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Katsu: A Python package for Mueller and Stokes simulation and polarimetry

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Summary

High-performance simulation of physical optics phenomena is instrumental in accurately designing and understanding optical systems. The propagation of light can be described in multiple regimes. The geometrical regime treats light as a ray, enabling the expeditious optimization of optical surfaces. Pythonic examples in open source include `ray-optics` (Hayford, 2025) and `batoid` (Myers, 2025). The physical regime treats light as a wave, enabling a precise understanding of the field distribution as light propagates through a given system. Many Python-based packages exist for wave optics propagation, including `POPPY` (Perrin et al., 2016), `HCIPy` (Por et al., 2018), `prysm` (Dube, 2019; Dube et al., 2022), and ∂Lux (Desdoigts et al., 2022). However, all of the aforementioned packages treat light as a scalar field, and are unable to simulate the propagation of the vector nature of light. This property, called *polarization*, is critical for various instruments that interact with the vector nature of light.

To describe the propagation of light's polarization state, we can use Mueller calculus. This approach represents optical systems as a 4×4 *Mueller matrix* $\mathbf{M}$ that operates on a *Stokes vector* $\mathbf{s}$, which represents the polarization of light, as shown in the equation,

$$\mathbf{s}' = \mathbf{M}\mathbf{s}.$$

The Stokes vector contains the parameters used to describe the polarization of light,

$$\mathbf{s} = [s_0, s_1, s_2, s_3],$$

where s_0 represents the unpolarized intensity, s_1 describes the degree of polarization oriented along $0^\circ/90^\circ$, s_2 describes the degree of polarization oriented along $\pm 45^\circ$, and s_3 describes the degree of circular polarization. The Stokes parameters are equivalently represented with the letter notation,

$$\mathbf{s} = [I, Q, U, V].$$

Mueller calculus is particularly powerful because it is capable of describing light that is partially polarized, and the Stokes parameters are quantities that can be easily measured in the laboratory.

Katsu is an open-source Python package to address the need for polarimetric characterization of astronomical systems for the next generation of astronomical telescopes. It contains simple routines for the simulation of Mueller matrices and Stokes vectors to model how polarization is transformed by optical systems. This ability is not unique to Katsu. Another package capable of simple Mueller calculus is Pypolar (Prahl, 2023), which also contains excellent visualization tools as well as support for ellipsometric data reduction. However, one area where Katsu is distinct from other packages capable of Mueller calculus simulation is its emphasis on broadcasted matrix calculations. All Mueller matrices available in `katsu.mueller` take a shape keyword that appends an arbitrary number of axes to the front of the initialized array, with the final two axes containing the Mueller matrix. This functionality is critical for accelerated computing on spatial data, which enables the direct measurement of polarization aberrations in the lab (Ashcraft, Douglas, et al., 2024). Katsu also features a `polarimetry` module containing the data reduction routines for single-rotating retarder (SRR) Stokes polarimeters and dual-rotating retarder (DRR) Mueller polarimeters. In the pursuit of open-source instrumentation in the laboratory, Katsu supports an interface to the Newport Agilis series rotation mounts in the `motion` module to assist with performing polarimetry with rotating retarders.

To interpret the measurements made in the lab, Katsu features the polar decomposition of Mueller matrices published by Lu and Chipman (Lu & Chipman, 1996). This decomposes a Mueller matrix $\mathbf{M}$ into its constituent depolarizer $\mathbf{M}_\Delta$, diattenuator $\mathbf{M}_\mathbf{D}$, and retarder $\mathbf{M}_\mathbf{R}$, as shown in the following equation,

$$\mathbf{M} = \mathbf{M}_\Delta \mathbf{M}_\mathbf{R} \mathbf{M}_\mathbf{D}.$$

This function is critical for separating depolarization from the Mueller matrix, which enables the integration of polarization aberration in the laboratory into simulated data generated by a polarization ray tracer, e.g. `Poke` (Ashcraft et al., 2023), `PyAstroPol` (Pruthvi., 2020). Katsu also adopts the flexible interchangeable backend system of `prysm` (Dube, 2019; Dube et al., 2022) for hot-swappable NumPy-like backends (Harris et al., 2020) including CuPy for GPU-accelerated computing (Okuta et al., 2017) and JAX for automatic differentiation (Bradbury et al., 2018).

Statement of need

Polarimetric characterization in the laboratory is critical to the performance of astronomical instrumentation. The next generation of astronomical observatories has identified that wavefront errors induced by polarization, called *polarization aberrations*, could be a limiting factor in direct exoplanet imaging. Ample modeling has been done at the observatory level to understand the nominal polarization aberrations that arise in the telescope (Anche et al., 2023; Gaudi et al., 2020; Will & Fienup, 2019) but less work has been done to characterize instrumentation in the laboratory.

Katsu has recently been used as the primary backend of the Gromit polarimeter at the UA Space Astrophysics Laboratory (Ashcraft, Jenkins, et al., 2024), and used to measure the spatially-varying polarization aberrations of the Space Coronagraph Optical Bench (SCoOB, Ashcraft, Douglas, et al., 2024). The measurement and polarimetric data reduction capabilities available in Katsu enabled expeditious full Mueller polarimetry of an astronomical coronagraph testbed. In the future, we aim to add more polarimetric data reduction capabilities to Katsu, like a recently-published modification of DRRP data reduction to leverage insights from dual-channel polarimetry (Melby et al., 2024) for passive insensitivity to variations in total intensity.

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