ESO Phase 3 Data Release Description

Data Collection	HUGS_GOODSS_K
Release Number	1
Data Provider	Adriano Fontana
Date	22.09.2014

Abstract

HUGS (an acronym for Hawk-I UDS and GOODS Survey) is a ultra–deep IR imaging survey executed with the Hawk-I imager at the VLT, that observed in the K and Y bands the UKIDSS Ultra Deep Survey (UDS) and the Great Observatories Origins Deep Survey (GOODS)-South fields covered by the CANDELS survey.

The survey is a joint project between the Rome Observatory and the University of Edinburgh, and it is based on the data collected with a dedicated ESO Large Programs (P.I. A. Fontana, ESO programme no.: 186.A-0898) but includes all the imaging data taken with Hawk-I on the UDS and GOODS-S fields (in the case of GOODS-S, the survey includes data from the ESO programme no.: 181.A-0717).

The HUGS survey was designed to cover the two CANDELS fields accessible from Paranal that do not have suitably-deep K-band images: a sub-area of UDS and GOODS-S.

The depth of the images was chosen to be $0.5 mag$ shallower than obtained with the Wide Field Camera 3 (WFC3/IR) at the Hubble Space Telescope (HST) in H160, as appropriate to match the average H-K color of faint galaxies.

In the UDS field deep Y-band images have also been acquired. They are an essential complement to the CANDELS data set, since neither Y098 nor Y105 imaging of this field has been obtained within CANDELS.

This release contains deep K-band images of the GOODS-South field and the extracted source catalogue.

Overview of Observations

GOODS-S pointings

The WFC3 observations are deeper in a rectangular region (10 by 7 arcmin, named GOODS-Deep in CANDELS) that spans the entire width of the GOODS-S field. The coverage of the GOODS-S field with CANDELS is complex, and forced us to adopt a complicated pattern.

Our final layout has been designed to deliver a deeper image over the central, deeper area (named GOODS-Deep), while covering nearly the entire shallower CANDELS+ERS area (GOODS_Wide).

We therefore decided to cover the whole field with a 2×3 grid of pointings, as shown below: we show both the position of the 6 individual pointings overlaid upon the WFC3 exposure map as well as the final exposure map.

The two central pointings have been exposed for a total of about 31 hours, while the four upper and lower pointings have been exposed for about 11 hours each. We therefore name GD1 and GD2 the two deep exposures, and GW1, GW2,GW3, GW4 the four shallower ones.

The exposure time reaches about 85 hours of exposure time in the very central part, and it still reaches more than 40 hours of exposure time over the remaining part of the GOODS-Deep. This image currently provides a unique combination of depth and area in the K-band.

The deeper area covers most of the Hubble Ultra Deep Field (HUDF), whose long series of campaigns of observations obtained with WFC3 from the Y_{098} to the H_{160} represent our deepest view of the Universe, reaching a final depth that in some case exceeds the 31st magnitude (Ellis et al. (2013); Koekemoer et al. (2013)).

In the next we compare the image obtained by HUGS in the center of GOODS-S with the image obtained with WFC3@HST from CANDELS, in the H band. It can be immediately appreciated that the depth and quality of the HUGS images is comparable in all aspects to the WFC3 data.
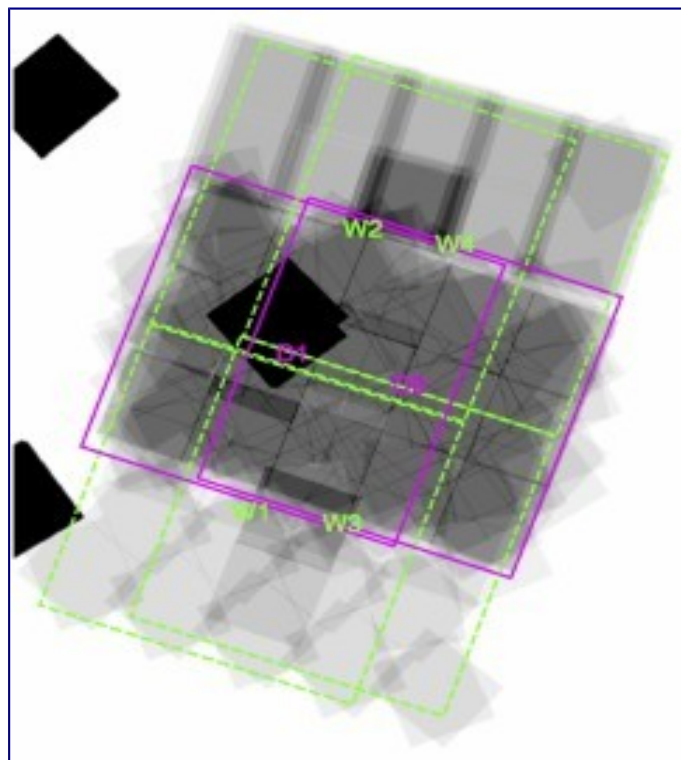
Figure 1: Location of the Hawk-I pointings overlaid on the exposure map of the WFC3 data available within the GOODS-South field. Magenta lines show the field-of-view of pointings D1 and D2, while the green lines show pointings W1, W2, W3 and W4. The black square at the centre is the HUDF12 region (Koekemoer et al. 2013). The greyscale of the WFC3/IR images is on a linear stretch that saturates at the deepest levels of the CANDELS data; the HUDF12 is deeply oversaturated.
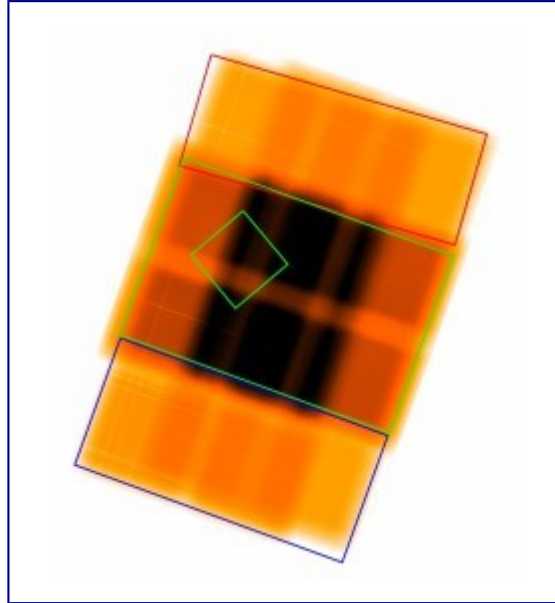
Figure 2: The exposure map of the final HUGS image of the GOODS-South field, in the K band. Darker regions corresponds to longer exposures. Overlaid are also the main WFC3 regions: CANDELS-deep (green large box), CANDELS-wide (blue), ERS (red), HUDF (small green).
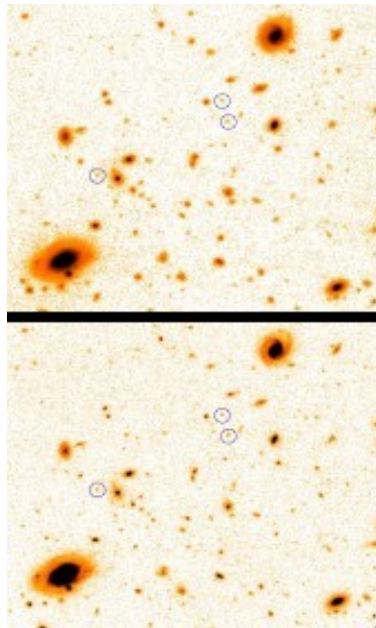

Figure 3: The centre of the deepest GOODS-S field as observed with Hawk-I in the K-band (upper) and with WFC3/IR in the H-band (lower). The displayed area is 1' wide. Objects encircled have H magnitude of ≈26 and a colour H-K≈0.5, typical of faint galaxies.
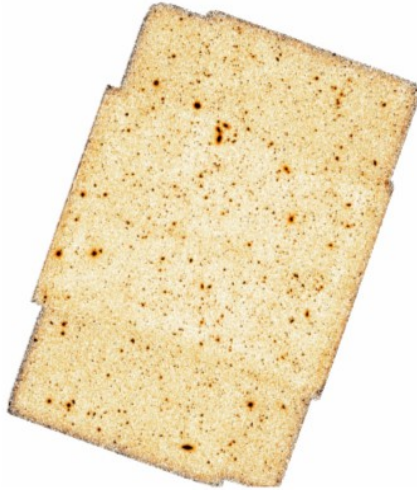
Figure 4: The final stacked mosaic on the GOODS-South field.

This is a brief summary of the observations this data release is based upon:

Table 1 – Summary of GOODS-S observations for the various pointings

Field	Band	Exposure time	Seeing	Lim. mag (AB, 1σ arcsec^{-2})
GOODS-DEEP 1,2	K (2.2 μm)	31.5 hours	0.38" - 0.39"	27.8
GOODS-WIDE 1,2,3,4	K (2.2 μm)	11.3 - 13 hours	0.38" - 0.42"	27.3 – 27.4

A full data paper (Fontana et al, 2014, A&A, in press) describes the survey, where all technical details are given. Please refer to it for full details.

Release Content

The public release of the HUGS GOODS-S K-BAND data includes coadded images of the individual pointings, as well as full mosaics and a release catalogue.

The following data set are made available:

1. **Individual mosaics (K band):** All the 6 coadded images (one for each pointing GOODS-D1, D2, W1, W2, W3 and W4) each with its own ancillary weight map are provided. Exposure times are about 31.5 hours for the two deep pointings (D1 and D2) and 11-13hours for the four wide pointings (W1-W4).

2. **Homogenized-seeing mosaic (K band):** A global mosaic of the GOODS-S field, obtained combining all images (GOODS-D1, D2, W1, W2, W3, W4) after homogenizing to the same PSF, and its ancillary weight map are provided. This has been done by degrading the highest quality images to the one with the poorest seeing. The number of combined science data files is 3559, that is the sum of all the combined data files as shown in the summary above.

3. **Natural-seeing mosaic (K band):** A global mosaic of the GOODS-S field, obtained combining all images (GOODS-D1, D2, W1, W2, W3, W4) without any correction for the different PSFs, and its <u>ancillary weight map</u> are provided. These mosaics have varying PSF across the fields (in a smooth way across the overlapping region) but do not show a varying degree of correlation in the background. The number of combined science data files is 3559, the same of the homogenized-seeing mosaic.

4. **Single K-band catalog:** We have obtained K-band detected catalog using the seeing-averaged images described above.

Please refer to the HUGS paper (Fontana et al. 2014, A&A, in press) for full details.

Release Notes

Data Reduction and Calibration.

We initially used two pipelines to independently reduce the images acquired in the first year of observations. One pipeline has been developed at the Rome Observatory, and is derived from a pipeline used to reduce LBT imaging data both in the visible and in the infrared. The second pipeline has been developed at the University of Edinburgh. We then compared the two pipelines and the resulting reduced images, both in terms of conceptual steps and algorithms adopted, as well as in terms of the final image mosaic. The two results agreed very well and this comparison was utilized to help yield a final, optimized version of the Rome pipeline. The basic steps of the pipeline follow the usual recipe of infrared imaging data reduction and can be summarized as follows:

- *Pre-reduction*. The raw images were retrieved from the ESO archive and each Observing Block was processed separately at this stage. The initial reduction procedure consists of the removal of the dark current and application of a flat-field in order to normalize the response of each image pixel. At first each scientific frame is subtracted by a median stack dark image obtained by combining a set of dark frames with the same EXPTIME and NDIT values of the observation set images. Then a median stack flat image (masterflat) is created, by combining a set of sky flats taken with the same filter as the observation set, each subtracted by its own dark. While combining, each flat is normalized by its own median background level, in order to obtain a final median stack flat normalized to unity. Each scientific image is then divided by the masterflat, so the response of pixels is finally homogenized. During this pre-reduction stage pixel masks are also created to flag saturated regions, cosmic ray events, satellite tracks and bad (hot/cold) pixels.

- *Background subtraction.* After the pre-reduction, the image backgrounds are still far from flat. Structures appear both at small and at large scales due to a variety of causes, such as pupil ghosts, dust, and sky-background variation during the observation (which is particularly strong in the near-infrared, especially in K). We have developed specialized algorithms to carefully remove these structures. Since they are assumed to be additive

features, the basic operation is to create and then subtract maps of the background from each image. The first map is a sigma-clipped median-stacked image of the observations included in a temporal window – typically of about 10 minutes – around the processed image. A further large-scale polynomial fit to the residual features has been subtracted from the images. At the end of this stage, in which each Observing Block has been processed separately, images are flat and ready to be processed to create the final mosaic.

- *Astrometric solution.* In order to perform the coaddition, an accurate astrometric calibration has to be performed. In fact images show geometrical distortions arising from the positional errors of each pixel due to many causes, such as optical distortions, atmospheric refraction, rotation of chips, non-integer dithering pattern, etc. The procedure of astrometric calibration consists of two basic operations: the correction of relative linear offsets between exposures and the refined absolute global calibration. For each exposure, a SEXTRACTOR (Bertin & Arnouts 1996) catalogue is created, and the relative linear calibration between exposures is achieved by correcting for the offsets between source coordinates, computed by the cross-matching with a catalogue chosen as reference. The absolute calibration is done by providing an absolute reference catalogue and correcting for distortions through the cross-matching of source coordinates and by storing the final corrected solution into the header of the images.

- *Estimate of absolute noise image.* Absolute noise maps for each exposure are created directly from the raw images. They are based on the assumption that the noise is given by the Poisson statistics of the counts detected in each pixel of the original frames. This contribution is propagated to take into account the scaling applied to each pixel during processing (including flat-fielding, normalization of exposure times rescaling of zero-points etc).

- *Coaddition.* Our pipeline uses SWarp (Bertin et al. (2002)) to resample all the processed images, implementing it into a procedure designed to properly propagate the absolute r.m.s. obtained as above. In order to obtain a physical exposure and an r.m.s. map of the final mosaic, during the resampling the internal WEIGHT TYPE parameter has to be set to the MAP RMS modality, so that a noise map has to be given for each exposure. During the resampling stage, images with bad astrometric information are rejected, while for each resampled image SWarp provides a weight map in output. The last step is to perform a final weighted coaddition of all the resampled images with the final associated weight and r.m.s. maps.

- *Photometric calibration.* At the end of each reduction we have adopted a careful procedure to calibrate the photometry and estimate the relative zero point independently for each pointing, making use of sets of standard stars observed at the same airmass as the scientific images, and as close as possible in time to the observations. After the relative calibration, all images (science and ancillary weight maps) were finally flux calibrated in nJy yielding AB magnitudes if a zero-point of 31.4 is adopted.

- *Catalog*. The catalog has been obtained using the homogenized seeing mosaic. Note that this is formally correct to avoid systematic effects across the field due to inhomogeneous coverage, but somewhat limits the possibility of detecting the faintest galaxies in the pointings with the best seeing. The catalog has been obtained with SExtractor using a minimal detection area of 9 pixels and requiring S/N>3 in such an area.

Please refer to the HUGS paper (Fontana et al. 2014, A&A, in press) for full details.

Data Quality.

Thanks to exquisite image quality and extremely long exposure times, HUGS delivers the deepest K-band images ever collected over areas of cosmological interest, and in general ideally complement the CANDELS dataset in terms of image quality and depth. In the deepest region, that includes most of the Hubble Ultra Deep Field, exposure times exceed 80 hours of integration, with a $1-\sigma$ magnitude limit per square arcsec of about 28.0 mags (AB). The seeing is remarkably exceptional and constant across the various pointings, ranging between 0.38" and 0.43" as shown in the table:

Pointing	Central RA	Central DEC	Area (arcmin^2)	Exposure time (s/hr)	Final seeing	maglim[a]	maglim[b]
			K-band				
GOODS-D1	03:32:36.835	−27:47:45.24	70	113520 / 31.53	0.39	27.8	26.5
GOODS-D2	03:32:24.890	−27:48:33.22	70	112800 31.33	0.38	27.8	26.5
GOODS-W1	03:32:41.080	−27:51:44.32	70	47220 /13.12	0.43	27.4	26.0
GOODS-W2	03:32:29.650	−27:44:37.26	70	40800 / 11.33	0.38	27.3	26.0
GOODS-W3	03:32:31.796	−27:52:01.74	70	37320 /10.37	0.38	27.3	25.9
GOODS-W4	03:32:20.242	−27:44:59.97	70	41880 /11.63	0.42	27.3	25.8

[a] at 1σ arcsec^{-2}; [b] at 5σ in 1 FWHM

The final quality of the output data is simply spectacular, and shows that Hawk-I on VLT is capable of approaching HST performances even in the case of near-IR deep imaging, where HST is unrivaled.

Please refer to the HUGS paper (Fontana et al. 2014, A&A, in press) for full details.

Data Format

Files Types

This is a summary with the file naming conventions, the total numbers of combined science data files which yielded the imaging release data products and the associated weight maps:

Mosaic name	# of combined data files	Ancillary weight map
HUGS_GOODSS_K_GD1.fits	946	HUGS_GOODSS_K_GD1.wht.fits
HUGS_GOODSS_K_GD2.fits	940	HUGS_GOODSS_K_GD2.wht.fits
HUGS_GOODSS_K_GW1.fits	431	HUGS_GOODSS_K_GW1.wht.fits
HUGS_GOODSS_K_GW2.fits	555	HUGS_GOODSS_K_GW2.wht.fits
HUGS_GOODSS_K_GW3.fits	336	HUGS_GOODSS_K_GW3.wht.fits
HUGS_GOODSS_K_GW4.fits	351	HUGS_GOODSS_K_GW4.wht.fits
HUGS_GOODSS_K_homogenizedseeing.fits	3559	HUGS_GOODSS_K_homogenizedseeing.wht.fits

HUGS_GOODSS_K_naturalseeing.fits   3559   HUGS_GOODSS_K_naturalseeing.wht.fits

This is a summary with the file naming conventions, the total number of detected sources and the total data volume related to the release catalogue:

Catalogue name	# of detected sources	Total data volume (megabytes)
HUGS_GOODSS_K_homogenizedseeing.ldac.fits	15902	3.0

Catalogue Columns

This is also the list of the contents of the catalogue columns:

Label	Data format	Description
SOUCE_ID	25A	HUGS source designation
NUMBER	I	Running object number
ALPHA_J2000	D	Declination of barycenter in decimal degrees (J2000)
DELTA_J2000	D	Declination of barycenter in decimal degrees (J2000)
X_IMAGE	D	Object position along x
Y_IMAGE	D	Object position along y
CLASS_STAR	E	Source classification (star, galaxy...)
MAG_BEST	E	K MAG_BEST
MAGERR_BEST	E	K MAG_BEST error
FLUX_BEST	D	K flux best
FLUXERR_BEST	D	K flux best error
MAG_APER1	E	K fixed aperture magnitude (1", AB)
MAG_APER2	E	K fixed aperture magnitude (2", AB)
MAGERR_APER1	E	K fixed aperture mag error (1", AB)
MAGERR_APER2	E	K fixed aperture mag error (2", AB)
FLUX_APER1	D	K fixed aperture flux (1", AB)
FLUX_APER2	D	K fixed aperture flux (2", AB)
FLUXERR_APER1	D	K fixed aperture flux error (1", AB)
FLUXERR_APER2	D	K fixed aperture flux error (2", AB)
MAG_ISOCOR	E	K isocor magnitude
MAGERR_ISOCOR	E	K isocor mag error
FLUX_ISOCOR	D	K isocor flux
FLUXERR_ISOCOR	D	K isocor flux error
MAG_AUTO	E	K MAG_AUTO
MAGERR_AUTO	E	K MAG_AUTO error
FLUX_AUTO	D	K auto flux
FLUXERR_AUTO	D	K auto flux error
FLUX_RADIUS	D	Radius of aperture containing half the flux of K MAG_AUTO
FLAGS	I	K Flag (SeXtractor)

Acknowledgements