HAOT: A Python package for hypersonic aero-optics analysis

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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

The equation below was introduced by (Smith & Weintraub, n.d.), and it is crude approximation for the change in the index of refraction as a function of altitude.

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

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 this equation are provided in the figure below. As expected the index of refraction and the atmospheric density have a close relationship.
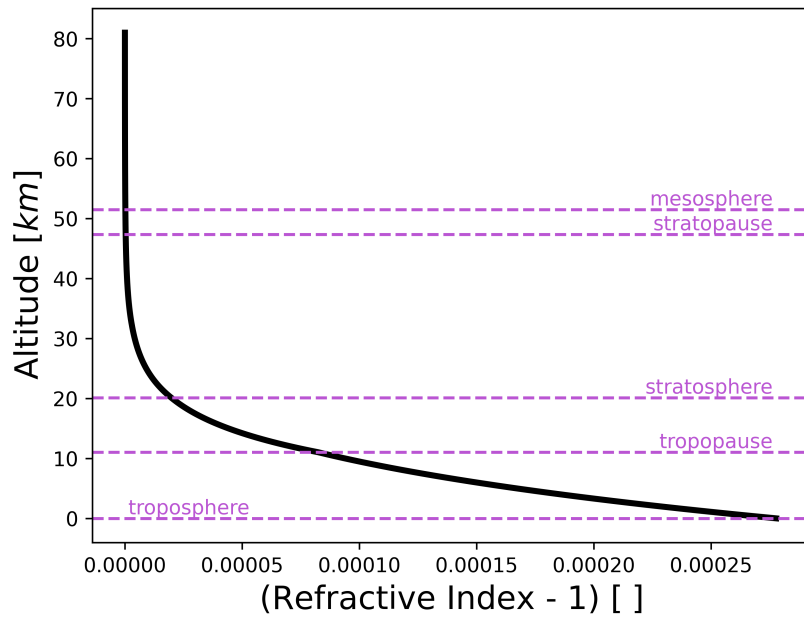

Figure 1: Atmospheric index of refraction for dry air.

The Gladstone–Dale constant is an important constant used to calculate the index of refraction, for a dilute gas, the index of refraction can be approximated as:

$$n - 1 = \frac{1}{2\epsilon_0}\sum_{i=1}^{N}\alpha_i N_i$$

Where: n is the index of refraction, ϵ_0 is the dielectric constant in vacuum, α_i is the species polarizability, and N_i is the species partial fraction.

Figure 2 Results for this equation are provided in the figure below. This particular results required the use of a Computational Fluid Dynamics (CFD) tool, SU2 (W. T. Maier et al., 2021), (W. Maier et al., 2023), to calculate the fluid properties used by the HAOT tool.
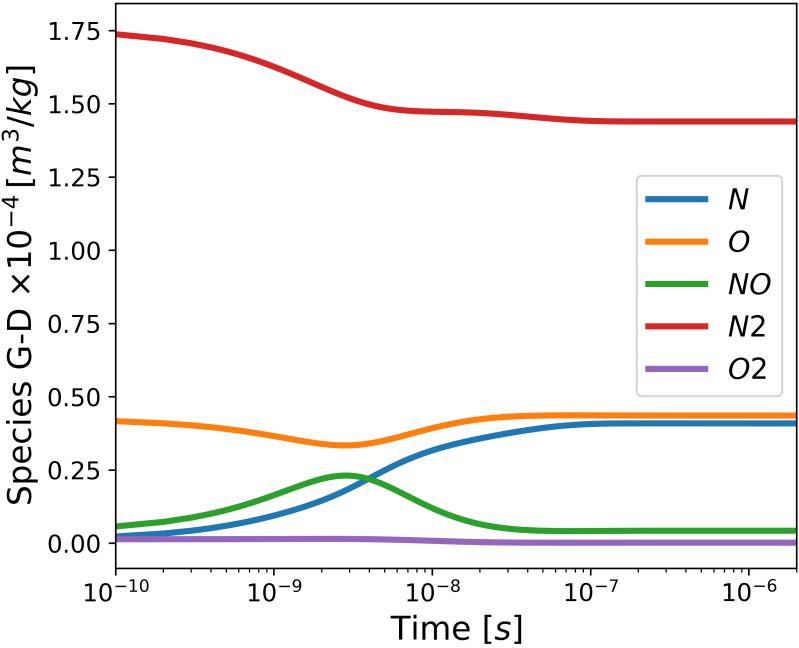
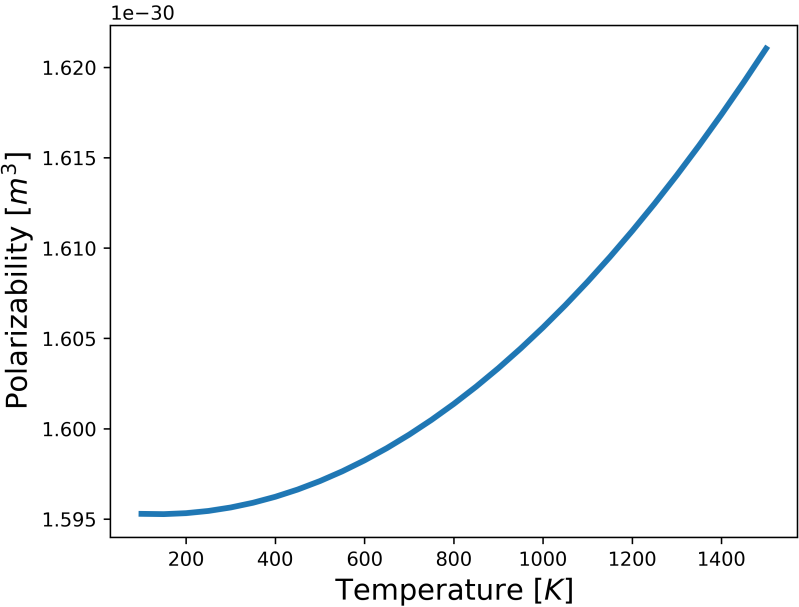**Figure 2:** Species Gladstone-Dale constants for a five-species gas.

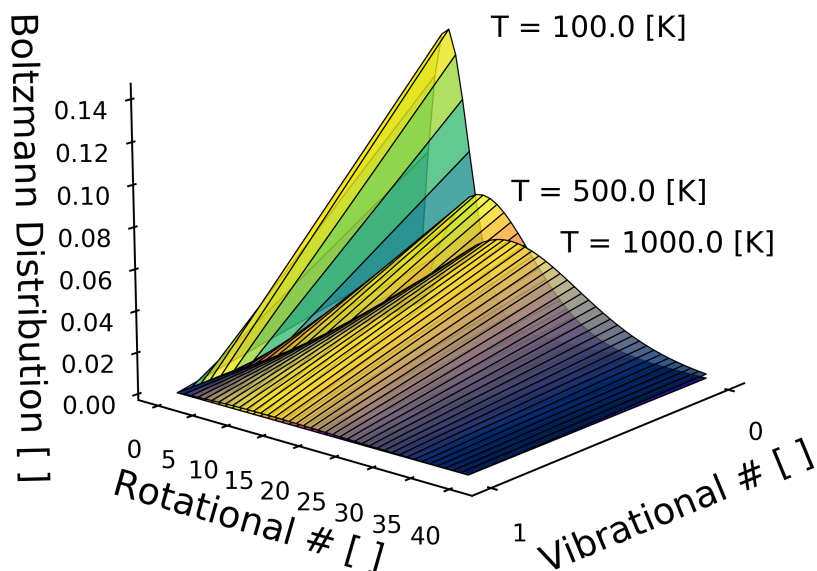**Figure 3:** Polarizability of $O2$ using Kerl's method [@Kerl1992].

Figure 4: Boltzmann Distribution for $N2$.

Acknowledgements

References

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Maier, W. T., Needels, J. T., Garbacz, C., Morgado, F., Alonso, J. J., & Fossati, M. (2021). SU2-NEMO: An open-source framework for high-mach nonequilibrium multi-species flows. *Aerospace*, *8*, 193. https://doi.org/10.3390/aerospace8070193

Maier, W., Needels, J. T., Alonso, J. J., Morgado, F., Garbacz, C., Fossati, M., Tumuklu, O., & Hanquist, K. M. (2023). Development of physical and numerical nonequilibrium modeling capabilities within the SU2-NEMO code. *AIAA AVIATION 2023 Forum*. https://doi.org/10.2514/6.2023-3488

Smith, E., & Weintraub, S. (n.d.). https://doi.org/10.1109/JRPROC.1953.274297