Manual for the open loop LGS-AO data taken with elongated LGS in ELT geometry configuration

Contents

Chapter 1

Introduction

Adaptive Optics (AO) allows to improve the performance of optical systems by compensating the distortion of incoming wavefronts (WFs), caused by the turbulent atmosphere. This is typically achieved in three steps: the distortion is measured by a wavefront sensor (WFS), a computer calculates in real time the optimal mirror shape to correct the distortion and the deformable mirror is reshaped accordingly. In order to measure the deformation of a WF reliably, a sufficiently bright guide star has to exist in close proximity to the observed object. As natural guide stars (NGSs) above a certain brightness are sparsely distributed in the sky, this limits the observable area. To overcome this deficiency, laser guide stars (LGSs) are used as these artificial stars can be generated at any position, allowing observations almost anywhere in the sky.

A sodium LGS is created by pointing a high power laser beam in the sky, operated at the D2 sodium line (589.16 nm in vacuum). At this wavelength, the mesospheric sodium (Na) atoms are excited, residing predominantly in a 10 km thick layer centred around a height of about 90 km. As soon as an excited sodium atom return to its ground state, it emits a photon at the same wavelength (scattering). At the ground from where the laser beam is launched, the sodium scattering atoms are seen superimposed and look similar to a star, hence the name 'artificial guide star' for the LGS.

However, for the upcoming class of extremely large telescopes (ELTs) with diameters of 30–40 m, the interplay of two circumstances creates a challenge: first, the thickness, the abundance of atoms and the mean height of the sodium layer change with time (Pfrommer & Hickson 2014). Second, the perspective effect: seen from a distance at the side of the laser launching location, the laser beam crossing the 10 km sodium layer appears as an elongated bright source, or 'plume'. The size of an ELT plays a crucial role: since the LGS has an elongated shape at a finite distance, the WFSs subapertures located at the further edge of the pupil in a 30–40 m diameter telescope will see an elongated LGS, with an elongation of 20 arcsec or more (Bardou et al. 2016). The principal effect can be seen in Fig. 1.1. Thus, the LGS spot elongation, together with the variability of the sodium layer challenge the determination of the atmospheric turbulence using a LGS. Details on all limitations are summarized in e.g. Bardou et al. (2016).

This has driven the proposal, within the ESO Technology Development program, to demonstrate on sky the performance of LGS-AO when using elongated LGS, in closed loop. Open loop data have been taken during the experiments, which are deemed useful for the numerical simulations of LGS-AO performance with ELT-based instruments.

1.1 Technical setup

In order to infer strategies for the AO design of an ELT, it is necessary to study the implications of the spot elongation which is why D. Bonaccini Calia (ESO), G. Rousset (LESIA) and R. Myers (Durham Univ.), Rousset et al. (2014) proposed an on-sky, ELT scaled experiment to be done using the ESO transportable laser unit, and the CANARY AO system at the William Herschel Telescope (Isaac Newton Group of telescopes in La Palma), including a real time sodium profiler placed at the Isaac Newton Telescope, 426 m from the laser source.

The main goal of such an experiment was to assess the performance of LGS-AO in the case of an ELT under real atmospheric conditions, as well as capture the variability of the sodium layer at an unprecedented 150 Hz rate. The AO system was based on Shack-Hartmann (SH) WFSs. The proposed experiment was realized by interconnecting three different systems as shown in Fig. 1.1.

- The multi-object AO demonstrator **CANARY** (Myers et al. 2008; Gendron et al. 2011) at the 4.2 m William Herschel Telescope (WHT) in the Canaries Islands was used as the AO platform. It was equipped with in total five SH WFS: one on-axis NGS WFS (also called the truth sensor, TS), one on-axis LGS WFS, and three off-axis NGS WFSs, used to obtain the turbulence profile during the observations. CANARY observed all NGSs and the LGS simultaneously in open and closed loop operation, all data taken synchronously.

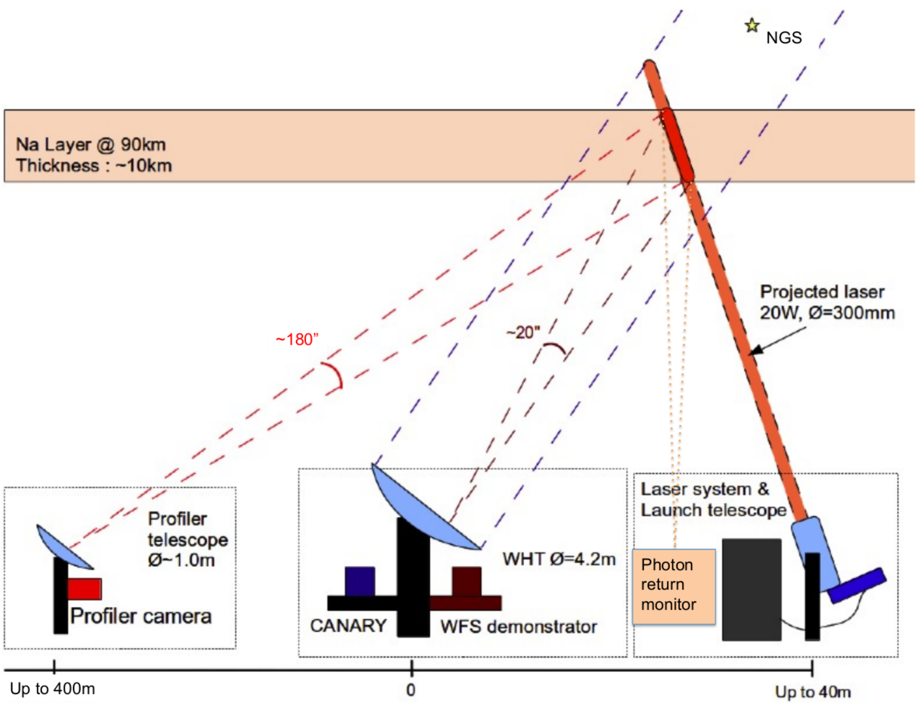

Figure 1.1: Setup of the experiment. Image taken from Rousset et al. (2014).

- The LGS was generated by the ESO Wendelstein Laser Guide Star Unit (**WLGSU**, Bonaccini Calia et al. 2010) which was developed for LGS-AO systems tests in view of technology development strategic field tests, for future instruments. It is a compact, transportable 20 W continuous wave laser that was optimized for the excitation of mesospheric sodium at 589 nm. The WLGSU comes with its own 300 mm laser launch telescope (LLT) which was positioned 40 m away from the WHT, representing the E-ELT geometry foreseen for LGS-AO. Next to it, a LGS return flux monitor acquired synchronously photometric data on the LGS.

- The 1 m Isaac Newton Telescope (**INT**) observed the sodium plume in the mesosphere. It was equipped with a fast and sensitive sodium profiler camera (PCO) that was synchronized with the CANARY bench. It was run synchronously with the WFS of CANARY, i.e. at 150 Hz. This is an unprecedented speed for sampling the mesospheris sodium. Due to the large off-axis distance of 426 m between WHT and INT, the plume had an extension on the order of 180 arcsec and more, with a pixel scale of 0.16 arcsec. The synchronous recording of the mesospheric sodium profiles with high spatial accuracy allows for testing and comparing different centroiding algorithms using the open loop data distributed. It also allows to study the mesospheric sodium profiles and abundance evolution at high frequencies.

Moreover, an additional tip-tilt (TT) mirror and a dichroic filter were placed in the light path of the LGS WFS. The dichroic lets only the 589 nm photons from the sodium layer pass and blocks the photons from the NGS. The TT mirror compensates for the jitter of the laser and is therefore called jitter or steering mirror. In this way, the LGS spots can be kept in the center of the sub-apertures of the WFS to avoid truncating the elongated spot. The additional TT mirror has no influence on the accuracy of the measurement (Bardou et al. 2016) but might create some deviations between the measurements of the LGS and NGS WFS which is why the movement of the TT mirror is recorded.

With the above setup and geometry, the much smaller WHT pupil (4.2 m) represented the sub-apertures at the edge of the ELT pupil (approx. 40 m), which will see the maximum LGS elongation.

1.2 Observational strategy and deliverables

The laser is pointed to an asterism of bright NGSs. CANARY is set up such that the LGS and one NGS are observed with the on-axis WFSs while the remaining stars of the asterism are observed with the three off-axis NGS WFSs. All acquisitions are synchronous. The observational data was acquired in open as well as closed loop operation at a frequency of 150 Hz, or one measurement every 6.67 ms. Each acquisition consists of nominally 5000 frames which corresponds to a duration of 33.3 s. At the same time, the profiler camera at the INT was recording the LGS plume at a frequency of either 50 or 150 Hz. The lower frequency was used when the return signal was reduced, either because of the sodium abundance or because of the effects of the geomagnetic field lines on optical pumping of the mesospheric sodium. At regular intervals (once every 30 – 45 min on average), the atmospheric turbulence profile was estimated via tomographic reconstruction, based on the three off-axis NGS WFSs.

The observing run during which the present data was acquired took place from Sept, 27 until and including Oct, 2, 2017. It was the best of all observing runs done with this setup. From all available CANARY data, open loop observations of the LGS and NGS WFS, both on-axis, were selected. Each data set consists of the LGS and NGS WFS images – raw and calibrated – as well as the associated LGS and NGS slopes and the flux of the LGS which were inferred from the calibrated images. If a determination of the turbulence profile before and/or after the CANARY acquisition on the same target is available, it is also part of the data set. The data set is complemented with sodium profiles measured by the INT, acquired contemporaneously with the observations by CANARY at the WHT. An overview of the content of each data set is given in Table 1.1.

The presented data – along with this manual – is one of the deliverables of the project which is now available to the AO community. The query form for these data sets can be found here: `http://archive.eso.org/wdb/wdb/eso/wlgsu/form`.

Table 1.1: Overview of the content of a data set.

Content	Chapter
raw images of the LGS	3.1
calibrated images of the LGS	3.2
slopes of the LGS	3.3
slopes of the LGS TT mirror	3.4
flux of the LGS	3.5
raw images of the NGS	3.6
calibrated images of the NGS	3.7
slopes of the NGS	3.8
time stamps	3.9
previous $C_n^2(h)$ profile	3.10
next $C_n^2(h)$ profile	3.11
squeezed images	3.12
single sodium profiles	3.13
averaged sodium profiles	3.14
averaged sodium profiles meta data	3.15
center of gravity of the averaged sodium profiles	3.16
average length of the LGS	3.17

1.3 Basic information about the FITS format

The data is stored in the FITS (Flexible Image Transport System) format. All FITS files in this data package are organized such that they always consist of one so-called Primary HDU (Header/Data Unit) and a number of so-called Image HDUs, usually referred to as "extensions". Generally, a FITS file may contain ASCII and/or binary tables extensions which have not been used here. A sketch of the general structure of a FITS file is shown in Fig. 1.2. As the name HDU suggests, each unit consists of a header and an optional data unit that can be retrieved separately.

Each header unit contains a number of keyword records which have the general form: KEYNAME = value / comment string. In the present data sets, the value of any keyword is either a number (integer or floating point number) or a character string (enclosed in single quotes). In the comment string after the slash a short description of the particular keyword is given. A more detailed description of all available keywords can be found in Chap. 2.

The data unit of an Image HDU contains some sort of data but not necessarily a two dimensional image as the name suggests. Each unit of data can either have one, two, or three dimensions, meaning that a number of values are stored in a vector, a matrix, or a cube. A data unit may also be empty. Generally, to facilitate the use of the data, all data belonging to the same acquisition but obtained with different telescopes or methods are gathered and saved in one file. The size of each data set is about 3.7 GB.

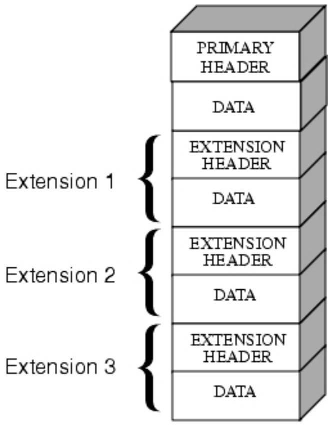

Figure 1.2: Sketch of the structure of a FITS file, here with three extensions. Image taken from `http://www.stsci.edu/instruments/wfpc2/Wfpc2_dhb/images/intro_ch2a.gif`.

1.4 Properties of the LGS and NGS WFS

The LGS and NGS WFS are both SH sensors with 7×7 sub-apertures, corresponding to 60 cm sub-apertures. Fig. 1.3 shows the illumination of both sensors; all sub-apertures with an illumination greater than 50% are considered in the analysis. The sub-apertures of both, LGS and NGS WFS, are numbered as shown in the figure which allows to retrieve the data of each sub-aperture individually. The physical sizes of the two WFSs, the size of each sub-aperture, the pixel size, and the field of view are summarized in Table 1.2. As can be seen, the sub-aperture size as well as the pixel size of the LGS WFS are both significantly larger as compared to the NGS WFS in order to fit the elongated spots entirely into a sub-aperture.

Table 1.2: Properties of the LGS and NGS WFS

	sensor size	sub-aperture size	pixel size	field of view
NGS WFS	128×128 pixels	16×16 pixels	0.24 arcsec	3.84×3.84 arcsec
LGS WFS	240×240 pixels	30×30 pixels	0.65 arcsec	19.5×19.5 arcsec

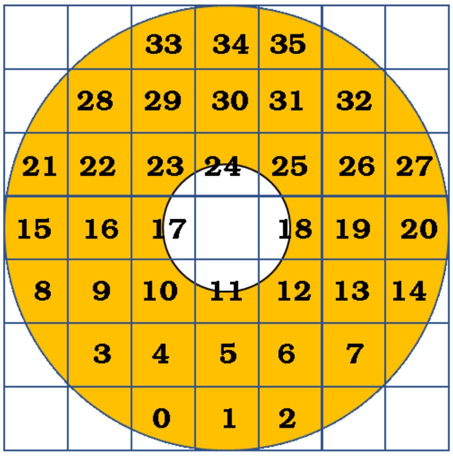

Figure 1.3: Sketch of the LGS and NGS SH WFS with 7×7 sub-apertures; x-axis is pointing to the right, y-axis up. All sub-apertures with an illumination greater than 50% are numbered as given in the figure. The numbering is zero-based as python was used to analyze and store the data.

1.5 Calculation of the slopes

The slopes were calculated based on the calibrated LGS and NGS WFS images for each sub-aperture separately based on the n brightest pixels in the sub-aperture:

1. select the n brightest pixels in the sub-aperture image (n is either NBR_1 or NBR_5, see Chap. 2.3.9),
2. subtract the pixel value of the $n + 1$ brightest pixel from all pixel values in the sub-aperture image,
3. set all pixel values that are below zero to zero.

Through step 2, the zero level of the transformed image is at the level of the $n + 1$ brightest pixel of the original sub-aperture image. To determine the slope of the sub-aperture image, a Center of Gravity (CoG) method was used. The following algorithm was applied to the transformed image (`image` in the code sample):

```
size = image.shape[0]
xx, yy = np.meshgrid(np.arange(0, size)-size/2.+0.5,
                     np.arange(0, size)-size/2.+0.5)
decx = np.sum(image*xx)/np.sum(image)
decy = np.sum(image*yy)/np.sum(image)
slopes = decx, decy
```

This code sample is written in python 2.7 and makes use of the `numpy` module (abbreviated to `np`). The resulting `slopes` consist of a x and y value which are both in pixels and can be converted to arcsec with the keywords PIXARC1 or PIXARC5 (see Chap. 2.3.8).

1.6 Imperfections of the data

1.6.1 Dropped frames

During the acquisition of the data, it happened that individual frames in the series of 5000 frames were not recorded which is referred to as "dropped frames". Since a dropped frame corresponds to a time gap in the data, those acquisitions were excluded. However, whenever it was possible to select a continuous sequence of at least 2500 frames without dropped frames, the acquisition was still considered after removing all frames before and/or after the dropped frame(s). Thus, the length of the data sets varies between around 16 and 33 s.

1.6.2 "Squeezed" images

Occasionally, the LGS WFS sensor had a read-out problem during which not all of the rows of the data were recorded. Because of the missing rows, the images look like squeezed vertically. As explained below in Chap. 3.12, each squeezed image (raw and calibrated LGS WFS images, see Chap. 3.1 and 3.2) has been replaced with the previous non-squeezed image. The total number of squeezed images in a data set is stored under the keyword SQZ_IMA (see Chap. 2.4.5) in the main header.

1.7 Access of the data

The processing of the data has been done with python 2.7 and for the visual inspection, SAOImage DS9 was used. For quickly checking the header(s) of FITS file(s), `dfits` is an useful tool, in particular in combination with `fitsort`.

To facilitate the usage of the data, a small script (`access_data.py`) is available on the query web page with which the different header and data units can be accessed. The script is written in python 2.7 and was tested on a Unix machine. How to use it:

1. in the script: enter the path to the data
2. in a terminal: change to the directory where the script is located and
    - make the script executable with `chmod u+x access_data.py`
    - run the script with `./access_data.py`

The user is of course free to modify the script according to her/his needs.

Chapter 2

Keywords

All keywords in the main header and their meaning are listed here. Keywords that are available for querying are marked in green.

2.1 Keywords defined by the FITS standard

The FITS standard defines a number of keywords that have to be present in the header(s) of every FITS file in a particular order. They were written automatically into the headers at the time when a FITS file was created based on the data in the corresponding data unit. The only exception is the COMMENT keyword (see Chap. 2.1.11).

2.1.1 SIMPLE and XTENSION

SIMPLE must be the first keyword in the primary header of any FITS file and has the value `T` to indicate that the file complies with the FITS standard. This keyword appears only in the main header of a FITS file and never in the headers of any of the extensions.

The first keyword in the header of any extension is XTENSION which has the value 'Image' since only Image HDUs have been used for storing data (see Chap. 1.3).

2.1.2 BITPIX

BITPIX has to be the second keyword any header. The absolute value of BITPIX tells how many bits each single data value has and what type of number it represents (see Table 2.1).

Table 2.1: Valid BITPIX values and corresponding data types

BITPIX value	data type
8	8-bit (unsigned) integer bytes
16	16-bit (signed) integers
32	32-bit (signed) integers
−32	32-bit single precision floating point real numbers
−64	64-bit double precision floating point real numbers

2.1.3 NAXIS

The next keyword according to the FITS standard is NAXIS. It reveals how many axes (i.e. how many dimensions) the data in the corresponding data unit has. NAXIS = 1 indicates that the data is stored in a vector, for NAXIS = 2 it is saved in a matrix, and for NAXIS = 3 in a cube. NAXIS = 0 implies that the corresponding data unit is empty.

2.1.4 NAXISm

There are as many indexed keywords NAXIS1, ..., NAXISm as given by the value NAXIS. The value of NAXISm represents the number of elements along axis m of the data array in the corresponding data unit.

2.1.5 EXTEND

After the last NAXISm keyword, the primary header contains the keyword EXTEND with the value `T` if the FITS file may contain extensions. However, the presence of this keyword does not imply that the FITS file has extensions.

2.1.6 BZERO and BSCALE

Unsigned 16-bit and 32-bit integers are not natively supported by the FITS standard because of its FORTRAN origins. However, there is a common convention to store unsigned integers as signed integers, along with a shift instruction using the keywords BZERO and BSCALE, according to the equation: physical_value = BZERO + BSCALE × array_value.

The only case where this is relevant are the raw images of the LGS and NGS WFS (see Chaps. 3.1, and 3.6) where the pixel values are always positive (i.e. unsigned) 16-bit integers. They are written to the FITS file as signed integers (with BITPIX = 16, see Table 2.1) after subtracting an offset of BZERO = $2^{\mathrm{BITPIX}-1}$ (here, BZERO = $2^{15} = 32\,768$) from each pixel value. Since the values are only shifted and not scaled, BSCALE is equal to 1. For example, if a pixel has a physical value of 0, it will be stored as $-32\,768$.

Python (in conjunction with astropy later than version 1.1.0) and SAOImage DS9, for instance, automatically recognize the two keywords and apply the shift instruction by default. Thus, when reading the data in the corresponding extensions, these tools restore the original values automatically. The user is recommended to check for her/his preferred program(s) whether the shift instruction is implemented there or whether she/he has to take care of it manually.

2.1.7 BUNIT

If present, BUNIT reveals physical units of all array values in the data unit.

2.1.8 PCOUNT and GCOUNT

The keywords PCOUNT and GCOUNT shall be present in the headers of any extension but not in the primary header. Their values are supposed to be PCOUNT = 0 and GCOUNT = 1.

2.1.9 EXTNAME

EXTNAME is the name of the extension and can be used to distinguish different extensions. This keyword can only be present in the header of extensions but never in the primary header.

2.1.10 CTYPEn, CRVALn, CRPIXn CUNITn, CDn_m and WCSAXES

These keywords describe the coordinate system frame on which the data pixels are to be interpreted. They have to be included in all HDUs that contain data. The indexes n and m are integers beginning with 1 and up to the value of the NAXIS keyword. CTYPEn reveals the type of projection and is always 'PIXEL', CRVALn give the reference point of the coordinate system are always set to 1.0, CRPIXn give the reference point in the data array and are 1.0 as well, and CUNITn are the pixel scale units and have the value 'pix'. CDn_m are the elements of the coordinate translation matrix; the elements on the diagonal are 1.0 and the others are 0.0. The indexes n and m can be smaller than the value of the NAXIS keyword, for instance if a cube contains a series of 2D images with identical coordinates as it is the case in Chap. 3.1 – 3.4 and Chap. 3.6 – 3.8. In those cases, the keyword WCSAXES is included in the header and set to 2, meaning that only the first two axis of the pixel coordinates are relevant.

The choice of the values reveals that the world coordinate system (WCS) and the pixel coordinate system cannot be related to each other. Some programs are able to recognize these keywords automatically which is why these keywords were included.

2.1.11 COMMENT

The optional keyword COMMENT may appear multiple times and is always located before the END keyword. It does not have an associated value and therefore no equals sign but is followed by a string of ASCII text. This type of keyword is used to explain the type of data and its units, saved in the corresponding data unit.

2.1.12 END

The last keyword in any header is always the END keyword which has blank value and comment fields.

2.2 ESO specific keywords

A number of keywords had to be added to the main header of the data cubes in order to make them compliant with ESO standards. Otherwise, the data cubes could not be included in the ESO archive. Some of these keywords exceed the limit of eight characters for the keyword name; it this case, the word HIERARCH is put in front of the keyword.

2.2.1 ORIGIN, TELESCOP, INSTRUME, and HIERARCH ESO INS NAME

ORIGIN describes the origin of the data and is set to be 'ESO'. The telescope name is stored under TELESCOP and is 'WHT'. INSTRUME and HIERARCH ESO INS NAME are both 'WLGSU' and tell the name of the instrument.

2.2.2 OBSERVER, PI-COI, and HIERARCH ESO OBS PROG ID

OBSERVER is the name of the observer and PI-COI lists the name of the proposer of the observing run. The value of both keywords is ‘D. BONACCINI CALIA’. All data in the archive has to have a unique ESO program identification number which is ‘60.A-9099(A)’ and stored under the keyword HIERARCH ESO OBS PROG ID.

2.2.3 HIERARCH ESO DPR CATG, HIERARCH ESO DPR TYPE, and HIERARCH ESO DPR TECH

There are three types of HIERARCH ESO DPR keywords: CATG, TYPE, and TECH. CATG is the category of the observations which can either be ‘SCIENCE’ for the science files or ‘CALIB’ for the calibration files. TYPE tells the type of observations and TECH reveals which technique was used. An overview of the CATG, TYPE, and TECH keywords for all available files can be found in Table 2.2.

Table 2.2: HIERARCH ESO DPR keywords of all files

	CATG	TYPE	TECH	number of files
data cubes	‘SCIENCE’	‘OBJECT’	‘IMAGE’	147
flat	‘CALIB’	‘FLAT’	‘IMAGE’	1
dark	‘CALIB’	‘DARK’	‘IMAGE’	26
LGS reference slopes	‘CALIB’	‘REFERENCE_SLOPES_LGS’	‘CALCULATION’	48
NGS reference slopes	‘CALIB’	‘REFERENCE_SLOPES_NGS’	‘CALCULATION’	1
geometric centers	‘CALIB’	‘GEOM_CENTERS’	‘CALCULATION’	1

2.2.4 RADESYS and EQUINOX

RADESYS and EQUINOX identify which coordinate system was used. RADESYS is ‘FK5’ and EQUINOX is 2 000.0 y.

2.2.5 HIERARCH ESO TEL GEOELEV, HIERARCH ESO TEL GEOLAT, and HIERARCH ESO TEL GEOLON

These three keywords reveal the geographic location of the telescope. For the WHT, HIERARCH ESO TEL GEOELEV is the elevation with 2 396.0 m, HIERARCH ESO TEL GEOLAT the geographic latitude of 28.7573° and HIERARCH ESO TEL GEOLON is the geographic longitude with -17.885°.

2.2.6 RA, DEC, and AIRMASS

RA and DEC give the right ascension and declination of the target in degrees and AIRMASS is the corresponding air mass. These three keywords are referring to the pointing of the WHT and their values were taken from the keywords WHTRA, WHTDEC, and WHTAIRM in Chap. 2.3.12.

2.2.7 EXPTIME and EXPOSURE

EXPTIME and EXPOSURE reveal the duration of the acquisition in seconds and have the same value. They were calculated based on the time stamps and are equal to the difference between the last and the first time stamp (Chap. 3.9).

2.2.8 DATE-OBS, DATE-END, MJD-OBS, MJD-END, and UTC

DATE-OBS and DATE-END give the UTC date and time of the start and the end of the acquisition, respectively, and have the format 'yyyy-mm-ddTHH:MM:SS.sss'. They were calculated based on the first and last time stamp (Chap. 3.9). DATE-OBS and DATE-END were used to calculate MJD-OBS and MJD-END, the modified Julian date at the start and the end of the acquisition. Moreover, the keyword UTC reveals the number of seconds elapsed since midnight at the start of the acquisition and was calculated based on DATE-OBS.

2.2.9 DATE

DATE has the format 'yyyy-mm-ddTHH:MM:SS.sss' and tells the date and time when the FITS file itself was created.

2.2.10 FILTER

The extensions containing the raw and calibrated images of the LGS WFS (Chap. 3.1–3.2) contain in their headers the keyword FILTER with the value 'SODIUM 589', indicating that a sodium filter was used during the observations.

2.3 CANARY specific keywords

2.3.1 OBSDATE

The date and time of the observation is given in the format 2017-..-.._..h..m..s where every dot is a one digit number. This keyword was originally called DATE-OBS during the observing run but had to be renamed because DATE-OBS is FITS standard with a slightly different format (see Chap. 2.2.8).

2.3.2 TELDIAM

TELDIAM is the keyword for the diameter of the telescope which has a size of 4.2 m.

2.3.3 TELOBS

TELOBS is the keyword for the central obstruction ratio which is 0.285.

2.3.4 OBJECT

The keyword OBJECT gives the ID of the asterism in which the NGS was located.

2.3.5 GAINDM, GAINTX, GAINTY, and GTWEET

These keywords give the loop integrator gain of the different mirrors:

- GAINDM = 0; high order loop integrator gain;
- GAINTX = 0; NGS path TT mirror loop X-axis integrator gain;
- GAINTY = 0; NGS path TT mirror loop Y-axis integrator gain;
- GTWEET = 0; tweeter loop integrator gain.

Since all these gains are always zero, all available data sets fulfill the requirement of being acquired in "open loop".

2.3.6 GSTEER and LOOP

GSTEER is the keyword for the loop integrator gain of the jitter/steering mirror of the LGS. It has either a value of 0.2 or 0.4. Since at least the jitter/steering mirror has a non-zero gain, the loop status keyword LOOP is 'ON' even if technically, all data is taken in open loop.

2.3.7 FREQ

FREQ is the keyword for frequency which is always close to 150 Hz.

2.3.8 PIXARC1 and PIXARC5

The keywords PIXARC1 and PIXARC5 are the conversion factors from pixels to arcsec of the LGS and NGS WFS, respectively. The LGS WFS has a conversion factor of PIXARC1 = 0.65 arcsec/pixel, while the NGS WFS has PIXARC5 = 0.241875 arcsec/pixel.

2.3.9 NBR_1 and NBR_5

NBR_1 and NBR_5 reveal how many of the brightest pixels of the LGS and NGS image, respectively, were used for the centroiding algorithm. Typically, NBR_1 has a value of around 100, while NBR_5 is usually close to 20.

2.3.10 STATBEN

STATBEN gives the wavefront static aberrations which are always 106 nm rms.

2.3.11 ALTLGS

The keyword ALTLGS reveals the altitude of the LGS in units of meters.

2.3.12 WHTRA, WHTDEC, WHTAIRM, WHTPA, and WHTTEMP

The keywords WHTRA, and WHTDEC tell in which direction the WHT is pointing in right ascension and declination, respectively. The corresponding air mass is given by the keyword WHTAIRM. Moreover, the parallactic angle can be found under the keyword WHTPA. WHTTEMP tells the temperature of the WHT at the time of the observation.

2.3.13 INTRA, INTDEC, INTRAO, and INTDECO

While INTRA, and INTDEC give the pointing direction of the INT in right ascension and declination, respectively, INTRAO and INTDECO reveal the pointing offsets of the INT in right ascension and declination, respectively.

2.3.14 INTPXL_X, INTPXL_Y, INTDIAM, and INT_DATA

The keywords INTPXL_X and INTPXL_Y are the conversion factors from pixels to arcsec of the INT profiler camera in x and y direction. Both have a value of 0.16 arcsec/pixel. INTDIAM is the diameter of the INT which is 2.5 m. The Boolean keyword INT_DATA tells whether INT data is available for the particular data cube.

2.3.15 LW_STAT, LW_MSG, and LW_DIST

The laser wavefront sensor stage status and motion are monitored by the keywords LW_STAT, and LW_MSG, respectively. Moreover, LW_DIST reveals the laser wavefront sensor conjugated altitude which is given in meters.

2.3.16 NA_ALT, NA_DIST, and NA_BASE

NA_ALT is the altitude at which the LGS excites the sodium, while NA_DIST is the distance between the sodium layer and the WHT pupil. Both quantities are given in meters. The keyword NA_BASE is the projected distance between LLT and WHT pupil, also given in meters.

2.3.17 GSWHTRA, GSWHTDEC, and GSS_STAT

The two keywords GSWHTRA and GSWHTDEC reveal the right ascension and declination of the geometry server. GSS_STAT shows the status of the geometry server during the observation.

2.3.18 LLT_RA, LLT_DEC, LLT_RAO, and LLT_DECO

While LLT_RA, and LLT_DEC give the pointing direction of the LLT in right ascension and declination, respectively, LLT_RAO and LLT_DECO reveal the pointing offsets of the LLT in right ascension and declination, respectively.

2.3.19 LLT_STAT, LLT_SIM, and LLT_TRAK

LLT_STAT is the keyword for the status between the LLT and the geometry server. LLT_SIM indicated whether the LLT is in simulation mode; this keyword is always

'False' as only open loop on sky observations were selected. LLT_TRAK is the status keyword of the LLT tracking and is always 'TRACK'.

2.3.20 LLT_POW, LLT_SHUT, and LLT_TUNE

LLT_POW tells the emitted power of the laser, given in Watt. The power is typically slightly above 18 W. LLT_SHUT is the status of the laser shutter which is always 'OPEN'. LLT_TUNE is the keyword for the tuning of the laser wavelength which is always equal to -1.

2.4 Keywords inferred from the data

2.4.1 NREC

The number of frames in the file is given by NREC. In the majority of the cases, the number is equal to or almost 5000.

2.4.2 R0_CALC

The Fried parameter r_0 is estimated from the slopes of the acquisition and given at a reference wavelength of 500 nm. The unit of r_0 is meters.

2.4.3 AVGSEEIN

Based on the estimated r_0 from Chap. 2.4.2, the average seeing during the acquisition can be calculated according to λ/r_0, both at a reference wavelength of 500 nm. The outcome is given in arcsec.

2.4.4 LGS_VIBR

The Boolean keyword LGS_VIBR reveals whether the data set is affected by vibrations in the images of the LGS WFS. If this is the case, LGS_VIBR is equals to `T`, otherwise it is `F`.

2.4.5 SQZ_IMA

The keyword SQZ_IMA reveals how many images of LGS WFS were squeezed (see Chap. 1.6.2 for details). The frame numbers of the squeezed images are listed in one dedicated extension of the data set as explained in Chap. 3.12.

2.4.6 LGSLENGT

LGSLENGT gives the length of the LGS in the INT data, averaged over the same period of time as the CANARY acquisition. If no INT data is available, the keyword is not present in the header. Unit is arcsec.

2.4.7 LGS_FLUX

The value of the keyword LGS_FLUX was calculated from the extension containing the flux of the LGS WFS (see Chap. 3.5) by computing the mean of the fluxes of all individual LGS WFS images.

2.5 Keywords related to a measurement of the turbulence profile

For all selected acquisitions, it was checked whether a measurement of the turbulence profile, $C_n^2(h)$, taken on the same target, is available before and/or after the acquisition. If this is the case, always the measurement closest in time is selected. If a previous and/or subsequent measurement is not available, the corresponding keywords – apart from TURB_BEF and TURB_AFT (Chap. 2.5.1) – are not present in any header.

2.5.1 TURB_BEF and TURB_AFT

TURB_BEF and TURB_AFT are Boolean keywords that reveal whether a measurement of the turbulence profile before and after, respectively, the acquisition is available. If this is the case, the corresponding keyword is `T`, otherwise it is `F`.

2.5.2 CN2H_BEF and CN2H_AFT

These two keyword are a reference to the day and time of the previous and subsequent $C_n^2(h)$ measurement.

2.5.3 TIME_BEF and TIME_AFT

The two keywords TIME_BEF and TIME_AFT tell how much time lies between a certain acquisition and the previous and subsequent $C_n^2(h)$ measurement. The difference was calculated with respect to the beginning of the acquisition. The values are given in the format ±hh:mm:ss.

2.5.4 L0_BEF and L0_AFT

These two keywords give the outer scale parameter L_0 at a reference wavelength of 500 nm at the time of the previous and subsequent $C_n^2(h)$ measurement. L_0 is given in meters.

2.5.5 WIND_BEF and WIND_AFT

The wind speeds WIND_BEF and WIND_AFT were measured during the previous and subsequent $C_n^2(h)$ measurement, respectively, and are given in meters per second.

2.5.6 HBAR_BEF and HBAR_AFT

The two keywords HBAR_BEF and HBAR_AFT describe the median height, $< h >$, of the turbulence layer which is generally calculated from

$$< h > = \frac{\int h\, C_n^2(h)}{\int C_n^2(h)} = \frac{\int h\, r_0^{-5/3}(h)}{\int r_0^{-5/3}(h)} = \frac{\sum h\, r_0^{-5/3}(h)}{\sum r_0^{-5/3}(h)} \tag{2.1}$$

with the turbulence profile, $C_n^2(h)$, as a function of height, h. The second equality is based on $C_n^2(h) \propto r_0^{-5/3}(h)$ and the fact that the constant factor vanishes. The last equality holds because of the discrete number of measurements. HBAR_BEF and HBAR_AFT are given in meters.

2.6 Keywords concerning the calibration

These keywords are only relevant for users, who do not want to use the calibrated LGS and NGS WFS images (Chap. 3.2 and 3.7) but prefer to calibrate the raw images (Chap. 3.1 and 3.6) on their own. Detailed instructions on how to proceed in this case can be found in Chap. 4.

2.6.1 FLATNAME

The keyword FLATNAME is equal to 2017-09-30_23h13m10s and points to the file flat_lgs_2017-09-30_23h13m10s.fits which contains the flat of the LGS WFS (see Chap. 4.1). Note that the NGS WFS does not require a flat and therefore does not have one.

2.6.2 DARKNAME

The keyword DARKNAME has the format 2017-..-.._..h..m..s – because there are multiple darks – and points to a file named dark_2017-..-.._..h..m..s.fits in which the darks of the LGS and NGS WFS are saved (see Chap. 4.2).

2.6.3 REFSLOP

The keyword REFSLOP is equal to 2017-09-23_14h17m49s and points to the reference slopes of the NGS WFS, saved under refslopes_ngs_2017-09-23_14h17m49s.fits (see Chap. 4.3).

2.6.4 REFLGS

The keyword REFLGS has the format 2017-..-.._..h..m..s – as there are multiple sets of reference slopes – and points to a file refslopes_lgs_2017-..-.._..h..m..s.fits in which the on sky references slopes of the LGS WFS can be found (see Chap. 4.3).

Chapter 3

Description of the data sets

To facilitate the usage of the data, all data belonging to the same acquisition but acquired with different telescopes or through different methods are gathered in one FITS file and stored in different extensions. The data in Chaps. 3.1–3.12 is an outcome of CANARY observations. The data in Chaps. 3.13–3.17 was acquired with the INT.

The primary HDU of each FITS file comprises only the main header with all keywords (see Chap. 2) but no data unit. For all data sets, DPR CATG is SCIENCE. The content of all extensions is summarized in the following sections and in Table 3.1. In all cases, the section number is identical to the extension number of the HDU. Alternatively, the extension can also be accessed with its keyword EXTNAME (Chap. 2.1.9). In the header of each extension, there is always a COMMENT keyword on the type of data in that extension and its units. If any additional keywords from the main header are relevant for a particular extension, they will also be listed in the corresponding header.

Each piece of data is stored in one dedicated extension of the corresponding FITS file. It was always saved as an ImageHDU (see Chap. 1.3) with either one, two, or three dimensions, i.e. a number of values stored in a vector, a matrix, or a cube. The format of the data is always given at the end of each section in python convention (`.shape`) and the different formats are explained below.

Part of the data is synchronous (Chaps. 3.1–3.8 and Chap. 3.13; denoted by "C" in the column synchrony in Table 3.1), all having the same number of frames, revealed by the keyword NREC (see Chap. 2.4.1). This is also the case for the data in Chaps. 3.14–3.17 (denoted by "A" in Table 3.1).

3.0.1 Image cube

All images are stored as three dimensional cubes (raw and calibrated LGS and NGS WFS images, Chaps. 3.1 – 3.2 and Chaps. 3.6 – 3.7). If viewed with SAOImage DS9, the first image in the sequence is displayed, along with an additional window which allows to select any other image in the sequence. In SAOImage DS9, all images are oriented such that the x-axis (represented by NAXIS1) it pointing to the right and the y-axis up (represented by NAXIS2) – i.e. in exactly the same way as shown by the sketch of the sub-apertures on the WFS in Fig. 1.3 – while the z-axis corresponds to the sequence of images (represented by NAXIS3). The image cube dimensions in python convention is (NAXIS3, NAXIS2, NAXIS1), with NAXIS3 = NREC and NAXIS2 = NAXIS1 equals to the number of pixels of the CCD sensor of the NGS and LGS WFS (see Table 1.2) in x and y direction.

Table 3.1: Content of each data set.

	extension number and name	content	data shape	synchrony
1	CANARY.LGS.RAW	raw LGS images	(NREC, 240, 240)	C
2	CANARY.LGS.CAL	calibrated LGS images	(NREC, 240, 240)	C
3	CANARY.LGS.SLOPES	LGS slopes	(NREC, 2, 36)	C
4	CANARY.LGS.TTSLOPES	LGS TT slopes	(NREC, 2, 36)	C
5	CANARY.LGS.FLUX	LGS flux	(NREC,)	C
6	CANARY.NGS.RAW	raw NGS images	(NREC, 128, 128)	C
7	CANARY.NGS.CAL	calibrated NGS images	(NREC, 128, 128)	C
8	CANARY.NGS.SLOPES	NGS slopes	(NREC, 2, 36)	C
9	CANARY.TIMESTAMPS	CANARY time stamps	(NREC,)	C
10	CANARY.CN2H_BEF	previous $C_n^2(h)$ profile	(2, 10)	—
11	CANARY.CN2H_AFT	next $C_n^2(h)$ profile	(2, 10)	—
12	CANARY.SQZ_IMA	squeezed images	(SQZ_IMA,)	—
13	INT.SINGLE_NA_PROFILE	single Na profiles	(NREC, 1500, 2)	C
14	INT.AVERAGED_NA_PROFILE	av Na profiles	(m, 1500, 2)	A
15	INT.AVERAGED_NA_PROFILE.METADATA	av Na profiles meta data	(m, 3)	A
16	INT.COG_AV_NA_PROFILE	CoG of av Na profiles	(m,)	A
17	INT.AVERAGED_LGS_LENGTH	av LGS length	(m,)	A

For the sake of consistency, all images of the LGS WFS as well as the corresponding calibration frames (see Chap. 4) have been re-oriented such that they are in the same reference frame as the images of the NGS WFS. Thus, the images of LGS and NGS WFS can be compared directly as the sketch of the subapertues in Fig. 1.3 is valid for both. Also, due to the particular positioning of the lenslet on the CCD of the NGS and LGS WFS, the images of both WFSs happen to have a strip of non-illuminated pixels at the bottom and at the right side of the CCD.

3.0.2 Slopes cube

Like the images, all slopes (slopes of the LGS and NGS WFS, Chaps.3.3 and 3.8, and the slopes of the TT mirror of the LGS WFS, Chap. 3.4) are stored as three dimensional cubes. The dimensions of the slopes cube in python convention is (NAXIS3, NAXIS2, NAXIS1), with NAXIS3 = NREC, NAXIS2 = 2, and NAXIS1 = 36. As above, the sequence of slopes corresponds to the z-axis of the cube (represented by NAXIS3). In x and y direction (NAXIS1 and NAXIS2), the slopes have the shape (2, 36), i.e. two rows with 36 values for the 36 sub-apertures. The first row contains all x values (SAOImage DS9: bottom row) while the second row contains all y values (SAOImage DS9: top row). In each row, the values are ordered according to the numbering of the sub-apertures in Fig. 1.3. A set of slopes and a calibrated image belong together if they stem from the same WFS and have the same frame number $n \in$ NREC. Note that the reference slopes as well as the geometric centers of the NGS and LGS WFS are stored in the same way (see Chaps. 4.3–4.4).

3.1 Raw images of the LGS WFS

In the first extension, the raw images of the LGS WFS are stored; units are ADUs. It is recommended to use the calibrated LGS images (see Chap. 3.2) for all kind of analyses or, alternatively, calibrate the raw LGS images as described in Chap. 4.

Occasionally, the images of the LGS WFS appear to be squeezed due to a read-out problem (see Chap. 1.6.2). The frame numbers of the affected images are listed in a dedicated extension (see Chap. 3.12). All affected images have been replaced with the previous, non-squeezed image.

Moreover, the physical pixel values are unsigned integers that have been saved as signed integers, along with a shift instruction, represented by the keywords BZERO = 32 768 and BSCALE = 1 (see Chap. 2.1.6) in the corresponding extension header. The user is advised to check whether the program she/he is using to retrieve the data restores the physical pixel values automatically or not. Note that this is also the case for the raw images of the NGS WFS (see Chap. 3.6).

Data format: cube with shape (NREC, 240, 240).
EXTNAME: CANARY.LGS.RAW

3.2 Calibrated images of the LGS WFS

The second extension contains the calibrated images of the LGS WFS; units are ADUs. The images were calibrated as explained in Chap. 4, i.e. the dark was subtracted from the raw LGS images and the result was multiplied with the flat. As mentioned in the previous chapter, the some images of the LGS WFS are affected by "squeezing" (see Chap. 1.6.2). These images (see Chap. 3.12) were replaced by the previous, non-squeezed image.

Data format: cube with shape (NREC, 240, 240).
EXTNAME: CANARY.LGS.CAL

3.3 Slopes of the LGS WFS

In the third extension, the slopes of the LGS WFS are stored in arcsec units. They were calculated from the calibrated LGS WFS images (Chap. 3.2) using the CoG method introduced in Chap. 1.5. After subtracting the associated set of LGS WFS reference slopes (Chap. 4.3), the resulting slopes are saved in the format explained in Chap. 3.0.2.

Data format: cube with shape (NREC, 2, 36).
EXTNAME: CANARY.LGS.SLOPES

3.4 Slopes reconstructed from the LGS TT mirror

As mentioned in Chap. 1.1, an additional TT steering mirror was placed in the light path of the LGS WFS to account for the movement of the laser. The contribution of this TT steering mirror to the slopes of the LGS WFS have been reconstructed from the voltages controlling this mirror by using its interaction matrix. They are saved in arcsec units in the format as explained in Chap. 3.0.2.

Data format: cube with shape (NREC, 2, 36).
EXTNAME: CANARY.LGS.TTSLOPES

3.5 LGS Flux

To calculate flux of each LGS WFS frame, the all pixel values of the calibrated LGS WFS image (see Chap. 3.2) were added up, giving F_{measured} in ADU. The actual flux F in units of photoelectrons/(s $\cdot$ m^2) was obtained from

$$F = \frac{F_{\text{measured}}\, f}{c\, A}, \tag{3.1}$$

with the frequency of observations $f = 150$ Hz, the conversion factor from ADU to photoelectrons of $c = 53.68$ ADU/photoelectron and the area A which can be calculated from

$$A = \pi \left(\frac{d_{\text{tel}}}{2}\right)^2 \left(1 - r_{\text{obscur}}^2\right), \tag{3.2}$$

with a telescope diameter of $d_{\text{tel}} = 4.2$ m (keyword TELDIAM, see Chap. 2.3.2), and an obscuration ratio of $r_{\text{obscur}} = 0.285$ (keyword TELOBS, see Chap. 2.3.3). The computation of the flux was done for each individual image separately, giving as many flux values as there are LGS WFS images. Moreover, the mean of all values defines the keyword LGS_FLUX in the main header (see Chap. 2.4.7).

Data format: vector with shape (NREC,).
EXTNAME: CANARY.LGS.FLUX

3.6 Raw images of the NGS WFS

In this extension, the raw images of the NGS WFS are stored; units are ADUs. If the user does not want to use calibrated NGS images (see Chap. 3.7), it is necessary to calibrate the raw NGS images as described in Chap. 4.

As for the raw images of the LGS WFS (see Chap. 3.1), the physical pixel values are unsigned integers that have been saved as signed integers, along with the same shift instruction, represented by the keywords BZERO = 32 768 and BSCALE = 1 (see Chap. 2.1.6) in the corresponding extension header. The user is advised to check whether the program she/he uses to retrieve the data restores the physical pixel values automatically or not.

Data format: cube with shape (NREC, 128, 128).
EXTNAME: CANARY.NGS.RAW

3.7 Calibrated images of the NGS WFS

The seventh extension contains the calibrated images of the NGS WFS; units are ADUs. The images were calibrated as explained in Chap. 4, i.e. the dark was subtracted from the raw NGS images. Note that flat fielding is not required as the NGS WFS does not have a flat.

Data format: cube with shape (NREC, 128, 128).
EXTNAME: CANARY.NGS.CAL

3.8 Slopes of the NGS WFS

In the eighth extension, the slopes of the NGS WFS are stored in arcsec units in the format explained in Chap. 3.0.2. They were calculated from the calibrated NGS WFS images (Chap. 3.7) using the CoG method introduced in Chap. 1.5 and are reference subtracted (Chap. 4.3).

Data format: cube with shape (NREC, 2, 36).
EXTNAME: CANARY.NGS.SLOPES

3.9 Time stamps

As mentioned previously, the data in the Chaps. 3.1–3.8 and Chap. 3.13 are synchronous. In this extension, the corresponding time stamps of the individual data frames are listed. They were measured in Unix time and are given in seconds.

Data format: vector with shape (NREC,).
EXTNAME: CANARY.TIMESTAMPS

3.10 Previous $C_n^2(h)$ profile

If available, the data of the turbulence profile, $C_n^2(h)$, taken before the acquisition of the current data set on the same target can be found in the tenth extension. It consists of a two row matrix with in total ten measurements: in the first row, the measured values of r_0 are given in units of $\mathrm{m}^{-5/3}$ as a function of the altitude h which is given in meters in the second row.

All keywords associated with the measurement of the turbulence profile can be found in Chap. 2.5. If a measurement of the $C_n^2(h)$ profile is not available, the data unit is empty and all corresponding keywords do not appear in the header.

Data format: matrix with shape (2, 10).
EXTNAME: CANARY.CN2H_BEF

3.11 Subsequent $C_n^2(h)$ profile

Similarly to Chap. 3.10, the data of the $C_n^2(h)$ profile taken after the acquisition of the current data set on the same target can be found in the eleventh extension. As above, the data is stored in a two row matrix with the measured r_0 values in units of $\mathrm{m}^{-5/3}$ in the first row and the altitude h in meters in the second row. If there is no measurement of the turbulence profile, the data unit is empty and all associated keywords do not appear in the header (see Chap. 2.5).

Data format: matrix with shape (2, 10).
EXTNAME: CANARY.CN2H_AFT

3.12 Squeezed images

All squeezed LGS WFS frames (Chap. 1.6.2) – raw and calibrated images (Chap. 3.1 and 3.2) are affected in the same way – are stored in this extension while their total number is given by the keyword SQZ_IMA (see Chap. 2.4.5). If squeezing did not occur, the data unit is empty. Otherwise, the numbers of the affected frames are listed in ascending order. Note that the numbering of the frames is zero-based (python convention).

Since the squeezed images are unusable for any analysis they do not appear in any data set but have been replaced with the previous non-squeezed LGS WFS image.

Data format: vector with shape (SQZ_IMA,).
EXTNAME: CANARY.SQZ_IMA

3.13 Single sodium profiles

To allow detailed studies of the sodium layer structure, sodium profiles have been extracted from the synchronous measurements of the profiler camera at the INT, whenever available to the same CANARY time stamp (Chap. 3.9). Each single profile is a two column matrix with the angular extent in arcsec in the first column and the relative profile intensity in ADU in the second column. There are always 1500 intensity measurements along the profile to be able to capture the full extension of the LGS plume independent of its actual length. In particular for shorter LGS plumes, the entries at the beginning and at the end of the profile have negative intensity values. This is induced by the post-processing of the data and not problematic since the given intensities are relative anyway. All profiles together are saved in a cube with as many single sodium profiles as there are time stamps, i.e. in total NREC profiles. Whenever there are gaps in the data (for instance because the profiler camera was not recording or the image was too noisy), the corresponding matrix is filled with zero values. During some nights, the profiler camera was acquiring data with 150 Hz as compared to CANARY observations with 50 Hz, meaning that a single sodium profile exists only for every third CANARY frame. In this case, the single sodium profile is not only assigned to the matching CANARY time stamp but also to the previous and subsequent CANARY time stamp. In this way, it is made sure that there are always the same number of profiles available as there are CANARY data.

There are a few cases where the profiler camera acquired data at a rate of 66 Hz. Since this does not match with the CANARY observations at 50 Hz, the corresponding data unit was left empty because a direct match between CANARY and INT stamps is not possible. Nevertheless, all data based on the averages of the sodium profile (Chap. 3.14–Chap. 3.17) were calculated and included in the data sets.

Data format: cube with shape (NREC, 1500, 2).
EXTNAME: INT.SINGLE_NA_PROFILE

3.14 Averaged sodium profiles

Using the single sodium profiles from Chap. 3.13, an averaged sodium profile was derived based on averages over 3 s, leading to $m \approx 10$ averaged sodium profiles per data set. The averaged profiles have the same format as the single profiles, i.e. the angular extent in arcsec in the first column and the relative profile intensity in ADU in the second column. The number of intensity measurements along the profile is 1500 as before.

Data format: cube with shape (m, 1500, 2).
EXTNAME: INT.AVERAGED_NA_PROFILE

3.15 Averaged sodium profiles metadata

The metadata belonging to the averaged sodium profiles in Chap. 3.14 can be found in this extension. It consists of three values for each averaged sodium profile: beginning time stamp, effective length (usually 3 s), and an averaged time stamp. For all three values, units are seconds. The metadata is saved in a matrix with as many rows m as there are averaged sodium profiles.

Data format: matrix with shape (m, 3).
EXTNAME: INT.AVERAGED_NA_PROFILE.METADATA

3.16 Center of gravity of the averaged sodium profiles

The center of gravity was calculated for each averaged sodium profile (Chap. 3.14) and is stored in a list with m entries, one CoG for each averaged sodium profile. Each entry tells at which position (i.e. data point) the CoG is located in the corresponding averaged sodium profile and has sub-pixel precision. The given values are zero-based. In combination with the metadata (Chap. 3.15) the center of gravity can be associated with the respective LGS WFS image.

Data format: vector with shape (m,).
EXTNAME: INT.COG_AV_NA_PROFILE

3.17 Average length of the LGS plume

The averaged sodium profiles (Chap. 3.14) were also used to calculated the average length of the LGS plume in arcsec. There are as many estimates of the LGS length as there are averaged sodium profiles. The value of the keyword LGSLENGT (Chap. 2.4.6) was calculated by taking the mean of all values in this extension.

Data format: vector with shape (m,).
EXTNAME: INT.AVERAGED_LGS_LENGTH

Chapter 4

Calibration data

Along with the data sets, the user has the opportunity to download the calibration files. In the following, it is described which types of files are available (cf. Chap. 2.2.3), and how to use the calibration files. For all calibration files, DPR CATG is CALIB. It is straightforward to find the right calibration files for a particular data set: It exists only calibration file each for the flat, the NGS reference slopes, and the geometric centers (cf. Table 2.2) defined by the keyword DPR TYPE which is also available in the query form. For the darks and LGS reference slopes files, read the keywords DARKNAME and REFLGS, respectively, in the header of the data set. As indicated in Table 4.1, the keywords have to match the keyword OBSDATE in the header of the corresponding calibration file. It is described in detail in the "quick guide", available on the query web page, how to download the desired calibration files.

Table 4.1: How to associate science and calibration files.

science file keyword		calibration file keyword	DPR TYPE	calibration type
—		—	FLAT	flat
DARKNAME	=	OBSDATE	DARK	dark
REFLGS	=	OBSDATE	REFERENCE_SLOPES_LGS	LGS reference slopes
—		—	REFERENCE_SLOPES_NGS	NGS reference slopes
—		—	GEOM_CENTERS	geometric centers

4.1 Flat

The LGS WFS has a flat while the NGS WFS does not have one. The LGS WFS flat has the `ORIGFILE` name flat_lgs_2017-09-30_23h13m10s.fits and DPR TYPE is FLAT. For the sake of completeness, the keyword FLATNAME (see Chap. 2.6.1) in the main header of each data set is 2017-09-30_23h13m10s and indicates under which name the LGS WFS flat can be found. If desired, the images can be calibrated as given in eq. 4.1.

The flat is a matrix with the shape (240, 240) and is stored in the primary HDU of the file. It is oriented in the same way as the raw and calibrated images of the LGS WFS (see Chap. 3.1 and 3.2).

4.2 Dark

The LGS as well as the NGS WFS have their own darks, which generally differ from acquisition to acquisition. The darks are always stored pairwise (one for the LGS WFS, one for the NGS WFS). The DPR TYPE is DARK and the `ORIGFILE` name is dark_2017-..-.._..h..m..s.fits. The exact file name can be deduced from the keyword DARKNAME (see Chap. 2.6.2) in the main header of the data set. It has the format 2017-..-.._..h..m..s for unambiguous assignment. In the dark file, the LGS WFS dark is stored in the primary HDU while the dark of the NGS WFS can be found in the first extension.

Both darks are matrices; the LGS WFS dark has the shape (240, 240) while the NGS WFS dark has the shape (128, 128), i.e. the same size as the corresponding WFS (see Table 1.2). Both darks are oriented in the same way as the associated LGS and NGS images (see Chap. 3.1/3.2 and Chap. 3.6/3.7).

If the user wishes to calibrate the data her/himself, the correction has to be applied as follows:

$$c = (r - d) \times f, \tag{4.1}$$

with c being the calibrated image, r the raw image, d the dark, and f the flat. Note that for the LGS WFS, contrary to the usual case, the flat has to be multiplied with the dark corrected image instead of divided by. Since the NGS WFS does not have a flat, the multiplication can be omitted; alternatively, to handle both types of WFS in the same way, a correctly shaped matrix with unity values can be used for f.

4.3 Reference slopes of the LGS and NGS WFS

As the alignment between light source, the light path and the WFSs is not perfect, whenever slopes of the LGS and NGS WFS are calculated from their images, the so-called reference slopes have to be subtracted. The NGS WFS has exactly one set of reference slopes: the `ORIGFILE` name is refslopes_ngs_2017-09-23_14h17m49s.fits and the corresponding keyword in the main header of each data set is REFSLOP (see Chap. 2.6.3), being always equal to 2017-09-23_14h17m49s. The associated DPR TYPE is REFERENCE_SLOPES_NGS. For the LGS WFS, a number of reference slopes exist as they are measured regularly on sky and thus vary slightly. The `ORIGFILE` name is refslopes_lgs_2017-..-.._..h..m..s.fits. The corresponding keyword REFLGS (see Chap. 2.6.4) is of the format 2017-..-.._..h..m..s to identify the correct set of LGS WFS on sky reference slopes. REFERENCE_SLOPES_LGS is the associated DPR TYPE.

The reference slopes are saved in the primary HDU of each reference slopes file, and are in both cases matrices with the shape (2, 36), i.e. have the same format as the provided slopes in all data sets (see Chap. 3.0.2). Note that in all data sets, the slopes of the LGS and NGS WFS (Chap. 3.3 and 3.8) are correctly calibrated, meaning that the reference slopes have already been subtracted.

4.4 Geometric centers of the sub-apertures

The geometric centers of the 36 sub-apertures of the LGS and NGS WFS are useful if the user wants to apply her/his own method to calculate the slopes from the LGS and NGS images. Taking the different sizes of the LGS and NGS sub-apertures into account (see Chap. 1.4), the geometric centers allow to identify the location of the individual sub-apertures in the LGS and NGS images from which the data can be extracted.

The geometric centers of the 36 sub-apertures of the LGS and NGS WFS have the `ORIGFILE` name centers.fits and their DPR TYPE is GEOM_CENTERS. The centers of the LGS WFS can be found in the primary HDU while the NGS WFS centers are saved in the first extension of the file. The geometric centers are shaped in the same way as the slopes (see Chap. 3.0.2), i.e. they are matrices with the shape (2, 36), with all x values in the first row, and all y values in the second row, ordered as given in Fig. 1.3.

Chapter 5

Acknowledgments

The experiments done to obtain these LGS-AO open loop data offered to the community, have involved a number of people and institutes working in close collaboration to prepare the hardware, to commission it on sky, to take data at telescopes and to reduce the data. Besides ESO, the users should acknowledge, in publications based on these data, the institutes of LESIA – Obs. de Paris, Durham University, and INAF-Osservatorio di Roma. Furthermore, part of the observing time has been obtained under the Observatorio del Roque de los Muchachos ITP program. The official acknowledgment should therefore contain the following statement:

"Based on data taken in the frame of the ESO Technology Development Program, Laser Systems R&D, by the LGS-AO teams of Durham University, LESIA Obs. de Paris, INAF-Osservatorio Astronomico di Roma, ESO, using the CANARY and the ESO-WLGSU instumentation located at the William Herschel Telescope, Observatorio del Roque de los Muchachos in La Palma (Canary Islands). This research has been carried out with telescope time awarded by the CCI International Time Programme of the Observatorios de Canarias of the IAC. The data have been reduced by L. Bardou (LESIA) and C. Schulz (ESO)."

References

The query form and the links to the “quick guide” and the script to access the data can be found here: `http://archive.eso.org/wdb/wdb/eso/wlgsu/form`.

Credit to L. Bardou for the image of the WHT on p. 1.

Background information in Chaps. 1.3 and 2.1 was taken from:
`https://fits.gsfc.nasa.gov/fits_primer.html`
`https://heasarc.gsfc.nasa.gov/docs/fcg/standard_dict.html`
`https://archive.stsci.edu/fits/fits_standard/node39.html`
`http://docs.astropy.org/en/stable/io/fits/`
`http://www.eso.org/sci/software/esomidas/doc/user/98NOV/vola/node112.html`

Bibliography

Bardou, L., Gendron, E., Rousset, G., et al. 2016, in Proc. SPIE, Vol. 9909, Adaptive Optics Systems V, 990944

Bonaccini Calia, D., Friedenauer, A., Protopopov, V., et al. 2010, in Adaptive Optics Systems II, Vol. 7736, 7736 – 7736 – 12

Gendron, E., Vidal, F., Brangier, M., et al. 2011, A&A, 529, L2

Myers, R. M., Hubert, Z., Morris, T. J., et al. 2008, in Adaptive Optics Systems, Vol. 7015, 70150E

Pfrommer, T. & Hickson, P. 2014, A&A, 565, A102

Rousset, G., Gratadour, D., Gendron, E., et al. 2014, in Adaptive Optics Systems IV, Vol. 9148, 91483M