The CARMENES pipeline

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Abstract

The CARMENES consortium constructs two high-resolution spectrographs (550–950 nm and 950–1700 nm) starting operation in 2015 at the 3.5 m telescope in Calar Alto (Spain). Designed for radial velocity precision of 1 m/s, CARMENES will target about 300 M dwarfs to search for low-mass exoplanets in the habitable zone. Our pipeline automatises the image processing and includes calibration, spectrum extraction and radial velocity computation aiming for the highest precision. It includes a simplified optimal extraction algorithm for stabilised spectrographs. Radial velocities are calculated with least square template matching. To evaluate the pipeline performance, we run end-to-end tests using forward simulated CARMENES spectra as well as real observations from HARPS. For both, we achieve a precision at the level 1 m/s. The precision might be further improved by combining emission lamp and Fabry Pérot etalon spectra to compute the wavelength solution.

CARMENES pipeline

The CARMENES pipeline will process the raw images of the calibrations and observations. It performs the standard reduction steps and creates master bias, master flat, non-linearity curves, order tracing, wavelength solution and instrument response from the calibration frames. Finally, barycentric RVs are computed [1].

The extraction pipeline builds up on the IDL REDUCE package [2]. We modified and complemented several routines, e.g.:

- file classification and trigger (automatisation)
- flat-relative optimal extraction (FOX [3], simple algorithm for stabilized spectrographs)
- stray light subtraction with 2D-*B*splines
- wavelength re-calibration

CARMENES simulation

We test the pipeline with the CARMENES spectrum forward simulator. It takes a 1D spectrum and performs a ray tracing with a simple physical spectrograph model. Read-out noise is added and photon noise is regulated by the numbers of traced rays.

Our **end-to-end simulations** include:

- forward simulation of raw échelle images
- full data reduction
- radial velocity computation.

Figure 1 shows a result of end-to-end simulations for 31 spectra (with input barycentric RVs from -30 to 30 km/s) for the visual channel of CARMENES (550–950 nm).

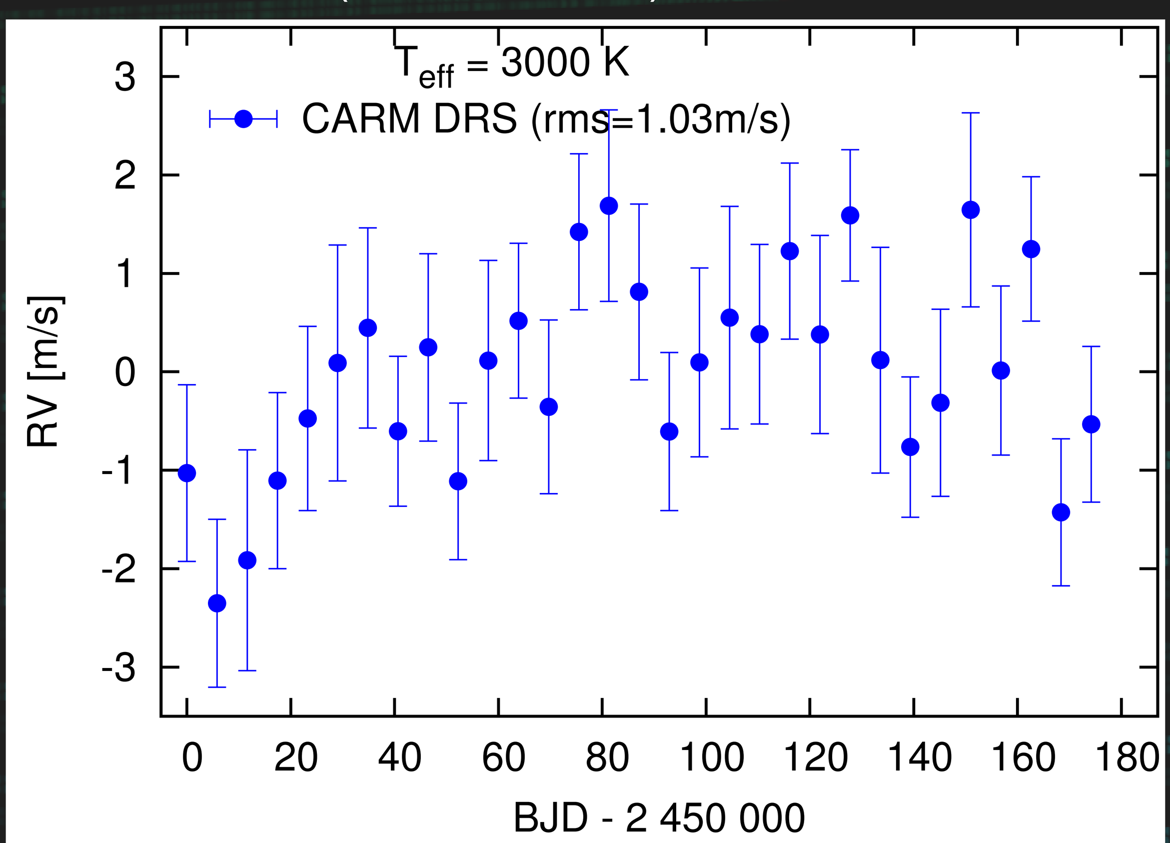

Fig. 1: *Radial velocities from a end-to-end simulation (VIS channel). The input was a PHOENIX spectrum ($T_{\rm eff}$ = 3000 K) with a SNR of 150 in J band.*

HARPS real data

We also test our pipeline with real HARPS data [4]. We used 263 spectra of the star Proxima Centauri (GJ 551, M5V) taken in 96 nights over 10 years.

We have reduced all available raw spectra and the associated nightly calibration files [5]. Our RVs have a dispersion of 3.3 m/s comparable to the results of the HARPS DRS pipeline (2.9 m/s, Fig. 2, [6]). The CARMENES wavelength calibration routine is yet not fully optimized (e.g. rejection of Argon lines).

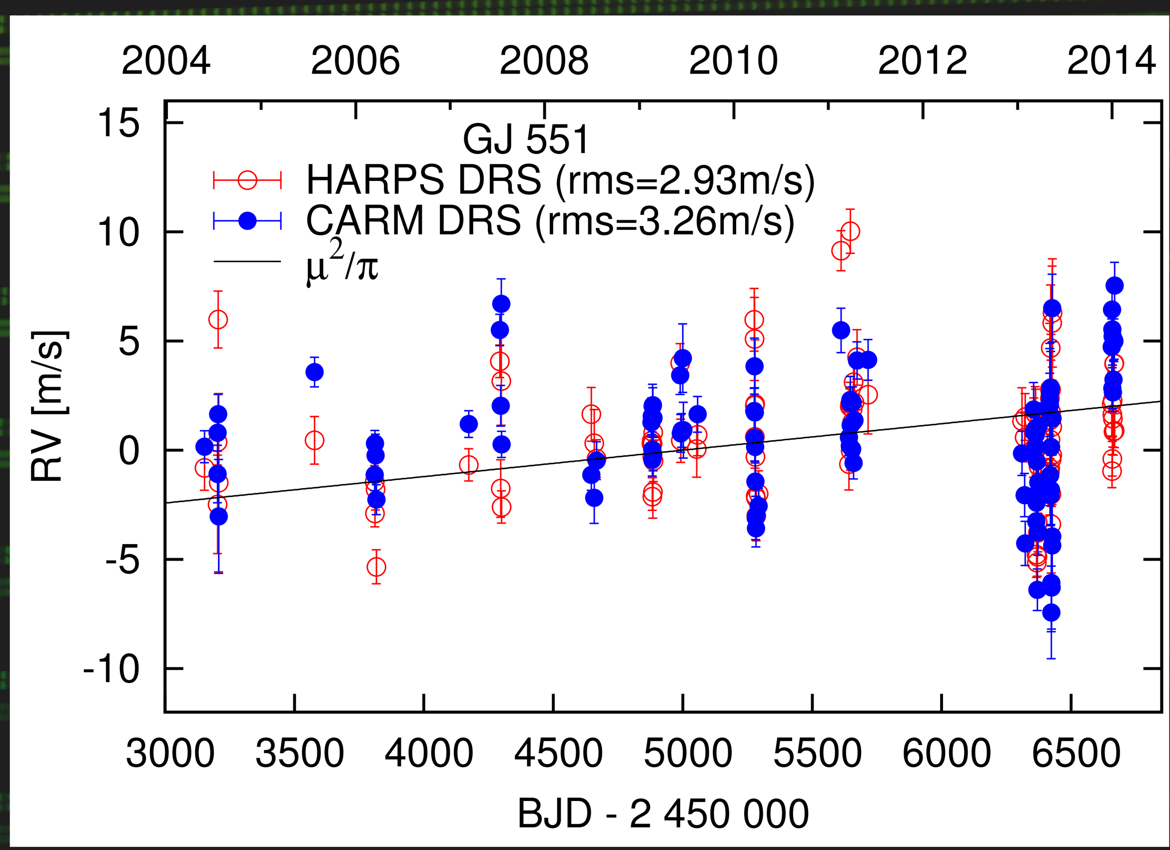

Fig. 2: *Radial velocities from HARPS spectra for Proxima Centauri from 96 nights.*

For data taken during one night, the CARMENES pipeline outperforms the HARPS DRS pipeline (Fig. 3), most likely due the RV computation via least square fit instead of cross-correlation [7]. The reproducibility of the (daily) wavelength solutions is less important in this case.

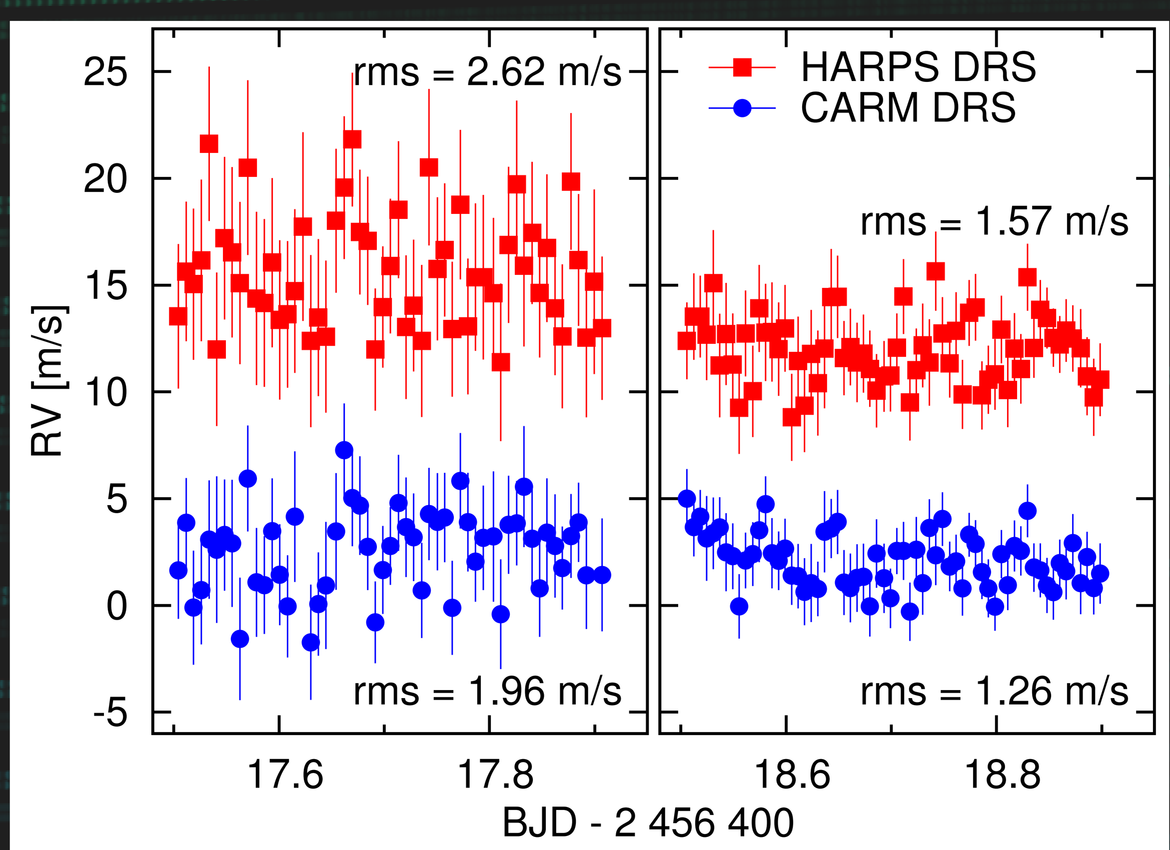

Fig. 3: *Comparison of two high cadence nights (2013-05-04 and 05-05) for GJ 551.*

Potential for further improvements

Optimum extraction, often used for spectrum extraction, assumes a 1D slit function, while in fact the PSF has a 2D shape. Therefore, sharp features have strong systematics in the residuals (Fig. 4) in the extraction and biased spectral estimates.

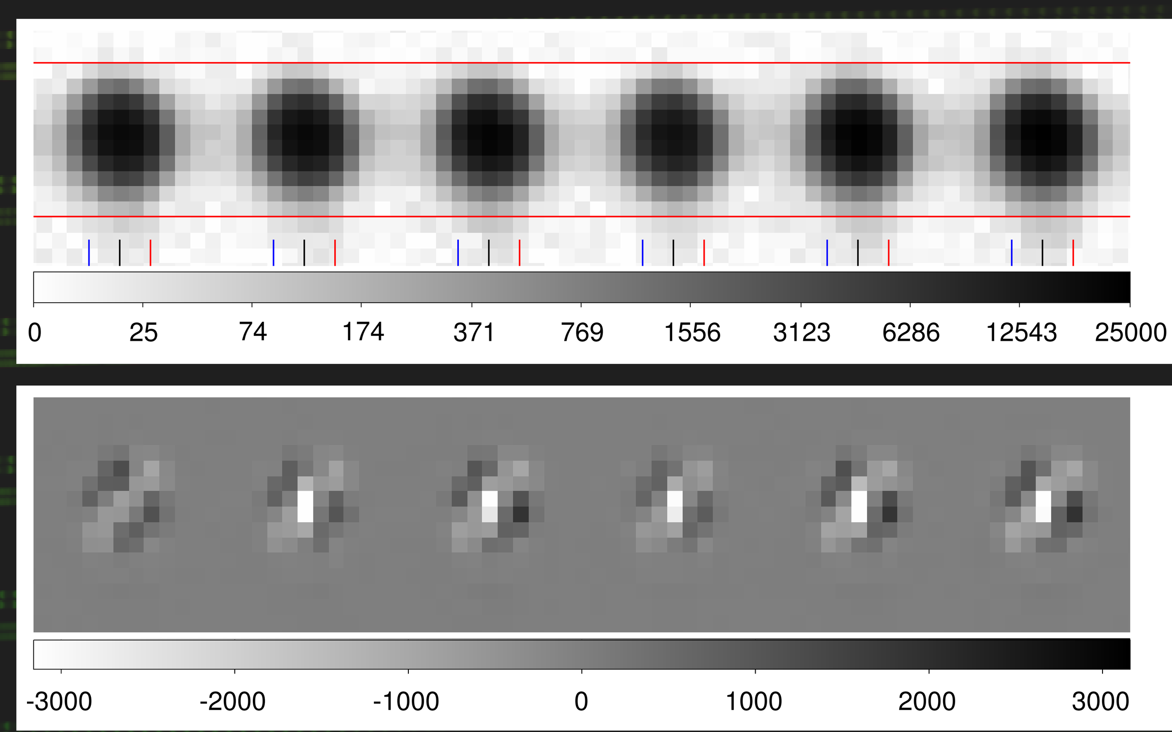

Fig. 4: *Section of a HARPS laser frequency spectrum (top, logarithmic intensity scale) and residuals after FOX extraction (bottom).*

The best solution to this general problem would be "perfect" extraction [8], but it is laborious and needs perfect calibration.

Summary

Our CARMENES pipeline:

- has arrived the 1 m/s precision in end-to-end simulation
- becomes competitive to the HARPS DRS pipeline
- needs optimization of the wavelength solution

To improve the precision, we will investigate new algorithms for the wavelength solution (e.g. by incorporating Fabry Pérot spectra, see poster by F. Bauer) and the feasibility of perfect extraction.

References

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