# ESO Phase 3 Data Release Description

# LIGO-VIRGO GW and GRB alerts: L'-band NaCo follow up observations in the thermal infrared

## Abstract

NaCo imaging observations were carried out under ESO program 60.A-9392(A), PI A. Kaufer, to constrain the spectral energy distribution at 3.80 micron of the source identified by the LIGO-VIRGO GW 170817 and the gamma-ray burst GRB 170817A alerts. The data were acquired in eleven different nights, from late-Aug –to early-Sep 2017, mostly under good conditions. The NaCo imaging was carried out with the L' filter and the L27 camera, with a pixel scale of 0.027 arcsec pixel$^{-1}$. The FWHM of the photometric standard star observed together with the science data indicates a seeing of about 0.11 arcsec. The images from individual nights were co-added using the offset parameters from the headers. The extended nearby galaxy NGC 4993 falls inside the NaCo field of view, and it was detected on some of the the combined frames, but no unresolved sources were detected in the field. This release includes only processed images form the nights when NGC 4993 was detected, because a standard was observed only on one night, and the galaxy was used to perform a consistent photometric calibration across the data from different nights. Detection limits were derived for single night observations, and for image products obtained from multiple nights combined together. The NaCo raw data were reduced by Valentin Ivanov of the Science Data Product group in the Back-Operation Department; the conversion to the ESO Science Data Product standard and Phase 3 publication process in the ESO Science Archive Facility was carried out by the Archive Science group.

## Overview of Observations

The location of GW 170817A was observed with the NACO instrument on VLT on eleven nights during the period from 24/25 August to 4/5 September, 2017, in imaging mode with the L' (L_prime) filter, centered at 3.80 microns (FWHM = 0.62 micron). The L27 objective was used, yielding a pixel scale of 0.02719 arcsec pixel$^{-1}$, and a field of view ~27.8" x 27.8". The field of view was roughly centered on NGC 4993 and the exact pointings varied by ~10-20 arcsec from night to night. The detector integration time (DIT) was 0.2 seconds, yielding a sky level at ~8,000-16,000 ADU on a single frame, depending on the temperature, humidity and airmass. The NDIT in the observing blocks (OBs) was set to 126. However, the data was saved in cube mode which suffers from a significant frame loss and a typical cube contains 77-78 frames (note that the last slice in the cube is an average of all frames, for example, a cube with 77 individual DITs actually contains 78 slices). The total number of cubes from all nights amounts to 329.
Table 1 contains the logs of the observations. A processed NaCo image obtained at L' filter, centered at 12.082 micron is shown in Fig. 1.


Fig. 1. Combined NaCo L‘ band image from the night of 2017-08-25, the field of view is ~38”x32”. North is on the top, East is to the left. The positions of three objects that fall inside are marked with circles (CXOU J130948.0-232304 is an unrelated x-ray source).

Table 1. Observing log.

| Date | UT range | Sec z | No. cubes | No. frames | Total Exp. Time, sec | Notes |
|---|---|---|---|---|---|---|
| 24.08.2017 | 23:06-23:29 | 1.47-1.64 | 27 | 2103 | 420.5 | GW out of the field of view |
| 25.08.2017 | 22:51-23:26 | 1.40-1.64 | 36 | 2759 | 551.8 | |
| 26.08.2017 | 22:45-23:27 | 1.39-1.68 | 45 | 3506 | 701.2 | GW close to the FoV’s edge |
| 27.08.2017 | 22:48-23:04 | 1.43-1.70 | 33 | 2562 | 512.4 | |
| 28.08.2017 | 23:05-23:22 | 1.56-1.71 | 20 | 1550 | 310.0 | photometric standard |
| 29.08.2017 | 22:44-23:23 | 1.45-1.76 | 40 | 3115 | 623.0 | |
| 30.08.2017 | 22:46-23:18 | 1.48-1.75 | 34 | 2648 | 529.6 | variable background |
| 31.08.2017 | 22:47-23:14 | 1.52-1.75 | 26 | 2025 | 405.0 | variable background, galaxy not detected |
| 1.09.2017 | 23:01-23:25 | 1.65-1.91 | 27 | 2102 | 420.4 | variable background |
| 3.09.2017 | 23:07-23:24 | 1.79-2.00 | 14 | 1092 | 218.4 | variable background, galaxy not detected |
| 4.09.2017 | 22:55-23:19 | 1.71-1.97 | 27 | 2093 | 418.6 | galaxy not detected |

# Release Content

The release consists of reduced images for a pointing, at RA = 13h09m48.2s DEC = -23d22m58s (J2000) for the nights from 25 to 29.08.2017, including. The reduced data products cover a contiguous field of view of ~29"x32" (~0.25 sq. arcmin), imaged in the filter L' filter at a central wavelength of 3.80 micron and a band width FWHM of 0.62 micron[1]. The release includes the reduced data from all four nights, processed independently for each night and four additional stacked image products, stacking the nights of 25 and 26.08, of 25 to 27.08, 25 to 28.08 and 25 to 29.08. This combination strategy was adopted to reflect the interplay between the increase of the sensitivity and the possible intrinsic fading of the source with time.

The 5-sigma detection and saturation limits in the Vega system for all products are listed in Table 2. These former were measured by adding artificial sources made with appropriately scaled standard star, observed on 28.08.2017. The formal uncertainty of the photometric standard is about 2%, but the transfer of the calibration from one epoch to another is ~20% (because of the faint galaxy that had to be used for this purpose), and this is the real uncertainty of the numbers listed in Table 2.

There is no unresolved source detection within the derived sensitivity limits at the sky position of the LIGO-VIRGO GW/GRB source in the reduced NaCo images. The nearby galaxy NGC 4993, located ~10 arcsec away, is detected at 5-10-σ.

The release contains 9 science fits images with the associated fits errors. The total data volume is ~150 Mb.

# Release Notes

## Data Reduction and Calibration

The data were processed with the ESO Eclipse Jitter, ver. 5.0.0[2]. This choice was driven by two reasons:
(i) the NaCo pipeline[3] does not propagate errors; the same is true for Jitter, but its source code can easily be modified, as it will be discussed later;
(ii) the NaCo pipeline is optimized for aligning of fields with a bright point sources and it had trouble aligning and cross-correlating this field with the faint extended NGC 4993 in fact, the galaxy is not detected on individual images; furthermore, the pipeline allows to turn off the pointing refinement via cross-correlation only for frames within the cube, but not for individual 2-dimensional frames – on the contrary, Jitter that allows to turn off the pointing refinement and we used this feature to process the data, relying only on the cumulative offsets in the image headers.

Jitter only can handle 2-dimensional fields, so first for each cube the last slice (that is the average of all individual slices with an integration of DIT seconds) was copied into a separate fits file. These 2D fits files were processed with Jitter. As a first step, the data from each night were processed separately.
The Jitter reduction algorithms are described in the manual of the Jitter software. They include sky subtraction, flat fielding, bad pixels masking, image alignment and combination. Twilight flats were generated with the NaCo pipeline. The bad pixel mask, in addition to the bad pixels identified in the flat, masked out also the hot columns in the lower left detector quadrant and trimmed out the outer ~20-40 px around the edges of the image, where the vignetting noticeably reduced the signal-to-noise of the image. An example of a bad pixel mask is shown in Fig. 2.

1 https://www.eso.org/sci/facilities/paranal/instruments/visir/inst.html
2 https://www.eso.org/sci/software/eclipse/faq/faq-jitter.html
3 http://www.eso.org/sci/software/pipelines/index.html

As pointed above, Jitter does not calculate an error for each pixel. To alleviate this problem we modified the Jitter source code, so the final product contains a sum of all input frames, instead of an average. This amounts to commenting out the normalization on line 876 in the file shift.c:

*finpix /= (double)(ncontrib-rejtot) ;*

Then we converted the total ADUs into a total number of photons using the inverse gain of 9.8 $e^-$/ADU for the HighWellDepth readout mode[4]. The readout noise for this mode is 4.4 $e^-$, much smaller than the noise contributed by the background of ~8,000-16,000 ADU per DIT, so the readout noise was neglected.

Jitter also did not perform an accurate astrometric calibration, so we established it by setting the center of NGC 4993 on the final combined image as a reference pixels, and assigning to it the equatorial coordinates of the galaxy. Experiments with different centering indicated that the accuracy of this procedure is of order of a pixel or less – smaller than the FWHM measured form the photometric standard

The photometric calibration was based on the observation of a HD205772 on 28.08.2017. This is a A5IV/V star from the list of van der Bliek, Manfroid & Bouchet (1996, A&AS, 119, 547). It has L'=7.695 mag which converts to ABOUT 0.20 Jy, after adopting a zero point of 244.2 Jy[5]. To account for the atmospheric extinction we adopted the average extinction coefficient calculated for the similar L-band filter of ISAAC: 0.08 dex[6] and for the purpose of the error propagation adopted an uncertainty to this coefficient of 0.01.

At the time of writing this document the available detection of GW 170817 closest in time and in wavelength (and with the smallest uncertainty) is the VISTA $K_S$-band observation from 25.08.2017 by Tanvir et al. (2017, ApJ, 848, L27): 18.25+/-0.03 mag.

### Data Quality

Direct test of the photometric and the astrometric calibrations with sources on the science data is not possible for the lack of suitable source detection. NGC 4993 is detected wit WISE, but the two filters are not identical, and the WISE pixels is larger than the nucleus of the galaxy that is detected on the NaCo images.

### Known issues

There are no known issues with the data.

### Previous Releases

This is the second data release of the Phase III GW_170817 data collection. The previous release provided the VISIR data products.

## Data Format

### Files Types

The reduced data products are two dimensional sky-subtracted and flux calibrated images, with the corresponding errors and bad pixel maps. All products are in FITS format.

### Catalogue Columns

The release contains no catalogs.

4 VERY LARGE TELESCOPE NACO User Manual Doc. No. VLT-MAN-ESO-14200-2761, Issue 101, Table 5-5, p. 27; https://www.eso.org/sci/facilities/paranal/instruments/naco/doc.html

5 http://svo2.cab.inta-csic.es/svo/theory/fps3/index.php?id=Paranal/NACO.Lp

6 http://www.eso.org/sci/facilities/paranal/decommissioned/isaac/tools/imaging_standards.html

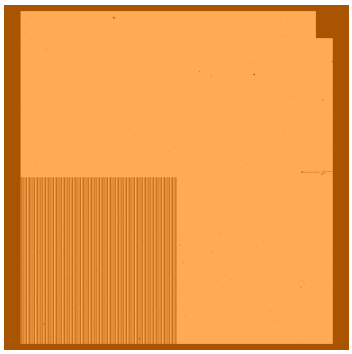

Fig. 2. Bad pixels mask. Note the lower left quadrant – three of every eight columns are hot and yield saturation level values, leading to 37.5% loss of signal, after combining the jittered images.

Table 2. Derived sensitivity and saturation limits in the Vega system (note that in the headers the limits are in AB system) for the individual nights and for some combinations of these data sets.

| Date set | File names | 5-σ limit, mag | Saturation limit, mag |
|---|---|---|---|
| 25.08.2017 | NACO_2017-08-25_image.fits | 16.70 | 6.46 |
| 26.08.2017 | NACO_2017-08-26_image.fits | 16.68 | 6.50 |
| 27.08.2017 | NACO_2017-08-27_image.fits | 16.48 | 6.71 |
| 28.08.2017 | NACO_2017-08-28_image.fits | 16.15 | 6.74 |
| 29.08.2017 | NACO_2017-08-29_image.fits | 17.70 | 6.61 |
| 25-26.08.2017 | image_56.fits | 16.99 | 6.46 |
| 25-26-27.08.2017 | image_567.fits | 17.09 | 6.46 |
| 25-26-27-28.08.2017 | image_5678.fits | 17.21 | 6.46 |
| 25-26-27-28-29.08.2017 | image_56789.fits | 17.61 | 6.46 |

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*Any publication making use of this data, whether obtained from the ESO archive or via third parties, must include the following acknowledgment:*

- "Based on data products created from observations collected at the European Organisation for Astronomical Research in the Southern Hemisphere under ESO programme(s) 60.A-9392(B), PI A. Kaufer"

*If the access to the ESO Science Archive Facility services was helpful for you research, please include the following acknowledgment:*

- "This research has made use of the services of the ESO Science Archive Facility."