

# HAOT: A Python package for hypersonic aero-optics analysis

Martin E. Liza <sup>1</sup>

<sup>1</sup> The University of Arizona

DOI: [10.xxxxxx/draft](https://doi.org/10.xxxxxx/draft)

## Software

- [Review](#)
- [Repository](#)
- [Archive](#)

Editor: [Open Journals](#)

## Reviewers:

- [@openjournals](#)

Submitted: 01 January 1970

Published: unpublished

## License

Authors of papers retain copyright and release the work under a Creative Commons Attribution 4.0 International License ([CC BY 4.0](#)).

## 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 the index of refraction of 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.

## Algorithms

The HAOT package, contains five modules:

- Aerodynamics
- Optics
- Quantum Mechanics
- Constants
- Conversions

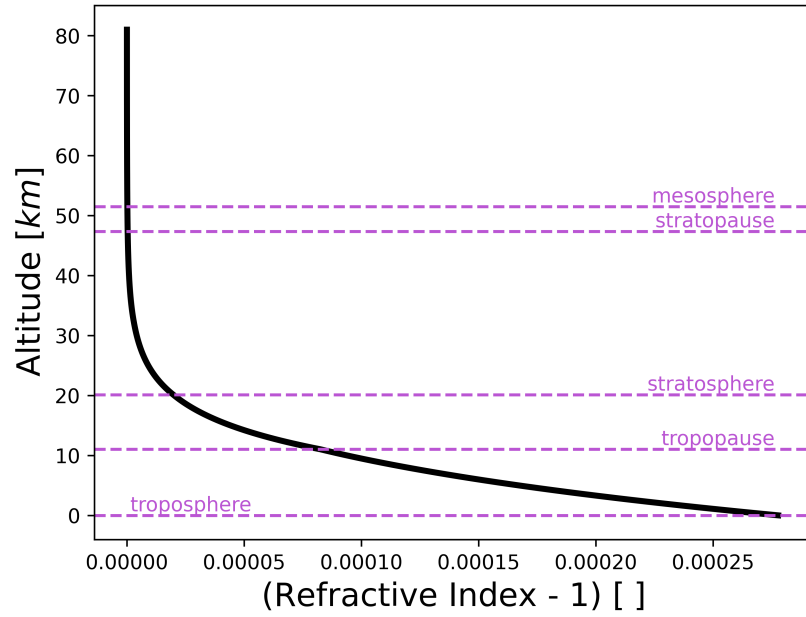
Each module can be imported independently. The [documentation](#) explains he functions in each module as well as their usage. Docstrings were used, so the function prototypes and usage are also available in an interactive Python session.

The equation below was introduced by ([Smith & Weintraub, n.d.](#)), and it is a good 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.

34 Results for this equation are provided in the figure below.



**Figure 1:** Atmospheric index of refraction for dry air.

35 The equation below shows the formula used to calculate the dilute index of refraction.

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

36 Where:  $\rho_s$  is the species density,  $\rho$  is the flow's density, and  $K_s$  is the species' Gladstone-Dale  
37 constant.

38 Results for this equation are provided in the figure below. This particular results required the  
39 use of a Computational Fluid Dynamics (CFD) tool, SU2 (W. T. Maier et al., 2021), (W.  
40 Maier et al., 2023), to calculate the fluid properties used by the HAOT tool.

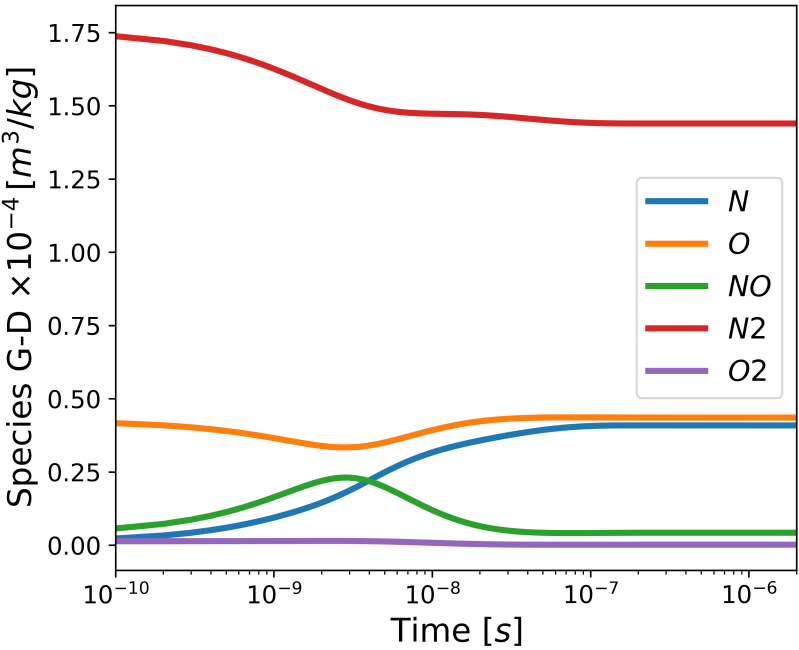


Figure 2: Species Gladstone-Dale constants for a five-species gas.

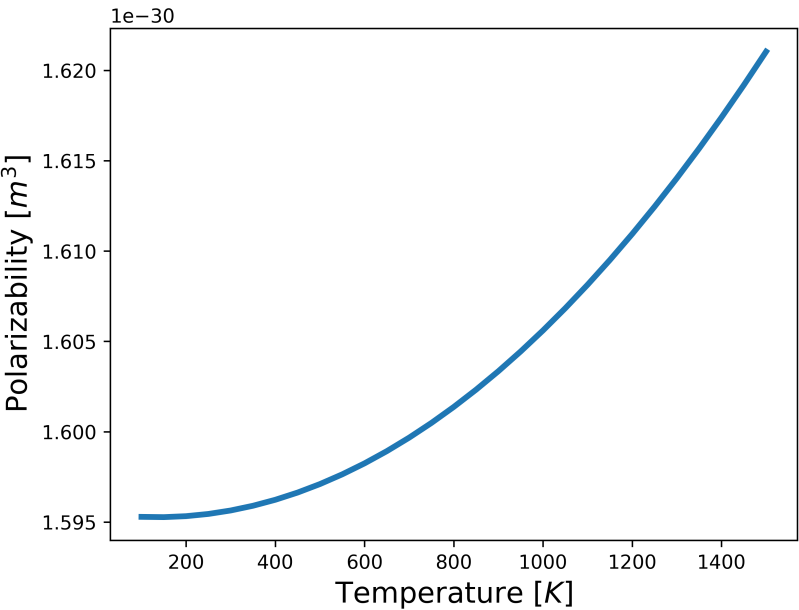


Figure 3: Polarizability of O2 using Kerl's method [Kerl1991].

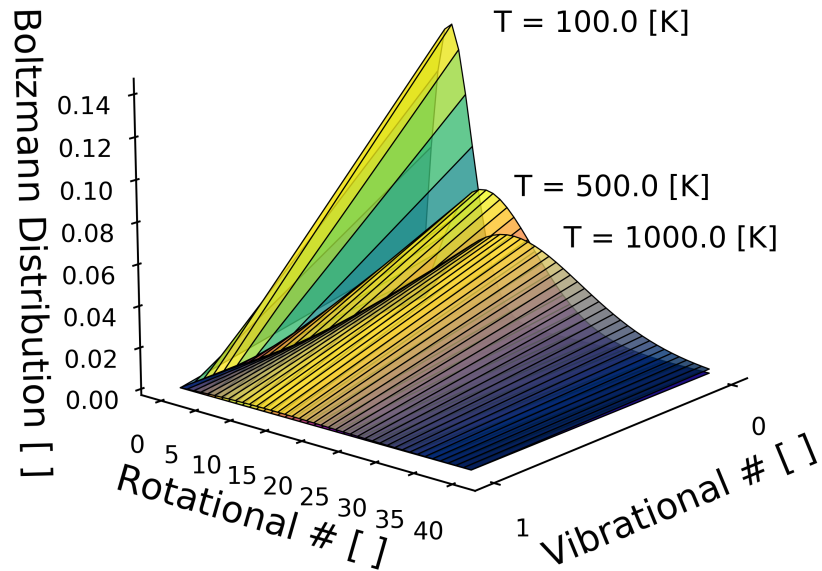


Figure 4: Boltzmann Distribution for  $N_2$ .

A more extensive work showing the results of this package was done by (Liza et al., 2023)

## Acknowledgements

The author gratefully thank Kyle Hanquist, who supported with the tool verification.

## References

- Liza, M., Tumuklu, O., & Hanquist, K. M. (2023, June). Nonequilibrium effects on aero-optics in hypersonic flows. *AIAA AVIATION 2023 Forum*. <https://doi.org/10.2514/6.2023-3736>
- 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>