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VIP: A Python package for high-contrast imaging

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Summary

Direct imaging of exoplanets and circumstellar disks at optical and infrared wavelengths requires reaching high contrasts at short angular separations. This can only be achieved through the synergy of advanced instrumentation, such as adaptive optics and coronagraphy, with a relevant combination of observing strategy and post-processing algorithms to model and subtract residual starlight. In this context, `VIP` is a Python package providing the tools to reduce, post-process and analyze high-contrast imaging datasets, enabling the detection and characterization of directly imaged exoplanets, circumstellar disks, and stellar environments.

Statement of need

`VIP` (Vortex Image Processing) is a collaborative project which started at the University of Liège, aiming to integrate open-source, efficient, easy-to-use and well-documented implementations of state-of-the-art algorithms used in the context of high-contrast imaging (Gomez Gonzalez et al., 2017). Two other open-source toolkits for high-contrast imaging with similar purpose and extent as `VIP` have become available in the last few years: `pyklip` and `pynpoint` (Amara et al., 2015; Stolker et al., 2019; Wang et al., 2015). In each of these, a core (and only) post-processing method is available: the Karhuenen-Loeve Image Projection (KLIP) algorithm (Soummer et al., 2012), and the (similar) Principal Component Analysis (PCA) algorithm (Amara & Quanz, 2012), respectively. In contrast, `VIP` not only implements the PCA algorithm with a variety of flavours, but it also includes a diversity of other post-processing methods, such as ANDROMEDA, KLIP-FMMF, LLSG, NMF or PACO (Cantalloube et al., 2015; Flasseur et al., 2018; Gomez Gonzalez et al., 2016, 2017; Ruffio et al., 2017). Furthermore, as opposed to `VIP`, `pyklip` does not offer any preprocessing options (e.g. PCA-based sky subtraction, image centering or bad frame trimming). `pynpoint` was originally developed as a PCA-based PSF-subtraction mini-package (Amara et al., 2015), which was later significantly expanded into an end-to-end processing pipeline including similar options as `VIP` regarding preprocessing (Stolker et al., 2019). Nonetheless, the PCA implementation in `VIP` offers a much wider diversity of options, such as the possibility to carry it out in concentric annuli, and to consider a parallactic angle threshold when creating the PCA library. Depending on the high-contrast imaging dataset at hand, different post-processing methods and reduction parameters can lead to better speckle suppression, helping with the detection of fainter companions (Dahlqvist et al., 2021). In that regard, `VIP` is thus better equipped than other existing toolkits. It is also worth mentioning that FFT-based methods are implemented in `VIP` (default option) for all image operations (rotation, shift and rescaling) as these outperform interpolation-based methods in terms of flux conservation (Larkin et al., 1997). To our knowledge, FFT-based methods for image operations had only been implemented in the non-public high-contrast imaging pipeline `graphic` to date (Hagelberg et al., 2016).

The `VIP` package follows a modular architecture, such that its routines cover a wide diversity of tasks, including:

- image pre-processing, such as sky subtraction, bad pixel correction, bad frame removal, or image alignment and star centering (`preproc` module);
- modeling and subtracting the stellar point spread function (PSF) using state-of-the-art algorithms that leverage observing strategies such as angular differential imaging (ADI), spectral differential imaging (SDI) or reference star differential imaging (Marois et al., 2006; Ruane et al., 2019; Sparks & Ford, 2002), which induce diversity between speckle and authentic astrophysical signals (`psfsub` module);
- characterizing point sources and extended circumstellar signals through forward modeling (`fm` module);
- detecting and characterizing point sources through inverse approaches (`invprob` module);
- assessing the achieved contrast in PSF-subtracted images, automatically detecting point sources, and estimating their significance (`metrics` module).

The features implemented in `VIP` as of 2017 are described in Gomez Gonzalez et al. (2017). Since then, the package has been widely used by the high-contrast imaging community for the discovery of low-mass companions (Hirsch et al., 2019; Milli, Hibon, et al., 2017; Ubeira-Gabellini et al., 2020), their characterization (Christiaens et al., 2019, 2018; Delorme et al., 2017; Wertz et al., 2017), the study of planet formation (Maucó et al., 2020; Reggiani et al., 2018; Ruane et al., 2017; Toci et al., 2020), the study of high-mass star formation (Rainot et al., 2022, 2020), the study of debris disks (Milli, Vigan, et al., 2017; Milli et al., 2019), or the development of new high-contrast imaging algorithms (Dahlqvist et al., 2020, 2021; Gomez Gonzalez et al., 2018; Pairet et al., 2021).

Given the rapid expansion of `VIP`, we summarize here all new features that were brought to the package over the past five years. Specifically, the rest of this manuscript summarizes all major changes since v0.7.0 (Gomez Gonzalez et al., 2017), that are included in the latest release of `VIP` (v1.3.5). At a structural level, `VIP` underwent a major change since version v1.1.0, which migrated it towards a more streamlined and easy-to-use architecture. The package now revolves around five major modules (`fm`, `invprob`, `metrics`, `preproc` and `psfsub`, as described above) complemented by four additional modules containing various utility functions (`config`, `fits`, `stats` and `var`). New `Dataset` and `Frame` classes have also been implemented, enabling an object-oriented approach for processing high-contrast imaging datasets and analyzing final images, respectively. Similarly, a `HCIPostProcAlgo` class and different subclasses inheriting from it have been defined to facilitate an object-oriented use of `VIP` routines.

Some of the major changes in each module of `VIP` are summarized below:

- `fm`:
  - new routines were added to create parametrizable scattered-light disk models and extended signals in ADI cubes, in order to forward-model the effect of ADI post-processing (Christiaens et al., 2019; Milli et al., 2012);
  - the log-likelihood expression used in the negative fake companion (NEGFC) technique was updated, and the default convergence criterion for the NEGFC-MCMC method is now based on auto-correlation (Christiaens et al., 2021);

- the NEGFC methods are now fully compatible with integral field spectrograph (IFS) input datacubes.
- invprob:
  - a Python implementation of the ANDROMEDA algorithm (Cantalloube et al., 2015) is now available as part of VIP;
  - the KLIP-FMMF and LOCI-FMMF algorithms (Dahlqvist et al., 2021; Pueyo, 2016; Ruffio et al., 2017) are now also available in the invprob module.
  - a Python implementation of the PACO algorithm (Flasseur et al., 2018) is now also available, including both the planet detection and flux estimation algorithms.
- metrics:
  - calculation of standardized trajectory maps (STIM) is now available (Pairet et al., 2019);
  - functions to calculate completeness-based contrast curves and completeness maps, inspired by the framework in Jensen-Clem et al. (2018) and implemented as in Dahlqvist et al. (2021), have now been added to the metrics module.
- preproc:
  - the module now boasts several new algorithms for (i) the identification of either isolated bad pixels or clumps of bad pixels, leveraging on iterative sigma filtering (cube_fix_badpix_clump), the circular symmetry of the PSF (cube_fix_badpix_annuli), or the radial expansion of the PSF with increasing wavelength (cube_fix_badpix_ifs), and (ii) the correction of bad pixels with iterative spectral deconvolution (Aach & Metzler, 2001) or Gaussian kernel interpolation (both through cube_fix_badpix_interp);
  - a new algorithm was added for the recentering of coronagraphic image cubes based on the cross-correlation of the speckle pattern, after appropriate filtering and log-scaling of pixel intensities (Ruane et al., 2019).
- psfsub:
  - all principal component analysis (PCA) based routines (Amara & Quanz, 2012; Soummer et al., 2012) have been re-written for improved efficiency, and are now also compatible with 4D IFS+ADI input cubes to apply SDI-based PSF modeling and subtraction algorithms;
  - an implementation of the Locally Optimal Combination of Images algorithm (Lafrenière et al., 2007) was added;
  - an annular version of the non-negative matrix factorization algorithm is now available (Gomez Gonzalez et al., 2017; Lee & Seung, 1999);
  - besides median-ADI, the medsub routine now also supports median-SDI.

We refer the interested reader to release descriptions and GitHub announcements for a more complete list of all changes, including improvements not mentioned in the above summary.

Two major convention updates are also to be noted in VIP. All image operations (rotation, scaling, resampling and sub-pixel shifts) are now performed using Fourier-Transform (FT) based methods by default. These have been implemented as low-level routines in the preproc module. FT-based methods significantly outperform interpolation-based methods in terms of flux conservation (Larkin et al., 1997). However, given the order of magnitude slower computation of FT-based image rotations, the option to use interpolation-based methods is still available in all relevant VIP functions. The second change of convention concerns the assumed center for even-size images, which is now defined as the top-right pixel among the four central pixels of the image - a change motivated by the new default FT-based methods for image operations. The center convention is unchanged for odd-size images (central pixel).

Finally, a total of nine jupyter notebook tutorials covering most of the available features in VIP were implemented. These tutorials illustrate how to (i) load and post-process an ADI dataset (quick-start tutorial); (ii) pre-process ADI and IFS datasets; (iii) model and subtract the stellar halo with ADI-based algorithms; (iv) calculate metrics such as the S/N ratio (Mawet et al., 2014), STIM maps (Pairet et al., 2019) and contrast curves; (v) find the radial separation, azimuth and flux of a point source; (vi) create and forward model scattered-light disk models; (vii) post-process IFS data and infer the exact astro- and photometry of a given point source; (viii) use FT-based and interpolation-based methods for different image operations, and assess their respective performance; and (ix) use the new object-oriented framework for `VIP`.

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