Detector related challenges for high-precision radial-velocity spectrographs

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Radial velocities (RVs) dominated the first fifteen years of exoplanet science, providing exciting discoveries and delivering the first statistical constraints on planet occurrence around a wide range of stars. With the field of exoplanets now in its third decade, the RV technique remains at the forefront of the field due to its unmatched sensitivity to planets around nearby stars and its important supporting role for exoplanet transit discoveries. A measurement precision of 1 ms^{-1} marks the state-of-the-art in the field but new instruments are pushing this limit to 30-50 cms^{-1} now, with the ultimate goal of discovering signals at the 10 cms^{-1} level - the signal our Earth imparts on the Sun. Detector systematics emerge as one of the remaining great challenges to obtain this precision.

The RV challenge

RV spectrographs have a typical resolving power of R=80,000 to 120,000. At this resolution, a shift in the spectrum equivalent to 1 ms^{-1} is 1/3000 of a resolution element or about 1/1000 of a pixel. Hundreds to thousands of spectral lines have to be analyzed in any given spectrum to reach this level of precision. The goal of reaching a measurement precision ten times of the current state-of-the-art pushes this requirement to detecting signals as small as 1.5 nanometers in the detector focal plane.

RV measurements have some commonality with high-precision astrometry. Shifts in the center of a line (in our case absorption features in a continuum) are measured in two dimensions, with one dimension (the main dispersion) carrying the bulk of the RV information. These measurements are relative to a fiducial, in most cases the emission spectrum of a ThAr lamp, an etalon, or a laser frequency comb (see Fig 1).

The challenge is to stabilize the instrument and its illumination such that measurements of the fiducial spectrum are applicable to the science spectrum to the minute levels outlined above over timescales of days to years. RV spectrographs are thus highly stabilized instruments under vacuum and tight temperature control (down to 1mK for the echelle grating). The spatial distribution of the light, both in the image and pupil plane is homogenized by non-circular optical fibers and special scramblers.

The field has reached a point where illumination effects and instrumental stability are no longer the dominating factors. Instead, calibration sources and detector effects remain as the most promising areas to improve the capabilities of RV spectrographs.

The low-hanging fruit: CCD inhomogeneities

Pixel boundary inhomogeneities from mask stitching effects create discrete jumps of tens of ms^{-1} in the wavelength solution of a spectrograph. They were first discovered in 2010 when laser frequency combs replaced traditional cathode lamps as spectral fiducials, providing a dense forest of regularly spaced emission lines. Once identified, these features can be corrected for, or better avoided in the first place by using full-size masks.

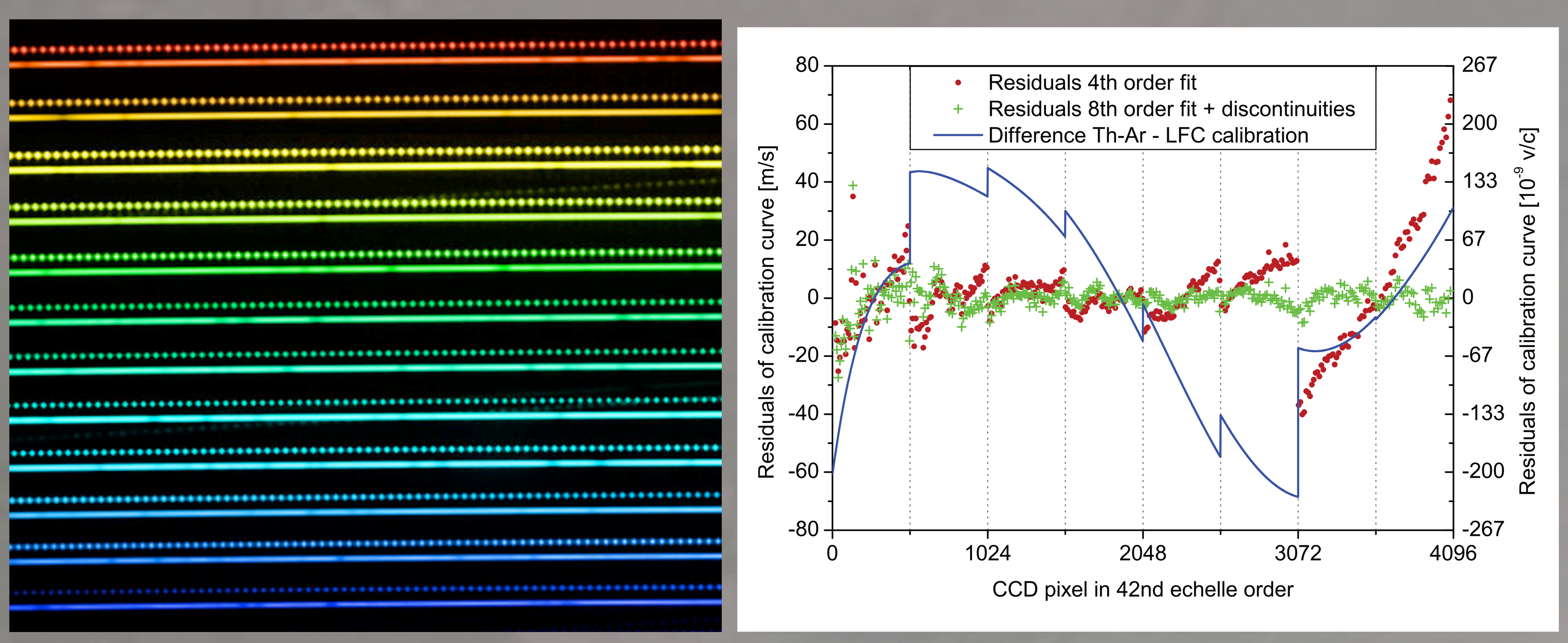

Figure 1 left: An example of the echelle spectra of a laser frequency comb (top) and a stellar spectrum (bottom), highlighting the evenly spaced emission lines of the LFC. (Courtesy: ESO). Right: The LFC spectrum revealed the stitching effects of the CCD previously un-identified in the sparse ThAr calibration spectra (Fig. 4 of Wilken et al. 2010, MNRAS 405). Note: 10 ms^{-1} is approximately 1/100 of a pixel or 150 nm.

Temperature stability effects

The readout of a CCD is creating a temporal heat source that leads to the expansion and subsequent contraction of the device in a non-homogenous way, effectively shifting the pixel centers of the CCD by minute, but noticeable amounts for the subsequent exposure. Ultra-stable and symmetric mounts as well as additional heating during the integration phase of the exposure can be used to mechanically stabilize the CCD. The latest generation of CCDs from STA Inc. have temperature sensors integrated on the chip itself and a thermal time constant ~50% lower than traditional CCD packages. This allows for the first time true sub-mK control of the CCD temperature and fast response times to varying heat load conditions.

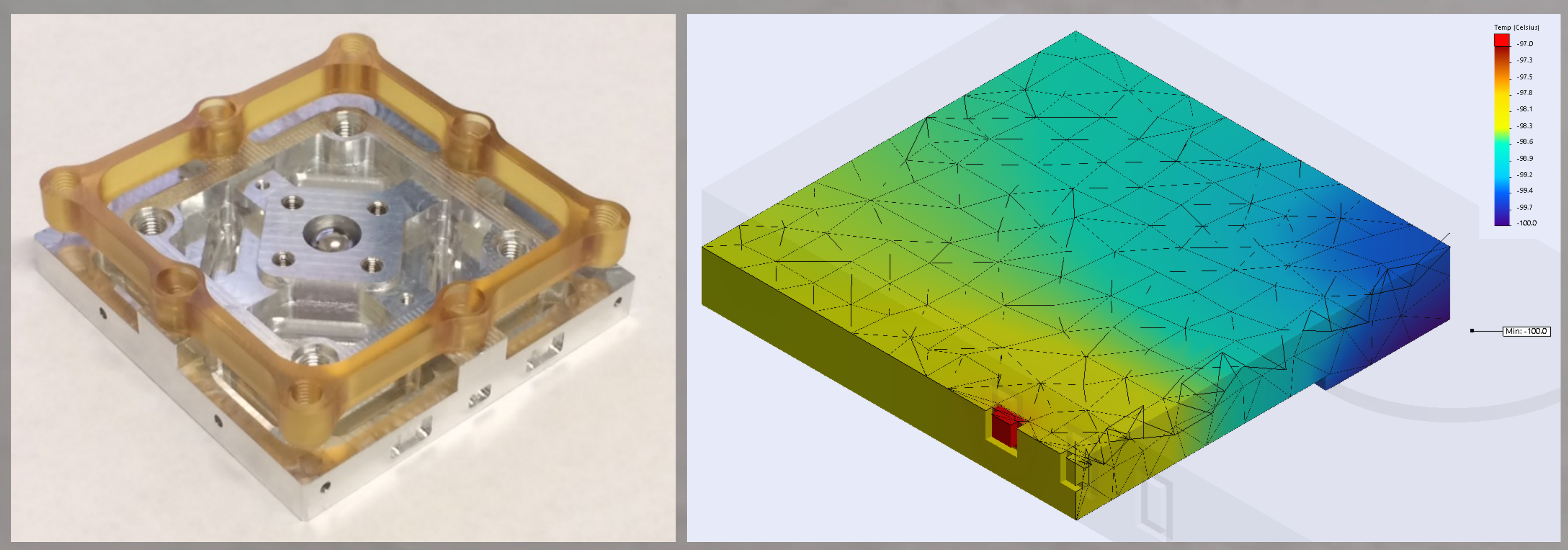

Figure 2 left: Prototype of the STA4850 CCD package allowing a symmetric mounting scheme with superior stiffness and an advanced temperature control mechanism. Right: FEA figure showing the steady-state temperature distribution inside the the STA4850 CCD package after settling with a total load of 1.77 W. Several temperature control and stabilization mechanisms are available for this new detector package.

Piling it on: Thick high-rho devices

The latest sweep of new RV instruments is extending its reach out to 900nm to make use of the exciting opportunities offered by detecting and characterizing exoplanets around mid to late M-type stars. Among them is MAROON-X, a spectrograph developed and build at the University of Chicago for deployment at the 8m Gemini North Telescope in early 2019. MAROON-X has two arms. The blue arm, covering 500-670nm is using a 4k x 4k, 30µm thick, epitaxial silicon STA4850 CCD. The red arm covers 650-900nm with a 4k x 4k, 100µm thick, high-rho silicon version of the same chip. Great care has been taken to optimize this chip for RV spectrographs by removing stitching errors altogether (see Fig. 1) and providing superior mounting and temperature control schemes (see Fig. 2).

While providing excellent QE and low fringing out to 900nm, a thick high-rho device adds other complications to the RV challenge. Among them are effect well know by now, such as

- Charge dependent CTE effects,
- Tree rings,
- Charge diffusion and the related brighter-fatter (B-F) effect.

Being more than an order of magnitude more sensitive to these effects than astrometry, careful characterization and compensation is essential for MAROON-X and other spectrographs to break the 1 ms^{-1} barrier.