Southern African Large Telescope

Title: **HRS MIDAS pipeline: accuracy and stability of radial velocities during three years of HRS observations**

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ABSTRACT

The MIDAS HRS data pipeline is working during last two years starting from the beginning of 2017. HRS data that were taken during 2016 were also mostly reduced by this pipeline. In this report I analysed HRS data for the velocity standard stars, which were obrained during last three years within ***the HRS Calibration Plan****, and were reduced and analysed by automatic HRS pipeline. I compiled all these numbers to present* ***the external accuracy and stability*** *of HRS data for both blue and red arms with LR, MR and HR modes.*

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1 Introduction

Knowledge on HRS accuracy and stability is very important for understanding of limits that any PI can get with current instrumentation. This is my third report on the topic of an accuracy and stability for HRS echelle data at SALT. In this report I present my study of **the absolute external** accuracy for HRS data which were reduced with HRS MIDAS pipeline. This analysis is based on all available spectral data for the radial velocity standards (RVs hereafter), that were observed regulary during last two years (2017 and 2018) and not very regulary during 2016. My analysis covers only data for the Low Resolution (LR), Medium Resolution (MR) and High Resolution (HR) modes of HRS, but for both arms in each mode.

2 The short outline fot the procedure of calculation velocities for RV stars

The MIDAS HRS pipeline procedure of the analysis of RV stars uses the following data:

- HRS data, what were reduced with the HRS MIDAS pipeline using the nearest (in time) flats and reference arc spectra;

- A stellar template for the cross correlation is selected automatically as the closest one from the list of model spectra with solar metallicity (Coelho, 2014). For the time being, the same resolution is used for ALL HRS modes, even the resolution models from Coelho (2014) is very close to MR mode (R$\approx$ 30000), but unfortunately, it is not optimized yet for LR mode and can not be optimised for HR mode.

The procedure consist of the following steps:

1. The heliocentric correction is calculated using standard MIDAS task based on Stumpff (2010) and the value is added to the FITS header.

2. Both reduced spectrum of the RV standard and the model spectrum are normalized.

3. The radial velocity is computed via Fourier cross correlation of reduced spectrum of RV standards with model spectrum of the template star.

4. The velocity is calculated independently **for each** echelle order.

5. The final table with calculated velocities for each echelle order and their errors is analysed to reject bad orders with calculated velocities, what are far away from the median value (for example, red arm orders with strong telluric lines). The final velocity and its error are calculated as a weighted average and added to the FITS header of the RV star and is saved on the disk as an ASCII-file.

3 Data for the analysis

The Astronomy Operations Team makes a big effort trying to obtain HRS calibrations (Bias, Flat-fields and Ars) for LR, MR and HR HRS modes regularly and observe RVs after that during nearest twilights to check the quality of calibrations. Altogether, I have in my list 165 observations, what were done up to date. Figure 1 shows the difference in days between observations of HRS calibrations and observations of RV standards during nearest twilights after that. The top panels show LR mode, the middle panels show MR mode and the bottom panels show HR mode. Left panels show blue arm for each mode and right panels show red arm for each mode. The positive numbers show that RV standards were observed AFTER HRS calibrations were done. The negative numbers show that some HRS data were re-reduced and nearest PREVIOUS calibrations were used in this case.

As it possible to see from Figure 1, observations of RV standards were done NOT very regular during the first half of 2016, where started to be taken much more regular after that. It is obvious, that the Astronomy Operations Team is keeping it under the control of about one week during last year.

Some observations of RVs were done during 2015, but there are very few of them and they were NOT included in this analysis, because HRS data reduction has many different problems for these data.

I have selected only those observations, where data have Signal-To-Noise ratio more than 50, to exclude very noisy spectra. No any other criteria were applied. Finally, I collected 128–152 observations for my analysis depending on the HRS mode and spectral arm.

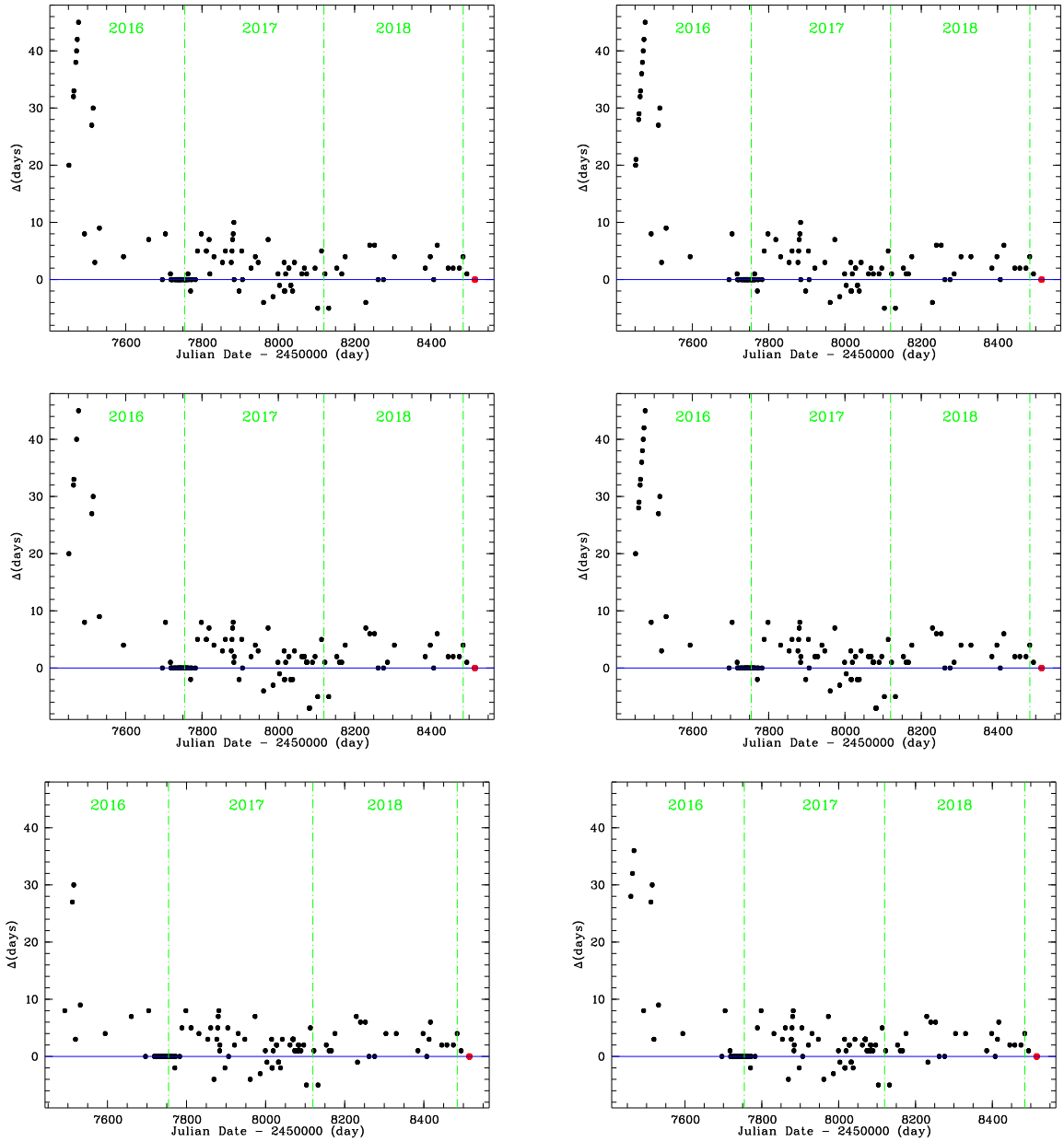

Figure 1: The difference in days between observations of HRS calibrations and observations of RV standards during nearest twilights after that. The positive number shows that RV standards were observd AFTER calibrations were done. The top panels show LR mode, the middle panels show MR mode and the bottom panels show HR mode. Left panels show blue arm for each mode and right panels show red arm for each mode.

Table 1: Calculated accuracy for RV stars

Mode & Arm	All time (km/s)	Last year (km/s)	The last (km/s)
(1)	(2)	(3)	(4)
LR Blue	0.255±0.460	0.369±0.434	0.639±0.315
LR Red	0.107±0.490	-0.056±0.333	-0.125±0.676
MR Blue	0.008±0.359	0.079±0.362	0.065±0.165
MR Red	0.028±0.414	-0.082±0.306	-0.112±0.290
HR Blue	0.075±0.318	0.223±0.352	-0.051±0.297
HR Red	0.029±0.319	0.010±0.298	-0.169±0.192

4 The absolute accuracy and stability of velocity measurements

The comparison of measured velocities with their catalogue values is shown in Figures 3, 2 and 4. The top panels show the difference between the catalogue velocities and measured velocities from the blue arm HRS spectra. The bottom panels shows the difference between the catalogue velocities and measured velocities from the red arm HRS 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 each arm is shown with horizontal red line in each panel, where $\pm 1\sigma$ errors for the total sample of each arm are shown with blue long dash lines.

All calculated numbers from my analysis are shown in Table 1.

Figure 2 altogether with Table 1 show that both blue and red arm velocities for MR mode do not show any systematic shift with mean and RMS during last year for the blue arm $\langle \Delta V \rangle = 79 \pm 362$ m/s, and for the red arm $\langle \Delta V \rangle = -82 \pm 306$ m/s. The error for the total time (3 years) is slightly larger and close to $\sim$400 m/s, but the total mean values do not show any systematic.

Figure 3 altogether with Table 1 show that the blue arm velocities for LR mode **possibly** show small systematic shift with mean $\langle \Delta V \rangle = 369 \pm 434$ m/s, where the red arm LR velocities do not show any shift with mean $\langle \Delta V \rangle = -56 \pm 333$ m/s. Data collected for the total time (3 years) shows the same small systematic shift for the blue arm and absence of any systematic for the red arm.

Figure 4 altogether with Table 1 show that both blue and red arm velocities for HR mode do not show systematic shift with mean $\langle \Delta V \rangle = 223 \pm 352$ m/s and $\langle \Delta V \rangle = 10 \pm 298$ m/s. Data collected for the total time (3 years) shows the same picture.

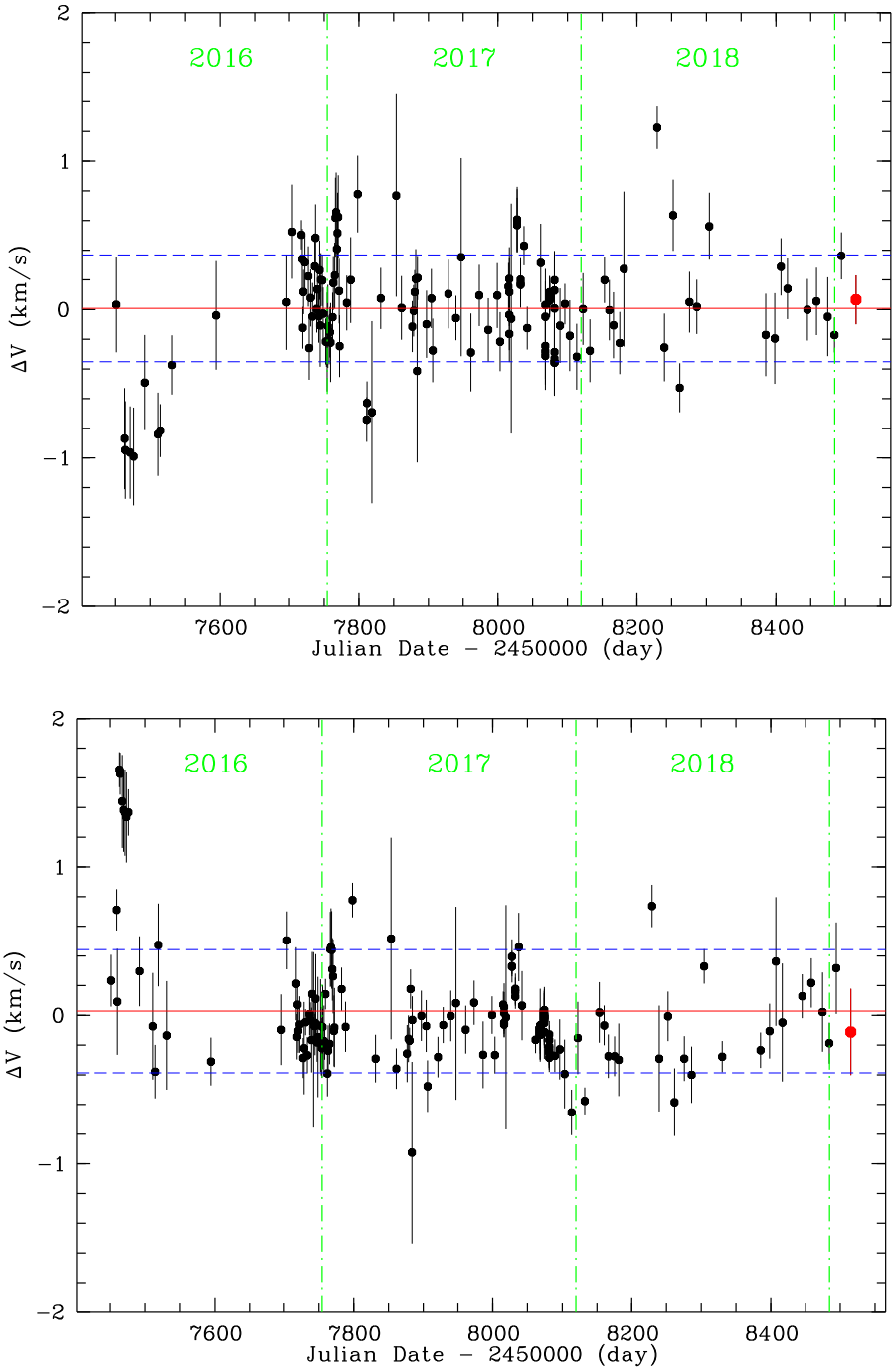

Figure 2: The comparison of measured velocities with catalogue values for RV standards obtained with MR mode of HRS. Calculated velocity for each spectrum is shown with black dots. 1σ errors are shown with bars. The calculated average value for the total sample is shown with horizontal red line and $\pm 1\sigma$ errors for the total sample are shown with blue long dash lines. The red dot is showing the last point. Vertical green lines show start of the new year. **The top panel** shows data for the blue arm and **the bottom panel** shows data for the red arm.

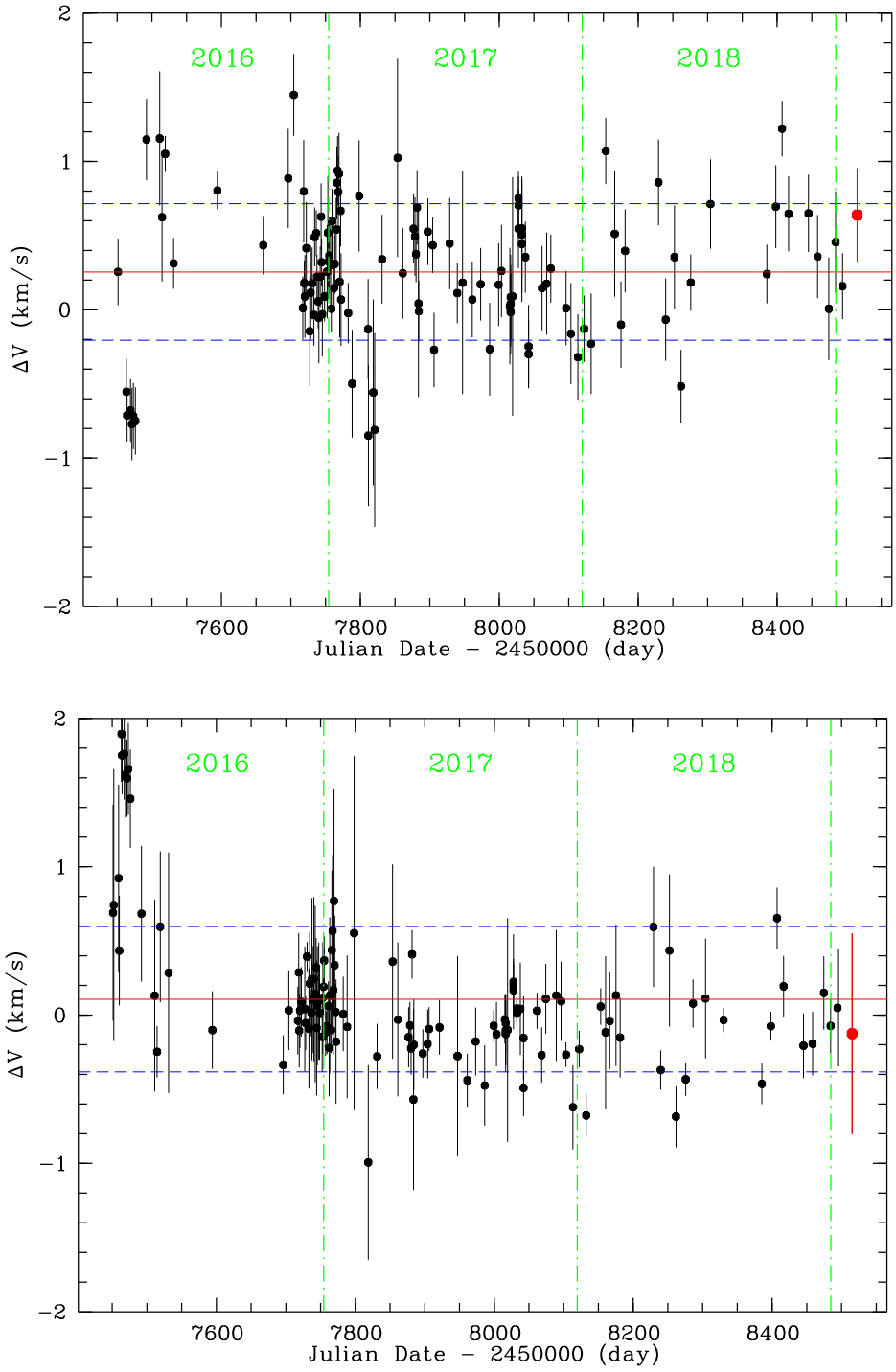

Figure 3: The comparison of measured velocities with catalogue values for RV standards obtained with LR mode of HRS. See captions for Figure 2 for more details.

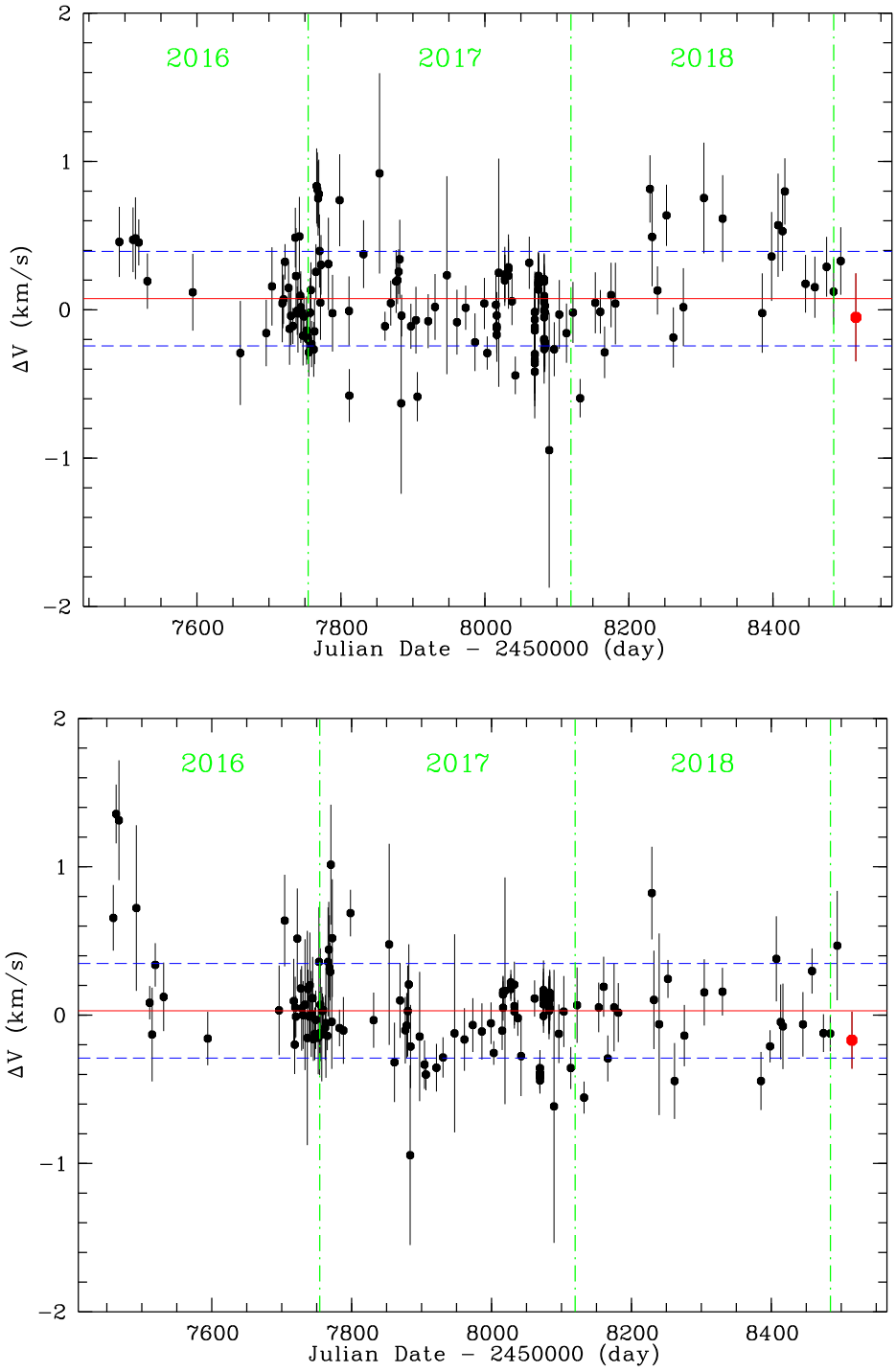

Figure 4: The comparison of measured velocities with catalogue values for RV standards obtained with HR mode of HRS. See captions for Figure 2 for more details.

5 Implications for the HRS Calibrations Plan and SALT Data Quality System

All above analysis results with two very important implications.

The first one, relates directly to our HRS Calibrations Plan and support the general rule of the Astronomy Operations Team **to obtain HRS calibrations (Flat-fields and Ars) for LR, MR and HR HRS modes once in 5–7 days and observe RVs after that during nearest twilights**. The analysis of all data for RV standards taken during last three years shows that such calibration plan guaranties **the external** accuracy of velocities of ~ 300 m/s for MR and HR modes and ~ 400 m/s for LR mode.

The second implication of above analysis directly supports us with the standard limits of our calibrations, which have to be used by the future SALT Data Quality System to check quality of taken HRS data.

6 Conclusions

I have collected and studied all available results of automatic calculation

HRS data for the velocity standard stars, which were obrained during last three years within **the HRS Calibration Plan**, and were reduced and analysed by automatic HRS pipeline. I am able to compile next conclusions:

1. In all studied HRS modes (LR, MR and HR) the **absolute** accuracy of velocity measurements is better than ~ 300 m/s for MR and HR modes and ~ 400 m/s for LR mode.

2. These accuracies looks very stable during all 2016–2018 years.

3. The HRS Calibrations Plan to produce standard calibrations once in 5–7 days looks totally reasonable.

References

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