European Southern Observatory
Observatoire de Genève
Observatoire de Haute-Provence
Universität Bern
Service d'Aéronomie

Observatoire de Genève

51 ch. des Maillettes
CH-1290 Sauverny - Switzerland
Phone: +41 (0) 22 755 26 11 - Fax: +41 (0) 22 755 39 83

HARPS

Final System Design and Performance Report

Doc. No. 3M6-TRE-HAR-33100-0013

Issue 1.0

February 28, 2001

	Name	Date	Signature
Prepared	Francesco Pepe	28/02/2001	
Approved	Michel Mayor	28/02/2001	
Released	Michel Mayor	28/02/2001	

Change Record

Issue/Rev.	Date	Section/Page affected	Reason/Remarks
1.0	February 28, 2001	All	First issue

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

1.1 Scope

This document gives an overview of the HARPS instrument. In contrast to the Preliminary Design Report presented at PDR the subsystems will be described in separate documents. Only a short description of each subsystem will be found in this document, but the reference to the corresponding documentation will be given.
As in the Preliminary Design Report we will try to demonstrate that the HARPS design is in line with the technical requirements of AD-1. At the end of the document we have joined a compliance matrix which reflects the compliance *status* of the requirements towards the system and the different subsystem. Since the high-level requirements, especially the expected RV accuracy of the instrument, cannot be demonstrated at this stage, we made a performance estimate by comparison with the CORALIE instrument. Additional tests on the CORALIE instrument have been carried out to demonstrate the potentialities of HARPS.

1.2 Documents

1.2.1 Applicable Document

AD-1	HARPS Technical Requirements Specifications	3M6-SPE-HAR-33100-0002	1.0	21/06/2000

1.2.2 Reference Document

RD-1	HARPS Scientific Proposal	HARPS-Sys-Prop-ObsGe-0101	1.0	29/01/1999
RD-2	HARPS Technical Proposal	HARPS-Sys-Prop-ObsGe-0102	1.0	29/01/1999
RD-3	Opto-Mechanic Unit for the Earth-Motion Compensator		1.0	19/02/2001
RD-4	HARPS Room Design Description	3M6-TRE-HAR-33101-0001	1.0	28/02/2001
RD-5	Vacuum System Design, Analysis, and Performance Report	3M6-TRE-HAR-33102-0004	1.0	28/02/2001
RD-6	Vacuum Vessel Temperature-Control System	3M6-TRE-HAR-33102-0005	1.0	28/02/2001
RD-7	Optics Final Design Report	3M6-TRE-HAR-33103-0004	2.0	28/02/2001

RD-8	Spectrograph Mechanics Design, Analysis, and Performance Report	3M6-TRE-HAR-33103-0006	1.0	28/02/2001
RD-9	Final Design of the HARPS Exposure Meter and Technical LED	3M6-TRE-HAR-33103-0007	1.0	28/02/2001
RD-10	CCD Detector Design, Analysis, and Performance Report	3M6-TRE-HAR-33104-0002	1.0	28/02/2001
RD-11	Detector Unit Mechanical Design Report	3M6-TRE-HAR-33104-0001	1.0	08/02/2001
RD-12	Fiber Link Design, Analysis, and Performance Report	3M6-TRE-HAR-33105-0001	1.0	28/02/2001
RD-13	HCFA and Calibration Unit Design, Analysis, and Performance Report	3M6-TRE-HAR-33106-0002	1.0	28/02/2001
RD-14	Control Electronics Design, Analysis, and Performance Report	3M6-TRE-HAR-33107-0001	1.0	28/02/2001
RD-15	DFS User Requirements and Design Report	3M6-TRE-HAR-33110-0001		
RD-16	ICS/OS User Requirements and Design Report	3M6-TRE-HAR-33110-0002		
RD-17	Calibration, Operation and Maintenance Plan	3M6-PLA-HAR-33100-0005	1.2	05/03/2001
RD-18	Fundamental Photon Noise Limit to Radial Velocity Measurements	Submitted to A&A		
RD-19	Extrasolar Planets in the Southern Hemisphere: The Coralie Survey	Proceeding on VLT Opening Symposium, 1999		

1.3 Acronyms

AAA	Astronomical Absolute Accelerometer
AD	Applicable Document
ADC	Atmospheric Dispersion Compensator
CCD	Charge-Coupled Device
CES	Coudé Echelle Spectrograph
CFC	Continuous-Flow Cryostat
DFS	Data-Flow system
DRS	Data-Reduction Software
ESO	European Southern Observatory
FDR	Final Design Review
FRD	Focal Ratio Degradation
FTS	Fourier Transform Spectrometer
HCFA	HARPS Cassegrain Fiber Adapter
HW	Hardware

ICD	Interface Control Document
ICS	Instrument Control Software
IP	Instrument Profile
IWS	Instrument Work Station
LCU	Local Control Unit
LSF	Line Spread Function
MS	Maintenance Software
NA	Not Applicable
OG	Observatoire de Genève
OHP	Observatoire de Haute-Provence
OPS	Observing Preparation Software
OS	Observing Software
PDR	Preliminary Design Review
PSF	Point Spread Function
RD	Reference Document
RON	Read-Out Noise
RV	Radial Velocity
S/N	Signal-to-Noise ratio
SA	Service d'Aéronomie du CNRS
SW	Software
TBC	To Be Confirmed
TBD	To Be Defined
TCS	Telescope Control System
ThAr	Thorium-Argon (calibration lamp)
UVES	UV to Visible Echelle Spectrograph (VLT)
VLT	Very Large Telescope
WS	Work Station

1.4 Contributions

Guiding and scrambler tests: A. Blecha, F. Carrier, C. Melo L. Weber
CORALIE accuracy estimates: F. Bouchy, D. Naef, D. Queloz

Chapter 2: Description of HARPS

2.1 Scientific and Performance Objectives

HARPS (High-Accuracy Radial-Velocity planetary Search) is an instrument designed for the measurement of Radial Velocities (RV) at highest accuracy. Our goal is to detect as many as possible new extra-solar planets and in particular to extend the detection limit to low-mass planets and long-period planets and to planetary system. For this purpose a large survey of a volume-limited sample of slowly-rotating and inactive G and K dwarfs will be carried out during the guarantee-time period. The scientific output will contribute to reduce considerably the observational biases, which limit present programs to the detection of massive (Saturn to Jupiter masses) and short-period systems. But the detection of a planet by means of the RV-technique provides automatically also important information about the projected mass, period, distance to the parent star, and eccentricity of such systems. In the same way as the detection of the first "hot Jupiters" put our theoretical understanding of planet formation to a severe test, the improved statistics of orbital elements will help to refine present theories and models.

HARPS will not only measure radial velocities of stars but it will provide, as a natural by-product, a huge amount of stellar spectra at high spectral resolution and at high S/N. Out of them, information on metallicity, activity, etc. could be extracted, as well. Additional information on some bright star can also be acquired by asteroseismology performing fast series of RV measurements.

The strength of this technique lies also in its complementarity to other techniques and programs. As an example we should mention the detection of transits, spectroscopy on stellar (and planetary) spectra, and, in near future, interferometry and precise astrometry. In the case of transit, for example, the combination of the RV data with the transit data allows us to determine the mass and the density of the planet. In many cases RV data are even *needed* in advance in order to predict events (e.g. transit) or to optimize observational efficiency.

A detailed description of the scientific program and an overview of the many possibilities provided by HARPS can be found in the HARPS Scientific Proposal (RD-1).

2.2 Overview of the Instrument

2.2.1 Philosophy and Baseline Design

The design philosophy and baseline are described in detail in RD-2. It will only be recalled here that the design of HARPS is based on the experience acquired with ELODIE (1.93-m Telescope, OHP) and CORALIE (Swiss Euler-Telescope, 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. Our efforts to increase the HARPS performance compared to its predecessors address mainly two issues:

a) **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 extend, all RV-drifts which would be produced by temperature variations or changes in ambient pressure.

b) **Increase of the S/N on single RV measurements:** The improvement is attained through different steps. First, HARPS will be 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 will also help to reduce instrumental errors. Third, the spectrograph optics, which is very similar to that of UVES, is very efficient. Finally, we have chosen to operate HARPS in the two-fiber calibration mode because of our excellent experience on that, and because it is by far more efficient than the iodine-cell technique.

This last point has been discussed extensively inside the Consortium, at ESO, and between ESO and the Consortium. During these discussion we have got the impression that the performance and the potential power of the proposed two-fiber method are generally somewhat underestimated. In Section 3.3 we will give a short summary of the accuracy attained presently with CORALIE and why HARPS will be able to attain 1 m/s accuracy by means of this method. We are convinced that, in order to perform high-quality scientific programs, not only highest accuracy is required but also high efficiency. To our opinion the two-fiber method provides both. However, and since the implications on the instrument design are not substantial, we have decided to include the iodine cell into the instrument baseline design. The corresponding calibration and observation modes will be implemented at all levels. The baseline DRS will be tailored on the two-fiber technique, however.

2.2.2 Iodine Cell and AAA

The iodine cell option has been fully integrated in the HARPS design and will be available to the observer. HARPS will therefore be the first high-resolution spectrograph dedicated to precise RV surveys which can be operated using both techniques, the simultaneous thorium and the iodine cell. This will offer the possibility to compare the two methods directly and under different aspects concerning high-accuracy RV measurement.

As required by ESO at PDR, the status of the AAA option has been analyzed in depth during the final design phase of HARPS. The conclusions of the Consortium is that we will not be able to implement and offer this mode on HARPS. The reasons for that are many, and only the main arguments are given here:

- Until present the technical and scientific performances of the AAA could not be demonstrated. The attained RV accuracy on long term does not exceed the accuracy of CORALIE or ELODIE, and there is no evidence that the AAA on EMILIE is able to attain an RV accuracy close to 1 m/s.
- Even if operational, the AAA and the EMILIE spectrograph are still under development. In December 2000 modifications to the spectrum displacement mechanism (also called Earth Motion Compensator) were being done. The prototyping phase is still not finished.
- A complete design of the AAA is missing. A trade-off analysis is required. Presently only the mechanical design of the called Earth Motion Compensator has been studied.
- The project of an AAA for HARPS has not sufficiently advanced. Organization, and required finances and manpower remain unclear.

All these aspects led us to the conclusion that the AAA is nor ready to be integrated into the baseline of HARPS. We have therefore decided that the option AAA is removed and will consequently not be offered.
Nevertheless, we agreed to keep the possibility to implement the AAA at a later stage. The SA has prepared a preliminary design of the Earth Motion Compensator (see RD-3), the part of the AAA inside the vacuum vessel, and the mechanical interface to the optical bench has been defined. On the vacuum vessel, a spare flange has been reserved for the Earth Motion Compensator electrical connections. And the HCFA is fully compatible with the AAA.
If in future the AAA proves without any doubt its capability of attaining 1 m/s, and simultaneously HARPS is not able of attaining the specified RV accuracy after one year of operation, the AAA option could be reevaluated and possibly submitted to ESO.

2.2.3 Description of the Instrument

An overview of HARPS can be found in Figure 1. It is composed of following subsystems:

1) **Spectrograph (RD-7, RD-8):** Fiber-fed and cross-dispersed echelle spectrograph. The optical design is similar to UVES. The 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 CCD mosaic of two 2k x 4K EEV CCD's. Two fibers feed the spectrograph, one object fiber and one reference fiber. The spectra of the light from both fibers are formed by the spectrograph on the detector at the same time. The spectrograph has no moving parts and has only one possible configuration.
2) **Exposure Meter (RD-9):** The spectrograph possesses an exposure meter which will serve to measure the star flux and determine the mean time of the exposure
3) **Detector Unit (RD-10, RD-11):** The detector is a mosaic of two 2k x 4K EEV CCD's. It is mounted in a ESO detector head an cooled to -120°C by means of an ESO CFC cryostat. The detector is controlled by 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.
4) **Vacuum System (RD-5, RD-6):** The whole spectrograph, including the detector head, is mounted on an optical bench of steel and installed within an stainless-steel vacuum vessel. The vessel will be evacuated and its temperature controlled precisely.
5) **HARPS Room (RD-4):** The spectrograph will be installed inside the HARPS Room (also called HARPS Enclosure) in order to control the temperature of the vacuum vessel environment. The HARPS Room is part of the Coudé-West room of the 3.6-m ESO telescope.
6) **Optical Fiber Link (RD-12):** The spectrograph is linked to the 3.6-m telescope via two optical fibers. The fiber link incorporates an image scrambler which is fixed on the vacuum vessel and contributes to stabilize the input PSF of the spectrograph.
7) **HARPS Cassegrain Fiber Adapter (RD-13):** The optical fibers are connected to the HCFA which forms the interface to the telescope. Several functions are provided by the HCFA:
   a) introduction of the iodine cell into the object light path
   b) illumination of the object and the reference fiber, each separately by the object, calibration source, sky, or dark
   c) correction for atmospheric dispersion effects by means of an ADC

   d) switching between HARPS or CES fibers
   e) feeding of the slit viewer

8) **Calibration Unit (RD-13):** The Calibration Unit contains a flat-field and a spectral-calibration lamp, as well as additional optional calibration lamps. It is connected via two optical fibers to the HCFA which redirects the light of the calibration sources into the spectrograph fibers when required. The calibration fibers can be fed either by the same or independently by two different calibration sources.

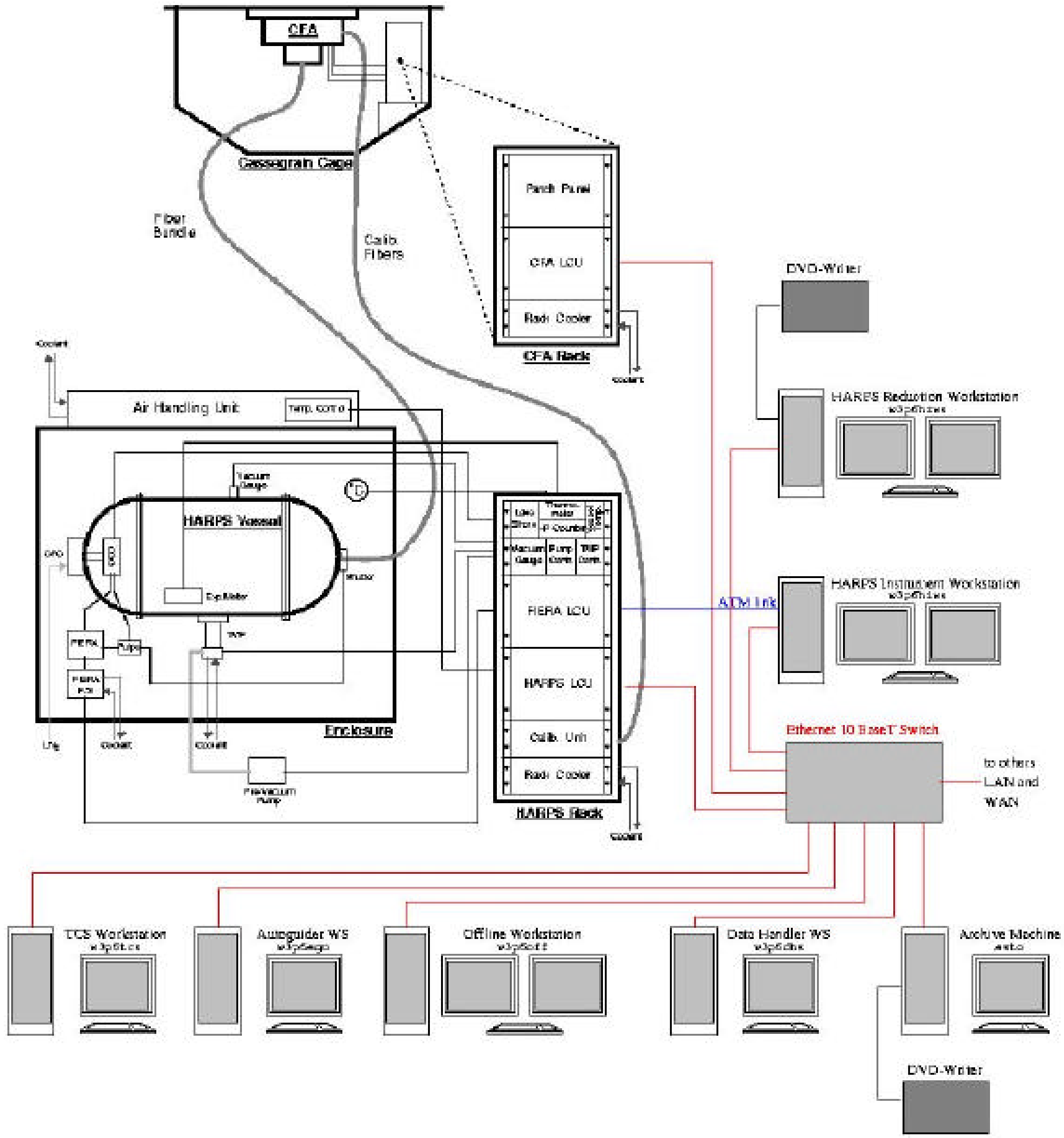
9) **Control Hardware (RD-14):** The HW consists of two LCU's (HARPS and HCFA LCU) and the different controllers to control the instrument functions. The LCUs are in turn controlled by the IWS. They are interconnected by a local network. The control hardware also includes additional control electronics and a set of environmental sensors and their controllers.

10) **Software (RD-15, RD-16):** The following main SW components can be distinguished:
    a) OS/ICS Observing and Instrument Control Software: instrument control and interface to the instrument
    b) DFS Data-Flow System: Integration of SW and data management into ESO's DFS. The DFS is itself composed of different SW units, i.e
       - OPS (=OSS) Operation Preparation Software: user support and preparation of observations.
       - DRS Data Reduction Software: Data reduction, spectra, extraction of RV data, monitoring of instrument performance.
       - Archiving: Standard ESO Archiving System to archive all raw frames and log files.
    c) MS Maintenance Software: An ensemble of SW tools which will help to monitor and maintain the instrument.

2.3 Calibration and Operation Modes of HARPS

The calibration and operation modes of HARPS, as well as all planned Templates are described in RD-17.

Figure 1: Functional Scheme of the HARPS hardware



d) HARPS HARDWARE FUNCTIONAL SCHEME

Chapter 3: Performances and Error Budget

3.1 Optical Performances

3.1.1 General Parameters

The main parameters of HARPS are summarized in Table 1.

Table 1: Main parameters of the HARPS spectrograph

# of fibers feeding the spectrograph	2
Accepted field by the fiber	1 arcsec
Fiber diameter	70 µm
Collimated beam diameter	208 mm
Spectral range	382 nm - 690 nm
Image quality over spectral format area	< 1.5 pixels
Spectral resolution	R ≈ 84'000
Spectral format (x,y)	62.74 mm x 61.44 mm
Photosensitive area	mosaic of two 2k x 4k CCDs
Pixel size	15 µm
Pixel sampling	4 pixels/SE
Distance (center to center) between object and reference fiber projected on the CCD	17 pixels

3.1.2 Spectral Format

The spectral format is shown in Figure 2 The horizontal axis represents the main-dispersion direction. It is denominated *y* for consistency with the general lens data. The vertical *x* axis corresponds to the cross-dispersion direction. The unit is [mm] for both axis. The spectrum ranges from 382 nm at the lower left edge to 690 nm at the upper right edge. The simulation shows the spectra of the object and reference (dashed) fibers. The camera optics F-number has been optimized to match the dimensions of the CCD chip. The bright part of the order indicates the free spectral range. The reference fiber spectrum is displaced by about 260 µm which corresponds to half the minimum inter-order distance attained in the blue. Due to the dispersion characteristics of the grism the inter-order distance between the different echelle orders increases from the blue towards the red from a minimum of 34 pixels to a maximum of 100 pixels. The gap between the two 2k4 CCD is situated at $x = 0$. The inclination of the orders varies as a function of the order. During optical alignment the CCD will be slightly tilted around the *z*-axis in order to align the central order with respect to this gap. The gap has been specified to be smaller than 1.3 mm. This way, only one object order, order 115, is lost in the gap between the two CCDs.

Figure 2: Spectral format. The gray rectangles represent a mosaic of two 2k4 CCDs.

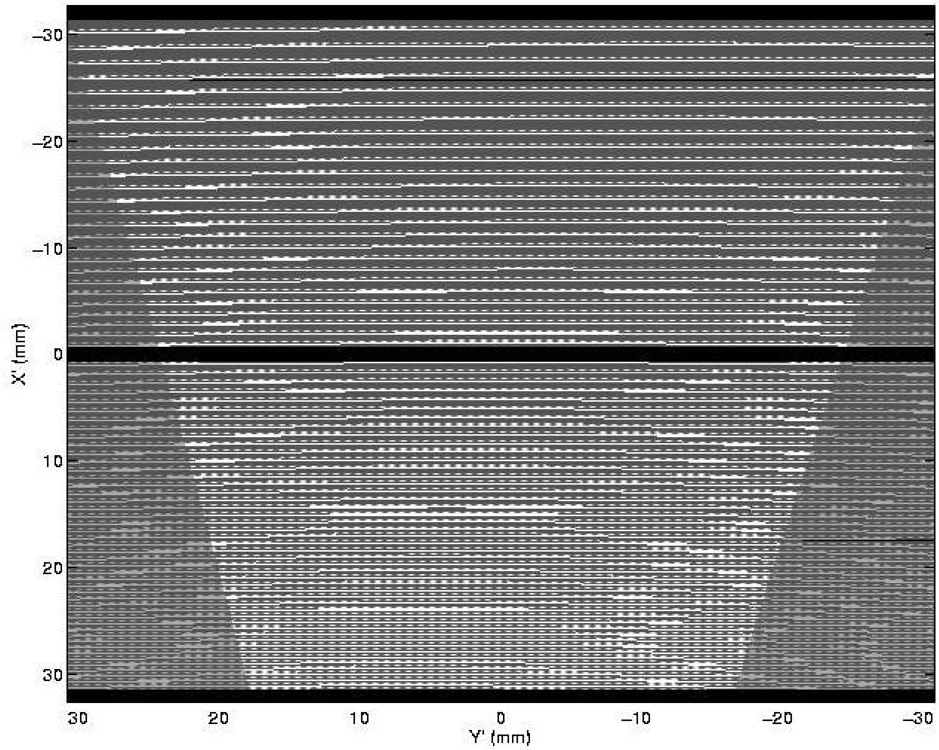


Table 2 indicates the inter-order distance, the inclination with respect to the CCD border, and the "deflection" for the three orders at the top, center, and bottom of the CCD. The deflection is measured as the distance of a point at the center of the order with respect to the straight line which connects the points at the left end of the order to the point at the right end.

Table 2: Geometrical characteristics of the echelle orders

Order N°	Central wavelength [Å]	Total spectral range $\Delta\lambda$ [Å]	Position *X* at center [mm]	Inter order distance d*X* [mm]	Slope [deg]	Curvature [mm]
89	6868.5	78.8	-30.371	1.510	1.424	-0.192
90	6792.2	77.9	-28.893	1.478	1.411	-0.197
114	5362.3	61.6	-0.928	0.940	1.139	-0.267
115	5315.6	61.0	-0.003	0.925	1.130	-0.269
116	5269.8	60.5	0.907	0.910	1.122	-0.271
159	3844.6	44.1	30.125	0.523	0.886	-0.352
160	3820.6	43.8	30.643	0.518	0.881	-0.353
161	3796.9	43.6	31.156	0.513	0.876	-0.353

3.1.3 Optical Efficiency

The efficiency of the single optical components as well as the total efficiency of HARPS is summarized in Table 3. The total efficiency does *not* include the efficiency of the 3.6-m telescope. The line "Fibers" includes the fiber transmittance, input/ouput losses and the FRD. The efficiency of the echelle grating indicates the value obtained at the blaze angle. The "slit efficiency has been calculated for a fiber of 1 arcsec in diameter and for average seeing conditions at La Silla (0.9 arcsec at λ = 550 nm).

Table 3: Optical efficiency of the HARPS instrument

Optical element \ l_{nm}	**380**	**400**	**480**	**550**	**650**	**690**
ADC	0.94	0.94	0.95	0.95	0.95	0.95
"Slit" efficiency	0.37	0.39	0.5	0.58	0.68	0.68
Fibers	0.44	0.47	0.59	0.61	0.64	0.64
Entrance F/N optics	0.97	0.97	0.97	0.97	0.97	0.97
Image scrambler	0.77	0.77	0.77	0.77	0.77	0.77
Exit F/N optics	0.97	0.97	0.97	0.97	0.97	0.97
4 mirrors	0.78	0.85	0.85	0.85	0.85	0.85
Echelle (@ blaze)	0.60	0.62	0.64	0.64	0.63	0.62
Grism	0.54	0.64	0.79	0.75	0.61	0.56
Camera (glasses)	0.90	0.94	0.96	0.98	0.98	0.98
Camera (surfaces)	0.88	0.88	0.88	0.88	0.88	0.88
Vignetting	0.97	0.97	0.98	0.98	0.99	0.99
Order-separating filters	1	1	1	0.95	0.95	0.95
CCD	0.68	0.80	0.90	0.90	0.85	0.85
Total	**0.015**	**0.027**	**0.065**	**0.072**	**0.067**	**0.061**

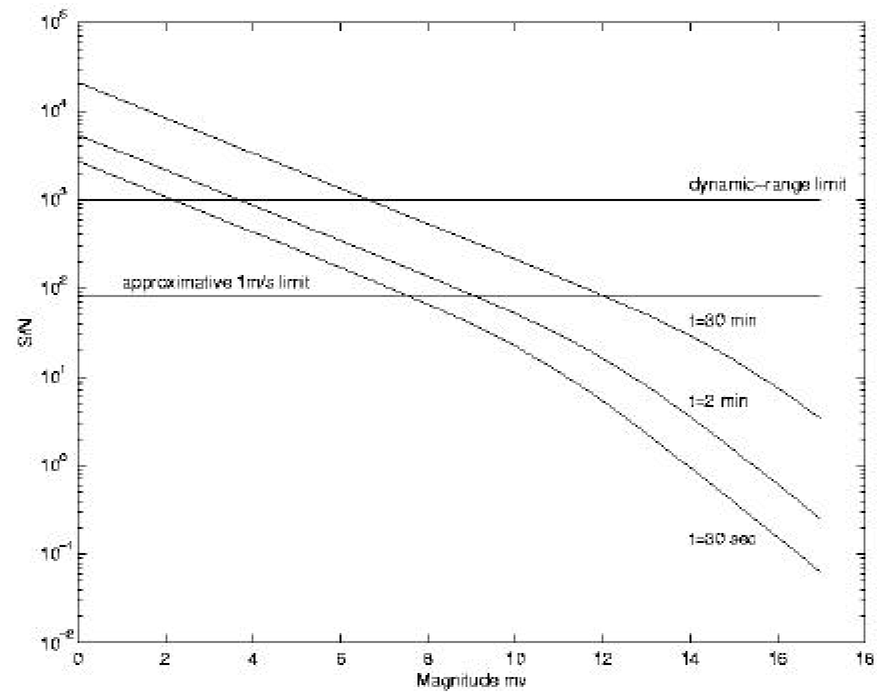
3.2 Photon Noise and Limiting Magnitude

In Figure 3 we have calculated the S/N ratio as a function of the visible magnitude of the star and for three different integration times *t*. These numbers have been derived for l = 550 nm assuming the transmission value shown in Table 3 and for a binning of (1,1), each pixel contributing with a RON of $5e^-$ and a dark current of $4e^-$/h. The telescope efficiency has been taken to be of 60%.

Under these conditions the spectrum of a star with $m_v = 9$ can be taken in 2 minutes with S/N of about 85 per spectral bin. We shall estimate the resulting RV accuracy by comparison with CORALIE: On a G8V star spectrum with S/N = 85, the RV accuracy provided by CORALIE and its DRS is of 2.2 m/s. Extrapolated for HARPS, which has a spectral resolution of about R = 84'000 compared to that of CORALIE of R = 50'000, the expected RV accuracy should be about $s_{RV} = 2.2/(84000/50000)^{1.5}$ m/s $\approx$ 1 m/s. The exact value depends however on the stellar spectral type and can be up to two times worse for an earlier-type star.
Within the specified range of integration time (30 sec to 30 min) the 1 m/s will be attained for magnitudes up to the 12^{th}. For a 16^{th} magnitude and an integration time of 30 min still a S/N of about 7.5 can be reached, which corresponds to a RV accuracy of about 10 to 15 m/s.

Besides the instrumental efficiency and the stellar magnitude, the fundamental photon-noise limit of HARPS will also depend on the RV-information contained within the recorded spectrum. This RV information is mainly a function of the spectral resolution of the instrument and the spectral type of the star. Bouchy et al. (RD-18) have calculated the RV-information content for various spectral types and expressed it in terms of a quality factor Q. From that performance figure the fundamental limits of HARPS have been deduced and presented in RD-18. This paper will be annexed to the present document.

Figure 3: Signal-to-Noise ratio per spectral element at *l* = 550 nm



3.3 RV Accuracy Limits

3.3.1 Error Budget

It is not an easy task to perform a realistic error budget in terms of attainable RV accuracy. If a complete simulation had to be done the instrumental profile IP$_l$(x,y), where (x,y) are the coordinates of the CCD pixels, would have to be known with sufficient accuracy in order to resolve effects of 1/3000 of the spectral element. These appears not realistic if we consider that the spectral range is *l l*=300 nm and that a spectral element measures *Dl*=0.05 nm. In addition, many parameters would have to be considered. We prefer instead to list in Table 4 all possible error sources and their estimated influence on the RV on CORALIE, and to extrapolate them for HARPS:

Table 4: Error sources on the RV measurement

Error source	**CORALIE accuracy σRV in [m/s]**	**HARPS accuracy σRV in [m/s]**	**What will be done for HARPS**
CCD pixel response and block-stitching error Contamination of the CCD	0.6 not quantified	0.3 to be investigated	• higher spectral resolution • higher pixel sampling periodic pumping of CCD dewar
Diffused light on the CCD	no effect	no effect	
Ghosts on the CCD	not quantified	to be investigated	
Optical, thermal, mechanical instabilities of the spectrograph and CCD IP variations induce different LSF for calibration and object	not quantifiable	not quantifiable	• in principle eliminated by simultaneous calibration • higher thermo-mechanical stability
Differential drift between object and reference fiber entrance	< 1 during a night	< 0.5 during a night	• higher instrumental stability • higher scale factor
Non-perfect scrambling, guiding	< 0.77	< 0.3	higher spectral resolution
Atmospheric dispersion Atmospheric extinction	1.0	< 0.5	• $Z \leq 1.5$, better ADC • detailed analysis • DRS to be optimized
Atmospheric absorption lines	< 3	to be investigated	eliminated by DRS
Contamination by moon light depends on magnitude and weather conditions	< 1 $m_v < 9$	< 1 $m_v < 9$	will be investigated further, can be eliminated by setting observational constraints
Contamination by nearby star visual binary, depends on seeing and distance (distance < 3 arcsec)	up to 30	eliminated	remove visual binaries from catalog
SW: zero-point variation of the wavelength solution (not instrumental!)	< 4	to be investigated	detailed analysis in progress, DRS to be optimized

3.3.2 Estimated RV accuracy

Instead of indicating the "theoretically" expected RV accuracy we will analyze the accuracy of CORALIE in order to get a feeling for the expected accuracy of HARPS.

a) **Short-term stability**
"Short term" means a time range of one hour up to one night. It can also be defined as the time between two subsequent wavelength-calibration exposures (ThAr-ThAr). We have made a sequence of 18 exposures on one single object (HD 20794, G8V, $m_v = 4.26$) from airmass

$Z = 1.5$ to $Z \approx 1$. These exposures have been made using always the same wavelength solution. *No a posteriori correction at all has been performed on these data.*
The recorded RVs and their errors are shown in Table 5. The rms of the measured RV series is 2.6 m/s which is very close to the mean of the calculated error arising from photon noise. We can therefore assume that the short-term error is already well below this limit and that the higher thermo-mechanical stability and the vacuum operation of HARPS will significantly increase the accuracy. For additional information see also Queloz et al. (RD-19).

Table 5: Short-term radial-velocity measurements on HD 20794

Nr.	**UNIX time [sec] - 910399180 sec**	***RV* [m/s] - 87761 m/s**	**σ_{RV} [m/s]**
1	1	1	2.7
2	1052	5	2.9
3	2107	-3	3.1
4	3164	-1	2.9
5	4222	1	3.0
6	5283	1	3.1
7	6347	-3	2.8
8	7413	0	2.9
9	8510	2	2.6
10	9579	-3	2.6
11	10814	1	2.2
12	11879	2	2.2
13	12937	-2	2.2
14	13987	-2	2.4
15	15036	-3	2.5
16	16083	4	2.5
17	17129	-5	2.3
18	18173	1	2.3
	mean	**87761.0**	**2.7**
	rms	**2.6**	

Additional measurements have been made during a technical mission on CORALIE in November 2000. In order to attain high S/N ratio we have performed measurements on the Sun. On the 60 RV measurements carried out in about 4 hours we attained an rms of 1.5 m/s. This value does not include possible guiding errors, since for these measurements a diffuser had been placed in front of the telescope. However, the attained accuracy is a clear indication that the spectrograph is able to deliver the aimed 1 m/s, and that LSF variations of the spectrograph do not produce any RV errors at this accuracy level.

b) **Long-term stability**
"Long term" is in our case defined on one end by the re-calibration of the instrument (few hours) and, on the other end, by the life time of the instrument (2 years for CORALIE). A calibration is done every few hours or at least once per night in the beginning of the exposure sequence. In principle the calibration procedure removes the zero-point drift (=internal errors) of the instrument: The relative drift between the two fibers is reset to zero and the wavelength

solution *l*(x,y) of the CCD (x,y = pixel coordinates) is recalculated. It is possible, however, that some residual errors may be left due to effects mentioned in Table 4. *Note that on the CORALIE data there is no a posteriori correction of the instrumental zero point by means of "standard" sources.*

Until present the quality of the wavelength solution was probably one of the limiting factors in the attained the RV accuracy of CORALIE. It could produce an offset between series of measurements belonging to different wavelength solution. We estimate that this effect introduced an error of about 4 to 5m/s rms on long term. One of the causes finds its origin in the reduction software, but also variations of calibration lamp flux might produce some effects.

In order to determine an upper limit for the present accuracy of CORALIE on a long term scale D. Naef (OG) has analyzed the dispersion on the RV for a sample of stars which show no significant RV variation during the two years of operation and with small photon error (typically 6 m/s). On these data no significant zero-point variations during two years have been detected (< 0.5 m/s). In average the dispersion around the mean value is about 9m/s rms which is confirmed by the (o-c) values obtained by orbital solutions of recently discovered exoplanets. This error estimate is an *upper limit* for the RV accuracy of CORALIE because it includes the errors produced by SW (wavelength calibration), photon noise, and especially by the star itself. Indeed small drifts due to a companion (small planets!?) or microvariability of the star cannot be distinguished from instrumental errors.

From measurements made by Delfosse et al. (The closest extrasolar Planet, A&A1999) on Gl 876 with both instruments, CORALIE and ELODIE, we are also able to determine the zero-point difference between the two instruments. It turned out that there is no RV offset between the two instruments within the measurement accuracy (photon noise) of 8 m/s. Although the IP of the two instruments is probably *very* different, residual systematic errors are thus suppressed to a high degree. This proves that the calibration by means of ThAr eliminates very efficiently zero-point errors arising from IP variations.

During the past months considerable efforts have been made by D. Queloz at OG to increase the stability of the wavelength solution. Important results have been achieved using long ThAr calibration series as test bench. The new algorithms delivers now a fit of the wavelength solution with an accuracy of 1.6 m/s rms. The "tracking accuracy", i.e. the accuracy by which the two fibers follow each other is 0.8 m/s and has attained practically the photon limit.

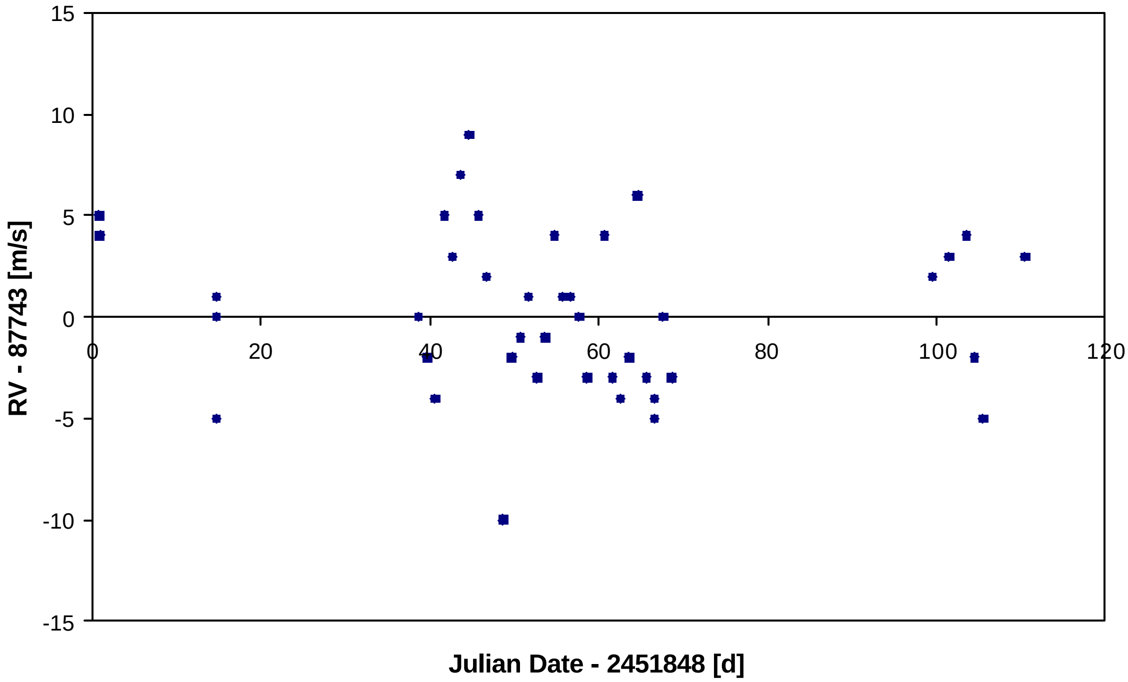
The new algorithms have been tested since mid November on HD 20794, on which more than 40 measurement have been carried out since then. The results are shown in Table 6 and Figure 4. The "all included" rms is 3.9 m/s. Taking into account the mean photon-noise error s_{RV} of 1.6 m/s, tracking accuracy, and fit accuracy on the wavelength solution the *overall* instrument stability of CORALIE results to be better than 3 m/s. The remaining 3 m/s include also possible stellar variability.

Note: The measurement presented in Table 6 show an offset compared to other measurement on HD 20794. This is due to the different algorithms used and is purely SW. It can be easily determined and corrected.

Table 6: Long-term radial-velocity measurements on HD 20794

Nr.	Julian Date [d] - 2451848 d	*RV* [m/s] - 87743 m/s	Photon-noise error s_{RV} [m/s]
1	0.81	5	1.9
2	0.87	4	1.9
3	14.69	0	1.1
4	14.70	1	1.1
5	14.71	-5	1.3
6	38.62	0	1.4
7	39.64	-2	1.2
8	40.60	-4	1.3
9	41.62	5	1.2
10	42.61	3	1.4
11	43.63	7	1.2
12	44.65	9	1.2
13	45.69	5	1.1
14	46.63	2	1.1
15	48.66	-10	1.3
16	49.67	-2	1.6
17	50.67	-1	1.3
18	51.69	1	1.4
19	52.68	-3	1.3
20	53.65	-1	1.1
21	54.68	4	1.5
22	55.69	1	1.4
23	56.63	1	1.3
24	57.63	0	1.3
25	58.61	-3	1.7
26	60.65	4	1.4
27	61.62	-3	1.6
28	62.60	-4	1.2
29	63.63	-2	1.5
30	64.58	6	2.4
31	65.63	-3	1.3
32	66.57	-4	3.1
33	66.61	-5	1.2
34	67.64	0	1.7
35	68.62	-3	1.6
36	99.53	2	3.3
37	101.52	3	1.6
38	103.52	4	1.7
39	104.52	-2	4.8
40	105.52	-5	1.7
41	110.51	3	1.6
	mean	**87743.1**	**1.6**
	rms	**3.9**	

Figure 4: Long-term radial-velocity measurements on HD 20794



3.3.3 Performance of the Image Scrambler

3.3.3.1 Stability

An upper limit for bad-scrambling effects is given by the short-term of the instrument. Over a time of several hours and up to one night it has been shown that the RV-Accuracy of CORALIE is higher than 2.5 m/s (see Section 3.3.2).

3.3.3.2 Scrambling

In order to demonstrate the efficiency of scrambling we have performed preliminary test on CORALIE. The idea was to measure the RV of a luminous object (HD 128621, $m_v = 1.45$) for (A) centered on the object fiber and (B) a position de-centered with respect to the fiber center. The guiding algorithm have been modified by A. Blecha and L. Weber (OG) in order to permit off-axis guiding on the fiber.
The fiber diameter of CORALIE is 2 arcsec. The test have been performed when meteorological conditions were good and seeing was of the order of 1 arcsec. The de-centered position corresponded to a displacement of 1 arcsec in y direction of the guiding camera. Under these condition the photometric barycenter at the fiber entrance is shifted by 0.62 arcsec or about 1/3 of the fiber diameter.
The results show that the detected shift of radial velocity B-A is significant and is of the order of 4.2 ± 0.6 m/s. If we consider that the fiber diameter projected on the CCD corresponds to 6 km/s we can deduce that the photometric barycenter shift has been reduced by about a factor 450. This

value is consistent with that measured by Casse and Vieira (SPIE Proceeding Vol. 2871, 1997) and corresponds well to the value required in AD-1.

Table 7: RV of HD 128621 for A) the star centered on the fiber and B) de-centered by 1 arcsec with regard to the center of the fiber entrance.

Unix time [sec] - 958950000 s	RV [m/s]		
	Position A + 21280 m/s	Position B + 21280 m/s	B-A
465	0		-4
646		-4	
896	1		-5
1078		-4	
2199	0		-4
2372		-4	
18246	6		-3
18423		3	
18668	4		-8
18859		-4	
1641515	-15		-2
1641687		-17	
1641921	-15		-9
1642092		-24	
1642324	-13		-2
1642502		-15	
1642734	-12		-8
1642916		-20	
1643146	-16		-4
1643318		-20	
1643562	-16		-3
1643735		-19	
1643967	-15		-5
1644144		-20	
1644379	-13		-1
1644551		-14	
1814688	-4		-3
1814856		-7	
1815085	-4		-2
1815257		-6	
1815489	-1		-5
1815661		-6	
Average	**-21287.1**	**-21291.3**	**-4.25**
Standard deviation	**7.9**	**8.1**	**2.3**

3.3.4 Spectrophotometric Stability Tests

As required at PDR we have performed spectrophotometric tests on CORALIE. The goal was to detect possible modal noise at the fiber exit. Such "noise" would produce fluctuations of the signal as a function of the wavelength. It could be seen as structure $s(l)$ on a spectral flat field. As long a the fibers do not move, this structure remains stable. When the fiber moves, the structure begins to move, too.

In order to detect this varying structure we took two series of 10 spectral flat fields. During the first series the telescope, and hence the fibers, were kept at a fixed position. During the second series the telescope was moved for each spectral flat field in a different position. For both series we have calculated on the extracted spectra and for each pixel the rms of the measured signal. We have then compared for each pixel the measured rms to the expected noise. These values were averaged over the whole CCD. The results are shown in Table 8.

Table 8: Results of the spectrophotometric test

	Ratio of measured rms per pixel to calculated rms per pixel Values averaged over CCD	
	Fiber A	**Fiber B**
Telescope remains still	1.0476	1.0503
Telescope moves	1.0580	1.0704

It is very difficult to deduce out of these results a clear statement. We can only say that the measured noise is close to the calculated noise. The small difference could be explained by a varying calibration lamp flux, or even by a small error in the assumed CCD gain. In any case the noise in the series where the telescope was not moving is not very different from the noise measured during the series where the telescope was moving. We think therefore that the modal noise contributes only little to the flat field noise. On the RV measurement, modal noise cannot produce very important effects, and it will be impossible to detect it by means of spectrophotometric tests.

Chapter 4: FDR Documentation Overview

Document No.	Issue	Date	WP No.	Title
3M6-LIS-HAR-33100-0004	2.0	28/02/2001	WP-2000	Configuration Item Data List
3M6-PLA-HAR-33100-0005	1.2	05/03/2001	WP-4900	Calibration, Operation and Maintenance Plan
3M6-TRE-HAR-33100-0007	2.0	28/02/2001	WP-2000	Final Hazard List and Analysis
3M6-TRE-HAR-33100-0013	1.0	28/02/2001	WP-2000	Final System Design and Performance Report
3M6-PLA-HAR-33100-0014	1.0	28/02/2001	WP-2000	System AIT and Alignment Plan
3M6-TRE-HAR-33100-0015	1.0	in prep.	WP-2000	Reliability Analysis
3M6-PLA-HAR-33100-0016	1.0	05/03/2001	WP-4900	Commissioning Plan
3M6-TRE-HAR-33101-0001	1.0	28/02/2001	WP-4500	HARPS Room Design Description
3M6-TRE-HAR-33102-0004	1.0	28/02/2001	WP-4400	Vacuum System Design, Analysis, and Performance Report
3M6-TRE-HAR-33102-0005	1.0	28/02/2001	WP-4400	Vacuum Vessel Temperature-Control System
3M6-TRE-HAR-33103-0004	2.0	28/02/2001	WP-4100	Optics Final Design Report
3M6-TRE-HAR-33103-0006	1.0	28/02/2001	WP-4200	Spectrograph Mechanics Design, Analysis, and Performance Report
3M6-TRE-HAR-33103-0007	1.0	28/02/2001	WP-4100	Final Design of the HARPS Exposure Meter and Technical LED
3M6-PLA-HAR-33103-0008	1.0	28/02/2001	WP-4100	Procédure d'Alignement du Spectrographe HARPS
3M6-TRE-HAR-33104-0001	1.0	08/02/2001	WP-4300	Detector Unit Mechanical Design Report
3M6-TRE-HAR-33104-0002	1.0	28/02/2001	WP-4300	CCD Detector Design, Analysis, and Performance Report
3M6-TRE-HAR-33105-0001	1.0	28/02/2001	WP-4620	Fiber Link Design, Analysis, and Performance Report
3M6-TRE-HAR-33106-0002	1.0	28/02/2001	WP-4610	HCFA and Calibration Unit Design, Analysis, and Performance Report
3M6-TRE-HAR-33107-0001	1.0	28/02/2001	WP-4800	Control Electronics Design, Analysis, and Performance Report
	1.0	19/02/2001		Opto-Mechanic Unit for the Earth-Motion Compensator

Chapter 5: Compliance Matrix

In the following table the Compliance Matrix is presented. It refers to the Verification Matrix presented in AD-1 and represents the compliance status at FDR. The following terms are employed:

A	Applicable
NA	Non applicable
C	Compliant
PC	Partly compliant (shall be commented)
NC	Non compliant (shall be commented)
NV	Not verified at this stage

The columns in the table refer to:

Section	Section number of AD-1
Title	Section title of AD-1
Item	Referred item
Appl.	Status of applicability
Compl.	Status of compliance
Comments	Comments/Exceptions

Section	Title	Item	Appl.	Compl.	Comments
2.1	**System Definition**				
2.1.1	Level 1 Requirements		A	PC	RV, only errors *estimates* are given
2.2	**Operation and Observing Modes**				
2.2.1	Operation Modes	1. Observing	A	C	
		2. Calibration	A	C	
2.2.2	Stand-by Mode	3. Engineering	A	C	
2.2.3	Observing Modes	1. Star with sim. cal. by ThAr	A	C	
		2. Star only	A	C	
		3. Star + Sky	A	C	
		4. Self-calibrating mode	A	C	
2.2.4	Calibration Modes	1. Spectral flat field	A	C	
		2. Wavelength cal. by ThAr	A	C	
		3. Pure iodine reference spectra	A	C	
2.3	**Performances**				
2.3.1	HARPS Room	1. General requirements	A	C	
		2. Equipment	A	C	
		3. Air conditioning	A	C	
2.3.2	Vacuum System	1. Vessel and chassis	A	C	
		2. Vacuum control	A	C	
		3. Temperature control	A	C	
		4. Vibration damping	A	C	
2.3.3	Spectrograph	1. Operational conditions	A	C	
		2. Optical parameters	A	C	
		3. Efficiency of the spectrograph	A	C	
		4. Stability 5. Stray light and ghosts	A A	C PC	Estimated stability Local ghosts might be > 10^{-4} AD-1 to be updated
		6. Exposure meter	A	C	

Section	Title	Item	Appl.	Compl.	Comments
		7. Optic al alignment	A	C	
2.3.4	Detector Unit	1. CCD chip	A	C	
		2. Mosaic alignment	A	C	
		3. Operation temperature	A	C	
		4. Detector head electronics	A	C	
		5. The FIERA LCU	A	C	
		6. Continuous-flow cryostat 7. Detector head and interface	A A	C C	
		8. Stability	A	C	
2.3.5	Optical Fiber Link	1. Efficiency	A	C	
		2. Image scrambler	A	C	
		3. Shutter	A	C	
		4. Interface to the CFA	A	C	
2.3.6	Cassegrain Fiber Adapter	1. Illumination configurations	A	C	
		2. Iodine cell	A	C	
		3. Field vis. and guiding camera	A	C	
		4. ADC	A	C	
		5. CFA control	A	C	
		6. Overhead time	A	NV	
		7. Calibration Unit	A	C	
		8. Optional items	A		
2.3.7	Hardware	1. VLT compliance	A	C	
		2. Instrument control	A	C	
2.3.7	Software	All	A	NV	To be verified at SW reviews
2.4	**Interfaces**				
2.4.1	A: HARPS - 3.6-m telescope	1. Mechanical interface	A	C	
		2. Dome seeing 3. Image Quality	A A	NV NV	To be substituted by "as delivered" To be substituted by "as delivered"
		4. Pointing	A	NV	
2.4.1	A: HARPS - 3.6-m telescope	5. Object acquisition	NA		Not automatic, to be discussed

Section	Title	Item	Appl.	Compl.	Comments
		6. Automatic guiding	A	C	
		7. TCS and data handling	A	C	
		8. Overhead time	A	NV	
2.4.2	B: HARPS - Telescope Building	1. Fiber path	A	NV	
		2. Coudé room	A	NV	
2.5	**Reliability**	1. Minor malfunctions 2. Medium malfunctions	A A	NV NV	
		3. Major malfunctions	A	NV	
		4. Critical Malfunctions	A	NV	
2.6	**Environmental Conditions**				
2.6.1	Packing and Transportation		A	NV	
2.6.2	Env. Conditions at 3.6-m telescope		A	NV	
2.7	**Maintenance**				
2.7.1	Preventive Maintenance		A	C	
2.7.2	Corrective Maintenance		A	C	
2.7.3	3.6-m-Telescope Maintenance		A	C	
2.8	**General Design and Construction**				
2.8.1	Material, Parts, Processes	1. El.-mech. components	A	C	
		2. Protection against corrosion	A	NV	
		3. Painting	A	NV	
		4. Vacuum operation	A	C	
2.8.2	EMC		A	NV	
2.8.3	Name Plates and Product Marking		A	NV	At present no requirements
2.8.4	Safety	1. General safety requirements 2. Oper. safety requirements	A A	PC PC	Verified by design Verified by design