Modeling the Image Distortion of Échelle Spectrographs with T & P Changes

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ABSTRACT
Even slight changes of temperature and pressure in high resolution Échelle spectrographs affect the spot image on the detector plane. At the same time astronomical applications require a stability of the measurement of up to 1/3000 of a pixel on the CCD (with a typical pixel size being 15 µm).

With this paper we present a study of the effects of thermal and pressure instabilities on ray tracing models of a typical Échelle spectrograph. We conclude the required minimum stability in these two parameters to reach the goal of precision spectroscopy.

Keywords: Spectrographs, radial velocity determination, planet finding, fiber coupling, FOCES, Fraunhofer Telescope Wendelstein

1. INTRODUCTION

Based on Doppler effect measurements precise radial velocity (furthermore RV) spectroscopy is a modern and often used tool to determine periodic radial velocity changes in stars. These changes, being attributed to either the presence of one or more planets, or to intrinsic pulsations of the stellar surface allow to detect extra-solar planets as well as to give us deep insight into the stellar interior.

While giant planets have been detected around hundreds of stars, the goal to go for low mass, probably Earth like planets on long period Earth like orbits requires enormous long and short term stability of the measurement equipment. Today’s best instruments are designed to recover RV signals of the order of tens of cm/s (about 1/10 of the speed of a pedestrian walking). According to Doppler's law, a signal of 1 m/s corresponds to a change in the wavelength of e.g. the Sodium D line at 590 nm of 1.9E-6 nm. Assuming a resolving power of a typical Échelle spectrograph of $R = \lambda/\Delta \lambda = 70000$ this corresponds to 1/4300 of a two pixel Nyquist resolution element or $\sqrt{2} \times 1/4300 \approx 1/3000$ of a single pixel.

As the period of a planet can reach many years the long term stability needed is also extremely high.

One crucial point in achieving high accuracy and stability of the instruments is to keep pressure and temperature in the spectrograph surrounding constant. This is necessary as changes in temperature affect the dimensions of the instrument through thermal expansion, glasses show variations of their properties with temperature, and air pressure changes result in changed refractive processes on air-glass-air surfaces.

Two different approaches to stabilize the spectrograph environment are being followed by contemporary instruments.

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Putting the whole spectrograph (or parts of it) into a vacuum chamber. This guarantees pressure stability and by preventing gas convection and conduction it makes thermal stabilization more easy. One contemporary instrument that follows this approach with great success is the ESO spectrograph HARPS [1] that has been designed for precision RV work.

Putting the spectrograph in several shells of thermal and pressure stabilized “boxes”, insulating it and pressurizing it. This approach is a more general purpose instrument method, that allows for easier maintenance and access to the spectrograph. It also avoids the use of vacuum proof materials and can be regarded a method to upgrade existing instruments at relatively moderate cost. The PEPSI [2] spectrograph is one example for this approach.

With this paper we explore the influence of temperature and pressure changes on a ray-tracing model of an existing spectrograph. Our goal is, to find reasonable estimates for the level of stabilization needed to do accurate RV work and to provide theoretical models that will in further work be confronted to measurements on the real instrument.

1.1 The spectrograph

Figure 1. Schematic drawing and photograph of the FOCES Échelle spectrograph.

Figure 1 shows a schematic drawing and a photograph of the FOCES spectrograph (see Pfeiffer et. al.[3]). FOCES was commissioned in 1997 at the 2.2m telescope of the Calar Alto observatory in southern Spain and since then been used successfully in many stellar astronomy and interstellar medium research projects. Basic data of FOCES are:

**Resolving power:** $R = 64000$ with 15 µm pixel size CCD.

**Spectral coverage:** $\lambda = 3800\AA \cdots 9000\AA$. (Orders overlap up to 7900Å.)

**Fiber link:** Telescope and spectrograph are connected via a 100µm silica-silica step index multi mode optical fiber. Light is coupled to and from the fibers using Fabry micro lenses glued to the fiber surface. A fiber-shaking device is used for mode scrambling (see Grupp [4]).

1.2 The spectrograph environment

Being set up in the Coudé room of the 2.2m telescope at 2160m height above see level FOCES experiences the un-stabilized air pressure condition of the observing site which normally varies around 780±30hPa. Temperatures in the spectrograph vicinity are 15±5 degrees Celsius. The spectrograph, having a approx 4cm thick insulation made from polysterene slowly follows these changes, damping short time temperature changes (open door, etc.).

It has to be noted, that wind around the telescope building, and the opening and closing of doors lead to second scale pressure variations on the order of 10 hPa in the Coudé room.
2. THE RAY-TRACING MODEL

We are using a ZEMAX∗ representation of the FOCES spectrograph. The model, shown in fig. 2 starts with the entrance slit not taking into account the Fabry micro lens and fiber exit. The last surface modeled is the detector plane.

While ZEMAX by default is able to model temperature and pressure dependencies of all refractive optical elements, including glasses and air, thermal coefficients of expansion (furthermore TCE) have to be assigned to the space between lenses and mirrors. In the case of our modeling we assigned a TCE of 13.0E-6 (stainless steel) to all distances between surfaces that are individually mounted on the optical bench (slit, collimators, échelle grating, fold mirror, prism and camera) and a TCE of 23.0E-6 (aluminium) to the distances between the individual lenses of the camera system and the space between the prisms.

Size changes of the échelle grating are not being modeled as it is grooved on a ZERODUR† substrate its TCE is below 0.1E-6/K. Effects introduced by thermal effects on anti reflection coatings or protection coatings are also not taken into account in this first step of our analysis.

Figure 3. The spot configuration modeled. The diffractive order is given in the plot, center wavelengths of the orders are - from top to bottom: 8743Å, 6608Å, 5518Å, 4777Å, 4148Å and 3840Å.

Figure 3 shows the 18 spots in 6 diffractive orders reaching from 3800Å up to 8700Å that have been modeled to cover the CCD area on a 2000×2000 pixel CCD detector with 15µm pixel size. Spot centers are evaluated using centroid fitting (functions CENX, CENY in ZEMAX).

∗ZEMAX is a trademark of ZEMAX Development Corporation, 3001 112th Avenue NE, Suite 202, Bellevue, WA 98004-8017 USA.

†ZERODUR is a trademark of SCHOTT AG, Hattenbergstrae 10, 55122 Mainz, Germany.
3. RESULTS

Based on the ray-tracing model presented in section 2 we calculated model centroid center positions for all 18 wavelengths for different pressures and temperatures. Table 1 states the pressure and temperature values used for modeling.

Table 1. Pressure and temperature variations modeled.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Base value</th>
<th>Variations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>800 hPa</td>
<td>±0.1hPa, ±0.2hPa, ±0.5hPa, ±1.0hPa, ±10.0hPa</td>
</tr>
<tr>
<td>Temperature</td>
<td>20°C</td>
<td>±0.01°, ±0.02°, ±0.05°, ±0.1°, ±1.0°</td>
</tr>
</tbody>
</table>

The resulting spot center changes for both pressure and temperature variations are shown in fig. 4. As a first result it can be noted that for pressure variations the main movement is along the cross order direction (y-axes). This is due to the fact, that the steepest and most affected glass-air transitions occur at the cross disperser double prism. Movements along the main dispersion direction are comparatively small for pressure changes.

Figure 4. Total change corresponding to the 18 modeled spot centers when pressure (left) and temperature (right) is varied according to table 1. The scale of both plots is pixels. The x-axes is parallel to the main dispersion direction of the grating, the y-axes is parallel to the dispersion direction of the cross disperser prisms. Please note the different scales of the x and y axes!
Being dominated by length changes of the optical bench and in the camera lens system the picture is less homogeneous for the spot movements induced by temperature changes. Again the system answer to changed conditions is largest in cross dispersion direction, but with much larger variations across the field of view.

In the next two sections we will address the two parameters varied in our analysis in more depth.

### 3.1 Pressure changes

![Image of spot center x (left) and y (right) movement when changing pressure by max\(\pm 10\)hPa.](image)
- Top panels: Absolute movement in pixels.
- Middle panels: Residuals when fitting a linear function to the data shown in the top panels.
- Bottom panels: Residuals when fitting a quadratic function to the data shown in the top panels.

As described in section 4 pressure changes act mostly in cross order direction. The change of the surrounding air's refractive index leads to changed refractive behavior at all glass-air and air-glass surfaces. As the transition angles are steepest at the 4 surfaces of the double prism cross disperser the pressure induced index change at these elements dominates the behavior. This fact is also illustrated in fig. 5. Y-axis movements are around \(\pm 0.2\) pixels for a pressure change of \(\pm 10\)hPa all over the CCD surface. Movements in x-axis - along the main dispersion direction - are about 1.5 orders of magnitude smaller and depend on the position on the CCD (see fig. 4).

Both, main- and cross-dispersion movement shows almost linear behavior with pressure changes. The mid panels in fig. 5 shows the residuals between simulated data and a linear least square fit to the data. With residuals being more than 5 orders of magnitudes smaller than the data values linear fitting already gives a very
promising approximation to represent the data well. This can even be improved applying quadratic fit functions (see bottom panels in fig. 5).

3.2 Temperature changes

Figure 6. Spot center x (left) and y (right) movement when changing temperature by max $\pm 1^\circ$.
Top panels: Absolute movement in pixels.
Middle panels: Residuals when fitting a linear function to the data shown in the top panels.
Bottom panels: Residuals when fitting a quadratic function to the data shown in the top panels.

Like in the pressure variation data, y-axes movement dominates the temperature variation data as well. With a total variation of $\pm 1.0^\circ$ a maximum spot center movement of $\approx \pm 0.2$ pixels is found. In contrast to the pressure change simulations the spot movement amplitude is now varying strongly across the detector surface for both axes. Again the movement in main dispersion direction (x-axis) is smaller than in cross order (y-axis) direction. This time the maximum amplitudes differ only by a factor of 0.4.

Applying linear fit functions to the data leads to significantly worse residuals as in the pressure change analysis. Still the fit is satisfactory regarding the fact that the residuals are still more than a factor of 1000 smaller than the data values.

The fact that main dispersion spot center movements are comparably large when temperature is being varied in our model will be important when estimating the limits for environment stability in the next section.
4. RESULTS AND DISCUSSION

As one goal of this analysis is, to estimate the stability range necessary to perform precision RV analysis using échelle spectroscopy, we will first have to define a reasonable value for the allowed movement on the detector CCD. As described on sect. 1 a signal of 1 m/s corresponds to a pixel movement per resolution element of $\approx 1/4300$ at the sodium D wavelength.

This movement is primarily considered to be in main dispersion direction. Nevertheless cross order direction movement do affect the RV stability as well. This is due to the fact that pixels with slightly different photon-electron efficiencies, bad pixels, traps, image distortion etc. lead to changes in the cross order integration of the total signal entering one (half) resolution element, when the image moves in cross dispersion direction. Ignoring cross order image movements would therefore be incorrect. At the same time it is extremely hard to evaluate the effect of cross order movement on the order spectra. We plan to carry out experiments on real systems in future. Grupp [4] shows that with well exposed spectra the fraction of non photon noise in the measured flux is normally well below 1/300 of the signal when comparing multiple exposures in a not stabilized system. We therefore conclude, that a conservative limit of cross order dispersion movement could be 1/100 of the value defined for main dispersion spot movement. This finally gets us to the point where we have to fix a value for ”allowed” movements along the spectral order.

4.1 Environmental stability

As the effects we consider are systematic movements we cannot help for much relieve from statistics. Nevertheless figures 4 through 6 show, that the x-movement (along main dispersion direction) is anti-symmetric with respect to the CCD center-line through x=0. We can therefore assume to gain a factor $1/\sqrt{2}$ in x-direction. Taking things together we find from the considerations in section 1 and the assumptions shown here a maximum ”allowed” x-movement of $\sqrt{2} \times 1/3000 \approx 1/2000$ pixels and a maximum allowed y-movement of $100 \times 1/3000 \approx 1/30$ pixels.

Having chosen these desired values, we can finally go back to our model calculations and translate these values to ”allowed” changes in environmental conditions.

For pressure changes we find maximum changes of 0.86 hPa in main dispersion and 1.8 hPa in cross dispersion direction using the simple linear model of figure 5. For temperature changes a maximum change of 0.10 K in main dispersion direction and 0.16 K in cross dispersion direction is found using the linear model shown in figure 6. At this point we explicitly state that these values are based on a simple model calculation and on our choice of what we assume to be a reasonable limit of movement. They will have to be verified in a more sophisticated model and even more important under controlled laboratory conditions. Especially the experiments will show whether these assumptions prove to be reasonable or if they have to be tightened or refined. Nevertheless, the model in its present form is necessary to plan the corresponding lab experiments.

In an overall view, the applied model and its assumptions lead to the conclusion, that environmental stability should reach a value better than 0.8 hPa and 0.1 K to do RV spectroscopy in the m/s region.

4.2 Shortcomings of the model

Being a quite idealized representation of a real spectrograph system our model does not consider some aspects that might be important in a more refined analysis.

Grating length changes Length changes due to thermal expansion affecting the ruling density of the échelle grating have not been modeled. As the linear dispersion is straight proportional to the ruling density, and as the ruling density is straight proportional to the length changes the linear dispersion changes by not more then 0.1E-6/K (TCE of ZERODUR). At a distance of 800 pixels away from the center of a spectral order this would account for only 8.0E-5 pixels for a 1 K change of grating substrate temperature.

Coatings Coatings and their thickness being affected by temperature variation as well as their air-coating and coating-air transition refractive index dependency on pressure are not modeled. Besides the anti reflection coated glass surfaces this affects the protection coatings of collimators, fold mirror and grating.
Mounting issues The most severe issue as far as the current mechanical setup of FOCES is concerned is the thermal behavior of the mechanics holding the optical components. Especially grating and prism mounts are asymmetric with respect to the grating angle and prism rotation axes. As FOCES was not designed as a RV instrument no attention was drawn on this fact during design and especially the grating mount acts as “thermometer” translating length changes of the micrometer screw and mechanics adjusting the grating angle to movements of the spectral orders on the CCD. This design shortcomings will be removed and a fixed, symmetric geometry chosen before lab tests with FOCES are going to be performed. Figure 7 shows the mechanical setup of the FOCES grating angle alignment.

These effects will have to bee addressed in more detail when setting up the lab system.

5. SUMMARY

We have shown a ray-tracing model to mimic the FOCES spectrograph. This model is being used to evaluate environmental stability conditions for precision RV spectroscopy. In our simplified model, a pressure stability of about 0.8 hPa and a temperature stability of about 0.1 K should be a good starting point to perform lab experiments on the stability of the instrument. Both, pressure and temperature stability of these orders of magnitude seem to be possible to achieve looking for example on the experiences with the PEPSI spectrometer [2].

In fact we plan to use FOCES as a full scale test spectrograph in the lab to test these sort of environmental influences before FOCES will go to the new Fraunhofer Telescope Wendelstein (see Hopper. al.[5]). In order to do these tests on a highly precise level we plan to incorporate frequency comb wavelength calibration into our lab setup. A thermo electrically cooled CCD system and some mechanical changes to FOCES will complement these efforts to turn FOCES into a RV instrument.

Beyond the FOCES project our results can be valuable for many échelle spectrographs already in use as we plan to concentrate on stabilization methods that can be applied to existing instruments.

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REFERENCES


