CARMENES: The VIS channel spectrograph in operation

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ABSTRACT

CARMENES is a fiber-fed high-resolution Echelle spectrograph for the Calar Alto 3.5m telescope. The instrument is built by a German-Spanish consortium under the lead of the Landessternwarte Heidelberg. The search for planets around M dwarfs with a radial velocity of 1 m/s is the main focus of the planned science. Two channels, one for the visible, another for the near-infrared, will allow observations in the complete wavelength range from 550 to 1700 nm. To ensure the stability, the instrument is working in vacuum in a thermally controlled environment.

The VIS channel spectrograph is covering the visible wavelength range from 0.55 to 0.95 µm with a spectral resolution of R=93,400 in a thermally and pressure-wise very stable environment.

The VIS channel spectrograph started science operation in January 2016. Here we present the opto-mechanical and system design of the channel with the focus on the (re-)integration phase at the observatory and the measured performance during the testing and commissioning periods, including the lessons learned.

Keywords: Instrumentation, spectrograph, échelle, optical fibres, visible, integration, commissioning, radial velocity, exoplanets, CARMENES

1. INTRODUCTION

The overall aim of the CARMENES (Calar Alto high-Resolution search for M dwarfs with Exo-earths with Near-infrared and optical Échelle Spectrographs; `http://carmenes.caha.es`) instrument is to perform high-precision measurements of stellar radial velocities with long-term stability. As most of the prospective exercises on exoplanet search have identified near-infrared as a key area for new development, the fundamental science objective is to carry out a survey of late-type main sequence stars with the goal of detecting low-mass planets. The precision of 1 m/s per measurement will permit to attain this goal.

CARMENES (Quirrenbach et al. 2010, 2012) consists of two channels to cover the complete wavelength range: a visible (VIS) part covering from 550 to 950 nm and a near-infrared (NIR) one working between 950 and 1700 nm. Each channel is a complete spectrograph in a thermally stabilized vacuum vessel at a pressure of about 10^{-5} mbar. The VIS spectrograph works at room temperature (~12°C), the NIR one at ~140 K. The thermal stabilization is within 0.01K. The

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spectrographs are placed in the Coudé room of the 3.5 m telescope at the Calar Alto Observatory, Almería, Spain (CAHA), with a fiber-link to the front-end at the telescope.

The optical design of the instrument is a grism cross-dispersed, white-pupil, Echelle spectrograph working in quasi-Littrow mode using a two-beam, two-slice, image slicer. The resolving power is 93400 per sampling element with a mean sampling of 2.5pixels. The design of the spectrographs is described in detail in Seifert et al., 2012. The optical design of the VIS channel spectrograph is shown in Fig. 1.

Two fibers are contained in each fiber head and fed to the spectrographs. Using a 100 µm fiber, the entrance aperture on sky is 1.5 arcsec. Non-circular (octagonal) fibers are used. This results an effective scrambling factor of 2000 with a high overall throughput.

The front-end of the instrument is attached to the Cassegrain focus of the Calar Alto 3.5m telescope. It includes a pick-up mirror, atmospheric dispersion corrector, dichroic beam-splitter, fiber heads for VIS and NIR and a guiding system. The front-end was installed at the telescope in April 2015 and had two pre-commissioning runs (still w/o the spectrographs) in April and June 2015.

	VIS
Wavelength range	550-1050 nm (53 orders)
Resolving power	$\lambda/\Delta\lambda = 93400$
Resolution element	2.5 pixels at the center of the detector (>2.2 pixels)
Inter-fibre spacing	7 pixels
Inter-order spacing	7 pixels (minimum)
Entrance aperture on sky	1.50 arcsec
Fibre input focal ratio	*f*/3.9
Fibre output focal ratio	*f*/3.5
Spectrograph beam size	154.8 mm
Off-axis collimator	*f*/10.274
Échelle grating	RGL-Newport 53B..174E mosaic, R4, 75.x deg, 31.6 grooves/mm, 154 mm x 596 mm
Cross-disperser grism	LF5 17.8 deg apex angle, 223 grooves/mm
Refractive camera	
f/#	*f*/2.94
Focal Length	455 mm
Detector	CCD EEV 231-84 4096 x 4096 pixels 15 µm/pix
Operating Temperature	285 K

Table 1. Overview of the system data for the VIS channels.

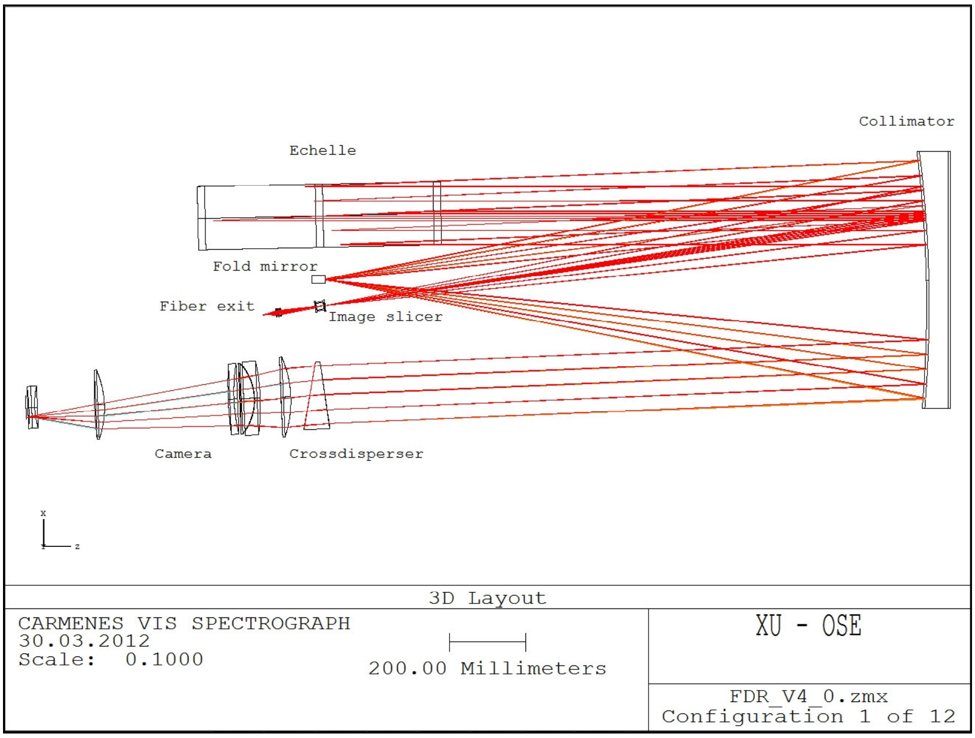

Figure 1.: Optical layout of the CARMENES spectrograph (VIS channel).

An optimized calibration unit for each channel is located in the Coudé room with a fiber link to the front-end. The basic calibration mode is taking wavelength calibration parallel to the on-sky object integration through the second fiber. For faint stars, the second fiber can be used for sky-background determination while calibrating during the day; this mode will only be used after the necessary instrument stability is proved.

The basic system data as built and measured are given in Table 1 and the optical layout is shown in Fig.1.

The schedule for the instrument has been driven by political factors and a so-called fast-track mode was put into place in order to reach a start of operation at January 1st, 2016 . This resulted in extremely compressed schedules for re-integration, technical and science commissioning without any contingency time.

The VIS channel of the instrument was shipped to CAHA in August 2015. The re-integration and system alignment have been performed in two periods during September 2015.

The first on-sky commissioning period – the so-called technical commissioning – was performed during October 2015. The science commissioning took then place from beginning of November to mid of December 2015. The instrument has started regular operation at January, 1st, 2016.

2. RE-INTEGRATION

The instrument was transported with all optical elements dismounted from the optical bench (OB). Due to the tight schedule, the OB met its radiation shield (RS) as well as the vacuum tank at CAHA for the first time. Therefore the first task has been to mount the RS on the OB support frame and to put all together into the vacuum tank (VT). This worked without flaw.

After extracting for the VT again and opening the upper part of the RS, the (re-)integration of the complete optics, opto-mechanics and the detector system have been started. This took place at CAHA in the special clean room tent provided for the instrument. See Figs.2, 3 and 4 for some impressions.

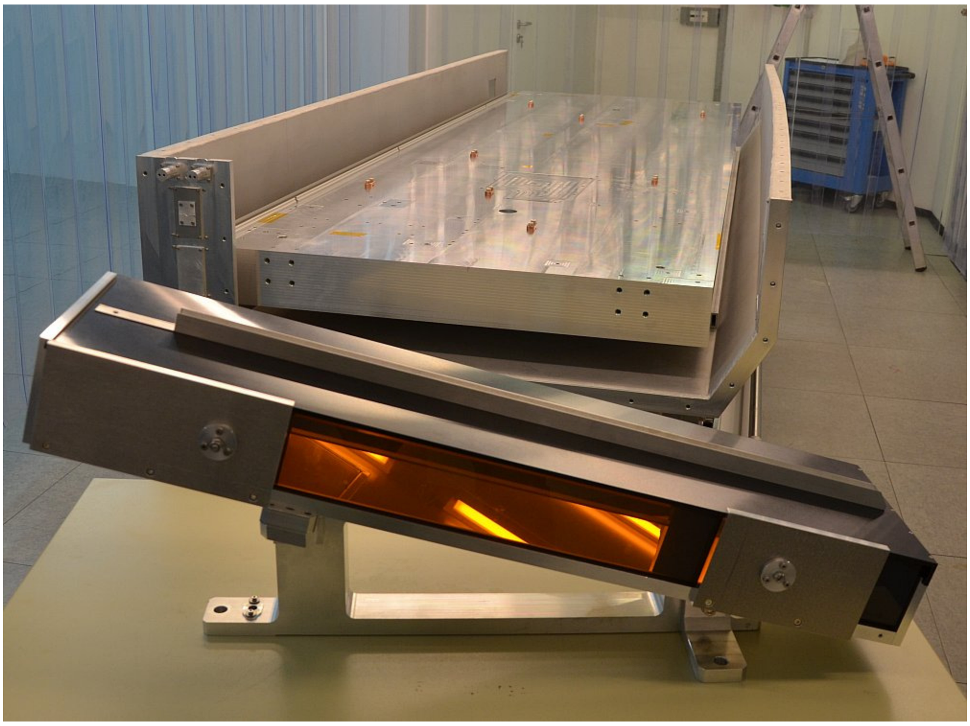

Figure 2.: OB installed in the lower part of the radiation shield, but still empty. In the front the Echelle mosaic with the top cover installed is visible.

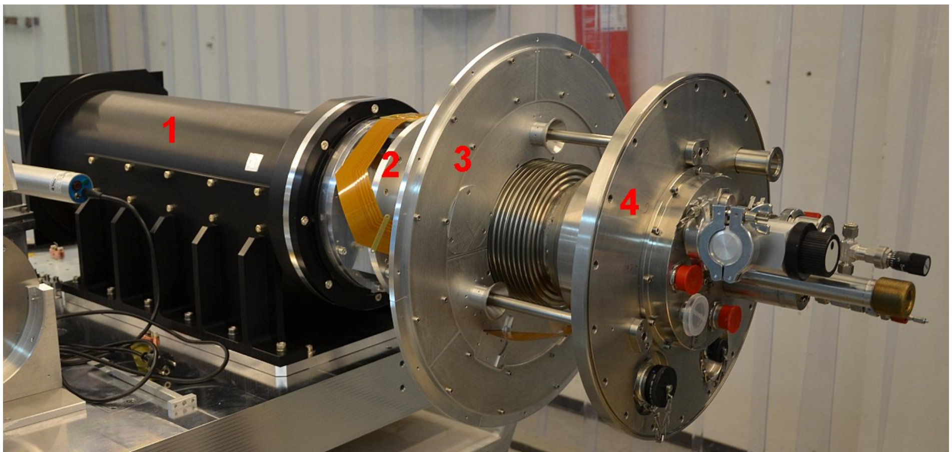

Figure 3.: Detail of the camera-detector-CFC; (1) Camera, (2) detector head, (3) radiation shield interface, (4) vacuum tank interface of the Continuous-Flow-Cryostat (CFC)

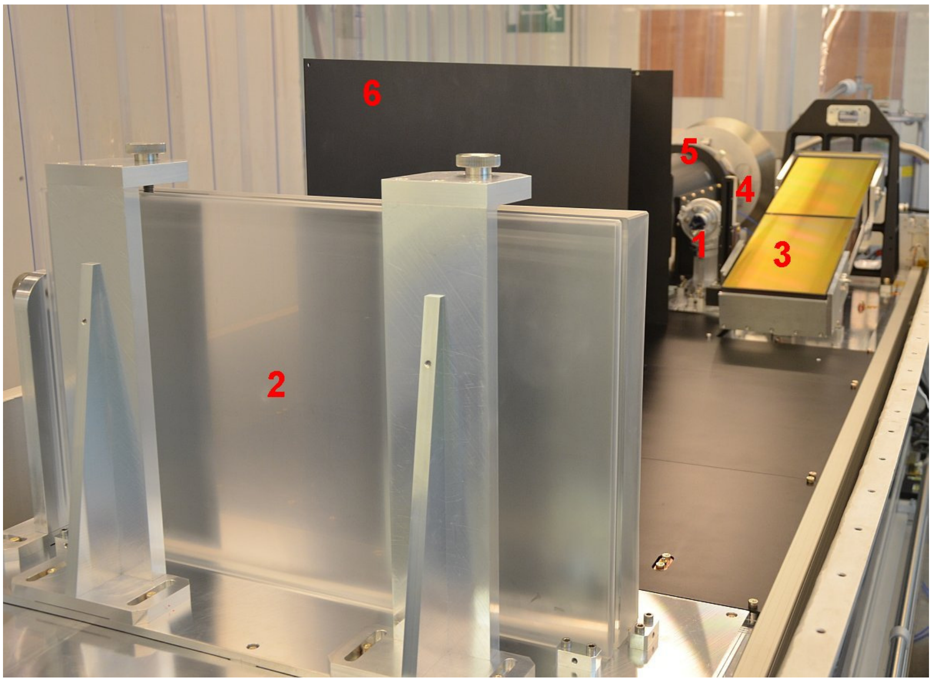

Figure 4.: The OB fully equipped. (1) Fiber Exit Unit, (2) Collimator, (3) Echelle mosaic, (4) Fold mirror, (5) Camera with detector head and continuous flow cryostat, (6) Baffles. Not visible is the cross-disperser grism in fornt of the camera (hidden by the baffles).

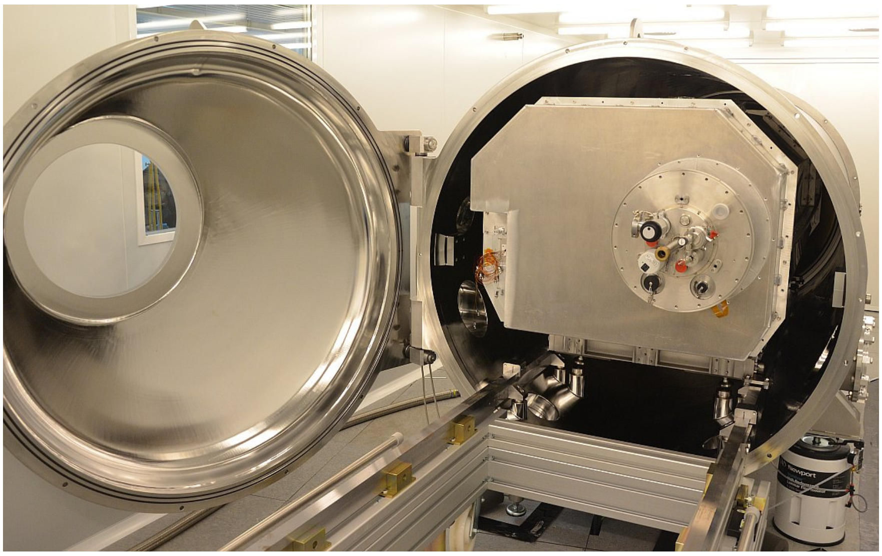

Figure 5.: OB and RS in the VT

The image slicer was found to be broken after the transport (see Fig.6): most likely, the sealing glue for the edges of the cover plates and prisms in optical contact was creeping into small edge chips due to the very high temperatures during transport. Now it turned out that the investment in a spare image slicer paid off: it could be installed instantaneously. After the alignment of the spare slicer with the fibers, the slicing quality was close to perfect as shown in Fig.7. The alignment of the complete system worked flawless for the opto-mechanics and the detector system. The first installation of the complete system into the VT showed that the interface plate between the detector continuous flow cryostat and the back door of the VT was not compatible (see Fig.4, item 4 and Fig.5): the screw pattern was different. With the help of the CAHA and IAA staff, this has been corrected within a day and the schedule could be kept.

After installation of the fibers and the connectors for the temperature sensors of the OB, the VT was closed and the system put into nominal operation conditions. The testing of the system performance using calibration lamps took place and showed that we are up and running for the first part of the on-sky commissioning.

Figure 6.: The image slicer broken after transport:. The dark surface had been treated with sealing paint which most probably caused the loss of optical contact due to high temperatures during transport..

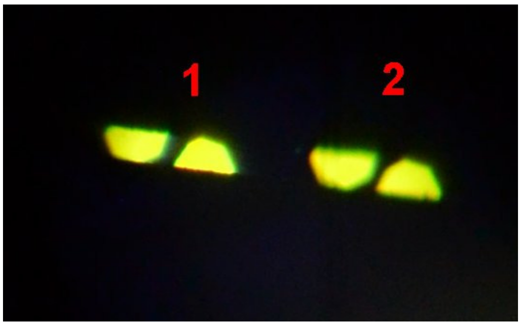

Figure 7.: The slices of the two fibers (1 and 2) with the spare image slicer. Note that the fibers used are of hexagonal shape.

3. COMMISSIONING

The technical commissioning period starting at the beginning of October 2015 was focused on the following main tasks:

- Ensure the proper functioning of the VIS channel in the telescope environment, including all hardware and software interfaces.
- Evaluation of the basic performance parameters such as spectral resolution, thermal stability, etc.
- Verification of the observation procedures including observation preparation and standard calibrations.

- Optimization of the VIS channel performance with regard to software adaptations and -if necessary- also hardware modifications. Re-evaluation of the VIS channel performance.
- Verification of the ADC in front-end adapter at the telescope

Thus this run needed night-time on-sky as well as day-time engineering support which was a significant effort. The major issues during this period have been:

- A broken resistor of the detector thermal stabilization system which was replaced even though the spare system worked well. This surely needed a warm-up of the detector system, opening the VT and dismounting the CCD head completely and was repaired.
- A much lower than expected flux on the exposure meter: for the grating we are using the 0th order efficiency is a least a factor 10 lower than assumed. This issue had no solution and implies that for the faintest program stars the VIS exposure meter is not working efficiently.
- The thermal coupling of the OB to the climatic room temperature is larger than simulated. The RV drifts shown in the next chapter are partly caused by this fact, but do not prevent us from reaching the RV precision required.

The science commissioning activities of the instrument took place between November 20, 2015, and December 23, 2015, with the goal of starting routine operations in January 1, 2016. The tight project schedule implied that these were carried out in parallel with the technical and scientific commissioning of the NIR channel. The tasks were defined to calibrate some operational parameters of the instrument and to check the performance under normal operating conditions, ensuring the fulfillment of the top level scientific requirements, and included:

- Measurement of the scrambling efficiency. Tests injecting light into different parts of the fibre showed that scrambling according to requirements was achieved.
- Definition of the calibration sequences. Hollow cathode lamps of ThNe, UAr, and UNe are used to define the baseline calibration. Simultaneous calibration with a Fabry-Perot etalon is employed during the integration.
- Definition of the FITS image keywords and contents.
- Accuracy and timing of the exposure meter. Tests showed that the timing accuracy requirement of 4 seconds (implying a change of 0.1 m s^{-1}) is met for targets brighter than 15.5 in the R band and therefore in agreement with the properties of the CARMENES sample. The task also included the determination of the relationship between exposure meter counts and resulting signal-to-noise ratio (SNR) of the spectrum. This is required for the nominal operation mode of the instrument, which is based on reaching a pre-set SNR value rather than on a specific integration time.
- Investigation of a potential systematic effect of SNR on radial velocity. No measurable effect was found, in part thanks to the design of the readout mode of the detector, which minimises the impact of charge transfer inefficiency (CTI).
- Science demonstration measurements. A selection of targets covering a wide spectral type range was observed intensively to monitor instrumental variations on all relevant timescales (minutes, hours, days).

4. PERFORMANCE

4.1 Spectral layout on detector

As given in Table 1, the wavelength range 0.55µm to 1.05µm separated into 53 orders is covered by the instrument by design. Due to the final decision on the dichroic cut on/off wavelength for the NIR channel, the actual red wavelength limit is 0.95µm.

A part of the 4k x 4k detector is shown in Fig.8. The object on-sky is the star β Cygni (Albireo), together with the individual lines of the ThNe calibration lamp. Fig.9 shows more detail with the two slices for both fibers (object and calibration) easily visible; for the simultaneous calibration, the Fabry-Perot etalon has been used.

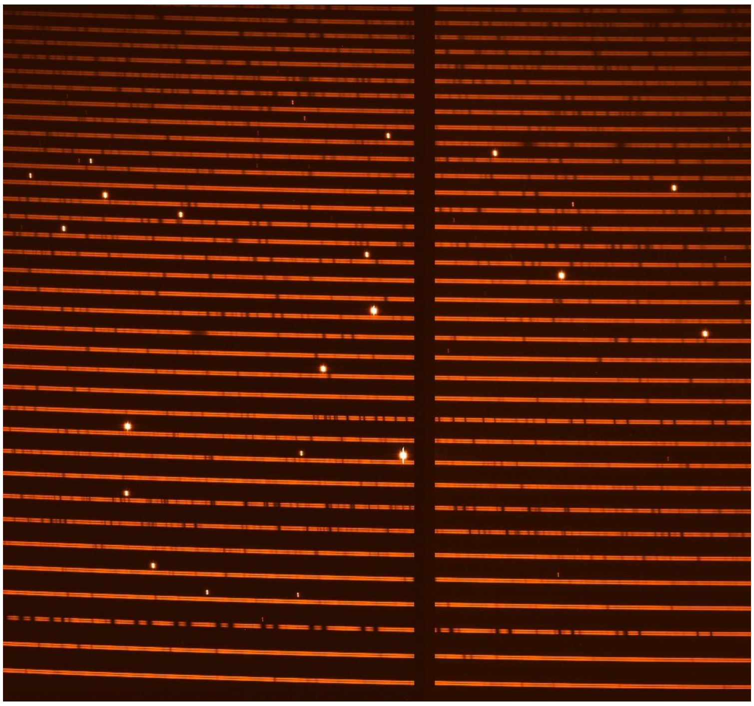

Figure 8.: Part of a spectrum of Albireo

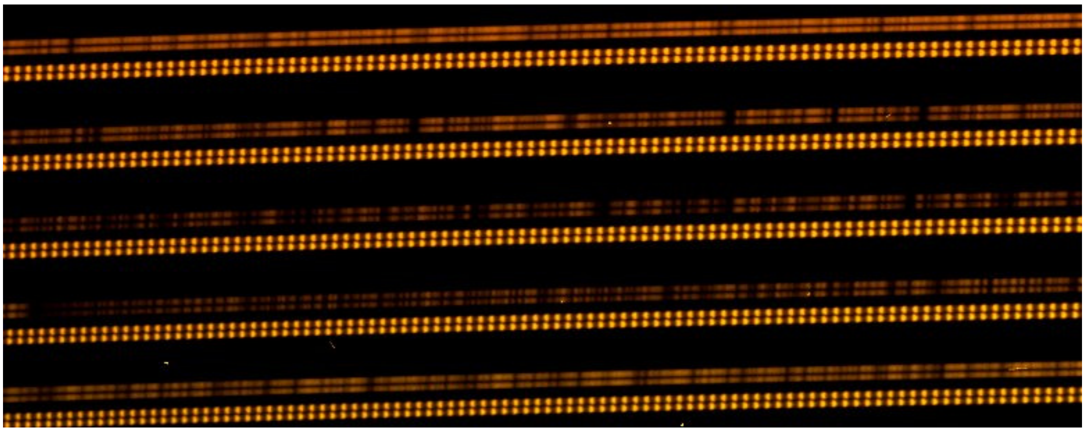

Figure 9.: Detail on a spectrum using the Fabry-Perot for simultaneous calibration; the separation into the two slices for each fiber is easily visible here.

4.2 Resolution, sampling

The resolution and sampling was measured using the calibration lamps over the full wavelength range. The results are shown in Fig.10.

The mean resolution is 93400, the mean sampling is 2.5pixels with a minimum sampling of 2.2pixels at the blue end of each order.

There is a slight discrepancy of requirements versus measurements: the requirements have been R>82000 for the resolution and a minimum sampling >2.35pixels. The discrepancy in resolution is mostly due to the Echelle angle being slightly different from the design value in order to optimize the total integrated efficiency by shifting the peak of the Blaze function on the detector. A detailed investigation of the effect of the reduced minimum sampling at the blue end on the systematic error is around 0.2m/s. As this value is significantly lower than the goal of 1m/s, it is acceptable.

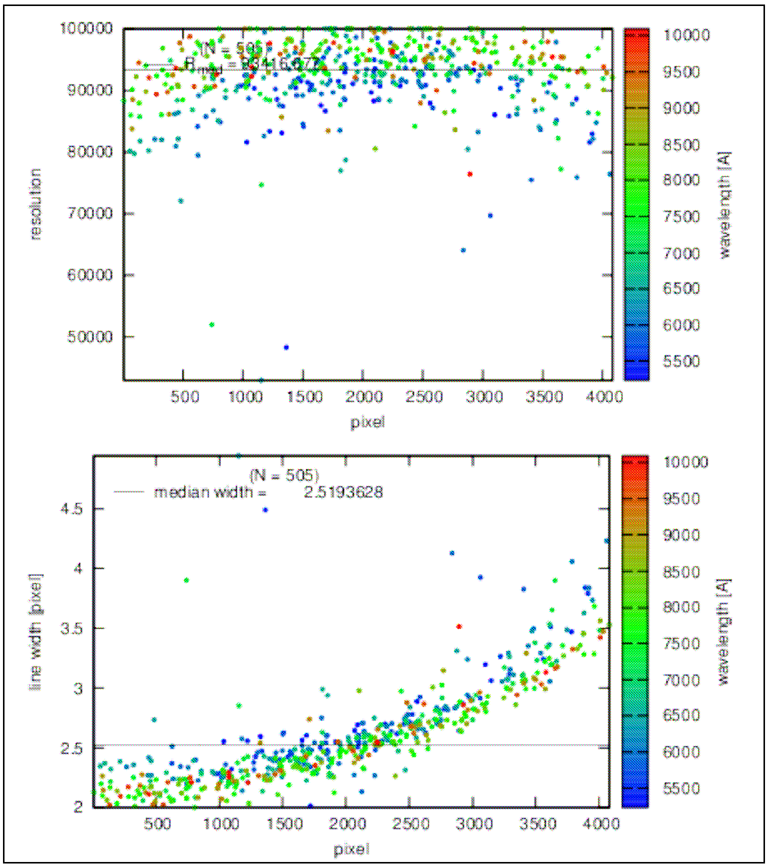

Figure 10.: Spectral resolution (top) and pixel sampling(bottom) as measured for the VIS channel spectrograph. X-axis is the position on the detector in the main dispersion direction (left blue, right red). Median resolution is 93400 over the full spectral range, median sampling is 2.5pix with a minimum of 2.2pix at the blue end

4.3 Throughput

The system throughput is another crucial number in order to characterize the system. During the commissioning phases there has been a continuous effort to measure the values, but were hampered most of the time by non-photometric conditions. In the end we could determine the throughput during the commissioning phases at 650nm and 850nm , the wavelength range which are most relevant for the CARMENES science program.

The values given here include the complete optical train from telescope through the front-end, fiber-feed and the spectrograph. The mean efficiency over the orders is given and the correction for the Blaze peak efficiency of the Echelle grating was taken into account. The system specification has been T>5.0%, the expected values have been calculated from the measured efficiency data of the various optical components. Note: the telescope mirrors will be re-aluminized during the time of this meeting and we assume the fresh coatings to increase the throughput by 0.3-0.7% to the expected values of 7.8% and 5.7% respectively.

Wavelength	Throughput Expected	Throughput Measured
650 nm	7.9%	7.2%
850 nm	5.7%	5.1%

Table 2.: Expected and measured mean efficiency values at 650nm and 850nm; the specification is T>5.0%

4.4 RV precision

The top-level requirement for CARMENES is surely the radial velocity precision of 1m/s to be reached. This was evaluated in detail during all commissioning phases and some results are shown. In Fig.11, the drift and final precision of the radial velocity over more than half a day are shown. The data have been taken during the commissioning phase after an intervention with the instrument not yet in full thermal stabilization and using the Fabry-Perot calibration on both fibers. The upper part of the plot shows the absolute drift, i.e. the drift of the spectrograph itself, which was still about 30m/s. The lower plot shows the relevant relative change in between the science and calibration fibers. The drift was less than ±1m/s during the measurement period with a rms value of 0.34m/s. Thus this early measurement already showed that we are reaching the requirement.

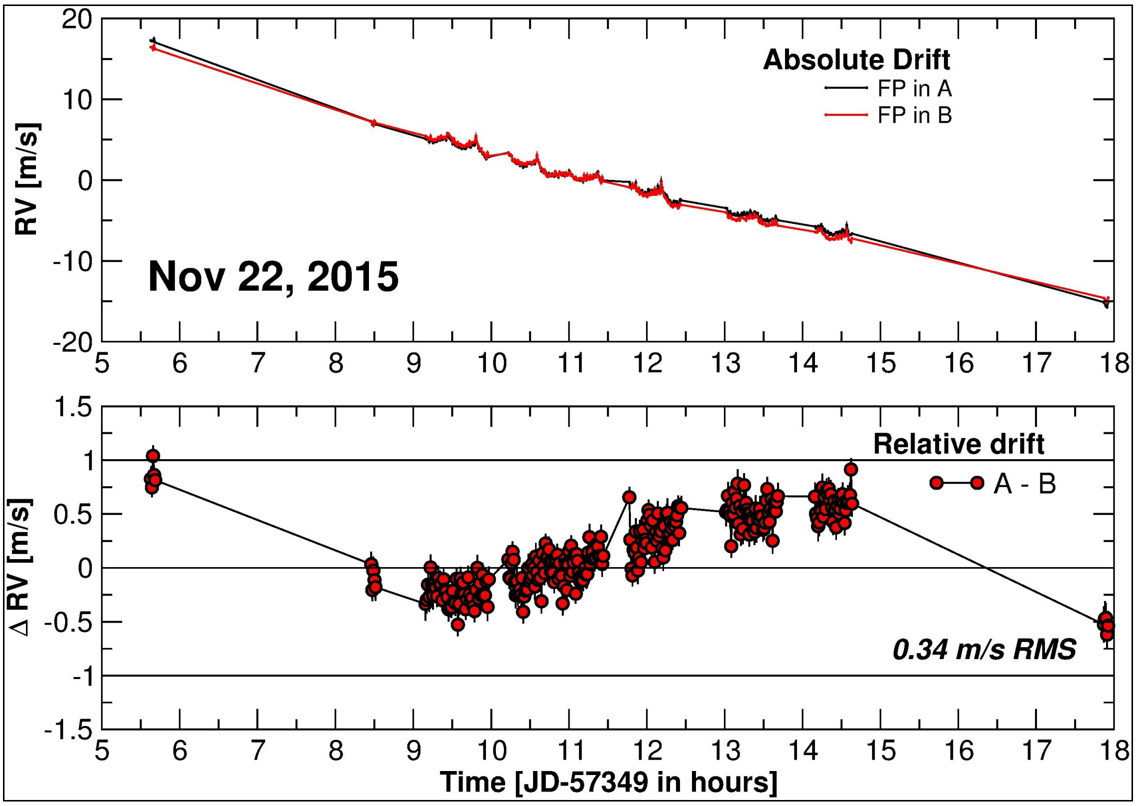

Figure 11.: Plot of the RV stability over half a day during the commissioning phase. Upper plot gives the absolute spectrograph drift, lower plot the relevant relative drift in between the fibers. See text for more details.

A recent stability and precision measurement is shown in Fig.12. Here is the relative drift shown over a period of 8hours. There is still a drift of <0.1m/s per hour present. The reason for this residual drift is under investigation. The rms deviation of the measured data from the drift fit is only 0.16m/s.

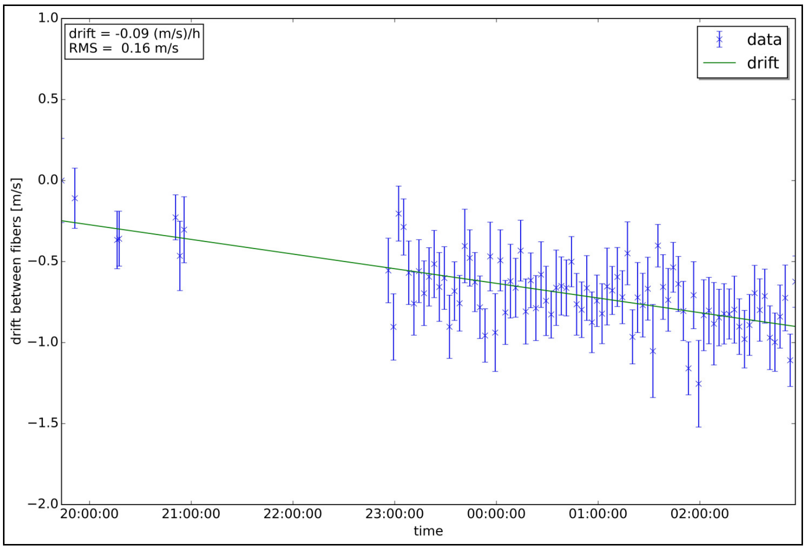

Figure 12.: RV stability, May 2016: the relative drift during 8 hours. The drift is <0.1m/s/h, the rms 0.16m/s.

4.5 Guiding accuracy

The guiding accuracy is an important number in order to evaluate the effects on scrambling and finally on the RV precision and any systematic effects introduced.. In Fig.13, the rms guiding accuracy for 1800 guided trackings all over the sky with a minimum time of 5min are plotted against the FWHM of the seeing during the observations. The mean value is 0.22arcsec with a slight increase for seeing values >3arcsec (Note: the on-sky fiber FoV is 1.5arcsec). Thus the reduction of scrambling factor by the guiding is negligible and systematic effects on the measured RVs are well below 1m/s.

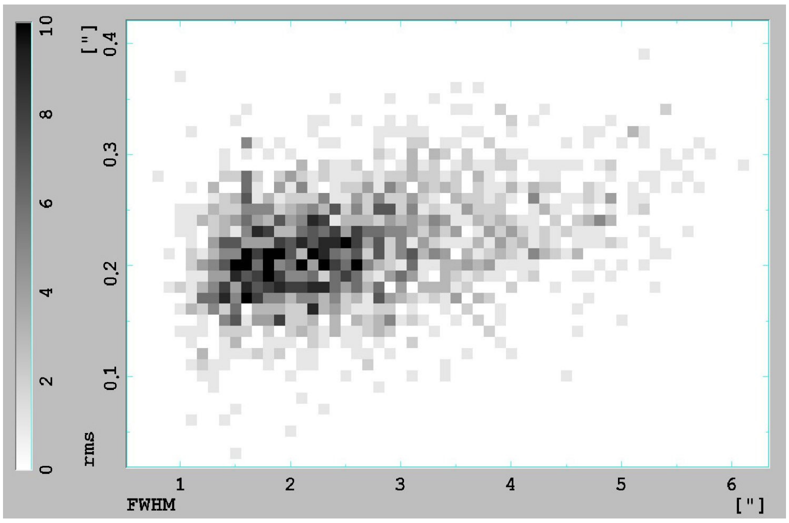

Figure 13.: Guiding accuracy histogram containing the data for 1800 trackings longer than 5min. The rms guiding values against the seeing are shown.

5. LESSONS LEARNED

5.1 Fast track

In spring 2015, the CARMENES management decided to proceed with the project in a fast track mode in order to meet the schedule requirement of starting science operation at January, 1st, 2016. As no additional manpower resources have been provided, this meant to skip quite some tasks of the lab testing and to compress the re-integration phase and especially the technical as well as the science commissioning phases by eliminating all contingency and even introduce negative contingency.

This resulted in sending the instrument to the observatory without finishing all typically needed characterizations and more severe, without the optical bench having met its radiation shield and the vacuum tank before. Even though the opto-mechanical re-integration worked in principle fine, small vacuum leaks and other issues related to detector cryostat and sorption pumps which could not have been tested before, required re-opening of the tank several times, even during the science commissioning phase.

The conclusion can only be that the potential saving of a few weeks by fast track had to be paid for by very significant additional effort and stress in the team during all phases of the instrument's re-integration and commissioning at the observatory. Quite several commissioning tasks have not been completed to 100%, just due to the lack of time. In the end CARMENES VIS channel started regular science operation in the given time frame, but the way to was far from smooth. Thus the well-known sentence of 'Never send a not completely tested instrument to the observatory' remains valid.

5.2 Image slicer damage

From many former instrument projects for ESO VLT, LBT and other large observatories, we have a lot of experience of packaging instrument components and especially optics in a proper and save way to prevent any transport damage and also never experienced any damage before. Nevertheless this time the most delicate optical part, the image slicer, broke as described above.

The lesson learned is to add significant additional thermal protection for parts connected by optical contact. Moreover the lacquer used for the sealing of the outer surface should be applied only in the minimum amount necessary and specified also for high temperatures up to 60°C.

5.3 Sampling/resolution prediction

As already mentioned before, we have a slight discrepancy of the minimum sampling value of 2.2pix versus the requirement of 2.35pix. The discrepancy came from the definition of the resolution element which was different in the real measurement from what's used in the design. In design the theoretical resolution element, i.e. the half fiber image size in spectral direction, was taken for the calculation of the sampling and resolution. In measurement the Gaussian FWHM is used. As the image quality of the CARMENES VIS channel is rather good, the FWHM is thus smaller than the blurred fiber image. This leads to the smaller sampling observed and higher resolution achieved.

For our next planned instruments like 4MOST and HIRES, much care is taken to define the resolution element in the instrument specifications in order to use identical evaluation method will be used for the design simulations and in later for the measurements.

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