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HAOT: A Python package for hypersonic aero-optics analysis

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Software

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Summary

Hypersonic flows present a unique challenges due to the complex interplay of fluid dynamics, chemical reactions, and optical phenomena. As a signal from a Light Detection and Ranging (LiDAR) travels through a hypersonic flow field, the beam would be affected by the flow, this can lead to errors on targeting and detection measurements.

`HAOT` is a Hypersonic Aerodynamics Optics Tools Python package developed to calculate different aerodynamic properties in a hypersonic medium. Its source code is available on GitHub, the documentation is available on Read the Docs and an example on the usage of the package is given on the GitHub repo under the example folder.

Statement of Need

Many techniques used to calculate optical properties are scattered across various papers, but there is no centralized repository containing all these calculations. Furthermore, some of these calculations require spectroscopy constants, which are often unclear or inconsistently presented in the literature. This package includes a constants module that provides and documents numerous spectroscopy constants for diatomic molecules.

This package has been used by (Liza et al., 2023). In this work he used results from Computational Fluid Dynamics (CFD) to calculate index optic properties of interest.

Algorithms

The `HAOT` package, contains five modules:

```
- Aerodynamics
- Optics
- Quantum Mechanics
- Constants
- Conversions
```

Each module can be imported independently. The documentation explains he functions in each module as well as their usage. Docstrings were used, so the function prototypes and usage are also available in an interactive Python session. Results from these algorithms were compared with literature and a unit test was developed and it is located under test.

This section provide some of the capabilities of the packages but not all of them. For instance the package can calculate some compressible flow properties such as isentropic, normal shock, and oblique shock relations. Please refer to the documentation to see the complete list of available functions.

Results

Equation 1 was introduced by (Smith & Weintraub, n.d.), and it provides approximation and approximation for the index of refraction as a function of atmospheric altitude.

$$n(h) \approx 1 + \frac{K_1}{T(h)} \left(p(h) + K_2 \frac{e(h)}{T(h)} \right) \tag{1}$$

Where: K_1 and K_2 are constants, T is the temperature as a function of altitude, p is pressure as a function of altitude, and $e(h)$ is the partial pressure of water vapor.

Results for equation 1 are provided in the figure 1. This approximation is a useful way of seen the region in which the index of refraction will have a higher impact in a seeker's performance. As expected the critical region is between $20[km]$ to $30[km]$ above sea level, which is a region where seeker's performance is very important.

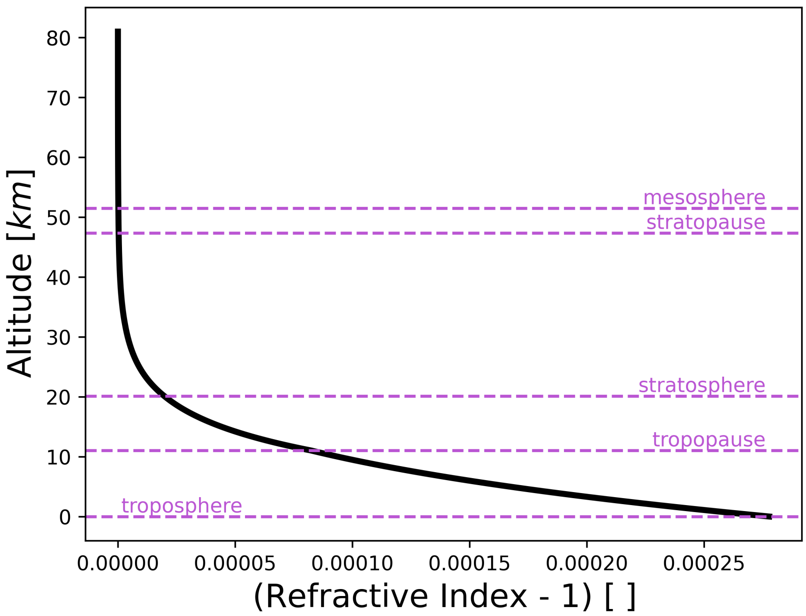

Figure 1: Atmospheric index of refraction for dry air.

The Gladstone-Dale constant is an important constant used to calculate the index of refraction (equation 2). For a dilute gas, the index of refraction can be approximated as:

$$n - 1 = \sum_{s=1}^{N} K_s \rho_s \tag{2}$$

Where: n is the index of refraction, K_s is the species Gladstone-Dale constants, and ρ_s is the species density.

Figure 2 shows the Gladstone-Dale constants for a five-species gas. The species density was calculated using Computational Fluid Dynamics (CFD) tool, SU2 (W. T. Maier et al., 2021), (W. Maier et al., 2023). These densities where then loaded into the HAOT tool calculate figure 2.

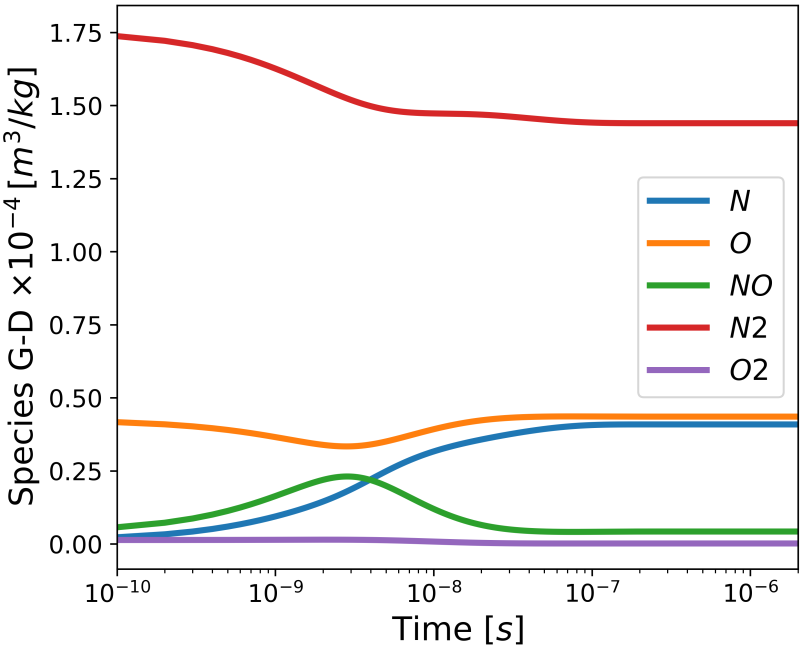

Figure 2: Species Gladstone-Dale constants for a five-species gas.

Another way of calculating the index of refraction is using the Polarizability, equation 3.

$$n - 1 = \frac{1}{2\epsilon_0} \sum_{s=1} \alpha_s N_s \tag{3}$$

Where: ϵ_0 is the dielectric constant in vacuum, α_s is the species polarizability constants, and N_s is the partial species mass fraction.

Figure 3 uses the extrapolation (equation 4) developed by (Kerl et al., 1992), based on (Hohm & Kerl, 1986) work.

$$\alpha(\omega, T) = \frac{\alpha(0,0)}{1 - \left(\frac{\omega}{\omega_0}\right)^2} \left(1 + bT + cT^2\right) \tag{4}$$

Where: α is the polarizability as a function of laser's frequency ω, and temperature T. b and c are extrapolation constants, all these constants are implemented in the `HAOT` package; and ω_0 is the oscillation's frequency of the diatomic molecule.

Figure 3 shows the change of polarizability as a function of temperature.

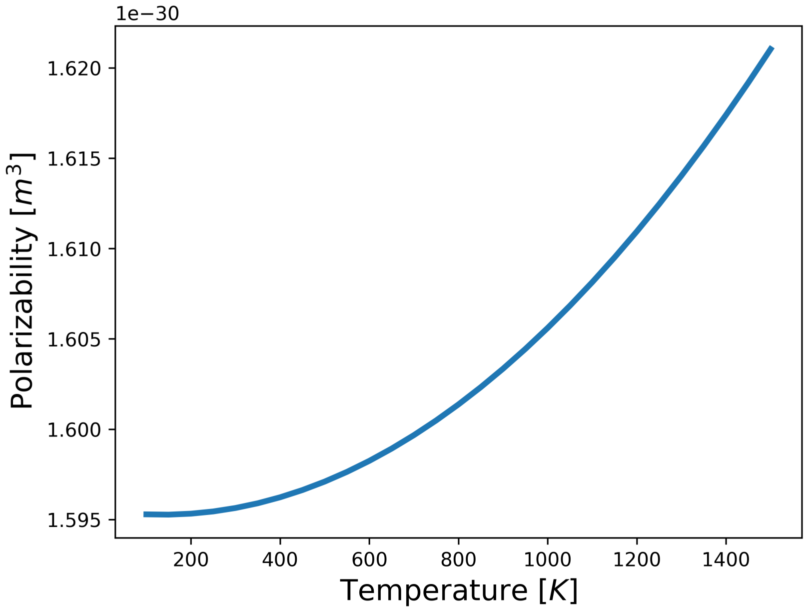

Figure 3: Polarizability of $O2$ using Kerl's method for a laser of $633[nm]$.

Results up to here show some of the capabilities of the aerodynamics and optics module. Figure 4 shows the results of the Boltzmann Distribution for $N2$, some aero-optics calculations (Buldakov et al., 2000), (Tropina et al., 2018) required a Boltzmann Distribution to calculate the polarizability and index of refraction for diatomic molecules.

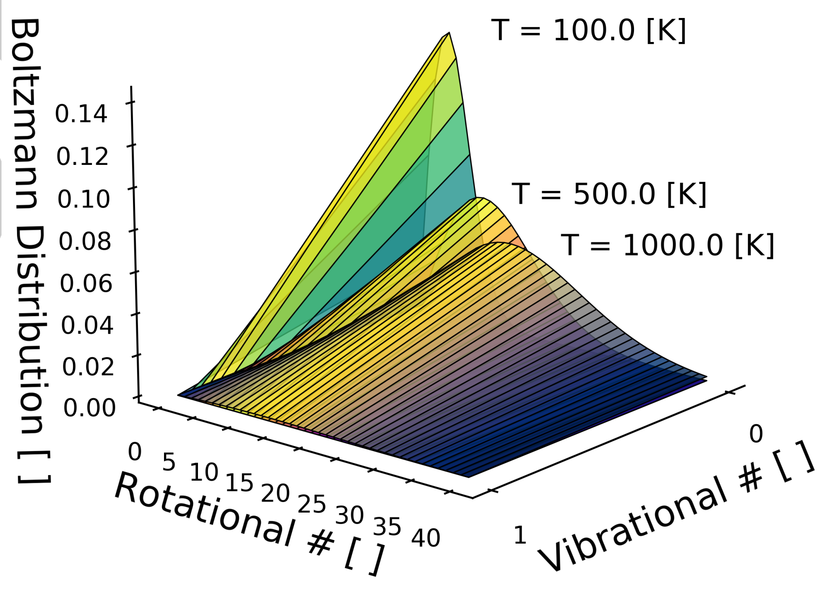

Figure 4: Boltzmann Distribution for $N2$.

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