European Southern Observatory
Organisation Européenne pour des Recherches Astronomiques dans l'Hémisphère Austral
Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

La Silla

# La Silla Observatory

# High Accuracy Radial Velocity Planet Searcher

# HARPS

# User Manual

3M6-MAN-ESO-33100-00XX

Issue: 1.0

Date: Nov 25th, 2003

La Silla Observatory ⋆ ESO ⋆ Chile

## Change Record

| Issue | date | sections affected | Reason/Remarks |
|---|---|---|---|
| 0.1 | February 2003 | all | First version |
| 0.2 | March 5, 2003 | all | for comments |
| 0.3 | March 10, 2003 | all | first public issue for P72 CfP |
| 0.4 | June 16, 2003 | all | GRU → DQU |
| 0.5 | July 8,2003 | all | DRS + end of Comm2/DQU |
| 0.6 | July 31 | all | DAU info DSo |
| 0.7 | Sept 17 | DRS related | data format +answer to comments DQU |
| 1.0 | Nov 25 | all | more information added and structure revised (GLO) |
| Editor: G. Lo Curto, T. Dall: ESO La Silla | | | |

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# Chapter 1

# Introduction

## 1.1 Scope

This User Manual is intended to give all necessary information to potential users of the HARPS instrument, to help them decide on the opportunity to use the instrument for their scientific applications, to be used as a reference when writing observing proposals and when preparing the observations.

For this purpose we give

- an overall description of the HARPS instrument, its performance and its observing modes;
- information on the preparation of the observations;
- information on the observing process;
- a description of the HARPS data and near real-time pipeline data reduction.

The following documents are closely related to this manual and should be consulted as well:

- the P2PP User Manual
- the HARPS Template Guide

Both are available through the "Information Sources" section of the HARPS web pages

`http://www.ls.eso.org/lasilla/sciops/harps/`.

## 1.2 Additional information

The latest information updates about the HARPS instrument can be found on the HARPS web pages

`http://www.ls.eso.org/lasilla/sciops/harps/`.

General information about observing at La Silla is available from the La Silla web pages

`http://www.ls.eso.org/`

## 1.3 Contact information

In case of specific questions related to visitor mode observations please contact the La Silla High Resolution Spectroscopy Team, likewise for specific questions related to Service Mode observations and proposal preparation:

`ls-hires@eso.org`.

## 1.4 Acknowledgments

Most of the contents of this manual is based on information from the HARPS Consortium (Observatoire de Genève, Observatoire de Haute Provence, Universität Bern, Service d'Aéronomie, ESO La Silla and Garching), in particular by F. Pepe and D. Queloz, and from La Silla Science Operations (G. Lo Curto and T. Dall). Releases of this documents are based on the original version edited by Gero Rupprecht.

Feedback on this User Manual from users is encouraged. Please email to `ls-harps@eso.org`.

# Chapter 2

# HARPS Characteristics

## 2.1 Instrument Overview

HARPS (High-Accuracy Radial-velocity Planetary Searcher) is an instrument designed for the measurement of Radial Velocities (RV) at highest accuracy. It was built by the HARPS Consortium consisting of Observatoire de Genève, Observatoire de Haute Provence, Physikalisches Institut der Universität Bern, Service d'Aéronomie du CNRS and with substantial contribution from ESO-La Silla and ESO-Garching. Its purpose is to reach a long term radial velocity accuracy of 1 m/s for slowly rotating G-dwarfs. Such precision enables the detection of low mass (Saturn like) extra-solar planets and low amplitude stellar oscillations.

The design of HARPS is based on the experience acquired with ELODIE (installed at the 1.93m telescope at OHP) and CORALIE (at the 1.2m Swiss Euler telescope at La Silla) during the past 10 years by the members of the HARPS Consortium. The basic design of HARPS is therefore very similar to these instruments. The efforts to increase the HARPS performance compared to its predecessors address mainly three issues:

- Increase of the instrumental stability: The spectrograph is installed in an evacuated and temperature-controlled vacuum enclosure. This allows to remove, to a very large extent, all RV drifts which would be produced by temperature variations or changes in ambient air pressure and humidity.
- Increase of the signal-to-noise ratio (SNR) on single RV measurements: The improvement is attained through different steps. First, HARPS is installed on the ESO 3.6-m telescope. Second, the spectral resolution is increased by a factor of about two. The higher spectral resolution helps also to reduce instrumental errors. Third, the spectrograph optics, which is very similar to that of UVES, is very efficient.
- Improvement of the online data reduction: includes better corrections for instrumental effects and zero point definition (wavelength calibration) and it is substantially faster.

HARPS is a fibre-fed, cross-dispersed echelle spectrograph located in the Coude' floor of the 3.6m telescope. For the sake of thermal and mechanical stability the spectrograph is enclosed in a vacuum vessel evacuated to a pressure $< 10^{-2} mb$ and maintained to a temperature of 17° C, constant within 0.2° C RMS. No moving parts are located inside the vacuum vessel (VV). The spectrograph itself has only one possible mechanical configuration. All necessary moving parts are located in the Harps Cassegrain Fibre Adapter (HCFA), with the exception of the shutter, which is located just outside of the vacuum vessel. The optical design, shown in figure 2.1, is similar to UVES at the VLT.

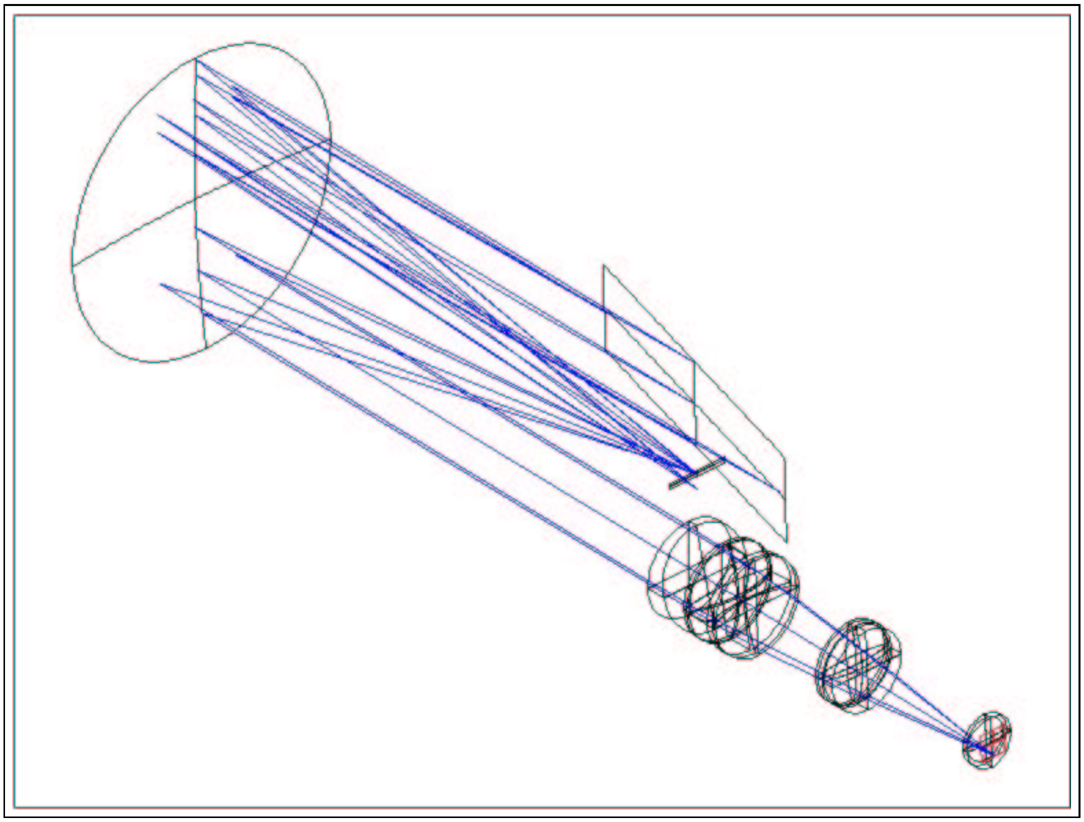

Figure 2.1: Optical layout of the spectrograph

Its echelle grating is operated in quasi-Littrow conditions (off plane angle = 0.721 deg blaze angle) and the collimator in triple pass mode. A white pupil configuration has been adopted with the cross disperser placed at the white pupil. The dioptric camera images the cross-dispersed spectrum on a detector mosaic of two CCDs. Two fibres (A and B) feed the spectrograph, one object fibre and one reference fibre (science fibres). The spectra of the light from both fibres are formed by the spectrograph side by side on the detector.

Although all care has been taken to avoid stray light and ghosts, both are present at some level, most noticeably in the blue part of the spectrum (table 2.1). Ghosts seems to be due to third order reflections in the collimator.

The instrument is coupled to the telescope through an adapter: the HARPS Cassegrain Fiber Adapter (HCFA). Two calibration fibers transmit the light from the calibration unit located in the Coude' floor to the HCFA and inject it in the two science fibers for calibration.

The characteristic optical data are given in table 2.2.

the spectral format is shown in Fig. 2.2.

In the following is presented a brief description of the HARPS components: the fibre adapter on the telescope, the calibration unit, and the fibre links connecting these components. The hardware part of the system is schematically illustrated in Fig. 2.4.

## 2.2 Fibre links

The spectrograph is linked to the 3.6-m telescope via two optical fibres. The fibre link incorporates an image scrambler which is fixed on the vacuum vessel and contributes to stabilize the input point

Halogen lamp (3000 K)

| Order n. | Wavelength (nm) | Diffused + stray light | Ghosts |
|---|---|---|---|
| 90 | 680 | 0.2% | 0.05% |
| 116 | 527 | 0.4% | 0.5% |
| 160 | 383 | $\approx$ 1% | 2% |

G3V star (5700 K)

| Order n. | Wavelength (nm) | Diffused + stray light | Ghosts |
|---|---|---|---|
| 90 | 680 | 0.2% | $<$ 0.2% |
| 116 | 527 | 0.3% | 0.2% |
| 160 | 383 | $<$ 1% | $<$ 4% |

Table 2.1: Level of diffuse + stray light and ghosts as a percent of the flux in the order.

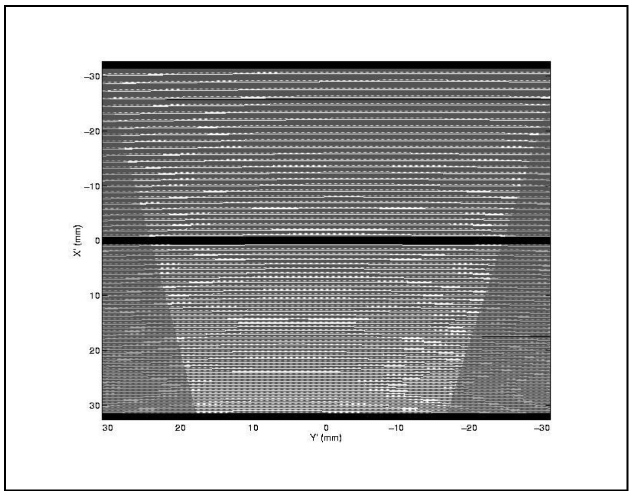


Figure 2.2: Spectral format of HARPS. Blue orders are down, red are up.

spread function (PSF) of the spectrograph. The scrambler serves also as vacuum feed-through for the fibres and in addition houses the exposure shutter. The shortest useful exposure time supported by the shutter is 0.2 seconds.

A second fibre link connects the Calibration Unit (section 2.3) next to the spectrograph with the HARPS Cassegrain Fibre Adapter (HCFA) on the telescope (see figure 2.1).

## 2.3 Calibration unit

The Calibration Unit contains a Tungsten flat-field lamp , two Thorium-Argon lamps for spectral calibration, and a tungsten lamp illuminating an iodine cell for tests purposes. It is connected via two optical fibres to the HCFA which redirects the light of the calibration sources into the spectrograph fibres as required. The two calibration fibres can be fed either by the same or independently by two different calibration sources.

## 2.4 Fibre adapter

All optical fibres are connected to the HCFA which forms the interface to the telescope. The HCFA provides several functions:

| | Wavelength of central column | | | | | | |
|---|---|---|---|---|---|---|---|
| Order | lambda (nm) | bin size (nm) | Eff. % | Obj e- | Sky e- | Imax e- | S/N per spectral bin |
| 89 | 687.76 | 0.0019 | 3.1 | 1.42e+04 | 0.01 | 5.1e+03 | 1.2e+02 |
| 90 | 680.12 | 0.0019 | 3.2 | 1.47e+04 | 0.0103 | 5.3e+03 | 1.2e+02 |
| 91 | 672.65 | 0.0018 | 3.4 | 1.53e+04 | 0.0106 | 5.6e+03 | 1.2e+02 |
| 92 | 665.34 | 0.0018 | 3.6 | 1.6e+04 | 0.0108 | 5.8e+03 | 1.3e+02 |
| 93 | 658.19 | 0.0018 | 3.7 | 1.63e+04 | 0.011 | 5.9e+03 | 1.3e+02 |
| 94 | 651.19 | 0.0018 | 3.8 | 1.7e+04 | 0.0111 | 6.2e+03 | 1.3e+02 |
| 95 | 644.34 | 0.0018 | 4 | 1.74e+04 | 0.0113 | 6.3e+03 | 1.3e+02 |
| 96 | 637.63 | 0.0017 | 4.1 | 1.78e+04 | 0.0114 | 6.5e+03 | 1.3e+02 |
| 97 | 631.06 | 0.0017 | 4.2 | 1.76e+04 | 0.0114 | 6.4e+03 | 1.3e+02 |
| 98 | 624.62 | 0.0017 | 4.2 | 1.77e+04 | 0.0113 | 6.4e+03 | 1.3e+02 |
| 99 | 618.31 | 0.0017 | 4.3 | 1.82e+04 | 0.0112 | 6.6e+03 | 1.3e+02 |
| 100 | 612.13 | 0.0017 | 4.4 | 1.82e+04 | 0.0113 | 6.6e+03 | 1.3e+02 |
| 101 | 606.07 | 0.0017 | 4.5 | 1.86e+04 | 0.0112 | 6.8e+03 | 1.4e+02 |
| 102 | 600.13 | 0.0016 | 4.5 | 1.83e+04 | 0.0111 | 6.6e+03 | 1.3e+02 |
| 103 | 594.31 | 0.0016 | 4.5 | 1.85e+04 | 0.0109 | 6.7e+03 | 1.4e+02 |
| 104 | 588.59 | 0.0016 | 4.5 | 1.69e+04 | 0.0107 | 6.1e+03 | 1.3e+02 |
| 105 | 582.99 | 0.0016 | 4.6 | 1.91e+04 | 0.0108 | 6.9e+03 | 1.4e+02 |
| 106 | 577.49 | 0.0016 | 4.7 | 1.91e+04 | 0.0108 | 6.9e+03 | 1.4e+02 |
| 107 | 572.09 | 0.0016 | 4.7 | 1.9e+04 | 0.0106 | 6.9e+03 | 1.4e+02 |
| 108 | 566.80 | 0.0015 | 4.7 | 1.82e+04 | 0.0104 | 6.6e+03 | 1.3e+02 |
| 109 | 561.60 | 0.0015 | 4.8 | 1.78e+04 | 0.0103 | 6.5e+03 | 1.3e+02 |
| 110 | 556.50 | 0.0015 | 4.7 | 1.8e+04 | 0.0101 | 6.5e+03 | 1.3e+02 |
| 111 | 551.48 | 0.0015 | 4.7 | 1.75e+04 | 0.0098 | 6.3e+03 | 1.3e+02 |
| 112 | 546.56 | 0.0015 | 4.7 | 1.73e+04 | 0.00955 | 6.3e+03 | 1.3e+02 |
| 113 | 541.73 | 0.0015 | 4.6 | 1.69e+04 | 0.00933 | 6.1e+03 | 1.3e+02 |
| 114 | 536.97 | 0.0015 | 4.6 | 1.63e+04 | 0.00909 | 5.9e+03 | 1.3e+02 |

| Order | lambda (nm) | bin size (nm) | Eff. % | Obj e- | Sky e- | Imax e- | S/N per spectral bin |
|---|---|---|---|---|---|---|---|
| 116 | 527.73 | 0.0014 | 4.5 | 1.5e+04 | 0.0068 | 5.4e+03 | 1.2e+02 |
| 117 | 523.22 | 0.0014 | 4.4 | 1.47e+04 | 0.00664 | 5.3e+03 | 1.2e+02 |
| 118 | 518.78 | 0.0014 | 4.4 | 1.34e+04 | 0.00648 | 4.9e+03 | 1.2e+02 |
| 119 | 514.43 | 0.0014 | 4.4 | 1.39e+04 | 0.00631 | 5e+03 | 1.2e+02 |
| 120 | 510.14 | 0.0014 | 4.3 | 1.4e+04 | 0.00613 | 5.1e+03 | 1.2e+02 |
| 121 | 505.92 | 0.0014 | 4.3 | 1.41e+04 | 0.00595 | 5.1e+03 | 1.2e+02 |
| 122 | 501.78 | 0.0014 | 4.2 | 1.29e+04 | 0.00579 | 4.7e+03 | 1.1e+02 |
| 123 | 497.70 | 0.0014 | 4.2 | 1.32e+04 | 0.00564 | 4.8e+03 | 1.1e+02 |
| 124 | 493.69 | 0.0013 | 4.1 | 1.31e+04 | 0.0055 | 4.7e+03 | 1.1e+02 |
| 125 | 489.74 | 0.0013 | 4.1 | 1.31e+04 | 0.00536 | 4.7e+03 | 1.1e+02 |
| 126 | 485.85 | 0.0013 | 4 | 1.09e+04 | 0.00521 | 4e+03 | 1e+02 |
| 127 | 482.03 | 0.0013 | 4 | 1.25e+04 | 0.00505 | 4.5e+03 | 1.1e+02 |
| 128 | 478.26 | 0.0013 | 3.9 | 1.23e+04 | 0.00492 | 4.5e+03 | 1.1e+02 |
| 129 | 474.56 | 0.0013 | 4 | 1.21e+04 | 0.00488 | 4.4e+03 | 1.1e+02 |
| 130 | 470.91 | 0.0013 | 4 | 1.14e+04 | 0.00486 | 4.1e+03 | 1.1e+02 |
| 131 | 467.31 | 0.0013 | 4 | 1.14e+04 | 0.0048 | 4.1e+03 | 1.1e+02 |
| 132 | 463.77 | 0.0013 | 4 | 1.16e+04 | 0.0047 | 4.2e+03 | 1.1e+02 |
| 133 | 460.29 | 0.0013 | 4 | 1.12e+04 | 0.00458 | 4.1e+03 | 1.1e+02 |
| 134 | 456.85 | 0.0012 | 3.9 | 1.12e+04 | 0.00446 | 4.1e+03 | 1.1e+02 |
| 135 | 453.47 | 0.0012 | 3.9 | 9.9e+03 | 0.00435 | 3.6e+03 | 99 |
| 136 | 450.14 | 0.0012 | 3.8 | 1.09e+04 | 0.00424 | 4e+03 | 1e+02 |
| 137 | 446.85 | 0.0012 | 3.8 | 9.75e+03 | 0.00415 | 3.5e+03 | 98 |
| 138 | 443.61 | 0.0012 | 3.8 | 9.58e+03 | 0.00407 | 3.5e+03 | 97 |
| 139 | 440.42 | 0.0012 | 3.8 | 8.72e+03 | 0.004 | 3.2e+03 | 93 |
| 140 | 437.28 | 0.0012 | 3.7 | 8.53e+03 | 0.0039 | 3.1e+03 | 92 |
| 141 | 434.18 | 0.0012 | 3.7 | 7.43e+03 | 0.00378 | 2.7e+03 | 85 |
| 142 | 431.12 | 0.0012 | 3.6 | 6.66e+03 | 0.00365 | 2.4e+03 | 81 |
| 143 | 428.11 | 0.0012 | 3.5 | 6.92e+03 | 0.0035 | 2.5e+03 | 82 |
| 144 | 425.13 | 0.0012 | 3.4 | 6.72e+03 | 0.00333 | 2.4e+03 | 81 |
| 145 | 422.20 | 0.0012 | 3.2 | 6.38e+03 | 0.00315 | 2.3e+03 | 79 |
| 146 | 419.31 | 0.0011 | 3.1 | 6.22e+03 | 0.00298 | 2.3e+03 | 78 |
| 147 | 416.46 | 0.0011 | 3 | 6.23e+03 | 0.00282 | 2.3e+03 | 78 |
| 148 | 413.65 | 0.0011 | 2.9 | 5.82e+03 | 0.00268 | 2.1e+03 | 75 |
| 149 | 410.87 | 0.0011 | 2.8 | 5.11e+03 | 0.00254 | 1.9e+03 | 70 |
| 150 | 408.13 | 0.0011 | 2.6 | 5.17e+03 | 0.0024 | 1.9e+03 | 71 |
| 151 | 405.43 | 0.0011 | 2.5 | 4.62e+03 | 0.00225 | 1.7e+03 | 67 |
| 152 | 402.76 | 0.0011 | 2.4 | 4.41e+03 | 0.0021 | 1.6e+03 | 65 |
| 153 | 400.13 | 0.0011 | 2.2 | 3.94e+03 | 0.00196 | 1.4e+03 | 62 |
| 154 | 397.53 | 0.0011 | 2.1 | 3.02e+03 | 0.00181 | 1.1e+03 | 54 |
| 155 | 394.97 | 0.0011 | 2 | 2.26e+03 | 0.00166 | 8.2e+02 | 46 |
| 156 | 392.44 | 0.0011 | 1.8 | 2.12e+03 | 0.00152 | 7.7e+02 | 45 |
| 157 | 389.94 | 0.0011 | 1.7 | 2e+03 | 0.00139 | 7.3e+02 | 43 |
| 158 | 387.47 | 0.0011 | 1.5 | 1.66e+03 | 0.00127 | 6e+02 | 39 |
| 159 | 385.03 | 0.001 | 1.4 | 1.5e+03 | 0.00115 | 5.4e+02 | 37 |
| 160 | 382.63 | 0.001 | 1.3 | 927 | 0.00104 | 3.4e+02 | 28 |
| 161 | 380.25 | 0.001 | 1.2 | 1.37e+03 | 0.000938 | 5e+02 | 35 |

Figure 2.3: Table showing the spectral format of HARPS and the expected number of electrons for a 1 minute exposure on a G2V star of magnitude 6. A seeing of 0.8", airmass = 1, and new moon are the values of the selected parameters. In the table the spectral bin is defined as one pixel. This table is obtained by the HARPS Exposure Time Calculator (ETC).

| Item | description |
|---|---|
| System | 2 fibres (each 1″diameter on sky, distance 114″), spectral range 380-690nm, collimated beam diameter 208mm |
| Echelle grating | R4, 31.6 gr/mm blaze angle 75°, mosaic 2×1 on Zerodur monolith 840 × 214 × 125mm, efficiency > 65% in the visible |
| Cross disperser grism | FK5 grism, 257.17 gr/mm blazed at 480nm, 240 × 230 × 50mm, T=73% (average) |
| Collimator mirror | Zerodur with protected silver coating, f=1560mm, used diameter 730mm, triple pass |
| Camera | all dioptric, 6 elements in 6 groups, f=728mm, f/3.3, T>85% |
| Detector | 2 2k × 4k EEV CCDs, pixel size $15^2$ $\mu m^2$ |
| Beam focal ratio | inside the spectrograph: 7.5 |
| Spectral format | "upper, red" CCD (Jasmin): orders 89-114, 533-691nm<br>"lower, blue" CCD (Linda): orders 116-161, 378-530nm |
| Spectral resolution | RS=115,000 (measured) |
| Sampling per spectral element | 3.4 px per FWHM |
| Spectrum Separation | 17.3 px (fibres A and B) |
| Order separation Jasmin | order 89: 1.510mm = 100.7px, order 114: 0.940mm = 62.7px |
| Order separation Linda | order 116: 0.910mm = 60.7px, order 161: 0.513mm = 34.2px |
| Spectrograph stability | ±1 m/s in one night under normal conditions |

Table 2.2: Characteristic optical data of HARPS

1. Illumination of the object and the reference fibres; each can be separately fed by the object, the sky, light from a calibration source, or it can be dark.
2. Correction of atmospheric dispersion by means of an ADC.
3. Switching between HARPS, or CES (from end 2004 on) fibres.
4. Feeding of the fibre viewer technical CCD camera for guiding.
5. Introduction of the Iodine cell into the object light path.
6. Attenuating the reference light beam from the ThAr lamp via a neutral density wheel to an equivalent exposure time of 20s. This can be done for exposure times from 20s to 2700s.

## 2.5 Detector

The detector is a mosaic of two 2k×4k EEV CCDs. It is mounted in a ESO detector head and cooled to 148K by means of an ESO continuous flow cryostat (CFC). The detector is controlled by the standard ESO CCD controller FIERA. The detector head is mounted on the optical bench while the CFC is fixed on the outer wall of the vacuum vessel. They are linked by a specially developed mechanical interface which is damping the CFC vibration.

Each of the two CCDs has 50 pre-scan and 50 over-scan columns (A.1).

The two CCDs are read by two different amplifiers and a difference of up to 10% in the bias level of the two CCDs might be expected.

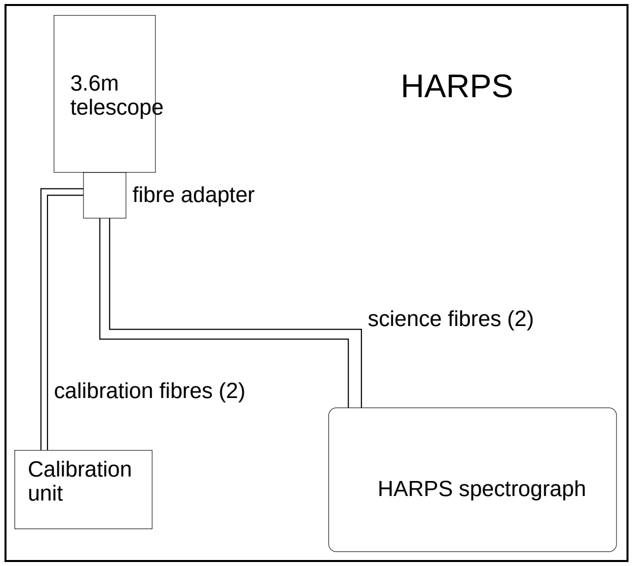


Figure 2.4: The main components of the HARPS system

| Property | Jasmin (red) | Linda (blue) |
|---|---|---|
| CTE vertical (50 kpx/s) | 0.999992 | 0.9999991 |
| CTE horizontal (50 kpx/s) | 0.999991 | 0.9999990 |
| CTE vertical (416 kpx/s) | 0.9999997 | 0.99999991 |
| CTE horizontal (416 kpx/s) | 0.9999995 | 0.9999990 |
| Non-linearity | not available | $< \pm 0.298\%$ |
| Read out noise (50 kpx/sec) | $2.87 \pm 0.1e^-$ | $2.76 \pm 0.09e^-$ |
| Read out noise (416 kpx/sec) | $7.05 \pm 0.23e^-$ | $5.5 \pm 0.16e^-$ |
| Conversion factor (50 kpx/sec) | $0.63 \pm 0.02e^-/ADU$ | $0.62 \pm 0.02e^-/ADU$ |
| Conversion factor (416 kpx/sec) | $1.42 \pm 0.04e^-/ADU$ | $1.4 \pm 0.04e^-/ADU$ |
| Dark current at $-110C$ | not measured | not measured |
| Quantum efficiency | peak 82% at 440nm | peak 85% at 460nm |
| Cosmetics | science grade (grade 1) | science grade (grade 1) |

| | |
|---|---|
| Readout time (4296x4096 px) | 50 kpx/s: 180s, 416 kpx/s: 23 s |
| Mosaic flatness (peak-to-peak) | $15\mu m$ |
| CCD parallelism | 12' |
| Chip to chip gap | $1215 \pm 45\mu m$ |

The two CCDs are nicknamed "Jasmin" (the "red" CCD) and "Linda" (the "blue" one). Their quantum efficiencies are given in figures 2.5 and 2.6, respectively.

## 2.6 Exposure meter

The spectrograph possesses an exposure meter which serves to measure the stellar flux and to accurately measure the mid-time of the exposure (flux weighted mean of the time). However, at the time of writing (18/11/2003) we need more testing in order to accurately define the mid-time of the exposure.

This exposure meter consists of two photomultipliers (one for each of the two fibres entering the spectrograph from the HFCA) which use the light picked up at the gap between the two sub-gratings

| Stellar magnitude | total count rate (cps) | error on mean time of exposure $\epsilon_{MTE}$ (sec) | worst case RV error (m/sec) |
|---|---|---|---|
| $m_v$=0 | saturated | <1 | 0 |
| $m_v$=3 | 2 850 000 | <1 | 0 |
| $m_v$=5 | 456 000 | <1 | 0 |
| $m_v$=9 | 12 000 | <4.8 | 0.1 |
| $m_v$=14 | 120 | <51 | 1 |
| $m_v$=16 | 19 | <165 | 2.5 |
| $m_v$=17 | 8 | <312 | 5 |

Table 2.3: Expected count rate of the exposure meter as a function of stellar magnitude and estimated errors associated with the error on the photometric mean time of the exposure. Count rates are indicative, depend heavily on atmospheric conditions and slightly on stellar spectral type.

of the echelle mosaic; no light is lost due to this design. The flux in both photomultipliers can be read at the instrument console. It is also recorded in the FITS header (cumulative, average and center of gravity). The expected count rates as a function of stellar magnitude and the estimated errors in RV are given in

table 2.3.

## 2.7 Data reduction pipeline

A sophisticated data reduction pipeline is an integral part of the HARPS system. It allows the complete reduction of all spectra obtained in all three observing modes in near real-time in about 2 minutes.

The start of the pipeline reduction is automatically triggered as soon as a new raw data file appears on the data reduction workstation (`whadrs`) in the `/data/raw/`*night* directory (where *night* is the name of the subdirectory named after the day on which the observing night started, e.g. *2003-02-11*).

The output of the pipeline is archived together with the raw data in `/data/reduced/`*night*. For a description of the reduction performed by the pipeline in the different observing modes see sections 3.1.4, 3.2.4 and 3.3.4. Pipeline execution times are given in section 5.4.1.

For each frame that processes, the pipeline performs basic quality checks. When a problem is encountered an error message is displayed to warn the user.

Calibration frames are also processed by the pipeline. If they pass the quality check then the calibration database is updated. Otherwise an error message will be displayed and the latest entry in the calibration database will be used.

## 2.8 System efficiency

The overall efficiency of the HARPS system over the complete wavelength range is given in table 2.4. In this table the atmosphere+telescope transmission is standard atmospheric transmission plus aluminum reflectivity. The “slit efficiency” indicates an average value corresponding to z=1 and is calculated from the HARPS 1″fibre together with the average La Silla seeing of 0.9″. The instrument efficiency includes the fibre link, scrambler and spectrograph (collimator in triple pass, echelle, cross disperser grism and camera). Instrument and CCD efficiencies are measured in the laboratory.

| Wavelength | 380 | 400 | 450 | 500 | 550 | 600 | 650 | 690 | nm |
|---|---|---|---|---|---|---|---|---|---|
| Tel+atm | 44 | 47 | 54 | 57 | 59 | 59 | 61 | 63 | % |
| "slit" | 46 | 47 | 48 | 49 | 50 | 50 | 51 | 52 | % |
| instrument | 10.2 | 15.7 | 20.7 | 22.2 | 24.2 | 21.8 | 19.3 | 16.4 | % |
| CCD | 65 | 78 | 85 | 85 | 81 | 79 | 76 | 72 | % |
| total | 1.35 | 2.67 | 4.44 | 5.18 | 5.70 | 5.07 | 4.58 | 3.81 | % |

Table 2.4: Overall efficiency of the HARPS system. See text.

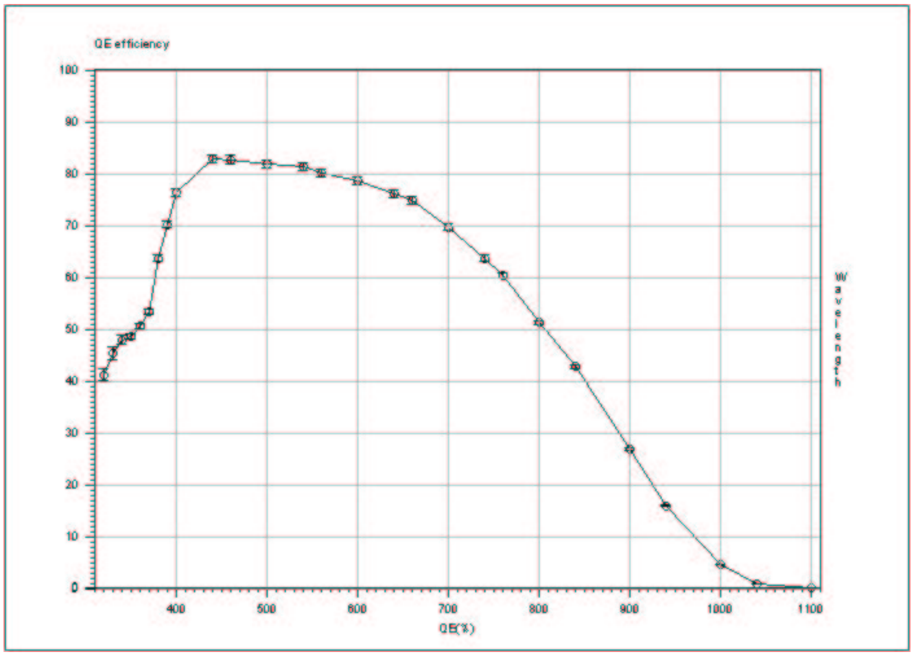


Figure 2.5: Quantum efficiency of Jasmin, the "red" CCD

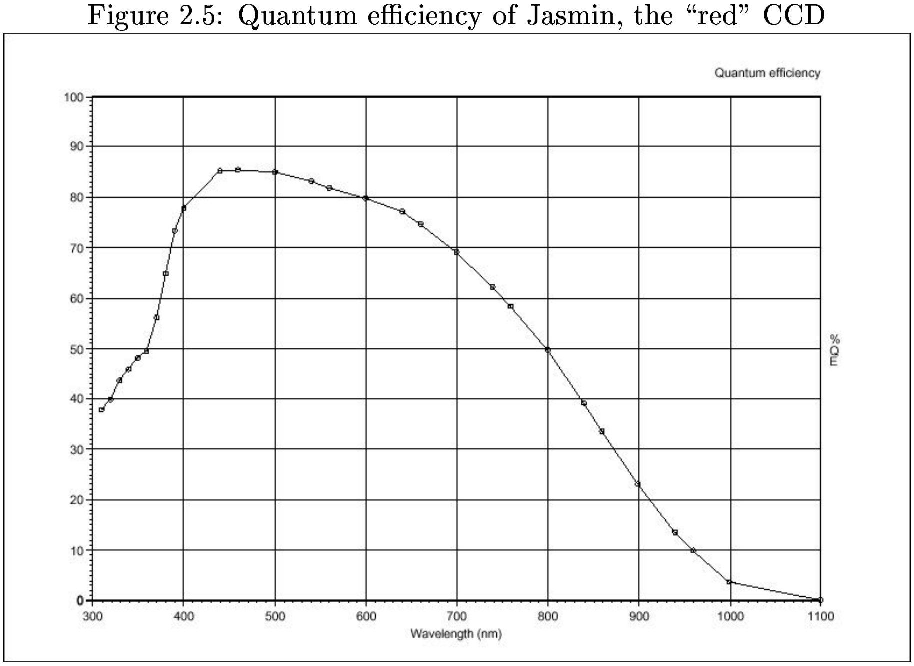


Figure 2.6: Quantum efficiency of Linda, the "blue" CCD

# Chapter 3

# Observing modes

HARPS, as it is implemented now, offers three observing modes:

1. Simultaneous Thorium Reference observation
2. Iodine self-calibration observation
3. Classical fibre spectroscopy (with and without sky)

## 3.1 Simultaneous Thorium reference method

The Simultaneous Thorium Reference mode is the base-line observation mode to get the best short term accuracy in radial velocity determination from the instrument. In this mode fibre B is fed by the Thorium lamp (located in the calibration unit, see figure 2.4) while fibre A is on the stellar target.

A variable neutral density (ND) filter is used to keep the Thorium spectrum at a flux level equivalent to a 20 seconds exposure with zero density. Since the density to which the ND filter is set is computed by the instrument software from the exposure time as defined in the template, *the exposure time should not be modified from within BOB* (Broker for Observing Blocks). Otherwise the flux levels of both fibres will not be balanced.

The Thorium spectrum which is recorded simultaneously with the stellar spectrum is used to compute the instrument drift from the last wavelength calibration, usually done at the beginning of the night.

The calibration unit contains two identical ThAr lamps. In principle both can be used, but it is recommended to use only one of these and not to mix exposures with one or the other lamp to improve the continuity within an observing program.

### 3.1.1 Performance

For estimates of the SNR under given observing conditions the Exposure Time Calculator (ETC) available via the HARPS web page (`http://www.ls.eso.org/lasilla/sciops/harps`) can be used with an accuracy of about 10% (see section 5.5). The relationship between photon noise induced radial velocity error and S/N is given by the following formula:

$$\mathrm{rms(m/s)} \approx \frac{100}{S/N_{550\mathrm{nm}}}. \tag{3.1}$$

As a rule of thumb, an photon noise error of 1 m/s (or S/N = 100) can be achieved for a 6th magnitude G-dwarf in 60 sec. Note, that due to the small fiber aperture on the sky (1″), the performances are critically seeing dependent.

### 3.1.2 Calibration

The Simultaneous Thorium Reference Method needs a sequence of calibration exposures to be taken before the beginning of the night. No further calibration exposures are required during the night.

In order to produce the correct calibration sequence the available observing block "RV Standard Calibration" should be executed *without changes* before the beginning of the night. It includes:

- 1 bias exposure. The CCD bias is very stable, only one bias is therefore needed by the pipeline.
- 2 Tungsten lamp exposures where respectively fibre A and fibre B are successively fed by the Tungsten lamp.
  These exposures are used for order location which is done automatically by the pipeline.
- A sequence of 5 Tungsten lamp exposures where both fibres are simultaneously fed.
  This sequence is used by the data reduction pipeline for producing a spectral "master flat-field" and a "master bias"; both are stored in the local calibration data base and used for the subsequent reduction of the scientific exposures of the following night.
- 2 (for reasons of redundancy) Thorium exposures where both fibres are simultaneously fed by light from the Thorium-Argon lamp.
  Each exposure is used to build a wavelength solution. The instrumental drift with respect to the previous calibration frames is measured (expressed in m/s). If accepted by the built-in quality control, the last one is stored in the local calibration data base and used for the subsequent reduction of the scientific exposures of the following night.

The user may then repeat a sequence of flat-fields with more than 5 exposures if a SNR higher than 300 is aimed at in later science exposures. The "RV Standard Calibration" made of 5 exposures reaches a flat photon noise limited signal at about $SNR_{pp}$=800 at 450 nm and 650 nm and $SNR_{pp}$=500 at 550 nm.

In case the "RV Standard Calibration" is not taken, the DRS will use the youngest available calibration data. This might introduce offsets, and possibly have a negative effect on the achievable precision.

The pipeline performs quality checks on each frame. In case one of the frames does not pass the quality check, the youngest available calibration data will be used. In this case is however advisable to contact the support astronomer on site, in order to make sure the general health of the instrument is not compromised.

### 3.1.3 Templates

The necessary acquisition and observing templates are available:

- `HARPS_ech_acq_thosimult` for acquisition and setup of simultaneous Th exposures
- `HARPS_ech_obs_all` for taking simultaneous Th exposures

For a detailed description of the templates see section 5.3 and the HARPS Template Guide.

### 3.1.4 Pipeline, data reduction

The online pipeline does spectrum extraction, wavelength calibration, RV calculation using a template spectrum of (ideally) the same spectral type as the target star. A comprehensive library of stellar spectral templates is being built up. Currently it contains templates of the following spectral type (others are in preparation):

- G2V

The pipeline applies the following corrections: detector bias , dark , flatfield, cosmic ray removal, and performs wavelength calibration.

Radial velocity and Julian date correction are calculated in the solar system barycenter reference (based on the Bretagnon & Francou 1988 VSOP87E planetary theory). Radial velocity computation is automatically done *for all exposure types* when a radial velocity value different from 99999 is provided by the `TARG_RV` parameter. Conversely, RV calculation can be turned off by entering "99999". The RV must be provided with an accuracy better than 1-2 km/s in order to reach the expected performance. For more details about the pipeline (Data Reduction Software, DRS) please, refer to the DRS user manual. For pipeline execution times see section 5.4.1.

## 3.2 Iodine self-calibration method

HARPS offers the possibility to use an Iodine cell as an alternative to the standard Simultaneous Thorium Reference method. In this mode fibre A is on the target, fibre B on DARK and the Iodine cell inserted in front of the fibre A entrance to superimpose an Iodine absorption spectrum on the stellar spectrum.

### 3.2.1 Performance

The Iodine cell used in HARPS absorbs about 40% of the continuum from the source. Exposure times supplied by the ETC have to be scaled accordingly. The precision of HARPS using the Iodine self-calibration method is still under investigation.

### 3.2.2 Calibration

A calibration sequence similar to the Simultaneous Thorium Reference method is recommended before the beginning of the night. Moreover the 5 tungsten exposures series should be repeated with and without the Iodine cell. However, a specific sequence of observations is additionally needed during the night to later extract the Iodine information. This sequence includes the observation of a star of spectral type B with and without the Iodine cell whenever a template of the target star is produced. The target star template is produced by observing it without the iodine cell, with a high signal to noise ratio.

### 3.2.3 Templates

The necessary acquisition and observing templates are available:

- `HARPS_ech_acq_I2cell` acquisition and setup for Iodine cell exposures
- `HARPS_ech_obs_all` for Iodine cell exposures.

For a detailed description of the templates see section 5.3 and the HARPS Template Guide.

### 3.2.4 Pipeline, data reduction

In the Iodine self-calibration method the pipeline does spectrum extraction and wavelength calibration, . If TARG_RV is not set to 99999 a radial velocity is computed using the CCF technique. Conversely, RV calculation can be turned off by entering "99999". Considering that I2 lines "pollute" the spectra the radial velocity should be considered as an approximate value, since the pipeline is aimed at the simultaneous-ThAr method only. For more details about the pipeline (Data Reduction Software, DRS) please, refer to the DRS user manual.

## 3.3 Classical fibre spectroscopy

Classical fibre spectroscopy can be done in two different ways, depending on the target and the goal of the program:

1. fibre A on target and DARK on fibre B (`objA` observation)
2. fibre A on target and fibre B on the sky (`objAB` observation)

`objA` observation should be preferred for objects much brighter than the sky/moon background where a careful CCD background correction may be needed. For this type of observation, the pipeline provides only the spectrum of the fibre A and uses fibre B order location to compute the CCD background.

`objAB` observation should be preferred when a sky-background correction may be needed. The data reduction pipeline provides an extracted spectrum for each fibre. The sky correction is left to the user.

The high stability of the instrument makes wavelength drifts very small. If the same calibration sequence than for the simultaneous Thorium reference method is run before the beginning of the night, a global wavelength calibration with an accuracy better than 3 m/s can be expected.

### 3.3.1 Performance

For estimates of the SNR with an accuracy of about 10% under given observing conditions the ETC available via the HARPS web pages (`http://www.ls.eso.org/lasilla/sciops/harps/`) can be used (see section 5.5).

### 3.3.2 Calibration

A calibration sequence similar to the Simultaneous Thorium Reference method is recommended before the beginning of the night.

### 3.3.3 Templates

The necessary acquisition and observing templates are available:

- `HARPS_ech_acq_objA` acquisition and setup for fibre spectroscopy with the object in fibre A

- HARPS_ech_acq_objAB acquisition and setup for fibre spectroscopy with the object in fibre A and sky in fibre B
- HARPS_ech_obs_all for fibre spectroscopy exposures

For a detailed description of the templates see section 5.3 and the HARPS Template Guide (section 1.1).

### 3.3.4 Pipeline, data reduction

The pipeline performs the same reduction as for the simultaneous Thorium reference method (section 3.1.4 but it does not correct for the instrumental drift (this one not being traced by the Thorium lamp as in the simultaneous Thorium reference method). It does *not* perform sky subtraction . For more details about the pipeline (Data Reduction Software, DRS) please, refer to the DRS user manual.

Pipeline execution times see section 5.4.1.

# Chapter 4

# RV accuracy

The high RV accuracy obtainable with HARPS is a result of an extremely stable and strictly controlled instrument and a data reduction software designed and optimized for the purpose. The pipeline RV determination is optimized for data taken in the simultaneous Thorium reference method, and nothing can be said at the moment about the obtainable RV accuracy with the iodine self calibration method with HARPS. However $I_2$ data were taken recently and an accuracy for the method with the HARPS instrument will be quoted in the near future. For reference, the method could yield a long term (2 years) accuracy of 2.65 m/s with the UVES spectrograph with a S/N of 66 per pixel and a resolving power of $100000 - 120000$, similar to the HARPS one of 115000 (M. Kürster et al., A&A 403, 1077, 2003).

**The short term RV accuracy of HARPS with the simultaneous Thorium reference method has been demonstrated, during the three commissioning phases, to be below 1 m/s.**

The RV accuracy can be affected by several factors external to the instrument:

- photon noise
- telescope focus
- centering errors
- Thorium calibration errors

As an example during the second HARPS commissioning (June 2003), a 7 hours series of short exposures on $\alpha$ Cen B was recorded, yielding a RV rms of 0.52 m/s. Of these, 0.45 m/s are due to the stellar oscillation, 0.17 m/s to photon noise, 0.08 m/s to Thorium calibration errors (drift tracking) and the remaining 0.18 m/s to centering errors, telescope focus errors and any other error source not yet identified.

The following systematic study is from data obtained with the simultaneous Thorium reference method only.

## 4.1 Photon noise

For a G2 star a RV $rms_{photon} \approx 1$ m/s due to photon noise only is reached with a S/N ratio of about 100 per pixel (at 550nm). The photon noise introduced in the RV measurement scales approximately as:

$$\text{rms(m/s)}_{\text{photon}} \approx \frac{100}{S/N_{550\text{nm}}}. \quad (4.1)$$

## 4.2 Telescope focus

A defocus of the telescope of 30 encoder units introduces a RV offset of 1 m/s. In a typical focus sequence, which can take from 5 to 10 minutes, is reached a precision in the determination of the optimum focus of 5-10 encoder units.

## 4.3 Centering errors

A de-centering of $0.5''$introduces a RV offset of 3 m/s. The present guiding and the dynamic centering systems introduce a RV error at most of $\approx 0.2$ m/s (rms).

## 4.4 Thorium calibration errors

An error of about 0.5 m/s is given to the Thorium calibration (drift tracking and zero point). The zero point error is by far the dominant source.

# Chapter 5

# Preparing The Observations

## 5.1 Introduction

HARPS uses the standard ESO way of observing, i.e. pre-prepared Observing Blocks. This chapter describes the philosophy behind this concept, the available tools and the HARPS specific input.

In order to reach the full performance of HARPS with respect to the determination of accurate radial velocities, the following items should be noted:

1. to achieve an accurate solar system barycentric Radial velocity, correction of 1 m/s, the target coordinates must be known to within $6''$ including proper motion
2. the RV of a star needs to be known to within 1-2 km/s to give the pipeline a reasonable starting point for the RV computation.

## 5.2 Introducing Observing Blocks

An **Observing Block (OB)** is a logical unit specifying the telescope, instrument and detector parameters and the actions needed to obtain a "single" observation. It is the smallest "schedulable" entity, which means that the execution of an OB is normally not interrupted as soon as the target has been acquired and centered on the fibre. An OB is executed only once; when identical observation sequences are required (e.g. repeated observations using the same instrument setting, but different targets), a series of OBs must be built.

Usually, one OB consists of two separate entities: the acquisition template and the observation template(s). For normal science observations HARPS uses four different acquisition templates (different for the various observing modes) and one common observing template . They are described in section 5.3 and the HARPS Template Guide.

## 5.3 P2PP

P2PP is the standard tool for the building of observing blocks from the instrument specific templates. A comprehensive description including the user manual is available from the ESO web pages at `http://www.eso.org/observing/p2pp/`.

Observers using HARPS in Visitor Mode should prepare their OBs in advance using the HARPS Instrument Package, which is automatically downloaded once P2PP is started and the HARPS program is selected from the list of the user's approved programs. OBs prepared at the observer's home institution can be quickly imported (after having ftp'ed them in the proper machine in La Silla) in the P2PP running at the telescope console and be ready for execution. Service Mode observers need to check in their OBs with ESO; see the La Silla web pages (`http://www.ls.eso.org/lasilla/sciops/`) for details.

For a concise description of all HARPS templates and the parameters selectable with P2PP consult the "HARPS Template Guide" (see section 1.1).

### 5.3.1 Acquisition templates

HARPS uses the acquisition template to preset the telescope and to set up the instrument configuration for the selected observing mode. The following acquisition templates are available:

- `HARPS_ech_acq_thosimult` for simultaneous Th exposures
- `HARPS_ech_acq_I2cell` for I2 cell exposures
- `HARPS_ech_acq_objA` for fibre spectroscopy (no sky)
- `HARPS_ech_acq_objAB` for fibre spectroscopy (with sky)

A concise description of the acquisition templates is given in the HARPS Template Guide (see section 1.1).

### 5.3.2 Observing template

HARPS uses one single observation template for all observing modes because all instrument setup is done by the acquisition templates:

- `HARPS_ech_obs_all` for exposures in all observing modes

A concise description of the observation template is given in the HARPS Template Guide.

### 5.3.3 Calibration templates

Several calibration templates are available. However, all calibrations necessary for a proper data reduction with the online pipeline are performed by the ready-to-run calibration OB (named "RV Standard Calibration"). The details of this OB are described in section 3.1.2.

Only if additional calibrations are deemed necessary one needs to use one (or more) of the following templates:

- `ech_cal_bias` for taking bias frames
- `ech_cal_dark` for taking dark frames
- `ech_cal_thoAB` for taking a wavelength calibration through both fibres
- `ech_cal_tun` for taking order location frames through fibres A and B
- `ech_cal_tunAB` for taking spectral flat field exposures simultaneously through fibres A and B
- `ech_cal_tunAI2`for taking spectral flat field exposures through the iodine cell using fibre A

- `ech_cal_tunUSER` for taking user defined tungsten exposures

If the number of exposures is set different from one in the ech_cal_tunAI2, ech_cal_tunAB or ech_cal_thoAB templates, the pipeline will wait for the last exposure, sum all the exposures and then process the resulting frame. A concise description of the observation template is given in the HARPS Template Guide.

## 5.4 Overheads

### 5.4.1 Execution time overheads

| Item | time |
|---|---|
| telescope preset incl dome rotation | 7 min (upper limit for large dome rotation)<br>2 min (typical for new pointing within a few degrees from the previous position) |
| Fibre automatic redefinition and centering of object on the fibre, start of guiding | 3 min |
| instrument configuration | <30 sec |
| readout time (incl writing of FITS headers and transfer to IWS) | 23 sec with 416kpx/sec readout speed,<br>ca 180 sec with 50kpx/sec readout speed |
| minimum time between successive exposures | 32 sec (416kpx/sec) |
| switching between ThAr and Iodine modes | 5 min |
| telescope focusing (at the beginning of the night, to be repeated 1-2 times during the night) | 5 min |

Table 5.1: Execution times overheads

### 5.4.2 "Off-line" overheads

| Item | time |
|---|---|
| DRS pipeline for `thosimul` without RV computation | 110 sec |
| DRS pipeline for `objA` without RV computation | 50 sec |
| DRS pipeline for `objAB` without RV computation | 70 sec |
| DRS pipeline extra time for each RV calculation | 30 sec/spectrum |
| ThAr lamp pre-heating (once at the beginning of the night) | 2 min minimum; 1 hour recommended |
| Iodine cell pre-heating (once at the beginning of the night) | 2 hours |

Table 5.2: "Off-line" overheads

The pipeline overheads are for reference only, observations can proceed without the need for waiting the pipeline results. ThAr lamp and iodine cell pre-heating overhead have to be considered before the start of the afternoon calibrations.

### 5.4.3 Fast time series observations

The shortest exposure time possible with the HARPS shutter is 0.2 seconds, while the shortest exposure in simultaneous thorium exposure mode is 15 seconds (minimum exposure time to achieve a 15 cm/sec instrument drift tracking). For each CCD frame there is an overhead (readout, attachment of fits header etc.) of ~32 seconds in the fast readout mode (416 kpx/sec). With 15 sec exposure time on sky, 50 seconds cycles have been achieved. The pipeline presently implemented is no longer able to reduce this flood of data in near real-time. At the end of the night there may be a substantial back-log of unreduced files, depending on the exposure time and the number of frames taken. The pipeline will automatically continue the reduction during the day. It has been demonstrated that up to 500 frames taken in Thorium simultaneous mode could be handled by the DRS before the beginning of the next night.

### 5.4.4 Iodine cell

The Iodine cell needs to be in a thermally stable state before it can be safely used. This means that it has to be switched on at least two hours before the first exposure through the cell should be done. This constraint holds both for science and for calibration exposures.

Target acquisition with the Iodine cell is done through the cell. This means that the position of the fibre hole image on the guide camera changes when the iodine cell is inserted in the light path. In addition the focus position of both the auto-guider and the telescope change and have to be re-adjusted. This takes about 5-10 min once during the night. If more changes (cell on / cell off) are required during the night the previously defined optimum values of the guide camera and telescope focus, as well as the fiber position can be re-set very quickly (overhead $\approx$ 30 s).

For a proper reduction of the data taken with the Iodine cell it is necessary to obtain the spectrum of a B star through the Iodine cell. This observation must be taken in the same night during which the template spectra are recorded. The minimum SNR for this B star spectrum and for the template (cell off) spectrum is **400**. Sufficient time for this spectrum must be foreseen.

## 5.5 The HARPS Exposure Time and Spectral Format Calculator

The HARPS Exposure Time Calculator (ETC) models the instrument and detector in their different configurations. It can be used to compute the detailed spectral format (wavelength and order number as function of position on the detector) and the expected SNR for the specified target under given atmospheric conditions as a function of exposure time. It is available via the HARPS web pages `http://www.ls.eso.org/lasilla/sciops/harps/`.

# Chapter 6

# Observing with HARPS

## 6.1 Before the night

Depending on the observing method applied (simultaneous Thorium reference, Iodine self-calibration, classical fibre spectroscopy) different sets of calibration exposures need to be taken before the start of the science observations.

For all three methods it is necessary to take a series of calibration exposures (Bias, Tungsten, Thorium) because they are needed for the pipeline to produce optimum results. A calibration OB ("RV Standard Calibration") is available at La Silla and ready for execution to take these exposures. Details are described in section 3.1.2. More calibration exposures are necessary during the night when using the Iodine self-calibration method, see section 3.2.2.

## 6.2 During the night

Observations are performed in the standard VLT way, i.e. OBs are selected by the Visiting Astronomer (VA) with P2PP and fetched by the Telescope and Instrument Operator (TIO) into BOB.

### 6.2.1 Target acquisition, guiding, focusing

Target acquisition is done by the TIO. The object is centered on the entrance of the science fibre and kept there by an automatic dynamic centering algorithm with an accuracy of better than 0.2 pixels (0.05″). This guiding accuracy introduces radial velocity errors of the order of 20 cm/s and is therefore negligible within the accuracy attainable with HARPS. Users with crowded fields, close binaries, faint objects etc., should prepare finding charts. The guide camera can guide on stars of magnitude up to 17.

In the fibre AB spectroscopy mode (object + sky) the observer should verify that the sky fibre is not contaminated by light from other sky objects. This should in the first place be done by checking on the Digital Sky Survey. At the telescope it can be verified by

- offsetting the telescope: the sky fibre entrance is exactly 114″west of the target fibre;
- watching the count rate of the exposure meter (photometer B).

It is important that the telescope is well focused at all times. It is recommended to have a through focus sequence performed using the guiding camera and the exposure meter two to three times per

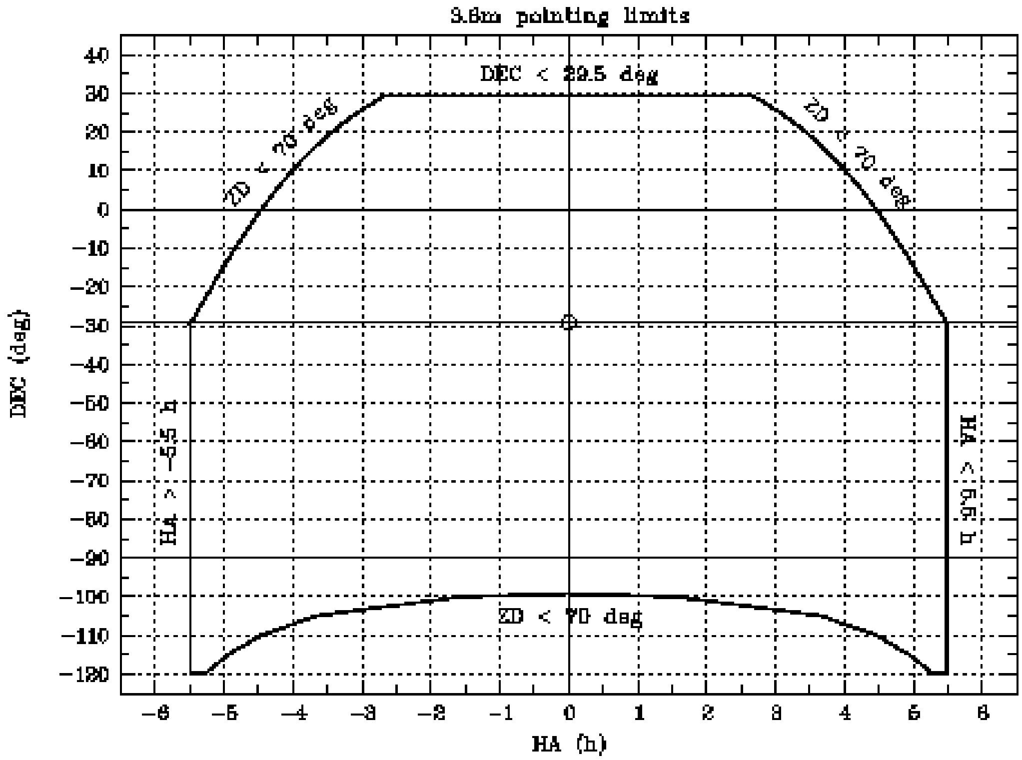


Figure 6.1: The sky area accessible for HARPS

night or whenever the image quality observed on the guiding camera deteriorates significantly, or whenever there is a significant temperature change (few °C). A defocusing of ±30 encoder units introduces an RV error of ±1m/s. The accuracy of the telescope focus determination is within 10 encoder units.

### 6.2.2 Pointing restrictions

The usual pointing limit restrictions of the 3.6m telescope apply, see Fig. 6.1.

The telescope dome shall be closed when any of the following weather conditions occur :

- Wind speed >20 m/sec (on the 3.6m monitor)
- Humidity >90% (on the 3.6m monitor)
- Temperature within 2° of dew point (on the MeteoMonitor)
- Dew on the dome (the TIO will check the dome in person when there is reason to believe that condensation may occur)

The telescope shall not be pointed into the wind when the wind speed is more than 14 m/sec (3.6m monitor).

Note: Weather conditions at the 3.6m telescope may be significantly different from those near the RITZ. In particular the wind speed is a few meters per second higher and the humidity lower.

The TIO will make the decision to close the dome as necessary. VAs should accept the decision since the reason is exclusively the protection of the telescope from damage. At any rate, in case of a disagreement the dome should first be closed and subsequently the VA may take up the issue with the support astronomer and finally the La Silla shift leader - though it is highly unlikely that the decision will be altered.

The dome may be re-opened if weather conditions improve and stay below the operating limits for at least 30 minutes. This waiting period is particularly important in case of humidity. The TIO will further confirm that the condensation on the dome has completely evaporated.

## 6.3 Night calibrations

Night calibrations in addition to the calibration observations taken before the start of the science observations are only necessary when using the Iodine self-calibration method, see section 3.2.2.

## 6.4 Real-time display

Raw data coming from the instrument are displayed on a FIERA Real-Time Display (RTD). Both CCDs are displayed in the same RTD (fig. 6.2).

## 6.5 Observing very faint stars

As explained in section 3.1 a variable neutral density filter is used to balance the intensity of the Thorium-Argon calibration spectrum depending on the exposure time. This works correctly for exposure times up to 2700 s.

For very faint stars which require even longer exposures this may lead to an overexposure of the calibration spectrum with contamination of the stellar spectrum. As the ultimate accuracy of HARPS (1 m/s) will usually not be reached on such faint stars, it is recommended not to use the simultaneous Thorium reference method but to rely on the excellent short-term stability of HARPS and take separate wavelength calibration exposures immediately before and after the science exposure to interpolate and remove possible instrumental drift errors. The additional time spent on this is negligible given the long science integration.

## 6.6 End of the night

No further calibrations are necessary after the end of the science observations. To prolong the life of the calibration lamps HARPS is switched to the so-called "Dark" mode. All lamps still in use at the time are thereby switched off and the dust cover in the fibre adapter is put in place to protect the fibre entrance. The $I_2$ cell will be left on until it is turned off manually. All electronics are in stand-by, all internal house-keeping functions (temperature and pressure control, logging) continue to operate.

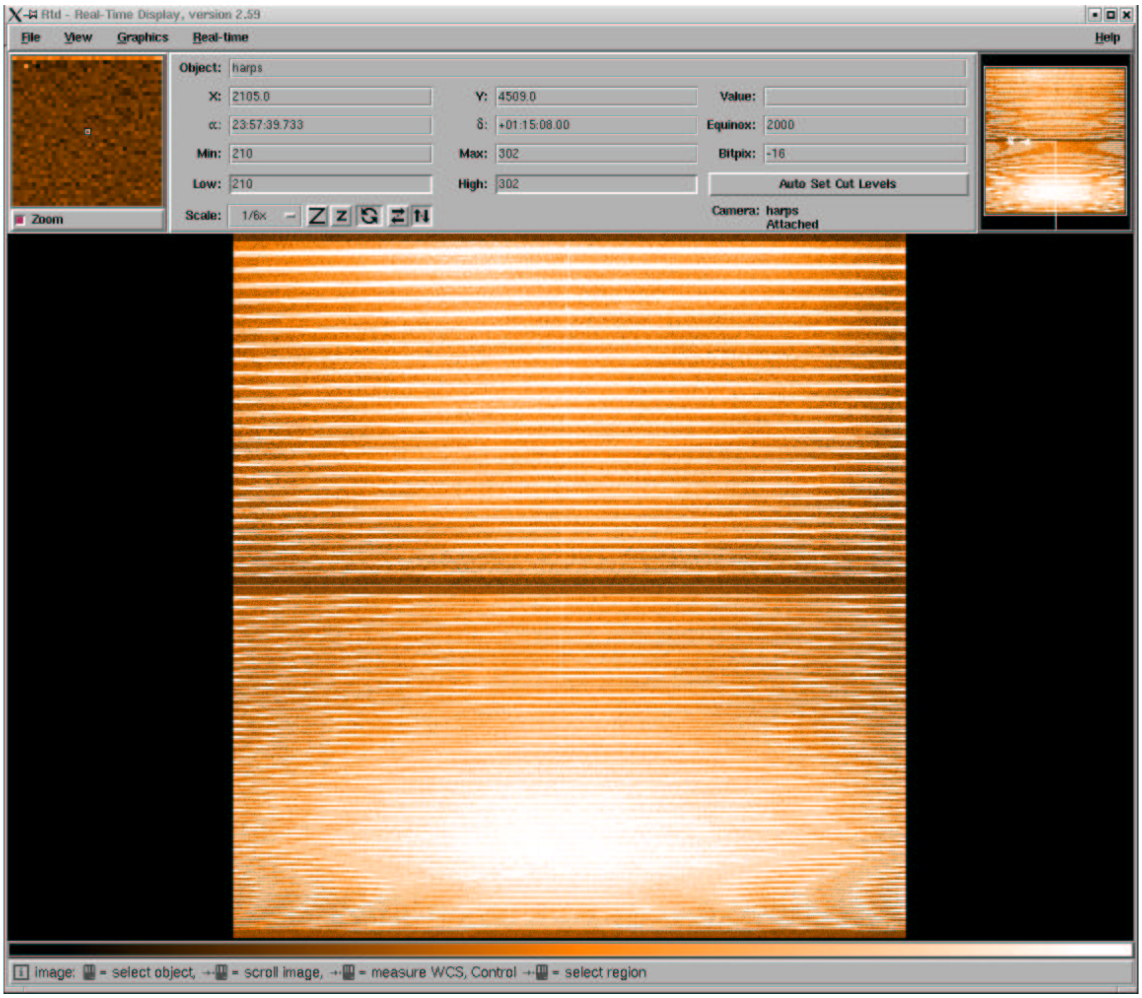


Figure 6.2: The Real Time Display of a HARPS spectrum taken with the tungsten lamp illuminating both fibers. The lower part is the blue chip ("Linda"), the upper one is the red chip ("Jasmin"). Wavelength increases from lower left to upper right.

# Chapter 7

# Data products and archiving

## 7.1 Data products

HARPS writes FITS files with extensions containing the data of both CCDs. The size of one raw data file is approximately 32Mb.

By default the data products of the online pipeline are archived as well. Following is an example of the files that are included in the archiving of one exposure:

- Raw data file:
  HARPS.2003-11-01T02:40:09.824.fits
- Cross correlation function summary table with extracted RV per each order:
  HARPS.2003-11-01T02:40:09.824_ccf_G2_A.tbl
- Cross correlation function matrix in fits format:
  HARPS.2003-11-01T02:40:09.824_ccf_G2_A.fits
- 1D extracted spectrum, one row per order:
  HARPS.2003-11-01T02:40:09.824_e2ds_A.fits
- 1D extracted full spectrum, wavelength calibrated:
  HARPS.2003-11-01T02:40:09.824_s1d_A.fits

Other summary tables are produced at the end of each night:

- **cal_BIAS_result.tbl**: bias table;
- **cal_loc_ONE_result.tbl**: order localization table;
- **cal_FF_result.tbl**: flat field table;
- **cal_TH_result.tbl**: Thorium table (for wavelength calibrations);
- **drift_result.tbl**: Th lines drift in m/s measured on fiber B, filled only in the simultaneous Thorium reference mode;
- **CCF_results.tbl**: results of the CCF, with measured RV and RV sigma, filled only when the $RADVEL$ field in the template is different by 99999.

All files with extension ".tbl" are ASCII files, not MIDAS tables !

For details and format description see the DRS user manual available in:
`http://www.ls.eso.org/lasilla/sciops/harps/manuals.html`

## 7.2 Data archiving

### 7.2.1 La Silla and Garching archives

HARPS raw data are compliant with the requirements of ESO's Data Interface Control Board (DICB). They are stored locally at La Silla and in the central Garching Science Archive (however, see 7.2.3). Since the amount of raw data generated by HARPS can be quite substantial (exceeding 20Gb/night in case of asteroseismology ) HARPS will use the Next Generation Archive System (NGAS).

### 7.2.2 La Silla data archiving unit

For convenient archiving of raw observation data and pipeline products a dedicated Data Archiving Unit (DAU) is available at La Silla. It allows the observers to write the results of their observing run on DVDs, choosing the data product they want (raw data, reduced data or both, log files). Appendix B contains the instructions on how to do this. ESO will make available the necessary blank DVDs for "normal" observing runs (e.g. planet search, classical fibre spectroscopy) to store the raw and reduced data in visitor and service mode.

However, due to the enormous amount of raw data produced during a typical asteroseismology run (>20Gb/night), the backup media will be a DLT tape if raw and reduced data are requested. In case only the pipeline products are requested they can fit in a single DVD, and the standard procedure (Appendix B) will be used to back up the data.

The reason for this is the impossibility to write all raw data to DVDs within a reasonable amount of time during the observing run with the resources (manpower and hardware) available at La Silla. The raw data and all the pipeline products will anyway be stored in the Garching Science Archive (using NGAS).

### 7.2.3 Use of archived HARPS data

HARPS data can be requested from the Garching Science Archive. Data taken by observers in Visitor or Service Mode are subject to the usual proprietary period of 1 year.

According to the Agreement between ESO and the HARPS Consortium the data taken by the Consortium during their Guaranteed Time are subject to special protection:

- Raw data and reduced spectra ($I=f(\lambda)$) in the Earth reference frame at the time of the observation will be made public one year after observations
- All raw data and radial velocity measurements obtained by the Consortium will be made public one year after the end of the 5 year Guaranteed Time period.

In practice this means that data obtained by the Consortium can be requested from the Garching Science Archive as usual one year after the observations. However, in order to make recovery of precise radial velocities impossible, the keywords containing information about the time of the observations will be filtered from all file (raw and reduced) headers by the Archive during the de-archiving process (details are **TBD**). This filtering will be applied until one year after the end of the 5 year Guaranteed Time period.

# Chapter 8

# The Reduction of HARPS Data

## 8.1 The HARPS data reduction pipeline

Every HARPS frame is processed by the online pipeline. Depending on the observation , the pipeline uses different reduction recipes. Results of the reduction are:

- extracted spectrum (all modes)
- precise radial velocity (only if parameter TARG_RV is defined)
- cross correlation function (CCF; only if parameter TARG_RV is defined).

The pipeline output is available immediately after the processing is finished (see section 5.4.1). It can then be transferred to the offline workstation for further analysis. It can also be saved to disk and CD/DVD using the "Data Archiving Unit" (see 7.2.2) available with HARPS. *Note that the archiving of pipeline products is currently the full responsibility of the visitor!* ESO however supplies blank DVDs and a simple procedure describing how to do it.

## 8.2 High accuracy radial velocities

The reduction concept applied by the pipeline for the calculation of high accuracy radial velocities using the Thorium reference method is described in the paper "ELODIE: A spectrograph for accurate radial velocity measurements" by Baranne, Queloz, Mayor et al., A&AS **119**,373(1996).

In order to get the full performance of the pipeline with respect to the determination of accurate radial velocities, the following items should be noted:

1. to achieve an accurate solar system barycentric Radial velocity, correction of 1 m/s, the target coordinates must be known to within $6''$ including proper motion
2. the RV of a star needs to be known to within 1-2 km/s to give the pipeline a reasonable starting point for the RV computation.

## 8.3 Iodine cell data

On I2 cell data the DRS provides to the user a wavelength calibrated spectrum. For further analysis the observer should consider the following input data:

1. template spectrum of the science object (without $I_2$ cell)
2. high SNR spectrum of a B star taken through and without the $I_2$ cell during the same night as the template spectrum of the science object,
3. Fourier transform spectrum of the Iodine cell. For the HARPS Iodine cell this FTS is available from the HARPS web site (`http://www.eso.org/instruments/harps/miscellaneous.html`).

The extraction of the I2 information itself is left to the observer.

The description of one method to model the $I_2$ data is given in the paper: "The planet search program at the ESO Coudé Echelle Spectrometer. I. Data modeling technique and radial velocity precision tests." Endl M., Kürster M., Els S., 2000, A&A, 362, 585
also available from the web:
http://aa.springer.de/bibs/0362002/2300585/small.htm

# Appendix A

# Description of archived HARPS data

## A.1 Data naming rules

The raw frames are stored in FITS format by the DFS with the ESO-VLT standard naming rules: `HARPS.YYYY-MM-DDTHH:MM:SS.SSS.fits` with YYYY-MM-DD and HH:MM:SS.SSS being respectively the date and time of the start of the observation.

Pipeline products are stored in FITS format with the same generic names plus an additional suffix describing its format (see next section for details) and the specific fibre name (A or B). For example: `HARPS.YYYY-MM-DDTHH:MM:SS.SSS_E2DS_A.fits` is an E2DS format image of the fibre A product by the DRS derived from the `HARPS.YYYY-MM-DDTHH:MM:SS.SSS.fits` raw frame.

Tables in ASCII format are also produced by the DRS.

The relevant log-books of the DRS is named `DRS-whadrs.YYYY-MM-DD`. It is stored with all the other logs in the `/msg` directory. It is automatically archived by the DAU on the DVD.

## A.2 Data formats

### A.2.1 Raw frames

The raw frame corresponds to a 4296 × 4096 integer (35'242'560 bytes) matrix written on disk in FITS format (see Fig. A.1). This image includes a 4096 × 4096 sensitive zone plus 4 overscan zones of 50 pixels each. The following generic descriptors are used by the DRS:

| | |
|---|---|
| **MJD-OBS** | Modified Julian Day start [float] |
| **EXPTIME** | Total integration time (s) [float] |
| **DATE-OBS** | Date and Time of observation [string] |
| **RA** | RA of the target [float] |
| **DEC** | DEC of the target [float] |
| **EQUINOX** | Equinox of observation [float] |

The DRS needs as well the following **HIERARCH ESO** descriptors:

**DET1 READ SPEED** CCD Readout mode (speed, port and gain) [string]

**DET OUTi GAIN** Conversion from electrons to ADUs of port i [float]

**DET OUTi RON** Readout noise of port i (e-) [float]

**DET WIN1 DIT1** Actual sub-integration time (s) [float]

**DET WIN1 DKTM** Dark current time (s) [float]

**DET DPR CATG** Observation category [string]

**DET DPR TYPE**[1] Observation type [string]

**INS DET1 TMMEAN** Normalized mean exposure time on fibre A [float]

**INS DET2 TMMEAN** Normalized mean exposure time on fibre B [float]

**INS OPTI5 NAME** Lamp name on fibre A [string]

**INS OPTI6 NAME** Lamp name on fibre B [string]

**OBS NAME** OB Name [string]

**OBS START** OB Start Date and time [string]

**TPL ID** Template signature ID [string]

**OBJECT TYPE**[2] What is on fibre A and B [string]

**OBJECT SP**[2] Object spectral type [string]

**OBJECT RV**[3] Object expected RV [string]

**TEL TARG RADVEL**[4] Object expected RV [string]

[1] the use of this keyword made by the DRS is wrong, the keyword shall be later replaced by OBJECT TYPE (not yet implemented by the DICB);
[2] shall replace some of the DPR TYPE current function, not implemented yet in the DICB;
[3] not implemented yet but needed for optimum RV computation;
[4] this keyword shall be later replaced by OBJECT RV

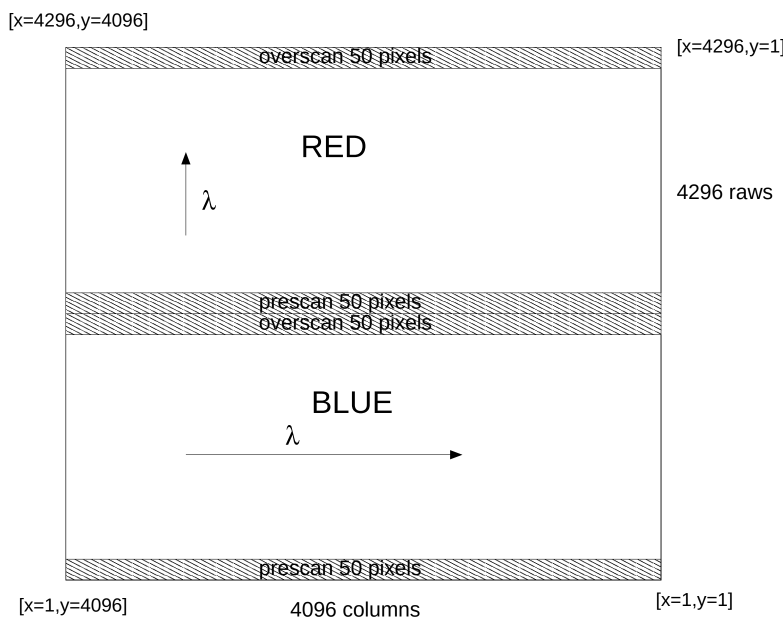


Figure A.1: Raw frame format.

# Appendix B

# Use of the Data Archiving Unit

This appendix describes the use of the Data Archiving Unit (DAU). This unit allows the VA to write his/her data (raw and reduced) to DVD **The disks have to be DVD-R "General"**.

In order to archive the data of one night the following has to be done:

1. launch the Data Archiving Unit on the wharch machine as harps user, the command is: dau.csh;
2. put a writable DVD (DVD-R "General") in the burner;
3. indicate the night date in the "Night" field (the only one which is white); pressing the "Enter" key validates the entered value;
4. wait until all the sizes are calculated (it takes a minute or two);
5. check the check-boxes for the files to be backed up;
6. click the "Go" button to start copying the files (may take up to 30 minutes);
7. de-select all the boxes;
8. press the "Compute size" button to see the total size of the files;
9. select the box "Prepare DVD";
10. press "Go" to start creating the image (may take 15 minutes);
11. de-select the Prepare DVD box, select the "Make DVD" one;
12. press "Go" to start burning the DVD (may take 45 minutes).

If the total data size is too big for one DVD, the raw files will be automatically compressed (by about 50%; approximately 170 gzipped FITS files fit on one DVD). If the volume is still too large the user has to split the night in two, e.g $< date >$ _1 and $< date >$ _2 directories. To archive both directories the complete name of the directory has to be put in the "Night" field. Both directories have to be archived separately. The DAU will automatically search /data/raw/<dir_name>, /data/reduced/<dir_name> etc.

The "Compute size" button computes the total size of the data saved in the BACKUP under the $< date >$ directory once the data are copied in the warch disk.

# Appendix C

# List of acronyms

| | |
|---|---|
| ADC | Atmospheric Dispersion Compensator |
| AG | Auto-Guider |
| BOB | Broker of Observing Blocks |
| CCD | Charge Coupled Device |
| CCF | Cross Correlation Function |
| CES | Coude Echelle Spectrograph |
| CFC | Continuous Flow Cryostat |
| DAU | Data Archiving Unit |
| DFS | Data Flow System |
| DHS | Data Handling System |
| DICB | Data Interface Control Board |
| DIMM | Differential Image Motion Monitor |
| DRS | Data Reduction Software |
| E2DS | Extracted 2-Dimensional Spectrum |
| ESO | European Southern Observatory |
| ETC | Exposure Time Calculator |
| FIERA | (name for ESO's standard CCD controller) |
| FITS | Flexible Image Transport System |
| HCFA | HARPS Cassegrain Fibre Adapter |
| HARPS | High Accuracy Radial velocity Planet Searcher |
| IWS | Instrument WorkStation |
| ND | Neutral Density |
| NGAS | Next Generation Archive System |
| NTT | New Technology Telescope |
| OB | Observing Block |
| OG | Observatoire de Geneve |
| P2PP | Phase 2 Proposal Preparation |
| PSF | Point Spread Function |
| RITZ | Remote Integrated Telescope Zentrum |
| RTD | Real Time Display |
| RV | Radial Velocity |
| SA | Support Astronomer |
| SNR | Signal to Noise Ratio |
| TBC | To Be Confirmed |
| TBD | To Be Determined |
| TIO | Telescope and Instrument Operator |
| UVES | Ultraviolet/Visible Echelle Spectrograph |

| | |
|---|---|
| VA | Visiting Astronomer |
| VLT | Very Large Telescope |
| XTC | eXtended exposure Time Calculator |

__Ω__