

A Tutorial Of:

Hypersonic Flight Effects on Optical Sensors

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Background:

In recent years hypersonic vehicles have received a lot of attention from the media. NASA and various military contractors are spending a lot of time and money investigating the potential for hypersonic flight. Applications include Space Shuttles, high speed aircraft and guided missiles. In order for these vehicles to study their environment, precisely target and track objects, and control their flight path a variety of sensors are used. Some of these sensors operate in the optical domain (many in IR). Therefore, the harsh environmental conditions brought upon by hypersonic flight must be well understood and accounted for. These conditions include turbulence, thermal effects, air compression, aerodynamic flow and shock waves. If not adequately accounted for these conditions will cause optical aberrations, defocus, secondary radiation and boresight error.

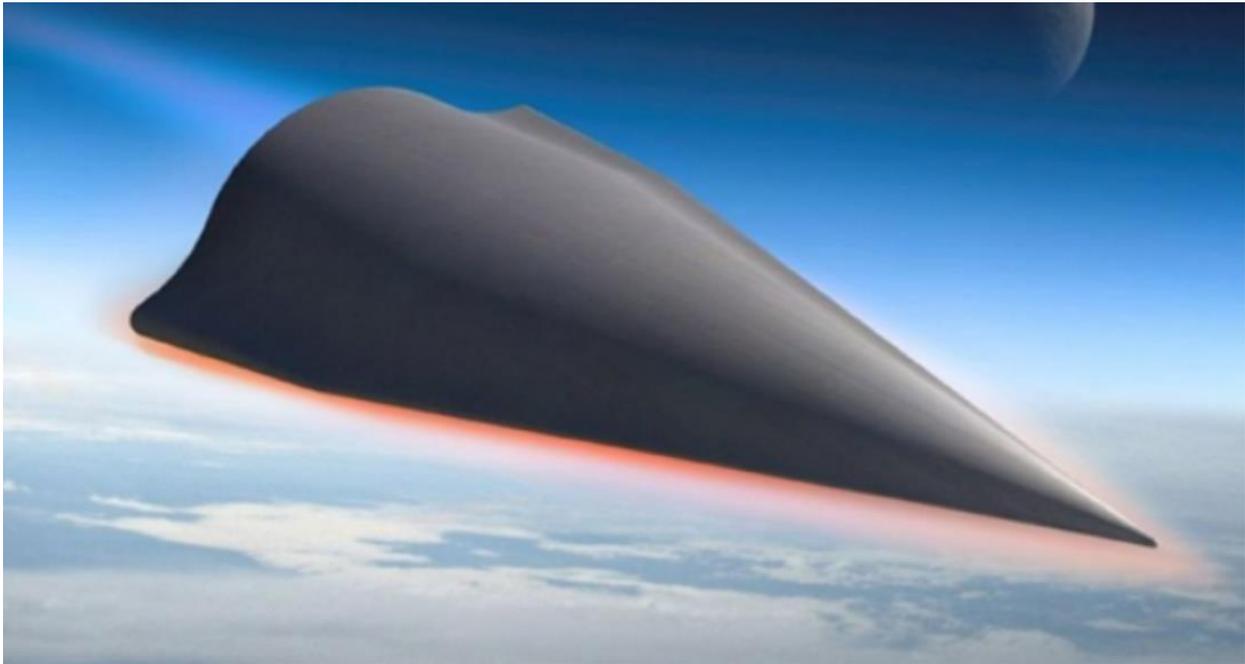


Figure 1: An artist's rendition of a hypersonic vehicle

Basics of Hypersonic Flight:

Hypersonic flight produces an extreme, highly complicated, hard to predict environment requiring a multidisciplinary team of fluid dynamics, heat transfer, optics and material science experts. Optical sensors are generally mounted in one of two ways; on the nose of the vehicle (blunt body) or in the side of the vehicle. Depending on the vehicles structure and speed various shock waves will be produced. These shock waves can interact with one another. When this happens expansion and shear waves are produced. A thin boundary layer also surrounds a vehicle in hypersonic flight. An example of all of these phenomena can be seen in Figure 2 below. The boundary layer, shock, expansion and shear waves all produce variations in the pressure, temperature and density of the air around the vehicle. These variations cause a change of index of the air which will impact the optical systems.

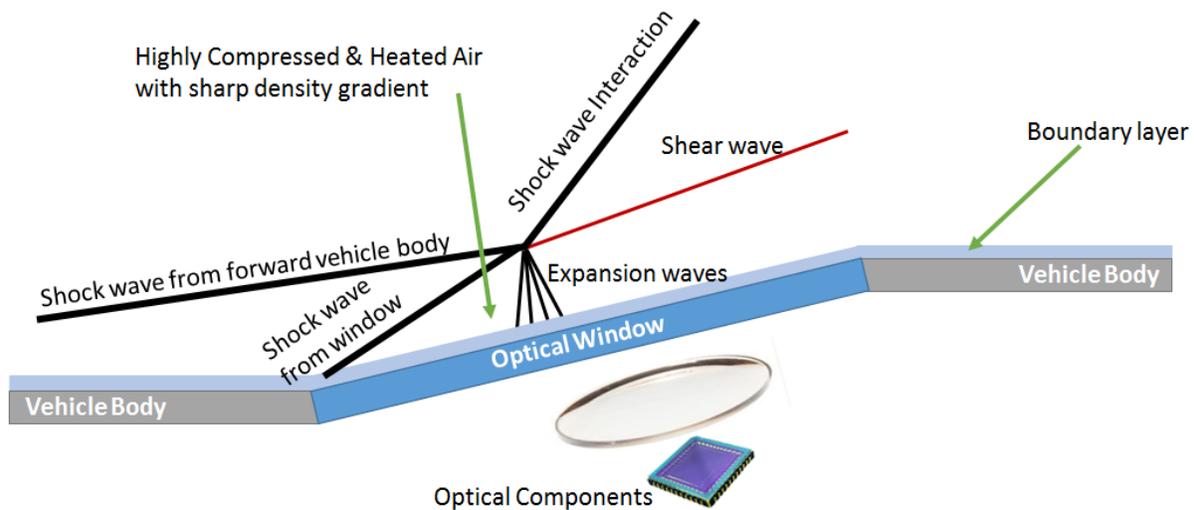


Figure 2: Phenomena surrounding a vehicle in hypersonic flight

Shock Waves:

Shock waves are discontinuities in the supersonic flow of the air. They cause abrupt changes in the density and temperature of the air. These density regions have a different index than the unperturbed air, therefore, they act like lenses.

The impact of the density of the air's density on the optical index is given by the Gladstone-Dale relationship:

$$n-1 = \beta\rho$$

Where β is a wavelength dependent constant ($\sim 2.2 \times 10^{-4} \text{ m}^3/\text{kg}$) and ρ is the mass density of the air. This mass density is a function of the speed and shape of the vehicle. In general, it can be calculated by:

$$\frac{\rho}{P_{\infty}} = \frac{6(M\sin\theta)^2}{(M\sin\theta)^2 + 5}$$

Where ρ is the density behind the shock, P_{∞} is the free-stream (unperturbed) density, θ is the shock angle and M is the Mach number. So as the speed of hypersonic vehicles get faster the optical effect of the shockwaves becomes greater. An example of these shock waves can be seen in Figure 3 below.

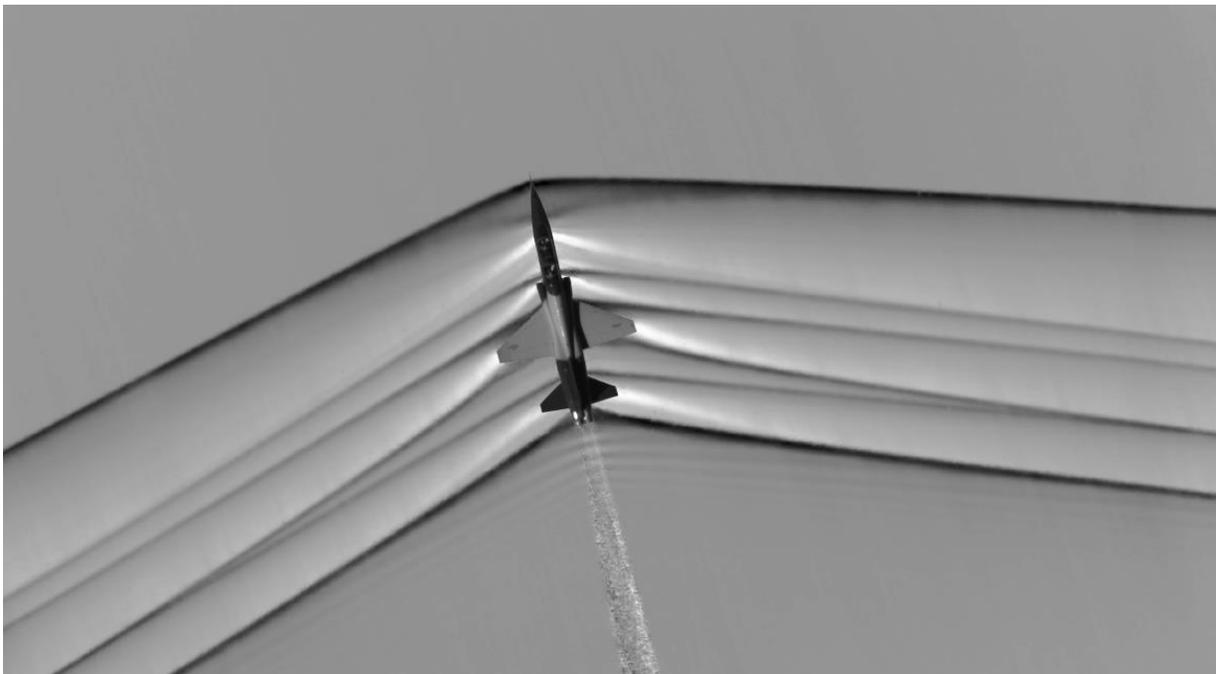


Figure 3: Shock waves imaged around a high speed plane

Expansion Waves:

Expansion waves are caused by the interaction of multiple shock waves as well as convex corners on the vehicle's body (Figure 4a). Similar to shock waves, expansion waves cause changes in the supersonic flow, but, unlike shock waves, these discontinuities occur gradually (Figure 4b). Therefore, they act like gradient index lenses. The density, pressure and temperature ratios decrease through the expansion waves while the Mach number increases.

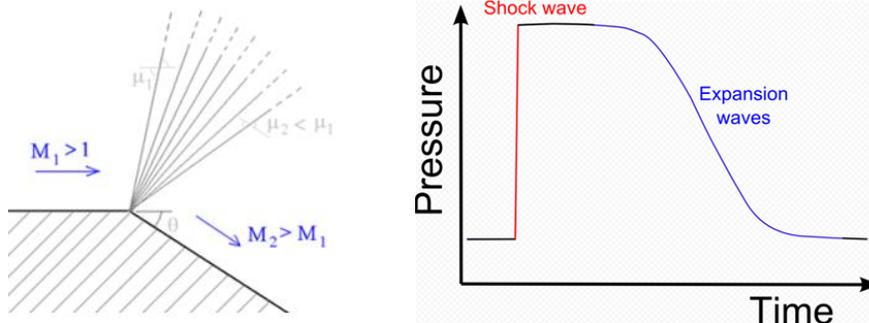


Figure 4a (left): Expansion wave caused by a convex corner

Figure 4b (right): Shock and expansion waves as a function of time

Boundary and Shear Layers:

The shock and expansion waves are separated from the hypersonic vehicle by a small boundary layer (Figure 6). Unlike shock and expansion waves the boundary layer properties are determined by the air viscosity, vehicle thermal conductivity and mass diffusion effect. The flow behavior of boundary can be described using the boundary layer flow equations. Generally, when using these equations, one assumes that the pressure across the boundary layer is constant. The density profile over a flat plate in a Mach 5 environment can be seen in Figure 7 (JHU APL experiment). As mentioned, the thermal conductivity of the vehicle plays a role in the boundary layer. Figure 7 shows two cases, one with a perfectly conductive material, and one with a perfectly non-conductive material.

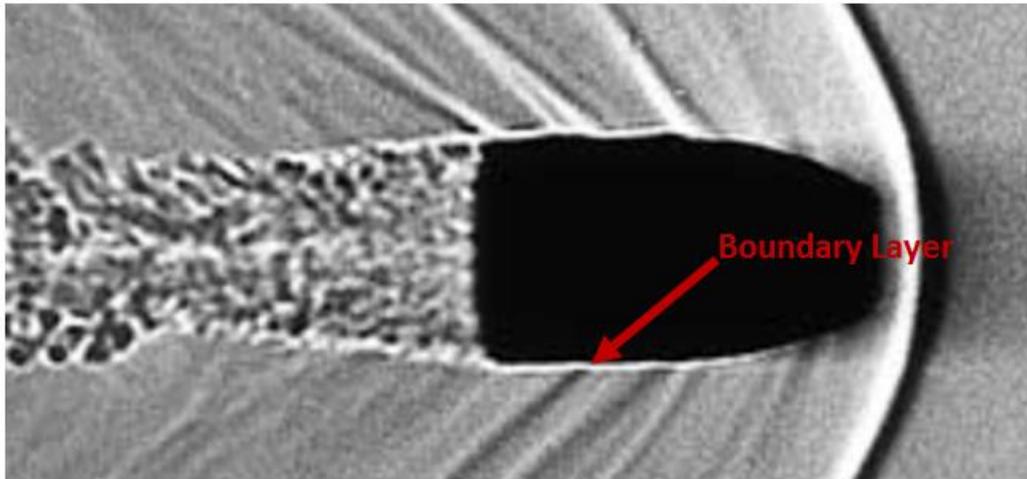


Figure 6: A clearly visible boundary layer around a traveling bullet.

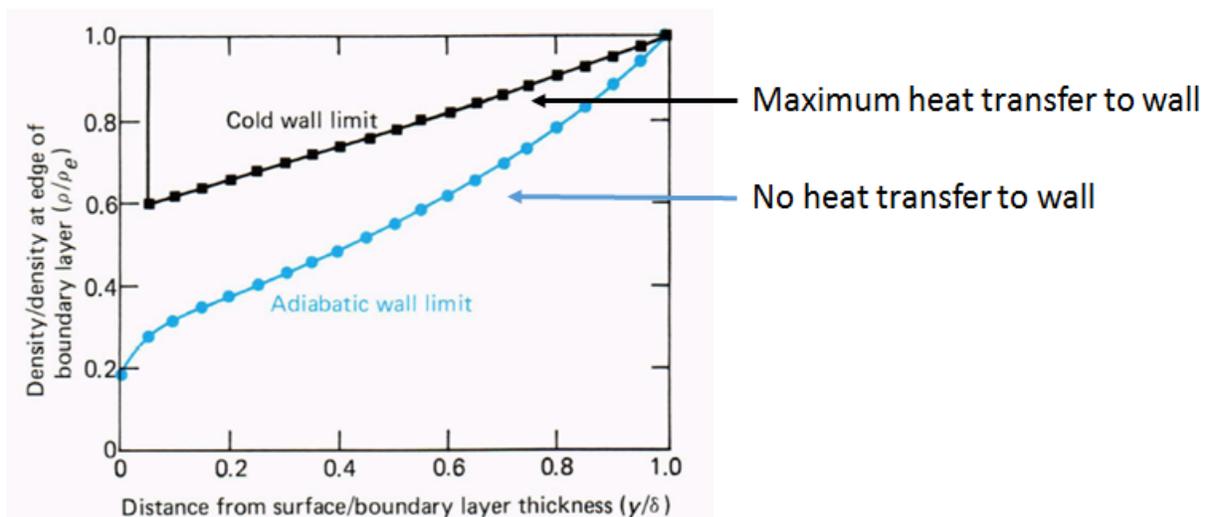


Figure 7: Density profile over a flat plate in a Mach 5 environment. (JHU APL experiment)

Shear layers are caused by the density and velocity differences produced when two shock waves interact with one another. Shear layers are also characterized by boundary layer theory using the same equations. The difference lies in the boundary conditions and shear layer mixing model. The density of the shear layer depends on the density and velocity of the flow of the two interacting shock waves.

Blunt Bodies:

Optical windows are often placed directly on the nose of a vehicle. This is referred to as a blunt body and is done so that a target can be tracked up until collision. In hypersonic flight a shock wave will be produced directly in front of the vehicle. This shock wave is slightly detached from the vehicle by a distance referred to as the standoff distance (Figure 8). This standoff distance can be calculated by:

$$d_o = 0.143R * e^{3.24/M_\infty^2}$$

Where d_o is the standoff distance and R is the nose radius.

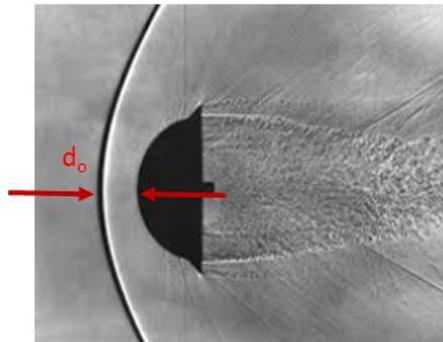


Figure 8: Standoff distance observed around a blunt body

The air behind this shock is extremely hot and has a density that is difficult to model. This is because it consists of both subsonic and supersonic regions as shown in Figure 9. A complete flow field and shock-structure greatly depends on the body geometry and flight speed.

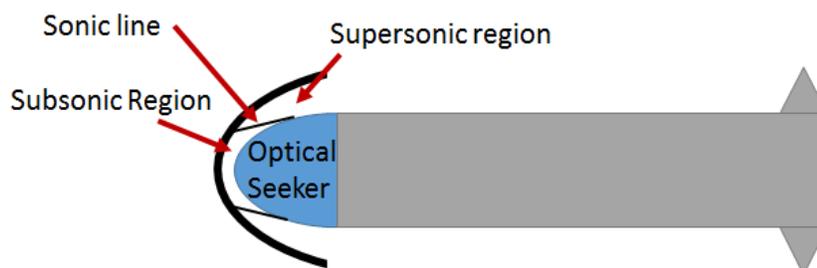


Figure 9: A very common example of a optical blunt body subject to hypersonic flight conditions. Both subsonic and supersonic regions exist in front of the sensor

Temperature Effects:

The air behind a shock wave is very hot and varies with respect to the vehicle speed. The temperature can be modeled as:

$$T/T_{\infty} = (7M_{\infty}^2 - 1)(M_{\infty}^2 + 5) / 36M_{\infty}^2$$

Where T is the air temperature behind a shock wave, T_{∞} is the unperturbed air temperature and M_{∞} is the Mach number. Although the thickness of this high temperature air is small the spectral radiance is generally much higher than normal scene background. At certain wavelengths the carbon dioxide and water in the air cause very high levels of IR radiation. This can be seen in Figure 10 below. Also, the high temperature causes the optical windows to radiate. Depending on the material used, this radiation can be higher than the background and the air behind the shock. The added radiation do to the high temperature environment greatly increases the noise present in the optical system.

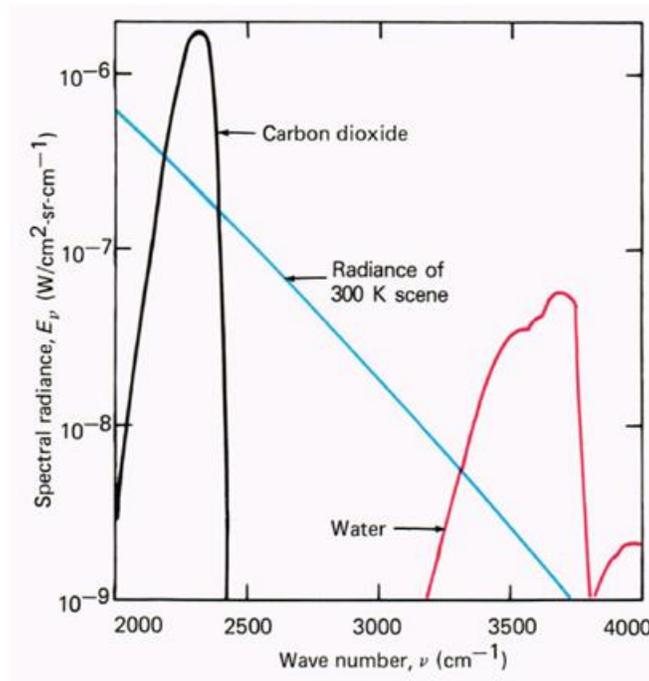


Figure 10: Radiance of gases due to a 7.1cm diameter hemispherical optical dome traveling at Mach 6.

Impacts on Optical Performance:

Temperature, boundary layers, shock and expansion waves all produce effects that impact the performance of an optical system. Changes in air density cause index variations which result in a loss of resolution, focus and boresight error. Temperature increases also result in a change of index of the air and optical window as well as secondary radiation. John Hopkins Applied Physics Lab has done many studies to determine the effects of these optical variations.

Studies involving highly conductive and non-conductive blunt body optical domes (7.1diameter hemisphere) at Mach 6 have shown index variation ranging up to 0.002. Although this is small, a larger diameter dome would cause a greater change in index. This can be seen in Figure 11.

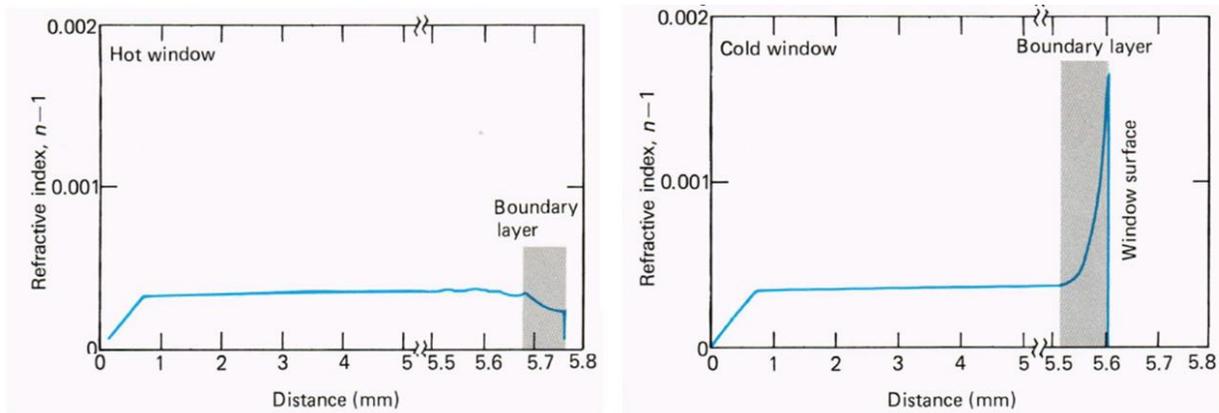


Figure 11: APL study on air’s index variation due to a 7.1cm diameter dome traveling at Mach 6.

Another study was performed to see the RMS spot size variation due only to air density changes (Figure 12). Multiple tests were done at varying speeds, altitudes and window mounting techniques.

Case	Mach Speed	Altitude (km)	Window Attachment
1	4.0	0.3	Free Expansion
2	5.0	15.2	Free Expansion
3	6.5	30.5	Free Expansion
4	5.0	15.2	Rigid
5	5.0	15.2	Titanium Ring

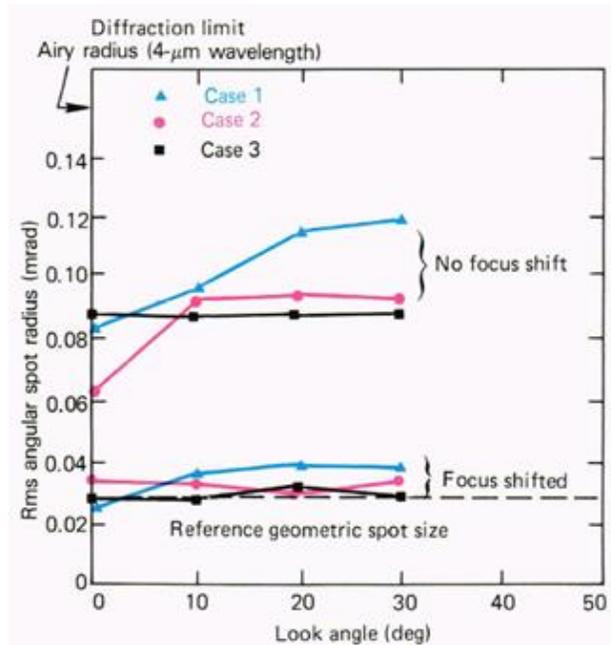


Figure 12: APL study on RMS spot size due to air density variations

As expected, the variation is real but low. The bigger concern is related to the temperature variation due to the shock. APL performed a second study to illustrate the impact of dome heating after 15s of hypersonic flight. Results are shown in Figure 13.

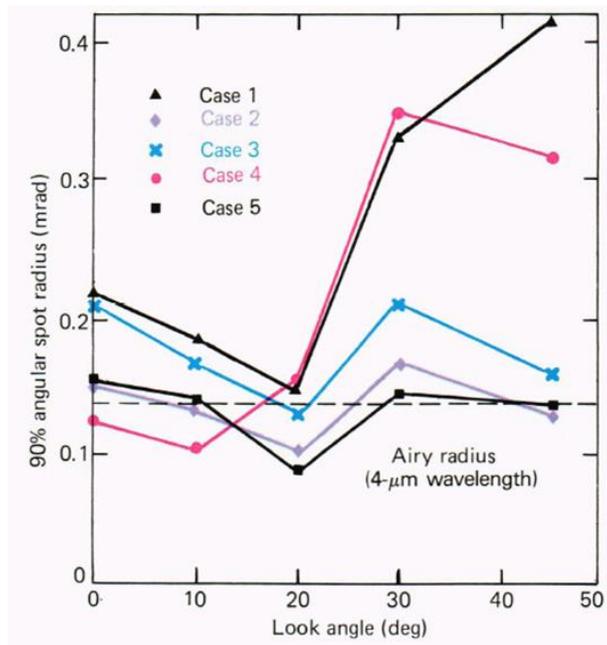


Figure 13: APL study on RMS spot size due to temperature variation

This time, the increase in spot size is much greater than the diffraction limit. The larger the aperture the larger the effect.

The density and temperature variation also effect the index of the glass and air (dn/dT). APL performed a study to see how this impacts the boresight error of the imaging system. Up to a 2mrad error was measured (shown in Figure 14).

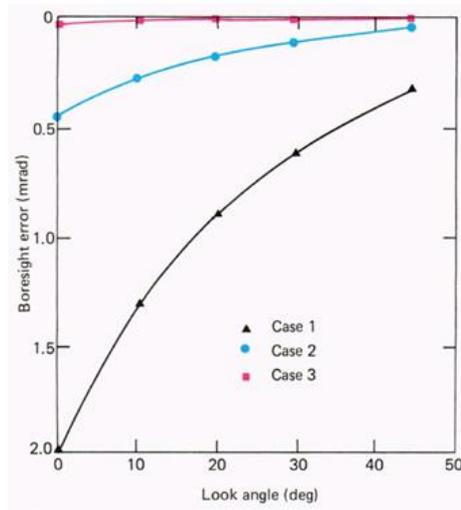


Figure 14: APL study on boresight error effect of a sidemounted optical sensor.

Lastly, APL performed a study on the wavefront error of a hemispherical window with a 45deg look angle. The window was exposed to 15s of Mach4, 30m altitude flight conditions. Optical path differences across the pupil in quarter wavelengths at $4\mu\text{m}$ are shown in Figure 15,

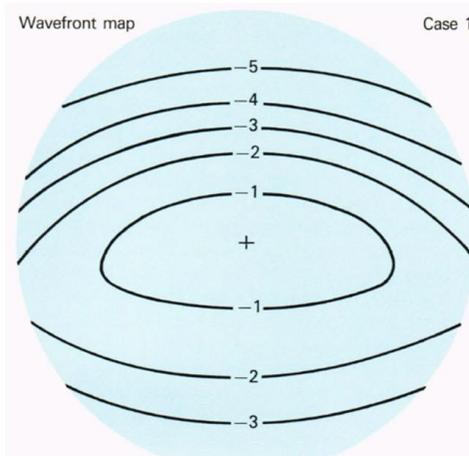


Figure 15: APL study on wavefront error of a hemispherical window

Conclusion:

In conclusion, hypersonic vehicles are subject to an extreme environmental conditions that can significantly degrade the performance of onboard optical sensors. In particular, a loss of focus, resolution and boresight error will occur. This tutorial was intended to give the reader a rough idea of the environmental conditions and their effect on the optical system. Sources are provided which will allow the reader to further investigate hypersonic flight effects. If research is performed in this area a team of fluid dynamics, heat transfer, optics and material science experts should be consulted.

Sources:

- http://www.jhuapl.edu/techdigest/views/pdfs/V08_N4_1987/V8_N4_1987_Tropf.pdf
- https://en.wikipedia.org/wiki/Oblique_shock
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- https://en.wikipedia.org/wiki/Prandtl%E2%80%93Meyer_expansion_fan