Stability of the Spectroscopic Data Reduction

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Radial Velocity Workshop, Penn State, August 2010

Are we serious about reaching 1 cm/s?

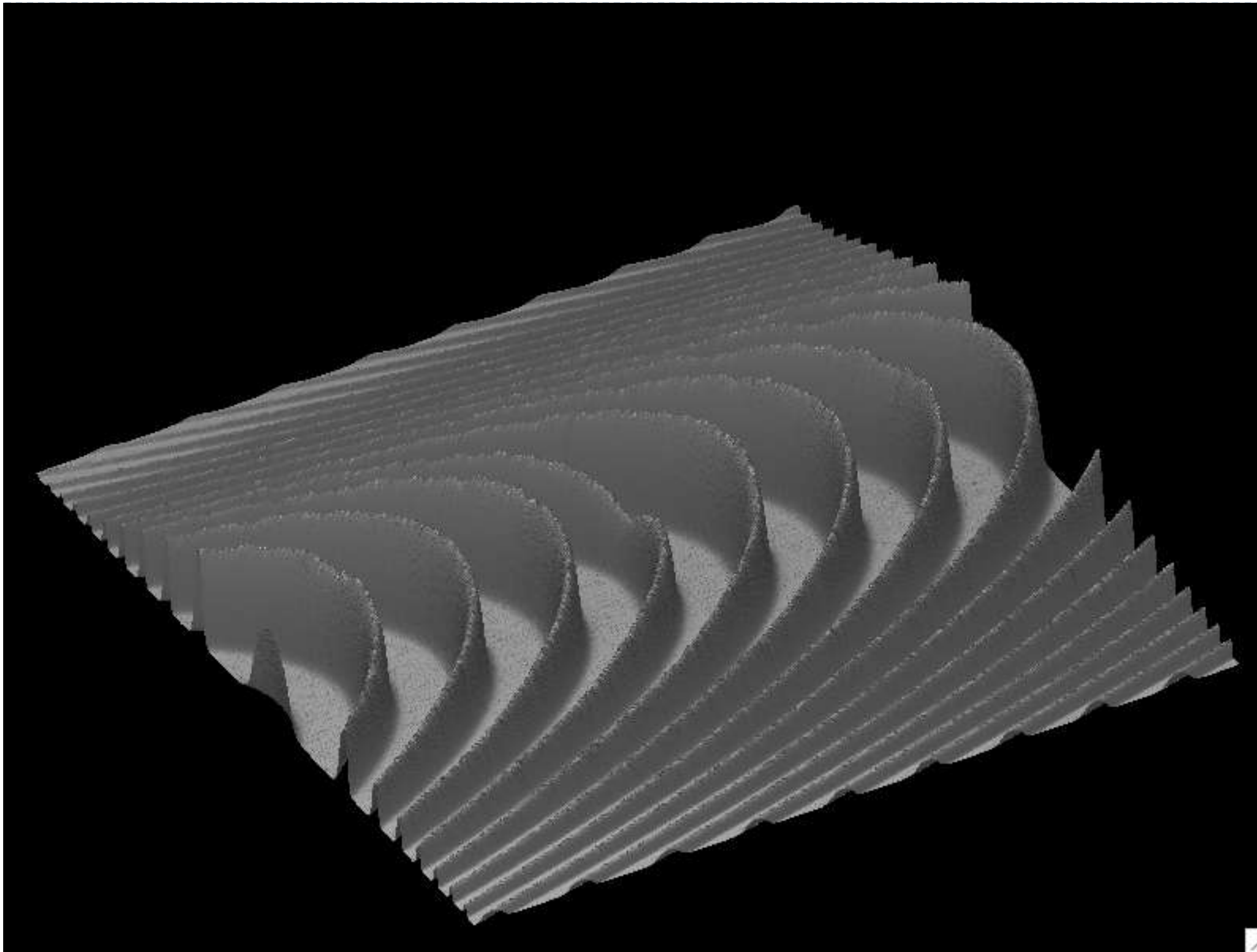
- How do we measure stellar RVs?
  Nearly philosophical intro
- What are the priorities today?
  Let's stop for a minute and think
- When our wavelength calibrations reach the precision better than 20 cm/s, do we get RV accurate to 20 cm/s?

  Some simple-minded simulations
- Is all hope lost?
  We are working on many new instruments, we need to do it right

How do we measure stellar RVs today?

- We need large wavelength coverage and high spectral resolution → a cross-dispersed echelle with large 2D detector(s)
- We measure relative RVs by comparing two spectra or a spectrum and a reference. RV is measured along one axis!
- We more or less ignore the curvature of the spectral orders, the change in slit orientation, aberrations of the imaging camera, blaze function of the spectrometer etc.
- References: ThAr, Iodine cell, FP and laser comb
- Amazingly, it works down to 1 m/s or even below!

Just to make sure everybody knows what I am talking about



Our way to 1D RV measurement is called **Data Reduction**

Data reduction steps:

- Create master blaze
- Create master flat
- Subtract bias from the flat
- Subtract bias from science frame
- Flat field
- Extract **1D** spectral orders
- (Correct for the blaze)
- (Splice)

Measure relative RV

Today our priority is set on measuring RV from the extracted 1D spectra

This is good because it allows us to focus on:

- our instruments
- observing strategies
- calibration procedures (for the wavelength)
- reference sources (for the wavelength)
- various RV corrections

The expertise we acquired in the last 15 years is enormous!

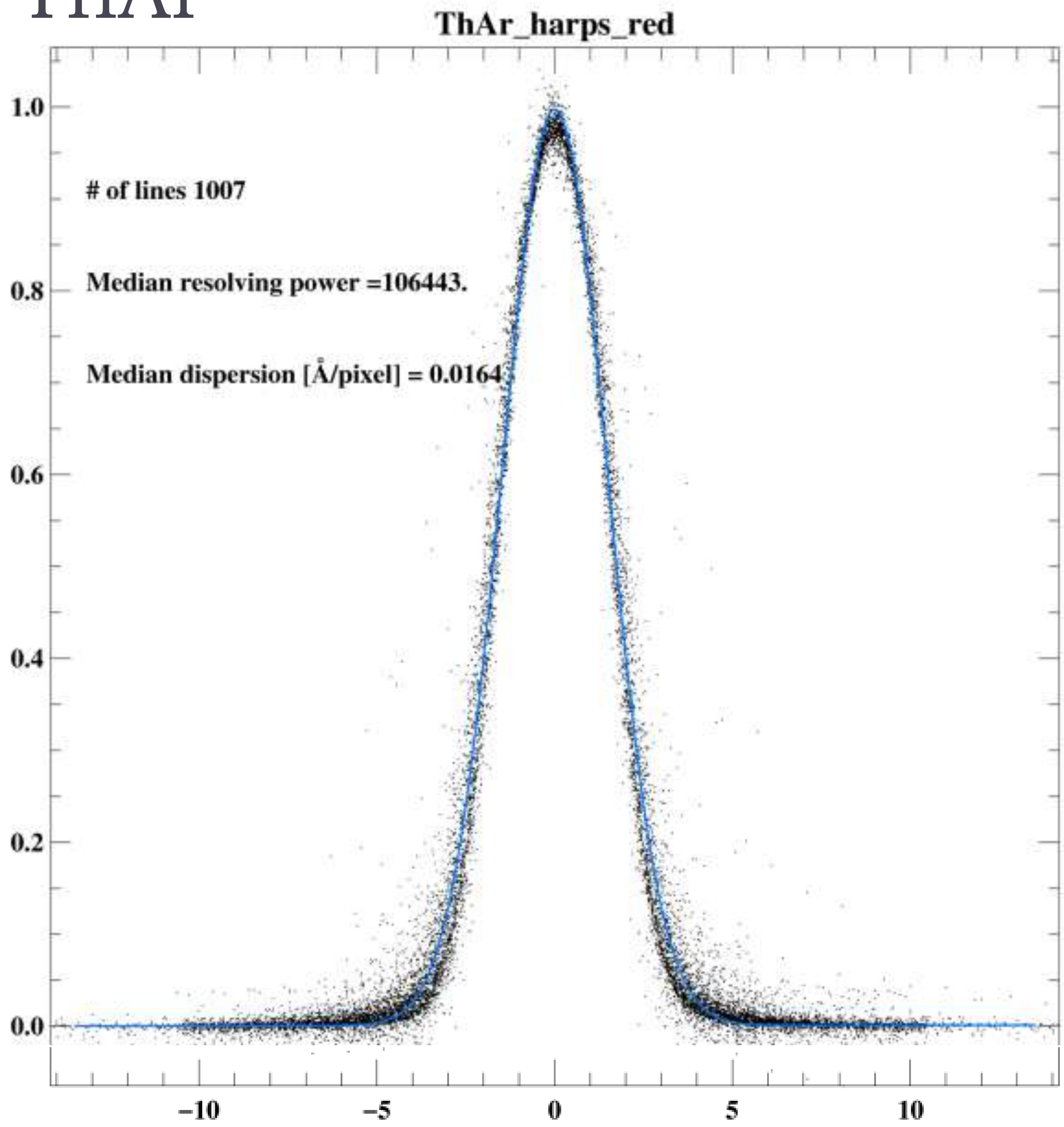
Today we are starting to reach the limit of this approach because the data reduction is not sufficiently stable.

Small example

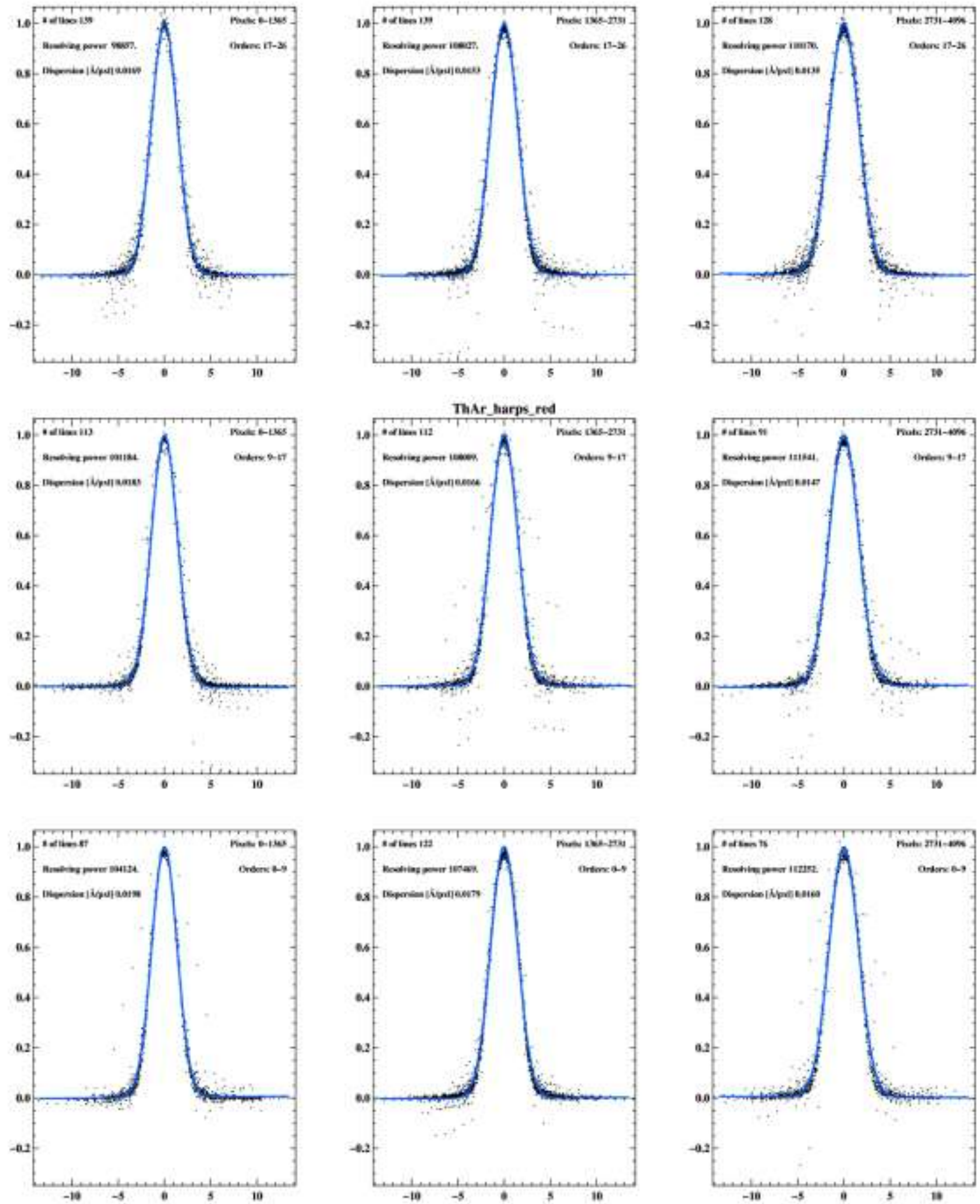
HARPS is the best high-resolution spectrometer in the world for RV measurements because:

- It is very stable (environmental control, vacuum)
- Has excellent camera keeping the slit vertical and the LSF shape nearly identical across both detectors
- It is fiber-fed
- Calibrations (ThAr) are well understood and maintained

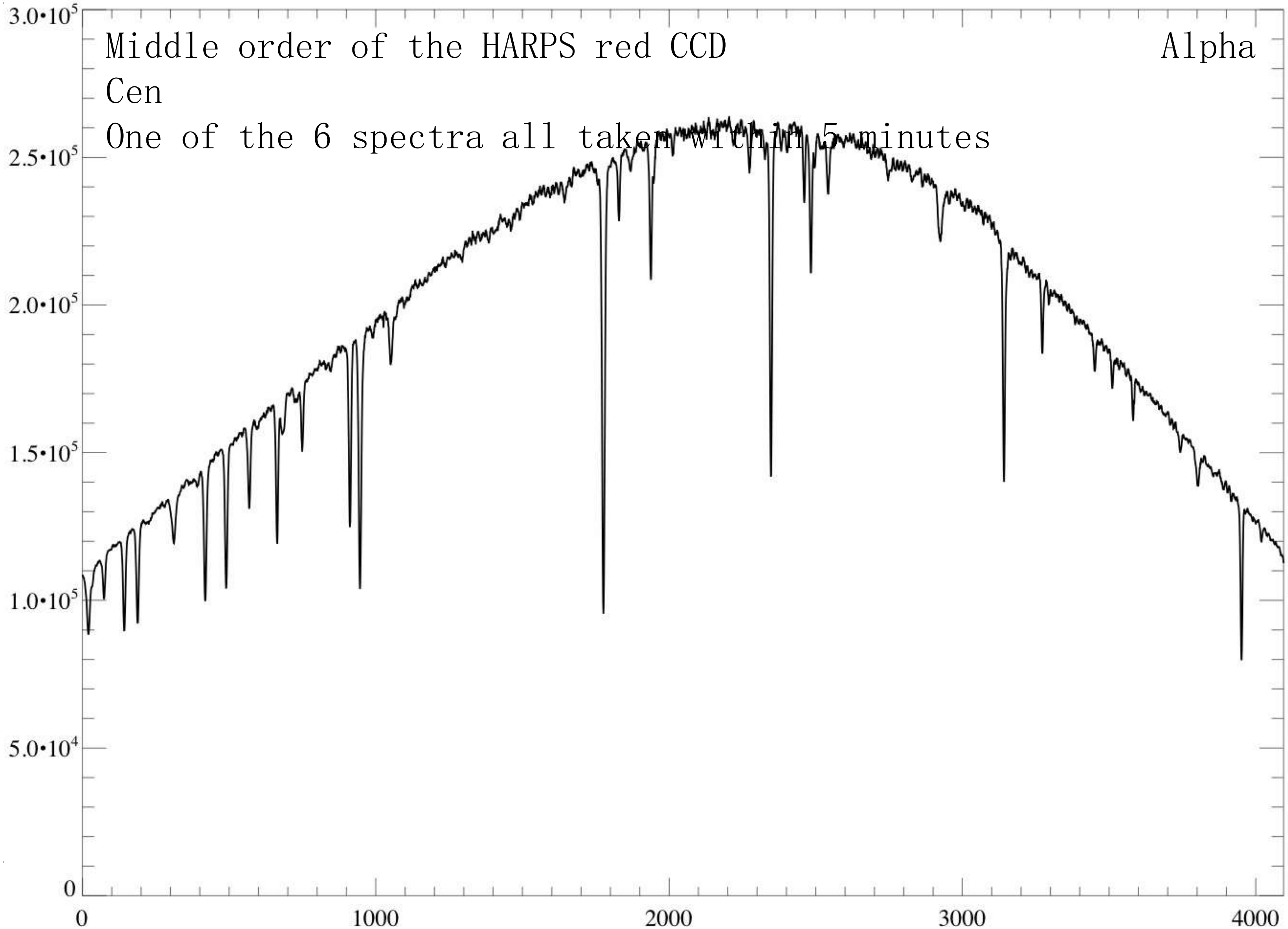
HARPS ThAr


ThAr_harps_red
# of lines 1007
Median resolving power =106443.
Median dispersion [Å/pixel] = 0.0164
1.0
0.8
0.6
0.4
0.2
0.0
−10
−5
0
5
10

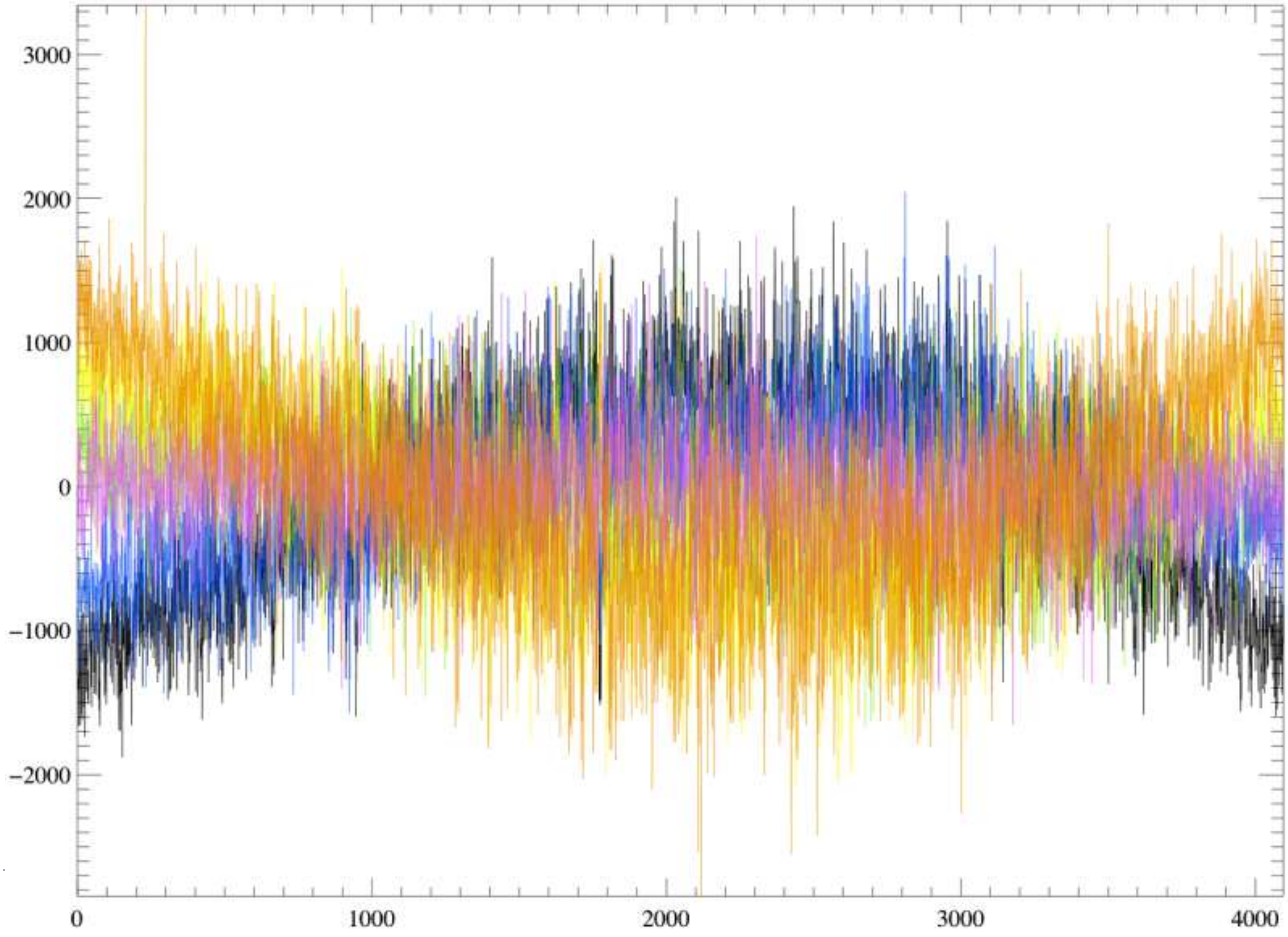
HARPS ThAr



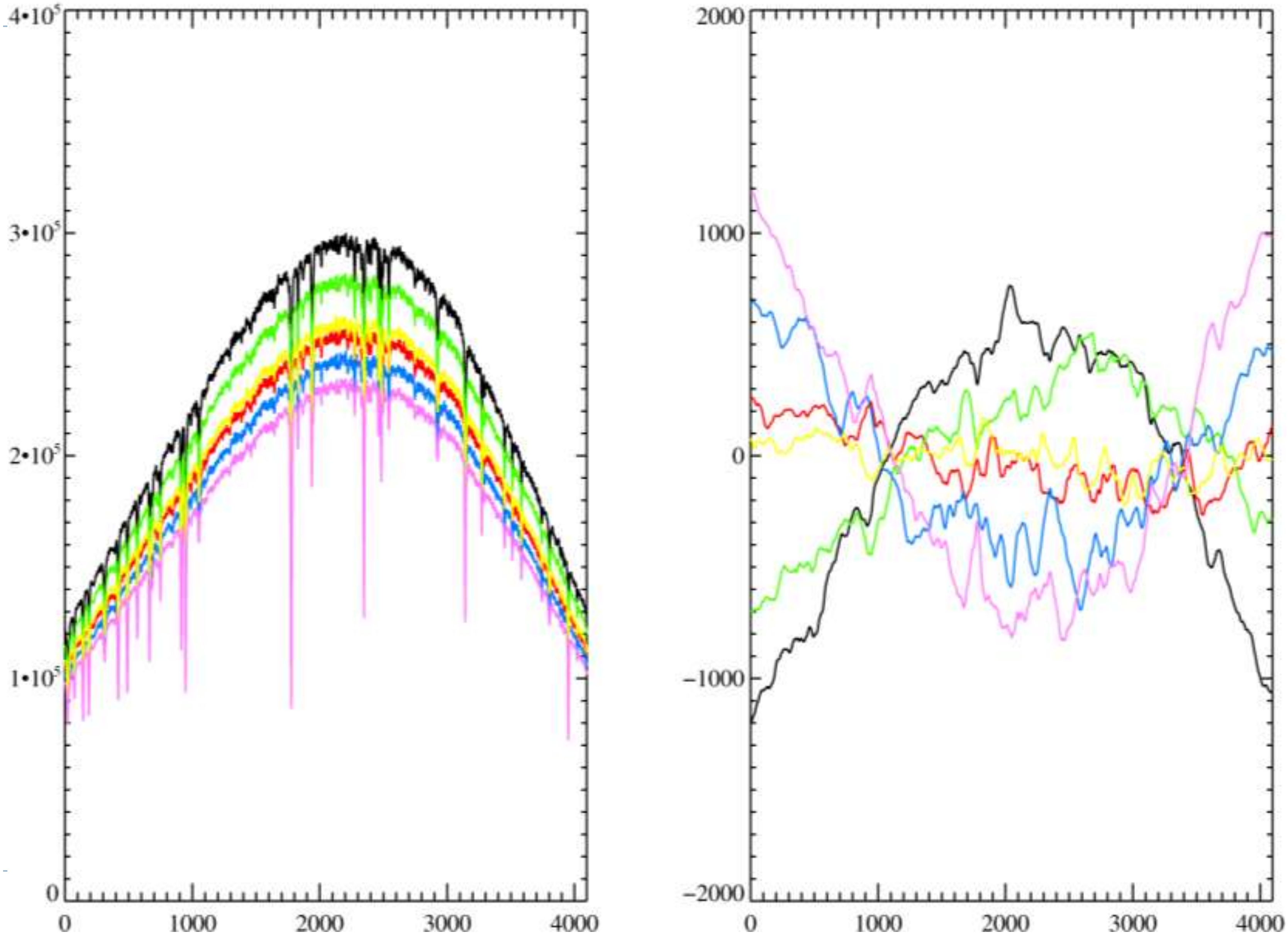
How reproducible are the extracted 1D spectra?



What do you think?



Seeing or guiding?

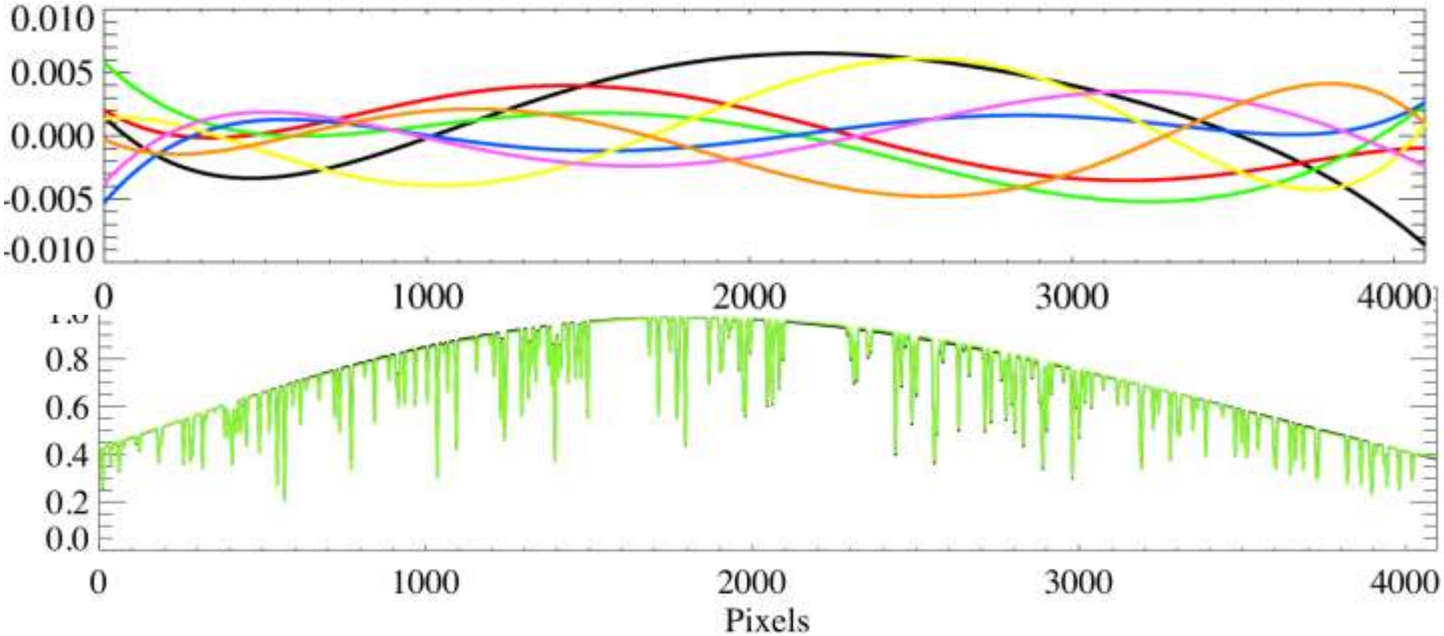


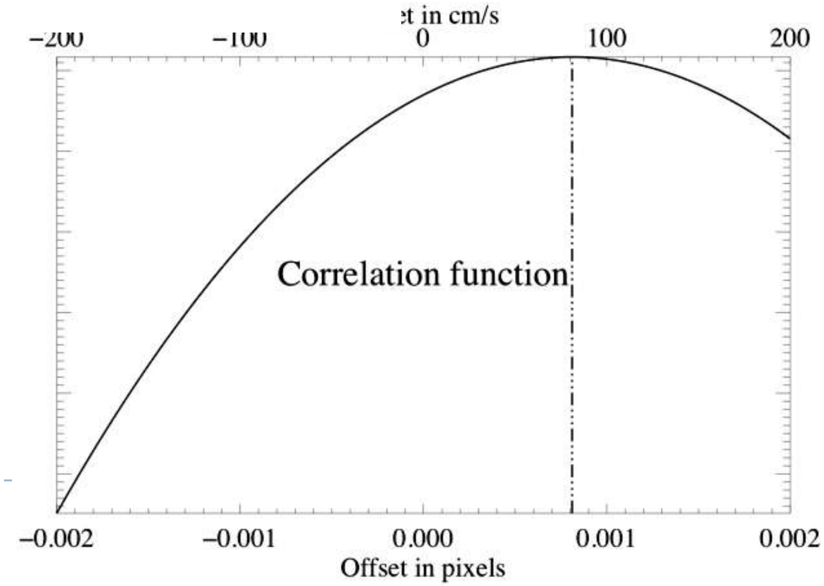
Now, what would this do the RV value?

Numerical experiment:

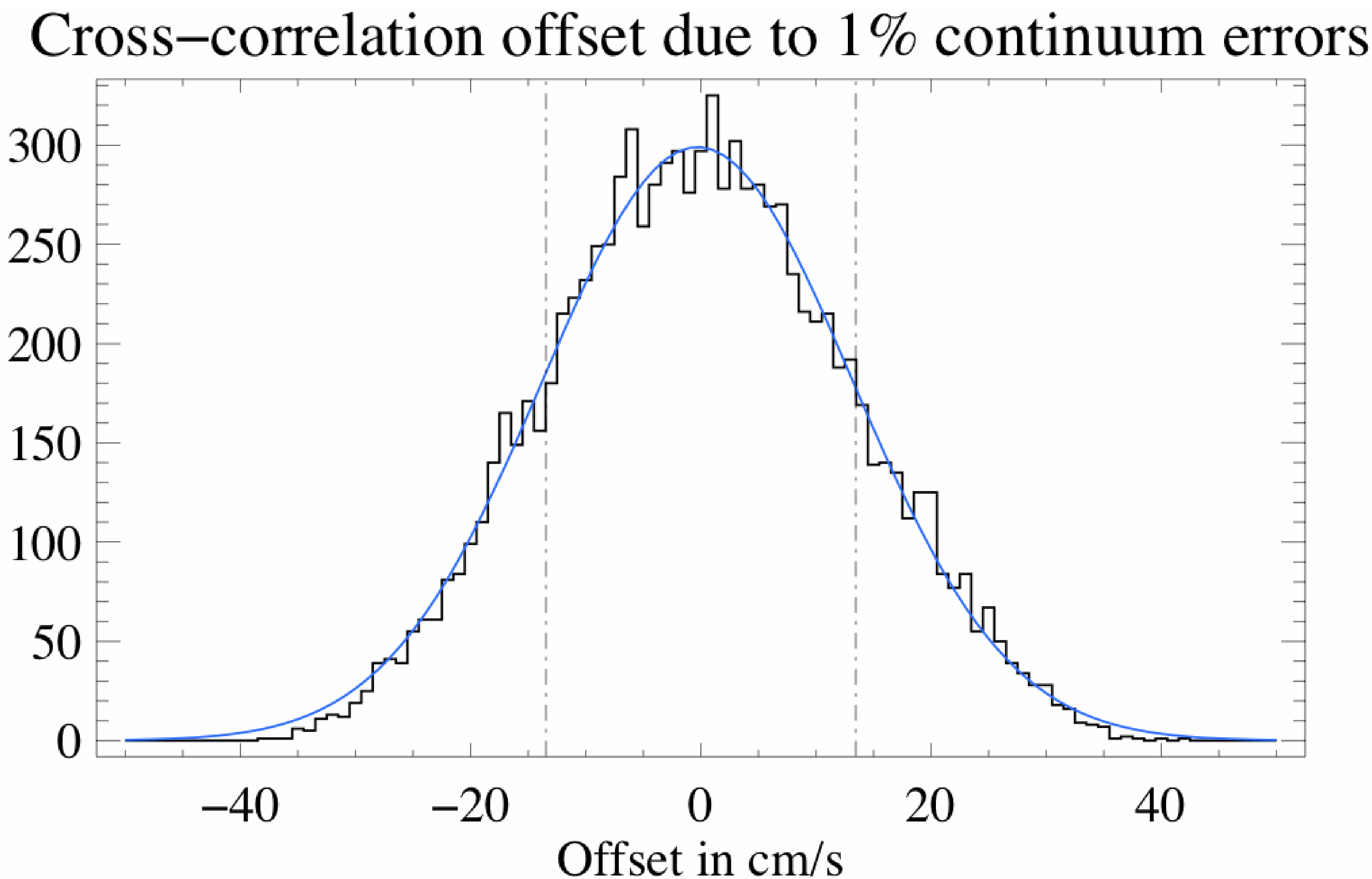
1. Take a spectral order
2. Perturb the intensity level: a smooth function with values between 0.99 and 1.01 and has 2-3 extrema across the order
3. Measure RV simulating cross-correlation and Iodine cell techniques
4. Repeat the procedure with different realizations of perturbing function

Perturbed spectral order and cross-correlations – single realization



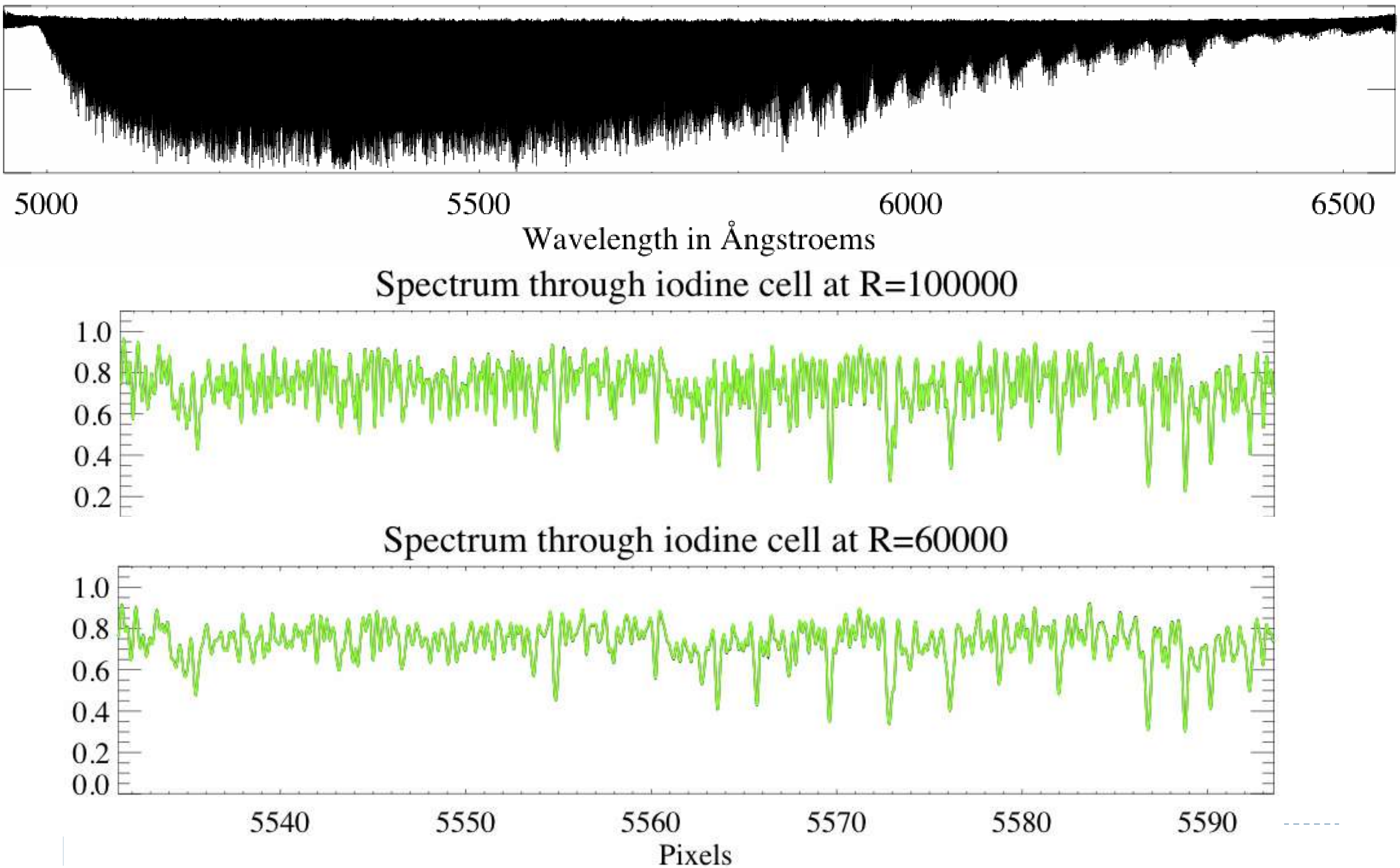


Statistics

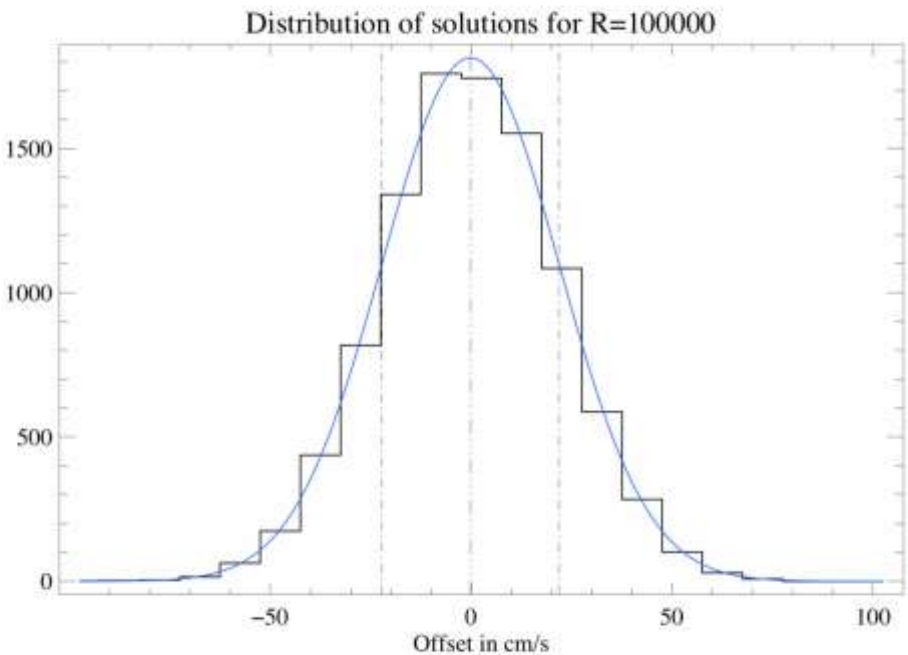


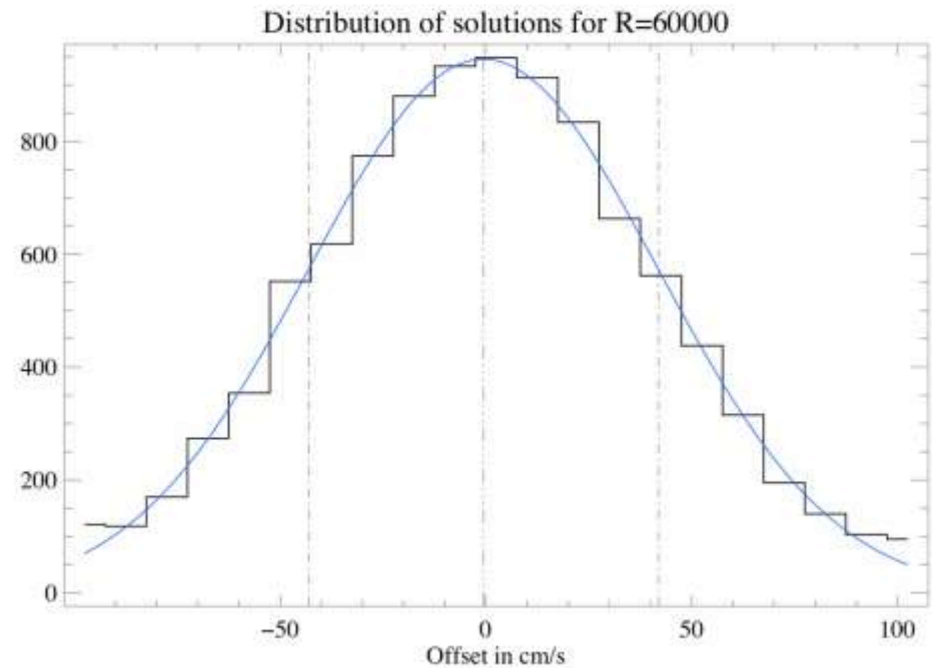
Cross–correlation offset due to 1% continuum errors
300
250
200
150
100
50
0
–40
–20
0
20
40
Offset in cm/s

HiRes: Iodine cell



Iodine cell


Distribution of solutions for R=100000
1500
1000
500
0
−50
0
50
100
Offset in cm/s


Distribution of solutions for R=60000
800
600
400
200
0
−50
0
50
100
Offset in cm/s

Conclusion 1

REPRODUCEABILITY

If the source we observe is constant (same SED and RV), our spectrometers calibrations and data reduction must give identical (within random noise) spectra!

Conclusion 2

Signal-to-noise ratio

Signal-to-noise ratio becomes much more important for super-precise RV measurements

Conclusion 3

CALIBRATIONS

Clearly the standard calibrations we do today are insufficient.

We know how to do very accurate calibrations for the wavelength.

The challenge is to calibrate the intensity to the precision of 0.1% or better.