR and FT-NIR Measurement Capabilities [11]. Then, it is possible to have, in accordance with visible and IR wavelengths, the transmittance of the acrylic and its compatibility to IR transmition. The setup is presented in Fig. 10.

Fig. 10. Spectrum400 and the experimental setup for acrylic transmittance.

The Spectrum 400 provides an extensive software suite, which guides and trouble-shoots method development and validation, providing a simple interface for research analysis. These properties provide much faster method development, more robust testing procedures and a high level of confidence in results.

Fig.10. shows a sample of acrylic being analyzed. Through the IR spectrometry, it is possible to know, for each wavelength, what is the ratio of the total radiance power transmitted through the sample. The results can be seen in Fig.11.

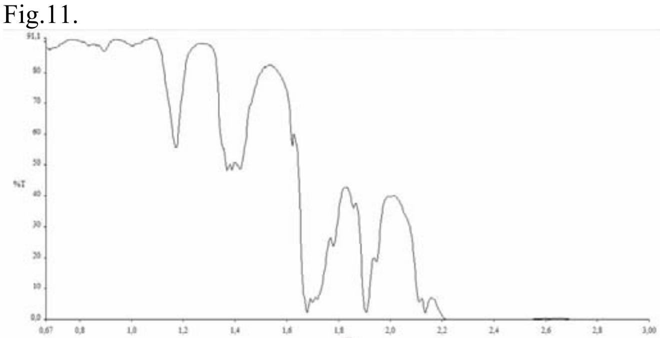


Fig. 11. Experimental results for acrylic transmittance in the visible, NIR and MIR range.

Fig.11. shows the most important analysis of this specific topic, presenting the main results. Considering the first part of the spectrum, up to 1.1µm where the final part of the visible spectrum and the Near Infra Red (NIR) spectrum can be seen, there is a clear transmittance of 90%. This trend explains the easy and clear visibility and detection of electromagnetic waves in this range. According to Fig.7., in the visible range there is almost total transparence of the acrylic. It can be supposed too that if used a NIR camera, the IR radiation could be detected as well, up to 1.1µm.

After these first bands, it can be seen a clear degradation of the transmittance, alternating bands of high absorption and transmittance bands ever smaller. After 2.2µm it is impossible to detect IR radiation, because of the total absorbance of the acrylic used in canopies. The wavelengths that present high absorption (mainly in 1.2, 1.4, 1.7 and 1.9µm) are related to frequencies of vibration of water molecules existing in the environment.

Knowing these results it can be understood why the micro bolometer imager could not detect the 6363 element. As it detects in the 7-18µm range, the acrylic of canopies is completely opaque, avoiding IR propagation.

Although another camera could be employed, for example in MIR (3-5μm), it could not detect the IR radiation, which reduces the chances of detection to cameras that operate in the near infrared where can be seen a high transmittance.

IV. CONCLUDING REMARKS

It was presented a through-canopy radiance analysis of electromagnetic waves in the infrared spectrum. As previous results, it was shown the detection of a gray body at 1075K, with the use of a micro bolometer camera, operating from 7-18μm. The detection could be done without problems of interface, once the atmosphere is relatively transparent to this IR range. With the interposition of an acrylic plate between the target and the sensor, it was shown the total opacity of the medium to the micro bolometer camera.

Finally, a Spectrometer was used to check the transmittance of the acrylic to NIR and MIR ranges. Based on these results, it can be concluded that up to 1.1μm the plate is transparent (90% of transmittance). After this wavelength, a clear degradation of transparence is noted, up to 2.2μm, when it is completely opaque.

This study allows the understanding of the transmittance concepts, the effects of the interfaces to the IR detection and finally the impossibility to the use of some compounds as interfaces in special operational applications.

Particularly, it is possible, based on these results, to plan a special setup to evaluate the infrared signatures of aircrafts and flares during flight, filling a long-standing demand of Comando da Aeronáutica. It is important to highlight that systems like this are not available for buying and the domain of this technology allows, in addition to a great economy of means, the achieving of technological independence in infrared signatures mapping.

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