Southern African Large Telescope

Title: **MIDAS pipeline for HRS: the absolute accuracy of radial velocities**

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ABSTRACT

In this report I present a way to calculate radial velocities for HRS. An automatic procedure was developed to compute radial velocities of observed RV standards via Fourier cross correlation with model spectra of stars. In all studied HRS modes (Blue and Red arms for LR, MR and HR) the **absolute** *accuracy of HRS data is better than* **300 m/s**.

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1 Introduction

Study of HRS stability is very important for understanding the limits which have to be taken into account for any science PIs are going to do with this instrument. I have attempted to investigate the absolute accuracy for the Low Resolution (LR), Medium Resolution (MR) and High Resolution (HR) modes of HRS, studying the velocity standards data, taken with HRS during one month in 2016. The results of this work are presented in this report.

2 Short description of the procedure

I wrote a special MIDAS procedure, which uniformly calculates velocity in the same manner for all obtained velocity standards (RV hereafter) in LR to HR modes. I added this procedure as the standard step for the MIDAS pipeline of HRS data and it will calculate velocities for EACH RV standard taken with HRS. This procedure uses the following data:

- HRS data reduced with the MIDAS pipeline using the nearest (in time) flats and reference arc spectra.
- A stellar template for the cross correlation. For this work I used a model spectrum of a G5V star of solar metallicity given with R=20000. For the time being, the same resolution was used for all HRS modes, which is very close to LR mode (R=16000) and unfortunately not optimised for MR and HR modes.

This procedure consist of the following steps:

- Both the reduced spectrum of the RV standard and the model spectrum are normalised.
- Radial velocities are computed via Fourier cross correlation of reduced spectra of RV standards with model spectrum of the template star.
- The velocity is calculated independently for each echelle order.
- The heliocentric correction is calculated using standard MIDAS task based on Stumpff (2010) and the value is added to the FITS header.
- The final table with calculated velocities for each echelle order and their errors is analyzed to reject bad orders (for example, red arm orders with strong telluric lines). The final velocity and its error is calculated as a weighted average and added to the FITS header.

Some examples of such analysis for different HRS modes and arms are shown in Figures 1–6.

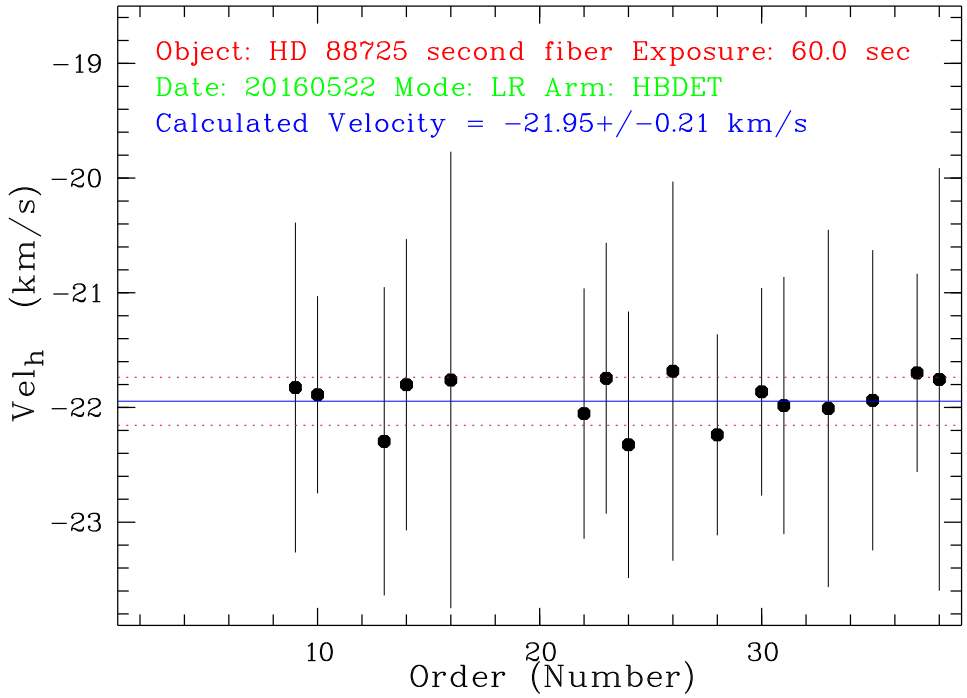

Figure 1: LR Blue arm data. Calculated velocity for each order is shown with black dots. 1σ errors are shown with bars. The final found velocity is shown with blue line. Red dotted lines show 1σ error.

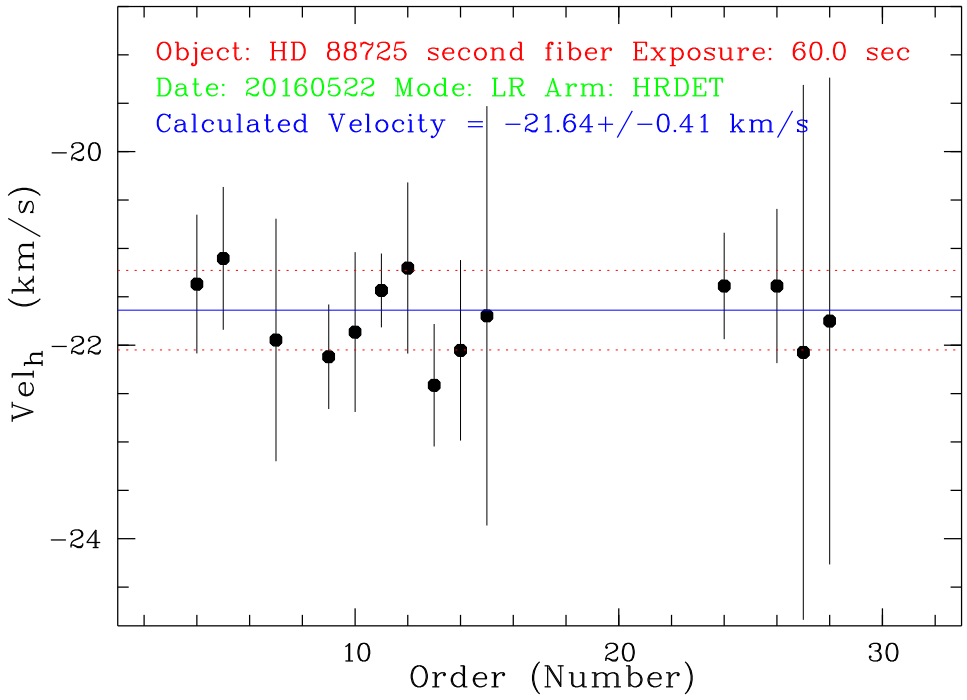

Figure 2: LR Red arm data. The figure caption is same as for Figure 1.

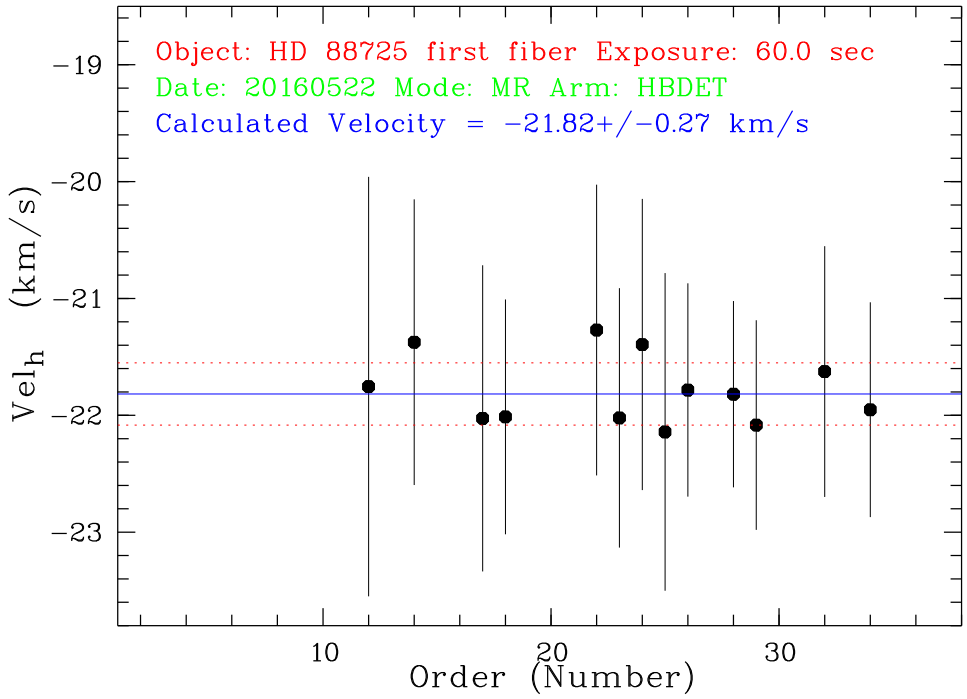

Figure 3: MR Blue arm data. The figure caption is same as for Figure 1.

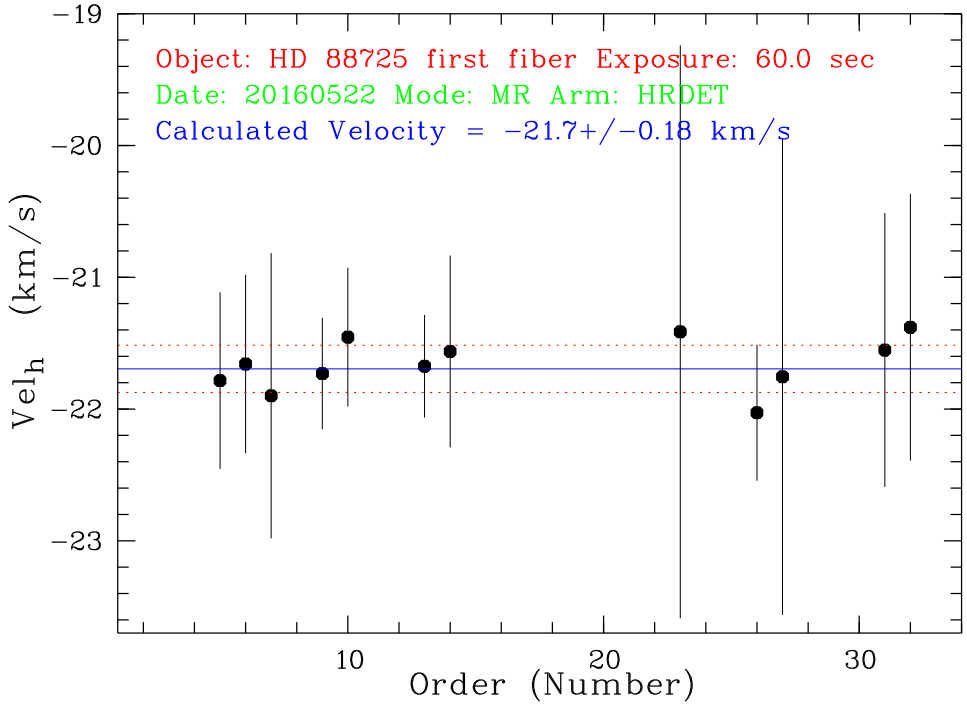

Figure 4: MR Red arm data. The figure caption is same as for Figure 1.

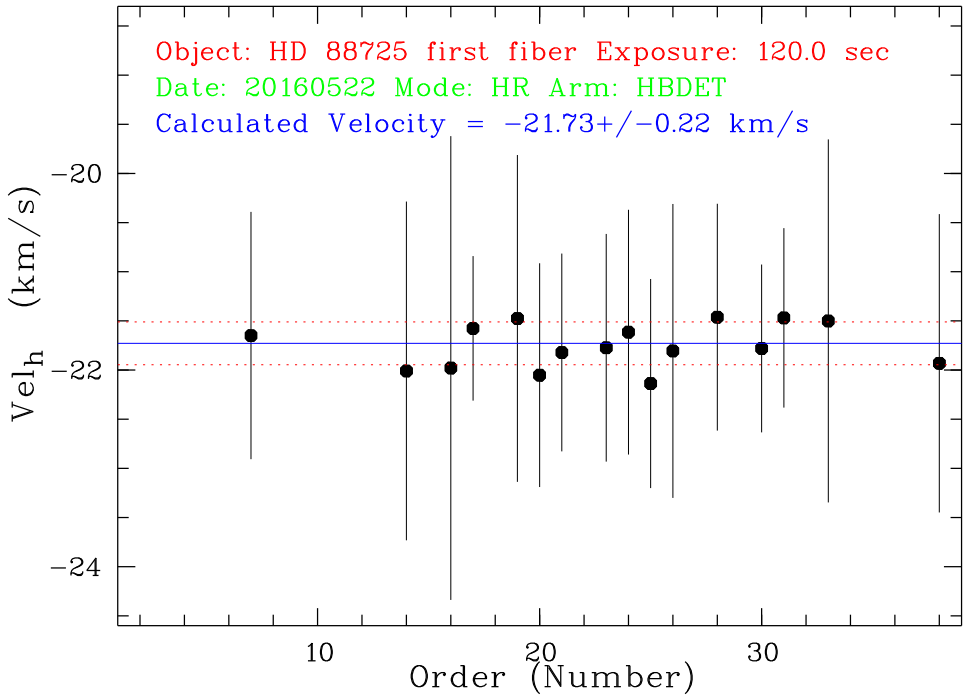

Figure 5: HR Blue arm data. The figure caption is same as for Figure 1.

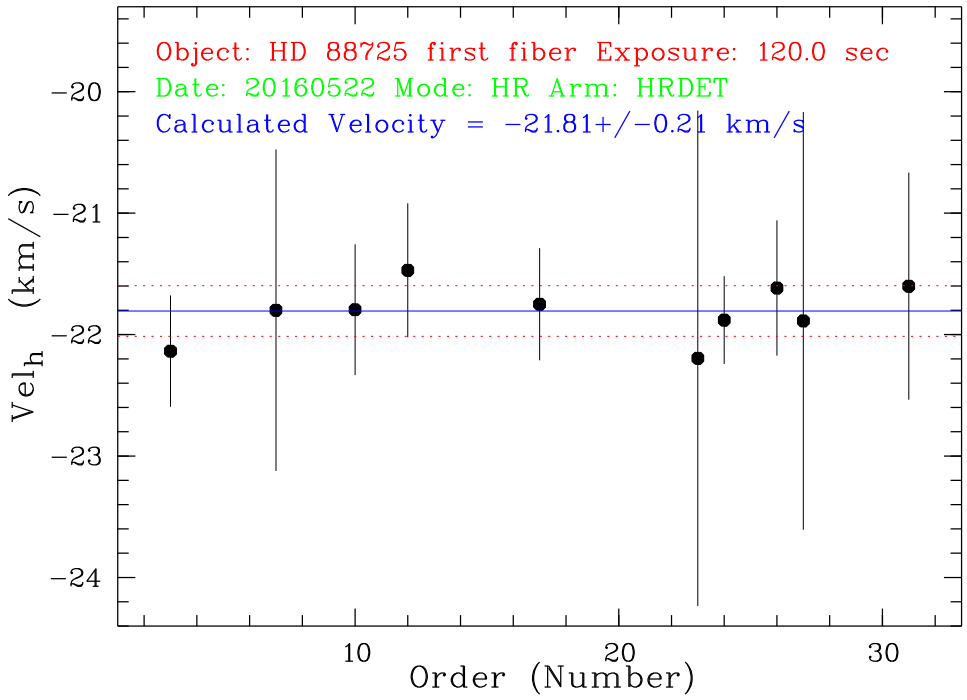

Figure 6: HR Red arm data. The figure caption is same as for Figure 1.

3 Results for Low resolution mode

All calculated velocities for the RV standards observed during March 2016 in LR mode are presented in Table 1. This table shows the following information: (1) Name of star; (2) Date of observation; (3) HRS Arm; (4) Date of arc observation; (5) Heliocentric radial velocity and its error from SIMBAD; (6) Signal-to-Noise ratio for Hβ (Blue arm) and Hα (Red arm) regions; (7) Calculated heliocentric radial velocity and its error.

The comparison of measured velocities with their catalogue values is shown in Figure 7. The top panel shows the difference between the catalogue velocities and measured velocities from the Blue arm HRS spectra. The middle panel shows the difference between the catalogue velocities and measured velocities from the Red arm HRS spectra. The bottom panel shows the same but for the total Blue+Red arm spectra.

Data for each spectrum are shown with blue dots and their $\pm1\sigma$ errors are shown with vertical bars. The calculated average value for the total sample is shown with horizontal red long dash line and $\pm1\sigma$ errors for the total sample are shown with red dotted lines. Vertical magenta dash-dot lines show important specific *events* which in my view affect results, and are described below. These events are also marked in Table 1 with additional comments.

The story starts from 20160303 date, where calibrations were done on 20160226. Blue arm spectra show very small differences, 70±135 m/s and 112±146 m/s. At the same time the Red arm 2D-spectra had problems with electronics, due to which the 2D Red arm spectra for 20160303 had to be rejected. Regardless, the HRS MIDAS pipeline plus cross-correlation gives the possibility to calculate velocities, but the errors for these values are much larger compared to the Blue arm – 487 m/s and 458 m/s respectively for 20160303 and 20160304 dates.

The first vertical magenta line shows the date where HRS started to have some problems and both its CCD dewars were baked and cooled down. The process was finished before 20160311 night, **but no new flats and arcs were done for LR mode** and reduction of these observations was done with flats and arcs taken on 20160226. This immediately results in the *jump* of measured velocities up to 3 km/s for the Blue arm and $\sim$ 600 m/s for the Red arm on 20160311 and 20160312. These two dates were not taken into account in the calculation of the average values of the total sample.

New LR calibrations were done on 20160315, but for whatever reason the intensity of arcs was much lower than normally. For example, only $\sim$ 200 emission lines where found in the 33 orders of the Red arm reference spectrum compared to the usual $\sim$ 400 lines. As result, the accuracy of the fit decreased to $\sim$ 0.01 Å and it results in systematic shifts for both Blue arm spectra (mean=-353 ± 37 m/s) and Red arm spectra (mean=282 ± 296 m/s) with larger errors for the Red arm spectra up to $\sim$ 600 m/s.

Finally, "normal" LR calibrations were done on 20160321, where fit accuracy returns to $\sim$ 0.007 Å and comparison of velocities shows average accuracy $\langle\delta\rangle = 58 \pm 71$ m/s for the Blue arm LR spectra and $\langle\delta\rangle = 37 \pm 53$ m/s for the Red arm LR spectra, where each observation has an average error 161 m/s for the Blue arm and 177 m/s for the Red arm.

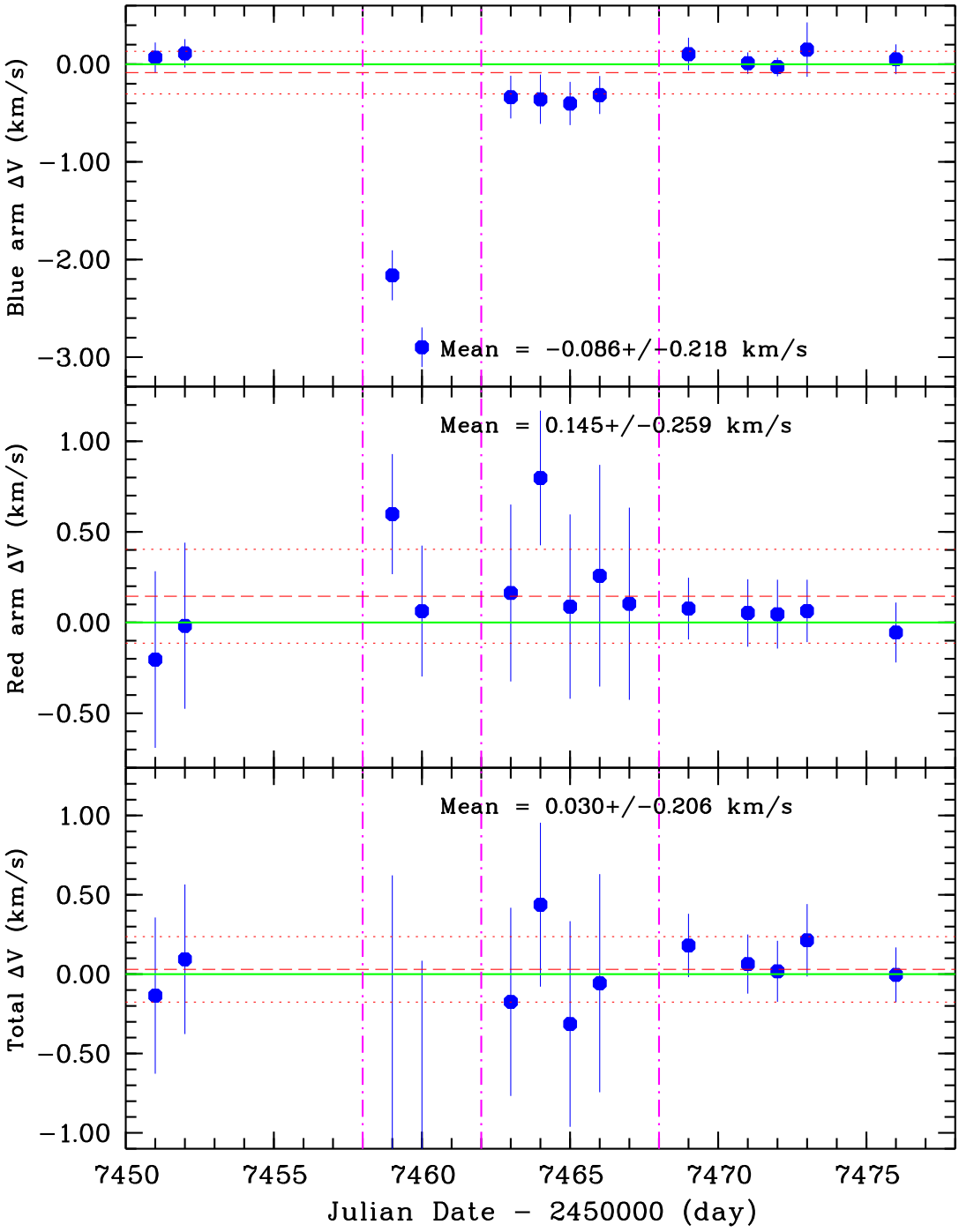

Figure 7: Velocities for RV standards obtained with LR mode. All explanation are given in the text of Section 3.

4 Results for Medium resolution mode

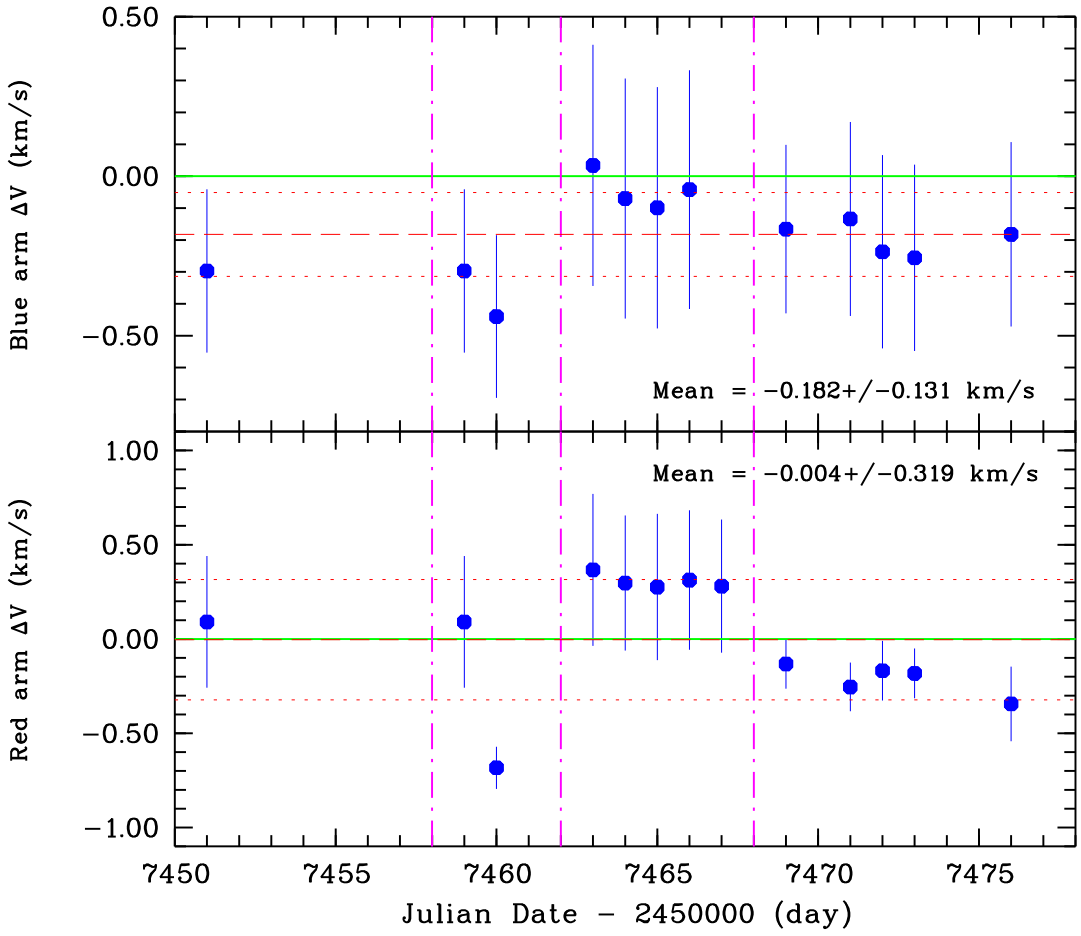

Figure 8: Velocities for RV standards obtained with MR mode. All explanation are given in the text of Section 4.

All calculated velocities for the RV standards observed during March 2016 in MR mode are presented in Table 2. This table shows the same information as in Table 1.

The comparison of measured velocities with their catalogue values is shown in Figure 8. The top panel shows the difference between the catalogue velocities and measured velocities from the Blue arm HRS spectra. The bottom panel shows the difference between the catalogue velocities and measured velocities from the red arm HRS spectra.

The history of the sequence is the same as it was described for the LR mode in Section 3 with the only exception being that after the CCD dewars were baked and cooled down, the calibrations for MR mode were done at the beginning of the night 20160311 marked by the first magenta line. Unfortunately, even with these new calibrations we have some systematic

shifts which are very hard to describe. Could it be that system is still "breathing" some more nights? We need more systematic study to answer this question.

Anyway, even after the "correct" calibrations on 20160321, marked with the third vertical magenta line, our measurements show systematic shift $\langle\delta\rangle = -195 \pm 50$ m/s for the Blue arm and $\langle\delta\rangle = -216 \pm 84$ m/s for the Red arm data, where each observation has an average error 290 m/s for the Blue arm and 150 m/s for the Red arm.

I can suggest two possible sources of these systematic shifts and larger errors compared to LR mode. First, the wavelength calibration for LR mode was done using a global bivariate polynomial only, because generally the mode has fewer good arc lines. For the MR and HR modes, the final solutions were computed for each independent order after the global bivariate polynomial was done. Could it add some systematics? Second, the model with R=20000 was used for cross-correlation with all HRS modes. It is optimal for LR mode (R=15000–16000), but is not so optimal for MR (R=40000–43000) and far from optimal for HR (R=67000–74000). More work needs to be done to decrease errors in MR mode.

5 Results for High resolution mode

All calculated velocities for the RV standards observed during March 2016 in HR mode are presented in Table 3. This table shows the same information as in Table 1.

The comparison of measured velocities with their catalogue values is shown in Figure 9. The top panel shows the difference between the catalogue velocities and measured velocities from the Blue arm HRS spectra. The bottom panel shows the difference between the catalogue velocities and measured velocities from the red arm HRS spectra.

All history is absolutely the same as was described for the LR mode in Section 3 and only the last five measurements could be counted as "normal" ones.

After the "correct" calibrations on 20160321, marked with the third vertical magenta line, measurements for HR mode show systematic shift $\langle\delta\rangle = -323 \pm 71$ m/s for the Blue arm, but no any systematic $\langle\delta\rangle = 113 \pm 130$ m/s for the Red arm data, where each observation has an average error 195 m/s for the Blue arm and 149 m/s for the Red arm.

I can suggest the same possible sources of this systematic error and larger errors compared to LR mode as explained in Section 4. More work needs to be done to decrease errors in HR mode.

6 Conclusions

I have studied the absolute accuracy of HRS data in determination of velocities and tried to study HRS stability. This work results in the following conclusions:

1. In **all** studied HRS modes (LR, MR and HR) the **absolute** accuracy of HRS data is better than **300 m/s**, if **proper** calibrations were done.

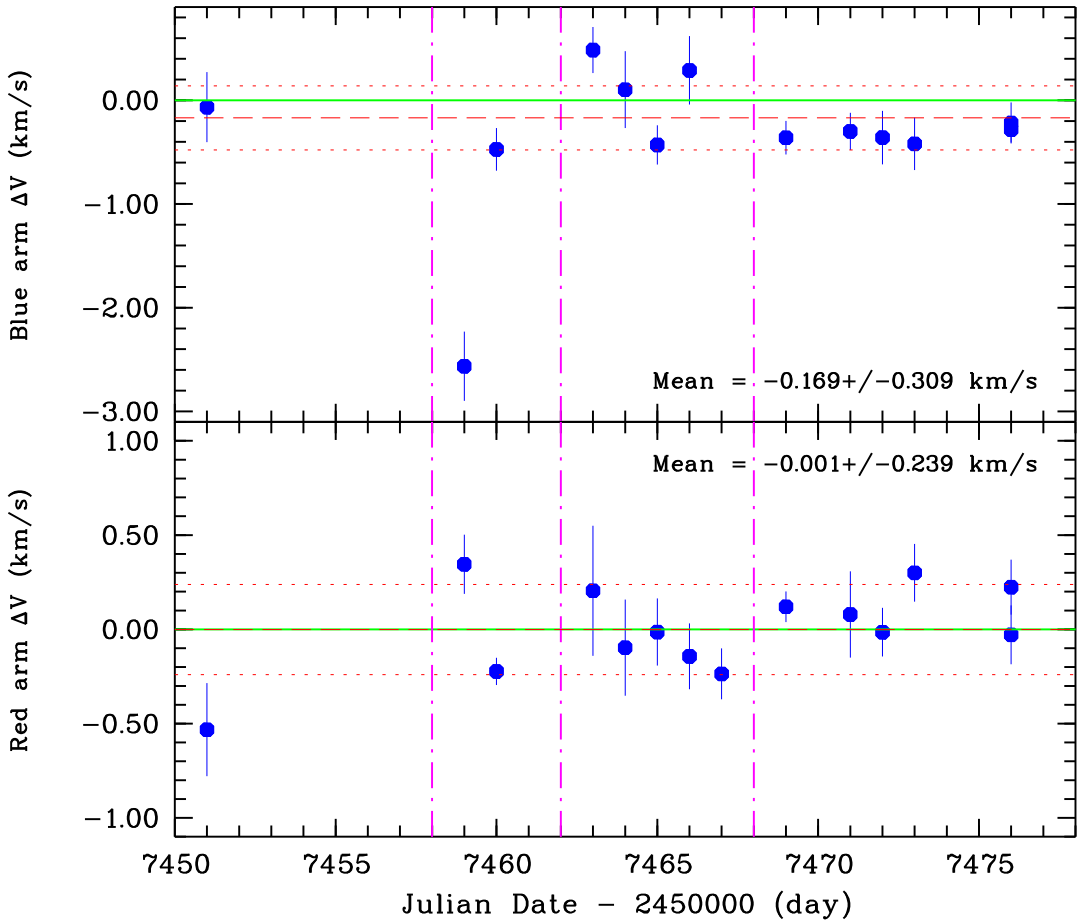

Figure 9: Velocities for RV standards obtained with HR mode. All explanation are given in the text of Section 5.

2. New HRS calibrations **must be done immediately** after any technical break or intervention of the instrument, e.g. when CCD dewars are baked and cooled down.

3. Any newly taken HRS calibrations **must be checked and verified** immediately or at the latest during the following day (cf. data quality monitoring).

4. I recommend that RV standards must be observed as minimum once per week to check HRS stability.

5. With my method of velocity determination I did not find any hints suggesting that Astro Ops should produce HRS calibrations more often than once per week. Of course, I am not able to reject the possibility that any systematics exist at higher levels of accuracy, but to detect those, the HRS community needs to develop new methods, or to polish the current one.

Table 1: The results for LR HRS mode

#	Star	Night	Arm	Arc.Night	V_h^c	SNR	V_h
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
1	HD 42618	20160303	Blue	20160226	-53.440±0.0021	130	-53.509±0.154
1		20160303	Red	20160226	-53.440±0.0021	60	-53.236±0.487[a]
1	HD 42618	20160304	Blue	20160226	-53.440±0.0021	140	-53.552±0.146
1		20160304	Red	20160226	-53.440±0.0021	60	-53.422±0.458[a]
1	HD 42618	20160311	Blue	20160226	-53.440±0.0021	100	-51.278±0.256[b]
1		20160311	Red	20160226	-53.440±0.0021	140	-54.038±0.331[b]
1	HD 42618	20160312	Blue	20160226	-53.440±0.0021	260	-50.542±0.202[b]
1		20160312	Red	20160226	-53.440±0.0021	320	-53.503±0.361[b]
1	HD 42618	20160315	Blue	20160315	-53.440±0.0021	140	-53.103±0.219[c]
1		20160315	Red	20160315	-53.440±0.0021	180	-53.603±0.488[c]
1	HD 42618	20160316	Blue	20160315	-53.440±0.0021	300	-53.081±0.252[c]
1		20160316	Red	20160315	-53.440±0.0021	360	-54.237±0.371[c]
1	HD 42618	20160317	Blue	20160315	-53.440±0.0021	300	-53.038±0.221[c]
1		20160317	Red	20160315	-53.440±0.0021	380	-53.528±0.508[c]
1	HD 42618	20160318	Blue	20160315	-53.440±0.0021	280	-53.125±0.195[c]
1		20160318	Red	20160315	-53.440±0.0021	360	-53.698±0.611[c]
1	HD 42618	20160319	Blue	20160315	-53.440±0.0021	—	—
1		20160319	Red	20160315	-53.440±0.0021	340	-53.544±0.530[c]
1	HD 42618	20160321	Blue	20160321	-53.440±0.0021	240	-53.544±0.168
1		20160321	Red	20160321	-53.440±0.0021	300	-53.517±0.170
1	HD 42618	20160323	Blue	20160321	-53.440±0.0021	200	-53.451±0.111
1		20160323	Red	20160321	-53.440±0.0021	260	-53.493±0.186
1	HD 42618	20160324	Blue	20160321	-53.440±0.0021	200	-53.412±0.095
1		20160324	Red	20160321	-53.440±0.0021	260	-53.486±0.190
1	HD 42618	20160325	Blue	20160321	-53.440±0.0021	250	-53.590±0.278
1		20160325	Red	20160321	-53.440±0.0021	300	-53.504±0.172
1	HD 42618	20160328	Blue	20160321	-53.440±0.0021	300	-53.491±0.152
1		20160328	Red	20160321	-53.440±0.0021	380	-53.385±0.165
2	HD 88725	20160522	Blue	20160513	-21.976±0.0012	105	-21.946±0.209
2		20160522	Red	20160513	-21.976±0.0012	120	-21.638±0.411

[a] - Red image have problems with electronics.

[b] - HRS was stopped. Both red and blue dewars were baked and cooled down. The process was finished before 20160311 night, but no new flats and arcs were done for LR.

[c] - New arc were done on 20160315, but reference spectrum is very weak.

Table 2: The results for MR HRS mode

#	Star	Night	Arm	Arc.Night	V_h^c	SNR	V_h
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
1	HD 42618	20160303	Blue	20160226	-53.440±0.0021	140	-53.143±0.256
1		20160303	Red	20160226	-53.440±0.0021	180-	-53.531±0.349
1	HD 42618	20160311	Blue	20160311	-53.440±0.0021	110	-53.143±0.256
1		20160311	Red	20160311	-53.440±0.0021	140	-53.531±0.349
1	HD 42618	20160312	Blue	20160311	-53.440±0.0021	200	-53.000±0.255
1		20160312	Red	20160311	-53.440±0.0021	260	-52.757±0.112
1	HD 42618	20160315	Blue	20160315	-53.440±0.0021	90	-53.474±0.378[b]
1		20160315	Red	20160315	-53.440±0.0021	130	-53.807±0.403[b]
1	HD 42618	20160316	Blue	20160315	-53.440±0.0021	230	-53.370±0.376[b]
1		20160316	Red	20160315	-53.440±0.0021	300	-53.737±0.358[b]
1	HD 42618	20160317	Blue	20160315	-53.440±0.0021	240	-53.341±0.378[b]
1		20160317	Red	20160315	-53.440±0.0021	300	-53.716±0.388[b]
1	HD 42618	20160318	Blue	20160315	-53.440±0.0021	190	-53.398±0.374[b]
1		20160318	Red	20160315	-53.440±0.0021	240	-53.753±0.370[b]
1	HD 42618	20160319	Blue	20160315	-53.440±0.0021	—	—
1		20160319	Red	20160315	-53.440±0.0021	250	-53.721±0.353[b]
1	HD 42618	20160321	Blue	20160321	-53.440±0.0021	190	-53.274±0.264
1		20160321	Red	20160321	-53.440±0.0021	250	-53.308±0.131
1	HD 42618	20160323	Blue	20160321	-53.440±0.0021	120	-53.306±0.304
1		20160323	Red	20160321	-53.440±0.0021	160	-53.186±0.129
1	HD 42618	20160324	Blue	20160321	-53.440±0.0021	130	-53.203±0.303
1		20160324	Red	20160321	-53.440±0.0021	180	-53.272±0.158
1	HD 42618	20160325	Blue	20160321	-53.440±0.0021	190	-53.184±0.292
1		20160325	Red	20160321	-53.440±0.0021	250	-53.258±0.132
1	HD 42618	20160328	Blue	20160321	-53.440±0.0021	230	-53.258±0.289
1		20160328	Red	20160321	-53.440±0.0021	290	-53.096±0.198
2	HD 88725	20160522	Blue	20160513	-21.976±0.0012	70	-21.817±0.267
2		20160522	Red	20160513	-21.976±0.0012	100	-21.695±0.179

[b] - New arc were done on 20160315, but reference spectrum is very weak.

Table 3: The results for HR HRS mode

#	Star	Night	Arm	Arc.Night	V_h^c	SNR	V_h
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
1	HD 42618	20160303	Blue	20160226	-53.440±0.0021	16	-53.374±0.338
1		20160303	Red	20160226	-53.440±0.0021	20	-52.908±0.247
1	HD 42618	20160311	Blue	20160226	-53.440±0.0021	50	-50.875±0.334[a]
1		20160311	Red	20160226	-53.440±0.0021	60	-53.785±0.157[a]
1	HD 42618	20160312	Blue	20160312	-53.440±0.0021	40	-52.967±0.205
1		20160312	Red	20160312	-53.440±0.0021	50	-53.217±0.072
1	HD 42618	20160315	Blue	20160315	-53.440±0.0021	50	-53.925±0.222[b]
1		20160315	Red	20160315	-53.440±0.0021	60	-53.645±0.345[b]
1	HD 42618	20160316	Blue	20160315	-53.440±0.0021	20	-53.543±0.371[b]
1		20160316	Red	20160315	-53.440±0.0021	24	-53.343±0.255[b]
1	HD 42618	20160317	Blue	20160315	-53.440±0.0021	20	-53.010±0.189[b]
1		20160317	Red	20160315	-53.440±0.0021	24	-53.426±0.178[b]
1	HD 42618	20160318	Blue	20160315	-53.440±0.0021	35	-53.729±0.330[b]
1		20160318	Red	20160315	-53.440±0.0021	45	-53.297±0.175[b]
1	HD 42618	20160319	Blue	20160315	-53.440±0.0021	—	—
1		20160319	Red	20160315	-53.440±0.0021	65	-53.204±0.135[b]
1	HD 42618	20160321	Blue	20160321	-53.440±0.0021	34	-53.079±0.162
1		20160321	Red	20160321	-53.440±0.0021	40	-53.560±0.081
1	HD 42618	20160323	Blue	20160321	-53.440±0.0021	26	-53.141±0.179
1		20160323	Red	20160321	-53.440±0.0021	34	-53.519±0.229
1	HD 42618	20160324	Blue	20160321	-53.440±0.0021	34	-53.081±0.258
1		20160324	Red	20160321	-53.440±0.0021	40	-53.425±0.129
1	HD 42618	20160325	Blue	20160321	-53.440±0.0021	26	-53.020±0.253
1		20160325	Red	20160321	-53.440±0.0021	30	-53.740±0.153
1	HD 42618	20160328	Blue	20160321	-53.440±0.0021	22	-53.222±0.198
1		20160328	Red	20160321	-53.440±0.0021	25	-53.664±0.146
1	HD 42618	20160328	Blue	20160321	-53.440±0.0021	30	-53.157±0.123
1		20160328	Red	20160321	-53.440±0.0021	35	-53.411±0.156
2	HD 146233	20160403	Blue	20160405	11.79±0.08	350	11.37±0.19
2		20160403	Red	20160405	11.79±0.08	300	11.50±0.14
3	HD 88725	20160522	Blue	20160513	-21.976±0.0012	70	-21.728±0.218
3		20160522	Red	20160513	-21.976±0.0012	100	-21.806±0.208

[a] - HRS was stopped. Both red and blue dewars were baked and cooled down. The process was finished before 20160311 night, but no new flats and arcs were done for HR.

[b] - New arc were done on 20160315, but reference spectrum is very weak.

References

P. Stumpff, 1980, A&A Suppl. Ser., 41, 1