Infrared Spectrograph Calibration Issues: Using CRIRES, the High Resolution Infrared Spectrograph for ESO's VLT as an Example

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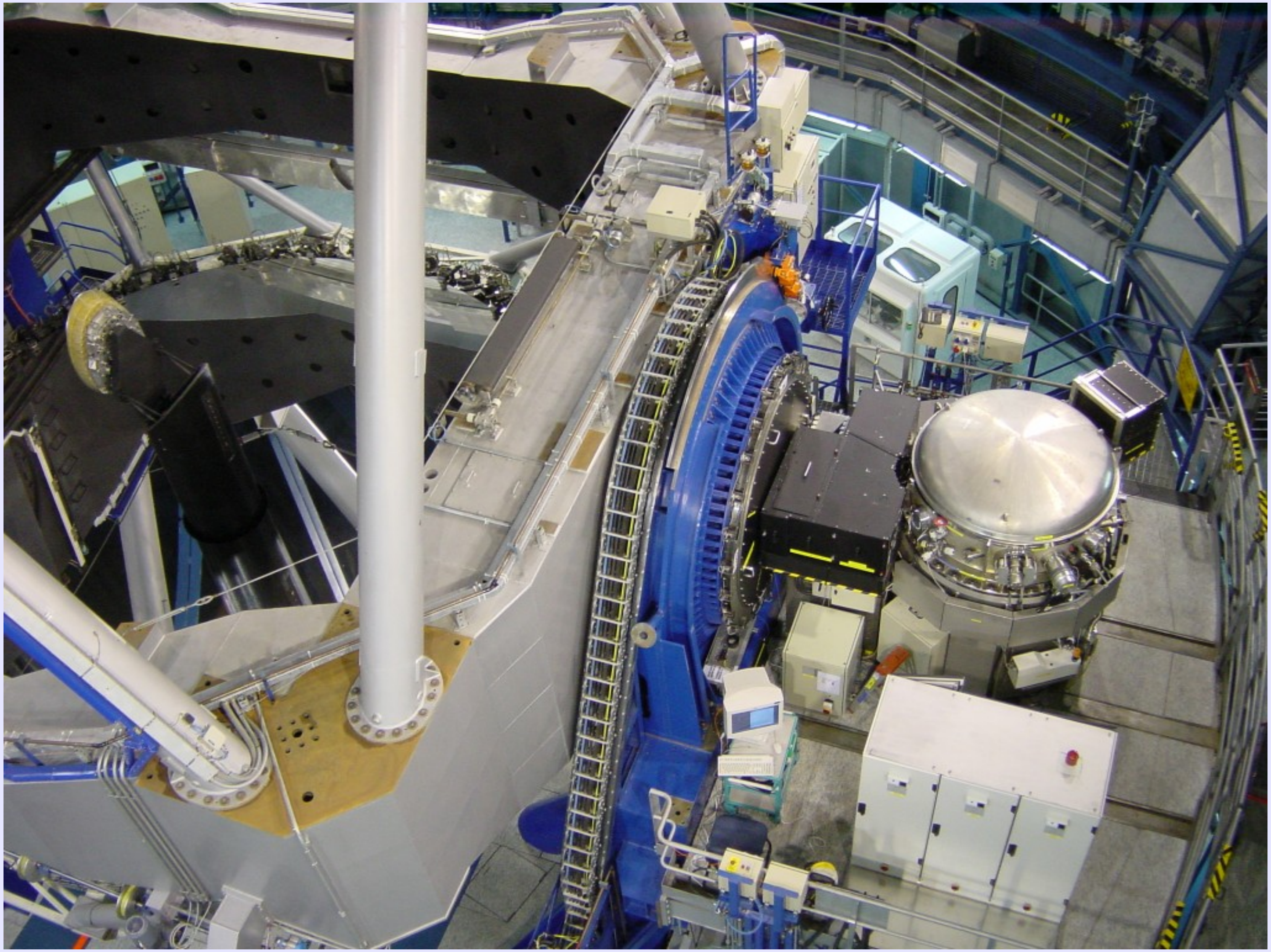


◄ UT1 Nasmyth-A with CRIRES after commissioning 2 and science verification in August 2006

CRIRES:

Cryogenic Infrared Echelle Spectrograph

The team standing behind CRIRES:

Paola Amico, Pascal Ballester, Peter Biereichel, Paul Bristow, Mark Casali, Bernhard Delabre, Reinhold Dorn, Siegfried Eschbaumer, Raul Esteves, Enrico Fedrigo, Gert Finger, Gerhard Fischer, Gordon Gillet, Domingo Gojak, Michael Hilker, Gotthard Huster, Yves Jung, Florian Kerber, Jean-Paul Kirchbaumer, Jean-Louis Lizon, Lars Lundin, Enrico Marchetti, Leander Mehrgan, Manfred Meyer, Alan Moorwood, Sylvain Oberti, Jerome Paufique, Jean-Francois Pirard, Eszter Pozna, Francesca Primas, Hughes Sana, Ricardo Schmutzer, Andreas Seifahrt, Ralf Siebenmorgen, Armin Silber, Alain Smette, Barbara Sokar, Jörg Stegmeier, Lowell Tacconi-Garman, Sebastien Tordo, Stefan Uttenthaler, Elena Valenti, Jakob Vinther, Burkhard Wolff

and many more in Garching, Paranal and/or Vitacura

many thanks to all of them!

CRIRES genealogical tree:

IRSPEC (1986) TIMMI (1994) SOFI (1998)

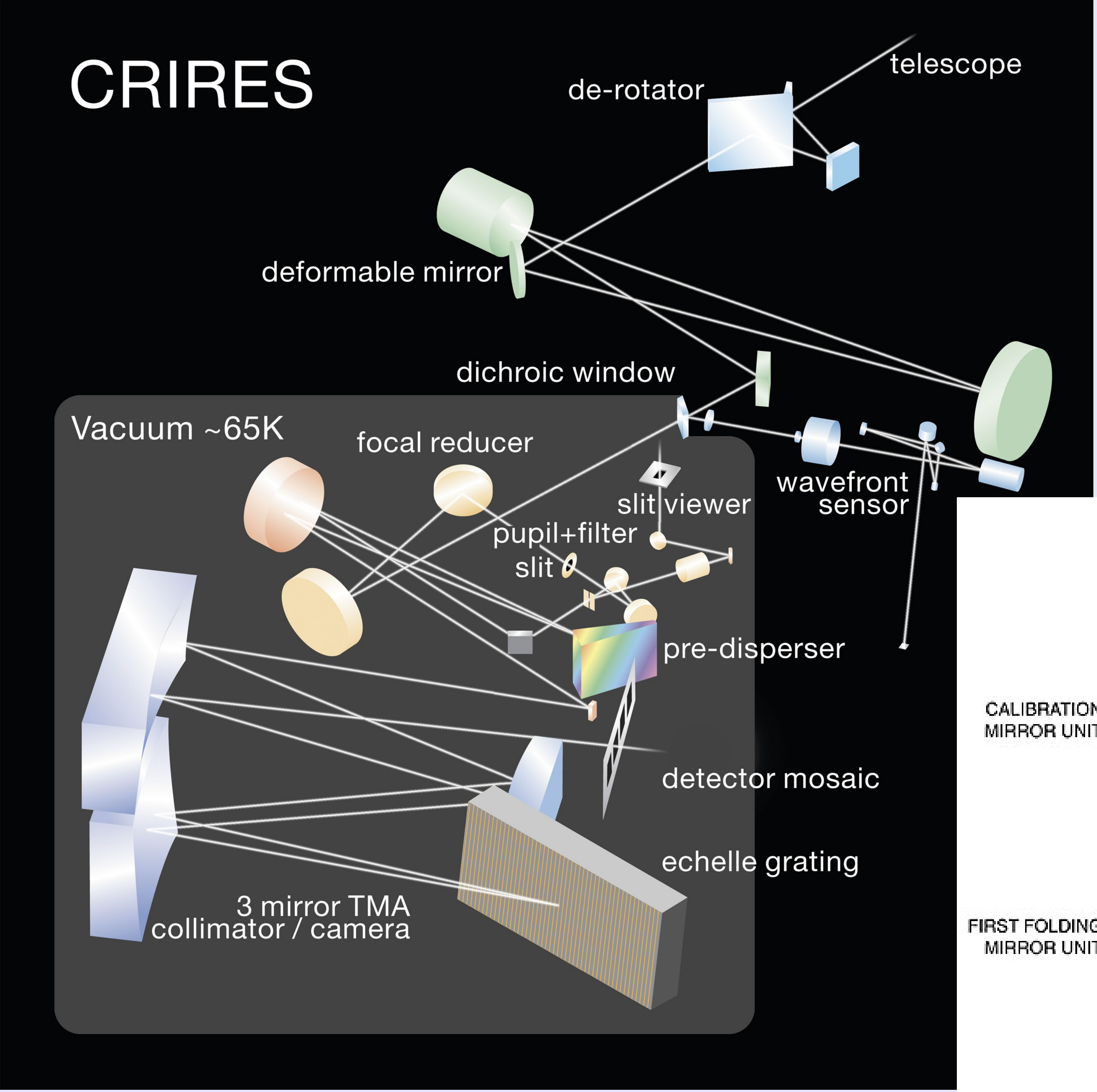
ISAAC (1999) TIMMI2 (2000) VISIR (2004)

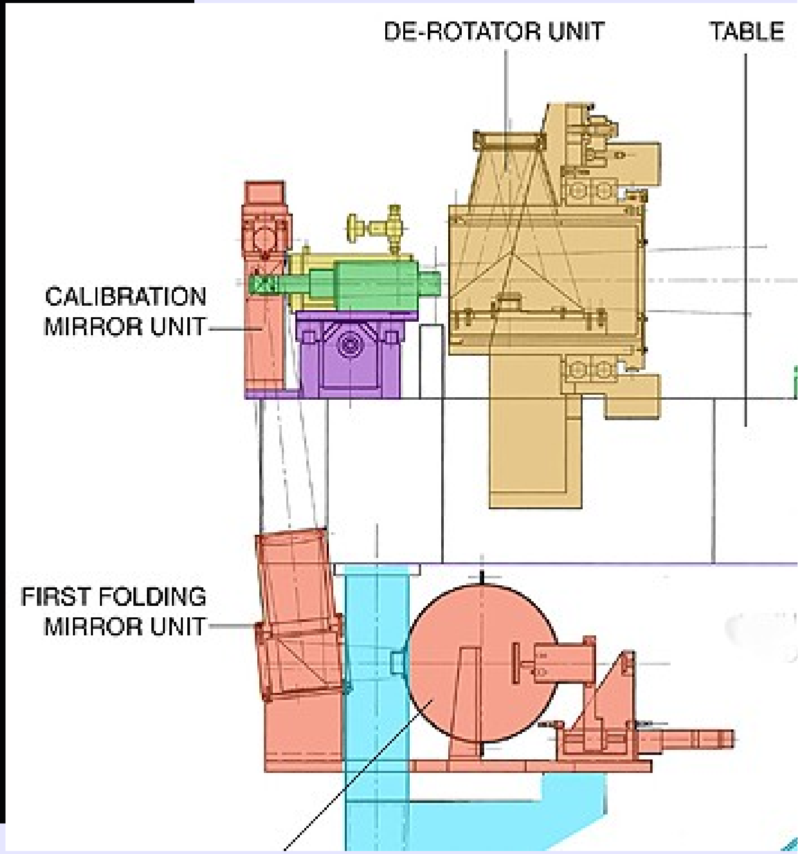
Outline:

CRIRES

- **general calibration issues:**
  ☞ scale along slit
  ☞ scale of slit viewer
  ☞ position angle on sky
  ☞ differential effects
  all those are identical to optical spectrographs
  thus not dicussed
- **infrared specific issues**
  - molecules are everywhere
  - in the IR it is always high resolution spectroscopy, even filter imaging
  - special considerations for absorption lines
  - spectro-photometry
- **CRIRES specific issues and solutions**

Schematics of CRIRES

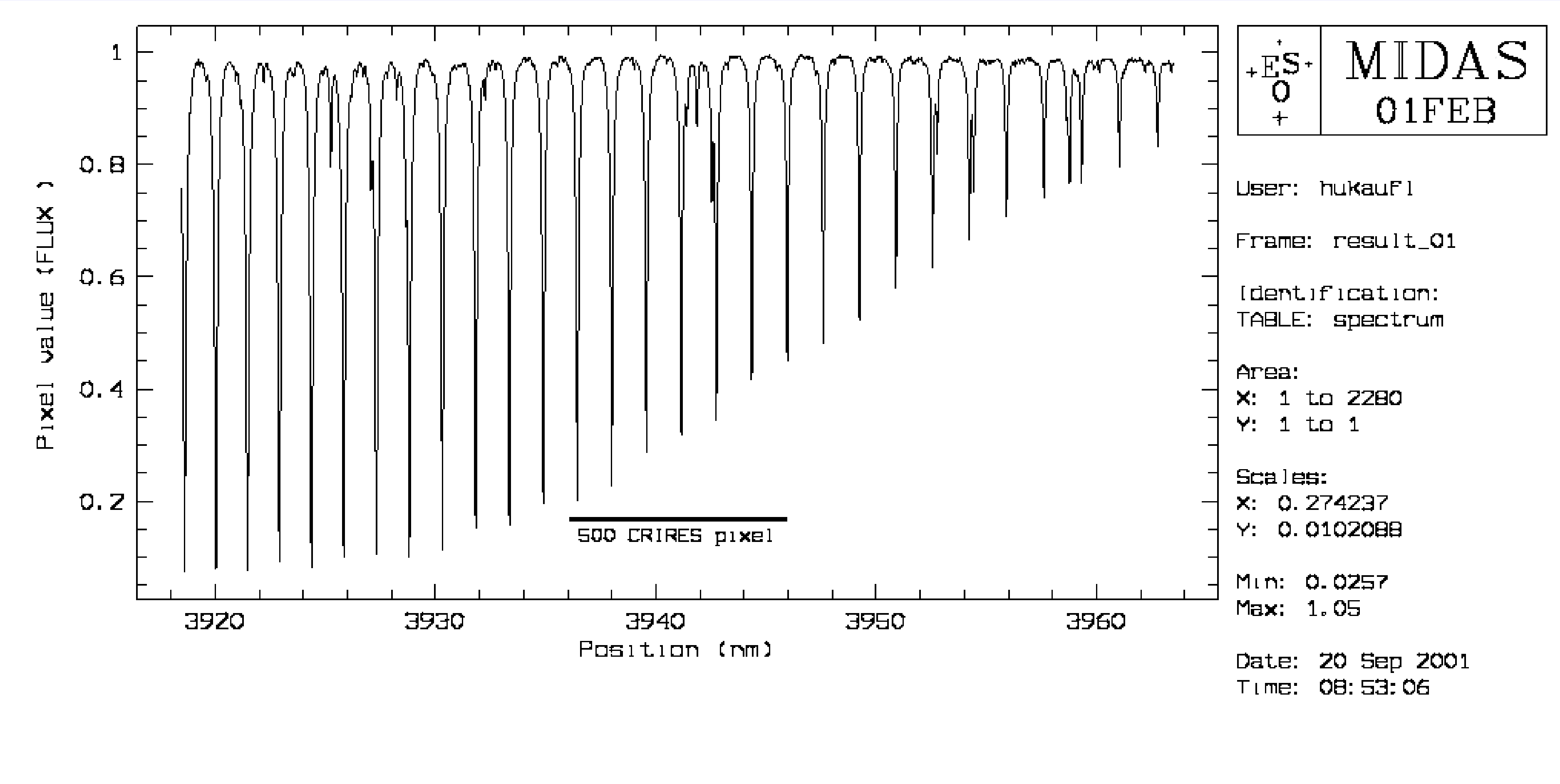




CRIRES main characteristics

- **wavelength coverage:** $\lambda \sim 950 - 5200$ nm
  $\nu \sim 58 - 310$ THz
- **spectral resolution:** $\lambda / \Delta\lambda$ ($\nu / \Delta\nu$) $\approx 10^5$ or $\Delta v \approx 3$km/s
  (2 pixel Nyquist sampling)
- **array detector mosaic:**
  4 x 1024 x 512 Aladdin III InSb mosaic
  ☞ instantaneous λ - coverage > 2.0 %
  pixel scale 0.1”/pix
- **infrared slit viewer** (Aladdin III) with J,H & K-filters
- **precision** for calibration and stability ~ 75m/s
  i.e. 1/20th of a pixel or 5 mas tracking error
- Piezo-electric actuator in pre-disperser collimator for
  vernier adjustment of spectrum on detector
  using sky-lines or fiber-injected light as reference

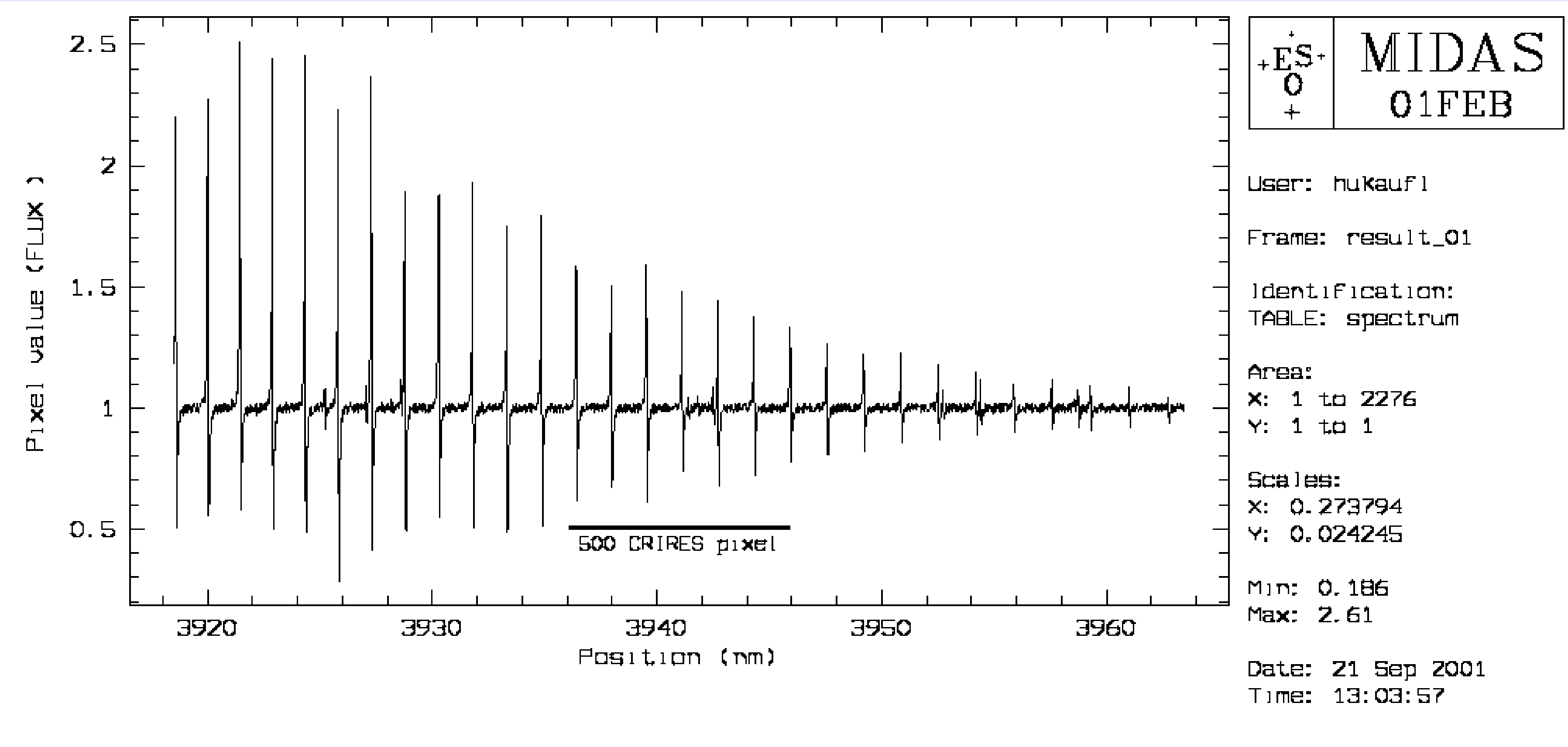
Why spectrum stability ~ 75 m/s ?



rebinned telluric FTS-spectra (McMath data) around 4000nm:

- astrophysically relevant region: overtones of SiO & Brackett α
- spectral resolution and stability requirements for CRIRES set by science **and** by the need to reject telluric lines

spectrum stability ~ 75 m/s ?

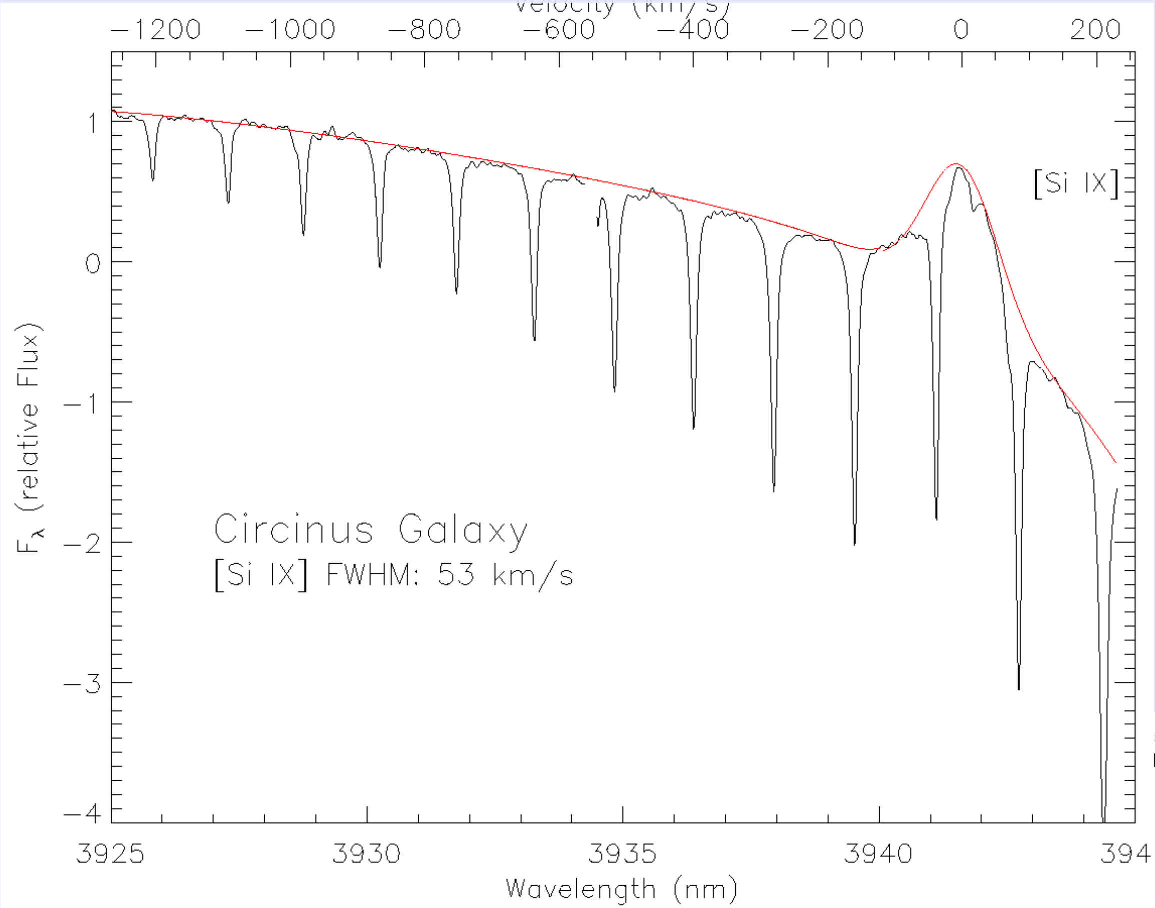


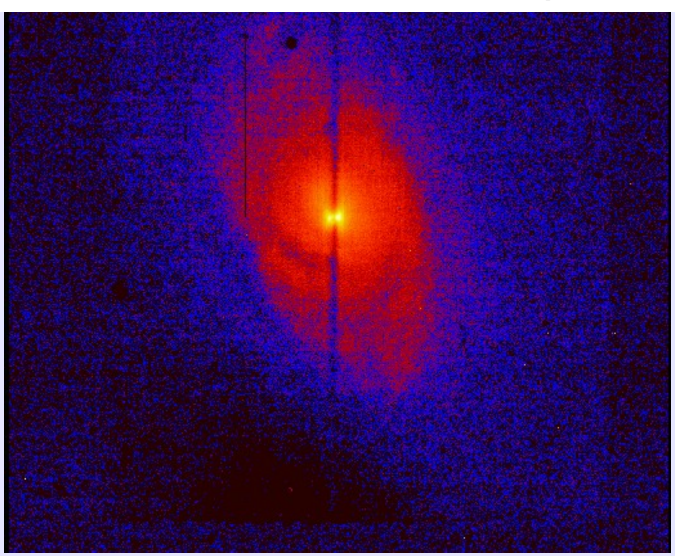
- result spectrum in case of 0.5 pixel "flexure" or "calibration error" between science exposure and calibration exposure
- => effect is only tolerable, if differential effects ≤ 0.05 pix
  (minimizes the need for "fudging" in the pipeline software &
  renders flat-fielding uncritical)

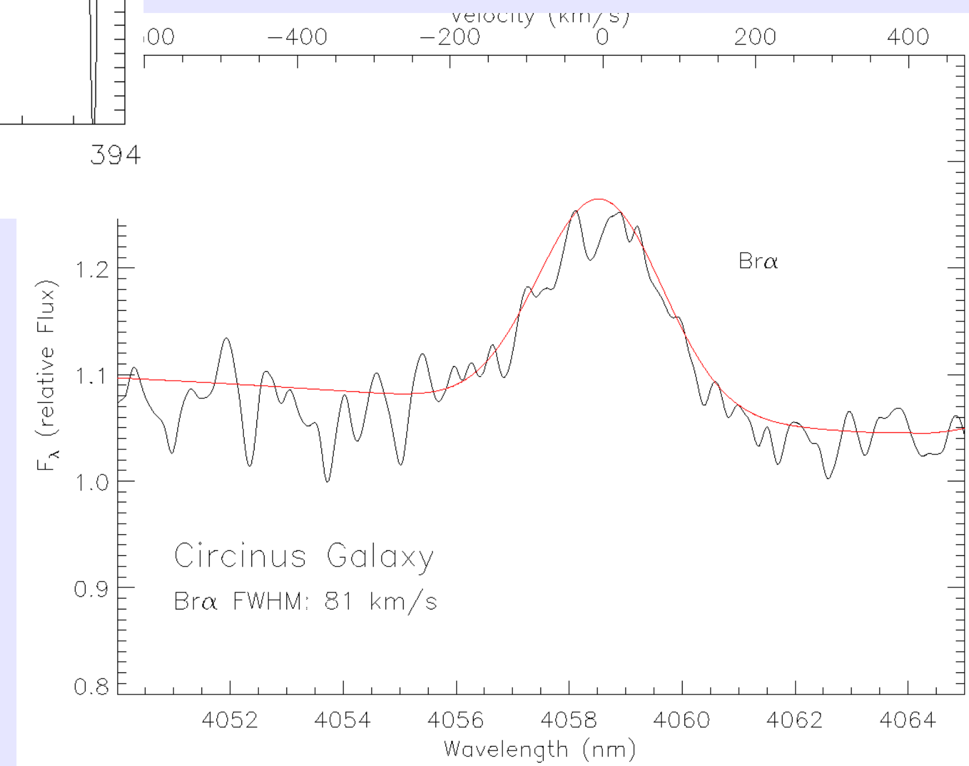
spectra of closest known AGN:

Circinus @ 4000nm

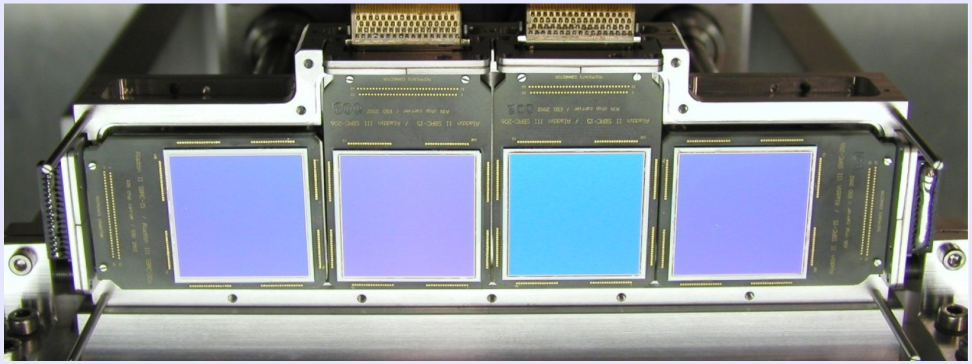
=> $\lambda / \Delta\lambda_{relevant} \neq \lambda / \Delta\lambda_{source}$



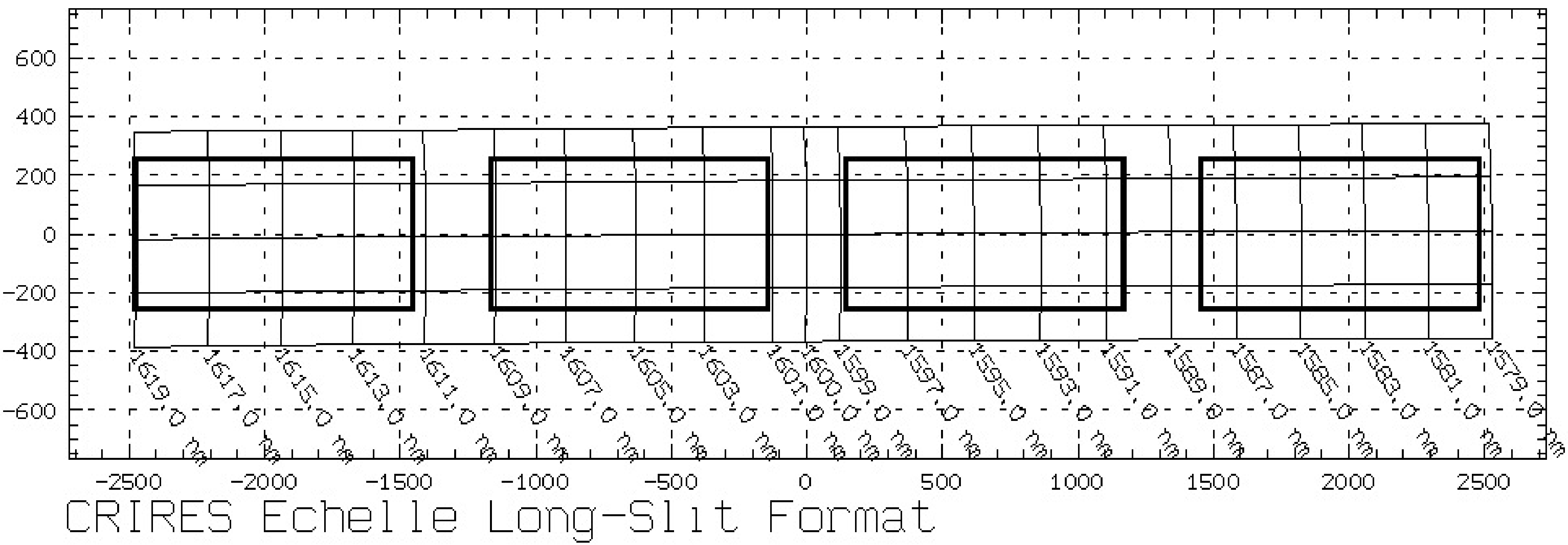




CRIRES spectral format



▼example of how the interval
λ 1579.0 - 1619.0 nm
is mapped on the array



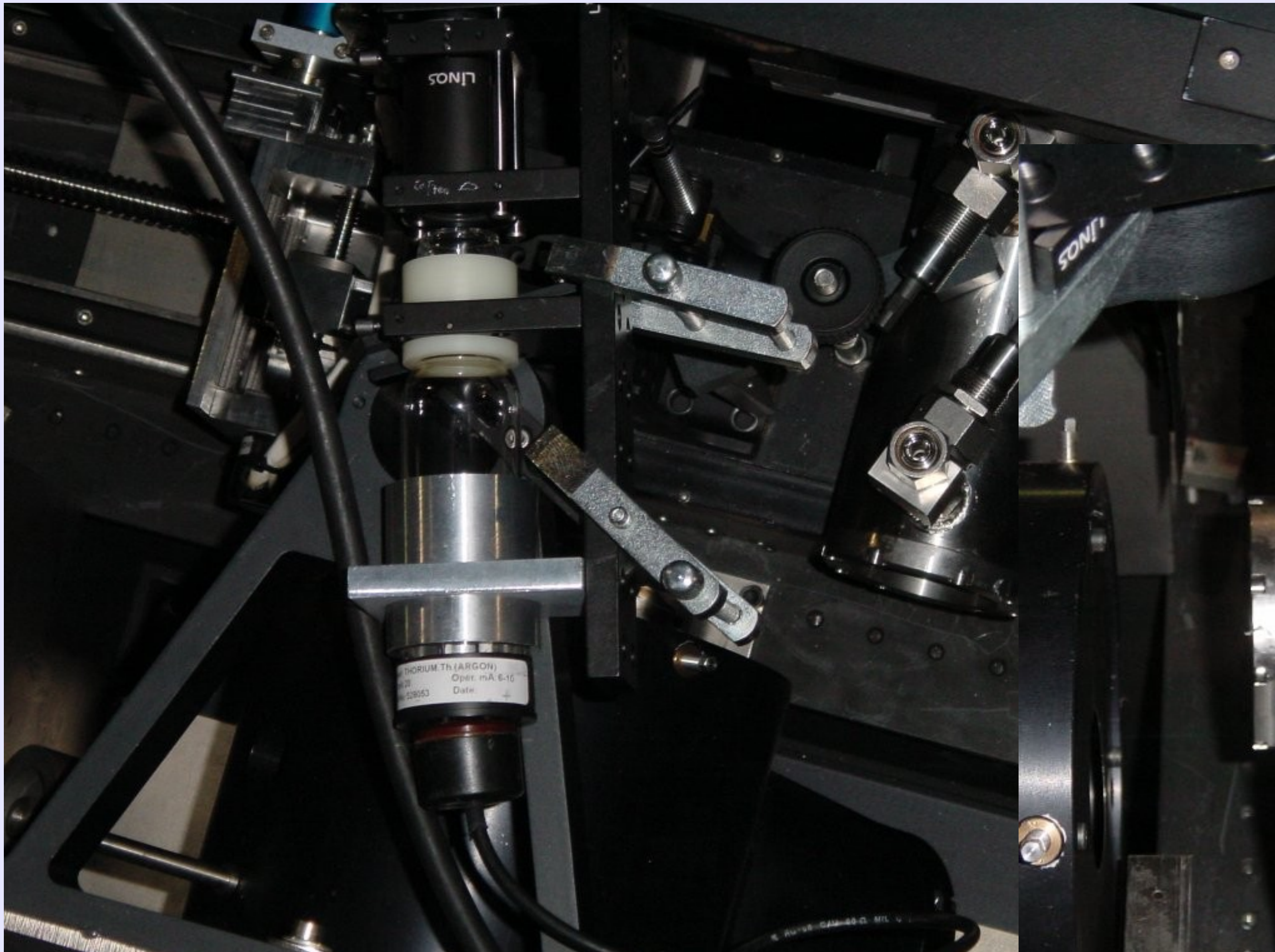
frequency calibration

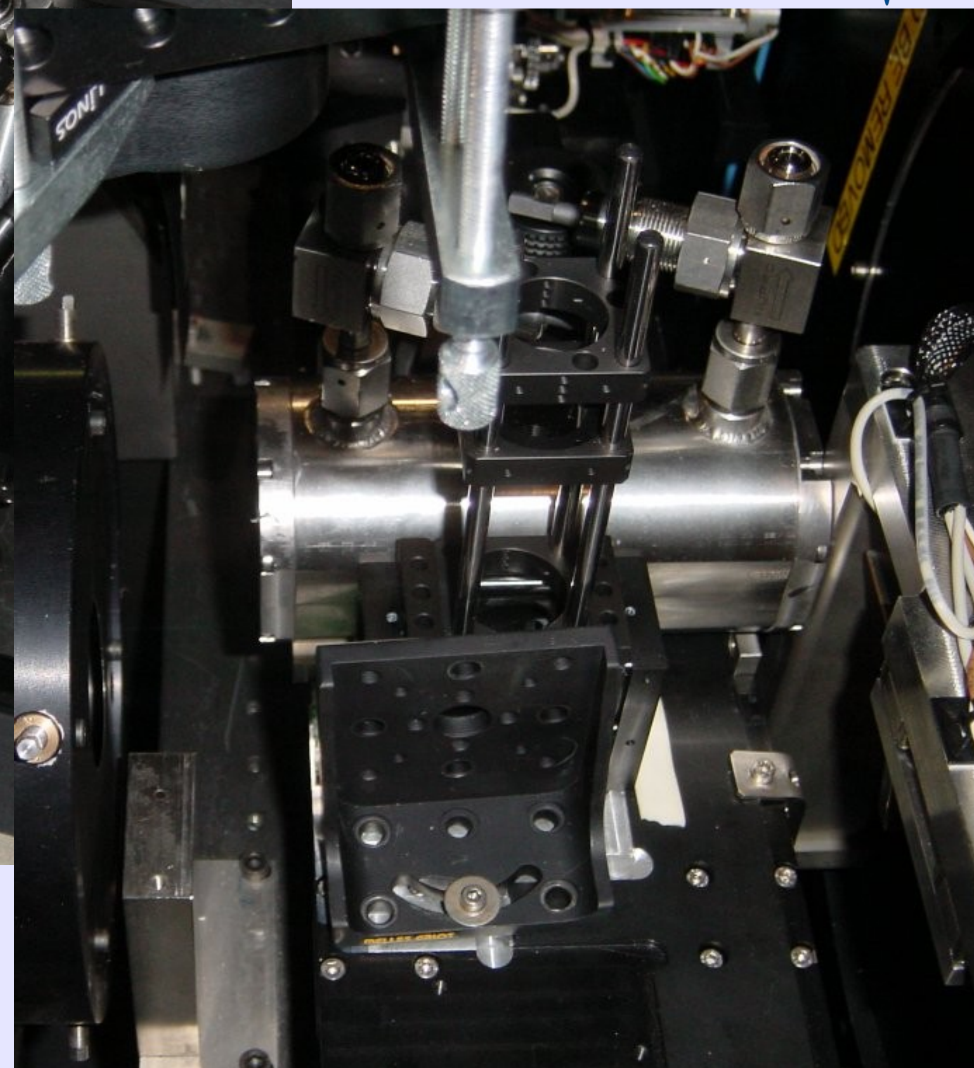
CRIRES

- **general calibration lamp requirements:**
  ☞ sufficient line density
  ☞ wavelength range 1000 – 5200 nm
  ☞ uniform illumination of pupil and slit
  ☞ reproducible
  ☞ NIST/PTB traceable
- **potential infrared calibrators**
  - atmospheric lines, non-thermal: air glow
  - atmospheric molecular absorption lines
    note: for $\lambda > 2000$nm also in emission
  - gas discharge lamps (Ne, Kr, Ar)
  - hollow cathode lamps (ThAr)
  - gas cells with or without back-illumination
  - IR lasers (e.g. HeNe)

CRIRES wavelength / frequency calibration

CRIRES





top: ThAr lamp
right: ThAr re-imager, gascell (N_2O)

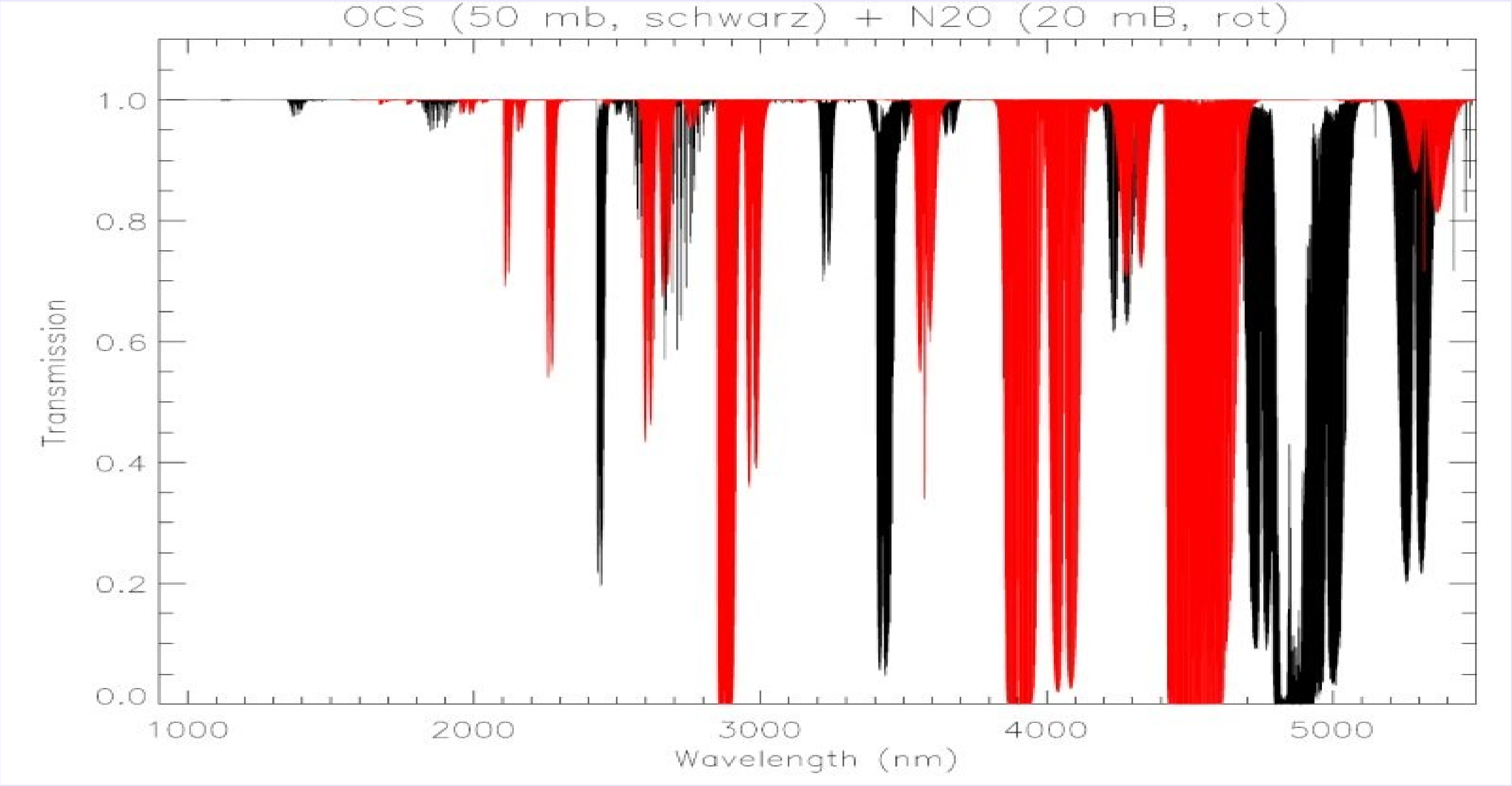
frequency calibration trade-offs

CRIRES

source	*λ – range [nm]*	*brightness*	*line-density*	*operational constraints*	*absolute precision*
OH-airglow	950 – 2000	acceptable	marginal	needs tel. @ night	~20m/s (tbc)
atmospheric absorption lines	950 – 1900	na	marginal to acceptable	not for long-slit mode	~15-20m/s (tbc)
	1900 – 5200	acceptable – good	acceptable to good	needs tel. @ night	~ 15-20ms (tbc)
gas cell absorption (std)	2000 - 5200	acceptable – good	good to very good	cumbersome operations	< 1m/s ν **absolute (!)**
gas discharge lamps	950 – 2500	very good	inappropriate	none	< 10 m/s
hollow cathode lamps	950 – 2500	marginal	good to very good	illumination compromises	< 10 m/s (c.f. P 17)

☞ pointing errors limit precision to 50-100 m/s
(Bowen-Walraven image slicer under study)

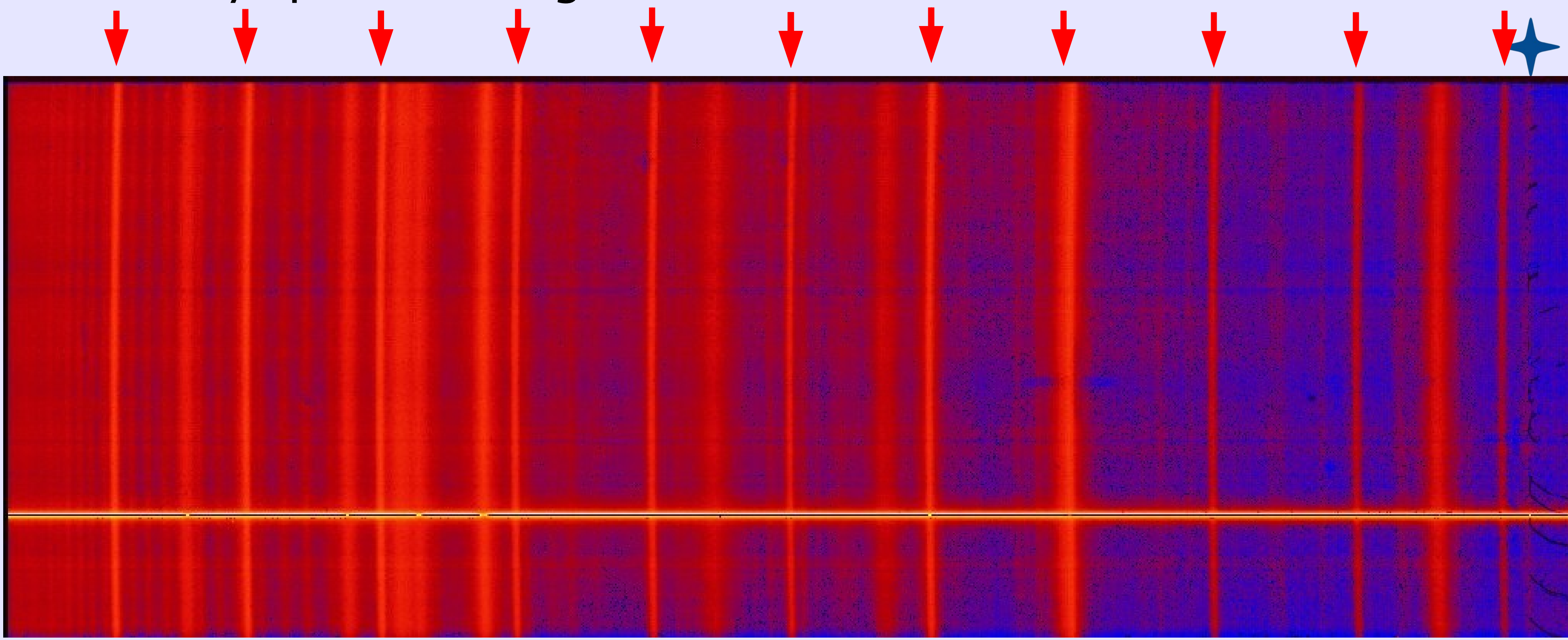
spectral coverage N_2O and OCS



- ideal would be a mixture, but chemical stability to be proven
- potential problem with any gas cell: leakage and pressure shifts

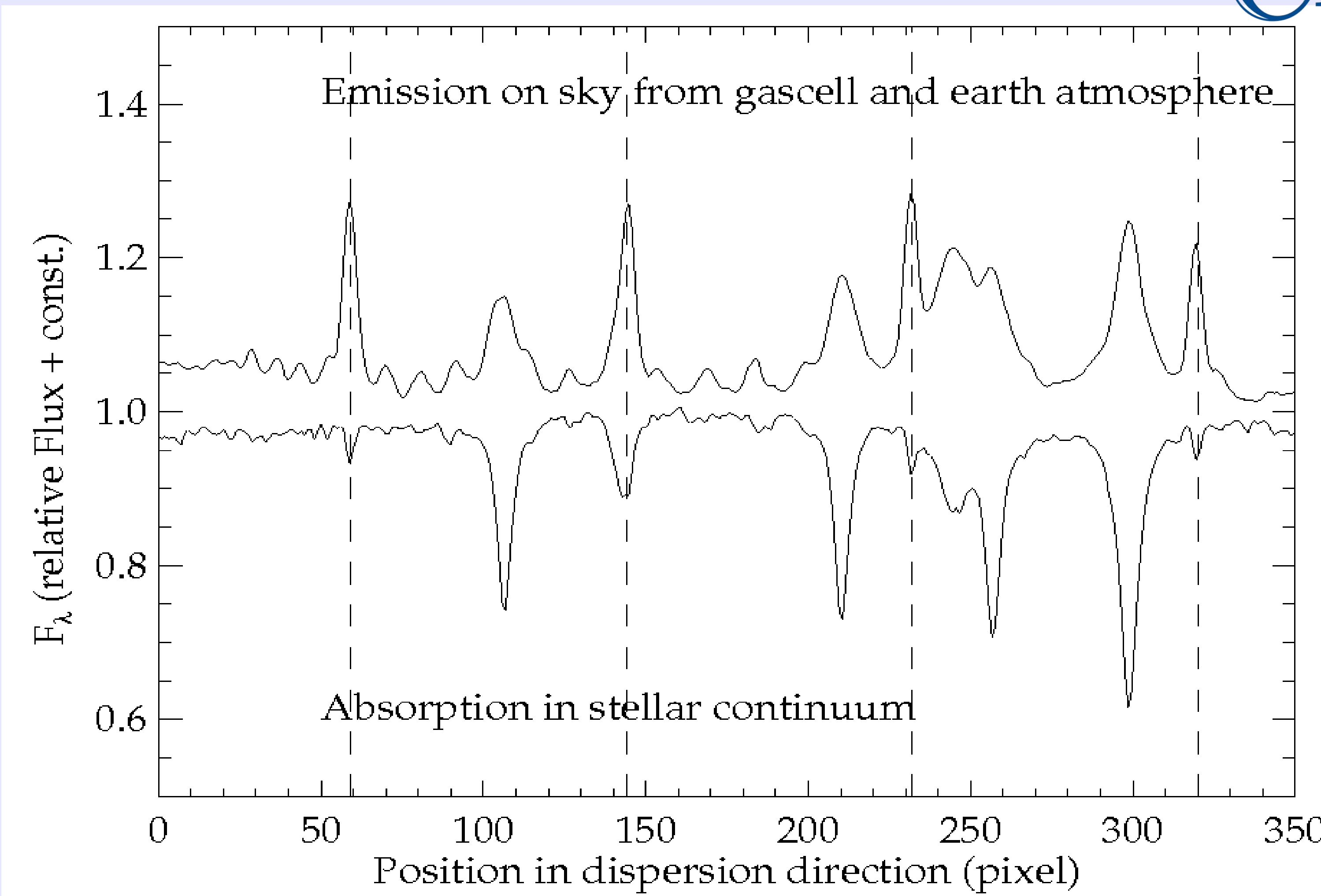
Example of CRIRES 2-D Spectrum

evenly spaced N2O gas cell lines



- K-band: late type star through gascell (N_2O overtone) and atmosphere (CRIRES SV2, E. Guenther)
- detailed analysis of relative stability pending

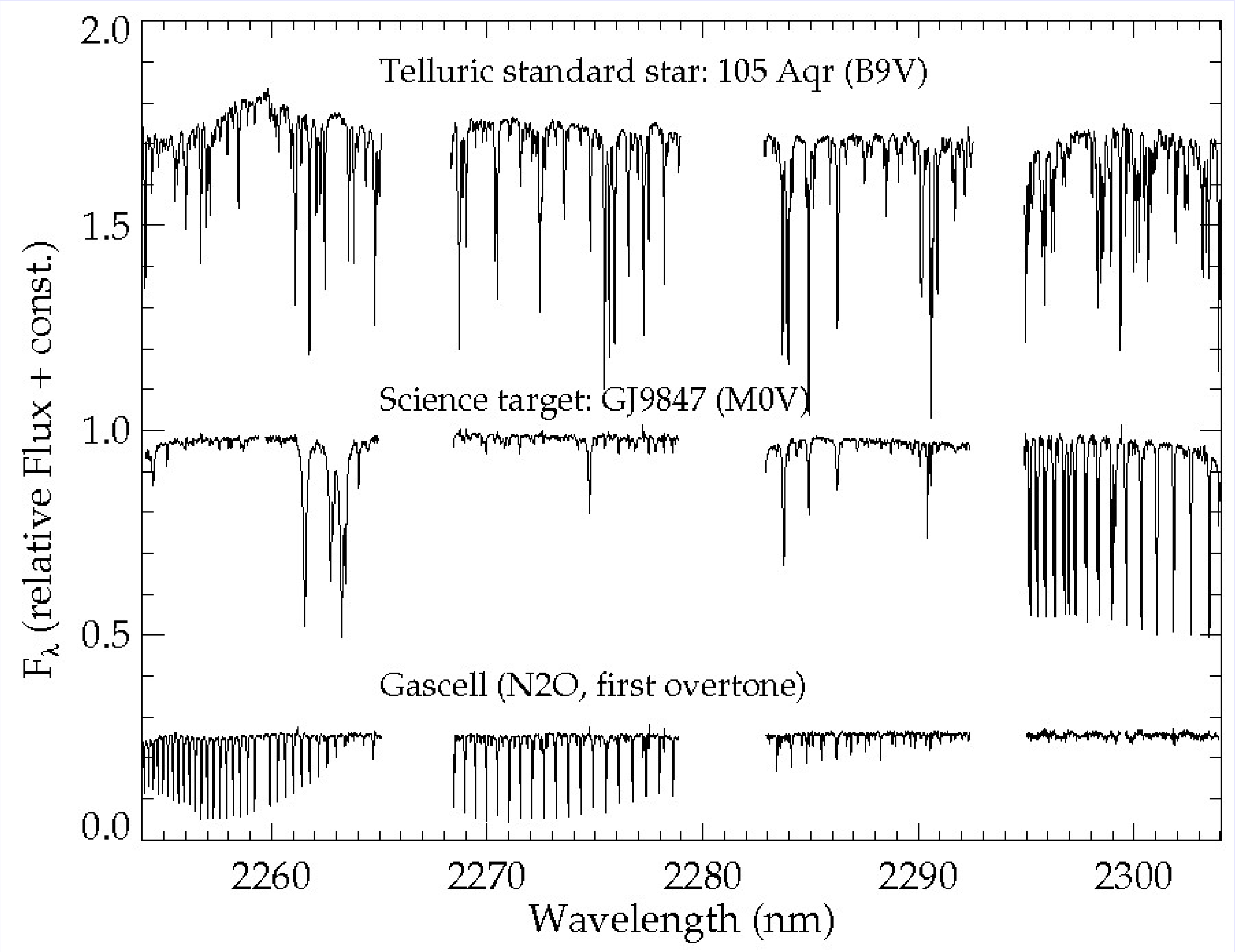
Projection of CRIRES 2-D Spectrum



Kirchhoff's radiation law: sky and gascell lines:

- in emission, against sky (if $\lambda > 2000$nm)
- in absorption against stellar continuum

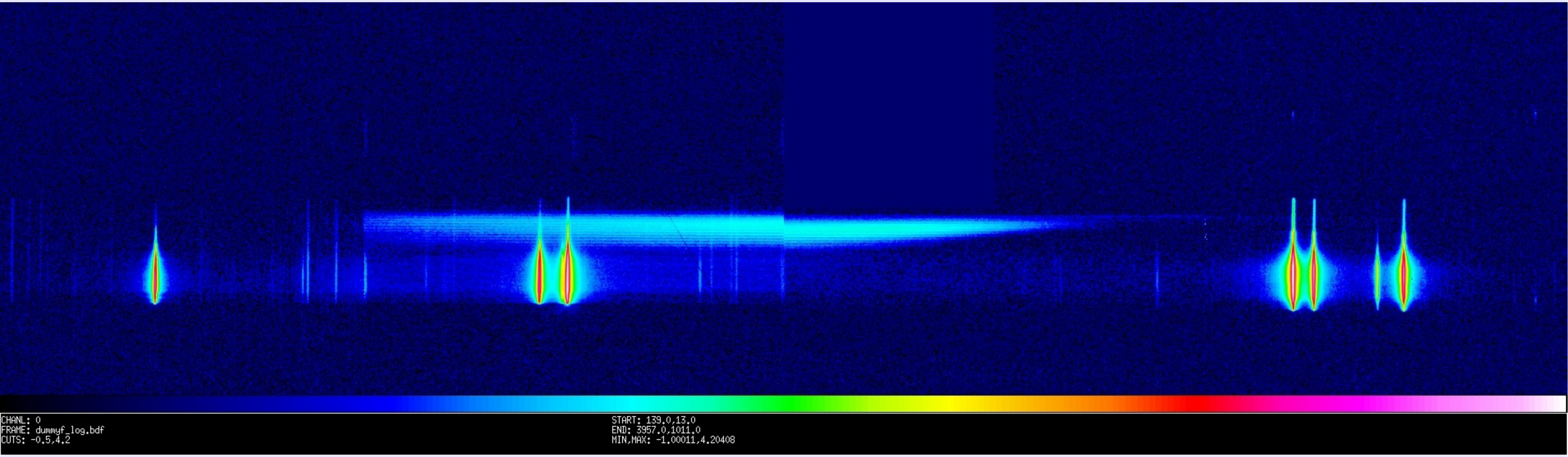
Example of CRIRES 2-D Spectrum



assessing inter-order straylight

otherwise absorption spectroscopy meaningless

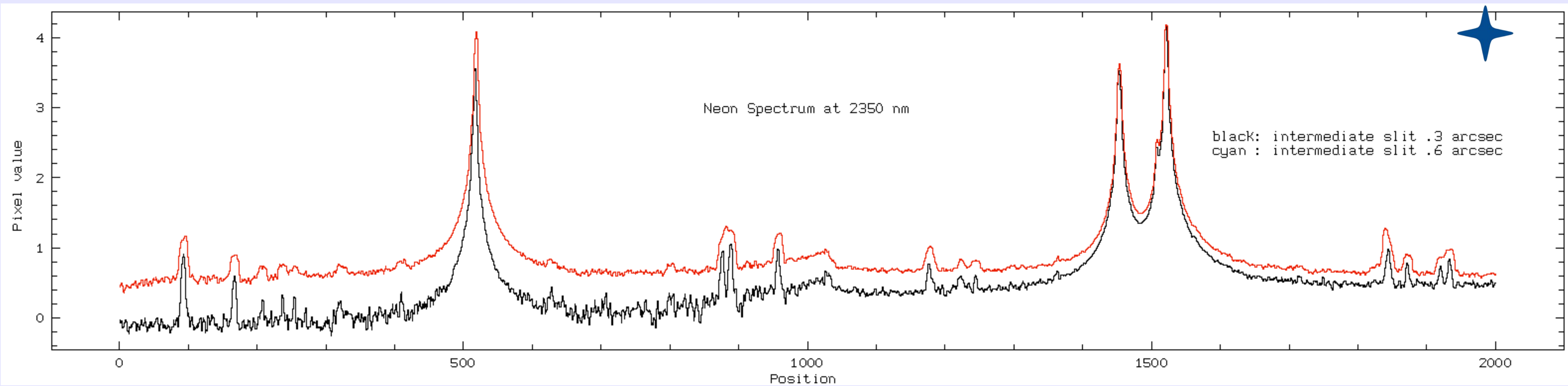
- ▼4 detector spectrum, logarithmic K – band, Neon lamp



- some of the interorder light is thermal continuum of the lamp bulb

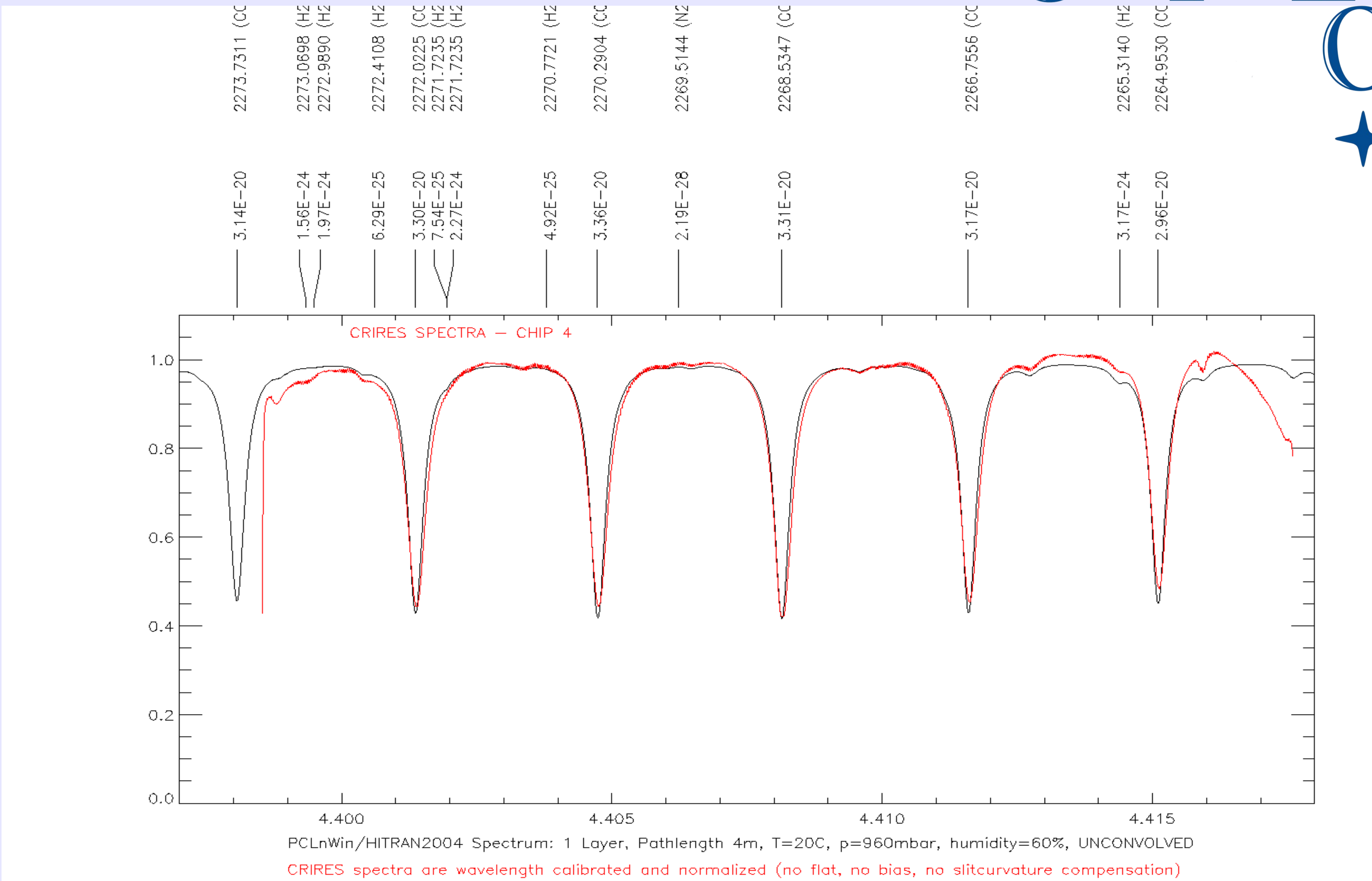
assessing inter-order straylight (2)

- ▼1-D cut, <u>logarithmic</u> , part of K – band, Neon lamp



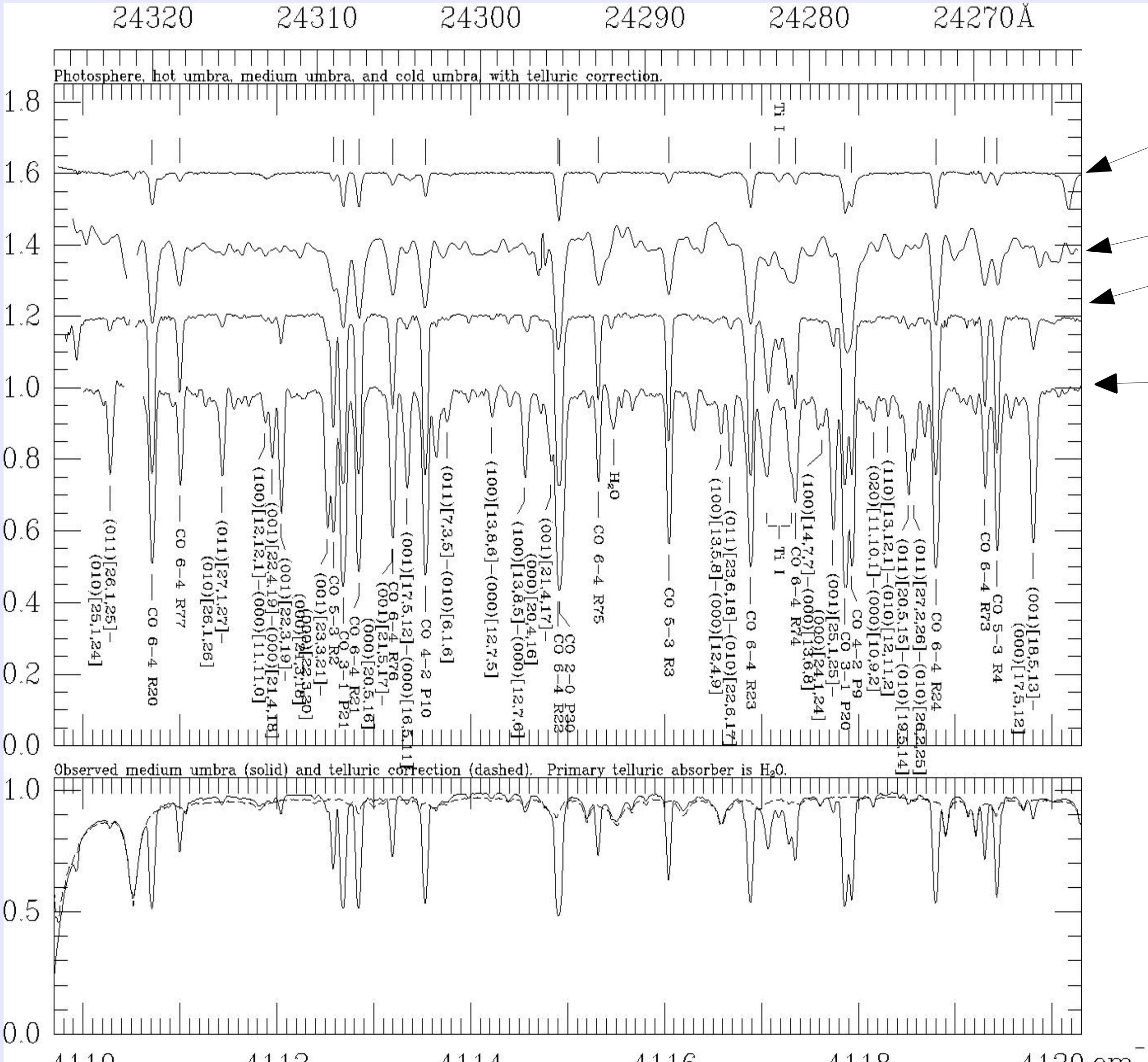
- black: intermediate slit 0.3 mm (nominal)
  red: intermediate slit 0.6 mm (test)
  - evidence for ghosting at the 5 * 10^{-4} level (originating in pre-disperser; room for improvement)
  - some in-dispersion stray-light; grating ?
  - no real worries for photometric precision of absorption cores

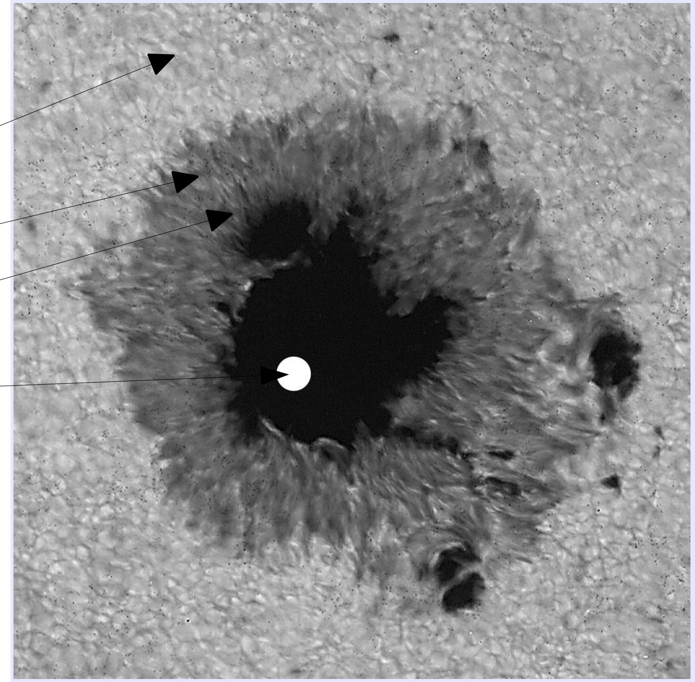
absorption spectroscopy: gas-cell test



set-up: 4400nm sample spectrum: black-body with CO-gascell

flatfielding / telluric absorption: the problem



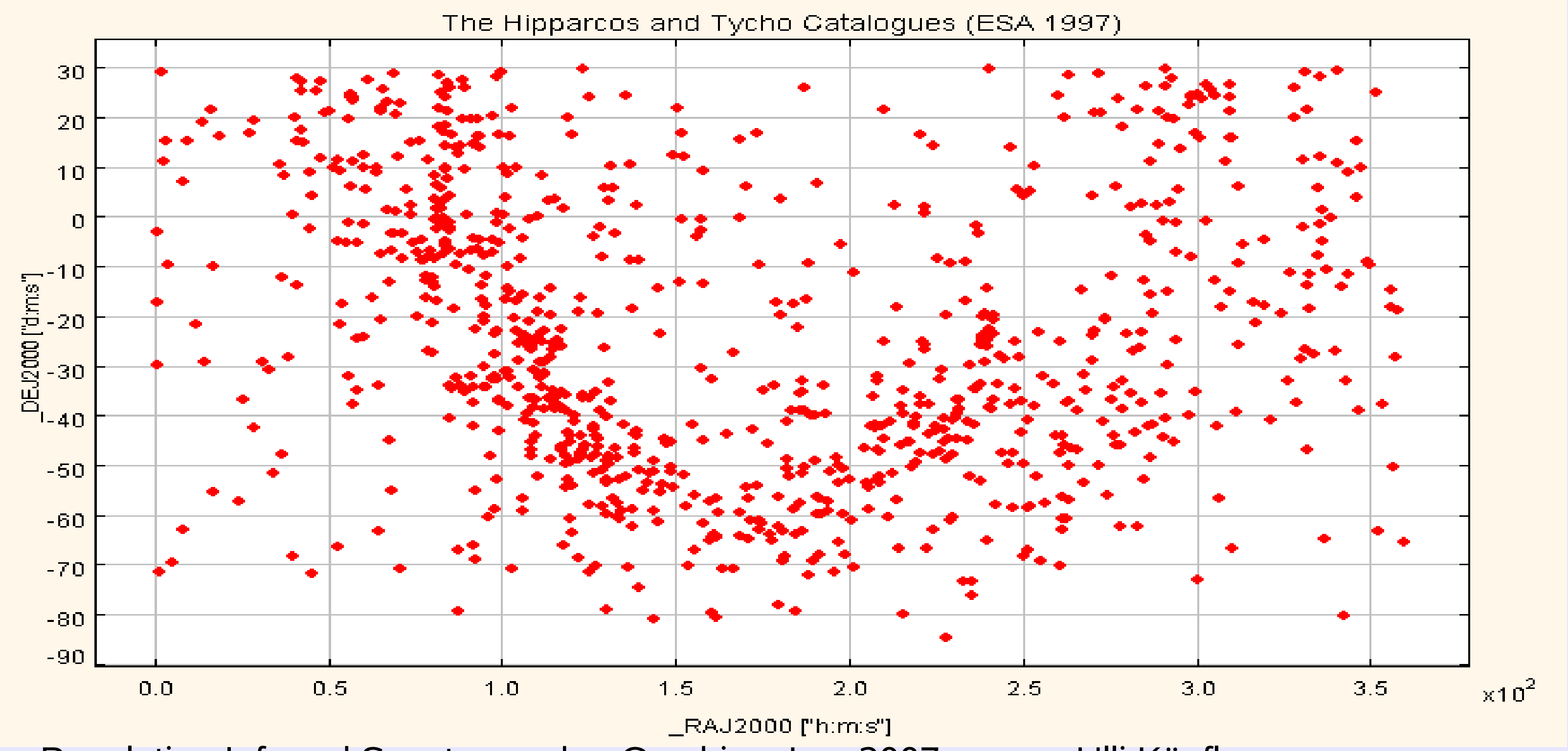


FTS-spectra of sunspot; molecular absorption "hell breaks loose once T_{chromo} < 5000K

Calibration Plan (cont.)

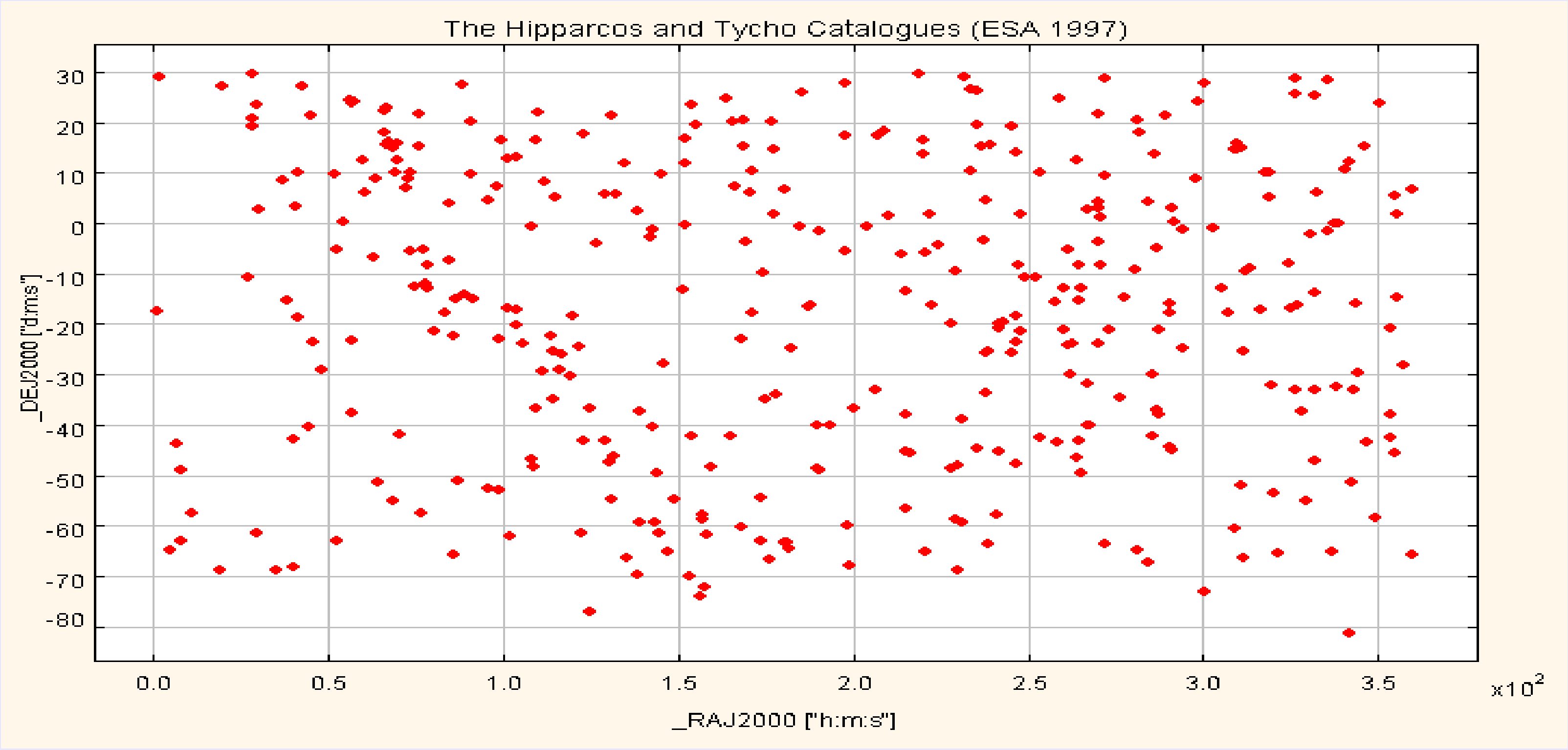
- flat-fielding 0-th order in-dispersion and along slit with internal calibration source
- refinement of flatfield with sky + calibration stars
  => development of a system of spectroscopic standards
  based on Hipparcos/Tycho catalogs and stellar models:
  - for **1000-4000nm** : A1 or earlier, $v_{mag} < 6.0$, $\delta < +30^{o}$

  => 900 stars ; model atmospheres in prep. (ESO with P. Coelho)

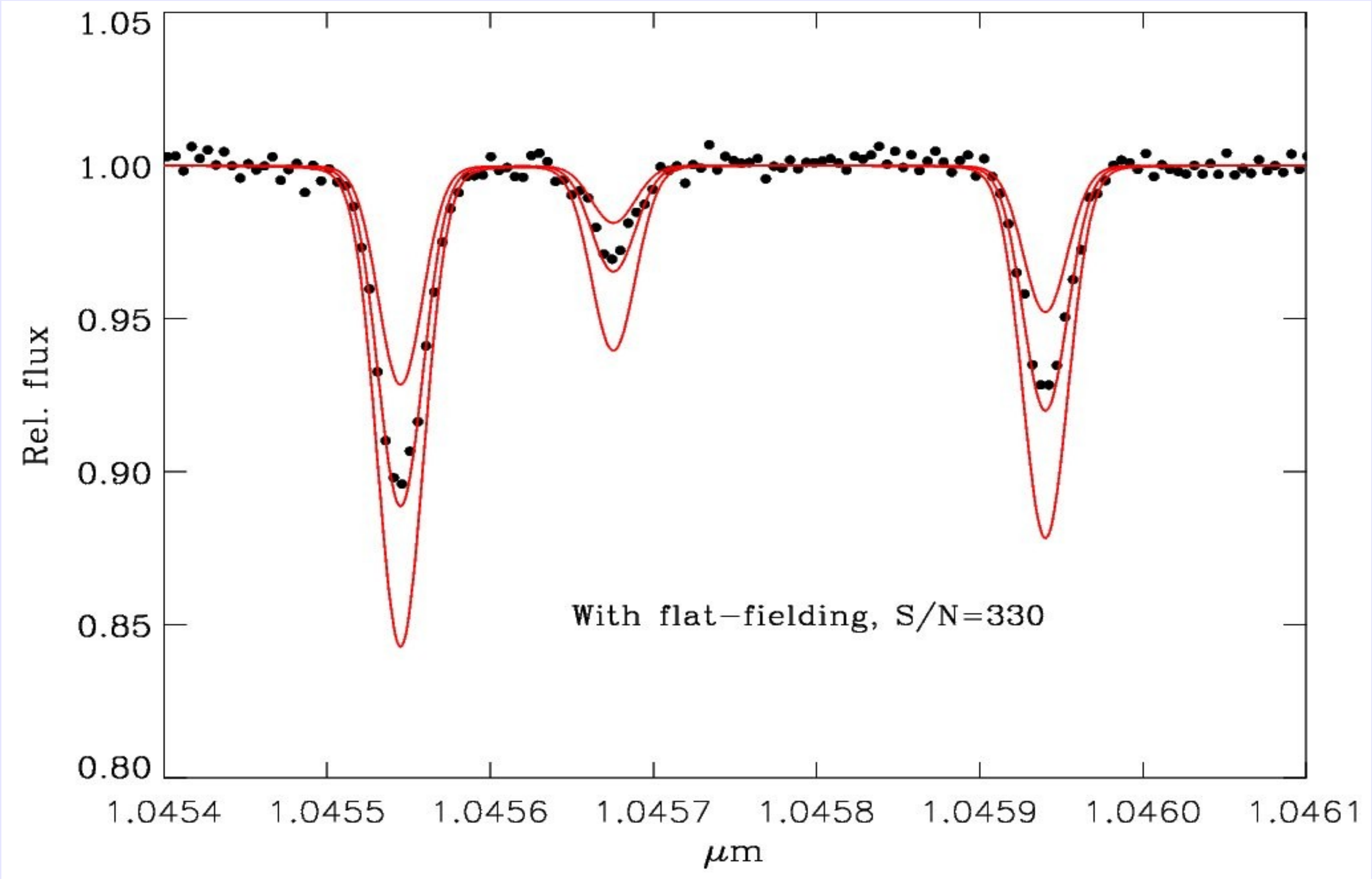


Calibration Plan (cont.)

- for **4000-5200nm**: B8 or earlier, v_{mag} < 4.0, B8-G0, v_{mag} < 4.8
  => 466 stars, model atmospheres in preparation (ESO with P. Coelho)

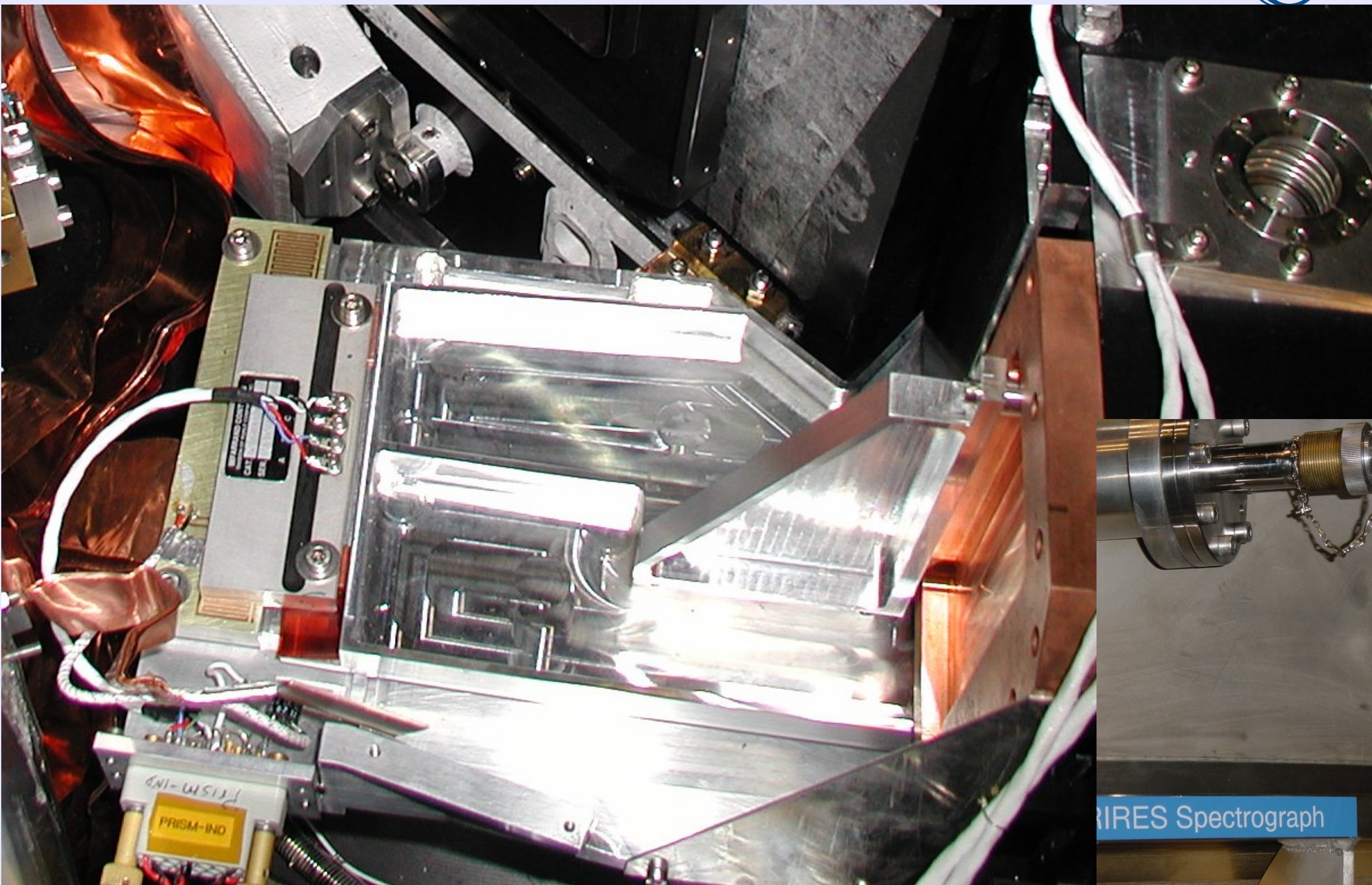


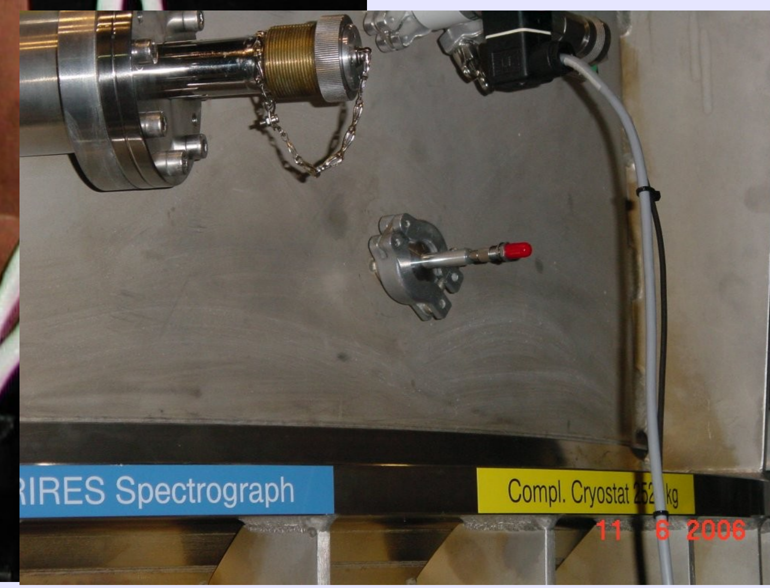
An Example from CRIRES early Science Verification



- Sulfur triplet in an extremely metal poor star graphics/analysis courtesy Poul Eric Nissen
- S/N ~ 330 achieved with simply dividing with a B-star

stability and reproducibility: tools

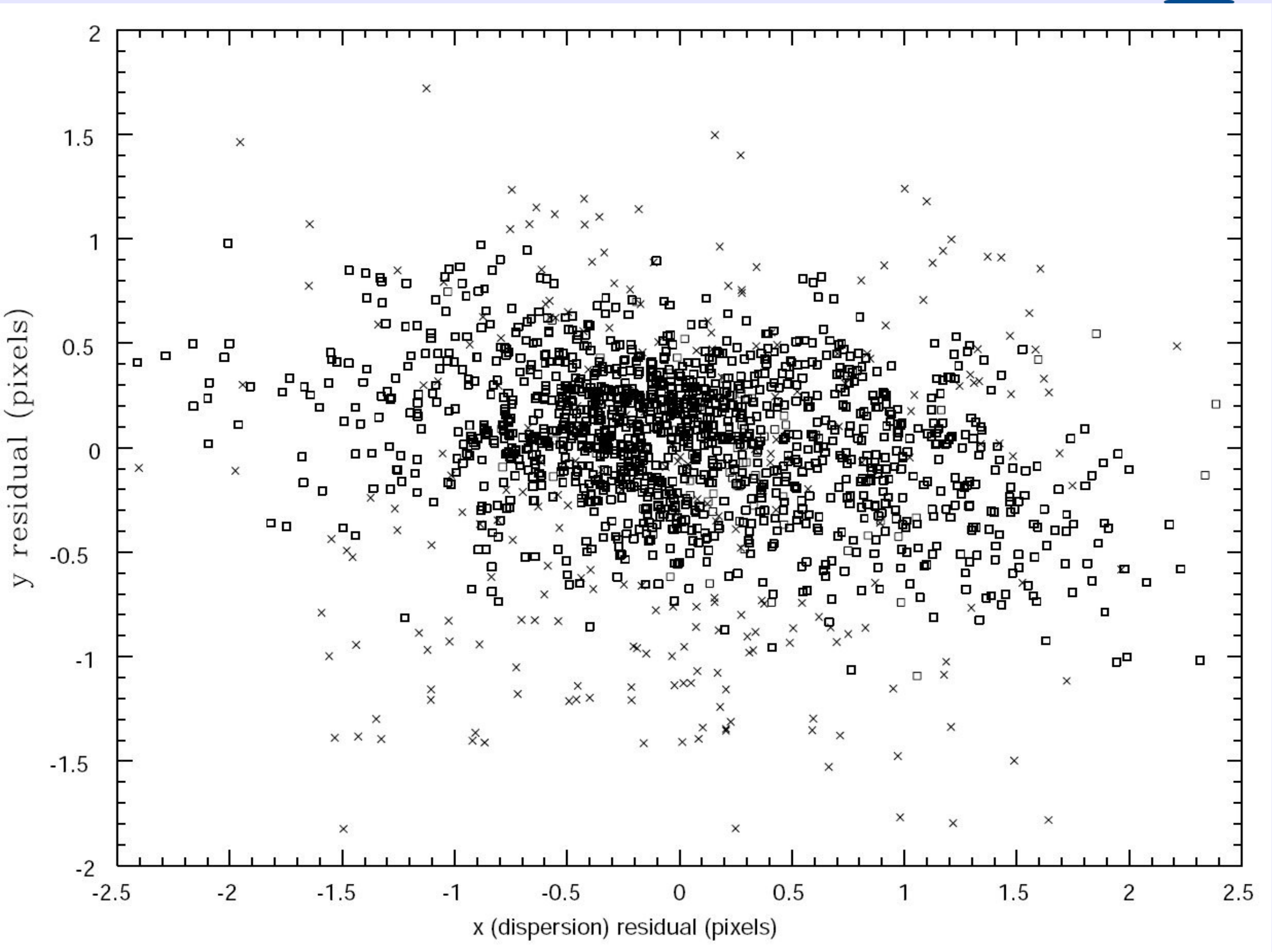




prism drive encoder plus temperature stabilisation plus precise measurement of dn/dt (with NASA/GSFC) plus physical model of spectrograph plus ThAr for the infrared (with NIST), Kerber & Bristow

Conclusions

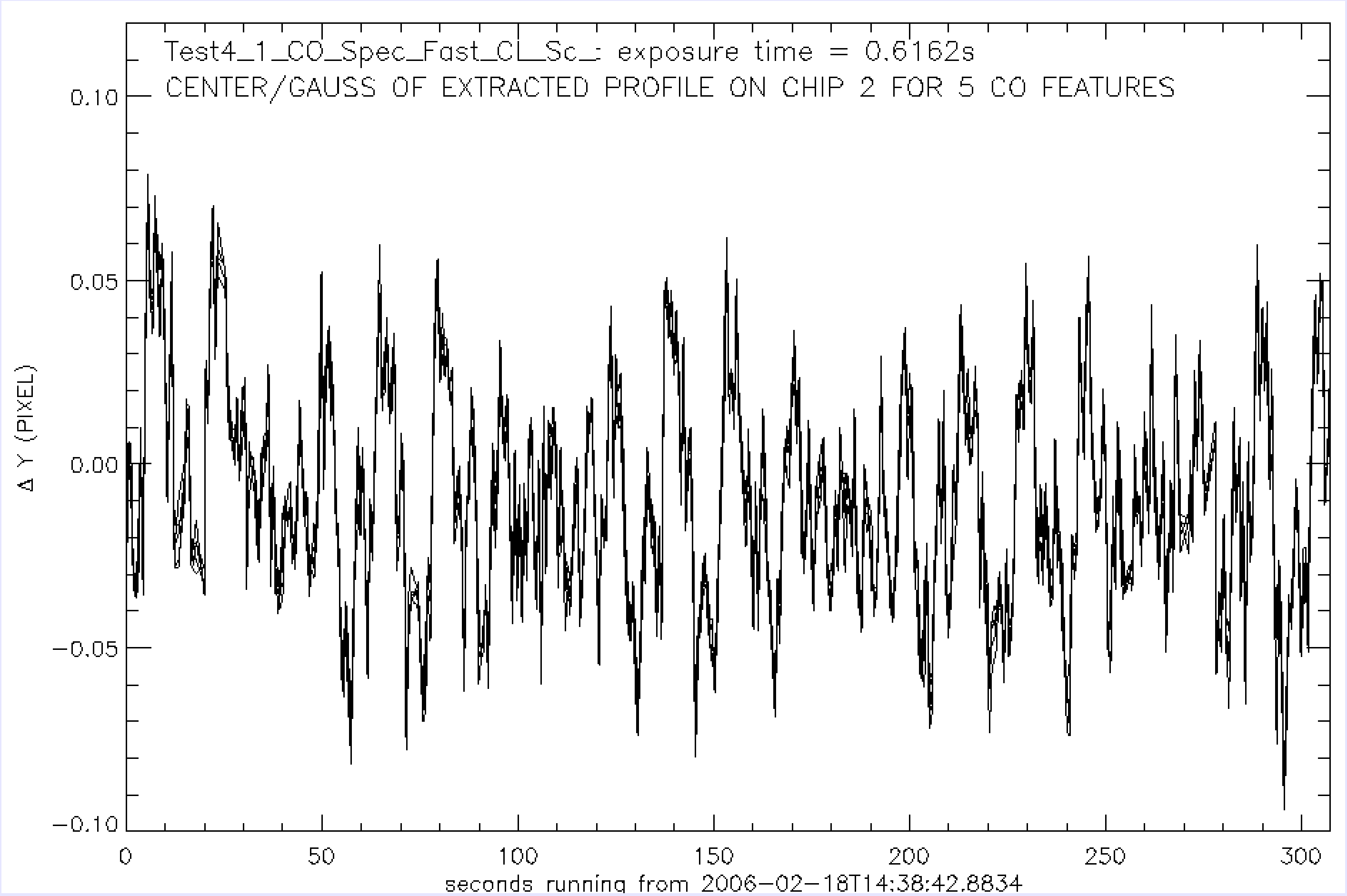
- CRIRES is an unique facility instrument for the VLT
- CRIRES can be calibrated
- physical model available,
  very useful but suffers from encoder noise and stick-slip effects
  right: plot of model residuals (P. Bristow et al.)
- improvements ongoing



- ultimate goal: the self-calibrating spectrograph

Reserve Slides

end to end laboratory test (I)

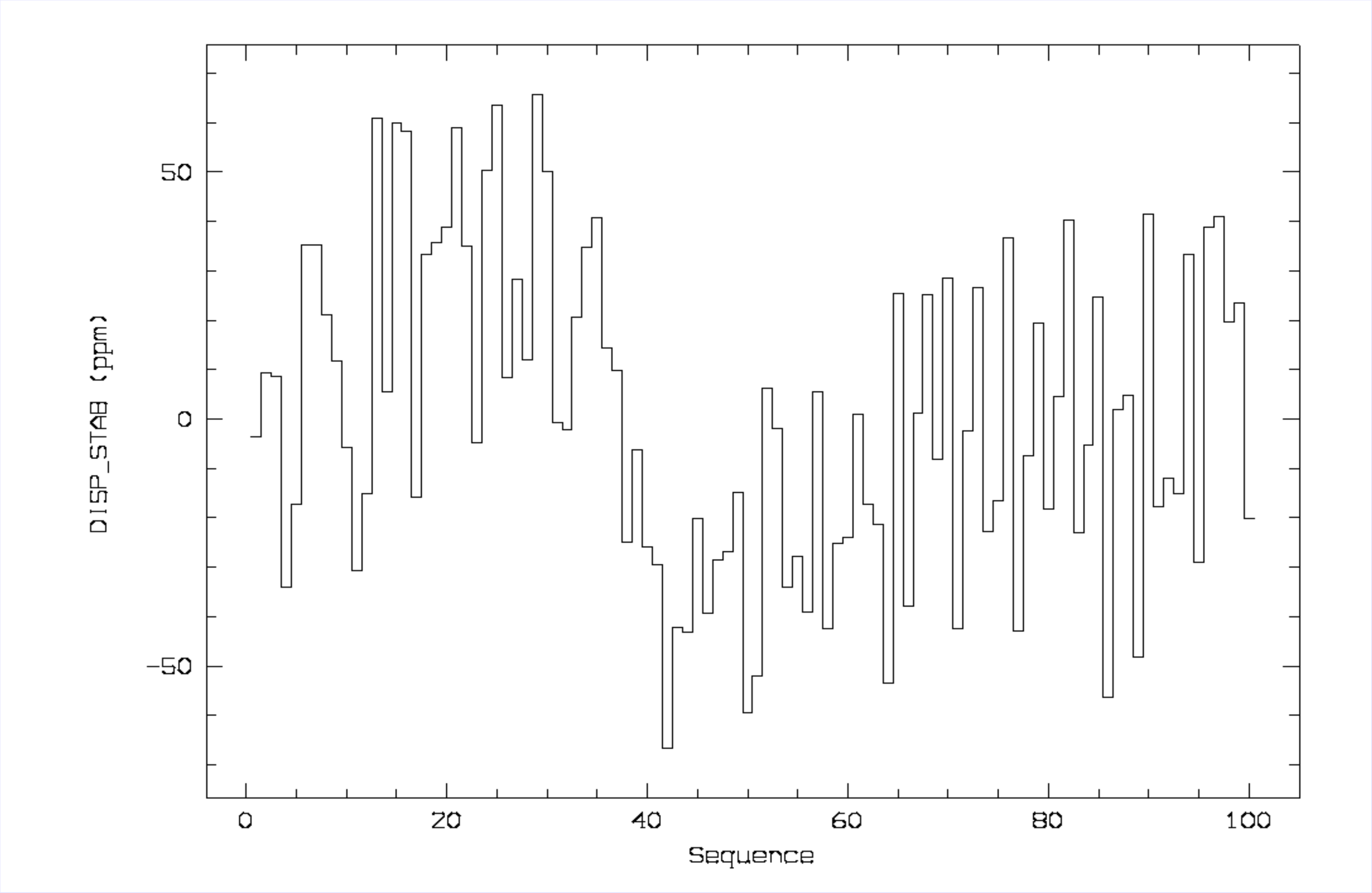


set-up: K-band, black-body with CO-gascell, fibre-feed to turbulence generator, adaptive optics loop closed, CRIRES nominal

note: data analysis very basic => some numeric noise as well

constancy of dispersion

CRIRES



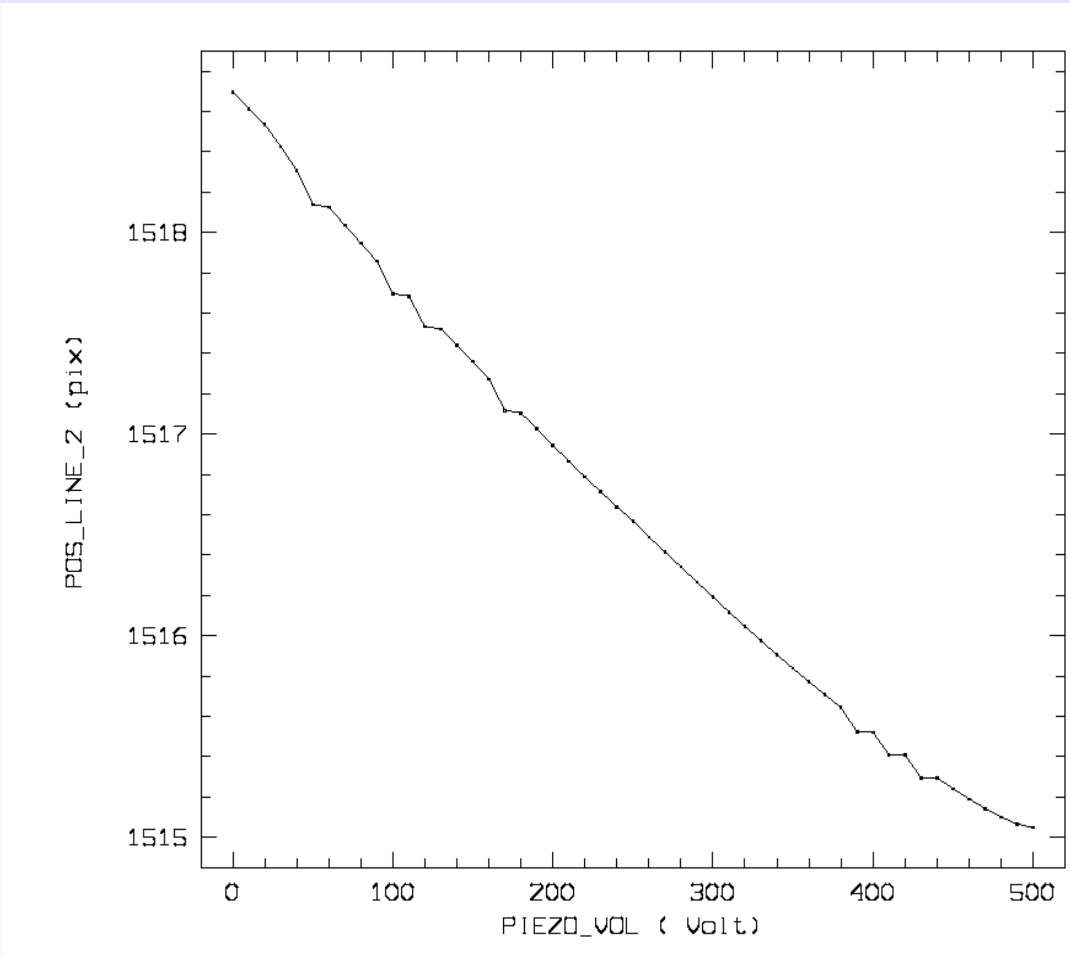
set-up: Ne-lamp, J-band, scatter of dispersion vs. grating repositioning
stability peak to peak 100ppm (σ 32 ppm) goal 50ppm RMS

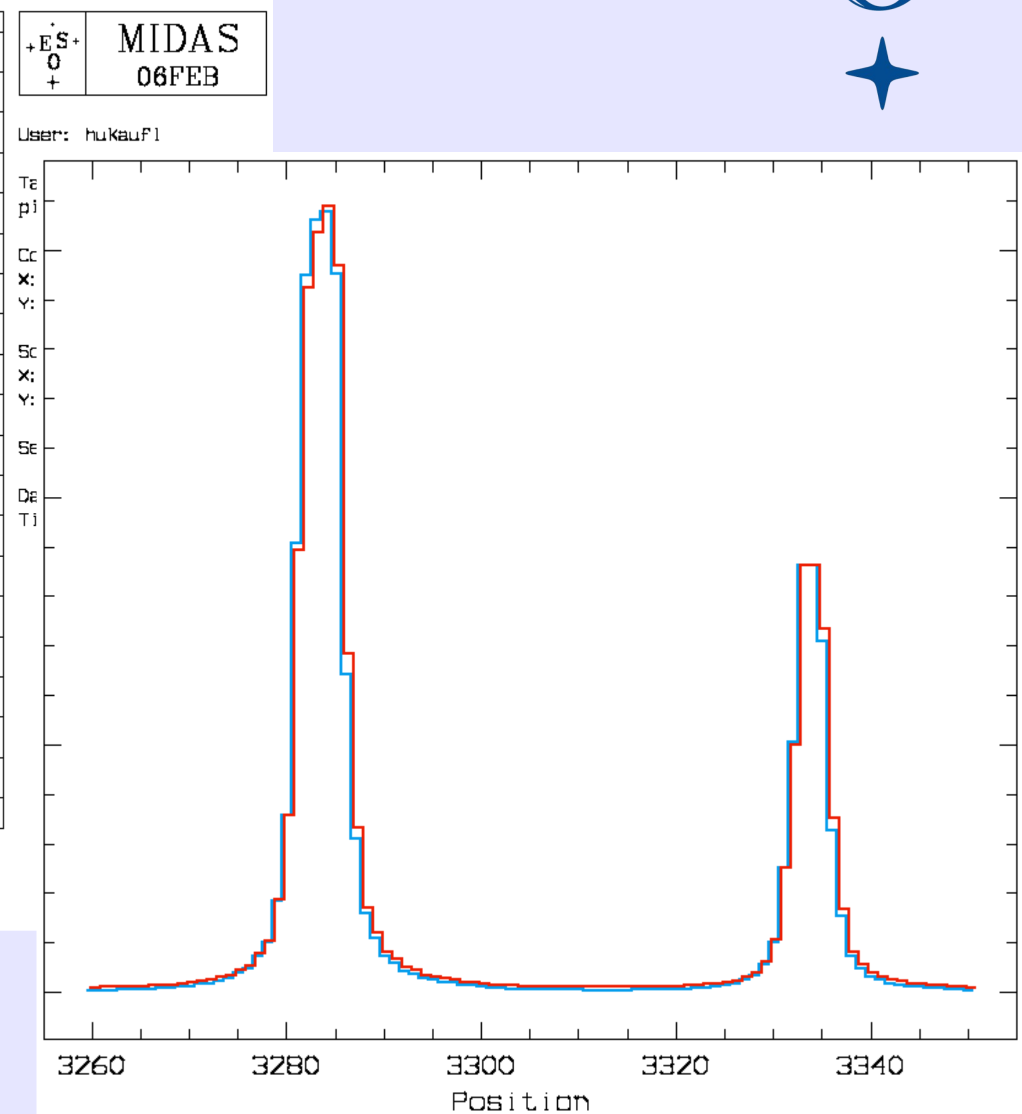
note: suffers some “numeric” noise, i.e. reality might be better

CRIRES main characteristics (cont)

- spectrograph **intrinsic stability goal** <<< 75m/s
  thus, preference in design was given to stability
  ☞ gas cells for high precision radial velocity work
- curvature sensing **Adaptive Optics**
  ☞ 0.05" spatial resolution per pixel of SV
- calibration unit part of instrument
- **spectro-polarimetry in lines under way:** magnetic fields
  - goal to measure all 4 Stokes parameter
  - $\lambda / 4$ Fresnel rhomb and $\lambda / 2$ plate
    in rotary mounts at the gas-cell slide
  - cold kinematic MgF_2 Wollaston prism in fore-optics

test of cryogenic Piezo



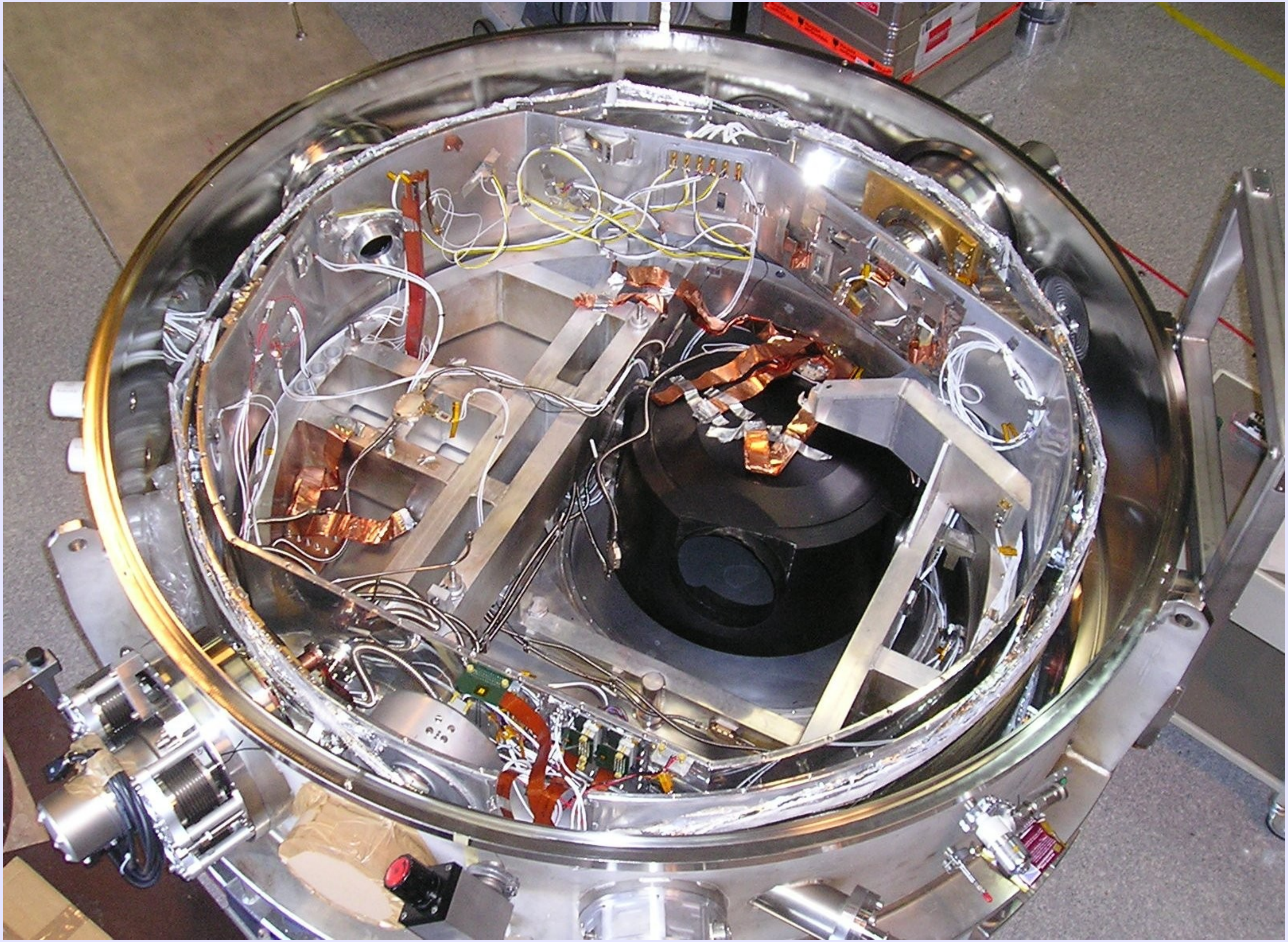


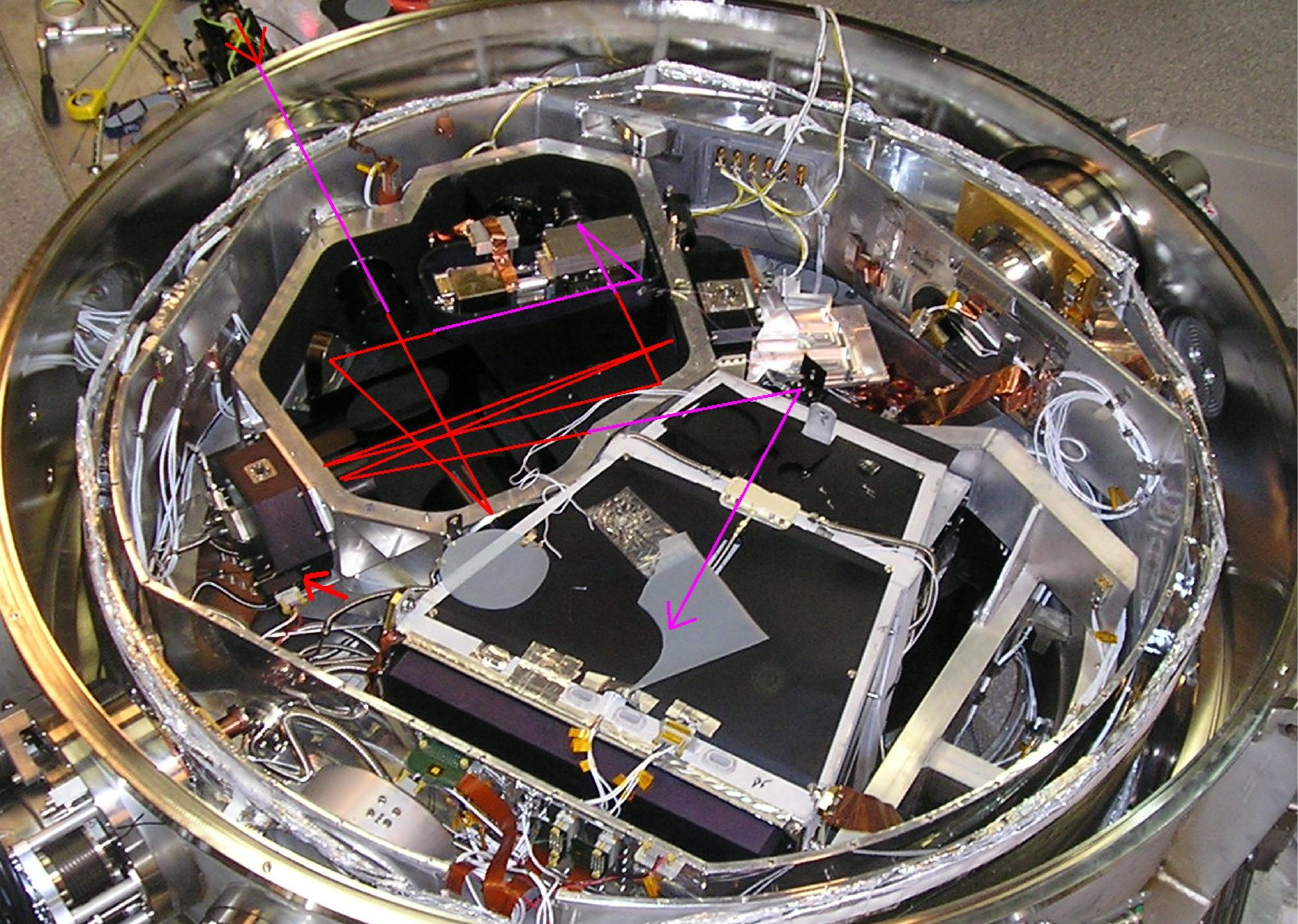
set-up: Neon lamp

K-band, 10 V steps

comparison of 2 consecutive spectra

‘CRIRES without CRIRES’





Calibration Plan

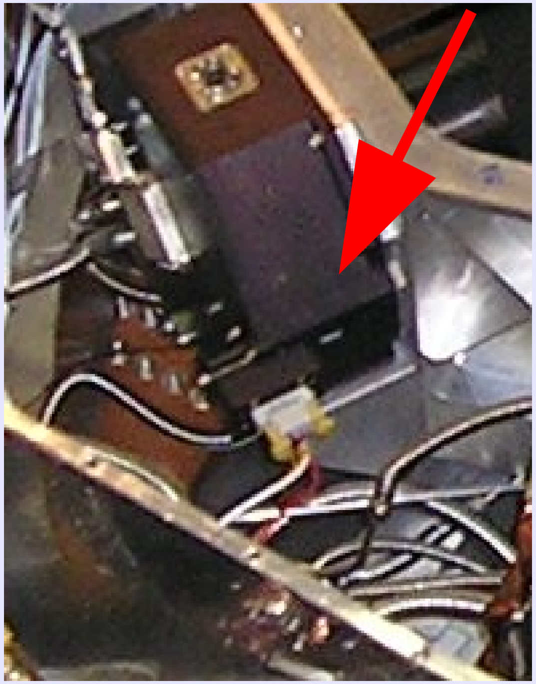
- based on simplified physical model for CRIRES optics
  - based on output of optical design calculation
  - goal here is, to have the minimum number of free parameters and to use a “physical”-parametrisation
  - collaboration with ST/ECF group to recycle the UVES & STIS experiences
- internal calibration unit (arc-lamps, continuum sources) to establish first model (also for the control software) for spectral calibration
- ThAr-spectrum extended into IR up to 4µm
- final spectral calibration and extraction using the OH-airglow and telluric absorption lines

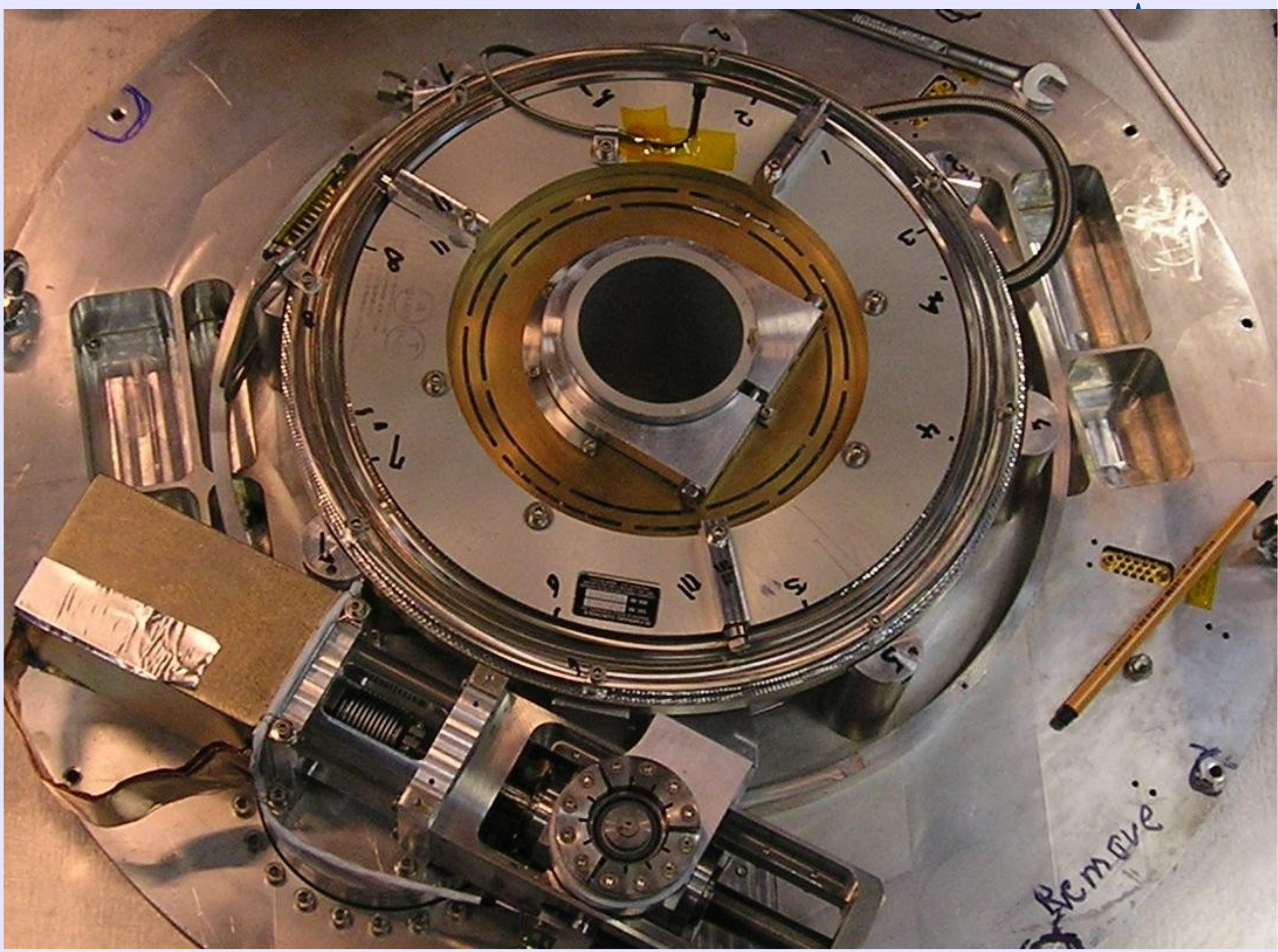
stability and reproducibility: tools

CRIRES

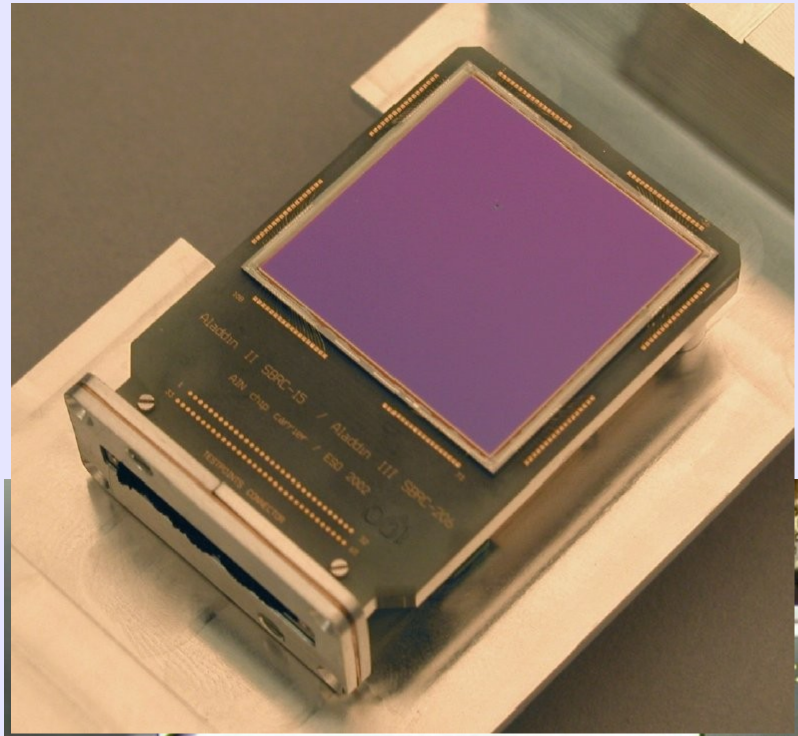
grating drive ►
with 1arcsec resolution
cryogenic encoder **but**
still not good enough

Piezo in pre-disperser collimator compensates stick slip effects ▼





spectrograph focal plane assembly



◄ left: one of the four hybrids

▼complete assembly of mosaic

- 4 Aladdin III arrays, hybridized
- gap reduced to 286 pixel
- use band of 8 512x512 arrays
- detector upgrade invisaged