ANDROMEDA: User-manual
Version-1.0

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Contents

List of the files included in the package:
- README containing a summary of instructions and important information for quick hands on;
- IDL library, *libANDROMEDA*, containing all the needed functions and procedures to run ANDROMEDA;
- Batch to process images from VLT/NaCo (TYC-8979-1683-1) which are inside the example folder;
- This user-manual containing detailed information on how to use the input, output etc.;
- The papers *Mugnier et al., 2009* and *Cantalloube et al., 2015* containing a respectively theoretical and practical description of the ANDROMEDA method.

If you are willing to use this software, please contact the authors: faustine.cantalloube@univ-grenoble-alpes.fr and/or laurent.mugnier@onera.fr and/or david.mouillet@univ-grenoble-alpes.fr.

1 ANDROMEDA: Summary of the different steps

ANDROMEDA is an ADI-based algorithm which analytically estimates the position and flux of point sources present in the field of view thanks to a maximum likelihood estimation (MLE). This algorithm thus allows the user to perform an automatic detection, and the detected point sources are associated with a probability of presence. It also provides a direct estimate of the flux without any bias due to subtraction. The detection limit can be directly computed from the ANDROMEDA output, without needing extensive processing of the images. To give a rough idea, ANDROMEDA runs in about 20 minutes for a 512x512x128 images cube. Its overall performance in terms of detection capabilities is limited by the ADI process so it shows the same acuteness than common ADI-based methods such as LOCI or PCA.

Two main calls are made by the software:

-The function `ANDROMEDA.PRO` delivers three main output: a *flux map*, a so-called *SNR map* and a *flux standard deviation map* (see Sect. 2 for details about its input and Sect. 3 for details about its output).

-The procedure `DETECTION_ANDROMEDA.PRO`, uses these output to perform the detection, to derive the astrometry and photometry of the probable companions and to compute the detection limit. The latter was developed in line with the characteristics of the ANDROMEDA function, but could be used for other purposes if similar input are given (see Sect. 4).

Fig.1 is a summary of the different steps performed by the method to process on-sky data.

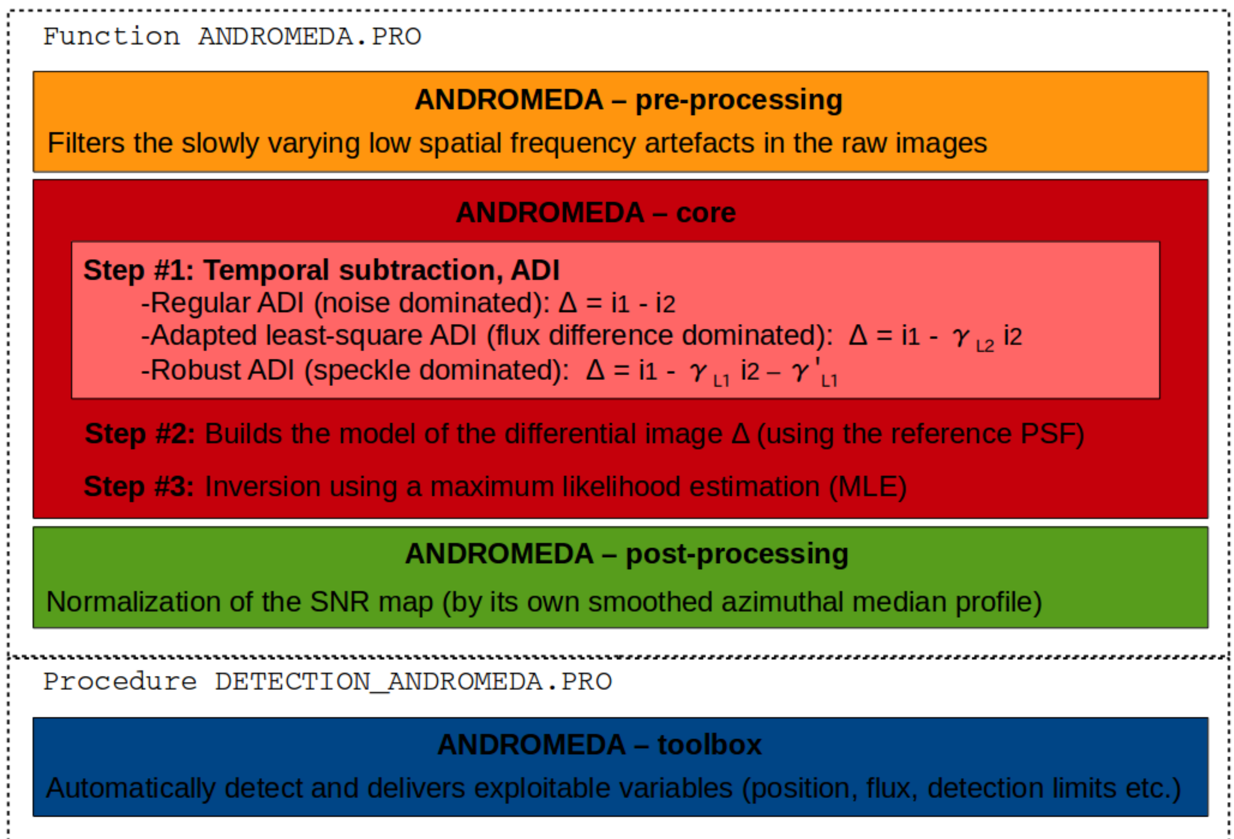


Figure 1: Detailed description of the different steps performed by the ANDROMEDA software.

The whole operational algorithm is described in Cantalloube et al. 2015, including the description of additional steps that are necessary to run ANDROMEDA on real data.

2 Required input to run ANDROMEDA

The classical use of ANDROMEDA is ADI only. Below is the description to run ANDROMEDA in ADI only, see the last subsection for hints to run the SDI+ADI mode of ANDROMEDA.

2.1 Science frames: `IMAGES_1_INPUT`

The images must be either saturated or coronagraphic and taken in pupil tracking mode.
Its dimension should be: $(N_{pix}, N_{pix}, N_{img})$, where N_{img} is the total number of images in the cube and N_{pix} the number of pixels along the x and y axis.

-The images must be square and N_{pix} even.

-The images must be centered in between four pixels.

That is to say (in IDL), if the images size are of $N_{pix} \times N_{pix}$ (eg. 600 x 600 px) then the center must be set in between the pixel number $N_{pix}/2. - 1$ and $N_{pix}/2.$ (eg. 299 and 300). The computations are made assuming that the center lays at $(N_{pix} - 1)/2.$ (eg. at 299.5).

If the images are not centered, the Onera function *images_centered.pro* can be used to shift the image of a subpixel amount. This function uses Fourier transforms to avoid interpolation between pixels. For instance, if the images are centered on the central pixel $[N_{pix}/2.; N_{pix}/2.]$ (eg. [300;300]) -as it is the case with the SPHERE data reduced with the DRH client-, its use is the following to shift the images in between four pixels:

$$\begin{array}{l} images\_centered = dblarr(Npix, Npix, Nimg) \\ FOR\ \ i = 0,\ \ Nimg - 1\ \ DO\ \ \$ \\ images\_centered[0, 0, i] = SUBPIXEL\_SHIFT(images[*, *, i], x = -0.5, y = -0.5) \end{array} \tag{1}$$

Otherwise, it is also possible to use the built-in option in andromeda.pro by adding the coordinate of the centers of *each* frame within the cube as an input of the function: `COORD_CENTRE_1_INPUT = center_image` with the following definition of the center:

$$\begin{array}{l} center\_image = dblarr(2, Nimg) \\ center\_image[0, n_i] = x\_cent \\ center\_image[1, n_i] = y\_cent \end{array} \tag{2}$$

Where $Nimg$ is the total number of images in the cube, x_cent and y_cent the fraction of pixels from which the center is shifted respectively along the x and y direction in the regarded image n_i.

Note that images might have /NaN or outliers (usually on the edges) that could corrupt the MLE (since the model of noise is then completely inconsistent). Thus it is advised to check the edges and, if needed, to crop the images to get rid of these /NaN values (which usually do not impact other algorithms such as c-ADI).

2.2 Reference PSF: `PSF_PLANET_INPUT`

The so-called *reference PSF* is used to build the model of a planetary signature which is then sought by performing a MLE. This reference PSF is the non-coronagraphic image of the star or the unsaturated image of the star (so that the star is the dominant object in the image, hence the "PSF" denomination). The time when this reference PSF is taken wrt to the observations does not matter since this version of ANDROMEDA does not include a follow-up of the PSF quality with time. Of course it is however better to have a PSF whose Sthrehl ratio (SR) is as close as possible to the mean SR of the science cube frames.

-The reference PSF must be in a square window of even size N_{psf}.

-The reference PSF must be centered in between four pixels.

-The size of the PSF window must be small enough to reduce the running time and large enough to include at least the central core. It is advised to include the secondary ring within the window.

To crop the PSF around its center, the function *centering_max.pro* can be used. It works as follow:

$$psf\_planet = centering\_max(psf, Npsf) \tag{3}$$

Where $Npsf$ is the new dimension of the PSF used as an input for ANDROMEDA.

Note that if the PSF centering is shifted of 3 pixels, it biases the astrometry by up to 3 pixels (depending on the position of the companion in the field and the direction of the PSF core shift). **Thus, the reference PSF and images centering must be carefully made before running the ANDROMEDA function.**

2.3 Parallactic angles: `ANGLES_INPUT`

The angles must be given as a vector of dimension $Nimg$ and should follow the same order than the image cube (eg. images_input[*,*,1] have the parallactic angle given by angles_input[1]).

If there is a corresponding offset angle wrt to the true North direction, it is possible to include it in the ANDROMEDA function via the keyword `ROTOFF_INPUT` which takes this offset angle as an input.

Both the parallactic angles and the rotoffset must be given in degrees.

Note that some reduction pipelines give the inverted set of angles compared to the one needed by ANDROMEDA. ANDROMEDA has been set to handle the data output by the DRH client of SPHERE but if one is using another reduction pipeline, it happens that -angles should be input instead of +angles (it is the case with the NaCo data of TYC-8979-1683-1 given in the Example folder of the package). Thus, if ANDROMEDA does not seem to provide the correct SNR maps, it is advised to try running the algorithm on a well known target to check the angles sign.

2.4 Oversampling factor: `OVERSAMPLING_1_INPUT`

The oversampling factor is needed to convert from pixels to lambda/D units within the ANDROMEDA process. We recall that the oversampling factor is one at Shannon, else it is greater than one. This factor can be computed knowing the wavelength of the images ($lambda$, given in meters) and the pixel scale of the camera under use ($pixscale$, given in mas/px), following:

$$\begin{array}{c} pixscale\_nyquist = (1/2. * lambda/D)/!dpi * 180. * 3600. * 1.e3 \\ OVERSAMPLING\_1\_INPUT = pixscale\_nyquist/pixscale \end{array} \tag{4}$$

With D the diameter of the telescope entrance pupil in meters (for the VLT, $D = 8.0$m).

2.5 User-defined parameters to run the ANDROMEDA function.

There is *seven* user-defined parameters needed to run ANDROMEDA, within which only two have to be fine tuned. Here is a description of these parameters in the order of their use in the ANDROMEDA call.

2.5.1 High-pass filtering of the raw data: `FILTERING_FRACTION_INPUT`

The filtering fraction, that is to say the amount of low spatial frequencies removed from the raw images, must be specified. This parameter stands between 0 (no filtering) and 1 (everything is removed). Its highest theoretical value is limited by the cutoff spatial frequency, that is $1/oversampling$.

`FILTERING_FRACTION_INPUT` default value is set to 1/4 (if this keyword is not provided or set to 0).
If `FILTERING_FRACTION_INPUT = 1`, no filtering is performed.
If `FILTERING_FRACTION_INPUT` has a value less than 0 or greater than 1, an error message is returned.

To remain consistent with the ANDROMEDA's principle, the ANDROMEDA function filters the PSF used to build the model for the MLE *in the exact same way* as the filtering applied to the images. This way, the flux estimation is not biased and can be directly retrieved.

2.5.2 Inner working angle: `IWA_INPUT`

The distance to the star from which the search for companions is started (given in λ/D unit). This value is limited by the total field rotation of the frames (Δ_{parang}): If the frames do not have enough field rotation, either this value should be increased or the value δ_{min} decreased (see following subsection).

`IWA_INPUT` default value is set to 1.0 lambda/D (if this keyword is not provided or set to 0).

2.5.3 Parameters for the ADI: `MINIMUM_SEPARATION_INPUT` and `ANNULI_WIDTH_INPUT`

Any ADI-based method is limited by the choice of the minimum angular separation, δ_{min} between the companion in the first frame and its position in the frame to be subtracted. This angular separation (given in λ/D unit) should be as close as possible for the speckles to be stable enough between the two frames and, at the same time, it must be large enough to avoid the self-subtraction of the companion. This value might have a major impact if the quasi-statics speckles are quickly moving in the field. If the speckle field is temporally stable, then it is advised to favor a large δ_{min} to efficiently separate the two signals, which will be beneficial for the ANDROMEDA MLE.

MINIMUM_SEPARATION_INPUT default value is set to 0.5 lambda/D (if this keyword is not provided or set to 0).

As this value varies with the distance from the star, ANDROMEDA performs the image differences for annuli centered around the star. The width of these annuli, d_r, (also called *subtraction area*) must be given as an input (in λ/D unit). The size of the annuli does not have a major impact in the process.
ANNULI_WIDTH_INPUT default value is set to 1.0 lambda/D (if this keyword is not provided or set to 0).

Note that the whole images are subtracted one to another (resulting in a so-called *differential image*, and that the MLE is done over the whole field of view. Only the determination of couples to be subtracted within the limit given by δ_{min} are considered, at each distance from the star, separated of d_r.

2.5.4 Optimization method for the ADI: OPT_METHOD_ANG_INPUT and RATIO_OPT_AREA_INPUT

Several methods can be used to perform the ADI of the images $i(t_1)$ and $i(t_2)$. The parameter opt_method_ang_input is an integer which calls for one of these methods:
-If opt_method_ang_input = 1: no optimization is performed.
The differential image is simply $\Delta = i(t_2) - i(t_1)$. This basic subtraction is advantageous when the noise (other than speckle noise) is dominant in the images.
-If opt_method_ang_input = 2: a so-called 'total ratio' optimization is performed.
The differential image is created following $\Delta = i(t_2) - \gamma_{TR}\, i(t_1)$, with $\gamma_{TR} = \sum_{(x,y)} i(t_1) / \sum_{(x,y)} i(t_2)$. This method must not be used if the images have been pre-filtered since the mean of the filtered images is set to zero, which makes the computation of γ_{TR} diverge.
-If opt_method_ang_input = 3: a so-called 'least-square' optimization is performed.
The differential image is $\Delta = i(t_2) - \gamma_{LS}\, i(t_1)$, with $\gamma_{LS} = \sum_{(x,y)} i(t_1).i(t_2) / \sum_{(x,y)} i(t_2)^2$. This method is advantageous when the average flux difference between the two annuli is dominant. However this fit can be biased by the presence of high intensity signals (either from planets or speckles) in one of the images. Moreover the radial flux evolution of the star PSF is not spatially linear, as assumed by this fit.
-If opt_method_ang_input = 4: a so-called 'L1-affine' optimization is performed.
The differential image is $\Delta = i(t_2) - \gamma i(t_1) - \gamma'$, with γ and γ' computed using a robust estimation (using bracketing and bisection, see Numerical Recipes 3rd edition (2007) - p.818). This method is advantageous when the flux of some residual speckles varies a lot from one image to another.
OPT_METHOD_ANG_INPUT default value is set to 3 (least-square optimization).

As the optimized subtraction can induce discontinuities between adjacent annuli (if gamma varies a lot), the optimization (the computation of the gamma factors) is made over an *optimization area* which is equal or wider than the effective *subtraction area*. The ratio between the subtraction to the optimization area, R_A, must be set equal or greater than 1.
RATIO_OPT_AREA_INPUT default value is set to 2.

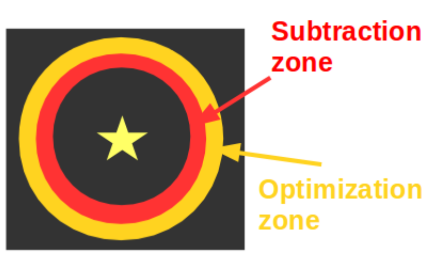


Figure 2: Description of the subtraction zone (red annulus) and the optimization zone (red and orange annuli).

2.5.5 Normalization of the SNR map: NSMOOTH_SNR_INPUT

As the model of noise is inconsistent with the real residual noise distribution in the differential images (assumed to be white and Gaussian), mostly at short separation, there is a discrepancy between the given threshold and the probability of false alarm. Instead of tunning the threshold as a function of the distance to the star, one idea is to empirically get rid of this radial trend by normalizing the SNR map by its own radial profile. This profile is obtained by computing the azimuthal variance at each distance from the star. The robust variance is actually

computed to avoid taking into account outliers (such as substellar companions).
The profile is then smoothed over a certain number of pixels given by the value N_{smooth}. This smoothing allows the user to take into account the global radial trend and not the detailed variance profile. Also one considered pixel is smoothed wrt to the pixels at larger separation (and not to pixels before *and* after).

If N_{smooth} is too large, then the information about the radial trend is lost (since it becomes an almost flat profile) and consequently, too many artifacts could appear above threshold and regarded as detections. If N_{smooth} is too small, the normalization profile may be quite jagged (if the speckle field is varying a lot through time) though only the global trend is needed for the normalization. Thus this normalization factor depends on the quality of the data.

For basic SPHERE data, N_{smooth} can be quite low since the speckle field is stable and the ADI subtraction is quite homogeneous.

`NSMOOTH_SNR_INPUT` default value is set to 18 pixels (if this keyword is not provided).
If `NSMOOTH_SNR_INPUT = 1`, no normalization is performed.

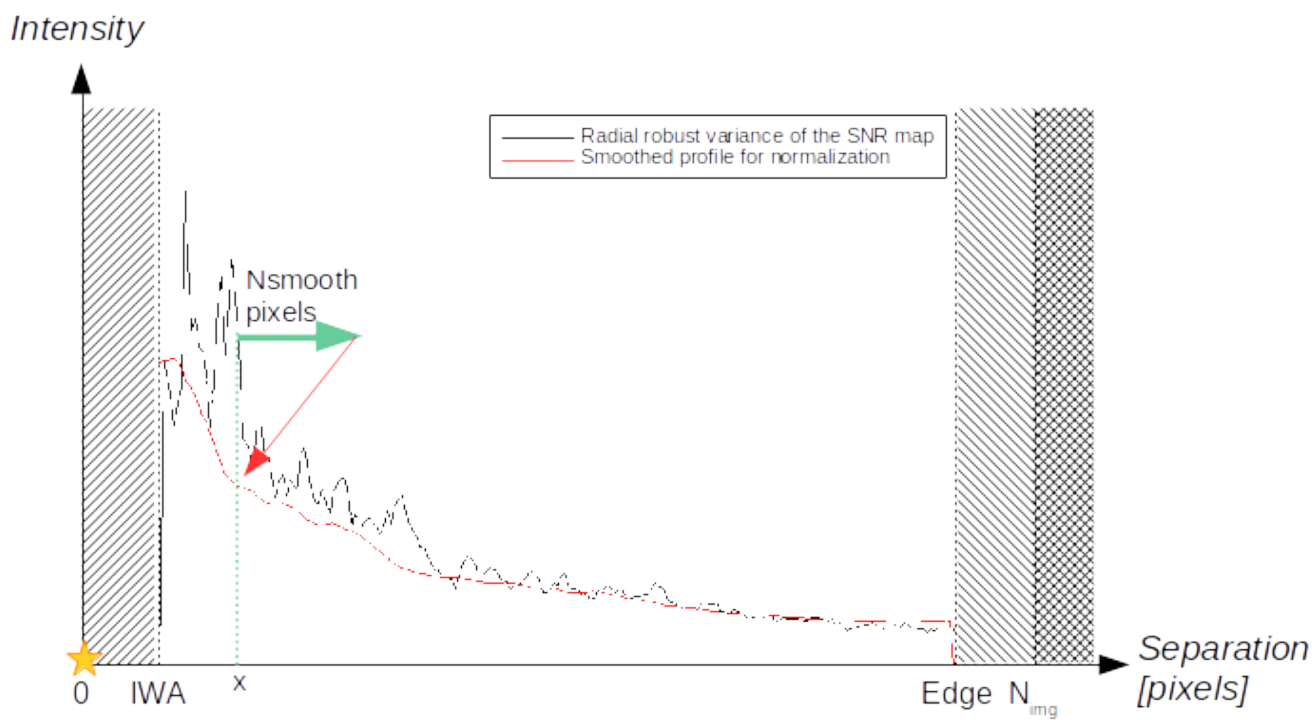


Figure 3: Schematic drawing of the smoothing made to build the normalization profile (red curve).

It is advised in a first step to perform the normalization *after* the ANDROMEDA function ran. The normalization can be done by using the function `normalize_snr.pro` which needs as input: the SNR map, the chosen N_{smooth}, the IWA and OWA (via respectively the keywords `dmin_input` and `dmax_input`, both given in pixels). It is thus possible to change the N_{smooth} value quickly and visualize the profiles used (by using the keyword `/SHOW`), to check if it is consistent with the data. (Note that it is possible to perform a polynomial fit of the 4th order, by using the keyword `/FIT`, but it is not efficient in practice). This function also provides the 2D image of the smoothed profile, via `snr_stddev_output`, which must be used to normalize the standard deviation of the flux map in the same way. **The detection procedure must be launched using the normalized SNR map and on the normalized flux standard deviation map.**

NB: This normalization procedure artificially increases the SNR close to the star, but since $SNR = \hat{a}/\sigma(\hat{a})$, this is taken into account inside the estimated flux error-bars (which therefore increases). That is why the flux standard deviation map ***must*** *be normalized by the same profile than the one used to normalize the SNR. However, the normalization* ***does not*** *impact the flux estimation which remains the same. In other words, this normalization procedure 'helps' to detect companions close to the star and the associated probability of presence should be read with care.* ***However, the flux estimation is not biased by this method.***

2.5.6 Summary of the user-defined parameters and their impacts

The table below recalls the user-defined parameters and their impact on the companion extraction with ANDROMEDA for either NaCo like or SPHERE like data. For the NaCo data, more details about these parameters can be found in Cantalloube et al. (2015).

Table 1: Summary of the user-defined parameters default values and their respective significance.

Parameter	**Definition**	**Units**	**Default value**	**Impact**
F	Filtering fraction	-	NaCo: 1/4	low
			SPHERE: 1/6	low
$\delta_{\min}$	Minimum separation to build the differential images	λ/D	NaCo: 0.5	high
			SPHERE: 0.5	low
dr	Width of annuli on which ADI is performed	λ/D	1	low
Opt_meth	Optimization method used for ADI	#	NaCo: 3	high
			SPHERE: 1	low
R_A	Ratio optimization to subtraction areas	-	2	low
N_{psf}	Size of the square PSF image	pixels	see text	low
N_{smooth}	Smoothing of the S/R robust standard deviation profile	pixels	NaCo: 18	high
			SPHERE: 2	low

3 Output provided by the ANDROMEDA function.

In this section, the output are described, regardless of the user-parameters used to run ANDROMEDA. This section intents at giving an idea of how to interpret images in the ideal use of the software.

3.1 SNR map: `SNR_OUTPUT`

This is a 2D image, given in sigma units. *Its value at a given pixel position is linked with the probability of presence of a point source to be at this exact pixel position.* That is to say, the higher the value, the higher the probability of presence of a planetary companion.

This map is thus used to perform the **detection**, by simply thresholding it by a constant value (usually 5-sigma). Hence the automatic detection that the ANDROMEDA solution enables.

The usual shape of a planetary signal is oval, its major axis within the star-companion direction (see Fig. 4b-*Left*). This map is also used to derive the **astrometry** of the detected point sources by performing a 2D Gaussian fit of the planetary signal. The estimated sub-pixel position of the companion is given by the maximum of the Gaussian fit.

3.2 Flux map: `FLUX_OUTPUT`

This is a 2D image given in ADU units. *Its value at a given pixel position is the value of the flux that would have a signal at this exact pixel position.* The flux is given with respect to the PSF flux given as an input (`PSF_PLANET_INPUT`).

This maps is thus used to derive the **photometry** of the detected point sources by performing a 2D Gaussian fit of the planetary signature and retrieving the value of the flux at the sub-pixel position estimated earlier in the SNR map.

3.3 Flux standard deviation map: `STDDEVFLUX_OUTPUT`

This is a 2D image given in ADU units. *Its value at a given pixel position is the 1-sigma error on the estimated flux.* This map thus gives the errorbars on the companions estimated flux by simply reading the value at the subpixel position retrieved earlier.

This maps is thus used to derive the **detection limit** of the data set by averaging the azimuthal values to build its radial profile which is the detection limit at 1-sigma.

We thus have `SNR_OUTPUT` = `FLUX_OUTPUT` / `STDDEVFLUX_OUTPUT`, hence the similarity between the SNR and the flux map.

3.4 Other useful output

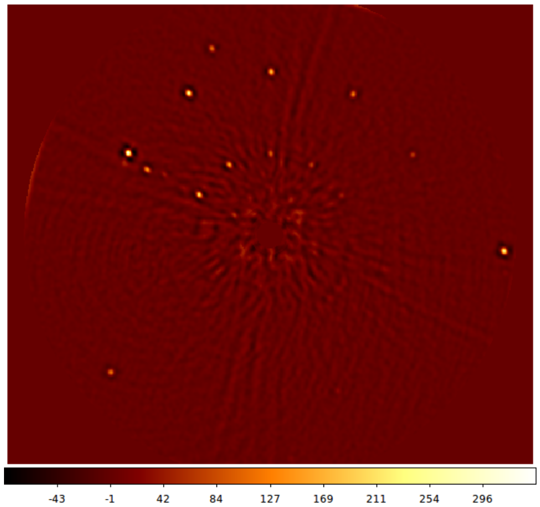
3.4.1 Likelihood map: `LIKELIHOOD_OUTPUT`

The 2D map of the computed likelihood. This output is not useful for the planetary companions extraction.

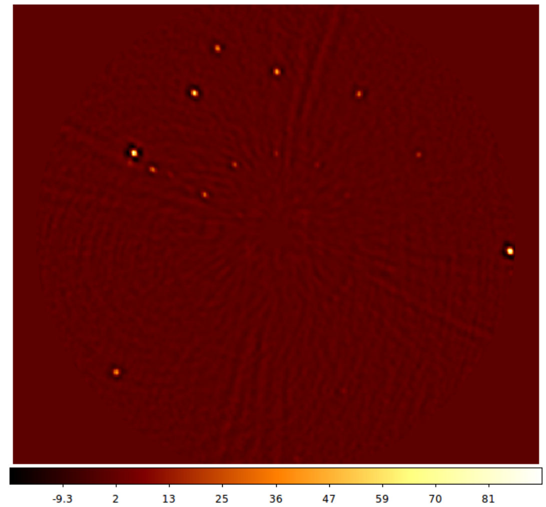
3.4.2 Information about the scaling and affine factors: `GAMMA_INFO_OUTPUT`

If asked in output, this value contains information about the scaling factor(s) that can be useful to better understand the noise distribution in the data (and choose for the most relevant ADI method).
`GAMMA_INFO_OUTPUT`[0,*,k] = min(factor)
`GAMMA_INFO_OUTPUT`[1,*,k] = max(factor)
`GAMMA_INFO_OUTPUT`[2,*,k] = mean(factor)
`GAMMA_INFO_OUTPUT`[3,*,k] = median(factor)
`GAMMA_INFO_OUTPUT`[4,*,k] = variance(factor)

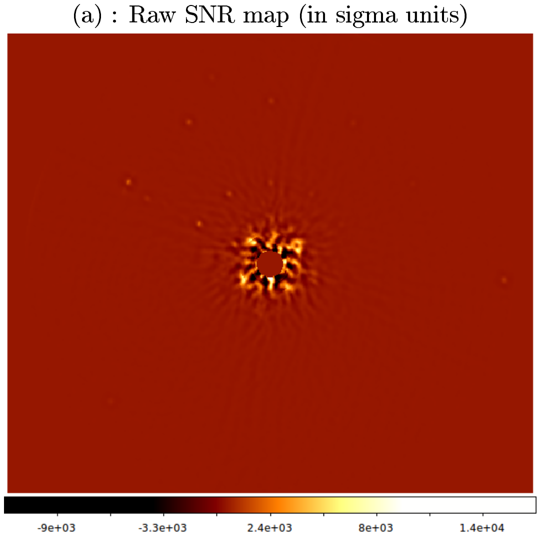
Where '*' is 0 (linear factor, γ) or 1 (affine factor, γ') and k the index of the couple of images that have been subtracted (ie. index of the differential image).



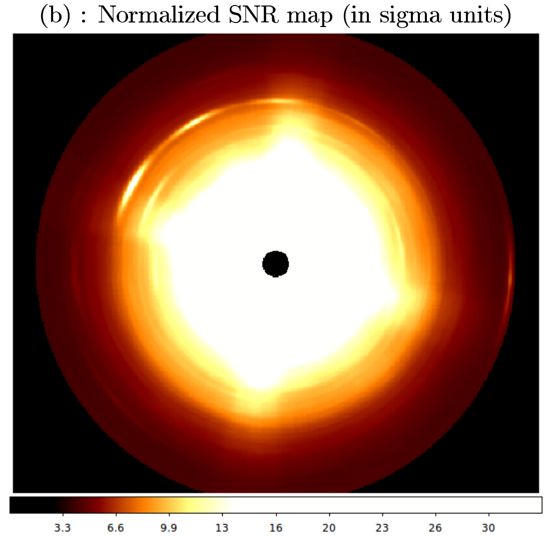
(a) : Raw SNR map (in sigma units)



(b) : Normalized SNR map (in sigma units)



(c) : Flux map (in ADU units, to be translated in contrast terms)



(d) : Normalized map of the standard deviation of the flux (in ADU units)

Figure 4: Maps output by the ANDROMEDA function and from which are made the detection, the astrometry, the photometry and the detection limit estimation.

3.4.3 Maximum investigated distance from the star: `EXT_RADIUS_OUTPUT`

Given the size of the psf used as a model and the width of each investigated annuli, this output gives the value (in lambda/D) of the farthest annulus investigated by ANDROMEDA (See Fig. 3). This output is useful to be aware of the range of distance from the star where a planetary companion is looked for (from IWA to this OWA value) and is used as an input of the function `normalize_snr.pro`.

3.5 SADI mode of ANDROMEDA

There is an SDI+ADI mode included in ANDROMEDA, which is intended to process images taken in pupil tracking simultaneously at two wavelengths.

This SDI mode simply spatially shrinks one of the image to correspond to the wavelength of the other, by using a basic rescaling model in λ^2. The shrank image is then subtracted to the other image. After this step, ANDROMEDA runs in basic ADI mode, as described in the previous sections, on the spectrally subtracted image. As a consequence this ANDROMEDA-SADI mode is fully adapted in the two following cases:

1. In one of the image, the companion is *completely absent* (it corresponds to an absorption band in the planet atmosphere). This image is the one that must be rescaled in wavelength and subtracted to the other;

2. Or the companion angular separation to the star is great enough to have at least a $1\lambda/D$ radial shift in the two images when rescaling in wavelength.

Thus this option performs a very basic SDI, not fully adapted to ANDROMEDA, yet very efficient to better subtract the speckles and reveal detections in the field of view, particularly in the two cases mentioned above.

Only two more keywords are required to run ANDROMEDA in this mode:

`-IMAGES_2_INPUT`, which contains the image cube to be rescaled in wavelength.

`-OVERSAMPLING_2_INPUT`, the oversampling factor at the wavelength to be subtracted.

These input must have the same characteristics than the input at the main wavelength (centered in between four pixels, same parallactic angles etc.). The reference PSF used to build the model for the MLE, `PSF_PLANET_INPUT`, is thus the one corresponding to the 1st wavelength (of `IMAGES_1_INPUT`, not rescaled).

Note that the optimized subtraction evoked at Sect. 2.5.4 are possible to perform the spectral subtraction via the keyword `opt_method_spec_input` whose input are defined the same way (but for the images at the main wavelength and the rescaled images). By default the chosen optimization method for the spectral subtraction is the same than the optimization method chosen for the temporal subtraction.

3.6 Multispectral data processed with ANDROMEDA

For now, no specific work has been done to adapt ANDROMEDA to multispectral data. However, simply making a `FOR loop` on all the wavelengths of the multispectral cube to run ANDROMEDA, had proved efficient to retrieve the companions spectrum.

The N_λ SNR maps obtained can be combined (stack or correlation map) to perform the detection. Once the detection is made and the astrometry retrieved, it is possible to simply read the flux of the detections on the N_λ flux maps obtained to derive the full spectrum of the detection. This spectrum must be associated with the standard deviation spectrum at each wavelength by following the same procedure but reading the standard deviation of the flux map instead of the flux map (at a given threshold). This last step directly gives the confidence of level of the flux estimation, in line with the detection capabilities of ANDROMEDA.

In other words, if the companion is not visible in the SNR map, the flux is however retrieved in the flux map (along with the errorbars given by the standard deviation of the flux map). That is why it is necessary to note the SNR of the companion in each band.

4 Automatic detection and characterization procedure

This section describes how to exploit the previously described output by using the `detection_andromeda.pro` procedure to automatically extract the companions information. It also describes how to interpret the files produced by this procedure.

Important: *Before launching the characterization (and the post-processing, if this step is done afterwards), you sometimes must redefine the variables defined before the ANDROMEDA function call. This is due to IDL which does not handle properly the calls to several variables having the same name inside the functions called.*

4.1 Input needed for the analysis module

The required input for the analysis of the maps provided by the Andromeda functions are the following:

4.1.1 SNR map: `SNR_MAP_INPUT`

The normalized SNR map (see ANDROMEDA output).
This map is used to perform the automatic detection and to retrieve the position of the detections (at the maximum of the detected signal, ie: where its probability of presence is higher). On this map, the SNR of a detected signal is simply read (in units of sigma) but as reminded above, close to the star, this retrieved value should be interpreted with care since the normalization procedure artificially biases it.

4.1.2 Flux map: `FLUX_MAP_INPUT`

The flux map (see ANDROMEDA output).
On this map, the estimated flux of the detected signals are simply read, at the estimated subpixel position.

4.1.3 Flux standard deviation map: `STDDEVFLUX_MAP_INPUT`

The normalized map of the flux standard deviation (see ANDROMEDA output).
This map is used to compute the detection limit (given by performing an azimuthal median of this map) and to compute the errorbars on the flux estimations (since this map gives the 1σ errors on the flux estimation).

4.1.4 Reference PSF: `PSF_PLANET_INPUT`

The cropped and centered reference PSF used as an input of the Andromeda function (see ANDROMEDA input).

4.1.5 Chosen threshold: `THRESHOLD_INPUT`

The value by which the normalized snr map will be thresholded (given in sigma). In other words, *any signal inside the SNR map whose value is greater than the threshold will be regarded as a detection.* These detections will be later sorted out upon morphological criteria to reject potential remaining artifacts.

Default is set to 5σ since it is linked with a substantial probability of presence. However, in case signals are faint, one should try a lower threshold.

4.1.6 Size of the subimages for the detected signal analysis: `SIZE_SUBWINDOW_INPUT`

Size of the subwindow in which the detected signal will be analyzed (in the SNR map and in the flux map): The planetary signal pattern must be fully enclosed in the subwindow (see Fig. **??**). The size of the subimages must be given in number of pixels and must be odd (the sub-window is then automatically made square) else it is automatically set to `SIZE_SUBWINDOW_INPUT`+1.

`SIZE_SUBWINDOW_INPUT` default value is set to: 3lambda/D (typical window size needed).

4.1.7 Distance to tertiary lobes artifacts (if image filtering has been applied): `DIST_NEIGHBOURS_INPUT`

Distance at which two very close signals could be a primary and a tertiary lobe due to the pre-filtering procedure (in pixels) - see paper for more details.

`DIST_NEIGHBOURS_INPUT` default value is set to: 5lambda/D (typical distance to a third lobe artifact).

4.1.8 Chosen threshold: DITIMG_INPUT

Exposure time of the science images (in seconds).
DITIMG_INPUT default value is set to: 1 second.

4.1.9 Chosen threshold: DITPSF_INPUT

Exposure time of the reference PSF image (in seconds).
DITPSF_INPUT default value set to the same than DITIMG_INPUT.

4.1.10 Chosen threshold: TND_INPUT

If a neutral density was used to image the reference PSF, then this is the transmission factor of this neutral density (between 0 and 1).
TND_INPUT default value set to: 1 (ie: transmission factor of 100%).

Note that this input can also be used to put any other factor that would affect the image flux to reference PSF flux ratio (e.g: the transmission factor of the coronagraph, the airmass etc.)

4.1.11 Other parameters:

The following parameters are also needed to perform the automatic detection:
- PIXSCALE_INPUT: Pixel scale of the camera under use, in units of mas/pixel.
- IWA_INPUT: See ANDROMEDA.pro input. Closest distance to the star investigated, in lambda/D units.
- EXT_RADIUS_INPUT: See ANDROMEDA.pro output. Farthest distance to the star investigated, in lambda/D units.

4.1.12 Filenames:

The filenames in which results will be stored must be given as an input (string arrays).
The following keywords must refer to:

- FILENAME_DETECTION: the name of the '.dat' file containing the detection estimations (see next section).
- FILENAME_ERRORS: the name of the '.dat' file containing the errorbars of the detection estimations (see next section).
- SUBIMAGES_NAME: the name of the '.png' image created showing the subimages containing the potential planetary signal and in which the detection analysis is made (see Fig. 8a).
- DETECTION_MAP_NAME: the name of the '.png' image created showing the SNR map with each detection indexed (see Fig. 8b).
- DETLIM_PNG_NAME: the name of the '.png' image created showing the detection limit curve and the detections at the given threshold (see Fig. 5a).
- DETLIM_FITS_NAME: the name of the '.fits' file containing the detection limit curve at the given threshold.

4.2 Output given by the detection and characterization procedure

This section describes the output of the detection module and how to interpret them.

4.2.1 Images and screen display

Three images are displayed and recorded when launching the detection procedure:

1. The subimages, recorded in the '.png' file SUBIMAGES_NAME, (see the Fig. 8a for an example). Each detection is analyzed within such a subwindow (whose size is given as the user-parameter SIZE_SUBWINDOW_INPUT in pixels) which should fully enclose the planetary like signal. A 2D Gaussian fit of the detected signal is performed and the semi-major axis and semi-minor axis of the fitted Gaussian are printed on the subwindow (the center thus corresponds to the estimated position).

2. The detection map, recorded in the '.png' file `SUBIMAGES_NAME`, (see the Fig. 8b for an example). This is the SNR map (with a peculiar color scaling so as to spot the detections easily), on which each detection is denoted by an index whose lowest value correspond to the highest SNR and whose color corresponds to a range of contrast wrt the star. If the signal is likely to be an artifact (if the 2D Gaussian fit could not converge and/or the constraints were not respected), the index is white and accompanied by an asterisk. If the detected signal is assessed to be a tertiary lobe due to the pre-filtering of the raw images, the signal is replaced by a dark blue symbol @. (see Cantalloube et al. 2015 for more details on how to determine these particular cases).

3. The detection limit curve, recorded in the '.png' file `DETLIM_PNG_NAME`, (See the Fig. 5a for an example). The detection limit at the threshold chosen by the user is plotted as a solid line. This detection limit is the azimuthal median of the standard deviation of the flux map, multiplied by the chosen threshold. The azimuthal minimum of the standard deviation of the flux map is over-plotted as a dashed line (still at the given threshold). It means that, for the given threshold, a signal could *never* be found below the dashed line but the azimuthal median gives a better idea of the detection limit for the whole data set.

4.2.2 Estimation files .dat

Two '.dat' files are created and stored within the path provided by the user.

1- The files containing the results, under the name given in `FILENAME_DETECTION`: From the numerous tests

Parameter name	Meaning	Units
Index	Index of the detection (the lower, the higher SNR)	integer
coord_x	x position in the map (IDL coordinates)	pixel
coord_y	y position in the map (IDL coordinates)	pixel
sep-[mas]	estimated separation from the star	mas
err_sep	3-sigma errorbar on the estimated separation	mas
PA-[deg]	position angle from true North	degree
err_PA	3-sigma errorbars on the estimated position angle	degree
SNR	estimated SNR of the detection	sigma
nb_px>thresh	number of pixels of the signals above the threshold set	integer
Flux-[ADU]	estimated flux of the companion	ADU
Contrast	estimated flux translated into contrast wrt the star	-
Contrast-[mag]	estimated contrast of the companion in terms of magnitude	mag
Err_mag	3-sigma errorbars on the contrast in terms of magnitude	mag
flag_pos	**0**: The fit of the signal in the SNR map converged within the given constraints **1**: The 2D-Gaussian fit does not converge The recorded signal position is the one of the pixel having the maximal value **2**: The 2D-Gaussian fit does not respect the imposed constraints The fit is however forced and the estimated subpixel position recorded **3**: The detected signal is too close to the edge and cannot be analyzed	
flag_flux	**0**: The fit of the signal in the flux map converged within the given constraints **1**: The 2D-Gaussian fit does not converge. The recorded signal flux is the one read at the previously estimated position **2**: The 2D-Gaussian fit does not respect the imposed constraints. The fit is however forced and the flux estimated at the recorded position	
flag_lobe	**0**: No detection is found in this signal's nearby area **1**: There is a detection close-by but its SNR is either lower or comparable **-X**: The detection is assessed to be the tertiary lobe of the signal indexed **X**	

performed, no signals having a flag different from 0 was an actual planetary signal. However, a signal may not be assessed as an artifact but could be one. In that case, other methods should be used to confirm or infirm the companion existence. It is also possible to run ANDROMEDA with another set of user-parameters (optimization method used for ADI wrt δ_{min}) to check if the signal remains or use another diversity (such as SDI) if the signal is persistent.

2- The files containing the range of the estimations, under the name given in `FILENAME_ERRORS`:

Parameter name	Meaning	Units
Index	Index of the detection (the lower, the higher SNR)	integer
Err_sep_pos	Maximum estimated separation from the star	mas
Err_sep_neg	Minimum estimated separation from the star	mas
Err_pa_pos	Maximum estimated position angle	degree
Err_pa_neg	Minimum estimated position angle	degree
Err_contrast	3-sigma errorbars on the estimated contrast wrt the star	contrast
Err_mag	3-sigma errorbars on the estimated contrast in terms of magnitude wrt the star	mag

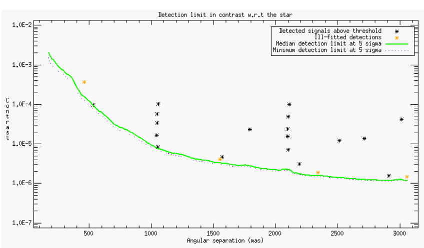
4.2.3 Computation of the detection limits

In case there is no detection (ie. no signal is found above the threshold set), it is still possible to derive the detection limit by using an independent IDL procedure called `DETECTION_LIMIT.PRO`. This procedure displays and record as a *.png* image and as a *.fits* file the detection limit. This detection limit is computed as the azimuthal median of the (normalized) standard deviation of the flux map, at the given threshold. Moreover, this function has three options:

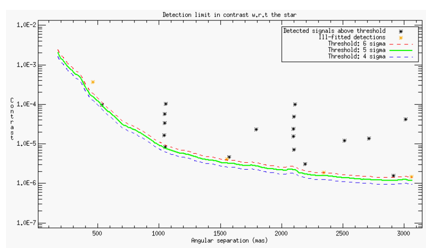
-If the keyword `\MIN` is set: the minimum value of (normalized) standard deviation of the flux map at each distance from the star is over-plotted at the given threshold (dashed curve). It means that planetary companions could be found in between the two curves but never below this dashed curve (see Fig. 5a).

-If the keyword `\MEAN` is set: the detection limit at threshold+1 and threshold-1 are over-plotted to the main curve (see Fig. 5b).

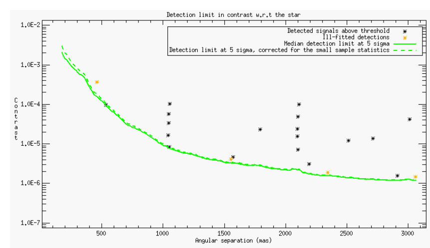
-If the keyword `\SSS` is set: the detection limit taking into account the small sample statistics is over-plotted to the main curve (as described in Mawet et al. 2014), (see Fig. 5c).



(a) : Detection limit obtained with the `/MIN` option.



(b) : Detection limit obtained with the `/MEAN` option.



(c) : Detection limit obtained with the `/SMALL` option.

Figure 5: Detection limits obtained with the data set presented in Sect. 5.

ANDROMEDA package: Conclusion

The ANDROMEDA package contains the necessary IDL procedure and a batch to process high contrast images taken in pupil tracking mode. This methods as the following notable advantages:

- It performs an objective detection based on the SNR map thresholding.
- It estimates the sub-pixel position of the detected signals.
- It estimates the flux of the detected signals without bias self induced by the method.
- The toolbox permits to automatically sort out potentially true planetary companions from potential artifacts.
- The whole process runs quite fast (e.g: 30 minutes for an image cube of 150 images of 512×512 pixels and from a IWA of $2\lambda/D$).

Fig.6 is a summary of the different input needed to process on-sky data with ANDROMEDA.

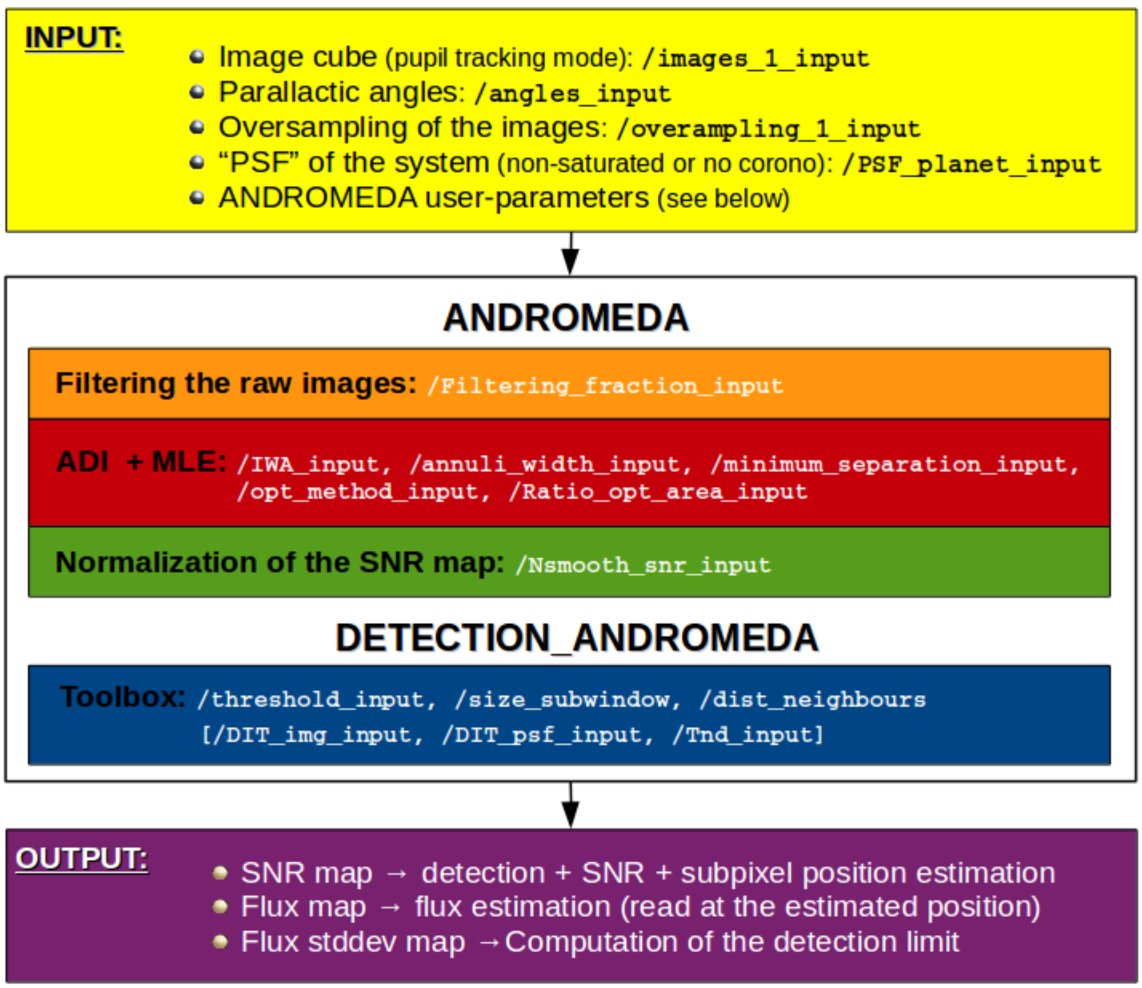


Figure 6: Input and output of the ANDROMEDA method and names of the variables as in the IDL code.

5 Example: *TYC-8979-1683-1* observed with VLT/NaCo in H-band

5.1 Data TYC-8979-1683-1

The data used to run the batch and test the ANDROMEDA method are described in details in the Section 4.1 of Cantalloube et al., 2015.

The central star is TYC-8979-16683-1 (called TYC-8979 hereafter in this manual) observed on 2010 February the 18th within the ESO program 184.C-0567 (PI: J.-L. Beuzit). These data are non-coronagraphic (they are sequences of saturated exposures) and taken in pupil tracking mode with VLT/NaCo (total field rotation of 18.5 degree) using the H-band filter of NaCo which is centered around $1.66\mu m$. The data provided in the DATA_TYC8979 folder have been previously reduced (essentially sky subtraction,flat fielding, bad pixels correction and rejection of poor-quality exposures). One unsaturated exposure was taken before the main observation sequence to serve as a reference PSF to build the model of the planet signature (`PSF_PLANET_INPUT`).

Twenty additional synthetic substellar companions have been inserted in the image cube in five rows of respective position angles of 30, 60, 90, 120 and 150 degree on the first image and at angular separations of $0.26 arcsec$, $0.53 arcsec$, $1.06 arcsec$ and $2.12 arcsec$. Each row of synthetic companions contains objects of equal flux, with peak intensities corresponding to magnitude differences of 12.85, 12.10, 11.35, 10.60, and 9.85, as shown in Fig. 7.

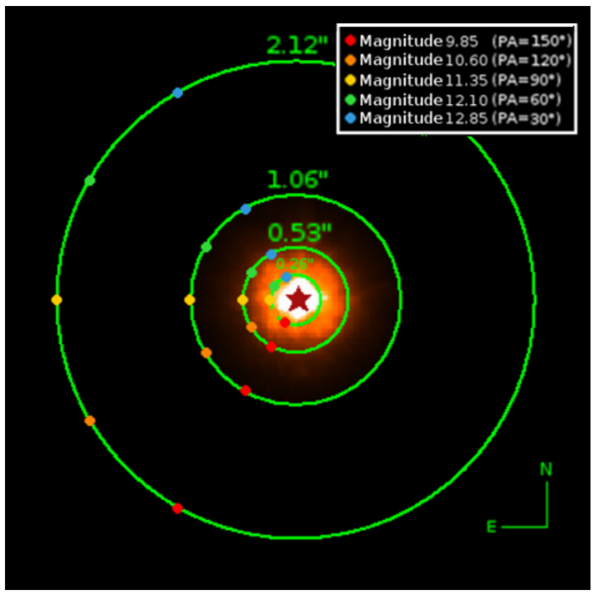


Figure 7: One of the reduced images of TYC8979, cropped in a 512×512 pixels frame, from the example data cube on which is indicated the locations and magnitude of the synthetic planetary signals injected.

The main characteristics of this data-set are gathered in the table 2.

Images size ($Npix \times Npix$)	512×512 px
Total number of images ($Nimg$)	296
Total field rotation ($\Delta Parang$)	18.525° ($-22.2470° \rightarrow -3.72198°$)
Filter	H (1.66μm)
Pixel scale of the camera used ($PIXSCALE$)	13.22 mas/px
Oversampling factor	1.58287
Offset angle from true North direction ($ROTOFF$)	90.4°
Integration time of each frame (DIT_{IMG})	6.8sec
Integration time of the reference PSF (DIT_{PSF})	1.7927
Transmission of the neutral density used for the reference PSF	1.19% (ND$_{short}$)
Turbulence conditions	seeing: $0.57 \sim 1.15$; τ_0: $4 - 9ms$; $SR_{PSF}: 21\%$

Table 2: Summary of the main characteristics of the data TYC-8979.

5.2 Input to process this data set

The center of the images must be set in between four pixels. This is done by hand using the `SUBPIXEL_SHIFT` function and checking by looking at the center of the median stack of the images.

In H-band, a good compromise is to crop the PSF in 32×32 window.

There is several user-defined parameters that can be modified at the convenience of the user to perform tests.

The optimized user-defined parameters on this test case, that are used to run ANDROMEDA on this data set, are gathered in the following table:

Parameter	**Definition**	**Used value**
`FILTERING_FRACTION_INPUT`	Filtering fraction	1/4
`MINIMUM_SEPARATION_INPUT`	Minimum separation to build pseudo-data	0.5 λ/D
`ANNULI_WIDTH_INPUT`	Radial width of annuli for performing ADI	1 λ/D
`OPT_METHOD_ANG_INPUT`	Least square optimization	option #3
`RATIO_OPT_AREA_INPUT`	Ratio optimization to subtraction areas	2
`NSMOOTH_SNR_INPUT`	Smoothing of the SNR robust standard deviation radial profile	18 pixels
`IWA_INPUT`	Separation from which the planetary signals are being sought	4 λ/D
N_{psf}	Size of the reference PSF image	32×32 pixels

Table 3: User-defined parameters used to run ANDROMEDA in order to obtain the results presented in the article.

It takes about 30min to run ANDROMEDA under these conditions.

5.3 Output and results from the analysis procedure

The 3 maps output by ANDROMEDA on this test-case are the flux map (Fig. 4c), the SNR map (Fig. 4b, already normalized) and the standard deviation of the flux map (Fig. 4d).

From these three map, the detection procedure is ran using the following default parameters:

Parameter	**Definition**	**Used value**
`THRESHOLD_INPUT`	Threshold above which any signal is regarded as a detection	5 sigma
`SIZE_SUBWINDOW_INPUT`	Size of the subwindow in which signal analysis is performed	11 pixels ($3.4\lambda/D$)
`DIST_NEIGHBOURS_INPUT`	Distance of a potential tertiary lobe artifact	16 pixels ($5\lambda/D$)

Table 4: User-defined parameters used to run DETECTION_ANDROMEDA.PRO on the test-case.

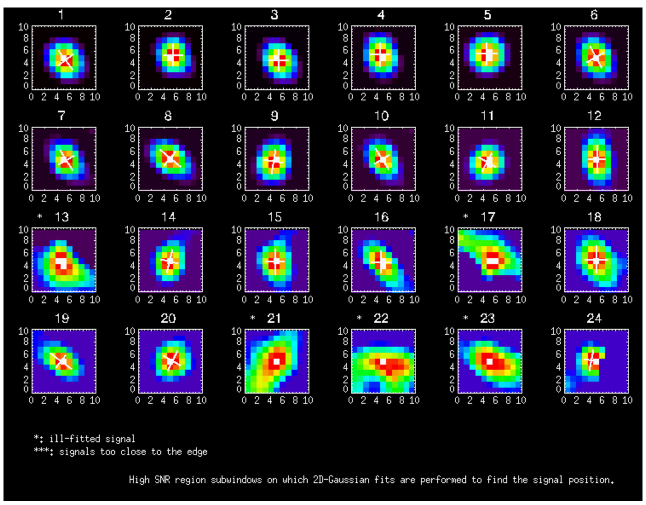
The package contains, in the *Example* folder, the two files '.dat' containing the information about the detections, for a threshold of 5-sigma. Notably on a total of 24 signals detected above threshold in the field of view, there is 19 true potential planetary signals, 2 detections regarded as tertiary lobes and 3 detections assessed to be artifacts (residual speckle noise like #22 or diffraction pattern like #21 and #23); See Cantalloube et al. 2015, Sect. 3 for more details.

Performance with respect to the injected fake companions can be found in Cantalloube et al. 2015, Sect. 4

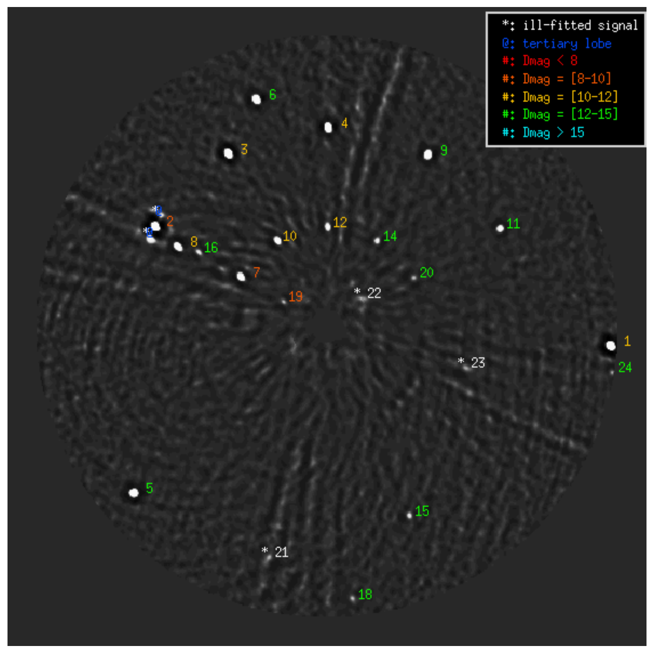
6 Conclusion

ANDROMEDA has been tested on VLT/NaCo data (with and without coronagraph), on VLT/SPHERE data and Gemini/GPI data under different observation conditions. This method has also been successfully tested on different type of data (such as narrow band filters, dual band images, broadband filter and multispectral images).

As a conclusion, this algorithm proved to be very efficient in extracting in a systematic way the point source present in the field of view. It is also a very convenient method since it relies on very few user parameters and provides non-subjective detections and unbiased flux estimation. For these reasons, ANDROMEDA is a very good tool for a quick look. However it does not have better but comparable extraction capabilities than other widely used algorithm since its performance are also limited by the ADI process prior to the MLE estimation.



(a) : SNR subimages enclosing all the detected signals above the threshold set in which the analysis is made. When the 2D Gaussian fit could converge, its parameters are in-printed on the subwindow (maximum, semi major axis and semi minor axis.



(b) : SNR map displaying the detections and their properties (position, SNR rank, flux range and if it is an artifact)

Figure 8: Images displayed when analyzing the ANDROMEDA output (Fig. 4) with the provided detection module.