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

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# Chapter 1

# Introduction

## 1.1 Scope

This User Manual is intended to give all necessary information for potential users of the HARPS instrument to decide on the feasibility of the instrument for their scientific applications, for the writing of observing proposals, for the actual preparation of their observations and for the subsequent data reduction.

For this purpose we give

- an overall description of the HARPS instrument
- information on the preparation of observations
- a description of the different observing modes
- information on the actual observing process
- additional information

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

- the P2PP User Manual
- the HARPS Template Guide (in preparation)

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

`http://www.eso.org/instruments/harps`.

## 1.2 Additional information

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

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

`ls-hires@eso.org`.

For specific questions related to Service Mode observations and proposal preparation please contact the La Silla High Resolution Spectroscopy Group

`ls-hires@eso.org`.

## 1.4 Acknowledgements

Most of the contents of this manual is based on information from the HARPS Consortium (F. Pepe and D. Queloz, both at Observatoire de Genève).

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

# Chapter 2

# HARPS Characteristics and Observing Modes

## 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 in particular the search for extrasolar planets. Another scientific application will be asteroseismology.

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

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

1. Simultaneous Thorium Reference observation
2. Iodine self-calibration observation
3. Classical fibre spectroscopy

These three modes are described in the sections following the instrument overview.

Figure 2.1: The main components of the HARPS system

| Item | description |
|---|---|
| System | 2 fibres (each 1″diameter on sky, distance 114″), spectral range 380-690nm, collimated beam 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 $15^2$ $\mu m^2$ |
| Spectral format | "upper" CCD (Jasmin): orders 89-114, 533-691nm<br>"lower" CCD (Linda): orders 116-161, 378-530nm |
| Spectral resolution | RS=120,000 (measured) |
| Sampling per spectral element | 4.1 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 |

Table 2.1: Characteristic optical data of HARPS

### 2.1.1 System components

This section gives a short description of the HARPS system, consisting mainly of the spectrograph proper, the fibre adapter on the telescope, the calibration unit, and the fibre links connecting these components. The system is illustrated in Fig. 2.1.

### 2.1.2 Spectrograph

HARPS is a fibre-fed, cross-dispersed echelle spectrograph. The optical design, shown in figure 2.2, is similar to UVES at the VLT. Its echelle grating is operated in quasi-Littrow conditions. 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 2k × 4k EEV CCDs. Two fibres (A and B) feed the spectrograph, one object fibre and one reference fibre. The spectra of the light from both fibres are formed by the spectrograph side by side on the detector. The spectrograph has no moving parts and has only one possible configuration. The characteristic optical data are given in table 2.1, the spectral format is shown in Fig. 2.3.

### 2.1.3 Detector

The detector is a mosaic of two 2k×4k EEV CCDs. It is mounted in a ESO detector head and cooled to -120° C 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.

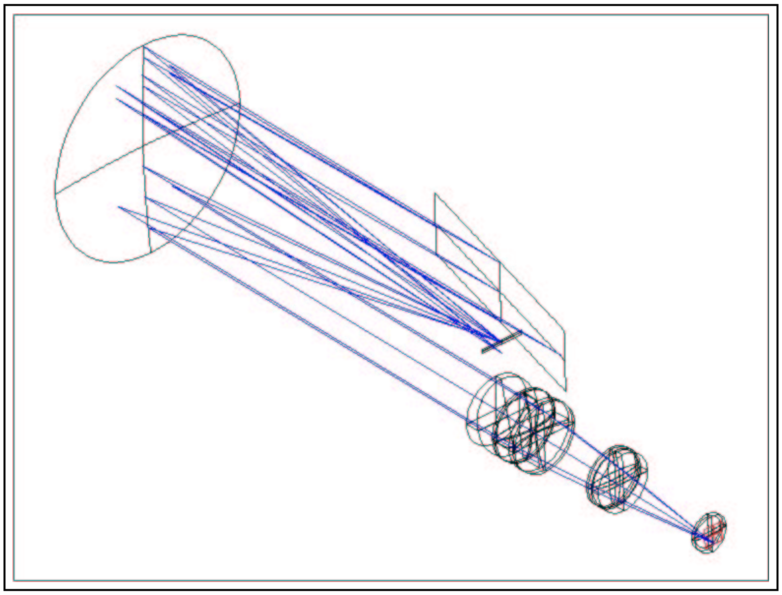

Figure 2.2: Optical layout of the spectrograph

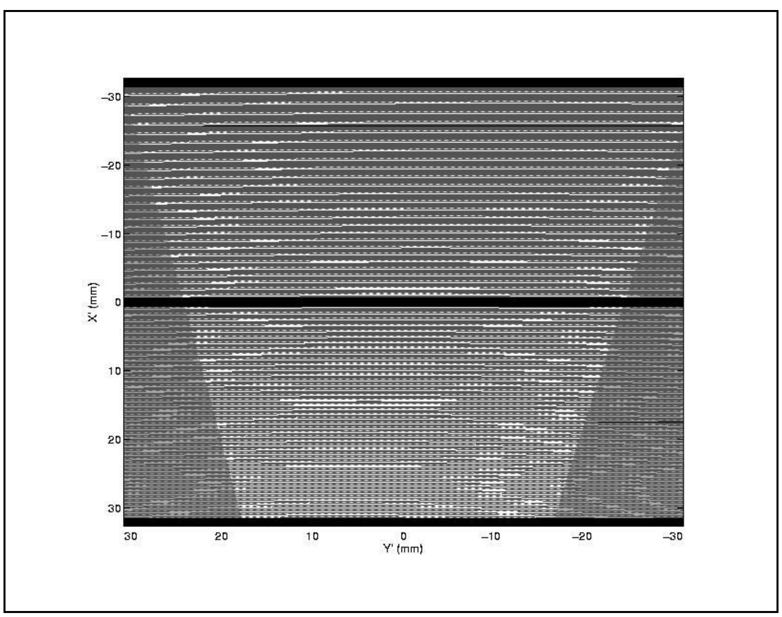


Figure 2.3: Spectral format of HARPS

The two CCDs are nicknamed "Jasmin" (the "red" CCD) and "Linda" (the "blue" one). Their quantum efficiencies are given in figures 2.4 and 2.5, respectively.

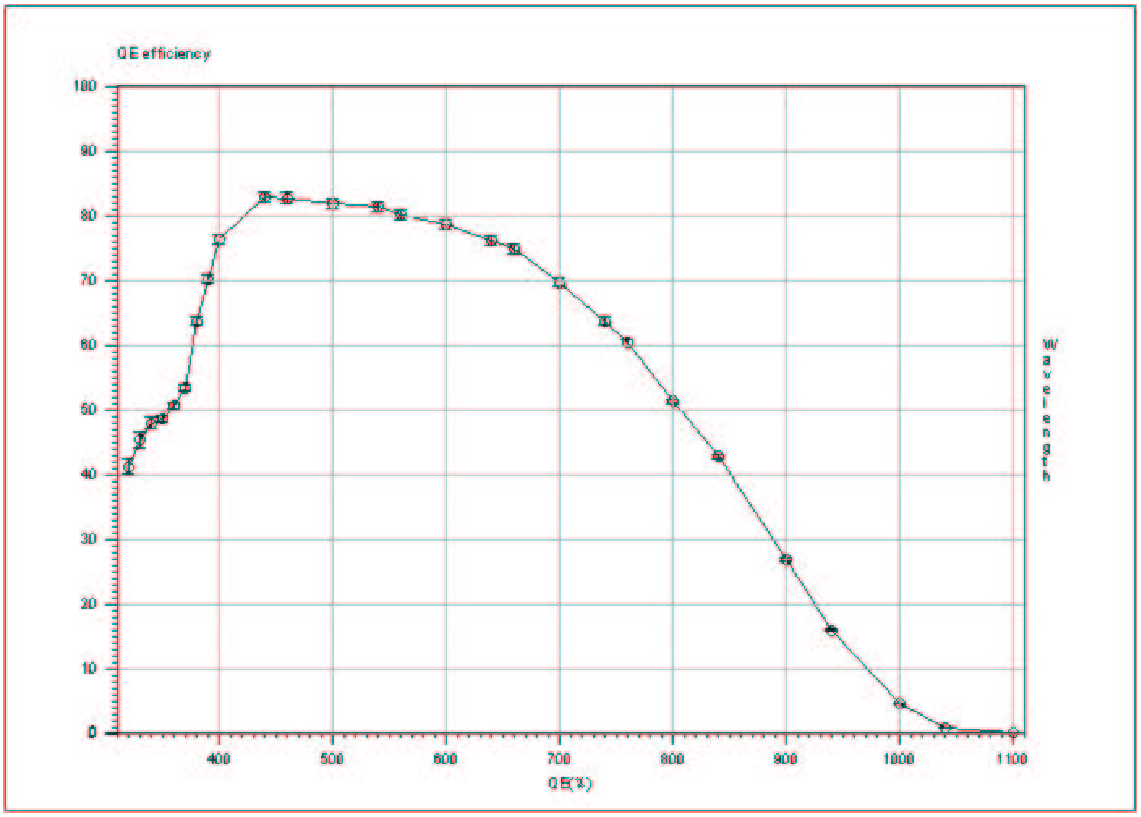


Figure 2.4: Quantum efficiency of Jasmin, the "red" CCD

### 2.1.4 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 stabilise the input point 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 2.1.5) next to the spectrograph with the HARPS Cassegrain Fibre Adapter (HCFA) on the telescope.

### 2.1.5 Calibration unit

The Calibration Unit contains a Tungsten flat-field and a Thorium-Argon spectral calibration lamp, as well as additional maintenance calibration lamps. 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.

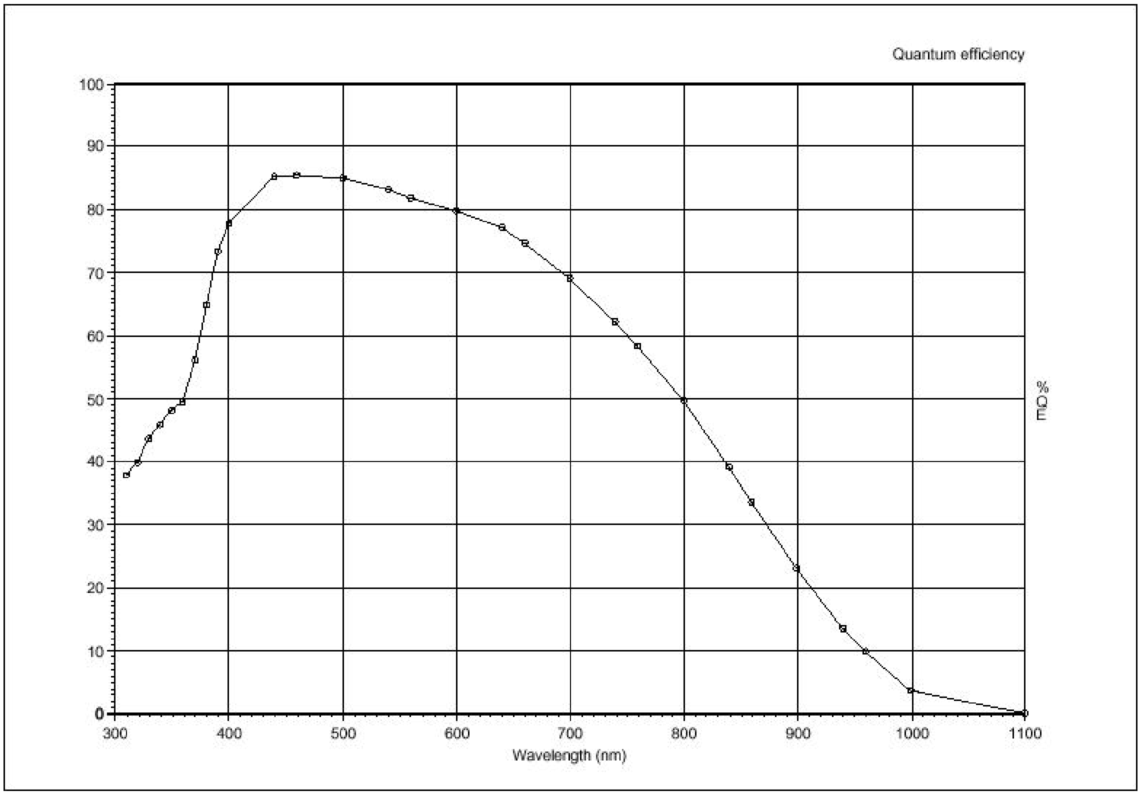


Figure 2.5: Quantum efficiency of Linda, the "blue" CCD

### 2.1.6 Fibre adapter

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

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 fibres (from end 2003 on)
4. feeding of the fibre viewer technical CCD camera
5. introduction of the Iodine cell into the object light path.

### 2.1.7 Exposure meter

The spectrograph possesses an exposure meter which serves to measure the stellar flux and to determine 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 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 centre of gravity).

## 2.2 Simultaneous Thorium reference method

The Simultaneous Thorium Reference mode is the base-line observation mode to get the best accuracy in radial velocity determination from the instrument. In this mode fibre B is fed by the Thorium lamp while fibre A is on the stellar target.

A variable neutral density (ND) filter is used to keep a Thorium spectrum at a flux level equivalent to a 15 seconds (TBC) 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**. Otherwise the flux levels of both fibres will not be balanced any more thus possibly decreasing the quality of the pipeline reduction.

The Thorium spectrum which is recorded simultaneously with the stellar spectrum is used to compute the instrument velocity drift from the last wavelength calibration.

### 2.2.1 Performance

Analysis of the data taken during the Commissioning 1 period in February 2003 is currently in progress. Performance figures will be given as soon as they are available. For estimates of the SNR under given observing conditions the Exposure Time Calculator (ETC) available via the HARPS web page (`http://www.eso.org/instruments/harps`) can be used with an accuracy of about 10%.

### 2.2.2 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 "Standard Predefined Calibration" should be executed before the beginning of the night. It includes:

- 2 Tungsten lamp exposures where respectively fibre A and fibre B are successively fed by the Tungsten lamp
- a sequence of 5 Tungsten lamp exposures where both fibres are simultaneously fed. This sequence is used by the data reduction pipeline for measuring the "spectral" flat-field
- A Thorium exposure where both fibres are simultaneously fed by light from the Thorium-Argon lamp.

### 2.2.3 Templates

The necessary acquisition and observing templates are available:

- `HARPS_ech_acq_thosimult`
- `HARPS_ech_obs_all`

For a detailed description of the templates see section 3.3

### 2.2.4 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 types:

- G2V, K0V, M0V

If the observer regards it as useful or necessary, (s)he can provide own spectral templates. Their format is **TBD, the procedure will be announced in due time.**

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

Radial velocity correction is done to the solar system barycentre (i.e. it includes Earth orbital motion, Moon/Earth barycentre motion, diurnal motion).

Pipeline execution times see section 3.3.3.

## 2.3 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.

### 2.3.1 Performance

The iodine cell used in HARPS absorbs 40% of the continuum from the source. Exposure times supplied by the ETC have to be scaled accordingly. Other performance data will be assessed during the second commissioning period in June 2003.

### 2.3.2 Calibration

A calibration sequence similar to the Simultaneous Thorium Reference method is recommended before the beginning of the night. This sequence 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 once per night. Details are TBC and will be explored during the Commissioning 2 period scheduled for June 2003.

### 2.3.3 Templates

The necessary acquisition and observing templates are available:

- `HARPS_ech_acq_I2cell`
- `HARPS_ech_obs_all`

For a detailed description of the templates see section 3.3

### 2.3.4 Pipeline, data reduction

In the Iodine self-calibration method the pipeline does spectrum extraction and wavelength calibration, but NO calculation of radial velocities. This has to be done by the observer.

## 2.4 Classical fibre spectroscopy

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

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 bright objects 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 high stability of the instrument makes wavelength drifts very small. If the proper calibration sequence is run before the beginning of the night a global wavelength calibration with an accuracy better than 10 m/s can be expected.

### 2.4.1 Performance

Analysis of the data taken during the Commissioning 1 period in February 2003 is currently in progress. Performance figures will be given as soon as they are available. 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.eso.org/unstruments/harps/`) can be used.

### 2.4.2 Calibration

A calibration sequence similar to the Simultaneous Thorium Reference method has to be carried out before the beginning of the night (see section 2.2.2. However, the usual number (5) of flat-field exposures may be increased if a SNR higher than TBD is required.

### 2.4.3 Templates

The necessary acquisition and observing templates are available:

- `HARPS_ech_acq_objA`
- `HARPS_ech_acq_objAB`
- `HARPS_ech_obs_all`

For a detailed description of the templates see section 3.3

### 2.4.4 Pipeline, data reduction

For the Classical Fibre Spectroscopy method the pipeline does spectrum extraction and wavelength calibration as well as calculation of radial velocities. To enable it, it is necessary to take the proper calibration sequence at the beginning of the night.

# Chapter 3

# Preparing The Observations

## 3.1 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.

## 3.2 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 centred 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 three different acquisition templates (different for the various observing modes) and one common observing template. They are described in section 3.3.

## 3.3 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 and bring them for their observations. Service Mode observers need to check in their OBs with ESO; details are TBD.

### 3.3.1 Acquisition templates

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

- `HARPS_ech_acq_thosimult`

- `HARPS_ech_acq_I2cell`
- `HARPS_ech_acq_objA`
- `HARPS_ech_acq_objAB`

A concise description of the acquisition templates will follow asap.

### 3.3.2 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`

A concise description of the observation template will follow asap.

### 3.3.3 Execution time overheads

| Item | time |
|---|---|
| telescope preset incl dome rotation | 2 min (upper limit)<br>1 min (typical for new pointing within a few degrees from the previous position) |
| centring of object on the fibre, start of guiding | 2 min |
| instrument configuration | <30 sec |
| readout time (incl writing of FITS headers and transfer to IWS) | 65 sec with 416kpx/sec readout speed,<br>ca 190 sec with 50kpx/sec readout speed |
| pipeline execution time: spectrum extraction<br>pipeline execution time: RV calculation | 5min<br>3min |
| ThAr lamp pre-heating (once at the beginning of the night)<br>Iodine cell pre-heating (once at the beginning of the night) | 2 min<br>2 hours |
| telescope focusing (at the beginning of the night, to be repeated 1-2× during the night) | <5 min |

Table 3.1: Execution times overheads

The pipeline execution time corresponds to the current performance (mid-February 2003). It is expected that the given times can be reduced, but it is not yet known by how much.

The ThAr lamp needs to be pre-heated at the beginning of operations; this takes about 2 minutes.

#### 3.3.3.1 Fast time series observations

The shortest exposure time possible with HARPS is 0.2 seconds. Per frame there is an overhead (readout, attachment of fits header etc) of 65 seconds in the fast readout mode (416 kpx/sec). However, the pipeline presently implemented will no longer be able to reduce this flood of data in near real-time. It will result in a substantial back-log of unreduced files, depending on the number of frames taken. It is foreseen that a new high performance pipeline will be available through the HARPS Consortium in 2004, subject to an agreement with OG.

In addition there is a risk of disk space shortage as the DRS workstation is currently (mid-February 2003) equipped with only a 36 Gb hard-disk. It is expected that this situation will be eased by the beginning of P72 by the installation of more hard-disk capacity.

#### 3.3.3.2 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 though the cell should be done.

Target acquisition with the Iodine cell is done through the cell, which means that the focus position of both the auto-guider and the telescope change and have to be re-adjusted. This takes about 5 min. It is therefore not recommended to “mix” observations using the simultaneous Th reference and Iodine self calibration methods in order to avoid these substantial overheads.

## 3.4 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.eso.org/instruments/harps/`.

# Chapter 4

# Observing with HARPS

## 4.1 During the night

Observations are performed in the standard VLT way, i.e. OBs are selected with P2PP and fetched and executed by BOB.

### 4.1.1 Target acquisition, guiding

TBD

### 4.1.2 Pointing restrictions

The usual pointing limit restrictions of the 3.6m telescope apply, see Fig. 4.1.

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 Telescope and Instrument Operator (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 17 m/sec (3.6m monitor)

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

The TIO will make the decision to close the dome as necessary. Visiting Astronomers (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 co-ordinator - 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 45 minutes. This waiting period is particularly important in case of humidity. The TIO will

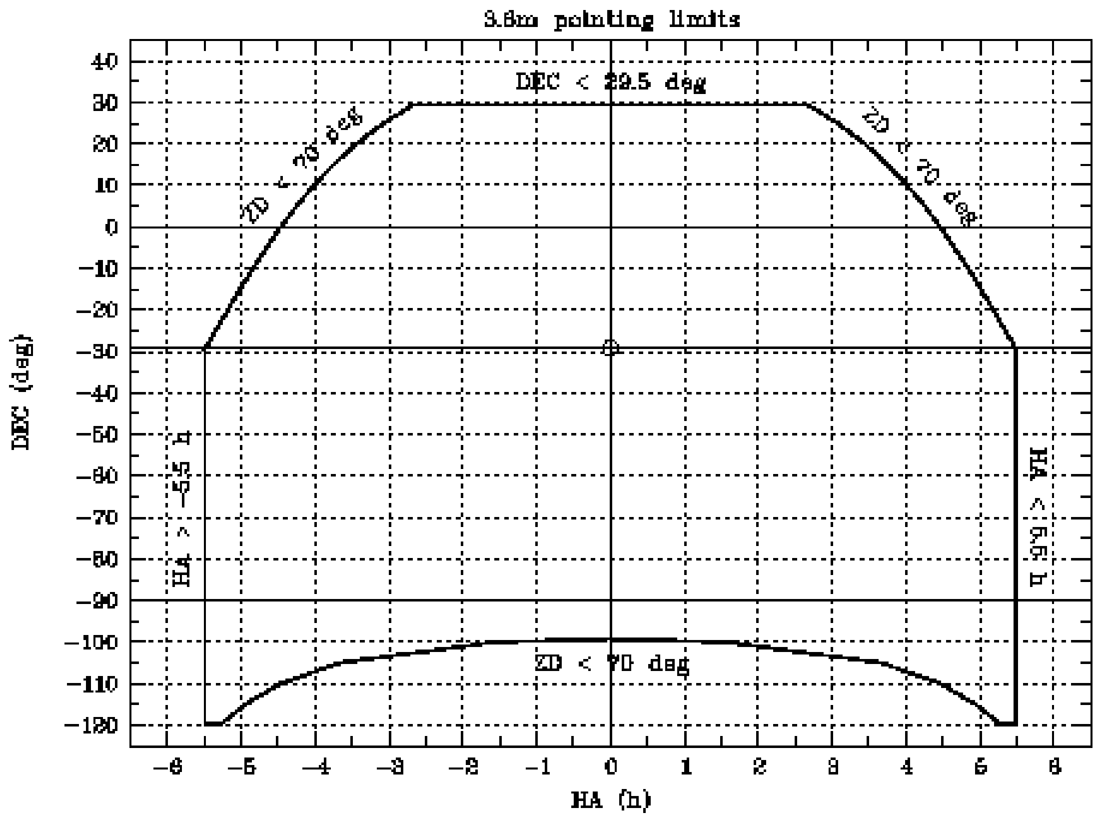


Figure 4.1: The sky area accessible for HARPS

further confirm that the condensation on the dome has completely evaporated and finally rotate the dome for 10 minutes.

## 4.2 Data archiving

### 4.2.1 Raw data structure

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

### 4.2.2 La Silla and Garching archives

HARPS data are DICB compliant and are stored locally at La Silla and in the central Garching Science Archive.

### 4.2.3 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 observer to write the results of their observing run on CD/DVD.

### 4.2.4 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 by the Archive (details are TBD). This filtering will be applied until one year after the end of the 5 year Guaranteed Time period.

# Chapter 5

# The Reduction of HARPS Data

## 5.1 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.

## 5.2 The HARPS data reduction pipeline

Every science frame is processed by the online pipeline. Depending on the observing mode used, the pipeline uses different reduction recipes. The pipeline output is available immediately after the processing is finished (see section 3.3.3). 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 4.2.3) available with HARPS. *Note that the archiving of pipeline products is currently the full responsibility of the visitor!*

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 accuracy in RV of 1 m/s, the target coordinates must be known to within $6''$incl 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 line identification.

# Appendix A

# List of acronyms

| | |
|---|---|
| ADC | Atmospheric Dispersion Compensator |
| AG | Auto-Guider |
| BOB | Broker for Observing Blocks |
| CCD | Charge Coupled Device |
| 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 |
| DRS | Data Reduction Software |
| 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 |
| NTT | New Technology Telescope |
| OB | Observing Block |
| OG | Observatoire de Geneve |
| P2PP | Phase 2 Proposal Preparation |
| PSF | Point Spread Function |
| RTD | Real Time Display |
| RV | Radial Velocity |
| SNR | Signal to Noise Ratio |
| TBC | To Be Confirmed |
| TBD | To Be Determined |
| TIO | Telescope and Instrument Operator |
| UVES | Ultraviolet/Visible Echelle Spectrograph |
| VLT | Very Large Telescope |

# Index

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