Southern African Large Telescope

Title:	**HRS MIDAS pipeline: accuracy and stability for the radial velocities**
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ABSTRACT

In this report I present one more try to study (1) the **absolute** *accuracy of HRS data for LR, MR and HR modes and (2) how often calibrations for all these modes need to be taken. I am able to produce the main conclusion that in all but one studied HRS modes (Blue and Red arms for LR, MR and HR) the* **absolute** *accuracy of HRS data is better than* **200 m/s***, if calibrations were taken inside of one week from science observations and no more than* **500 m/s***, if calibrations were taken as far as* **50 days** *from observations.*

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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 science which any PI is going to do with this instrument. With my second report on this topic I have another try 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, which taken during about two months time from the end of November, 2016 till the end of January 2017. I also tried to study topic how often calibrations for all these HRS modes need to be taken for the certain accuracy in the velocity measurements. The results of this work are presented in this report.

2 The Method

The Astronomy Operations Team makes a HUGE effort trying to obtain HRS calibrations (Bias, Flat-fields and Ars) for all modes altogether with observations of velocity standards (RV) for each observational night from 20161124 till 20170118. Altogether, 41 observational sets were collected during this period of time, which were used in this study.

My additional analysis of all data results to remove from this list some nights, where not all proper calibrations were done. I also finally excluded from my analysis five nights, when RV standard HD 16141 was observed, since this RV gives the systematic shift in all HRS modes and arms.

For the rest 30 observational sets I make study for two items:

1. All velocity measurements, which were done in the automatic mode with the MIDAS HRS pipeline (see Section 3 for details), were summarized in one table and a comparison with the catalogue values was done. This step should to show the **absolute** accuracy measurements for HRS data in case calibrations were done **in the same night** with science data.

2. After that it was suggested that calibrations were done on the first night of the dataset sample (20161124) and **ALL** data for RVs for the rest of 29 nights were recalculated with this solution, their velocity measurements were done in the same automatic mode as previously, and were summarized in the output table and compared with the catalogue values for RVs. The same step was done in the loop 29 times for all selected dates, where calibration calculations were done for the only one night and data for the rest 29 sets were recalculated with solutions for this night. Altogether, ~ 6500 reductions and velocity measurements were done during this second step to study the radial velocities measurements stability for HRS data.

3 Short Description of the Procedure

In this report I used the same MIDAS procedure, which was created previously and which is used as the standard step for the MIDAS HRS pipeline for the automatic velocity calculations for all observed velocity standards (RV) observed in LR, MR and HR modes. This procedure uses the following data:

- HRS data, which were reduced with the HRS MIDAS pipeline using the nearest (in time) flats and reference arc spectra;
- A stellar template for the cross correlation, which is selected automatically as the closest one from the list of model spectra with solar metallicity from Coelho (2014). For the time being, the same resolution is used for all HRS modes, which is very close to LR mode (R=16000), but unfortunately, it is not optimized yet for MR and HR modes.

The procedure consist of the following steps:

- Both reduced spectrum of the RV standard and the model spectrum are normalized.
- The radial velocity is computed via Fourier cross correlation of reduced spectrum 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 of the RV star.

Some examples of such analysis for different HRS modes and arms are shown in my previous SALT reports.

4 The absolute accuracy of velocity measurements

The comparison of measured velocities with their catalogue values is shown in Figures 1, 2 and 3. 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.

The weighted average values for each spectrum are shown with black dots and their $\pm 1\sigma$ errors are shown with vertical bars. The calculated average value for the total sample is shown with horizontal long dash line (blue color for the blue arm, red for the red arm and black for blue+red arms) and $\pm 1\sigma$ errors for the total sample are shown with green long dash lines.

Figure 1 shows that the blue arm spectra for LR mode **possibly** show systematic shift with mean $\langle \Delta V \rangle = -250 \pm 226$ m/s, where the red arm LR spectra does not show any shift with mean $\langle \Delta V \rangle = 60 \pm 176$ m/s. Each observation has an average error 77 m/s for the

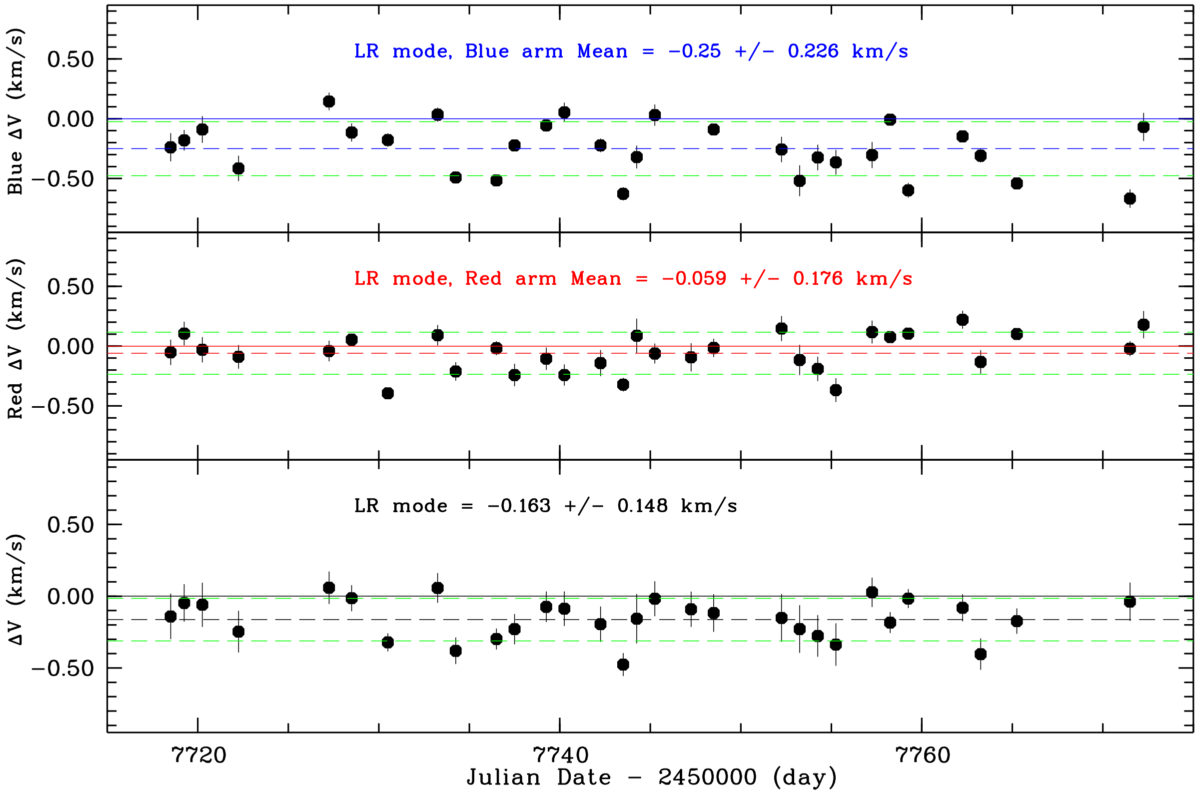

Figure 1: The comparison of measured velocities with their catalogue values for RV standards obtained with LR mode. Calculated velocity for each spectrum is shown with black dots. 1σ errors are shown with bars. The calculated average value for the total sample is shown with horizontal long dash line (blue color for the blue arm, red for the red arm and black for blue+red arms) and $\pm 1\sigma$ errors for the total sample are shown with green long dash lines.

blue arm and 86 m/s for the red. The combined Blue+Red arm values have mean accuracy $\langle \Delta V \rangle = -163 \pm 148$ m/s and mean error 117 m/s for each observation.

Figure 2 shows that the blue arm spectra for MR mode do not show any systematic shift with mean $\langle \Delta V \rangle = -30 \pm 194$ m/s, where the red arm MR spectra **possibly** show systematic shift with mean $\langle \Delta V \rangle = 112 \pm 136$ m/s. Each observation has an average error 70 m/s for the blue arm and 67 m/s for the red. The combined Blue+Red arm values have mean accuracy $\langle \Delta V \rangle = 54 \pm 121$ m/s and mean error 99 m/s for each observation.

Figure 3 shows that both blue and red arm spectra for HR mode does not show systematic shift with mean $\langle \Delta V \rangle = 51 \pm 302$ m/s and $\langle \Delta V \rangle = -28 \pm 144$ m/s, where each observation has an average error 65 m/s for the blue arm and 76 m/s for the red. The combined Blue+Red arm values have mean accuracy $\langle \Delta V \rangle = 12 \pm 161$ m/s and the average error 102 m/s.

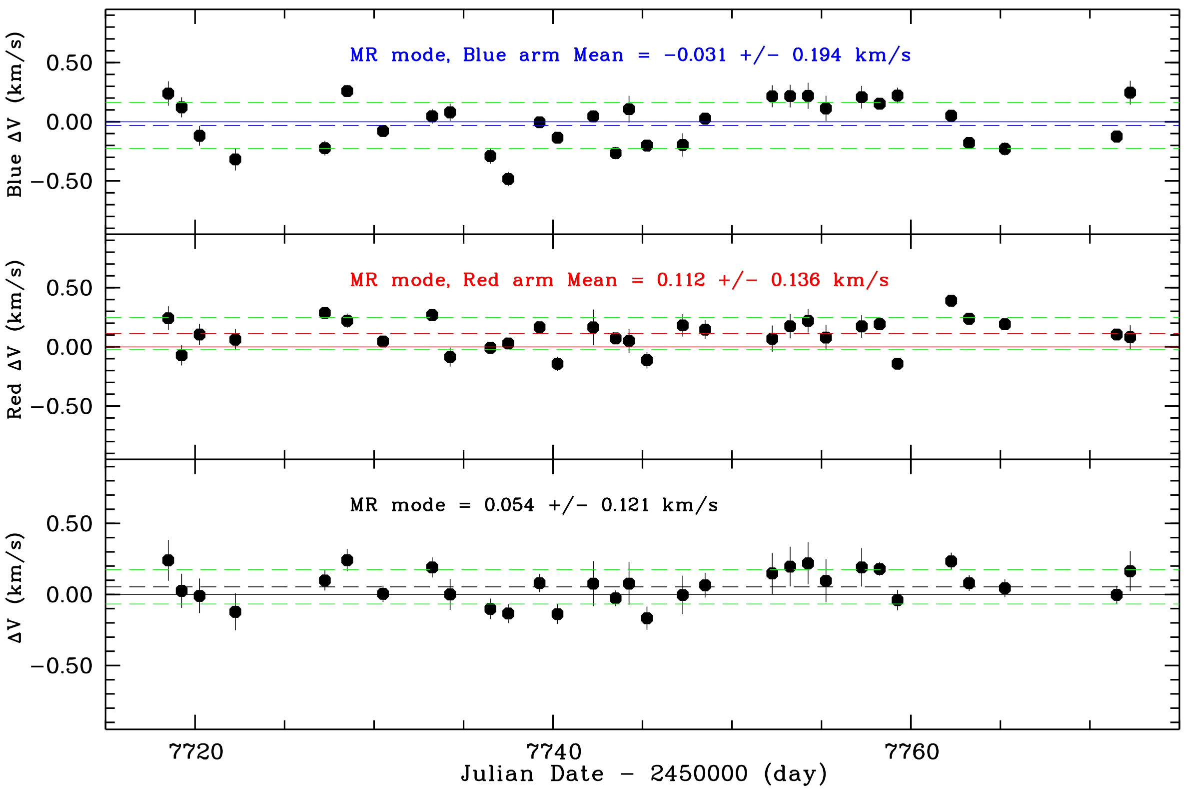

Figure 2: The comparison of measured velocities with their catalogue values for RV standards obtained with MR mode. The figure caption is same as for Figure 1.

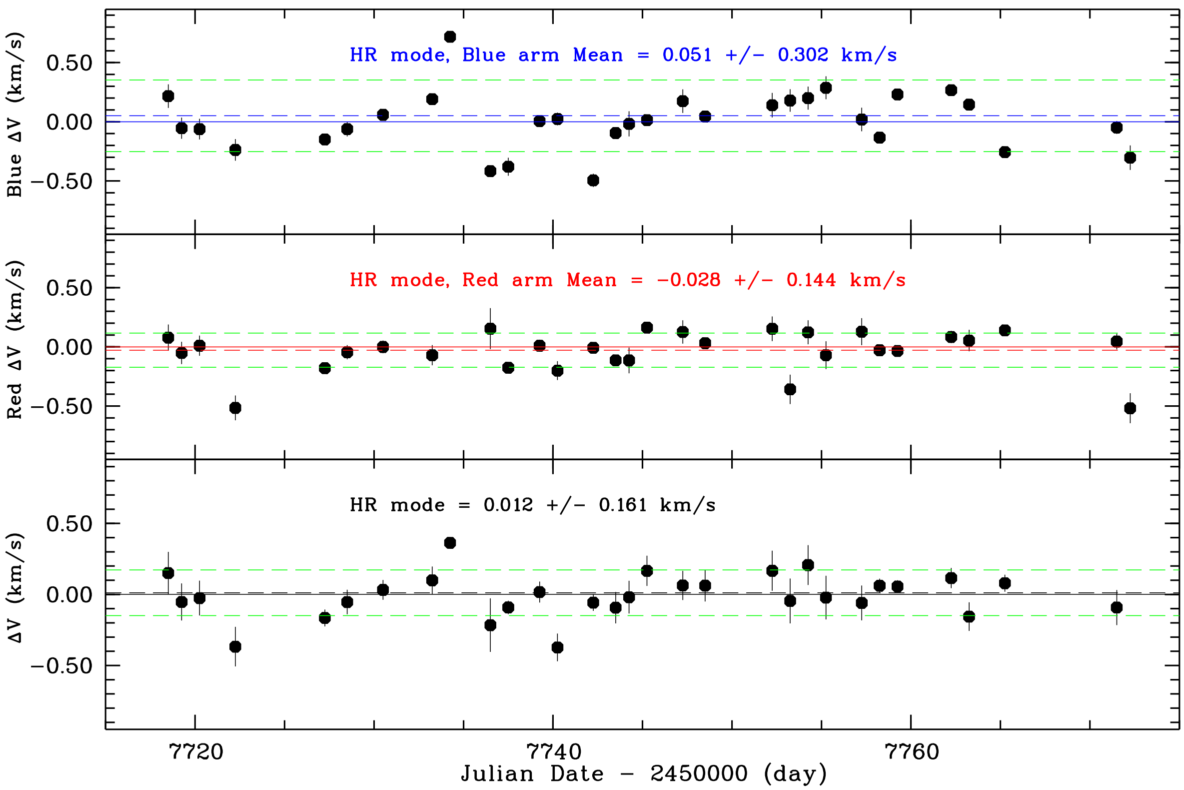

Figure 3: The comparison of measured velocities with their catalogue values for RV standards obtained with HR mode. The figure caption is same as for Figure 1.

5 The radial velocity measurements stability

The comparison of measured velocities for RV standards with their catalogue values versus difference in days between date of observations and calibrations is shown in Figures 4, 5 and 6. The top part there shows calculated velocity for each measured spectrum as black dot and 1σ errors are shown with bars. The bottom part shows the same as above, but weighted averages and their error were calculated and shown for each Δ(Days).

Figure 4 shows that for LR mode even use of wavelength solution of 35 days away DOES NOT produce errors large than 500 m/s even systematic shift will change with time for the blue arm and will be practically zero for the red arm measurements. In case of using only the red arm data for the velocities measurements, it is possibly to keep accuracy less than 200 m/s in case calibrations will be done inside of ± 3 days from observations.

The situation with MR mode is much better as it is shown in Figure 5. Both blue and red arm data for this mode DO NOT show any obvious systematic in case calibrations could be done inside of $\pm 5 - 7$ days from observations. In this case it is easy to get accuracy less than 150 m/s using both arms data or only red one.

The situation with HR mode is shown in Figure 4. Unfortunately, the blue arm data show some systematic after $\pm 5 - 7$ days after calibrations, where the red arm data do not. In case that calibrations will be done less than 5–7 days before/after, it is easy to get accuracy less than 150 m/s using red arm data only.

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 velocity measurements is better than **300 m/s**, if **proper** calibrations were done.

2. In reality, the accuracy better than **200 m/s** except the blue HR mode, that could be the result of use models with R=20000 only. From this point of view, I think that my results for MR and HR are only UPPER limits and real accuracies are even better for these modes.

3. The produce of calibrations once per week looks reasonable and doing such calibrations even for each night does not improve accuracy drastically.

4. If no any technical breaks or interventions of the instrument were done, the **absolute** accuracy of velocity measurements is better than **500 m/s** even calibrations were done $\pm 35 - 40$ days from HRS observations.

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 some systematic exist at higher levels of

accuracy, but to detect those, the HRS community needs to develop new methods, or to polish the current one.

References

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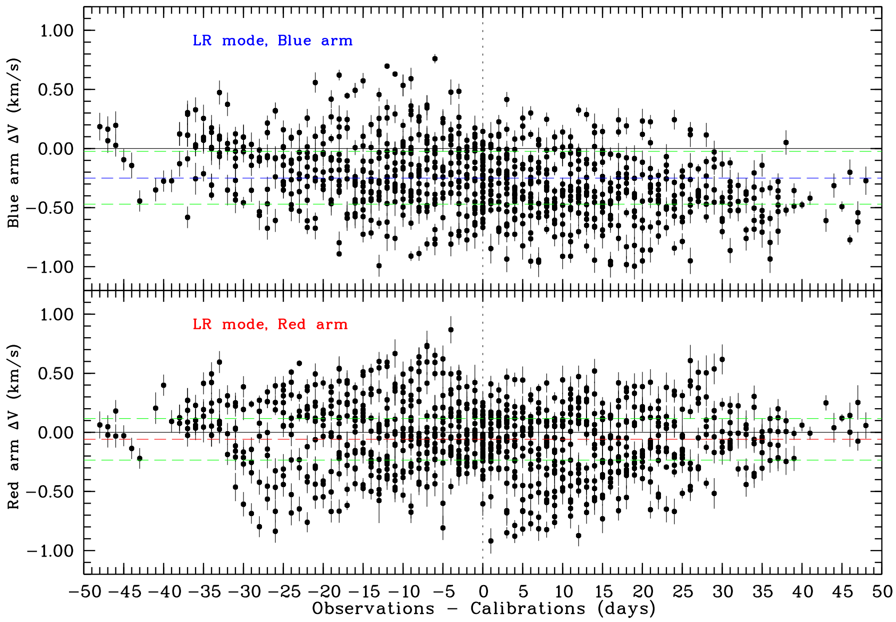

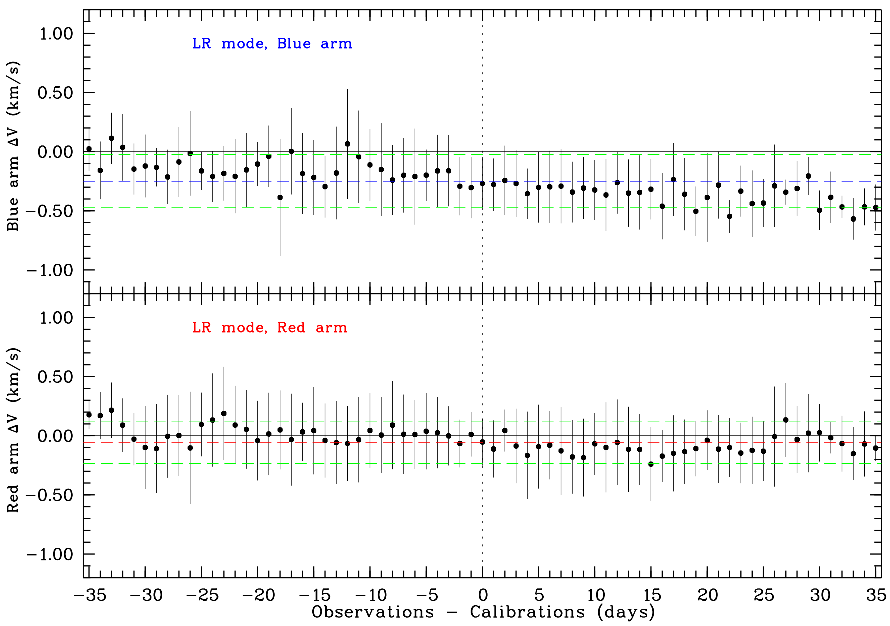

Figure 4: The comparison of measured velocities with their catalogue values for RV standards obtained with HRS LR mode depending on the time (in days) between calibrations and science observations. The calculated average value for the total sample as it is described in Figure 1 is shown with horizontal lines. In this case it is coincide with $\Delta\text{Days} = 0$. **Top:** Calculated velocity for each calculated spectrum is shown with black dots and 1σ errors are shown with bars. **Bottom:** The same as above, but weighted average and its error is calculated and shown for each date.

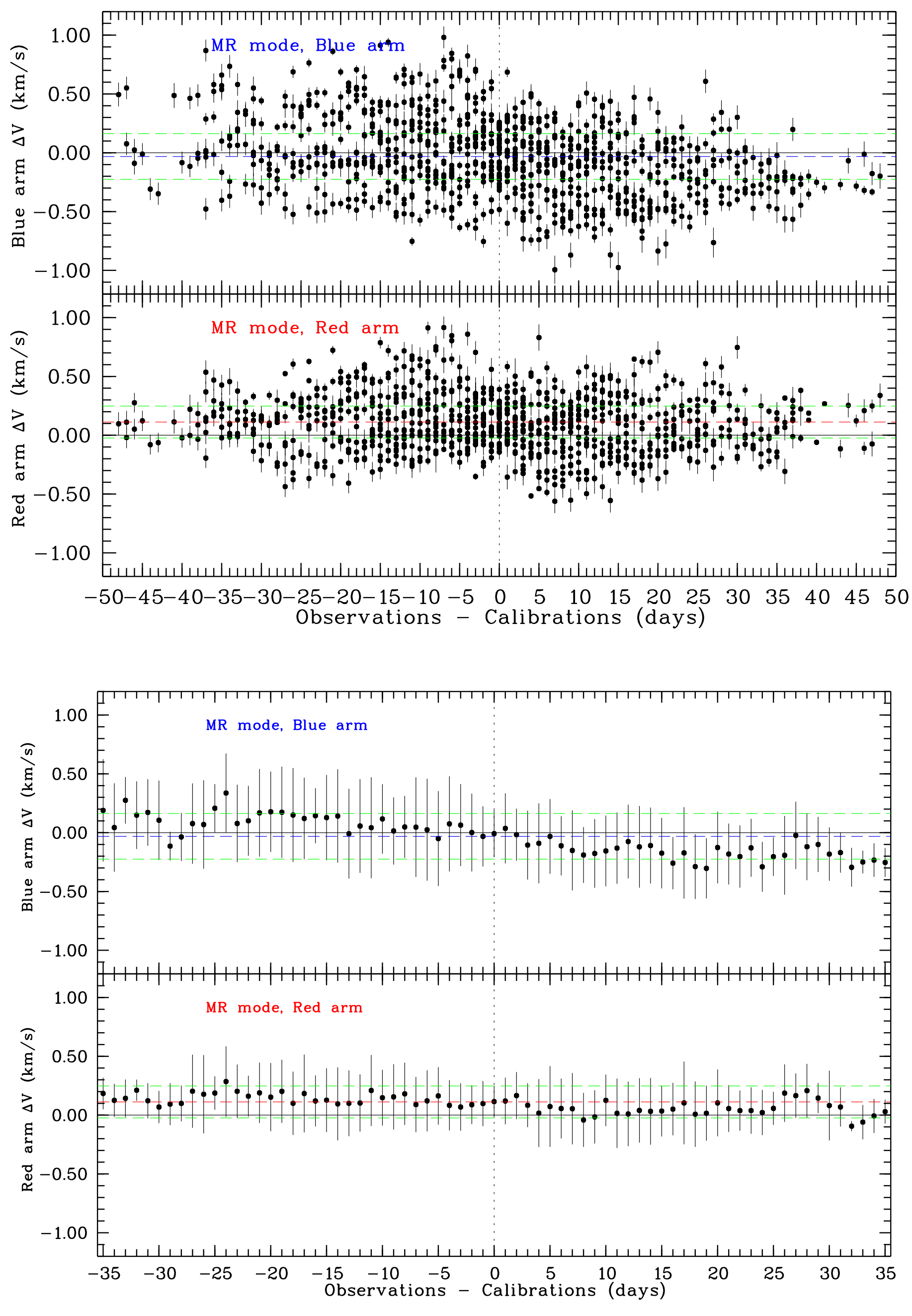

Figure 5: The comparison of measured velocities with their catalogue values for RV standards obtained with HRS MR mode depending on the time (in days) between calibrations and science observations. The calculated average value for the total sample as it is described in Figure 1 is shown with horizontal lines. In this case it is coincide with $\Delta\text{Days} = 0$. **Top:** Calculated velocity for each calculated spectrum is shown with black dots and 1σ errors are shown with bars. **Bottom:** The same as above, but weighted average and its error is calculated and shown for each date.

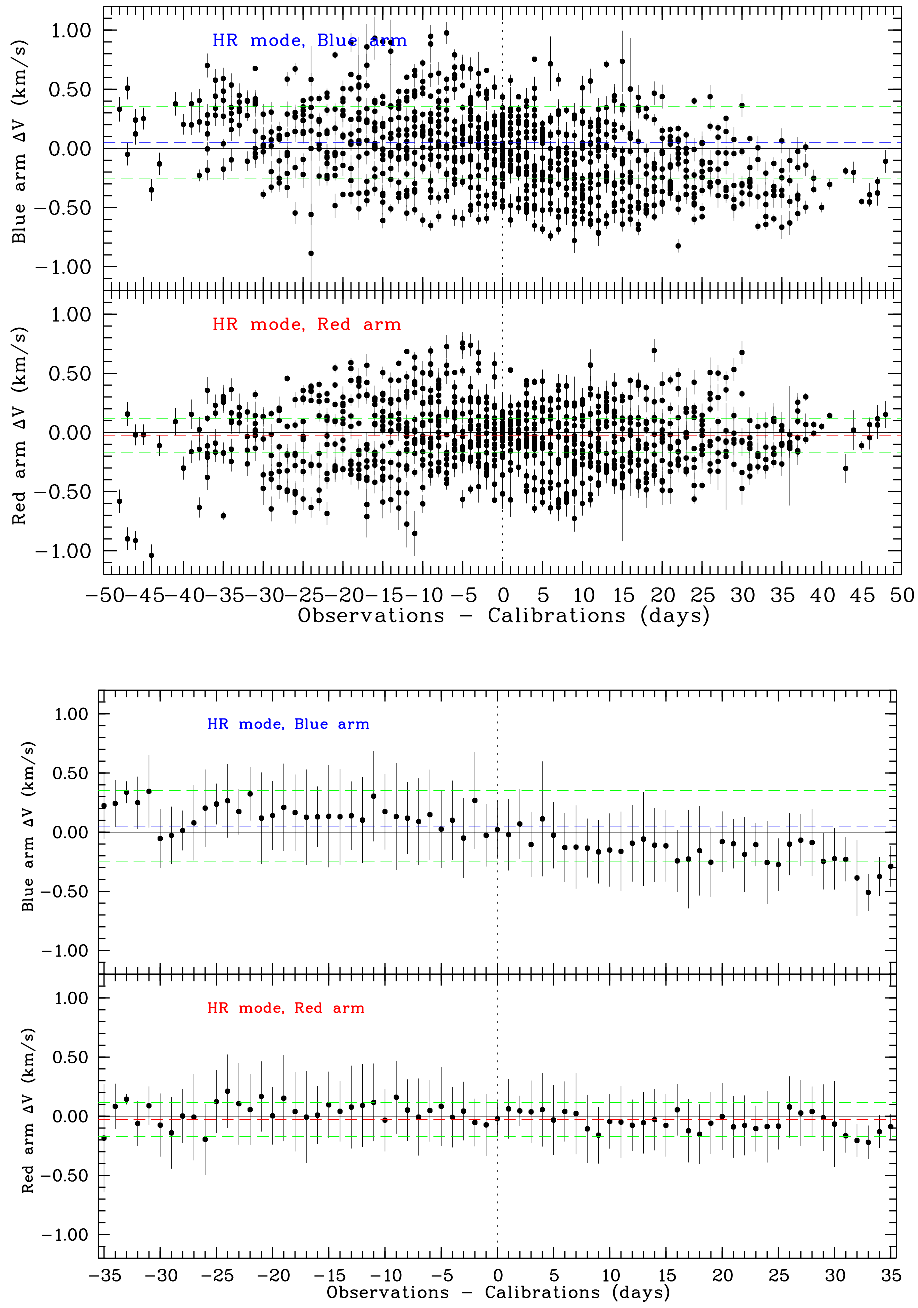

Figure 6: The comparison of measured velocities with their catalogue values for RV standards obtained with HRS HR mode depending on the time (in days) between calibrations and science observations. The calculated average value for the total sample as it is described in Figure 1 is shown with horizontal lines. In this case it is coincide with $\Delta\text{Days} = 0$. **Top:** Calculated velocity for each calculated spectrum is shown with black dots and 1σ errors are shown with bars. **Bottom:** The same as above, but weighted average and its error is calculated and shown for each date.