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ALICE Data Release: A Revaluation of *HST*-NICMOS Coronagraphic Images

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Abstract

The *Hubble Space Telescope* NICMOS instrument was used from 1997 to 2008 to perform coronagraphic observations of about 400 targets. Most of them were part of surveys looking for substellar companions or resolved circumstellar disks to young nearby stars, making the NICMOS coronagraphic archive a valuable database for exoplanets and disks studies. As part of the Archival Legacy Investigations of Circumstellar Environments program, we have consistently reprocessed a large fraction of the NICMOS coronagrahic archive using advanced starlight subtraction methods. We present here the high-level science products of these re-analyzed data, which we delivered back to the community through the Mikulski Archive for Space Telescopes: doi:10.17909/T9W89V. We also present the second version of the HCI-FITS format (for High-Contrast Imaging FITS format), which we developed as a standard format for data exchange of imaging reduced science products. These re-analyzed products are openly available for population statistics studies, characterization of specific targets, or detected point-source identification.

Key words: catalogs – methods: data analysis – techniques: image processing

1. Introduction

Direct imaging of exoplanetary systems is one of the greatest challenges in modern astronomy due to the very high contrast between the host star and surrounding circumstellar objects at close angular separation. To obtain direct astrophysical signal of these circumstellar objects, dedicated coronagraphic instruments are required to attenuate the starlight in the images to enable fainter object detection. Yet, because of imperfect starlight suppression and wavefront variations, the coronagraphic images are still dominated by the starlight at short separations. To detect the faintest objects, this residual starlight, i.e., the coronagraphic point-spread function (PSF),[6] must be subtracted out using post-processing data reduction techniques.

Classical differential imaging methods consist of subtracting a typical PSF image from the science image, using a single image (Lowrance et al. 2005) or a median image (Marois et al. 2006) either from a reference star or from the science target itself using angular diversity to limit self-subtraction of the astrophysical source. These classical differential imaging methods usually have limited performance due to significant wavefront variations between acquisitions, causing temporal variations in the PSF. For instruments on the *Hubble Space Telescope*'s (*HST*), instrumental deformations on timescales from a few seconds to several days (Lallo et al. 2006; Makidon et al. 2006) introduce additional temporal variations in the PSF that typically limit point-source detections to contrast lower than 10^4 within $\sim 1''$ from the star with differential imaging (e.g., Lowrance et al. 2005). Yet, these methods have been very successful at detecting brown dwarf companions and circumstellar disks (e.g., Schneider et al. 1999; Kalas et al. 2006; Schneider et al. 2014).

Over the past decade, advanced post-processing techniques have emerged that take advantage of a library of instrument PSFs. The temporal variations of the PSF introduced in the instrument PSF library can be combined to create an optimal synthetic PSF that is then subtracted from the target PSF. The synthetic PSF can be created using a linear combination of instrument PSF images (LOCI and its variants; Lafrenière et al. 2007) or using principal component analysis (PCA) on the PSF library (Amara & Quanz 2012; Soummer et al. 2012). For first-generation instruments on *HST*, these techniques are more efficient when using PSFs from many different stars (multiple reference star differential imaging, MRDI), even when observations are separated by large time intervals. This has been demonstrated by the re-discovery of HR 8799 planets (b, c, and d) in archival NICMOS data from 1998 (Lafrenière et al. 2009; Soummer et al. 2011). Indeed, depending upon the size and quality of the PSF image library, these techniques can offer a significant improvement in comparison to classical PSF subtraction.

With the advent of these advanced post-processing techniques, it is worth considering reanalyzing some of the data obtained with first-generation coronagraphic instruments. We started the Archival Legacy Investigations of Circumstellar Environments (ALICE) project with the goal to consistently reprocess the NICMOS coronagraphic archive with advanced post-processing methods (Choquet et al. 2014a). NICMOS operated on board *Hubble* for about 8 years between 1997 and 2008. Its mid-resolution channel NIC2 (pixel size $0''.076$) was equipped with a $0''.3$ radius coronagraphic mask and a Lyot stop. During its time in operation approximately 400 stars were observed, most as part of surveys looking for debris disks and planets around nearby stars. The ALICE pipeline assembles and aligns large PSF libraries from consistent subsets of this database that are used to process each individual target with the KLIP algorithm (Soummer et al. 2012). This project has revealed new images of 12 debris disks previously undetected

[5] Hubble Fellow.
[6] From hereafter the authors use "PSF" when referring to residual starlight.

from the NICMOS data, among which 11 had never before been imaged in scattered light (Soummer et al. 2014; Choquet et al. 2016, 2017; Choquet et al. 2018). In addition, we found a total of 452 point sources uncovered in the data (Choquet et al. 2015).

We are now delivering the reprocessed products of the ALICE program back to the community, openly accessible as High-Level Science Products through the MAST archive[7] doi:10.17909/T9W89V. We also further improved the HCI-FITS standard format for high-contrast imaging science products to make it compatible with any high-contrast imaging instrument, and we present here version two of this format.

In Section 2, we present the content of the ALICE archive and the reprocessed data sets. In Section 3, we present the HCI-FITS format used for the delivered science products.

2. Released Data Sets

2.1. ALICE Inputs

The input data for the ALICE program come from the Legacy Archive PSF Library and Circumstellar Environments (LAPLACE) program[8] (*HST* program AR-11279, PI: G. Schneider; Schneider et al. 2010). This program delivered a homogeneous re-calibration of a large fraction of the raw NICMOS coronagraphic archive, optimized for imaging at separations close to the coronagraphic-mask inner working angle (radius of 0″3) using PSF subtraction techniques. This re-calibration was performed using contemporary flat-field frames optimally matched to the location of the coronagraphic mask (as opposed to epochal flats), and using an improved bad-pixel correction. During the second era of NICMOS operations (after replacement of its cooling system), dark calibration observations were obtained with less frequency than during the first era, and the LAPLACE program delivered two versions of re-calibrated images: one using observation-optimized dark frames when available, and one using synthetic model dark frames.

For consistency, the ALICE program re-analyzed all the non-polarimetric data from the LAPLACE program that were calibrated with contemporary flats for NICMOS Era 1,[9] and with contemporary flats and observed dark frames for NICMOS Era 2,[10] which represent 72% of the non-polarimetric NICMOS archival data sets. Furthermore, we also re-analyzed a few selected data sets that were not re-calibrated by the LAPLACE program (from *HST* programs 7248, 10897, and 11155).

2.2. ALICE Outputs

The outputs of the ALICE program—and delivered data described through this document—all come from the input data detailed above. Data that were not reprocessed may have: (1) not been part of the LAPLACE inputs described above, (2) suffered from bad acquisition images not centered on the coronagraphic mask, or (3) failed sub-pixel alignment within a PSF library. The complete list of NICMOS coronagraphic programs (non-polarimetric data) is detailed in Table 8 in Appendix A. The table also reports the number of targets per *HST* program that have been partly or entirely reprocessed as part of the ALICE program. The complete list of reprocessed images for each *HST* program, target, and filter set can be accessed on the MAST archive. Details on how these data were re-analyzed (field of view, alignment procedure, PSF subtraction, and analysis methods) are described in Choquet et al. (2014a).

NICMOS data from 401 targets were used as input for the ALICE program, some observed in multiple *HST* programs (451 different target observations) and/or with multiple filters. In total, there were 590 different data sets, i.e., 590 unique observations with respect to program, target, and filter. The number of input images that were re-analyzed by the ALICE program amounts to a total of 4879 images (83% of them were acquired with the F110W or F160W filters). Reprocessed data are delivered for 494 data sets out of the 590 input ones. Of the 96 data sets not delivered, 56 of them were entirely composed of bad acquisition images and 40 others could not be properly aligned within a PSF library (often because the target was not a bright star or the target was a binary or contained a bright companion causing the alignment to fail). The majority of these data sets were acquired with the F110W or F160W filters (408 data sets). This amounts to a total of 3955 reprocessed images (86% in F110W or F160W), delivered back to the community.

2.3. Note on the Reprocessing Efficiency

The PSF libraries assembled by the ALICE pipeline are much larger in the F110W and F160W filters than in the other filters, as the F110W and F160W were commonly used for surveys and specific object characterizations. The mediumband and narrowband filters were exclusively used for characterization of known circumstellar objects. Furthermore, as ALICE's reprocessing is based on MRDI and excludes images with detected circumstellar material from the reference PSF libraries (except in "planet mode," which includes images of the science target acquired in a different orientation of the spacecraft, when available; Choquet et al. 2014a), the mediumband and narrowband filter data were reprocessed with PSF libraries of very small sizes (see Table 1). ALICE's reprocessing for these data sets is not expected to improve much upon classical PSF subtraction techniques. The real added value from the ALICE program mostly concerns NICMOS data acquired with the F110W and F160W filters.

3. Released Products

For each data set reprocessed by the ALICE program, we provide three outputs: (1) A high-level science FITS file, gathering all the high-contrast imaging metrics in the standard HCI-FITS format for the combined data at the target level. This is the main output product of the ALICE program and should be used for detection purposes. (2) A folder with FITS files for each reprocessed image of the data set, gathering the material needed to perform forward modeling of an astrophysical signal. These should be used for characterization of signals detected in the main high-level science product. (3) A folder with preview PDF files of the main outputs of the data set.

[7] https://archive.stsci.edu/prepds/alice/
[8] https://archive.stsci.edu/prepds/laplace
[9] https://archive.stsci.edu/missions/hlsp/laplace/dd1/LAPL/NICMOS-LAPL-DD1/LAPL_DATA/contemp_flats/repaired/, see *_clc_*.fits files.
[10] https://archive.stsci.edu/missions/hlsp/laplace/dd2/LAPL/NICMOS-LAPL-DD2/LAPL_DATA_DD2/comtemp_flats-DD2/, see *_o_clc_*.fits files.

Table 1
ALICE Reference PSF Libraries

Filter	Era 1		Era 1	
	# Images[a]	# PSF[b]	# Images[a]	# PSF[b]
F110W	144	54	1854	809
F160W	824	360	1248	655
F165M	42	16	49	19
F171M	36	16	66	6
F180M	98	46	69	14
F187N	5	0	9	6
F187W	3	0	0	0
F190N	5	0	18	0
F204M	4	4	74	19
F205W	11	0	0	0
F207M	174	76	0	0
F212N	28	10	0	0
F215N	28	10	18	0
F222M	15	0	52	7
F237M	5	5	0	0

Notes.
[a] Number of images used as input of the ALICE program.
[b] Number of images used as references for PSF subtraction.

3.1. Definition of Data Set

We refer to a *data set* as the set of images acquired with the same filter element, as part of the same *HST* program, and under the same target identifier (*HST* TARGNAME keyword). Data sets are thus composed of a homogeneous group of images as designed by the PI of the program. A data set may combine images acquired with different spacecraft orientations, with different exposure times, and different epochs (within a year). We assume that any potential astrophysical source remains unchanged in all the images of a data set when combining them in the main ALICE science FITS file.

A few targets have several data sets with the same filter element, in different *HST* programs (despite *HST* policies not to re-observe a target in the same mode), or within the same program (target re-observed after a failed acquisition).

3.2. The HCI-FITS File

The main science output of the ALICE program is a multi-extension FITS file (Pence et al. 2010) that gathers all the high-level information about the reprocessed data set.

In an effort to facilitate high-level data exchange and to make exoplanet population statistical analyses easy, we developed a specific format for these data, and we propose that it becomes a standard for reduced products of high-contrast imaging data (Choquet et al. 2014b). We describe below the main choices we made for the Version 2 of this format and provide a detailed description of its content. We hereafter call this format the HCI-FITS file, for High-Contrast Imaging FITS file. It is inspired from the OI-FITS format, which is the standard for calibrated data exchange from optical interferometers (Pauls et al. 2004, 2005). In addition to the products delivered by ALICE, the HCI-FITS format presented here has also been implemented in the Direct Imaging Virtual Archive (DIVA), another large-scale database dedicated to high-contrast imaging data (Vigan et al. 2017).[11]

[11] http://cesam.lam.fr/diva/

A single FITS file—To enable high-level science analyses of high-contrast imaging data, several products are mandatory (e.g., the reduced image, detection limits, source detections). In order to prevent information loss when exchanging data, all the information must be gathered in a single file. The FITS file format offers the structure needed to achieve that, through the use of extensions. Extensions may contain different types of data, including images (IMAGE extension type) which is appropriate for the reduced images, sensitivity and SNR maps, and multi-dimension tables (BINTABLE extension type), which is appropriate for radial detection limits, characteristics of potentially detected sources, or general characteristics of the reduced products. Moreover, having a single file as reduced product makes databases more convenient to both implement and use.

A flexible standard—We developed HCI-FITS format to be compatible with any type of data set, regardless of the instrument, or observing mode, or processing method used to obtain the final reduced products. It can be used for both ground-based and space observation, for coronagraphic and saturated imaging, for broadband imaging, integral-field spectroscopy, and polarimetric imaging. Depending on the observer/analyst's choice to present the reduced data, a HCI-FITS file may contain products for either a single image or an image cube. For example, this format supports all options between combining all reduced images from an Integral Field Spectrograph (IFS) in one broadband image and keeping each reduced image separated in a spectral cube, while tracking specific image characteristics in all cases.

Structure of the HCI-FITS format—We identified five main products that are necessary for a high-level use of reduced HCI data: the reduced images, the SNR maps, the sensitivity maps (or "noise" maps), the radial detection limits (or "contrast curves"), and the characteristics of any detected point sources. The HCI-FITS format is thus composed of 6 extensions, one for each of these products, plus one which tracks the main characteristics of each image provided in the file. The extensions may appear in any order in the FITS file, but must have mandatory EXTNAME values to enable compatibility between files. The structure of the HCI-FITS format is provided in Table 2. The SOURCE_DETECTION extension is optional but must respect the specified format if present. This structure is not exclusive and may include additional data in other extensions (e.g., intermediate products such as the instrument PSF image). Reading software or codes should not presume the presence of such additional extensions.

The mandatory products enable analyses such as detection limit comparisons and astrophysical signal comparisons, but does not enable precise characterization of an unreported signal. Such characterization requires a forward modeling process (Lagrange et al. 2010; Milli et al. 2012; Soummer et al. 2012; Pueyo 2016) for which intermediate products are needed (instrument PSF image, raw data, eigenimages of the PSF library). Such detailed characterization is out of the scope of the HCI-FITS format use.

The DATA_INFORMATION extension is critical to identify the characteristics of each reduced image in the file. It is the extension that makes this format compatible with any collection of high-contrast images. It is a BINTABLE extension that must be composed of 12 fields that track the field orientation, polarization state, epoch, and spectral information

Table 2
Structure of the HCI-FITS Files

Label	Type	Dimensions	Description
DATA_INFORMATION	BINTABLE	$N_{\rm im} \times 12$	Characteristics of each image
REDUCED_DATA	IMAGE	$N_{\rm im} \times N_x \times N_y$	Reduced data products
SNR_MAP	IMAGE	$N_{\rm im} \times N_x \times N_y$	SNR maps
SENSITIVITY_MAPIMAGE	$N_{\rm im} \times N_x \times N_y$	2D detection limits	…
DETECTION_LIMITBINTABLE	$N_{\rm im} \times 2 \times N_\rho$[a]	Radial detection limits	…
SOURCE_DETECTION [optional]	BINTABLE	$N_{\rm source} \times 20 \times N_{\rm im}$	Detected point sources characteristics

Note.
[a] N_ρ is number of resolution elements.

Table 3
DATA_INFORMATION Extension

Label	Type[a]	Description	Units/Form
Image_Number	I	Index of the image in the cube	…
Orientation	D	Sky-orientation of the image vertical (+Y) axis from North axis (East of North)	Degrees
Combined_Rotation_Angle	D	Parallactic angle combined in the image	Degrees
Number_of_Exposures	I	Number of exposures combined in the image	…
Exposure_Time	D	Total exposure time combined in the image	Seconds
Observation_Start	D	Mod. Julian Date at the start of the exposure	Days
Observation_End	D	Mod. Julian Date at the end of the exposure	Days
UT_Midpoint_Date_of_Observation	A	UT date at the image mid-point	YYYY-MM-DD
UT_Midpoint_Time_of_Observation	A	UT time at the image mid-point	HH:MM:SS
Wavelength	D	Effective wavelength of the image	Angstroms
Bandwidth	D	Effective bandwidth of the image	Angstroms
Polarization	A	Polarization state of the image	…

Note.
[a] L = logical (8 bit), I = integer (16 bit), E = real (32 bit), D = double (64 bit), A = character string (160 bit).

of the images. It must have as many rows as images provided in the file, and if several images are provided, the order must be the same in the DATA_INFORMATION table as in the image cubes. We present in Table 3 the structure of this table.

The DETECTION_LIMIT extension is also `BINTABLE` and reports the radial point-source detection limits for each image present in the file. It must be composed of two mandatory fields reporting the separation from the star and the corresponding detection limit. The header of this extension must indicate the confidence level of the detection limit using the mandatory `NSIGMA` keyword. As the high-contrast imaging community is currently in the process of improving the definition of detection limits (Mawet et al. 2014; Jensen-Clem et al. 2018), we note that the header of this extension may be further developed in subsequent versions of the HCI-FITS format. The structure of this extension is presented in Table 4.

The third optional `BINTABLE` extension reports the characteristics of the point sources detected in the data. For each source it must indicate its astrometry, photometry, and SNR in each image provided in the file.

Specifics of the ALICE HCI-FITS files—For the specific case of ALICE, the HCI-FITS files always contain the reduced data for each combined-roll and for the combination of all images, so the ALICE products present cubes of $N_{\rm im} = N_{\rm roll} + 1$, where $N_{\rm roll}$ is the number of spacecraft orientations used to observe the target.

Table 4
DETECTION_LIMIT Extension

Label	Type[a]	Description
Radius	D ($N_{\rm im}$)	Radial separation from the star
Detection_Limit	D ($N_{\rm im}$)	Point-source detection limit

Note.
[a] L = logical (8 bit), I = integer (16 bit), E = real (32 bit), D = double (64 bit), A = character string (160 bit).

As the ALICE data were reprocessed using the PCA-based KLIP algorithm using large PSF libraries, we provide in the REDUCED_DATA header some specific keywords describing the reduction parameters we used for the data set (see Table 5).

The images in the SENSITIVITY_MAP extension are computed from the temporal variance of the residual speckle field through the PSF library. To do so, we reprocessed the reference images from the PSF library with the same parameters as the science images, and rotated-combined groups of them with the same numbers, weights, and angles as for the science combined images. We then compute the covariance matrix of these combined reference images, convolve it with a $1\lambda/D$ aperture, and compute its square root to estimate the temporal speckle noise map per resolution element. The images in the SNR_MAP extension are computed by convolving the reduced images from the

Table 5
ALICE Keywords in the HCI-FITS File Extension Headers

Keyword	Type[a]	Description
	REDUCED_DATA	
EXTNAME	A	Extension name
BUNIT	A	Brightness units
REDALGO	A	Reduction algorithm
REDSTRAT[b]	A	Strategy to build the PSF library
EXCLANG	E	Exclusion angle for ADI strategy (deg)
TKL	I	Number of subtracted KL-modes w. KLIP
NPSFLIBR	I	Number of images in the PSF library
	SNR_MAP	
EXTNAME	A	Extension name
BUNIT	A	Brightness units
NOISEMET	A	Method used for the detection limit
APERTRAD	D	Aperture radius (pix)
SPATSCAL	A	Spatial unit
	SENSITIVITY_MAP	
EXTNAME	A	Extension name
BUNIT	A	Brightness units
NOISEMET	A	Method used for the detection limit
NSIGMA	I	Detection limit confidence level (sigma)
APERTRAD	D	Aperture radius (pix)
SPATSCAL	A	Spatial unit
	DETECTION_LIMIT	
EXTNAME	A	Extension name
NOISEMET	A	Method used for the detection limit
NSIGMA	I	Detection limit confidence level (sigma)
APERTRAD	D	Aperture radius (pix)
SPATSCAL	A	Spatial unit

Notes.
[a] L = logical (8 bit), I = integer (16 bit), E = real (32 bit), D = double (64 bit), A = character string (160 bit).
[b] Two values may be found in ALICE-generated HCI-FITS files: "RDI" when all images of the target have been excluded from the PSF library, or "ADI+RDI" when the the PSF library also includes images of the target acquired at a complementary orientation of the spacecraft, respecting the EXCLANG exclusion angle.

REDUCED_DATA extension with the same aperture, and dividing it with the images from the SENSITIVITY_MAP. The tables provided in the DETECTION_LIMIT extension are the radial averages of the images in the SENSITIVITY_MAP extension, computed in 2-pixel wide annuli. They are normalized by the stellar flux converted to count s^{-1} (keyword `STARFLUX` in the primary header) to give a measure of the point-source detection limit in terms of contrast to the star. We provide in the header of these three extensions keywords describing the parameters used to compute these metrics (see Table 5). It is important to note that the sensitivity map and the detection limit delivered here do not include the processing throughput.

The characteristics of the detected sources in extension SOURCE_DETECTION are computed from a matched-filter process with a synthetic, unocculted NICMOS PSF, computed for the corresponding filter element with the TinyTIM software package (Krist et al. 2011). The source astrometry is determined with the position that maximizes the cross-correlation between the reduced images and the normalized synthetic PSF. The photometry of the source is retrieved with the maximum value of the cross-correlation, subtracted from the local background level, corrected from post-processing oversubtraction with analytical forward modeling (Soummer et al. 2012), and corrected from correlation losses between the synthetic and the real PSF by using photometric calibration data acquired on calibration white dwarfs. The contrast is computed by normalizing the photometry by the stellar flux converted in count s^{-1} (keyword `STARFLUX` in the primary header). Table 6 provides a description of the SOURCE_DETECTION extension.

Table 6
SOURCE_DETECTION Extension

Label	Type[a]	Description	Units
Candidate	I	Index of the detected source	⋯
SNR	D (N_{im})	SNR of the source	⋯
dRA	D (N_{im})	Relative R.A. from the star	Arcseconds
err_dRA	D (N_{im})	Uncertainty on the dRA	Arcseconds
dDEC	D (N_{im})	Relative Dec. from star	Arcseconds
err_dDEC	D (N_{im})	Uncertainty on the dDEC	Arcseconds
Sep	D (N_{im})	Separation from the star	Arcseconds
err_Sep	D (N_{im})	Uncertainty on separation	Arcseconds
PA	D (N_{im})	Position Angle (east of north)	Degrees
err_PA	D (N_{im})	Uncertainty on the PA	Degrees
Flux_cs	D (N_{im})	Photometry	Counts s^{-1}
err_Flux_cs	D (N_{im})	Uncertainty on Flux_cs	Counts s^{-1}
Flux_mag	D (N_{im})	Photometry	Mag
err_Flux_mag	D (N_{im})	Uncertainty on Flux_mag	Mag
Flux_Jy	D (N_{im})	Photometry	Jansky
err_Flux_Jy	D (N_{im})	Uncertainty on Flux_Jy	Jansky
Flux_erg	D (N_{im})	Photometry	erg cm^{-2} s^{-1} A^{-1}
err_Flux_erg	D (N_{im})	Uncertainty on Flux_erg	erg cm^{-2} s^{-1} A^{-1}
Contrast	D (N_{im})	Contrast from the star	⋯
err_Contrast	D (N_{im})	Uncertainty on the Contrast	⋯

Note.
[a] L = logical (8 bit), I = integer (16 bit), E = real (32 bit), D = double (64 bit), A = character string (160 bit). In instances where these values are unknown, the value *NaN* is used.

The primary header of the ALICE HCI-FITS files is described in Table 9 in Appendix B. It gathers a selection of keywords useful at a science level, and comes from the raw *HST* FITS header, LAPLACE program added keywords, and from our work.

3.3. Data Image Products

In addition to the main HCI-FITS file, which provides science metrics for the combined products of a data set, we also provide a "Products" folder gathering intermediate products for each image in the data set. These files are complementary to the combined HCI-FITS products. While the purpose of main HCI-FITS file is to provide high-level science metrics to quantify the detection limits and detected sources in the data set, the data image products are useful for diagnostic and astrophysical signal forward modeling.

Table 7
Structure of the Exposure-level Science Product FITS Files

Label	Type	Dimensions	Description
REDUCED_IMAGE	IMAGE	$N_x \times N_y$	Reduced data image
RAW_IMAGE	IMAGE	$N_x \times N_y$	Calibrated raw data image
REDUCTION_ZONE	IMAGE	$N_x \times N_y$	Reduction zone
EIGEN_IMAGES	IMAGE	$N_x \times N_y \times N_{\mathrm{kl}}$	Cube of eigenimages used for KLIP subtraction
REF_FILE_NAMES	BINTABLE	$N_{\mathrm{ref}} \times 5$	List of the reference image filenames

For each exposure, we provide a multi-extension FITS file gathering the products described in Table 7. Unlike the main HCI-FITS file, these products are specific to ALICE and their format is not compatible with all types of high-contrast science products.

The REDUCED_IMAGE extension provides the reduced image computed by the ALICE pipeline using the KLIP algorithm. The image is not derotated and is presented with the same field orientation as the raw NICMOS image. The star is centered on pixel (41, 41) with pixel (1, 1) at the bottom left of the image. The header of the extension provides detailed information on the reduction parameters used to compute the image (see Table 10 in Appendix C).

The RAW_IMAGE extension provides the raw NICMOS image calibrated by the LAPLACE program. The LAPLACE image has been cropped to a field of view smaller than the NICMOS full frame (80 × 80 pixels or ∼6.1 × 6.1 arcsec), and the star is centered on pixel (41, 41). The header of the extension lists the keywords provided in the raw *HST* file, as well as the position of the star center in the full NICMOS field of view (see Table 10 in Appendix C).

The REDUCTION_ZONE extension provides a binary image of the reduction zone (pixels with 0 value were excluded from the reduction). In most cases, the reduction zone correspond to the full image except for a central mask of a few pixels radius. The parameters used to define the reduction zone are provided in the extension header (see Table 10 in Appendix C).

The EIGEN_IMAGES extension provides the cube of the first principal components of the PSF library used for the PSF subtraction, truncated at the number of components actually used to reduce the data. This cube can be used to analytically compute the impact of the PSF subtraction process on an astrophysical source using forward modeling.

The REF_FILE_NAMES extension provides a table with the file name of the NICMOS images composing the PSF library used to reduce the image. The table also provides the position of the star center in these reference images in the full NICMOS field of view, around which they have been aligned and cropped to 80 × 80 pixels.

3.4. Preview Folder

Finally, we also deliver for each data set a "Preview" folder that contains PDF and CSV files of the content of each extension of the main HCI-FITS file. The PSF files show images of each frame of the REDUCED_DATA extension (one version with the point-source detections circled and one version without) of the first frame (North-combined frame) of the SNR_MAP extension and of the DETECTION_LIMIT extension. The CSV files show all the data contained in each BINTABLE extension (DATA_INFORMATION, DETECTION_LIMIT, SOURCE_DETECTION).

4. Conclusion

We have presented the reprocessed NICMOS data that we re-analyzed as part of the ALICE program. We deliver these science products to the community so that they may aid population studies through detection limits and substellar candidate identifications. We also presented version 2 of the HCI-FITS format, a standard format for high-contrast imaging science products that can be used with any type of high-contrast imaging data set. We hope this effort will help gather consistent data sets throughout the community.

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Appendix A
The NICMOS Coronagraphic Archive

We report in Table 8 the comprehensive list of *HST* programs that used the coronagraphic mode of the NICMOS instrument for non-polarimetric observations. We also report the number of target observed per program, as well as the number of these which have been re-calibrated as part of the LAPLACE program, and re-analyzed as part of the ALICE program.

Table 8
Non-polarimetric NICMOS Coronagraphic Programs

Prog.	Cy.	Type	LAPL[a]	ALICE[b]	PI	Title
			ERA 1			
7038	7	SM2/NIC	0/3	0/3	G. Schneider	NICMOS Target Acquisition Test
7052	7	SM2/NIC	0/1	0/1	G. Schneider	NICMOS Coronagraphic Performance Verification
7157	7	SM2/NIC	0/1	0/1	G. Schneider	NICMOS Optimum Coronagraphic Focus Determinaton
7179	7	GTO/NIC	1/1	0/1	B. Smith	Search for Volcanic Activity on Enceladus
7220	7	GTO/NIC	4/5	4/5	R. Weymann	Imaging of Quasar Host Galaxies
7221	7	GTO/NIC	3/3	0/3	J. Hill	Imaging of Quasar Absorber Systems
7226	7	GTO/NIC	44/44	39/44	E. Becklin	Search for Massive Jupiters
7227	7	GTO/NIC	29/29	28/29	G. Schneider	A Search for Low Mass/Sub-Luminous Companions to M-Stars
7233	7	GTO/NIC	18/23	17/23	B. Smith	Dust Disks around Main Sequence Stars
7248	7	GTO/NIC	0/1	1/1	B. Smith	Spectroscopy and Polarimetry of the Beta Pictoris
7329	7	SNAP	20/20	0/20	M. Malkan	The Nature of the Damped LyAlpha Absorbers—A New Study of Young Galaxies
7418	7	GO	3/3	3/3	D. Padgett	NICMOS Imaging of Young Stellar Object Circumstellar Nebulosity
7441	7	GO	0/6	0/6	M. Brown	A Search for Zodiacal Dust around Bright Nearby Stars
7808	7	ENG/NIC	1/1	1/1	G. Schneider	NICMOS Coronagraphic Hole Location Test
7828	7	GO	0/1	0/1	J. Hollis	Detection of the Infrared Jet in the R Aquarii Binary System
7829	7	GO	6/6	5/6	C. Johns-Krull	Mapping H_2 Emission Around T Tauri Stars
7834	7	GO	7/7	6/7	R. Rebolo	A Search for Giant Planets Around Very Young Nearby Late-type Dwarfs
7835	7	GO	8/14	7/14	E. Rosenthal	A Search for Superplanets Embedded in Beta Pic&Vega-like Circumstellar Disks
7857	7	GO	7/8	7/8	A.-M. Lagrange	Investigating the missing link between disks around Pre Main Sequence and Main Sequence stars
7897	7	SNAP	20/20	17/20	M. Clampin	Probing planetary formation around main- sequence stars: A snapshot survey
7924	7	ENG/NIC	1/1	1/1	G. Schneider	NICMOS Coronagraphic Hole Location Re-Test
8079	7	CAL/NIC	2/2	2/2	A. Schultz	Mapping the Light Scatter in the NICMOS Coronagraphic Hole {PSF Recovery Orbits}
			ERA 2			
8979	10	SM3/NIC	1/1	1/1	G. Schneider	NICMOS Optimum Coronagraphic Focus Determinaton
8983	10	SM3/NIC	2/2	2/2	G. Schneider	NICMOS Mode-2 Target Acquisition Test
8984	10	SM3/NIC	1/1	1/1	G. Schneider	NICMOS Coronagraphic Performance Assessment
9693	11	CAL/NIC	2/3	1/3	G. Schneider	NICMOS Coronagraphic Performance Assessment
9834	12	GO	7/7	6/7	J. Debes	Finding Planets in the Stellar Graveyard: A Faint Companion Search of White Dwarfs with NICMOS
9845	12	GO/DD	1/1	1/1	M. Liu	NICMOS Confirmation of a Young Planetary-Mass Companion
10147	13	GO	0/2	0/2	M. Endl	Detecting the elusive low mass companion around epsilon Indi
10167	13	GO	8/8	7/8	A. Weinberger	Imaging of Ices in Circumstellar Disks
10176	13	GO	111/111	108/111	I. Song	Coronagraphic Survey for Giant Planets Around Nearby Young Stars
10177	13	GO	56/56	54/56	G. Schneider	Solar Systems In Formation: A NICMOS Coronagraphic Survey of Protoplanetary and Debris Disks
10228	13	GO	2/2	2/2	P. Kalas	Multi-color *HST* imaging of the GJ 803 debris disk
10244	13	GO	2/2	2/2	M. Wyatt	Coronagraphic imaging of Eta Corvus: a newly discovered debris disk at 18 pc
10448	13	GO	1/1	1/1	A. Schultz	NICMOS 2-gyro Coronagraphic Performance Assessment
10464	14	ENG/NIC	1/1	1/1	A. Schultz	NICMOS 2-gyro Coronagraphic Performance Assessment
10487	14	GO	11/11	9/11	D. Ardila	A Search for Debris Disks in the Coeval Beta Pictoris Moving Group
10527	14	GO	23/23	22/23	D. Hines	Imaging Scattered Light from Debris Disks Discovered by the *Spitzer Space Telescope* Around 20 Sun-like Stars
10540	14	GO	10/10	9/10	A. Weinberger	Imaging Nearby Dusty Disks
10560	14	GO	1/1	1/1	J. Debes	Confirming Planetary Candidates in the Stellar Graveyard with NICMOS
10599	14	GO	4/4	4/4	P. Kalas	Multi-color imaging of two 1 Gyr old debris disks within 20 pc of the Sun: Astrophysical mirrors of our Kuiper Belt
10847	15	GO	0/1	0/1	D. Hines	Coronagraphic Polarimetry of *HST*-Resolved Debris Disks
10849	15	GO	23/23	23/23	S. Metchev	Imaging Scattered Light from Debris Disks Discovered by the *Spitzer Space Telescope* around 21 Sun-like Stars
10852	15	GO	3/6	2/6	G. Schneider	Coronagraphic Polarimetry with NICMOS: Dust grain evolution in T Tauri stars
10854	15	GO	0/6	0/6	K. Stapelfeldt	Coronagraphic Imaging of Bright New Spitzer Debris Disks II.
10857	15	GO	0/4	0/4	A. Weinberger	Are Organics Common in Outer Planetary Systems?
10896	15	GO	0/1	0/1	P. Kalas	An Efficient ACS Coronagraphic Survey for Debris Disks around Nearby Stars
10897	15	GO	0/2	1/2	J.-F. Lestrade	Coronagraphic imaging of the submillimeter debris disk of a 200 Myr old M-dwarf
11148	16	GO	0/3	0/3	J. Debes	High Contrast Imaging of Dusty White Dwarfs
11155	16	GO	0/8	5/8	M. Perrin	Dust Grain Evolution in Herbig Ae Stars: NICMOS Coronagraphic Imaging and Polarimetry
11157	16	GO	0/26	0/26	J. Rhee	NICMOS Imaging Survey of Dusty Debris Around Nearby Stars Across the Stellar Mass Spectrum

Notes.
[a] Number of targets in the program with at least one image re-calibrated by the LAPLACE program.
[b] Number of targets in the program with at least one image reprocessed by the ALICE program.

Appendix B
ALICE HCI-FITS File Primary Header

In the primary header of the HCI-FITS file, we selected keywords from the raw *HST* data keywords, and calibrated LAPLACE keywords that may be useful for a high-level science analysis of these data. We also added useful keywords specific to our work. The list of keywords present on the ALICE HCI-FITS file is presented in Table 9.

Table 9
Primary Header of the HCI-FITS File for ALICE Products

Keyword	Type[a]	Description	Reference
		File Information	
FILETYPE	A	Type of data found in the file	This work
ORIGIN	A	FITS file originator	FITS standard
DATE	A	Date this file was written (yyyy-mm-dd)	FITS standard
		FITS File Structure	
DATATYPE	A	Data type	This work
NEXTEND	I	Number of extensions	This work
EXT[k]NAME	A	Name of Extension [k]	This work
EXT[k]TYPE	A	Type of Extension [k]	This work
		Data Structure and Description	
FRAMFORM	A	Structure of each frame	This work
FRAMENUM	I	Number of frames in the data set	This work
FRAME[k]	A	Description of frame [k]	This work
		Program and Instrument Information	
TELESCOP	A	Telescope used to acquire data	*HST* keyword
INSTRUME	A	Identifier for instrument used to acquire data	*HST* keyword
PROPOSID	I	PEP proposal identifier	*HST* keyword
PR_INV_L	A	Last name of principal investigator	*HST* keyword
PR_INV_F	A	First name of principal investigator	*HST* keyword
CAMERA	I	Camera in use (1, 2, or 3)	*HST* keyword
FOCUS	A	In-focus camera for this observation	*HST* keyword
APERTURE	A	Aperture in use	*HST* keyword
FILTER	A	Filter wheel element in beam during observation	*HST* keyword
		Target Information	
TARGNAME	A	Proposer's target name	*HST* keyword
ALTNAME[k][b]	A	Alternative name #[k] of the target	SIMBAD
EQUINOX	I	Equinox of celestial coord. system	*HST* keyword
RA_TARG	D	RA of target (deg) (J2000)	SIMBAD
DEC_TARG	D	Declination of target (deg) (J2000)	SIMBAD
SC_EMAJ	D	Sky coord. error ellipse major axis	SIMBAD
SC_EMIN	D	Sky coord. error ellipse minor axis	SIMBAD
SC_EPA	D	Sky coord. error ellipse position angle	SIMBAD
SC_BIB	A	Sky coord. bibliography code	SIMBAD
PARALLAX[c]	D	Parallax for target found (mas)	SIMBAD
PAR_ERR[c]	D	Parallax mean error	SIMBAD
PAR_BIB[c]	A	Parallax bibliography code	SIMBAD
PROPRA[c]	D	Proper motion (R.A.) of target (mas yr^{-1})	SIMBAD
PROPDEC[c]	D	Proper motion (decl.) of target (mas yr^{-1})	SIMBAD
PM_EMAJ[c]	D	Proper motion error ellipse major axis	SIMBAD
PM_EMIN[c]	D	Proper motion error ellipse minor axis	SIMBAD
PM_EPA[c]	D	Proper motion error ellipse position angle	SIMBAD
PM_BIB[c]	A	Proper motion bibliography code	SIMBAD
		Information on other astrophysical sources	
CANDNUM	I	Number of point-source detections	This work
DISKDET	L	Disk detected in this data set	This work
		Photometric Information	
ADCGAIN	D	Analog-digital conversion gain (electron/DN)	*HST* keyword
STARFLUX	D	Star flux computed from synphot (count s^{-1})	This work
J_2MASS	D	Target J band magnitude (2MASS catalog)	LAPLACE keyword
JE_2MASS	D	2MASS J magnitude uncertainty	LAPLACE keyword
H_2MASS	D	Target H band magnitude (2MASS catalog)	LAPLACE keyword
HE_2MASS	D	2MASS H magnitude uncertainty	LAPLACE keyword
K_2MASS	D	Target K band magnitude (2MASS catalog)	LAPLACE keyword
KE_2MASS	D	2MASS K magnitude uncertainty	LAPLACE keyword
F160W_EF	L	K band SED flux density excess flag (Y, N)	LAPLACE keyword

Table 9
(Continued)

Keyword	Type[a]	Description	Reference
F160W_JY	D	Filterband target flux density estimate (Jy)	LAPLACE keyword
PHOTMODE	A	LAPLACE keyword	…
PHOTFLAM	D	Inverse sensitivity (ergs/cm**2/Angstrom/DN)	*HST* keyword
PHOTFNU	D	Inverse sensitivity (JY*sec/DN)	*HST* keyword
PHOTZPT	D	ST magnitude system zero point (mag)	*HST* keyword
PHOTPLAM	D	Pivot wavelength of the photmode (Angstrom)	*HST* keyword
PHOTBW	D	Rms bandwidth of the photmode (Angstrom)	*HST* keyword
		Astrometric Information	
PIXSCALE	D	Pixel scale (arcsec)	…

Notes.
[a] L = logical (8 bit), I = integer (16 bit), E = real (32 bit), D = double (64 bit), A = character string (160 bit).
[b] For this data set delivery, we only provide ALTNAME1—the resolved SIMBAD name.
[c] When the information is available.

Appendix C Data Image Fits File Headers

In Table 10, we describe the header of the Data image FITS file provided in the "Products" folder. Most of the keywords in the primary header come from the raw NICMOS FITS file primary header, and we only describe here the keywords that we modified or added. Similarly, the RAW_IMAGE extension header corresponds to the SCI extension header in the raw NICMOS file, and we describe here the added keywords.

Table 10
Header of the Data Image FITS File

Keyword	Type[a]	Description
		Added/edited keywords in the Primary Header
FILETYPE	A	Type of data found in data file
ORIGIN	A	FITS file originator
DATE	A	Date this file was written (yyyy-mm-dd)
DATATYPE	A	Data type
NEXTEND	I	Number of standard extensions
EXT[k]NAME	A	Name of Extension [k]
EXT[k]TYPE	A	Type of Extension [k]
FRAMFORM	A	Structure of the frame
ALTNAME1	A	Simbad name for target
PIXSCALX	E	Pixel scale in X direction
PIXSCALY	E	Pixel scale in Y direction
		Keywords in the REDUCED_IMAGE extension header
EXTNAME	A	Extension name
BUNIT	A	Brightness units
REDALGO	A	Reduction algorithm
REDSTRAT	A	Strategy to build the PSF library
EXCLANG	E	Exclusion angle for ADI-type strategy (deg)
TKL	I	Number of eigenimages used for KLIP-type subtraction
NPSFLIBR	I	Number of images in the PSF library
STARCENX	E	Star center X position in the full NICMOS frame (pix)
STARCENY	E	Star center Y position in the full NICMOS frame (pix)
		Added/edited keywords in the RAW_IMAGE extension header
EXTNAME	A	Extension name
STARCENX	E	Star center X position in the full NICMOS frame (pix)
STARCENY	E	Star center Y position in the full NICMOS frame (pix)
		Keywords in the REDUCTION_ZONE extension header
EXTNAME	A	Extension name
BUNIT	A	Brightness units
ZONECPA	I	Zone center PA to North (deg)
ZONEDPA	I	Zone delta PA (deg)
ZONERIN	I	Zone inner radius (pix)
ZONEROU	I	Zone outer radius (pix)
		Keywords in the EIGEN_IMAGES extension header
EXTNAME	A	Extension name
REDALGO	A	Reduction algorithm
REDSTRAT	A	Strategy to build the PSF library
EXCLANG	E	Exclusion angle for ADI-type strategy (deg)
NPSFLIBR	I	Number of images in the PSF library

Note.
[a] L = logical (8 bit), I = integer (16 bit), E = real (32 bit), D = double (64 bit), A = character string (160 bit).

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