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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 considering 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, hence help 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, these FFT-based methods for image operations are not available in other high-contrast imaging packages.

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 novelties 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` (v1.3.1). At a structural level, `VIP` underwent a major change since version v1.1.0, which aimed to migrate 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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References

Aach, T., & Metzler, V. H. (2001). Defect interpolation in digital radiography: how object-oriented transform coding helps. In M. Sonka & K. M. Hanson (Eds.), *Medical imaging 2001: Image processing* (Vol. 4322, pp. 824–835). https://doi.org/10.1117/12.431161

Amara, A., & Quanz, S. P. (2012). PYNPOINT: an image processing package for finding exoplanets. *MNRAS*, *427*, 948–955. https://doi.org/10.1111/j.1365-2966.2012.21918.x

Amara, A., Quanz, S. P., & Akeret, J. (2015). PynPoint code for exoplanet imaging. *Astronomy and Computing*, *10*, 107–115. https://doi.org/10.1016/j.ascom.2015.01.003

Cantalloube, F., Mouillet, D., Mugnier, L. M., Milli, J., Absil, O., Gomez Gonzalez, C. A., Chauvin, G., Beuzit, J.-L., & Cornia, A. (2015). Direct exoplanet detection and characterization using the ANDROMEDA method: Performance on VLT/NaCo data. *Astronomy and Astrophysics*, *582*, A89. https://doi.org/10.1051/0004-6361/201425571

Christiaens, V., Casassus, S., Absil, O., Cantalloube, F., Gomez Gonzalez, C., Girard, J., Ramírez, R., Pairet, B., Salinas, V., Price, D. J., Pinte, C., Quanz, S. P., Jordán, A., Mawet, D., & Wahhaj, Z. (2019). Separating extended disc features from the protoplanet in PDS 70 using VLT/SINFONI. *MNRAS*, *486*(4), 5819–5837. https://doi.org/10.1093/mnras/stz1232

Christiaens, V., Casassus, S., Absil, O., Kimeswenger, S., Gonzalez, C. A. G., Girard, J., Ramírez, R., Wertz, O., Zurlo, A., Wahhaj, Z., Flores, C., Salinas, V., Jordán, A., & Mawet, D. (2018). Characterization of low-mass companion HD 142527 B. *Astronomy and Astrophysics*, *617*, A37. https://doi.org/10.1051/0004-6361/201629454

Christiaens, V., Ubeira-Gabellini, M.-G., Cánovas, H., Delorme, P., Pairet, B., Absil, O., Casassus, S., Girard, J. H., Zurlo, A., Aoyama, Y., Marleau, G.-D., Spina, L., van der Marel, N., Cieza, L., Lodato, G., Pérez, S., Pinte, C., Price, D. J., & Reggiani, M. (2021). A faint companion around CrA-9: protoplanet or obscured binary? *MNRAS*, *502*(4), 6117–6139. https://doi.org/10.1093/mnras/stab480

Dahlqvist, C.-H., Cantalloube, F., & Absil, O. (2020). Regime-switching model detection map for direct exoplanet detection in ADI sequences. *Astronomy and Astrophysics*, *633*, A95. https://doi.org/10.1051/0004-6361/201936421

Dahlqvist, C.-H., Cantalloube, F., & Absil, O. (2021). Auto-RSM: An automated parameter-selection algorithm for the RSM map exoplanet detection algorithm. *656*, A54. https://doi.org/10.1051/0004-6361/202141446

Delorme, P., Schmidt, T., Bonnefoy, M., Desidera, S., Ginski, C., Charnay, B., Lazzoni, C., Christiaens, V., Messina, S., D'Orazi, V., Milli, J., Schlieder, J. E., Gratton, R., Rodet, L., Lagrange, A.-M., Absil, O., Vigan, A., Galicher, R., Hagelberg, J., … Wildi, F. (2017). In-depth study of moderately young but extremely red, very dusty substellar companion HD 206893B. *Astronomy and Astrophysics*, *608*, A79. https://doi.org/10.1051/0004-6361/201731145

Flasseur, O., Denis, L., Thiébaut, É., & Langlois, M. (2018). Exoplanet detection in angular differential imaging by statistical learning of the nonstationary patch covariances. The PACO algorithm. *618*, A138. https://doi.org/10.1051/0004-6361/201832745

Gomez Gonzalez, C. A., Absil, O., Absil, P.-A., Van Droogenbroeck, M., Mawet, D., & Surdej, J. (2016). Low-rank plus sparse decomposition for exoplanet detection in direct-imaging ADI sequences. The LLSG algorithm. *589*, A54. https://doi.org/10.1051/0004-6361/201527387

Gomez Gonzalez, C. A., Absil, O., & Van Droogenbroeck, M. (2018). Supervised detection of exoplanets in high-contrast imaging sequences. *Astronomy and Astrophysics*, *613*, A71. https://doi.org/10.1051/0004-6361/201731961

Gomez Gonzalez, C. A., Wertz, O., Absil, O., Christiaens, V., Defrère, D., Mawet, D., Milli, J., Absil, P.-A., Van Droogenbroeck, M., Cantalloube, F., Hinz, P. M., Skemer, A. J., Karlsson, M., & Surdej, J. (2017). VIP: Vortex Image Processing Package for High-contrast Direct Imaging. *The Astronomical Journal*, *154*, 7. https://doi.org/10.3847/1538-3881/aa73d7

Hirsch, L. A., Ciardi, D. R., Howard, A. W., Marcy, G. W., Ruane, G., Gonzalez, E., Blunt, S., Crepp, J. R., Fulton, B. J., Isaacson, H., Kosiarek, M., Mawet, D., Sinukoff, E., & Weiss, L. (2019). Discovery of a White Dwarf Companion to HD 159062. *The Astrophysical Journal*, *878*(1), 50. https://doi.org/10.3847/1538-4357/ab1b11

Jensen-Clem, R., Mawet, D., Gomez Gonzalez, C. A., Absil, O., Belikov, R., Currie, T., Kenworthy, M. A., Marois, C., Mazoyer, J., Ruane, G., Tanner, A., & Cantalloube, F. (2018). A New Standard for Assessing the Performance of High Contrast Imaging Systems. *155*, 19. https://doi.org/10.3847/1538-3881/aa97e4

Lafrenière, D., Marois, C., Doyon, R., Nadeau, D., & Artigau, É. (2007). A New Algorithm for Point-Spread Function Subtraction in High-Contrast Imaging: A Demonstration with Angular Differential Imaging. *The Astrophysical Journal*, *660*, 770–780. https://doi.org/10.1086/513180

Larkin, K. G., Oldfield, M. A., & Klemm, H. (1997). Fast Fourier method for the accurate rotation of sampled images. *Optics Communications*, *139*(1-3), 99–106. https://doi.org/10.1016/S0030-4018(97)00097-7

Lee, D. D., & Seung, H. S. (1999). Learning the parts of objects by non-negative matrix factorization. *Nature*, *401*(6755), 788–791. https://doi.org/10.1038/44565

Marois, C., Lafrenière, D., Doyon, R., Macintosh, B., & Nadeau, D. (2006). Angular Differential Imaging: A Powerful High-Contrast Imaging Technique. *The Astrophysical Journal*, *641*, 556–564. https://doi.org/10.1086/500401

Maucó, K., Olofsson, J., Canovas, H., Schreiber, M. R., Christiaens, V., Bayo, A., Zurlo, A., Cáceres, C., Pinte, C., Villaver, E., Girard, J. H., Cieza, L., & Montesinos, M. (2020). NaCo polarimetric observations of Sz 91 transitional disc: a remarkable case of dust filtering. *MNRAS*, *492*(2), 1531–1542. https://doi.org/10.1093/mnras/stz3380

Mawet, D., Milli, J., Wahhaj, Z., Pelat, D., Absil, O., Delacroix, C., Boccaletti, A., Kasper, M., Kenworthy, M., Marois, C., Mennesson, B., & Pueyo, L. (2014). Fundamental Limitations of High Contrast Imaging Set by Small Sample Statistics. *The Astrophysical Journal*, *792*, 97. https://doi.org/10.1088/0004-637X/792/2/97

Milli, J., Engler, N., Schmid, H. M., Olofsson, J., Ménard, F., Kral, Q., Boccaletti, A., Thébault, P., Choquet, E., Mouillet, D., Lagrange, A.-M., Augereau, J.-C., Pinte, C., Chauvin, G., Dominik, C., Perrot, C., Zurlo, A., Henning, T., Beuzit, J.-L., … Pragt, J. (2019). Optical polarised phase function of the HR 4796A dust ring. *626*, A54. https://doi.org/10.1051/0004-6361/201935363

Milli, J., Hibon, P., Christiaens, V., Choquet, É., Bonnefoy, M., Kennedy, G. M., Wyatt, M. C., Absil, O., Gómez González, C. A., del Burgo, C., Matrà, L., Augereau, J.-C., Boccaletti, A., Delacroix, C., Ertel, S., Dent, W. R. F., Forsberg, P., Fusco, T., Girard, J. H., … Wahhaj, Z. (2017). Discovery of a low-mass companion inside the debris ring surrounding the F5V star HD 206893. *Astronomy and Astrophysics*, *597*, L2. https://doi.org/10.1051/0004-6361/201629908

Milli, J., Mouillet, D., Lagrange, A.-M., Boccaletti, A., Mawet, D., Chauvin, G., & Bonnefoy, M. (2012). Impact of angular differential imaging on circumstellar disk images. *Astronomy and Astrophysics*, *545*, A111. https://doi.org/10.1051/0004-6361/201219687

Milli, J., Vigan, A., Mouillet, D., Lagrange, A.-M., Augereau, J.-C., Pinte, C., Mawet, D., Schmid, H. M., Boccaletti, A., Matrà, L., Kral, Q., Ertel, S., Chauvin, G., Bazzon, A., Ménard, F., Beuzit, J.-L., Thalmann, C., Dominik, C., Feldt, M., … SPHERE Consortium. (2017). Near-infrared scattered light properties of the HR 4796 A dust ring. *599*, A108. https://doi.org/10.1051/0004-6361/201527838

Pairet, B., Cantalloube, F., Gomez Gonzalez, C. A., Absil, O., & Jacques, L. (2019). STIM map: detection map for exoplanets imaging beyond asymptotic Gaussian residual speckle noise. *MNRAS*, *487*(2), 2262–2277. https://doi.org/10.1093/mnras/stz1350

Pairet, B., Cantalloube, F., & Jacques, L. (2021). MAYONNAISE: a morphological components analysis pipeline for circumstellar discs and exoplanets imaging in the near-infrared. *MNRAS*, *503*(3), 3724–3742. https://doi.org/10.1093/mnras/stab607

Pueyo, L. (2016). Detection and Characterization of Exoplanets using Projections on Karhunen Loeve Eigenimages: Forward Modeling. *824*(2), 117. https://doi.org/10.3847/0004-637X/824/2/117

Rainot, A., Reggiani, M., Sana, H., Bodensteiner, J., & Absil, O. (2022). Carina High-contrast Imaging Project for massive Stars (CHIPS). II. O stars in Trumpler 14. *Astronomy and Astrophysics*, *658*, A198. https://doi.org/10.1051/0004-6361/202141562

Rainot, A., Reggiani, M., Sana, H., Bodensteiner, J., Gomez-Gonzalez, C. A., Absil, O., Christiaens, V., Delorme, P., Almeida, L. A., Caballero-Nieves, S., De Ridder, J., Kratter, K., Lacour, S., Le Bouquin, J.-B., Pueyo, L., & Zinnecker, H. (2020). Carina High-contrast Imaging Project for massive Stars (CHIPS). I. Methodology and proof of concept on QZ Car (≡ HD 93206). *Astronomy and Astrophysics*, *640*, A15. https://doi.org/10.1051/0004-6361/201936448

Reggiani, M., Christiaens, V., Absil, O., Mawet, D., Huby, E., Choquet, E., Gomez Gonzalez, C. A., Ruane, G., Femenia, B., Serabyn, E., Matthews, K., Barraza, M., Carlomagno, B., Defrère, D., Delacroix, C., Habraken, S., Jolivet, A., Karlsson, M., Orban de Xivry, G., … Wertz, O. (2018). Discovery of a point-like source and a third spiral arm in the transition disk around the Herbig Ae star MWC 758. *Astronomy and Astrophysics*, *611*, A74. https://doi.org/10.1051/0004-6361/201732016

Ruane, Mawet, D., Kastner, J., Meshkat, T., Bottom, M., Femenía Castellá, B., Absil, O., Gomez Gonzalez, C., Huby, E., Zhu, Z., Jensen-Clem, R., Choquet, É., & Serabyn, E. (2017). Deep Imaging Search for Planets Forming in the TW Hya Protoplanetary Disk with the Keck/NIRC2 Vortex Coronagraph. *The Astronomical Journal*, *154*, 73. https://doi.org/10.3847/1538-3881/aa7b81

Ruane, Ngo, H., Mawet, D., Absil, O., Choquet, É., Cook, T., Gomez Gonzalez, C., Huby, E., Matthews, K., Meshkat, T., Reggiani, M., Serabyn, E., Wallack, N., & Xuan, W. J. (2019). Reference Star Differential Imaging of Close-in Companions and Circumstellar Disks with the NIRC2 Vortex Coronagraph at the W. M. Keck Observatory. *157*(3), 118. https://doi.org/10.3847/1538-3881/aafee2

Ruffio, J.-B., Macintosh, B., Wang, J. J., Pueyo, L., Nielsen, E. L., De Rosa, R. J., Czekala, I., Marley, M. S., Arriaga, P., Bailey, V. P., Barman, T., Bulger, J., Chilcote, J., Cotten, T., Doyon, R., Duchêne, G., Fitzgerald, M. P., Follette, K. B., Gerard, B. L., … Wolff, S. (2017). Improving and Assessing Planet Sensitivity of the GPI Exoplanet Survey with a Forward Model Matched Filter. *842*, 14. https://doi.org/10.3847/1538-4357/aa72dd

Soummer, R., Pueyo, L., & Larkin, J. (2012). Detection and Characterization of Exoplanets and Disks Using Projections on Karhunen-Loève Eigenimages. *The Astrophysical Journal*, *755*(2), L28. https://doi.org/10.1088/2041-8205/755/2/L28

Sparks, W., & Ford, H. (2002). Imaging Spectroscopy for Extrasolar Planet Detection. *The Astrophysical Journal*, *578*, 543–564. https://doi.org/10.1086/342401

Stolker, T., Bonse, M. J., Quanz, S. P., Amara, A., Cugno, G., Bohn, A. J., & Boehle, A. (2019). PynPoint: a modular pipeline architecture for processing and analysis of high-contrast imaging data. *621*, A59. https://doi.org/10.1051/0004-6361/201834136

Toci, C., Lodato, G., Christiaens, V., Fedele, D., Pinte, C., Price, D. J., & Testi, L. (2020). Planet migration, resonant locking, and accretion streams in PDS 70: comparing models and data. *MNRAS*, *499*(2), 2015–2027. https://doi.org/10.1093/mnras/staa2933

Ubeira-Gabellini, M. G., Christiaens, V., Lodato, G., Ancker, M. van den, Fedele, D., Manara, C. F., & Price, D. J. (2020). Discovery of a Low-mass Companion Embedded in the Disk of the Young Massive Star MWC 297 with VLT/SPHERE. *The Astrophysical Journal*, *890*(1), L8. https://doi.org/10.3847/2041-8213/ab7019

Wang, J. J., Ruffio, J.-B., De Rosa, R. J., Aguilar, J., Wolff, S. G., & Pueyo, L. (2015). *pyKLIP: PSF Subtraction for Exoplanets and Disks* (p. ascl:1506.001). Astrophysics Source Code Library, record ascl:1506.001.

Wertz, O., Absil, O., Gómez González, C. A., Milli, J., Girard, J. H., Mawet, D., & Pueyo, L. (2017). VLT/SPHERE robust astrometry of the HR8799 planets at milliarcsecond-level accuracy. Orbital architecture analysis with PyAstrOFit. *Astronomy and Astrophysics*, *598*, A83. https://doi.org/10.1051/0004-6361/201628730