User Manual for the Vortex Coronograph at NIRC2 on Keck II

Keck Adaptive Optics Note 1104

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Document Revision history

Revision Number	Revision Date	Summary of Changes	Author
1.0	03/11/2016	Initial	B. Femenía Castellá & the VORTEX team
1.1	03/14/2016	Updating vortex logo	B. Femenía Castellá

PREFACE

On March 2015 an L'-band vortex coronagraph based on an Annular Groove Phase Mask was installed on NIRC2 as a demonstration project. Commissioning of the new coronagraphic mask mode started on June 2015 with already very good initial results interlacing engineering nights with science nights by members of the VORTEX team with their respective scientific programs. The new capability and excellent results so far have motivated the vortex team and KSSC to offer the new mode in shared risk mode for 2016B.

This document presents technical details about the new mode, the main results from the commissioning. It is also a preliminary user manual describing instrument configuration and calibration, and execution guidelines.

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1. Introduction

More than 2000 exoplanets have been discovered to date and yet only for a small fraction of them it been possible to acquire direct images. The reason for this lies in the extraordinary technological challenges associated with the large flux ratio between the host star and its planets as well as the small angular separation between star and planets. To achieve exoplanet direct imaging we inevitably require high contrast imaging systems capable of suppressing the stellar light fed by high angular resolution systems. Nearly all high contrast imaging systems rely on the use of a coronagraphic system and the NIRC2 instrument fed by the Adaptive Optics (AO) system at Keck II telescope was designed with a classical Lyot coronagraph. With this mode NIRC2 has delivered fantastic results such as the first direct imaging of an exoplanet (Marois et al. 2008).

However, it is well known that classical Lyot coronagraphs are far from being the best current coronagraphic design. On the other hand the vortex coronagraphic approach, originally proposed by Mawet et al,.(2005), has been gaining credit as one of the most promising solutions due to its excellent properties in terms of very small inner working angle, high transmission, clear 360˚ discovery space and ease of implementation in existing coronagraphic systems. Delacroix et al. (2013) report laboratory L-band contrast ratios up to $6x10^{-5}$ (which corresponds to a ~500:1 peak rejection) at angular separation of just 2λ/D. Also, thanks to the ease of implementation in existing coronagraphic systems, vortex masks have already been installed at Palomar (Mawet et al., 2010), and in the last few years at different infrared instruments on 8-m diameter monolithic primary mirror class telescopes: VLT (Mawet et al., 2013), LBT (Defrère et al., 2014) and Subaru (Jovanovic et al. 2015).

2. Installation of the Vortex at NIRC2

The project to install a Vortex mask in NIRC2 was led by K. Matthews (CIT) with co-PIs by E. Serabyn (JPL) and D. Mawet (CIT) as a collaboration between JPL, CIT, the European VORTEX group (led by O. Absil from U. Liège) and WMKO (led by P. Wizinowich). Part of this team has also been involved in the installation of Vortex masks at Palomar, VLT (Mawet et al. 2013) and LBT (Defrère et al. 2014). The Keck vortex coronagraphs were installed in NIRC2 on March 17, 2015, replacing, at the focal plane, the grids of holes used for focusing and distortion tests on the slit mask stage (SLS), which also holds the spectroscopic slits and a number of conventional (pure amplitude) coronagraphic masks. The grids of holes have been removed from NIRC2 and are no longer available, but the old set of conventional coronagraphic spots with variable sizes, as well as the slits, remain unchanged and are still available for use.

From March until the commissioning nights on June 8^{th} to 10^{th} we improved the image quality of the Keck-2 AO bench (right rotation for the AO dichroic, re-alignment of OAPs and previous re-alignment of the K mirror). The work on the optical bench has also changed the solution of the distortion model employed so far in high astrometric precision program and will need to be re-evaluated. A lot of effort went into the development of user tools to accurately position the stellar spots on the vortex mask.

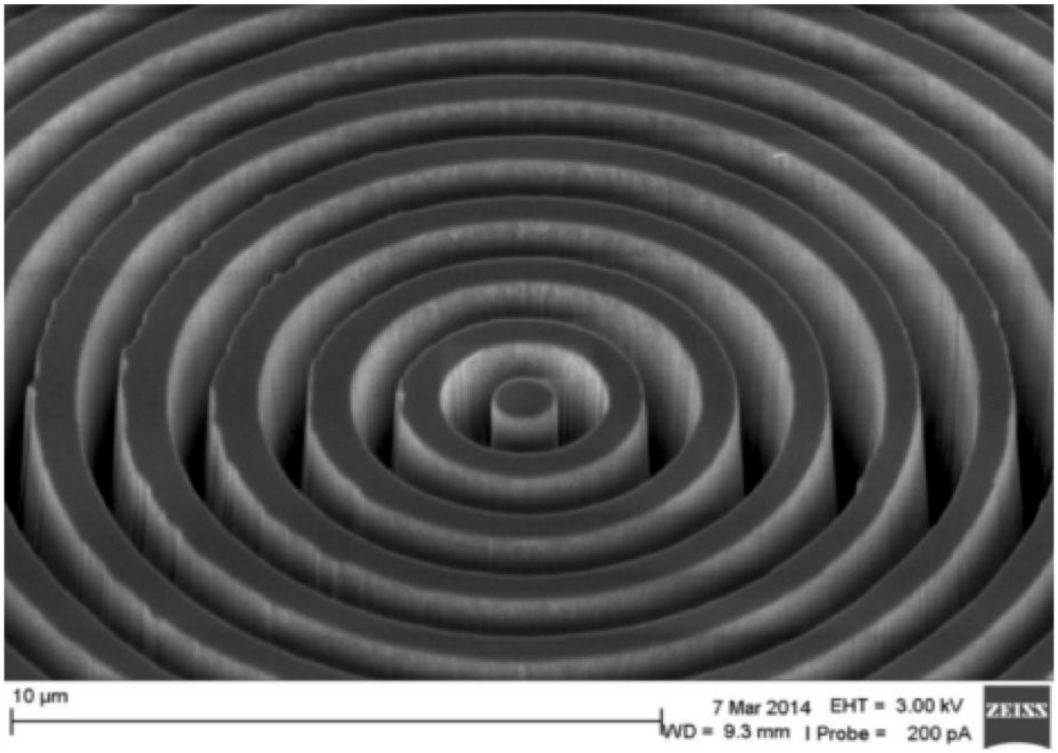

Figure 1: SEM picture of Keck L-band vortex made from sub-wavelength gratings etched into a synthetic diamond substrate.

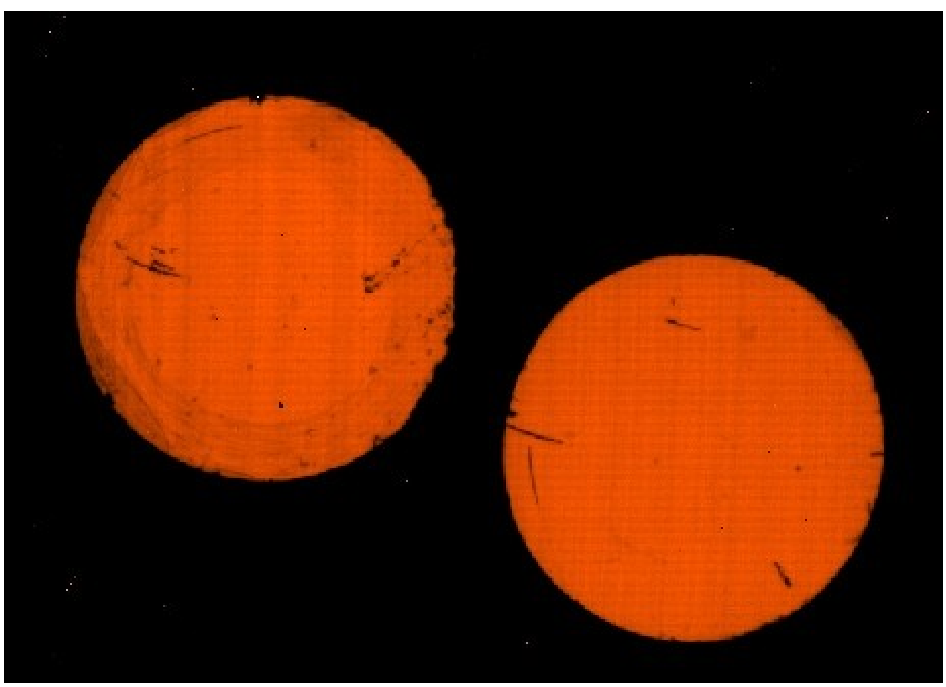

Figure 2: Two vortex masks as seen in the wide camera of NIRC2 at L band. The field of view of each mask is approximately 12 arcsec across During the commissioning we verified the upper left vortex (vortex2) performs slightly better than the one at bottom right (vortex1)

While it is true that for all kinds of coronagraphic set ups the positioning of the stellar spot is of paramount importance, given the very small Inner Working Angles (IWA) that a vortex is able to achieve, such a positioning is of critical relevance. In order to achieve this, we have implemented the QACITS algorithm (Huby et al, 2015.|) which processes the most recent acquired coronagraphic image in quasi real time. QACITS provides an estimate of the tip-tilt error upstream of the coronagraph, and triggers a closed-loop AO correction. More details in the QACITS are given below and the reader is referred to Huby (2015, KAON) for a quick QACITS user manual

While the implementation of this new observing mode has required relatively simple hardware modifications to NIRC2, the bulk of the commissioning work focused in the deployment of new software tools and modifications to the existing calibration procedures required to achieve the best performance of the coronagraph.

3. First on-sky commissioning results

First vortex light on-sky took place between June 8th and June 10th 2015 (three full nights). During those three nights we experienced excellent seeing conditions at the Maunakea site which together with the superb image quality delivered by the Keck-2 AO system with Strehl ratios in L band above 85%, allowed to achieve routinely ~50:1 peak starlight rejection and sporadically getting close to the ~100:1 regime.

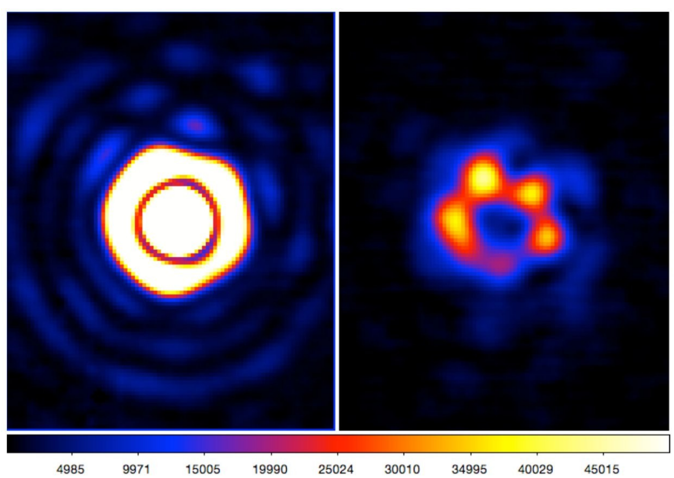

*Figure 3: **LEFT**: typical PSF in the L-band with Strehl ratio above 85%. It has been saturated on purpose in order to allow to see many diffraction rings. **RIGHT: post-vortex PSF** showing some residual speckles likely due to the combination of low-order aberrations and diffraction from the pupil obscuration.*

A key component for this success was the implementation and successful operation of QACITS. Our first commissioning results with QACITS demonstrated we could achieve a centering stability of ~ 2 mas. It is worth mentioning that this was the first time QACITS operated on sky.

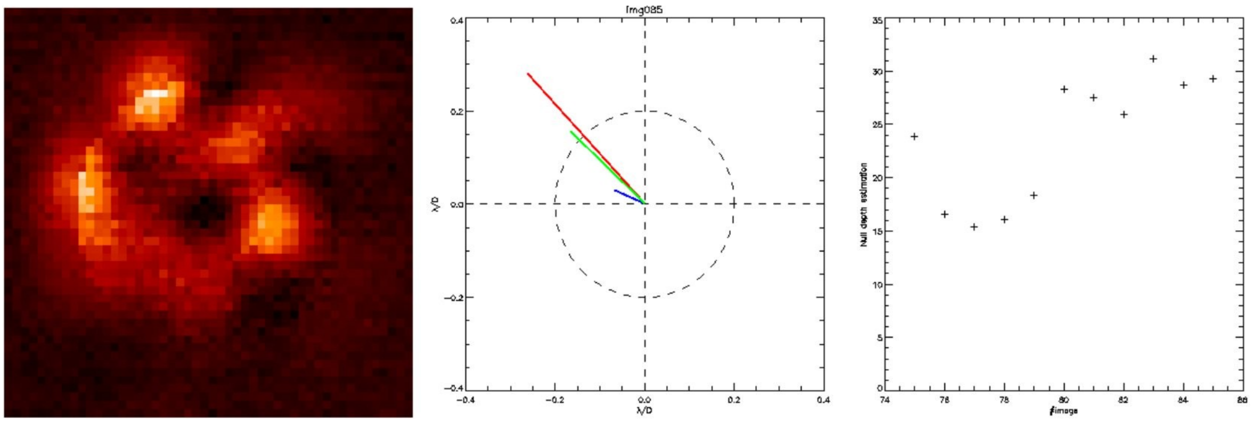

Figure 4: First on-sky light for QACITS. ***Left:*** *zoom on the post-vortex image center on NIRC2.* ***Middle:*** *tip-tilt direction and amplitude estimators (different colors for the estimator using the inner circle signal or the outer circle signal.* ***Right:*** *real-time estimate of average starlight rejection used for a quick diagnostic of the rejection performance: the lager the ratio the better the rejection. More details in the QACITS manual in Huby (2015).*

4. Current Vortex performance

As of today, the most representative data has been acquired on October 24th 2015 on the benchmark target HR8799 (Marois et al, 2008). For this sequence the target was observed for nearly two hours around zenith (except for a few minutes around the zenith blind spot). HR8799 has an R-band magnitude m_R=5.96 resulting in a very bright Natural Guide Star (NGS) allowing to achieve excellent AO correction The case for HR8799 is what we refer to as the bright on-axis NGS scenario.. In the scientific L' band m_L=5 and the target was observed at elevations above 81° (average air mass throughout the observation was only 1.014) with an excellent average seeing of 0.733±0.018 arcsec and seeing dispersion 0.16 arcsec as measured towards zenith with a DIMM monitor every ~90 seconds.

The long ~2-hr observation sequence on HR8799 is made of multiple 25 second exposures, on each of them running QACITS and Speckle Nulling[1]. The observations were carried out in vertical angle mode (ie. the pupil was kept fixed by the AO K-mirror rotator) in order to improve the contrast via Angular Differential Image (ADI) . The contrast curves are provided in Figure 5. The final contrast curves were generated using the PCA-|ADI algorithm in the python-based VIP post-processing package[2]. It is worth mentioning a 10^{-4} 5-sigma contrast gain at ~0.3".

1At the time of writing this version, Speckle Nulling is still under commissioning. It requires very long calibration sequence and it is not suggested until new notice.
2 The Vortex Imaging Processing (VIP) is the suggested data reduction package for vortex data. It is implemented in python and it is freely available at https://github.com/vortex-exoplanet

More modest, yet still impressive, contrast values are achieved when observing dimmer targets. The contrast at 0.5” reaches a plato and remains constant with increasing angular distance since the background sets the contrast limit at these magnitude values. The first target corresponds to a star with m_R=12.3. The second target corresponds to a dim m_R=13.29 which approaches the dim NGS regime and, under normal NIRC2 imaging programs, it could be argued on the benefits of directly considering Laser Guide Star AO correction. The data corresponding to targets in Table 1 was acquired under excellent seeing conditions but due to the declination of the targets at low elevations[3] which corresponds to effective seeing values of 0.52 arcsec for **04365738-161306** and 0.65 arcsec for **05425587-071838.**

Table 1: Representative contrast from two M3 dwarfs

Targetname	m_R	m_L	Elevation	DIMM Seeing	Contrast @ 0.3”	Contrast @ 0.5
04365738-161306	12.3	8.1	54°	0.48”	5.3e-3	1.2e-3
05425587-071838	13.29	10	61°	0.59”	9.8e-3	2.8e-3

3 Seeing values from DIMM refer at zenith distance and at 0.5 µm. Seeing scales with wavelength (λ) 1/6 and airmass (z) as $z^{3/5}/\lambda^{1/5}$

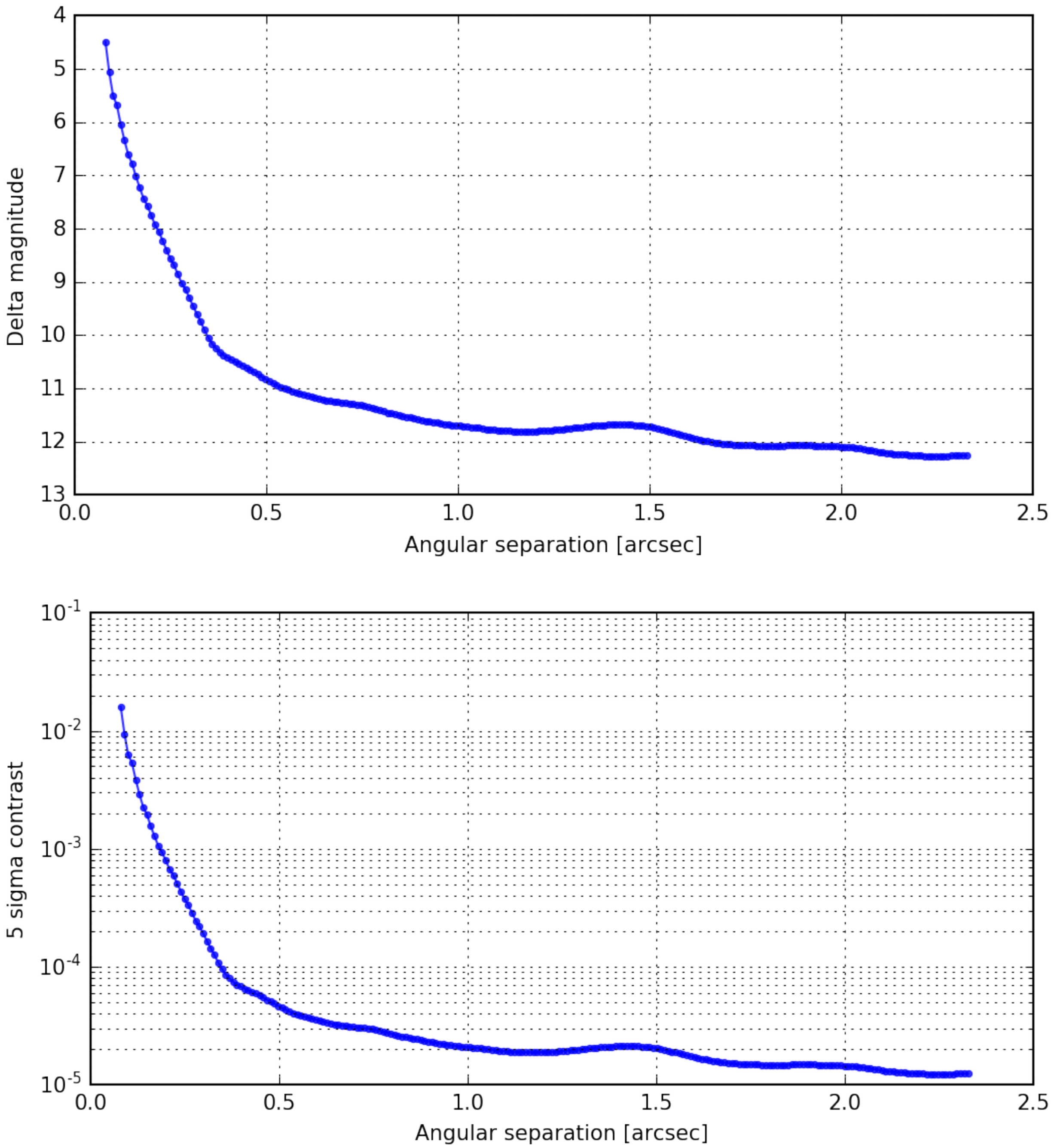

Figure 5: Flux and magnitude 5-sigma contrast curves on HR8799 on what as of today is the best performance achieved with the vortex at NIRC2

5. Observing with the Vortex at NIRC2

In this section we briefly described the main steps to carry out a successful observation with the vortex coronagraph in NIRC2.

5.1. Daytime Calibration Sequence

In this version we recommend standard calibration procedures. In a future version where Speckle Nulling has been successfully commissioned the calibration sequence will differ significantly from the standard calibration procedure. The standard calibration procedure is ran by the SA on the morning of the first day of the campaign and it consists of the following:

- K2AO/NIRC2 calibration setup. This step checks all optical stages are configured to the use of K2 AO and NIRC2, and sets the Wavefront Controller (WFC) and configures the WFS for calibration in NGS .
- Registration between the DM and the WFS lenslet array. This is essentially done by introducing a global waffle mode on the DM and moving the lenslet array until a zero signal is obtain from the WFS.
- ***<u>Standard</u>*** Image Sharpening (IS) with the usual Phase Diversity algorithm. The standard refers to the fact the IS procedure is conducted at the default calibration location on the NIRC2 chip which is roughly located at the center of the Field of View while, as depicted in Figure 2 the position of the two vorteces occur at detector pixel rows significantly different to the center of the NIRC2 detector. Notice also that the vortex mask holder can be moved along the x-axis on pixel coordinates (but not on y-axis).
- WFS calibration at the default calibration position (ie. optical axis for NIRC2 which falls off the detector).

5.2. Proper configuration for NIRC2 + vortex2

For on-sky observations the camera will have to be properly configured taking into account:

- Insertion of ***incircle*** NIRC2 pupil mask (see Figure 6) to act as the coronagraph Lyot mask. Run command **`pupil incircle`** in waikoko (waikoko is the NIRC2 server machine name) terminal.
- Using L' filter. Issue the waikoko console command `filt lp`.
- Make sure NIRC2 shutter is open: **`shutter open`** (obvious, but it happens these obvious things take precious telescope time until you discovered them!!).
- Optimize exposure parameters in NIRC2 taking into account not to saturate the camera due to background in L'. This is done by setting the number of coadds per exposure and integration time of each coadd with the terminal commands **`coadd`** and **`tint`**, respectively. For a given total exposure time in order to reduce the overheads as much as possible you want to minimize the number of coadds and increase the individual coadd exposure time without saturating NIRC2. Our experience during the commissioning

phase is that an exposure time of 0.5-1.0 seconds/coadd with 60 coadds or 30 coadds, respectively, is the optimal value to reduce overheads while avoiding NIRC2 detector saturation while in coronagraphic exposure.

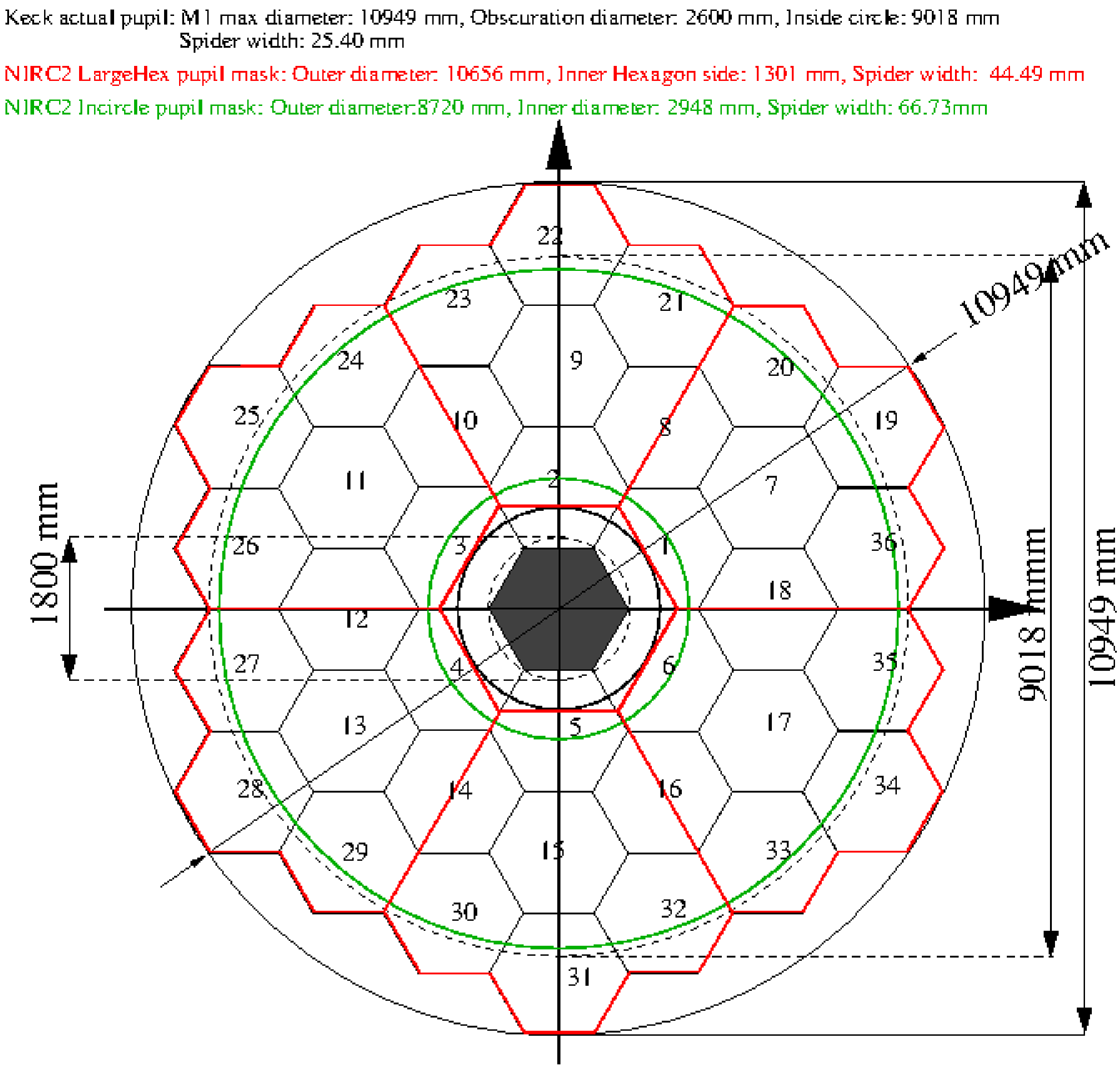

Figure 6: Illustration of the relative size of the Lyot mask used with the vortex (i.e. the incircle NIRC2 pupil mask) and the M1 shape.

5.3. Lyot mask alignment with telescope pupil

Once NIRC2 has been properly configured and with dome already open during twilight, first thing to do is to make sure the AO rotator mode is set up in vertical angle mode to keep the Lyot mask fixed with respect to the telescope primary mirror (M1) and the spiders in the Lyot mask block the shadows cast by the secondary mirror spiders. This is illustrated in Figure 7.

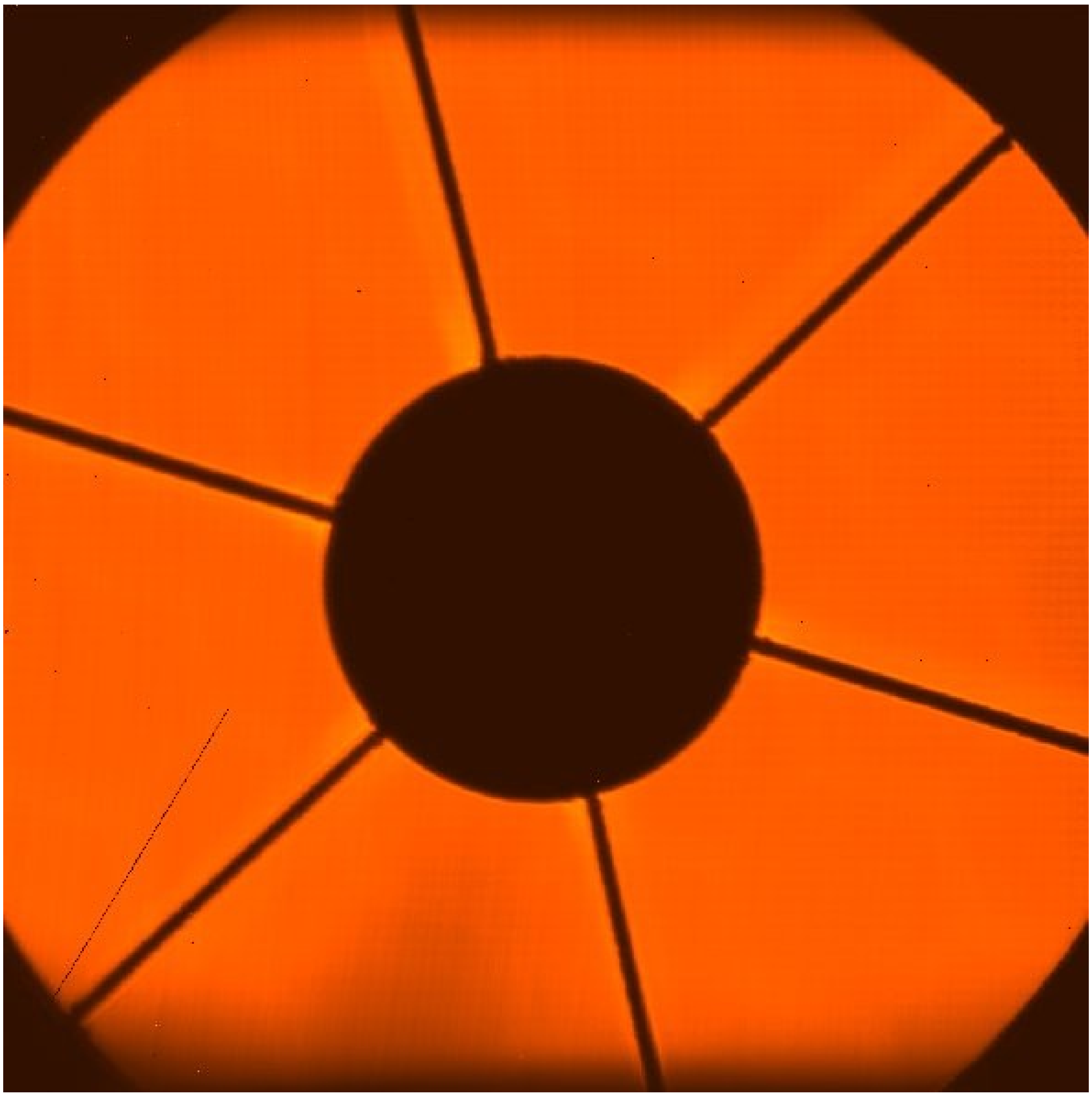

Figure 7: Incircle NIRC2 pupil mask image. Mask arms should cover shadows on M1 due to M2 spiders.

In order to setup NIRC2 in pupil imaging mode run in a waikoko terminal the command **`grism lens`**. The pupil mask rotator should be turned off using **`pmrrot off.`** M1 with the terminal command **`rotate XX vertang`** where XX is the rotation to be applied between masks in degrees. Once the incircle mask and M1 are properly aligned turn on the mask rotator with **`pmrrot on.`** Remember to go back to normal imaging mode by removing the pupil imaging optics with the waikoko terminal command: **`grism clear`**.

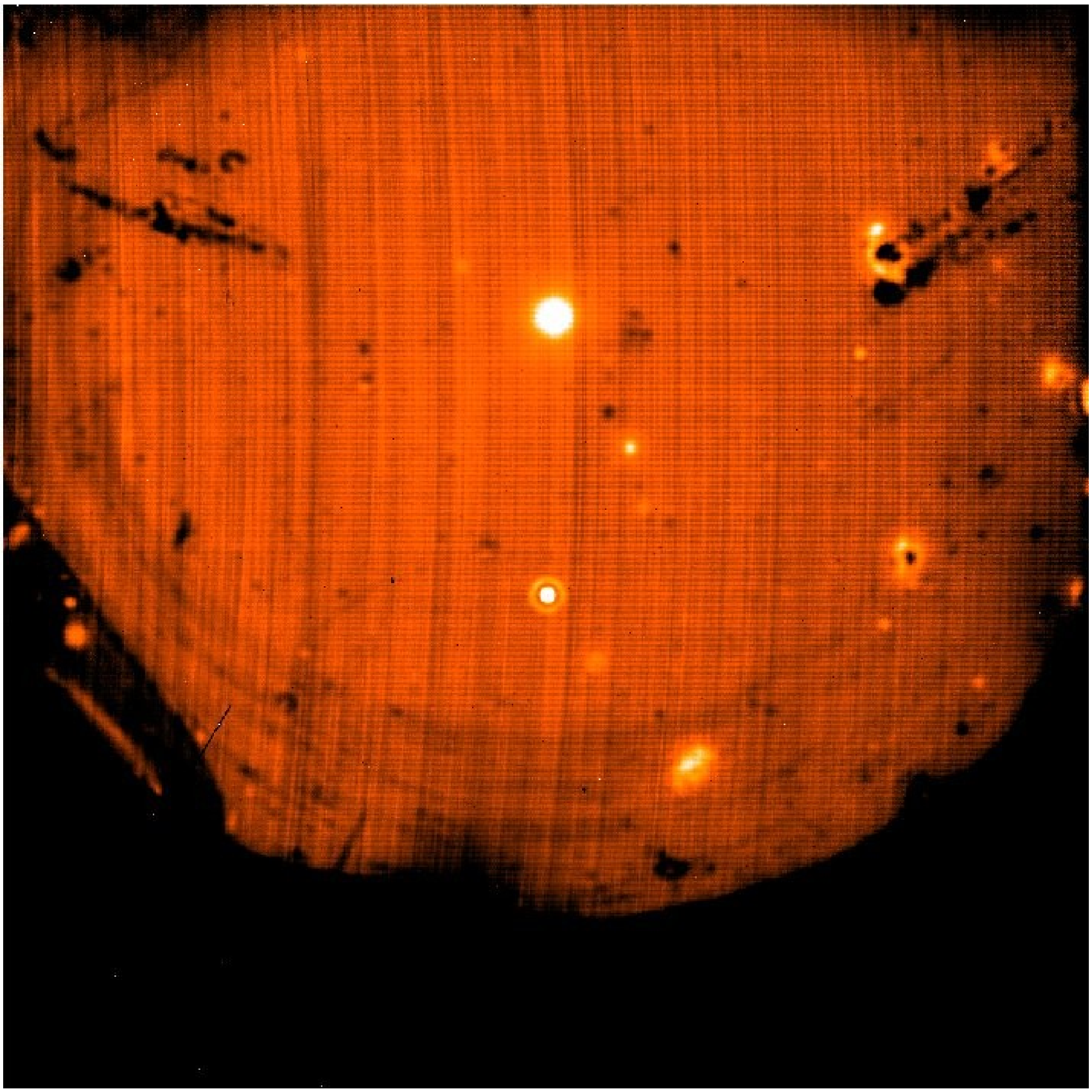

Figure 8: On sky image with vortex center glowing and target to the bottom of the mask. Notice the good PSF quality with the distinctive first Airy ring (in this image the AO loop has already been closed).

5.4. Inserting vortex focal plane mask. Identifying center of mask

As indicated in the section 5.1 only the x-location of the vortexes can be controlled. This is done via the console command **`vcorona vortex2 512`** which positions the vortex2 mask center around x-pixel 512. The exact location of the mask center is determined easily by taking a sky image since the vortex center glow at IR bands (see Figure 8); then it is just a question of moving the star PSF as close as possible to the vortex center by introducing telescope offsets of dx and dy detector pixels with waikoko terminal command **`pxy dx dy`**. Typically the values for dx and dy will be large. When the AO loop is closed and we need to recenter the star spot on the mask we'd rather use the command **`dtoff dx dy`** (now dx and dy can be as small as a fraction of a pixel). This **new command `dtoff`** introduces a small offset (down to ~ 2 mas) by introducing an overall centroid offset on the SH WFS. The AO system offloads the overall tip-tilt onto the down Tip-Tilt mirror generating in this way a very precise and small offset. This is in fact the same mechanism we employ on generating the offsets requested by QACITS.

5.5. QACITS: deployment, offline test and execution.

At this point you can request the SA/OA to close the AO loops. Because the internal mechanism in QACTIS and dtoff may interfere with the differential atmospheric refraction correction mechanism it is ***very important*** to request the SA and/or OA that:

1. DAR is ON for acquisition but OFF for tracking (this is done on the aoaqc GUI from which the AO system is managed)

2. wait4dar is set to OFF to avoid NIRC2 DAR offloading (command **`wait4dar`** on a waikoko terminal)

Once the star spot is as close as it can be positioned with dtoff manually (and by visual inspection of the NIRC2 images using the NIRC2 QuickLook tool) it is the moment to rung the QACTIS software. The different routines and ways to run QACITS are explained in the QACITS Quick User Manual in KAON 1105 by Huby (2015). The reader is referred to that document. Here we will mention that because QACITS requires IDL version 8.1 or higher, it is not possible to execute QACITS in waikoko (the NIRC2 server). Instead you need to run IDL from ***hamoa*** . This is the detail sequence of steps in order to launch QACITS:

1. Contact Bruno Femenia (BF, bfemenia@keck.hawaii.edu) or the SA on duty to arrange installation of QACITS before your observations starts. It is fine installing QACITS in the morning on your first day of observations, but we strongly suggest requesting this a couple of days in advance.
2. At the time of writing this document QACITS is mature enough and has not undergone any changes for at least a couple of months now. However it is an evolving software which is maintained under SVN version control by Huby et al. at Université de Liège. The current procedure is that either BF or the SA in charge will download the most

recent QACTIS version into the corresponding nirc2 user's account at hamoa (with identical password to access it). QACITS will be deployed at folder ~/qactis and also a set of test images in ~/qacits_data to perform and offline test that verifies QACITS has been properly deployed.

3. On the 24-bit color vnc display (typically session with the lowest vnc ID number and with light blue background), you will right-click on the background and bring up the “Root Menu” and under “IRAF/IDL” sub-menu you will select IDL sub-menu and IDL 8.1. This opens an IDL session in hamoa .
4. From within the IDL session in hamoa BF and/or the SA will have performed the following sequence of commands upon QACITS deployment to verify QACITS has been properly installed:
   - **IDL> cd,'qacits'**
   - **IDL> .r run_qacits_sci**
   - **IDL> run_qacits_sci, 10, .5, 50, data_dir = '~/qacits_data/', log_file_name = 'log/UT2015-10-26_nirc2_qacits.log', file_nb=575, /OFFLINE**

The last IDL command runs the code in OFFLINE mode and should open a series of graphical windows as illustrated in Figure 9. The top left displays zooms into the "SUBIMAGE" (sky subtracted) used by the QACITS estimator; the inner circle of radius 0.1 lambda/D is highlighted by 30%. The top right window "MEASURED TIPTILT ESTIMATOR" displays the current tip-tilt value using two different estimators: the blue vector uses the signal from the inner part of the image, the red vector uses the outer part of the image; the green dashed vector is the one that QACIST is currently using (in this case it can hardly bee seen but is superimposed on the red vector, i.e. using the outer signal). The bottom left display shows the history of tip-tilt values in the currently executed sequence of images. The bottom right panel provides an estimation of the null depth (ratio of the flux integrated over the central disk of the coronographic image and off-axis PSF). These same graphical windows are displays during normal execution of QACITS.

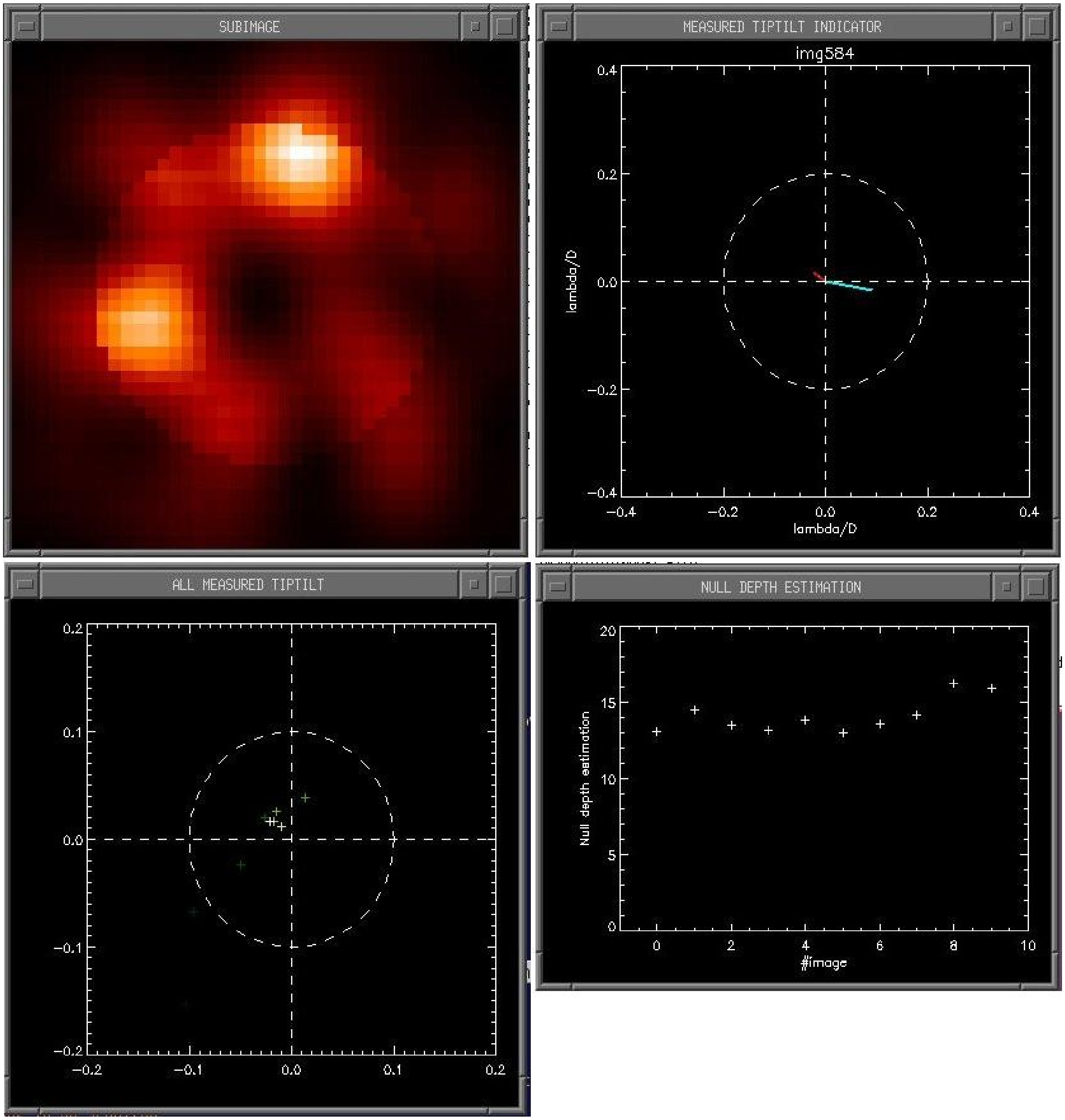

Figure 9: Displays opened during execution of QACITS (different arrangement on the vnc session). . See main text and the user manual in Huby (2015) for further details.

The last step in order to run QACITS while acquiring real data, is editing (either from within the IDL session in hamoa or by opening another xterm session in hamoa and from there launching a text editor) the file **`qacits_nirc2_params.pro`**. and update the nirc2 account you have been given (line 92 in qacits_nirc2_params.pro). Another parameter you may want to change are the width of the sub fram in the science acquisition sequence; the rest of the QACITS parameters are intended for full optimization of QACITS and you'd better use the values by default. At this point you are ready to execute QACTIS to acquire the coronagraphic scientific images by executing the IDL command (see Huby (2015) for a detail explanation):

```
IDL> run_qacits_nirc2, n_sci, tint_sci, coad_sci, data_dir=
data_dir, object_name=object_name,tint_opti=tint_opti, coad_opti=
coad_opti, do_calib=do_calib
```

where the inputs for this sequence are:

- **`n_sci`** : Number of acquisitions requested for the science sequence
- **`tint_sci`** : Integration time for the science acquisitions
- **`coad_sci`** : Coadd number for the science acquisitions
- **`data_dir`** : Path name of the directory where the data are saved (string)
- **`object_name:`** Name of the object, as written in the fits file (string)
- **`tint_opti`** : Integration time for the optimization acquisitions
- **`coad_opti`** : Coadd number for the optimization acquisitions
- **`do_calib`**: If set then it forces the calibration sequence.

As explained above, QACITS will use the same internal mechanism as the **`dtoff`** command to send demands to the down Tip-Tilt mirror. This is done by introducing overall centroid offsets on the WFS via the keywords DTCLXOFF and DTCLYOFF. From two consecutive QACITS iterations you expect a fraction of pixel with is < 0.01 increment in the keywords (units of arcsec). However for very long exposure sequences there is the risk these keywords build up to large values which eventually would saturate the WFS. To monitor you do not incur in this situation monitor the current value of DTCLXOFF and DTCLYOF: on a waikoko terminal issue the command **`xshow -s ao dtclxoff dtclyoff &`** and a little graphics windows open on the top left corner of the session. When moving to a different target remember to reset the dtclxoff and dtclyoff keywords with the command **`modify -s ao dtclxoff=0 dtclyoff=0`**.

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