Influences of the Atmospheric Composition on Infrared Radiation Transmittance

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***Abstract* — The technological advances and developments witnessed in recent decades in Electronic Warfare have enabled the production of weapons increasingly accurate and lethal. Amongst all of them, the IR weapons have proved to be of particular interest, once they are passive artifacts and have high efficiency against radiating targets. However, the radiation emitted by a target is subject to the propagation laws through the atmosphere, which directly impact on its detection and efficiency. In this paper it is investigated the way how the concentration of different components present in atmosphere influence the atmospheric transmittance of infrared radiation. Simulated/prospective results based on different compositions of the atmosphere allow analyzing different critical operational scenarios in Brazil, which were chosen based on the higher influence of each one of the analyzed atmospheric gases. Despite of the qualitative analysis, the results show a great potential for application of these concepts and tools in doctrinal development of combat techniques by the BAF, requiring however a more detailed analysis for specific actual applications, when must be considered the specific atmosphere and the detector of the operational scenario.**

***Key-words* – Infrared, atmosphere transmittance, operational doctrine development.**

I. INTRODUCTION

The technological advances witnessed in recent decades in Electronic Warfare have enabled the production of weapons increasingly accurate and lethal. Thus, the effective use and domain of the electromagnetic spectrum is able to greatly influence the definition of winners and losers of a war. Therefore, Electronic Warfare has shown to be, more than ever, a multiplier of combat capability of an Armed Force, which is present even in the simplest operation theaters [1] [2].

One of the main areas of interest within the Electronic Warfare is the studies on propagation of infrared radiation. Much of the weaponry used in operational theaters today employs systems that use this type of radiation for their guidance. Thus, the knowledge of how it is generated and the factors that influence the propagation of this type of radiation is a topic of great relevance for any Armed Force, since it leads to the use of this band of the electromagnetic spectrum in their favor, as well as the possibility to deny to enemy's weapons its use.

Considering the importance of technological independence of Brazil in the defense area, Electronic Warfare Laboratory (LAB-GE), in ITA, has developed several research areas related to the use of the infrared spectrum for military applications [2]. In addition to the topics which study and develop sensors and detection, it becomes very important to study the ways how the environment influences such infrared detection, which may be applied not only to military areas, but also in civil ones [3].

Once weapons and equipment operating in the IR spectra are subject to the law of propagation in the different layers of the atmosphere, and undergo not only the penalties but also the benefits of such influences, investment in this area (aimed not only at the development IR weapons but also at the domain of the knowledge of how they will operate and detect under certain scenarios) show to be fundamental and of strategic importance. A nation that neglects these facts is bound to, sooner or later, suffer the consequences.

Once the infrared radiation from a radiating target is generated, it will be transmitted through a medium until it is detected by a sensor. As this radiation propagates through this medium, it will be "affected" by it, being attenuated, diffracted, etc.

In the present study, it is presented a qualitative analysis on the atmospheric attenuation suffered by the infrared radiation in different and critical real scenarios of Brazilian territory, as well as the operational impacts arising from the knowledge of the behavior of each one of these factors. The main contributors that cause atmospheric absorption are analyzed, besides doing simulations in order to investigate the level of influence of these components in total absorption and IR detection sensors.

II. EXPECTED OPERATIONAL IMPACT AND THEORETICAL CONCEPTS

The infrared guided weapons' sensors have their principle of operation based on the fact that all bodies above 0 K emit radiation, which is greater as higher is the temperature of the body [4]. Such types of weapons represent a major threat to any aircraft flying in hostile territories [5].

Infrared radiation corresponds to the electromagnetic emission at wavelengths between 0.75µm and 1000 µm [4]. The infrared band is generally subdivided into four bands: near infrared (NIR - 0.75µm to 3µm), mid infrared (MIR - 3µm to 6µm), far infrared (FIR - 6µm to 15µm) and extreme infrared (XIR - 15µm to 1000µm) [4] [6].

One of the main laws that mathematically models the emission of infrared radiation was formulated by Max Planck in 1900, and is commonly known as Planck's Law. Equation (1) provides the radiant spectral emittance of a body, in

W/m^2.μm, depending on the temperature of the body [4] [6] [7].

$$M_\lambda = \frac{c_1}{\lambda^5} \cdot \frac{1}{e^x - 1} \qquad (1)$$

In (1), $x = \frac{c_2}{\lambda T}$, c_1=3.741844*10^4 [W.cm^{-2}.μm^{-1}], c_2=1.438769 [cm.K], λ is the wavelength [μm] and T is the absolute temperature [K]. From this analysis, it can be seen that the radiant emittance of a body depends on the temperature at which the body is, with a different value for each wavelength. In Fig.1, there is a graphical representation of this behavior for different temperatures.

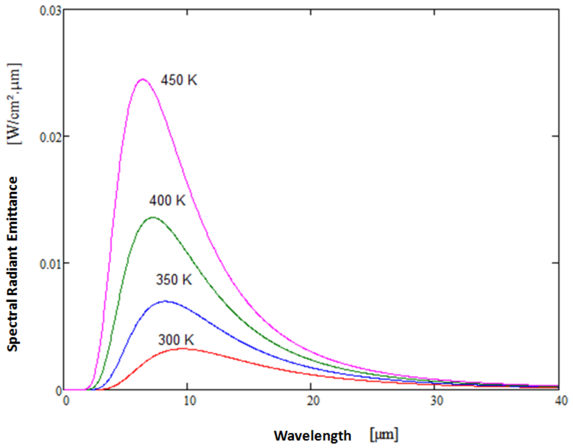

Fig.1 – Planck's Law curves for four different temperatures [4]

In Fig.1 one can see that the total emittance (emittance considering the full spectrum) increases rapidly with the increasing temperature. This relationship is approximately to the fourth power of temperature, being modeled by the Stefan-Boltzmann law

$$M = \sigma . T^4 \qquad (2)$$

where σ is the Stefan-Boltzmann constant, with a value of σ = 5.66961*10^{-8} [W.m^{-2}.K^4].

Based on the emittance and considering the radiating target as isotropic, the radiance (L) over an hemisphere can be modeled as [4] [7]:

$$M = \pi . L \qquad (3)$$

Planck's Law applies only to Blackbodies, which are perfect theoretical radiators. However, the emissivity of a body will correspond to the ratio between the emittance of a body when compared to the emittance of a black body, both at the same temperature [4] [6] [7], being described as:

$$\varepsilon = \frac{M(\lambda, T)}{M_{BB}(\lambda, T)} \qquad (4)$$

where M(λ, T) is the emittance of the body at a given temperature, and M_{BB} is the emittance of a blackbody (obtained by Planck's Law) at the same temperature.

The detection provided by the infrared guided weapons' sensors occurs passively, that is, the sensor acts only as a receiver, omitting its position during all time of detection. The crew of an aircraft under infrared surveillance will probably know that was detected when the weapons engage against them. Therefore, it is very important that "vectors" avoid to be detected, through the minimum possible exposure, during the minimum time.

Since for the detection of a target by a sensor it is required that a minimum level of radiation reaches the sensor (depending on the sensitivity of the sensor), the atmosphere absorption acts as a predominant factor, favoring targets to avoid its detection. As the radiation propagates through different paths in the atmosphere, it will be attenuated in different ways, so reaching values that can disable its detection by a sensor. Thus, the knowledge about how is this behavior can be used for raid missions or attacks planning inside hostile areas with infrared surveillance, in order to avoid the detection of these vectors.

III - ATMOSPHERIC ATTENUATION

During the IR propagation through the atmosphere, the radiation will be selectively absorbed and attenuated by different gases, also suffering scattering by small particles in suspension [4]. The transmittance of electromagnetic waves through the atmosphere can be expressed by:

$$\tau = \mathrm{e}^{-\sigma_{ext} . \mathrm{X}} \qquad (5)$$

where *x* is the path length traveled by the radiation, and σ_{ext} is the extinction coefficient, which can be expressed by:

$$\sigma_{ext} = \alpha + \gamma \qquad (6)$$

where α is the coefficient of absorption of atmospheric gases, and γ is the scattering coefficient [4]. For the infrared range, the scattering process has just little effect when compared with the absorption one [4], and thus it is not considered in this study, for the simplicity of calculation.

Analyzing (5), one realizes that the transmittance is lower as greater is the distance *x* to be traversed by the radiation, that is, higher trajectories incurs higher absorptions.

The main components of atmosphere responsible for absorption of infrared radiation are water-vapor (H_2O), carbon-dioxide (CO_2) and ozone (O_3), being attenuation influenced by a greater or lesser presence of these absorbing molecules in the atmosphere [4].

The atmospheric transmittance is not constant throughout the electromagnetic spectrum, there being ranges of low and high transmittance: the so-called "atmospheric windows". IR sensors are generally designed to operate in these bands in order to best achieve their goals of detection. The two major atmospheric windows are 3 to5 μm and 8 to 14μm, which are shown in Fig.2.

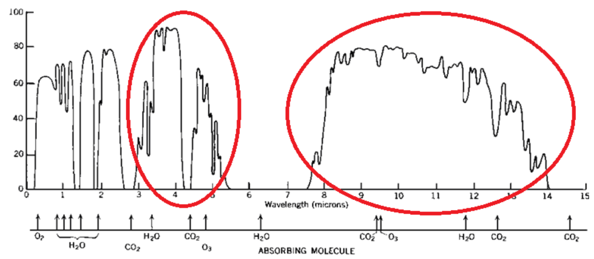

Fig.2 – Atmospheric transmittance to a distance of 6000ft [4]

Concerning to the atmosphere, water vapor presents higher concentrations at low altitudes while the CO_2 presents a more uniform concentration throughout the entire layer. Ozone, on the other side, is dominant at altitudes corresponding to 25 km, practically not influencing the transmission of IR radiation at lower levels, due to its low concentration [4]. Based on these assumptions, in this work it will be analyzed different concentrations of water vapor and CO_2, trying to isolate the effect of each one of these factors and assessing their impact on transmission. When not commented through the text, factors like atmospheric pressure must be considered the same in all analyses. These comparisons will be done in a qualitative way, without present detailed results (numerical), once the paper focus in the analysis of many different scenarios and in the concept demonstration of the usefulness of this kind of tool for operational applications. The different scenarios were chosen once they present the higher influence of each one of the analyzed atmospheric factors. Once air squadrons decide to use it as a doctrine development tool, detailed analyses must be done for the specific scenarios of operation and the specific existent detectors in the conflict area. For now, as a concept demonstration of the validity of the method, as many critical and different scenarios will be analyzed, what can be seen below.

IV - INFLUENCE OF WATER VAPOR IN TRANSMITTANCE

Water is the sole element of the atmosphere which can be found in more than one physical state at the same time, and showing to be one of the major IR radiation absorbing elements [4]. One approach to measure the total amount of water vapor in the atmosphere is the calculation of relative humidity in the air. This calculation takes into account the absolute humidity present in the air, as well as its temperature. The more humid is a sample, the greater its relative humidity.

In order to verify how the atmospheric transmittance behaviors at different levels of relative humidity, some simulations were made using the software PCModwin 3.7. It is a recognized standard for computing atmospheric transmission and radiance at medium spectral resolution. It is a Ontar's user interface and a display software that wraps around MODTRAN, making it easy to use, creating the necessary formatted input files to run MODTRAN. It also includes output plotting to quickly view the results of a calculation. While MODTRAN is a complex program with many options, PcModWin lets you concentrate on the problem you are solving, while insulating you from the details of setting up input files and running codes [3] [8] [12]. The software also includes a great number of input possibilities in order to model the atmosphere, as the Air Temperature, Relative Humidity, Visibility, Wind speed and Altitude. The calculations, after performed, will generate graphs of total transmittance, H_20 Transmittance, CO_2 Transmittance, Nitrogen Transmittance, all of them based on the input desired wavelengths.

In the simulations, it was tried to evaluate two typical different Brazilian scenarios: The atmospheres of Petrolina and Manaus, simulating a hot and dry and a hot and humid climate, respectively. The relative humidity levels were considered as the annual averages for both locations: 50% at 37°C in Petrolina, and 80% at 26.7°C in Manaus [9] [10].

Figures 3 to 5 illustrate the transmittance obtained by the simulation software in the spectral range 0-16 micrometers. The transmittance was obtained by isolating the effects of H_2O vapor, not considering other atmospheric elements. The comparison between the transmittances obtained for the two locations allows us to have an idea of the influence of different levels of relative humidity on the radiation transmission to actual data of possible operating scenarios.

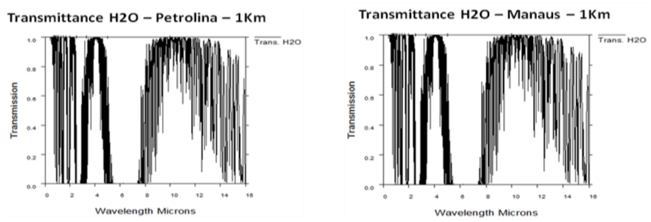

Fig.3 – Spectral transmittance comparison due to H_2O for a path of 1 km

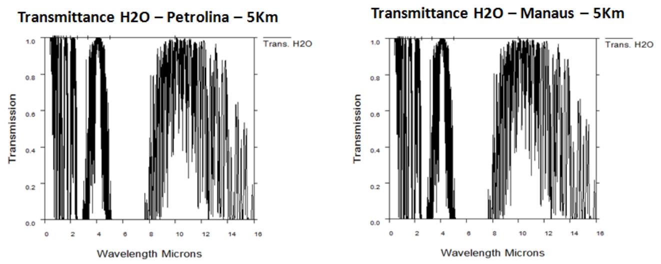

Fig.4 - Spectral transmittance comparison due to H_2O for a path of 5 km

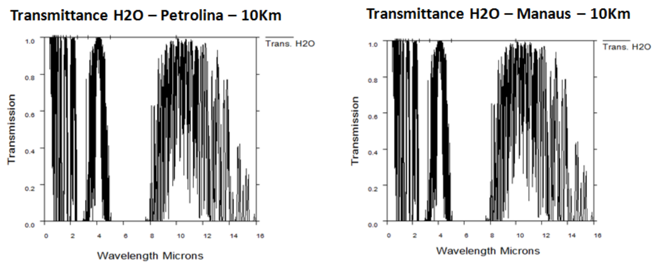

Fig.5 - Spectral transmittance comparison due to H_2O for a path of 10 km

Through the analysis of Fig. 3 to 5, it is possible to find that the spectral transmittance for both simulated atmospheric models is the same, showing no significant differences in a qualitative analysis. As the path to be traveled by the radiation increases, one can see that there is a gradual decrease in transmittance. This is due to the fact that higher the trajectory, more absorbing molecules must be overcome by radiation until its arrival to the sensors [3] [4]. Another relevant point is the similarity between Fig.2 and the curves obtained in the simulation, showing that water vapor is a major influencing factor to the generation of atmospheric windows.

Since most of IR sensors are designed to operate specifically in one of the atmospheric windows, simulations were carried out for the window 3 to 5 µm, since this is one of the most widely air weapons' sensor used [1] [3]. These simulations allowed a detailed analysis of the transmittances curves.

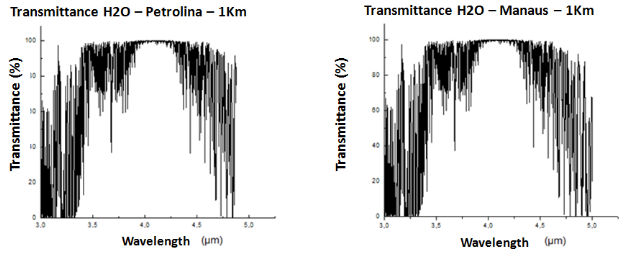

Fig.6 – Transmittance analysis between 3 to 5µm for the Petrolina and Manaus models of atmosphere, considering only the water vapor. In a path of 1 km

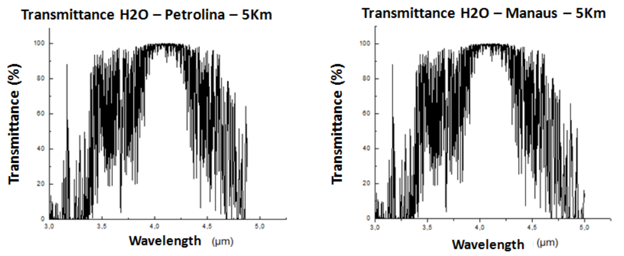

Fig.7 - Transmittance analysis between 3 to 5µm for the Petrolina and Manaus models of atmosphere, considering only the water vapor. In a path of 5 km

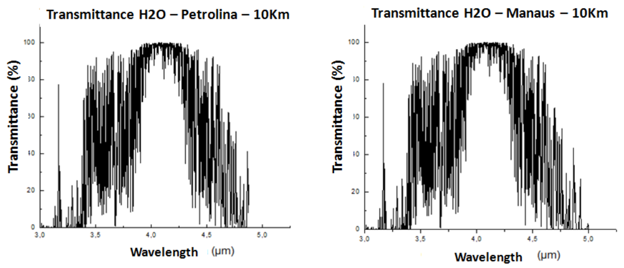

Fig.8 - Transmittance analysis between 3 to 5µm for the Petrolina and Manaus models of atmosphere, considering only the water vapor. In a path of 10 km

Analyzing Fig. 6 to 8, it is possible to find that, even a more detailed analysis of the atmospheric transmittance for the window 3 to 5 µm shows no significant differences for the atmospheric transmittance in different humidity levels.

V - INFLUENCE OF CARBON DIOXIDE IN TRANSMITTANCE

Carbon dioxide (CO_2), together with the water vapor, is a major atmospheric element responsible for the absorption of infrared radiation [4]. The burning of fossil fuels is the largest source of CO_2, being its level directly linked to the level of air pollution [8] [11].

CO_2 is also produced from the respiration of living organisms, being absorbed by plants during photosynthesis, which, at least, compensates its atmospheric concentration. Since photosynthesis is a phenomenon that occurs only during the day, in presence of natural light, it is expected that the concentration of CO_2 in regions with lots of vegetation, such as the Amazon rainforest, will be greater at night, since this kind of element will not be absorbed by plants [11].

In order to investigate how the transmittance behaviors at different concentrations of CO_2, new simulations were performed, this time for two other atmospheric models. The first one used the concentration of 370 ppm (parts per million), which is the average concentration of this component all around the world. In the second model, it was used the concentration of 533 ppm, which is the maximum value corresponding to the night period for rural Amazon rainforest, based on a study that measured CO_2 levels in 2004 [11].

The first simulations were performed to obtain the transmittance in the range of 0 to 16µm, and the results are shown in the following figures.

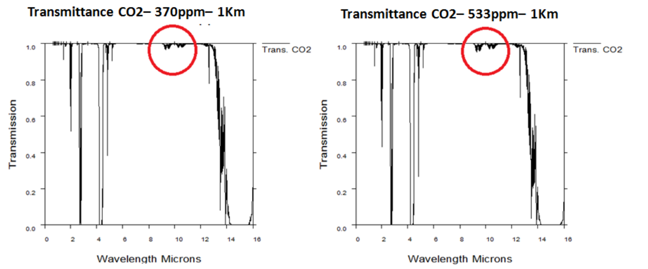

Fig.9 – Spectral transmittances analysis due to different CO_2 levels for a path of 1Km.

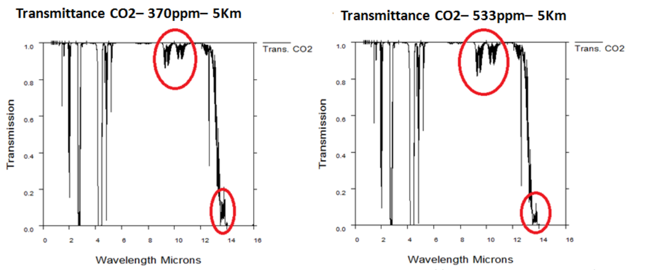

Fig.10 – Spectral transmittances analysis due to different CO_2 levels for a path of 5Km.

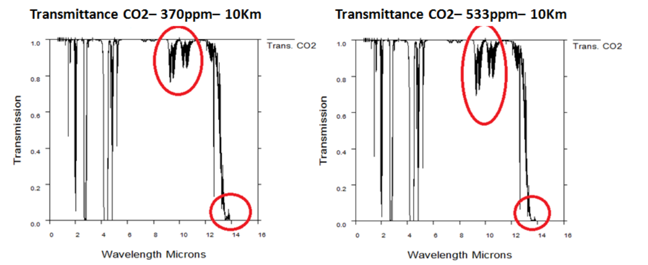

Fig.11 - Spectral transmittances analysis due to different CO_2 levels for a path of 10Km

Analyzing Fig. 9 to 11, it is possible to find that the differences between the transmittances for both atmospheric models are very small and occur in very narrow spectral bands, thus can be disregarded for practical purposes. In order to perform a more detailed analysis of the influence of CO_2, simulations were performed also for the atmospheric window 3 to5 micrometers. The data obtained can be seen in Fig. 12 to 14.

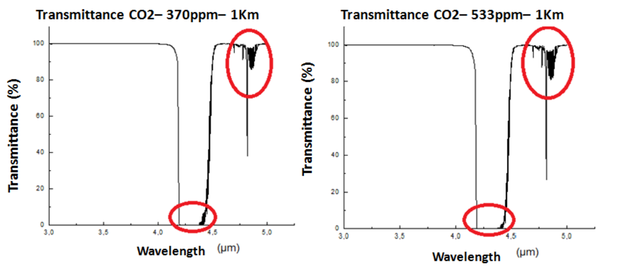

Fig.12 – Transmittance analysis between 3 to 5 µm for models where CO2 is equal to 370 ppm and 533 ppm, in a path of 1Km.

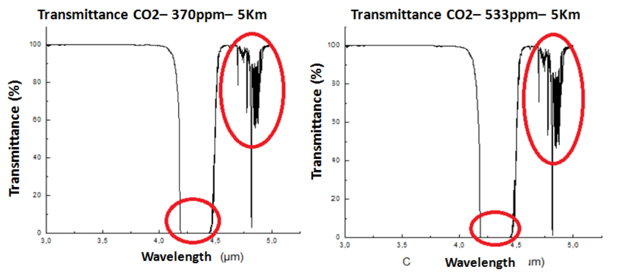

Fig.13 - Transmittance analysis between 3 to 5 µm for models where CO2 is equal to 370 ppm and 533 ppm, in a path of 5Km

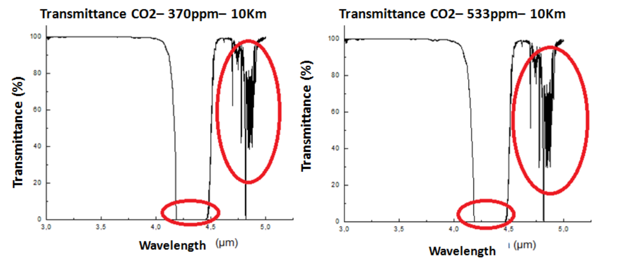

Fig.14 - Transmittance analysis between 3 to 5 µm for models where CO2 is equal to 370 ppm and 533 ppm, in a path of 10Km

The analysis of Fig. 12 to 14 shows that, even in a more detailed view, the differences between the transmittance of the models 370 and 533 ppm are not significant. The major difference occurs in a range close to 5 µm, in which the transmittance to the model of 533 ppm is a little lower than that of model of 370 ppm.

VI – GLOBAL ANALIZES - OVERVIEW

From the data obtained through the simulations, one could conclude that the different levels of the analyzed humidity and carbon dioxide concentration do not infer significant differences in atmospheric transmittances, what leads to the possibility of using the same doctrines of flight for different weather scenarios. For trajectories of the same length, even in regions with distinct atmospheres compositions, the transmittance remains almost the same. However, it is necessary to analyze the total transmittance influenced by simultaneous absorption of H_2O, CO_2 and all other atmospheric components together, in order to obtain conclusive results.

For this analysis, new simulations were done by checking the total transmittance (considering all atmospheric components). The simulations were made for paths of 5 km in a band of 3 to 5 µm, considering three different atmospheres, which were Petrolina, Manaus and São Paulo, the latter being an additional model considered for this case. In the model of São Paulo, it was considered the humidity as 78% and the temperature of 18°C, what are the average annual values for this city. The results are shown in Fig. 15 to 17.

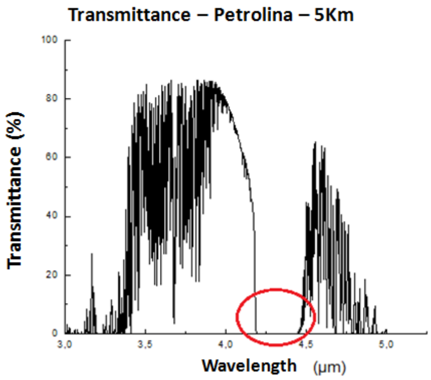

Fig.15 – Transmittance analysis in 3 a 5 µm band for the model of Petrolina - 5 km

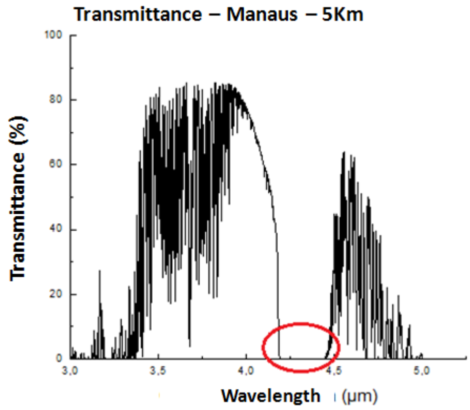

Fig.16 – Transmittance analysis in 3 a 5 µm band for the model of Manaus - 5 km

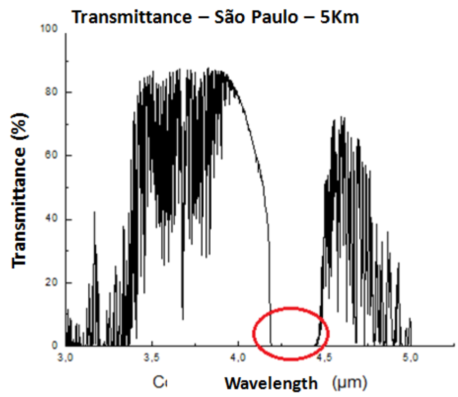

Fig.17 – Transmittance analysis in 3 a 5 µm band for the model of São Paulo - 5 km

Through the analysis of Fig. 15 to 17, it is perceived that there were no major differences between the transmittances of the simulated models. The curves obtained are very similar to curves obtained in the analysis of transmittance considering only to H_2O. There are, however, traces of strong absorption caused by the CO_2, what may be verified in the range 4.2 to 4.45 µm, where the transmittance is practically null.

After considering all the analysis presented in this study, it is possible to conclude that, for different existing Brazilian scenarios, the different levels of humidity, temperature and CO_2 concentration observed will not generate significant differences in the transmittance of infrared radiation. Thus, the same flight profile adopted for a specific Brazilian region can be applied to the others, from the viewpoint of detectability by equipment operating in the infrared range. Focusing on the development of doctrine for the employment of combat aerial vectors, the same techniques and tactics can be employed in different regions of Brazil, allowing the possibility of doctrinal standardization among the various air squadrons. Such standardization is very important, especially when operating in a joint operation that involves multiple Air Vectors.

IV. CONCLUDING REMARKS

Given that in the current combat scenarios the armaments that use infrared radiation for their guidance represent a major threat, it is extremely important for an Armed Force know the process of generation and transmission of such radiation [2] [3] [5]. Unfortunately, results in this area are very difficult to find and groups that study these subjects are often rare, making it impossible to compare results. In order to investigate the main factors that influence the transmission of infrared radiation, mainly aiming to flight doctrinal applications, technical studies and computer simulations of different atmospheric Brazilian models were described in this work. Although have being presented as qualitative analyses on the transmittance graphs, the results of the simulations using the software PCModwin 3.7 allow analyzing the level of influence that different concentrations of H_2O and CO_2 infer in the transmittance of infrared radiation. Through the modeling and simulation of different atmospheres, with actual characteristics, it was demonstrated that the differences in the concentrations of absorbing elements does not result in considerable differences in transmittances for infrared radiation. After a global analysis where all atmospheric components were considered, it also did not show significant differences for the transmittances of the different regions. These data lead to the conclusion that the same combat tactical and techniques may be employed in all Brazilian regions, since the transmittance for this type of radiation is practically the same. Once more precise results can be desired, the specific scenario must be analyzed and the transmittance must be considered according to the environment and the existent detector in order to calculate the detectability of the target under that specific situation.

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