OPTICAL DESIGN CHARACTERISTICS BASED ON AERODYNAMIC HEATING

Leite Junior, Paulo Roberto
Comando Geral de Tecnologia Aeroespacial (CTA)/ Instituto de Aeronáutica e Espaço (IAE)/ Divisão de Sistemas de Defesa(ASD)
DENEL Aerospace System / South Africa
prleitejunior@yahoo.com.br

Silva, Maurício Guimarães da
Comando Geral de Tecnologia Aeroespacial (CTA)/ Instituto de Aeronáutica e Espaço (IAE)/ Divisão de Sistemas de Defesa(ASD)
DENEL Aerospace System / South Africa
maugsilva@iae.cta.br

Abstract. *The influence of the aerodynamic heating for a missile dome flying at supersonic speed is evaluated in respect to optical performance. The fluid flow properties are obtained using an approximated method, whereas the convective heat flux is calculated from classical relationships provided in the literature to this type of problem. Since the thermal characteristics of the material change during the flight, a transient one-dimensional is applied. The finite difference method is then used to solve the resulting equations and the temperature distributions at the dome and inside it are obtained. Using the dome internal temperature distribution, the performance degradation of the optical system is estimated in terms of the energy focused on the detector. Using the software for optical simulations named ZEMAX®, the system is designed to suit the temperature range in order to achieve the specified performance.*

Keywords: *aerodynamic heating, missile technology, optical device, and optical performance*

1. Introduction

The influence of the aerodynamic heating for a missile dome flying at supersonic speed has a negative effect on optical system performance, since the thermal characteristics for the optical components, dome and the air inside and outside of it change during the flight (transient behavior). Under these conditions, the performance of the optical system, obtained from the changes in dimensions of the lenses, is degraded in terms of the energy focused on the detector (Rainer et al., 2007). As the flight envelope foresees rear engagement, what implies in very large scan angles for the seeker, the optical system must accomplish all the requirements defined in function of the flight envelope. It is a common practice to analyze the structural behavior (dome and optical components) through finite element method and the temperature distributions of air in/outside of the dome using CFD techniques of stagnation line method (critical case in terms of the heat flow per area unit). However, many details of theses approaches are not published, because this subject, when applied to the missiles, present high confidentiality level. In this context, the objective of this paper is to present a simple methodology to analyze the influence of the aerodynamic heating on the optical system for a general missile, in respect to optical performance, in order to illustrate the background knowledge used in this category of project. The fluid flow properties are obtained using semi-empirical relations, whereas the convective heat flux is calculated from classical relationships provided in the literature to this type of problem (Anderson, 1989). Since the thermal characteristics of the material change during the flight, a transient one-dimensional is applied. The finite difference method, implemented in a context of MATLAB®, is then used to solve the resulting equations and the temperature distributions at the dome vicinity and inside it are obtained. Using the dome internal temperature distribution, the performance degradation of the optical system, obtained from the changes in dimensions of the lenses, is estimated in terms of the energy focused on the detector. Using the software for optical simulations named ZEMAX®, the system is designed to suit the temperature range in order to keep the initial specified performance.

2. Optical Design

The dome is the first optical component and is designed to have very low magnification and to be uniform in all its extension; otherwise it will distort the image that reaches the internal optical system, because it does not stay pointed to only one position in the dome, but it can move in a large field of view, sometimes 75° or more, inside the dome. The material to be used in the dome will be magnesium fluoride (MgF_2). MgF_2 domes are widely used due the good qualities of hardness and transparency in very wide spectra, from visible to medium infrared (MIR). Besides, the knowledge in manufacturing and availability are also good characteristics that determine the option for MgF_2.

Once the dome material is chosen, it is very important to define the optical system to be designed and simulated. The most common and efficient system used is the Cassegrain, Fig. 1. Although there are many variations for this system, no specific model will be used. Instead, the program used to make the design will optimize the best configuration. The software used in this design is ZEMAX®, very powerful software widely used due to its characteristics of optimization and friendly interface.

The Cassegrain optical system was designed in the 17th century to be applied in astronomical telescopes. The system used in that time was purely catoptrics, e.g., made only using mirrors. The advantage in using mirrors is settled in the fact that mirrors do not introduce chromatic aberrations as lenses do. In the time of its invention, the catoptrics telescopes were very used, due to the low technology in manufacturing mirrors and materials available. Today, its possible to combine even mirrors and lenses to produce systems catadioptrics, e.g., using both mirrors and lenses.

The option for a system catadioptric is the best solution in a missile. In an intuitive design, since the material of the dome has dispersive power, which implies in different refraction index for different wavelengths, the use of a lens to correct the chromatic aberrations effects is required. Besides, a front lens can improve parameters as f-number, which is related to aperture and focal length.

Once defined the type of optical system to be used, it is important to know the general optical requirements. Typically, the main requirements are related to wavelength, field of view, diameter of dome, operational temperature of dome, and so on. The dome must be uniform, so, as first requirement, the outer diameter is 150mm. Since it is mandatory uniformity, the inner diameter will be the value of the outer diameter minus two times the thickness. So the optical magnification will be very low and the dome will have the same optical power in all its extension.

The next step is to define the front lens. Depend on the shape of lens it is possible to specify spherical or aspheric (lens with a shape that is not purely spherical) elements. In this work is chosen aspheric lens, due its really great advantages. Defining only one side as aspheric, it will be possible, through simulations, achieve a very good performance in terms of energy and axial colour distance, which means lower chromatic aberrations levels.

As the last issue, the Cassegrain system will be defined as two mirrors with conic constants determined by ZEMAX™. There are no requirements for conic constants, so the program will find the best values to accomplish the requirements. In order to understand the concepts of conic constants and aspheric elements, Eq. (1) provide comprehension about that:

$$z = \frac{cr^2}{1+\sqrt{1-(1+\mathrm{k})\mathrm{c}^2\mathrm{r}^2}} + \sum_{i=1}^{n} \alpha_i r^i \tag{1}$$

In Eq. (1), z is the surface coordinate, c is the curvature, r is the radial coordinate, k is the conic constant and α are the aspheric coefficients. For a pure spherical surface, the conic constant k and all the α coefficients are zero. If conic constant is less than –1, the surface will be a hyperbolas, -1 for parabolas, between -1 and 0 for ellipses, 0 for spheres, and greater than 0 for oblate ellipsoids. If the coefficients α are not zero, the surface will be aspheric. In this design, three conic surfaces will be defined: the front face of the 1st lens and the other two mirrors.

In this context, Fig. 1 presents the diagram in a cut view for the optical system. Figure 2 shows a first proposal about the optical system and its integration into missile. The gimbal motors were omitted to simplify the scheme.

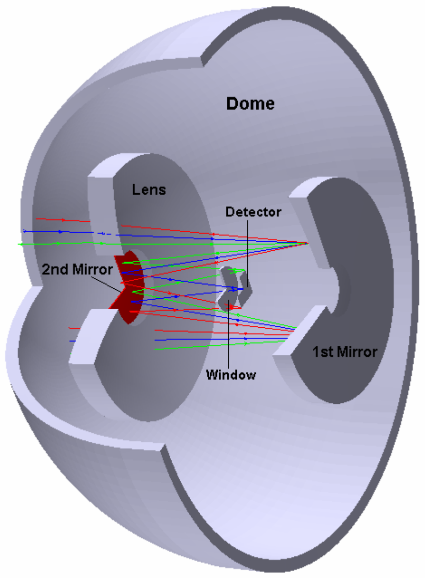


Figure 1 – Optical system proposed (3/4 View)

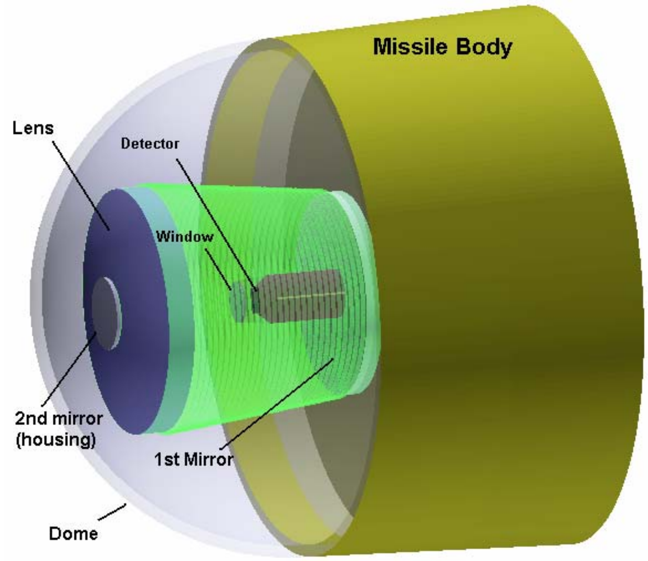


Figure 2 – Optical system integrated into missile

The bigger element is the dome and it surrounds completely the optical system. Its function is to protect the optical system and, physically provide an aerodynamic streamline flow. The first element inside the dome is a conic lens made from IRG100. This alternative is based on simple reasons: the IRG100 has very good optical properties and its dispersion diagram allows a good match with MgF2, accordingly to ZEMAX® glass catalogs. Using this material, it was possible to reduce the axial color to less than 40 μm. That distance is great compared to high precision imaging systems. However, in this design, only one optical element is being used to correct chromatic aberration and due to the pixel detector size, 40μm is sufficient, since the detector is 60μm wide. The next elements to be defined are the mirrors. Their role here is to focus the rays coming from the front lens into the detector. To construct the mirrors, the material to be used will be ZERODUR™. The reason is also simple: its thermal expansion coefficient is lower than $1x10^{-7}$ / ^{0}C in the range between -40 ^{0}C to 300 ^{0}C, which means that even under great temperature range, the mirrors will not considerably deform.

Finally, there is the detector. The detector is a matrix constituted of 14400 pixels arranged in 120 columns of 120 pixels each one. The size of each pixel is 60x60 μm, which provide a final image size of 7200 μm, or 7.2 mm. Consequently, the optical system must be able to generate a square image of 7.2x7.2 mm, achieving a 3.0^0 full field of view. Figure 3 illustrates that requirement.

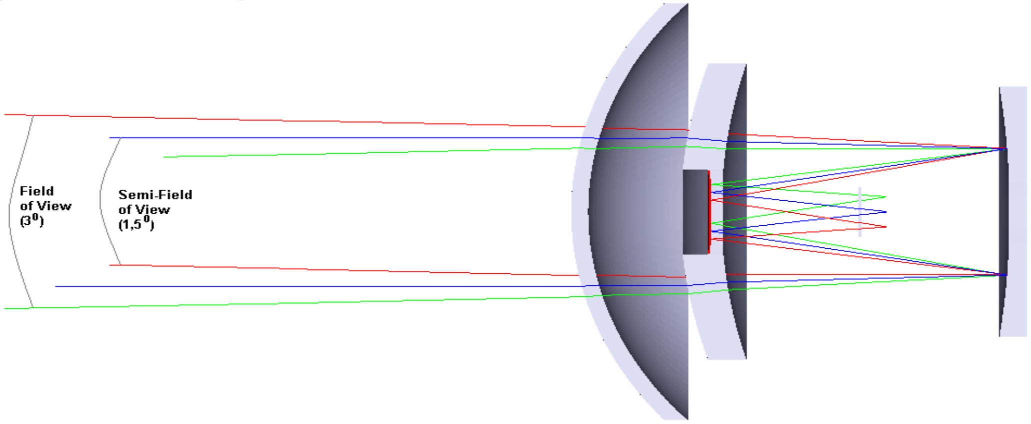


Figure 3 – Geometric scheme of the optical system

2.1 Thermal Analysis

One of the most important requirements to design an optical system is to determine the operational range in terms of temperature range. In this concept, all elements must be able to operate from -40C^0 up to 80C^0, considering the inner elements, and from -40C^0 to 300C^0 considering the external wall of the dome. Under so critical circumstances, it is very difficult to achieve a perfect optical design. However, it will be shown that due to very low thermal expansion of the elements, a system can be designed to operate in such variation of temperatures, with degradation inside the limits established.

There are many procedures to estimate the variation of temperature at the dome of missile. In this work, the project of the optical system was based on the dome/wall temperature estimated from the maximum time rate of local heat input (stagnation temperature). Since the objective of work does not aim a multidimensional analysis of optical components deformation, the heat loads were estimated based on traditional literature methods (Anderson, 1989).

2.1.1. Recovery Temperature Estimation Method

To determine the recovery temperature at each flight condition, it is necessary to obtain the trajectory profile for the baseline model of the missile. The following equation is solved to determine the ratio between the recovery temperature and the stagnation temperature at the boundary layer edge:

$$\frac{T_r}{T_0} = r + \frac{1-r}{1+\frac{\gamma-1}{2}M^2} \tag{2}$$

Where r is defined for laminar flows as:

$$r = \sqrt{\Pr} \tag{3}$$

and defined for turbulent flows as:

$$r = \sqrt[3]{\Pr} \tag{4}$$

The edge stagnation temperature is determined through isentropic flow properties. The recovery temperature is effectively the adiabatic wall temperature, and is also used in determining the convective heat flux within the boundary layer. In this case the time history of altitude and Mach number are entered into a function to produce the recovery temperature profile.

2.1.2. Maximum time rate of local heat input per unit area

The elemental surface which is subject to the greatest heat transfer per unit area is, except in unusual cases, the tip of the missile nose which first meets the air. It seems unlikely that a pointed nose will be of practical interest for high-speed missiles since not only is the local heat-transfer rate exceedingly large in this case, but the capacity away. Body shapes of interest for high-speed missiles would more probably, then, be those with nose shapes having nearly hemispherical tips. The following analysis applies at such tips.

It is well known that for any truly blunt body, the bow shock wave is detached and there exists a stagnation point at the nose (Fig. 4). Consider conditions at this point and assume that the local radius of curvature of the body is R. The bow shock wave is normal to the stagnation streamline and converts the supersonic flow ahead of the shock to a low subsonic speed flow at high static temperature downstream of the shock. Thus, it is suggested that conditions near the stagnation point may be investigated by treating the nose section as if it were a segment of a sphere in a subsonic flow. The following relation gives the heat transfer rate unit area at the stagnation ($\dot{q}_{stagnation}$):

$$\frac{dQ_0}{dt} = \dot{q}_{stagnation} = -\frac{Nu_r k_r}{R}\left(T_w - T_r\right) \tag{5}$$

where k_r is the thermal conductivity of the gas at the recovery temperature T_r, the variable T_w is the wall temperature, Nu_r is the Nusselt number of the flow; and R is the curvature radius of the body. If the flow is assumed laminar and incompressible, the Nusselt number is given by the relationship (Allen and Eggers, 1957):

$$Nu_r = 0.934\left(\mathrm{Re}\right)_R^{\frac{1}{2}}\left(\Pr\right)^{\frac{2}{5}}, \tag{6}$$

The Reynolds number Re is given by:

$$\left(\mathrm{Re}\right)_R = \frac{\rho V R}{\mu_r} \tag{7}$$

Note that ρ is the local density and V is the relative velocity at the air. It is well know that at the high temperature of interest here, the coefficient of viscosity, μ_r, varies nearly as the square root of the absolute temperature, namely:

$$\mu_r = 2.3110^{-8}\, T_r^{\frac{1}{2}}. \tag{8}$$

The equations (5-8) have been used with mathematical model to estimate the maximum time rate of heat per unit area.

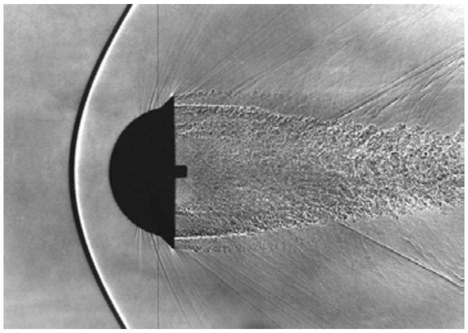


Figure 4 – Schematic representation of the cross section of the dome
(http://www.eng.vt.edu/fluids/msc/gallery/shocks/a2375b.htm).

2.1.4. Velocity of Flight

In aircraft close-in-combat scenarios, the ability to engage targets in the rear hemisphere is a significant advantage. Super-agility in missiles refers to this capability. Following a successful missile launch and separation, dynamic pressures are often too low for aerodynamic controls to make a quick turn. When the propulsion system ignites, vectoring the thrust (or using reaction jets) can provide this capability, and as the velocity increases, the aerodynamic surfaces become more effective. For the missile to possess super-agility (high-angle-of- attack capability) some form of alternate control is needed. Figure 5 illustrates the maneuvering of an agile missile from launch to endgame, indicating a high-angle-of-attack (AOA), maneuvering capability provided by either thrust vector control (TVC) or reaction control system (RCS) thrusters (Wise and Roy, 1998). From the analysis of benchmark results applied to the theoretical missile, it was defined two critical profile of flight, Fig. 6. The first result, Fig. 6a, is related to the missile in flight. The second, Fig. 6b, illustrates the case that is considered the maximum carriage flight profile

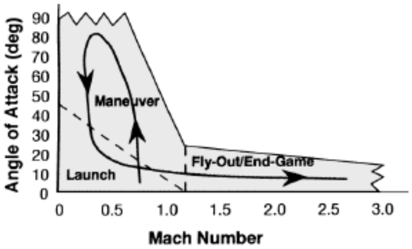
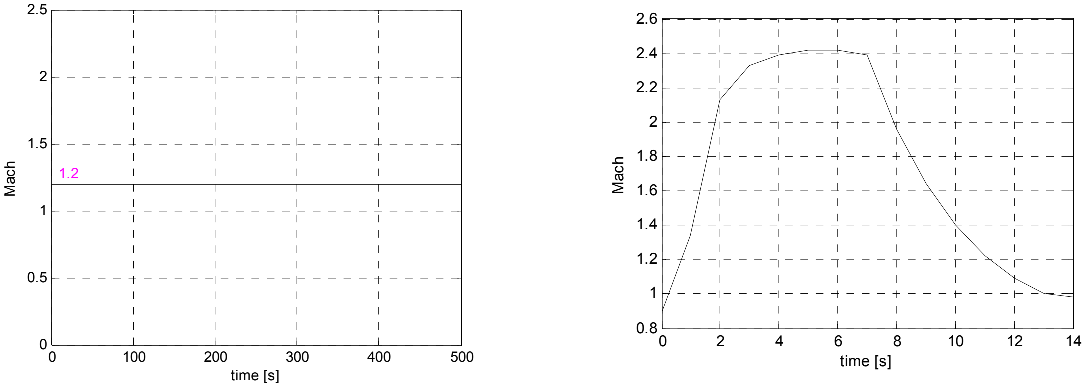


Figure 5 – Agile missile flight envelope (Wise and Roy, 1998)



(a) Carriage flight profile

(b) Missile in engagement profile (Altitude = 0 m)

Figure 6 – Profile of flight

2.1.5. Thermal Resistance

The mathematical formulation for determination of system temperature (missile front section) is based on "lumped parameters" method. It is important to salient that the main objective is to generate a range of possible thermal solicitations that may be supported by the system. It is not aim to define, exactly, the temperature of dome and optical components. In this context, the formulation "lumped parameters" is more practical when compared to the finite element, for example, since many flight profiles must be tested. So, it was considered the following thermal resistances: (1) Forced convection (R_h): between the air after shock wave and wall of dome; (2) Conduction (R_k): in wall of dome; (3) Free convection (R_{hf}): between air inside of dome and optical components. This formulation use results from experimental tests to estimate the loss heat from the system in carriage flight. From this circuit, it is possible to determine the wall temperature (T_w), which is:

$$T_w = \frac{T + \frac{R_k}{R_h} T_r}{1 + \frac{R_k}{R_h}} . \tag{9}$$

The parameter R_h was obtained from Eq.(5); R_k was defined for shells, R_{hf} was defined for vertical walls submitted to the temperature T (inside of dome). Based on this formulation, it can be estimated the temperature of optical components, since:

$$\frac{dT}{dt}=\frac{\dot{q}_{stagnation}S}{C_T} \tag{10}$$

$$\frac{dT_i}{dt}=\frac{\left(\dot{q}_{hs}-\dot{q}_{loss}\right)S_{op}^{i}}{C_{op}^{i}}\,. \tag{11}$$

The parameters C_T and C_{op}^{i} are the thermal capacity of the air inside of the dome and “i” is the number of each optical component, respectively (1 for the 1st lens, 2 for the 1st mirror, 3 for the 2nd mirror); S and S_{op}^{i} are the wet area of dome and optical components, respectively. The parameter $\dot{q}_{loss}$ is the loss heat flux parameter and it was estimated from the system in carriage flight. Obviously, it is a rough approach. However, since the main variations in temperature are obtained from the carriage flight, the method does not compromise the estimative of temperature of lens.

3. Results

3.1 Range of Temperature for Optical System Analysis

Figure 7 shows the thermodynamic parameters used in the aero thermal simulation. The atmosphere model is described by ISA model (block set of SIMULINK®). Figure 8 shows the distribution of temperatures at the dome (T_w), air in dome (T), optical system (T_i) and recovery temperature (T_r). The maximum temperature obtained for optical system from the critical flight conditions was 46.3°C. Another important observation, the stabilization of temperature of air in dome, occurs in a few seconds (Fig. 8). This event is due to physical properties (thermal conductivity = 140W/m/K) and geometrical configuration (radio = 75 mm; thickness ≅ 3.5 mm) of dome.

Figure 9 shows the results obtained for the case carriage flight. In this case was considered 50°C as initial temperature of dome and optical components. The maximum temperature obtained for optical system from the critical flight conditions was 82.6°C. The design of optical system will utilize the maximum free flight temperature profile as set forth in the specification discussed above.

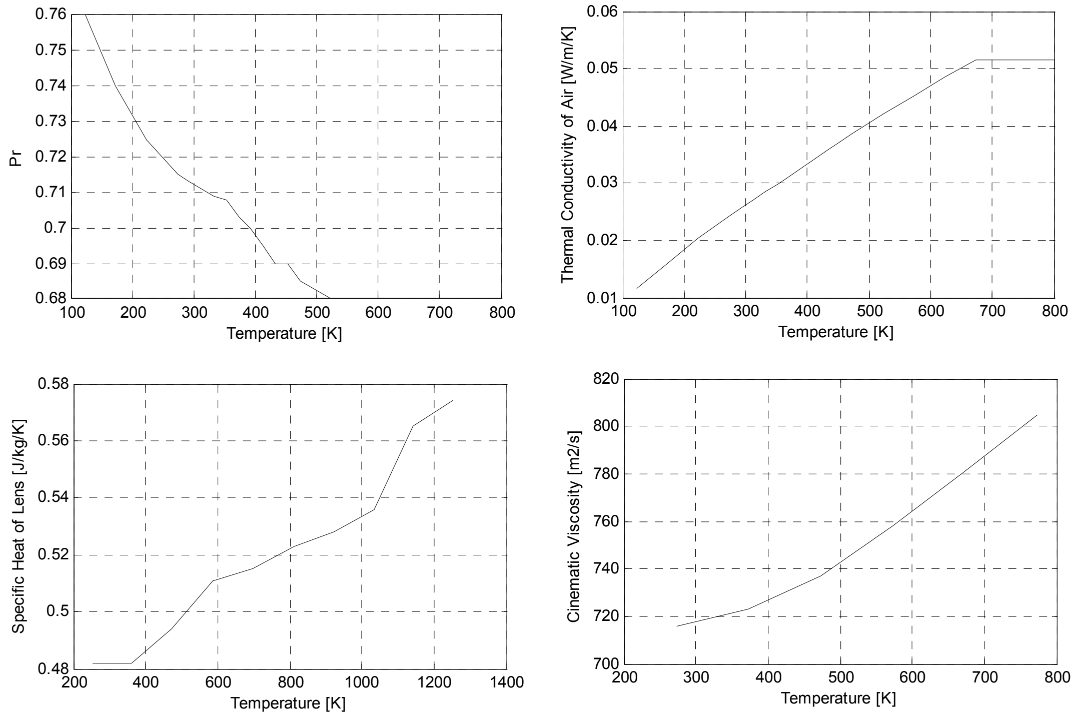


Figure 7 – Thermodynamic properties

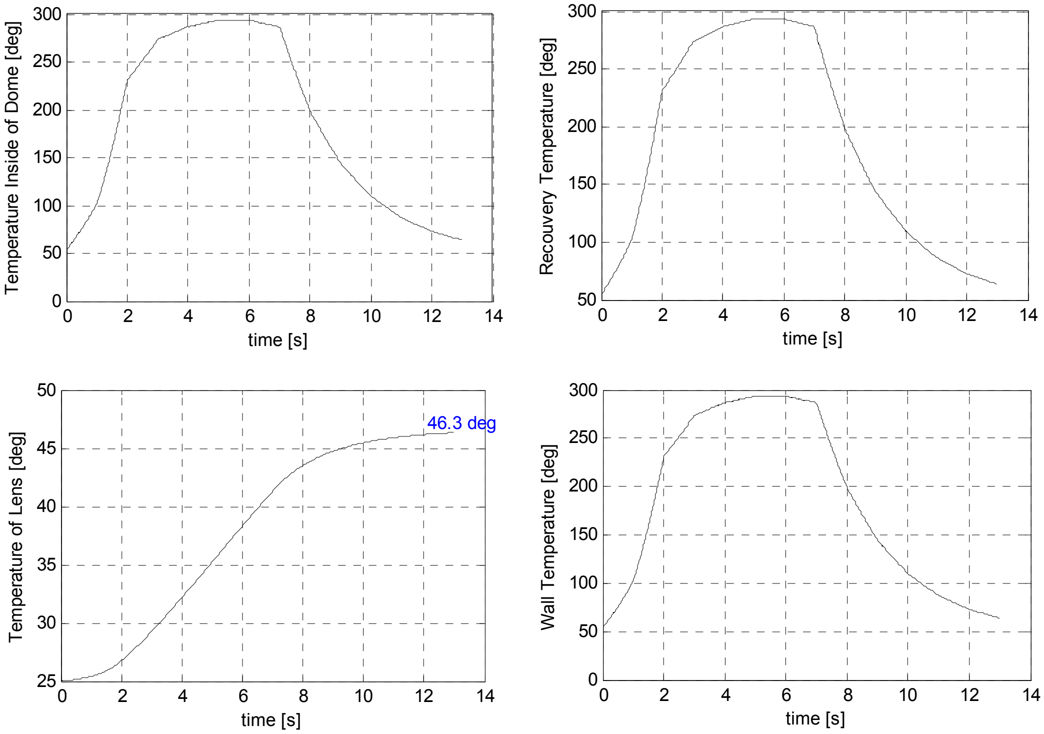


Figure 8 – Aero thermal analysis (profile: engagement of missile)

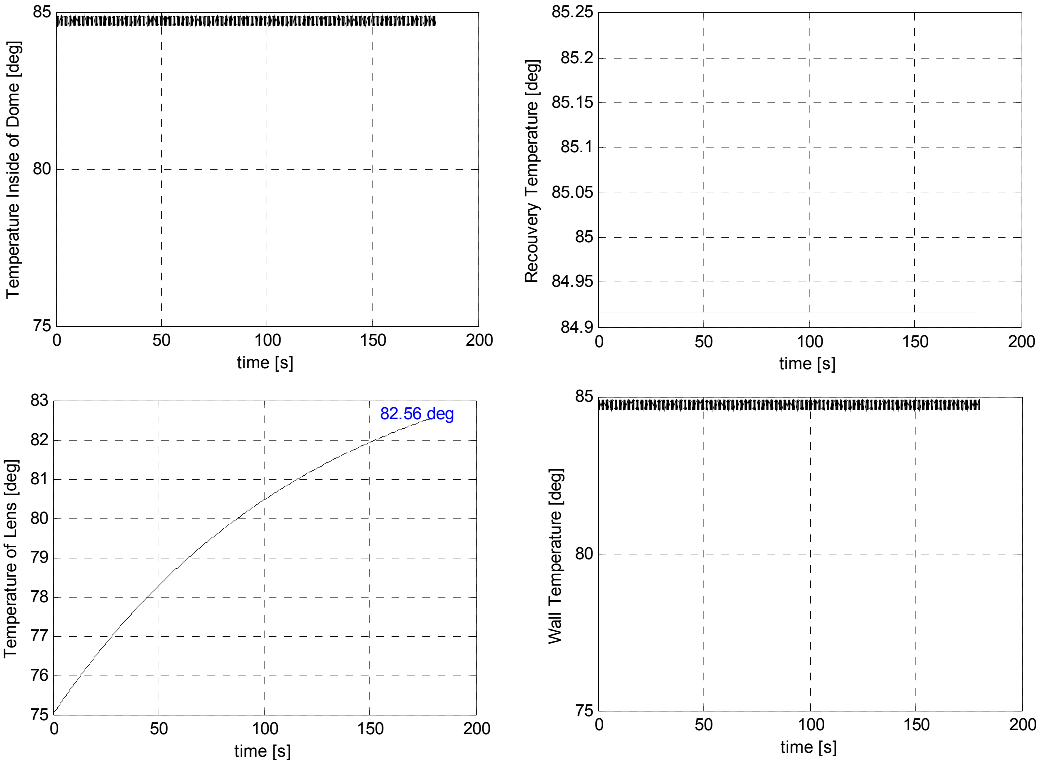


Figure 9 – Temperature of optical system (profile: carriage flight)

3.2 Requirements for Optical System

Table 1 shows the main requirements for the optical system proposed by this work. The temperature range has been obtained based on precedent thermal analysis.

Table 1 – Requirements for optical system

Requirement	Values	Requirement	Values
Wavelength	3,8μm – 5,0 μm	Energy focused on detector	≥80% over full field of view
Field of view	3.0^0	Image size (detector size)	Square array: 7.2mm width
Dome diameter	150 mm	Dome operational temperature	- 40 C^o to 300 C^o
F-number	1.92166	Optical operational temperature	- 40 C^o to 83 C^o
Axial color distance	≤ 40μm	Entrance pupil diameter	> 71 mm

3.3 Optimum Optical Design

To start the optimization process, seven configurations were defined, one for each temperature profile. The software ZEMAX™ is able to generate automatically a merit function that accomplishes all seven configurations. However, the parameters as f-number and entrance pupil diameter must be defined to avoid a system that might not fit inside the missile. Other parameters as lens and dome thickness cannot be excessively large; otherwise the optical system will lose maneuverability and will not move as fast as necessary. The distance between the dome and first mirror must be controlled, or else the optical system will become very long, taking a large space to be built. So, the merit function must accomplish these requirements to provide a viable system.

As the temperatures in the outer dome are different from the inner optical system, it is necessary to use different temperature profiles. Software ZEMAX™ has the option to select different temperatures profile, for each configuration. In Tab. 2 it is also possible to observe the optical elements values of radius curvature, thickness and the space between elements. It is also possible to observe the variation of the wavelength due to change in temperature. As the temperature changes, the index of refraction of the air also changes, which means that the wavelength will be different for each temperature.

The first approach is to design and optimize a system that works at $20C^0$, with very low performance. Using all the requirements (Tab. 1), a merit function is created to optimize this initial trial. As the first approach is done, it is time to create a merit function that optimizes all seven configurations. It is selected the range of temperature from $-40C^0$ up to $86C^0$ for inner elements and $-40C^0$ up to $300C^0$ for the dome. Since the first approach for the optical system was identified, it is necessary to optimize the optical design to accomplish the requirements of temperature from the main characteristics of the flight envelope. Table 2 shows the seven configurations used. The data for the semi-diameter were omitted to simplify the table.

Table 2 – Tested configurations

Type	Int1	Config 1	Config 2	Config 3	Config 4	Config 5	Config 6	Config 7
Temperature (^{0}C)	Outside Dome	20.0000	-40.0000	0.0000	50.0000	80.0000	120.0000	300.0000
Radius (mm)	Dome Front	75.0000	74.9577	74.9859	75.0212	75.0423	75.0705	75.1974
Thickness (mm)	Dome Front	3.4918	3.4898	3.4911	3.4928	3.4937	3.4951	3.5010
Wavelength (μm)	Outside Dome	3.8000	3.7997	3.7999	3.8001	3.8002	3.8003	3.8005
Wavelength (μm)	Outside Dome	5.0000	4.9997	4.9999	5.0001	5.0002	5.0003	5.0007
Temperature (^{0}C)	Inside Dome	20.0000	-40.0000	0.0000	26.3300	53.3300	60.0000	86.0000
Wavelength (μm)	Inside Dome	3.8000	3.7997	3.7999	3.8000	3.8001	3.8001	3.8002
Wavelength (μm)	Inside Dome	5.0000	4.9997	4.9999	5.0000	5.0001	5.0002	5.0002
Radius (mm)	Dome Rear	71.5084	71.4680	71.4949	71.5126	71.5308	71.5353	71.5527
Radius (mm)	1st Lens Front	113.2562	113.1542	113.2222	113.2669	113.3128	113.3241	113.3683
Radius (mm)	1st Lens Rear	125.6759	125.5628	125.6382	125.6878	125.7387	125.7513	125.8003
Radius (mm)	1st Mirror	-216.8746	-216.7965	-216.8486	-216.8828	-216.9180	-216.9267	-216.9605
Radius (mm)	2nd Mirror	-224.6631	-224.5822	-224.6362	-224.6717	-224.7081	-224.7170	-224.7521
Distance (mm)	Dome to 1st lens	18.9010	18.9119	18.9046	18.8999	18.8950	18.8938	18.8891
Thickness (mm)	1st lens	8.3601	8.3526	8.3576	8.3609	8.3643	8.3651	8.3684
Distance (mm)	1st lens to 1st mirror	59.0035	59.0091	59.0054	59.0029	59.0004	58.9998	58.9974
Distance (mm)	1st mirror to 2nd mirror	-61.0911	-61.0917	-61.0913	-61.0910	-61.0907	-61.0906	-61.0903
Distance (mm)	2nd mirror to window	30.0052	30.0052	30.0052	30.0052	30.0052	30.0052	30.0052

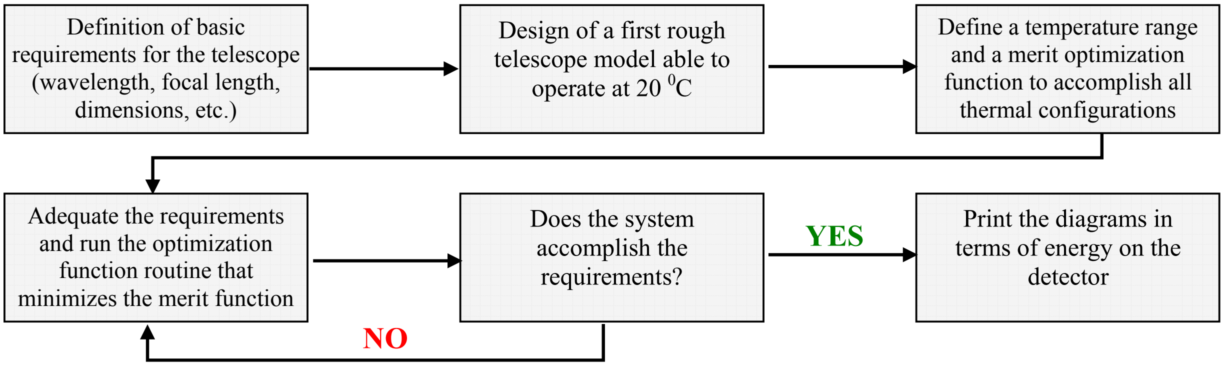


Figure 10 – Flow diagram for optimization

Figure 10 shows the flow diagram of the optimization process developed to design of the system. After the definition of requirements, a first optical approach was designed. Then, a thermal sheet configuration and a merit optimization function are defined and the optimization routine starts to run. After some interactions, the value of the merit function will stabilize because the system has found a minimum for its value. If the system is accomplishing the requirements, the system is frozen and the results are collected. If the system is not good enough, the requirements are relaxed and the routine runs again. If no system could be found, it is necessary to choose a new design, with new materials and shape for all elements, including thickness and radius of curvature.

Figures 11 to 13 illustrate a typical output from ZEMAX™. It is shown the optical system performance, in terms of its ability to focus the energy available at its entrance on the detector, excluding obscurations, under the parameters of configuration 1, 2 and 7. In Fig. 11 it is possible to observe the result for dome, lens and mirrors at 20^{0}C, condition used to first design the system. The performance achieved is very good in the center of the image, being a little degenerated on the edges, but with more than 90% of the energy available focused on the detector. For configuration 2, with the system at –40^{0}C, Fig. 12 exhibits a different tendency. In the center, the energy level is not so high, however, on the edges there is more energy available, but still accomplishing the requirements. For the last configuration, with dome at 300^{0}C and the rest of the system at 86^{0}C, Fig. 13 illustrate a strong degeneration in the center of the image, with a energy level lower than 74%. However, for this extreme condition, it might not be a threat, to the performance of the missile, such an energy level. If it is considered that the missile will not stay in this condition for longer that 2 or 3 seconds, it means that the target will not be lost. In addition, only in the center there is degradation. In the rest of the detector the energy focused on it is above 80% (the dark blue in Fig. 13 indicates levels lower than 74%, at the same time as the red color represents energy levels higher than 86%).

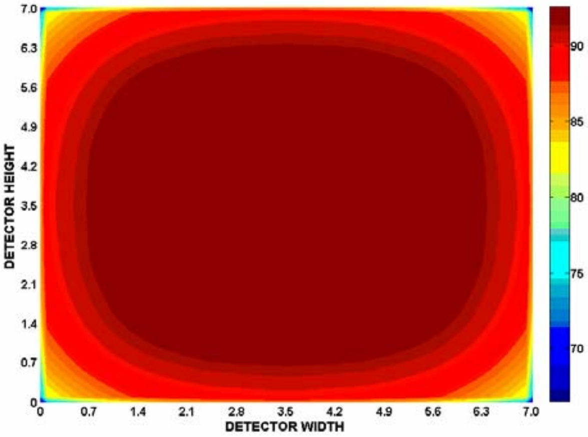


Figure 11: Configuration 1, system at 20^{0}C

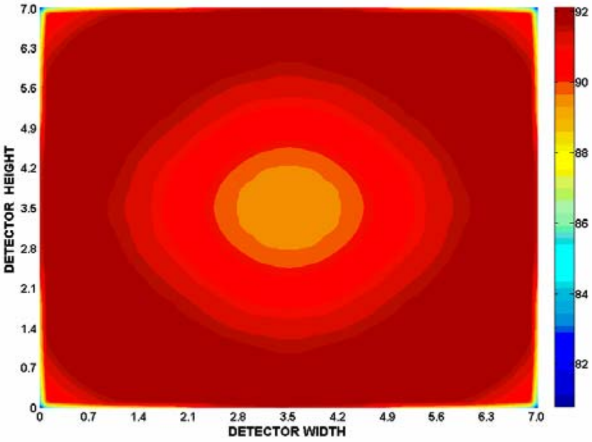


Figure 12: Configuration 2, system at -40^{0}C

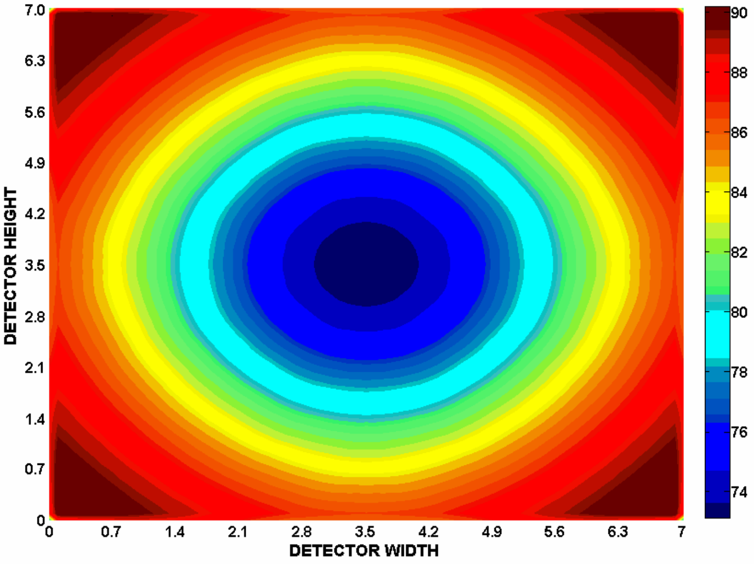


Figure 13: Configuration 7, system at 86^{0}C and dome at 300^{0}C

The results demonstrate that even under the most critical conditions of low or high temperatures, the optical system designed works in the specified range of temperature. As the requirements of temperature were achieved, it is important to check the other ones. The field of view and f-number were kept the same, since the variations in temperature do not change significantly their values. The image size and energy requirements were also accomplished, although in the last configuration the system could not achieve perfectly the requirement. Another important issue is the axial color distance, which will be important to quantify the amount of chromatic aberration. The value achieved was an axial distance of 7 μm, which accomplishes the requirement.

4. Conclusion

In this paper the effects of heating of the dome in a missile and its effects over the entire optical system have been considered. To calculate the heating on the dome and consequently the increase in optical system temperature, a formulation was developed to determine the flight profiles. Using the software Simulink® from Matlab®, the external and internal temperatures were calculated to achieve the temperature range to be employed in the optical simulation. Thus, an optical system was designed and optimized using the temperature range previously calculated. The requirements of energy focused on the detector, under different conditions of temperature have been accomplished, excluding the last configuration, which in the center is slightly below 75%.

It is important to have in mind that an analysis using finite elements on the missile front section structure and CFD techniques to analyze the flow field on the missile dome are essential to provide a solid foundation result for aero thermal model. Also, a tolerance analyze to the optical system is fundamental, due to precision assemble limits and lens quality. Since the distance between elements and even the curvature radii are essential parameters to the design, it is very important to know their manufacturing tolerances.

5. References

Allen, H.J., Eggers Jr, A.J., 1957, "A Study of the Motion and Aerodynamic Heating of Missile Entering the Earth's Atmosphere at High Supersonic Speed", NACA TN-4047.

Anderson, Jr, J.D., 1989, Hypersonic and High Temperature Gas Dynamic, McGraw Hill.

Sibulkin, M., 1952, "Heat Transfer Near the Forward Stagnation Point of a Body of Revolution", J. Aeronautical Science, Vol. 19, No. 8, pp. 570-571.

The MathWorks, Inc., 2002, Using Simulink (Version 5).

ZEMAX Development Corporation , 2007, (Version 01-2007)

Rainer B., Tobias I., Karl-Heinz M., Münzberg M., Werner Rode, 2007, "Long range thermal weapon sights for the German Future Infantryman program IdZ", Proceedings Vol. 6542 – Infrared Technology and Applications XXXIII, SPIE Defence & Security 2007.

6. Copyright Notice