

ABISM: an interactive image quality assessment tool for adaptive optics instruments

Julien H. Girard^a and Martin Tourneboeuf^{a,b,*}

^aEuropean Southern Observatory (ESO), Casilla 19001, Vitacura, Santiago, Chile

^bPontifica Universidad Católica de Chile (PUC), Vicuña Mackena 4860, Santiago, Chile

ABSTRACT

ABISM (Automatic Background Interactive Strehl Meter) is a interactive tool to evaluate the image quality of astronomical images. It works on seeing-limited point spread functions (PSF) but was developed in particular for diffraction-limited PSF produced by adaptive optics (AO) systems. In the VLT service mode (SM) operations framework, ABISM is designed to help support astronomers or telescope and instruments operators (TIOs) to quickly measure the Strehl ratio (SR) during or right after an observing block (OB) to evaluate whether it meets the requirements/predictions or whether it has to be repeated and will remain in the SM queue. It's a Python-based tool with a graphical user interface (GUI) that can be used with little AO knowledge. The night astronomer (NA) or Telescope and Instrument Operator (TIO) can launch ABISM in one click and the program is able to read keywords from the FITS header to avoid mistakes. A significant effort was also put to make ABISM as robust (and forgiven) with a high rate of repeatability. As a matter of fact, ABISM is able to automatically correct for bad pixels, eliminate stellar neighbours and estimate/fit properly the background, etc.

Keywords: Adaptive Optics, High Angular Resolution, Image Quality, Strehl Ratio, Quality Control, Software, Very Large Telescope, ESO Science Operations

1. A NEW "QC0" TOOL FOR AO INSTRUMENTS

ABISM has been developed between 2012 and 2014 as a prototype program to ease the QC0 (immediate Quality Control) classification of Adaptive Optics (AO) data in the framework of SciOps 2.0[†], a recently implemented operational scheme which allows to free up time for the astronomers/instrument scientists for to perform higher level tasks on their instruments, interact more with engineering teams, etc.

ABISM bases its SR estimation using the aperture photometry method. Its originality resides in its "smart" features to adapt to many types of AO data encountered with instruments like NACo or SINFONI (integral field spectrograph of the VLT/UT4). It was developed to respond to a need to ease the operations of an increasing number of AO instruments at the Paranal Observatory driven by professionals who are for the most part not AO experts. It is not necessarily the most accurate but it provides adequate measurements for our QC0 purposes and helps greatly to avoid mistakes (misclassification of OBs turning into time losses). In the future, the ABISM GUI can eventually be upgraded with a new Strehl calculation "engine". Similarly, ABISM and its features can influence the development of a more robust/professional tool, eventually integrated in an instrument's real time display for immediate assessment or in command-line recipes for batch operation on large sets of data (e.g monitoring performances through years, automatic health check, etc.).

* Now working for Direction Générale de l'Armement (FRANCE)

Corresponding author's e-mail: jgirard@eso.org

[†]Science Operations "SciOps" 2.0: new operations model at the Paranal Observatory in which the astronomer leaves the console between ~2am and ~4am (Dumas et al. 2014.¹) The remaining of the night's observations is performed by a certified Telescope and Instrument Operator (TIO). Several TIOs alternate with an operations specialist (OS) daytime shift and can also get more involved in SciOps projects to smoothen operations, develop tool, help the instrument operations team (IOT) for a given instrument of the Paranal suite.

1.1 Strehl ratio, measurement and calculation

The Strehl is a very common performance metrics for optical systems. A SR of 100% is not achievable in practice because optical components cannot be manufactured perfectly and therefore introduce aberrations which degrade the wavefront. The final SR hence decreases exponentially with the total variance σ_{Φ}^2 of the wavefront residuals (formula of Mahajan or Maréchal approximation) multiplied by the attenuation due to the variance of the log-normal amplitude σ_x^2 at the pupil plane (aperture "apodization"):

$$SR = e^{-\sigma_{\Phi}^2} \times e^{-\sigma_x^2} \quad (1)$$

In astronomy the SR is the most common performance metrics for AO systems. It is particularly suited for classical AO systems delivering imperfect near diffraction limited images. SR scales from below $\sim 2\%$ (seeing-limited image) to over 90% for extreme (x)AO systems (high contrast imaging/spectroscopy). It is a good metric for classical AO system such as NACO^{[‡2-5](#)} because it achieves Strehls of from few percents at $1\mu m$ to $\sim 80\%$ at $3.8\mu m$ under good conditions (M' filter at $4.8\mu m$ is only used marginally). For xAO systems performing in the 80-95% SR regime, the contrast is a much better metric. Indeed, a measurement uncertainty of the SR of 10% in this range can represent a variation of contrast of a factor 3 (more than a magnitude on sky)! For ground layer AO (GLAO) systems which aim at improving the seeing by a factor 2-3 and don't reach the diffraction limit, the SR is also a poor metric because it is typically between 0 and 5% and the better metrics are the full-width at half maximum (FWHM) or the encircled energy (EC) which vary significantly in this regime.

The Strehl ratio (here after SR) is defined as the ratio of the measured peak intensity of a real PSF $I(x = 0)$ over the peak intensity of a perfect diffraction limited PSF $P(x = 0)$ containing the same total energy.

$$SR = \frac{I(x = 0)}{P(x = 0)} \quad (2)$$

The theoretical PSF should represent the given optical system (e.g aperture geometry, central obscuration, etc.). For the VLT, it is a circular 8.2-meter aperture with a 1.15m central obscuration ($D_2/D_1=14\%$) which can eventually be altered in the instrument itself (e.g. by a Lyot stop).

1.2 The photometric method implemented in ABISM

In practice, the difficult part is to evaluate accurately the peak intensity (sampled data), the background which can seriously affect the integrated photometry, especially at low signa to noise ratios (SNR) or in crowded fields. ABISM is using aperture photometry and then a theoretical model to find $P(x = 0)$. Another 2-D fit (Moffat, Gaussian or Bessel) is performed on the real PSF to find its true peak PSF $I(x = 0)$ despite discrete sampling. The measurement accuracy depends greatly on the SNR and only works for Nyquist spatial sampling (2 pixels per resolution elements λ/D) or better.

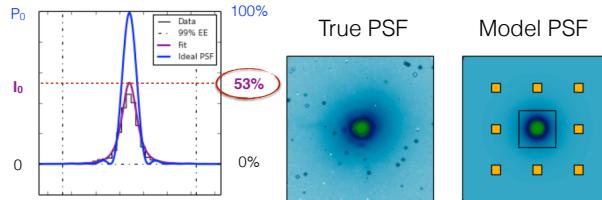


Figure 1. Illustration of a SR measurement yielding $I(x = 0)/P(x = 0) \sim 53\%$. The purple fit to the data (here, a Moffat function) determines the vertical position of the true peak despite discrete spatial sampling (black steps representing the detector pixels). The total integrated photometry of these pixels is injected into a perfect theoretical PSF (blue curve). The 8 yellow boxes on the rights are the background probes and determine what the zero is. A error in the fit (noisy data) or in the background measurement (e.g boxes positioned to close to the PSF where there is still signal can lead to great errors in the finale SR value.

[‡]NACO: Nasmyth Adaptive Optics System **NAOS** and the Near-Infrared Imager and Spectrograph **CONICA**

Other methods use the Fourier space to determine the SR. Several methods have been exposed in the Roberts et. al 2004 paper⁶ "Is that really your Strehl ratio?". A contest had then been set to compare different methods and implementations. For ABISM, we chose the photometric and fitting method because it also yields photometric and astrometric information, it is simple and didactic which is also something we wanted to increase the "AO awareness" among the staff, providing a visualisation of the SR measurement which indicates to the user how well the model fits and compares to the data, where the background was measured, etc.

2. WHAT CAN ABISM DO AND HOW?

In this section we are presenting some of ABISM's main features and functionalities also described in Figure 2. Some features are still in development/test and therefore are hidden from the default main window (i.e need to be called from the menus).

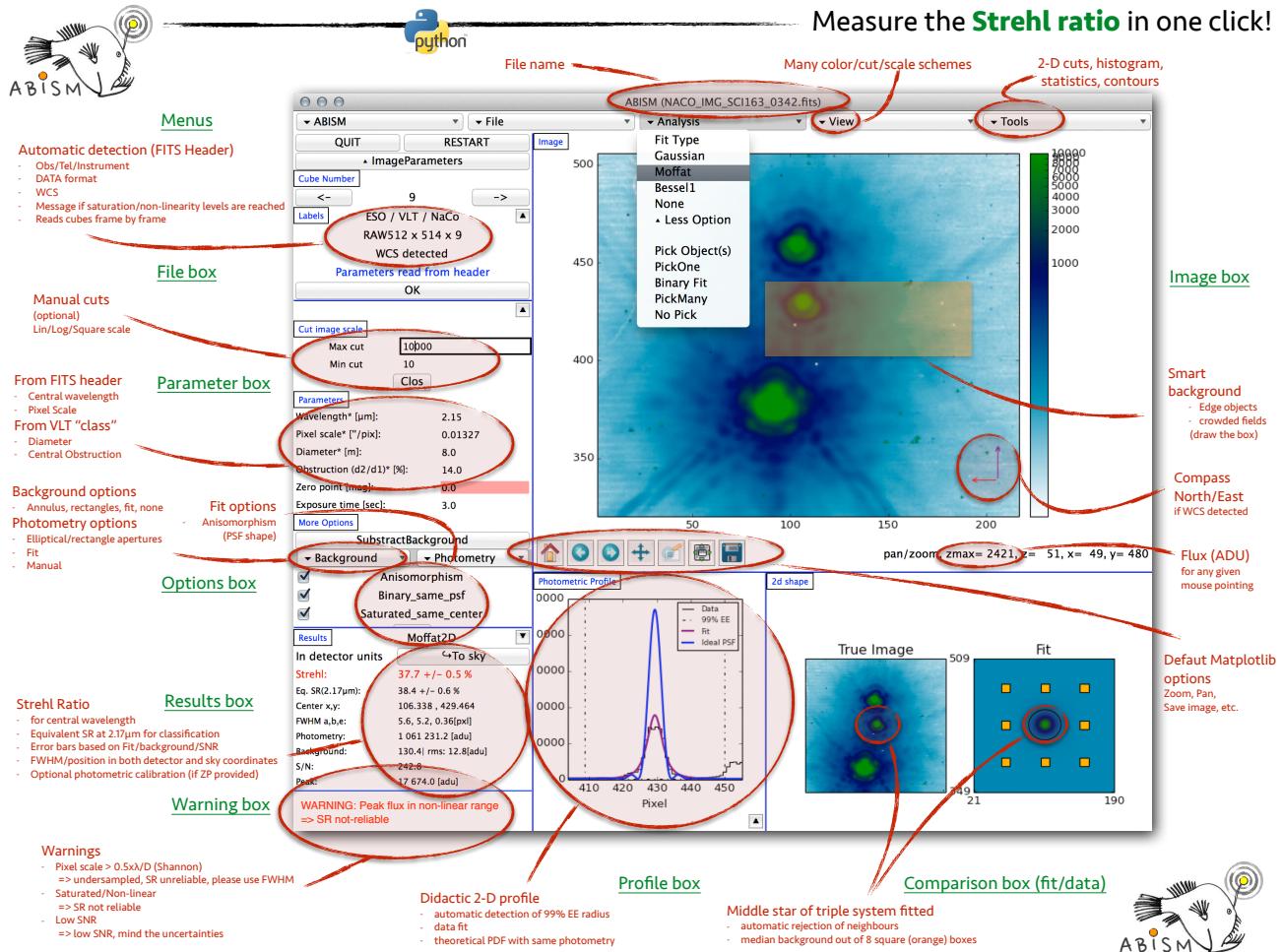


Figure 2. Screenshot of ABISM v0.96 with annotations of most of the boxes, menus and functionalities.

2.1 Graphical User Interface (GUI)

Quite a lot of thought has been put into this GUI: how to make ABISM user-friendly, how to display a maximum amount of information in a simple way, how to make the tool intelligible from the first sight and yet interactive.

For that we have created a single window GUI using the Python package *Tkinter* (derive from *Tcl/Tk*) because it is available on all machines running at the Paranal Observatory and easily installable on Linux and

Max OS platforms. The GUI is divided into horizontal menus (top items in Figure 2) and boxes (separated by blue lines and named in green on Figure 2).

2.1.1 Menus and boxes

Despite Figure 2 being self-explanatory, here is a description of the bars, boxes and menus.

1. **Title bar** with the name of the fits file which is open.
2. **Menu bar** with some pull-downs menus
 - **ABISM**: about, quick guide, advanced manual, appearance (background/foreground colours, sash) and Quit
 - **File** Open file, Display Header.
 - **Analysis**: Fit type (Gaussian, Moffat, Bessel1, None), "More Options—", Pick Objects (Pick One, Pick Many, Binary Fit, No Pick)
 - **View**: Colormaps, Scale (Square, Sqrt, Lin, Log, Arcsinh) and Cuts (99.5%, etc., None, Manual).
3. **Image frame** Shows the image with all the usual Matplotlib options, the orientation (North-East ruler) of the image if the World Coordinate System (WCS) has been detected in the header.
4. **Results frame**: displays results, Strehl ratio, equivalent Sr (default is for $2.17\mu\text{m}$ the Br γ ray wavelength in the K-band, the reference wavelengths for NACo AO performances and QC).
and z_max is the maximum value of z 10 pixels away from the pixel.
5. **Photometric Profile frame**: a didactic plot showing the real, discretised profile of the PSF, the fit (purple), the model with the same photometry (blue). This canvas is be used to display other thing (histogram, statistics, etc.) from the "Tools" menu.
6. **2D Shape frame**: Two images are displayed, the real PSF (with the background boxes or ellipses) versus the model PSF (e.g. with companion removed).

2.1.2 Colours

Colors scheme are easily changed from the "View" menu following the *Matplotlib* colours. The background and boxes colours can also be changed. The "look and feel" depends greatly on the platform on which you are running ABISM. The default background colour is grey on Linux and white on Mac OS (as shown in all Figures in this article for sake of homogeneity).

2.2 Main features & functionalities

2.2.1 Display FITS images

ABISM uses the most common graphical package in Python: *Matplotlib*. The FITS image is displayed in the main window of the GUI which takes - by default - about two thirds of the width and height of the whole window. The main functionalities of matplotlib ("home", "zoom", "save", "pan", etc.) are easily recognisable on the bottom left of the window (buttons with icons). On the bottom right the z and y pixel locations appear dynamically when the user moves his/her mouse across the image. To that we added the "z" axis which is the intensity value of the given pixel (a very useful feature that common FITS display programs like ds9 have). Contours are really useful to compare two adjacent PSFs as in Figure 3 [§].

[§]ESO Prog ID: 290.C-5203(A)

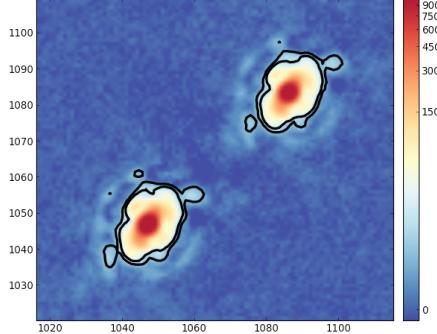


Figure 3. Illustration of a display of contours on the closest brown dwarf binary LUH 16AB observed with NACO L'-band. Both low-mass stars have a very similar brightness and the PSF is elongated along the AB axis due to the fact that with an angular separation of $1.5''$, they both enter the field of view of the wavefront sensor and causes some tip/tilt jumps.^{7,8} Contours are very useful to compare the morphology of both PSFs and use one to subtract to the other and vice-versa.^{7,8}

2.2.2 Recognize FITS header and parameters

Currently, only a subset of the VLT instruments are recognized by ABISM. For these VLT instruments (NACO, SINFONI), the important parameters such as the central wavelength and the pixel scale are automatically loaded. In addition, ABISM will automatically use the most optimal fitting parameters for these instruments, useful to get the Strehl ratio, FWHM separation, etc. (typically the pixel scale in arcsecond per pixel, the telescope diameter and central obscuration). One can easily create a python class for ABISM to treat other instruments. ABISM can work on other instruments (a simple image, a cube of images or reconstructed integral field spectrograph 2D images like SINFONI) but the parameters must then be entered manually each time a file is loaded.

2.3 Estimate Strehl Ratio & FWHM in one click

We wanted ABISM to be really easy to use by non-AO experts and therefore once the GUI is launched and an image is loaded, the user only needs to "right-click" on the star/PSF of interest or draw a rectangle around it with the left-button of the mouse to eventually force the program to integrate a certain zone (in the case of crowding for instance).

2.3.1 2D fitting engines

ABISM can adapt to different levels of AO corrections. With classical AO systems from the 1990's and 2000's (such as NACO) and at wavelengths shorter than $2.5\mu\text{m}$, the Sr is usually $\leq 50\text{-}60\%$ and therefore the most adapted fit (especially for a circular aperture such as the VLT's) is the Moffat which is also adapted to seeing-limited images. The Bessel1 function is well adapted for higher "extreme AO" (xAO) Strehl ratios. The fit type is important because the detection of the maximum in the data will highly influence the final Strehl ratio. For oversampled images, one can chose to just take

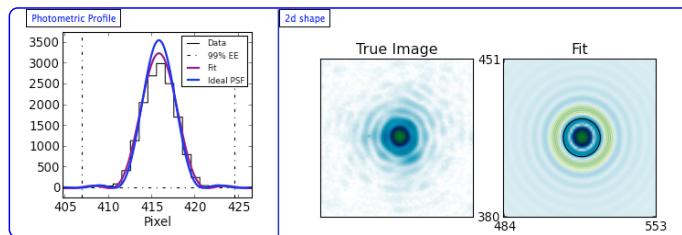


Figure 4. Example of a Bessel 2D fitting result.

2.3.2 Neighbour rejection

In the (default) single object fitting option, ABISM automatically rejects any neighbouring star or object. This is particularly useful for crowded fields (globular clusters, multiple systems, the galactic center or crowded regions in the galactic plane).

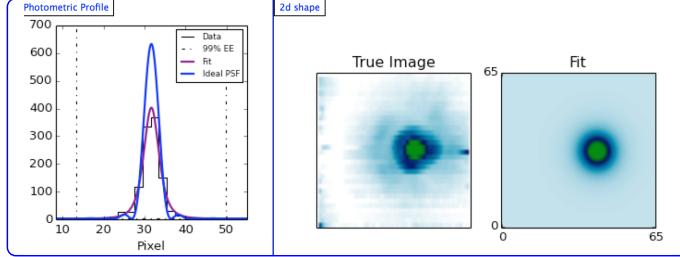


Figure 5. Example of a close companion rejection

2.3.3 Smart Background and Photometry

The default ways of measuring a SR on a single star is by either applying a right-click as close as possible to its photo-center or by drawing a rectangle with the left-button of the mouse around the star. By doing the latter, one can chose the rectangle in which the photometry will be computed. In principle, the bigger the rectangle is the more accurate the photometry (hence the background estimation) is. Of course, there are physical limitations to the detector and field of view (e.g.edges, bad pixel clusters in the IR, etc.) so one has to make a trade-off and use the biggest possible rectangle without introducing biases. The "right-click" manner of picking a star/PSF will simply use a square in which 99% of the flux is as baseline to compute the background. Several options are then possible:

- 8 rectangle boxes (ABISM computes a median value to eliminate eventual aberrant outliers). This is the best and most conservative approach when the image allows it (no crowding, large enough field of view).
- an elliptic aperture close to the star which is adapted to small fields of views.
- a manual entry of the background.

The background strategy is important because its level will highly influence the final Strehl ratio. Sometimes it is better to visually determine what the most realistic background is and use the manual entry box.

For the photometry to be used for the model PSF, ABISM can also use a rectangle box, an elliptic box, etc. The influence of the photometric aperture geometry is minor. However the final uncertainty given for the Strehl or FWHM directly depends on the signal to noise ratio of the star or PSF.

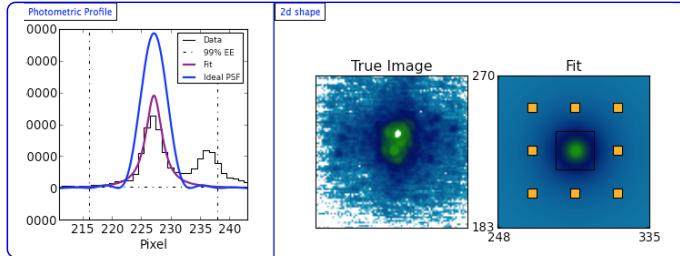


Figure 6. Example of a background adjusted to the real PSF background.

All these options are available under "More Options" which opens a special frame in the middle right hand side of the GUI window.

2.4 Basic Astrometry and Photometry

At the click close to a star (roughly on the star or drawing a rectangle around a star if the field is crowded), ABISM finds automatically the peak by performing an iterative center of gravity calculation. If proper zero points are entered in the "Parameters" frame (or read from the header), ABISM will return approximate apparent magnitudes.

ABISM is retuning the positions and FWHM of stars. ABISM does not produce distortion maps.

2.5 Other Options

- Binary Fit: fits a double peak function (Gaussian or Moffat) and determines the separation, flux ratio and position angle of a binary star (or simply between two stars).
- Physical units: by clicking on "To Sky" in the "Results" frame, ABISM converts everything to physical units (pixels into arc seconds, photometry into magnitudes if the proper zero points have been entered or read from the header).
- Pick Many: allows to perform several measurements sequentially and display the Sr to compare for instance two stars affected differently by anisoplanetic effects.
- When ABISM detects that the image is under sampled ($\text{pixel} \geq 0.5 \lambda/D$), a message is displayed in red in the "Results" box that the Sr is not suitable and that other metrics such as the encircled energy or FWHM are more appropriate.
- for NACo, ABISM is capable of detecting if an image is saturated, in the non-linear regime and will tell you in the "Results" box whether the Sr ratio is reliable or not.

2.6 How to use ABISM?

Basically, one just needs to draw a rectangle with the mouse around an isolated (and unresolved) star to get IQ parameters: Strehl Ratio, FWHM, position, etc.

- From ESO's Gasgano: Clicking on the "Script Board" icon, a small window open with a list of shell scripts. A double click on "AbismX.XX.sh" will launch ABISM, opening the FITS file that is highlighted. ABISM works better on reduced images but for NACo, it works on most RAW images as well (except for the ones acquired with the Uncorr readout mode). At the VLT, ABISM runs on the "off-line" machine of UT1, UT3 and UT4.
- From a personal computer running Python2.7: the best way to run it from the command line is to create an alias (e.g. in your .barshrc file) for ABISM and call **abism file.fits**.

2.6.1 Can ABISM be used on other instruments?

Yes! ABISM uses a Python "class" for each instrument. Different settings can be automatically set to the operator/user does not have to see the most complex settings (available from the GUI menus as shown below on the commented screenshot in Figure ??): In the (soon to be released) Advanced Manual we explain how to add more instruments (i.e create a class).

ABISM was tested with the data from the 2004 contest⁶ (simulation of the Palomar 5m telescope PSF) as well as real NACO and SINFONI PSF against other tools (internal to ESO).

Recently, it has also been used during the commissioning runs of the VLT's new planet imager SPHERE^{9,10} and gave comparable SRs than the ones measured and presented in Fusco *et al.*¹¹ in this conference.

2.7 Download & Install ABISM on your laptop

We are not professional software developers and therefore ABISM still has bugs and issues to solve. It is our intention to make it publicly available/downloadable in the very near future. Please check this web page repeatedly: github.com/tinmarino/ABISM. If you download and use ABISM, feel free to communicate with us any feedback or ideas for improvement. Also you are welcome to modify it and send us the better version. Please refer to this publication if you use ABISM or some of its source code! Currently, we lack time to improve ABISM but we will try to improve it and its documentation in the near future. Readers should free to contact us.

2.7.1 Prerequisites

- Python 2.7 (ideally), never tested on Python 3.x
- tkinter (GUI)
- matplotlib, pyfits, pywcs
- etc. (details on Github)

2.7.2 Note for Macs

Mac OS 10.x uses either X11 or Quartz as graphical environment. Depending how you configure your Python and tkinter installation, ABISM will be launched with either of them. With Quartz, the "look and feel" is more modern but the buttons' colors vanish and the fonts appear smaller.

3. STATUS AND FORESEEN IMPROVEMENTS

Here are some ideas to improve ABISM, its robustness, its known bugs or weaknesses:

- Implement a Fourier analysis (more robust to evaluate the background and remove biases, low spatial frequencies).
- Implement automatic cuts for images with any dynamic range, make sure the cuts are propagated to all sub frames and windows (currently, one needs to press enter in the "Manual cuts" box).
- Improve astrometric functionalities (currently a tight binary with a high flux ratio produces a biases position angle).
- Add classes for more instruments.
- Improve documentation and ergonomy.

4. CONCLUSION

ABISM is used extensively for quality control at the VLT for NACO and SINFONI. In addition it has been used a lot for SPHERE. Since two years the authors have had little time to keep developing it.

ACKNOWLEDGMENTS

Julien Girard would like to acknowledge The Office for Science at ESO Chile which partially supported the internship of Martin Tourneboeuf as well as the Science Operations Department which supported his two stays at the Paranal Observatory to test ABISM on site.

REFERENCES

- [1] Dumas, C., Boffin, H., Brillant, S., Hau, G., Ledoux, C., Mérand, A., Mieske, S., Pino, A., Rivinius, T., Smette, A., and Wright, A., “SciOps2.0: an evolution of ESO/VLT’s science operations model,” in [*Observatory Operations: Strategies, Processes, and Systems V*], *Proc. SPIE* **9149**, 91491G (Aug. 2014).
- [2] Lenzen, R., Hartung, M., Brandner, W., Finger, G., Hubin, N. N., Lacombe, F., Lagrange, A., Lehnert, M. D., Moorwood, A. F. M., and Mouillet, D., “NAOS-CONICA first on sky results in a variety of observing modes,” in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], M. Iye & A. F. M. Moorwood, ed., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **4841**, 944–952 (Mar. 2003).
- [3] Rousset, G., Lacombe, F., Puget, P., Hubin, N. N., Gendron, E., Fusco, T., Arsenault, R., Charton, J., Feautrier, P., Gigan, P., Kern, P. Y., Lagrange, A., Madec, P., Mouillet, D., Rabaud, D., Rabou, P., Stadler, E., and Zins, G., “NAOS, the first AO system of the VLT: on-sky performance,” in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], P. L. Wizinowich & D. Bonaccini, ed., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **4839**, 140–149 (Feb. 2003).
- [4] Girard, J. H. V., Kasper, M., Quanz, S. P., Kenworthy, M., Rengaswamy, S., Schoedel, R., Dobrzycka, D., Gallenne, A., Gillessen, S., G., Huerta, N., Kervella, P., Kornweibel, N., Lenzen, R., Lundin, L., Mérand, A., Montagnier, G., O’Neal, J., Witzel, G., and Zins, G., “Status and new operation modes of the versatile VLT/NaCo,” in [*Adaptive Optics Systems II, Proceedings of the SPIE*], Hubin, N., E., M. C., and Wizinowich, P. L., eds., *Astronomical Instrumentation* **7736**, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series (July 2010).
- [5] Girard, J. H. V., O’Neal, J., Mawet, D., Kasper, M., Zins, G., Neichel, B., Kolb, J., Christiaens, V., and Tourneboeuf, M., “Image quality and high contrast improvements on VLT/NACO,” in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8447** (July 2012).
- [6] Roberts, Jr., L. C., Perrin, M. D., Marchis, F., Sivaramakrishnan, A., Makidon, R. B., Christou, J. C., Macintosh, B. A., Poyneer, L. A., van Dam, M. A., and Troy, M., “Is that really your Strehl ratio?,” in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], Bonaccini Calia, D., Ellerbroek, B. L., and Ragazzoni, R., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **5490**, 504–515 (Oct. 2004).
- [7] Girard, J., “Direct Imaging and Interferometric Followup of Our Closest Low-Mass Stellar Neighbors,” in [*Habitable Worlds Across Time and Space, proceedings of a conference held April 28-May 1 2014 at the Space Telescope Science Institute. Online at jA href=”http://www.stsci.edu/institute/conference/habitable-worlds”>http://www.stsci.edu/institute/conference/habitable-worlds, id.17*], 17 (Apr. 2014).
- [8] Rodigas, T. J., Weinberger, A., Mamajek, E. E., Males, J. R., Close, L. M., Morzinski, K., Hinz, P. M., and Kaib, N., “Direct Exoplanet Detection with Binary Differential Imaging,” *ApJ* **811**, 157 (Oct. 2015).
- [9] Beuzit, J.-L., Feldt, M., Mouillet, D., Dohlen, K., Puget, P., Wildi, F., and SPHERE Consortium, “SPHERE: a planet imager for the VLT,” in [*In the Spirit of Lyot 2010*], 44 (Oct. 2010).
- [10] Kasper, M., Beuzit, J.-L., Feldt, M., Dohlen, K., Mouillet, D., Puget, P., Wildi, F., Abe, L., Baruffolo, A., Baudoz, P., Bazzon, A., Boccaletti, A., Brast, R., Buey, T., Chesneau, O., Claudi, R., Costille, A., Delboulbé, A., Desidera, S., Dominik, C., Dorn, R., Downing, M., Feautrier, P., Fedrigo, E., Fusco, T., Girard, J., Giro, E., Gluck, L., Gonte, F., Gojak, D., Gratton, R., Henning, T., Hubin, N., Lagrange, A.-M., Langlois, M., Mignant, D. L., Lizon, J.-L., Lilley, P., Madec, F., Magnard, Y., Martinez, P., Mawet, D., Mesa, D., Müller-Nilsson, O., Moulin, T., Moutou, C., O’Neal, J., Pavlov, A., Perret, D., Petit, C., Popovic, D., Pragt, J., Rabou, P., Rochat, S., Roelfsema, R., Salasnich, B., Sauvage, J.-F., Schmid, H. M., Schuhler, N., Sevin, A., Siebenmorgen, R., Soenke, C., Stadler, E., Suarez, M., Turatto, M., Udry, S., Vigan, A., and Zins, G., “Gearing up the SPHERE,” *The Messenger* **149**, 17–21 (Sept. 2012).
- [11] Fusco, T., Sauvage, J.-F., Petit, C., Costille, A., Dohlen, K., Mouillet, D., Beuzit, J.-L., Kasper, M., Suarez, M., Soenke, C., Fedrigo, E., Downing, M., Baudoz, P., Sevin, A., Perret, D., Baruffolo, A., Salasnich, B., Puget, P., Feautrier, F., Rochat, S., Moulin, T., Deboulbé, A., Hugot, E., Vigan, A., Mawet, D., Girard, J., and Hubin, N., “Final performance and lesson-learned of SAXO, the VLT-SPHERE extreme AO: from early design to on-sky results,” in [*Adaptive Optics Systems IV*], *Proc. SPIE* **9148**, 91481U (Aug. 2014).