METROLOGY on VLT Instruments and CRIRES+ Calibration

ESO Calibration 2017

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Overview

0. What is “metrology” (in the context of this talk)
1. Examples of metrology at the La Silla Paranal Observatory
2. CRIRES+ Calibration
3. CRIRES+ Metrology

What is Metrology?

- **Wikipedia**: Metrology is defined by the International Bureau of Weights and Measures as "*the science of measurement, embracing both experimental and theoretical determinations at any level of uncertainty in any field of science and technology.*"

Wikipedia, Courtesy NASA/JPL-Caltech

- **Me**: *If you're not confident that your instrument is going to do exactly what its supposed to do, all the time, every time, then you'd better include an automated reference measurement and preferably implement some kind of feedback.*

Metrology vs Calibration

- Calibration is *post processing*
- However, if the science data is not taken in the right way, then post-processing can't help, for example:
  - X-shooter: 3 slits must be aligned
  - (o)CRIRES(+): Spectral format must be identical at the sub-pixel level so that:
    - Daytime wavecals/flatfields are applicable
    - Repeat transit observations can be combined
  - *Adaptive Optics*
  - *Interferometry*
- "Metrology" ensures the intrinsic quality of the raw data
- "Metrology" may also provide:
  - reference data that is used in post calibration
  - quality control metrics
- Where possible, parallel to preset or science exposures

Calibration Reference Data

- Traceable to laboratory standards >> "ground truth"
- Meta Data describing "what and how"
- Error information
- Documented by original data provider
- Published

- …and ideally backed up by studies of devices:
  - ageing
  - sensitivity to operational parameters (current, voltage)
  - sensitivity to environment

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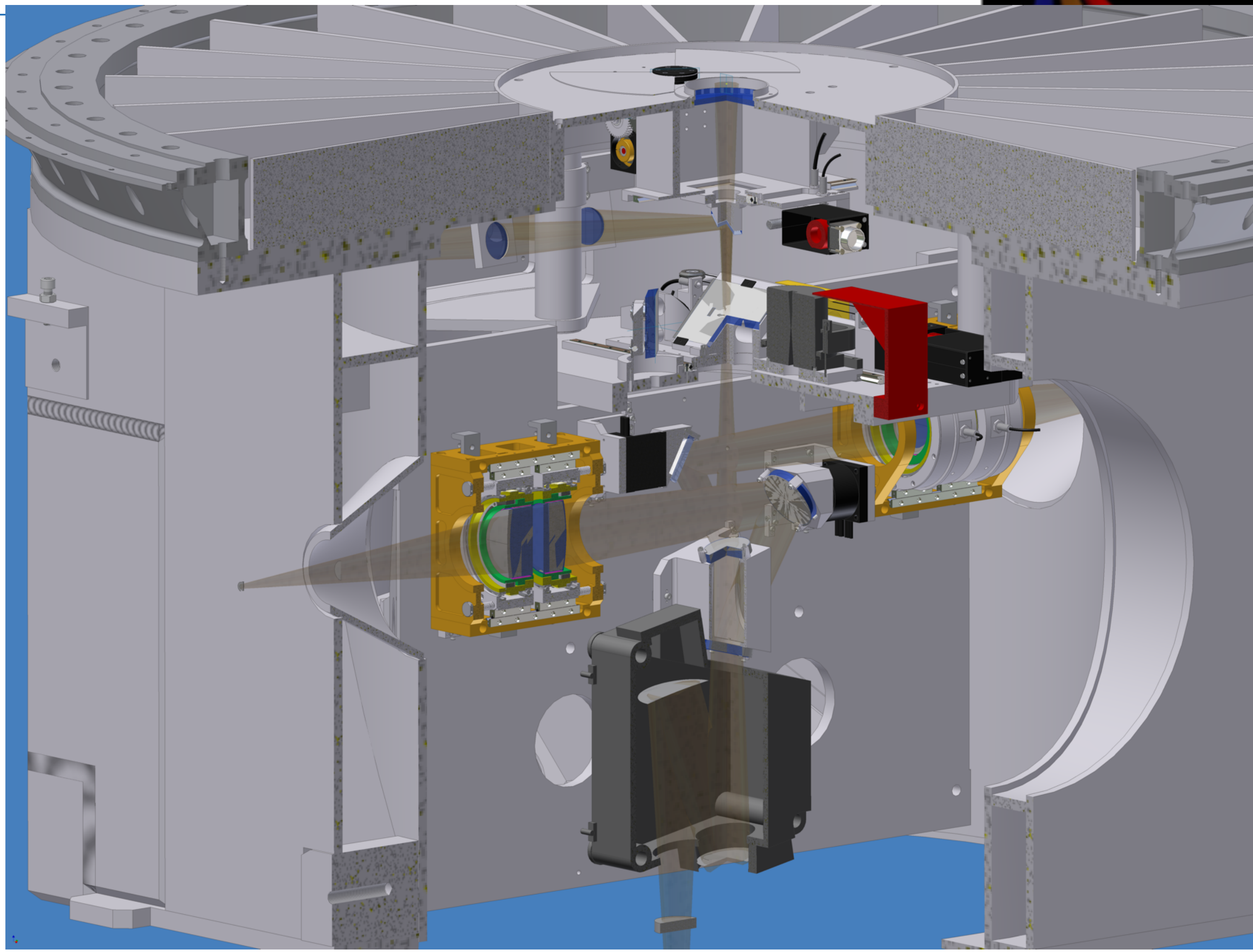
Metrology on VLT Instruments:

- **Problems:**
  1. Keep the target simultaneously centred on the entrance slit of all three arms regardless of the instrument orientation
  2. Correct the dispersion solution for flexure in the individual spectrographs
- **Timing:**
  1. Measurement and correction before each observation
  2. Correction during data reduction

Metrology on VLT Instruments: X-shooter



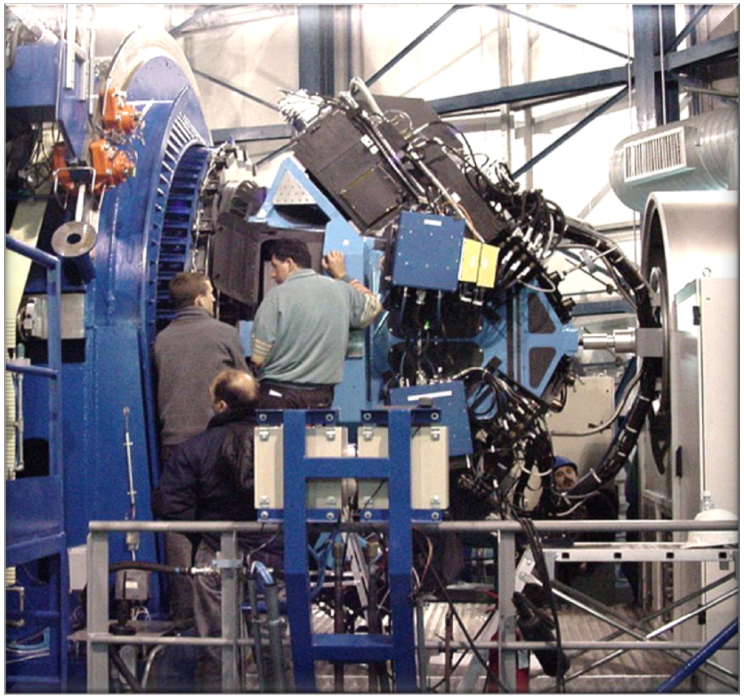
Metrology on VLT Instruments:

Reference: Image positions on the FPA of spectral lines from a dedicated pinhole.

1. **Active flexure compensation:**
   a) Obtain a calibration spectrum of each spectrograph via a pinhole at the spectrograph slit
   b) Obtain a calibration spectrum of a pinhole placed in the Cassegrain focal plane with each spectrograph
   c) Analyse and correct flexure: cross correlate frames taken in (a) and (b) and apply an appropriate shift to the piezo driven tip-tilt tables for each arm
2. **Physical Model Optimisation:** The X-shooter DRS then uses the higher order information from the exposures to refine the Physical Model parameters and achieve a customised dispersion solution.

Metrology on VLT Instruments: VIMOS

- **Problems:**
  1. Flexure causes the image to smear during long exposures, makes calibration more difficult, and reduces the accuracy of object position measurements taken in the imaging mode
  2. Inability to accurately predict slit aperture locations on slit masks for a given astrometric input catalogue
- **Timing:**
  1. Before/during observations
  2. Before observations

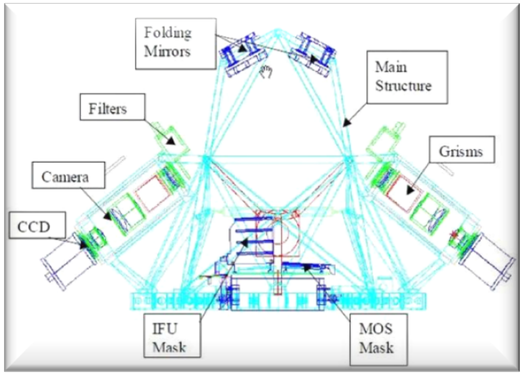


Metrology on VLT Instruments: VIMOS

Reference:

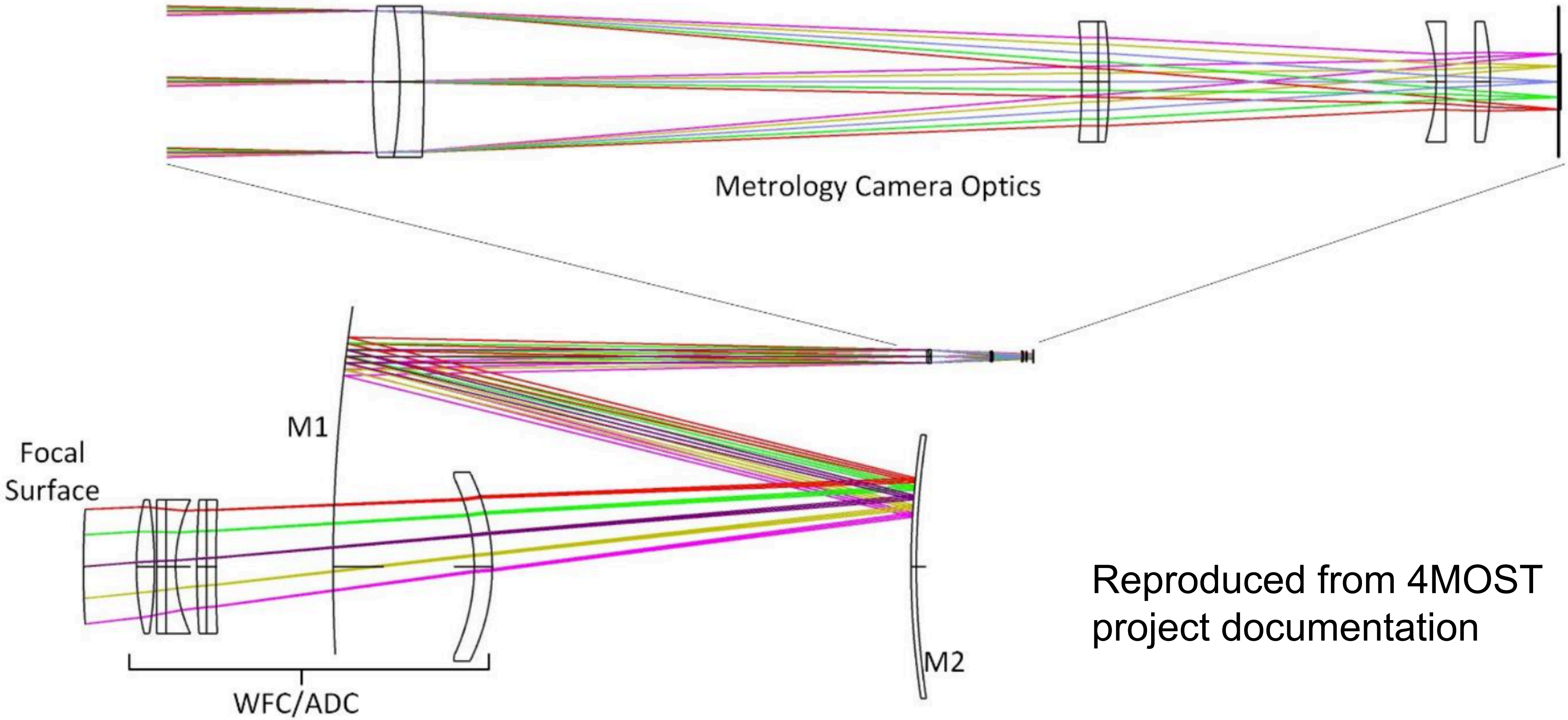
1. Diode point sources imaged on FPA detectors
2. Dedicated sky to mask calibrations

1. **Active Flexure Compensation:** Similar AFC to X-shooter with further blind correction during the exposure.
2. **Pre-imaging:** An example of clumsy metrology
   - A pre-image of the target field is obtained months prior to the science MOS mode
   - The mask slits are positioned according targets in the field
   - But this is not necessary!:
     - Re-evaluation during the VIMOS upgrade showed that it is possible to reliably predict slit aperture locations from a catalogue of target co-ordinates (PILMOS)



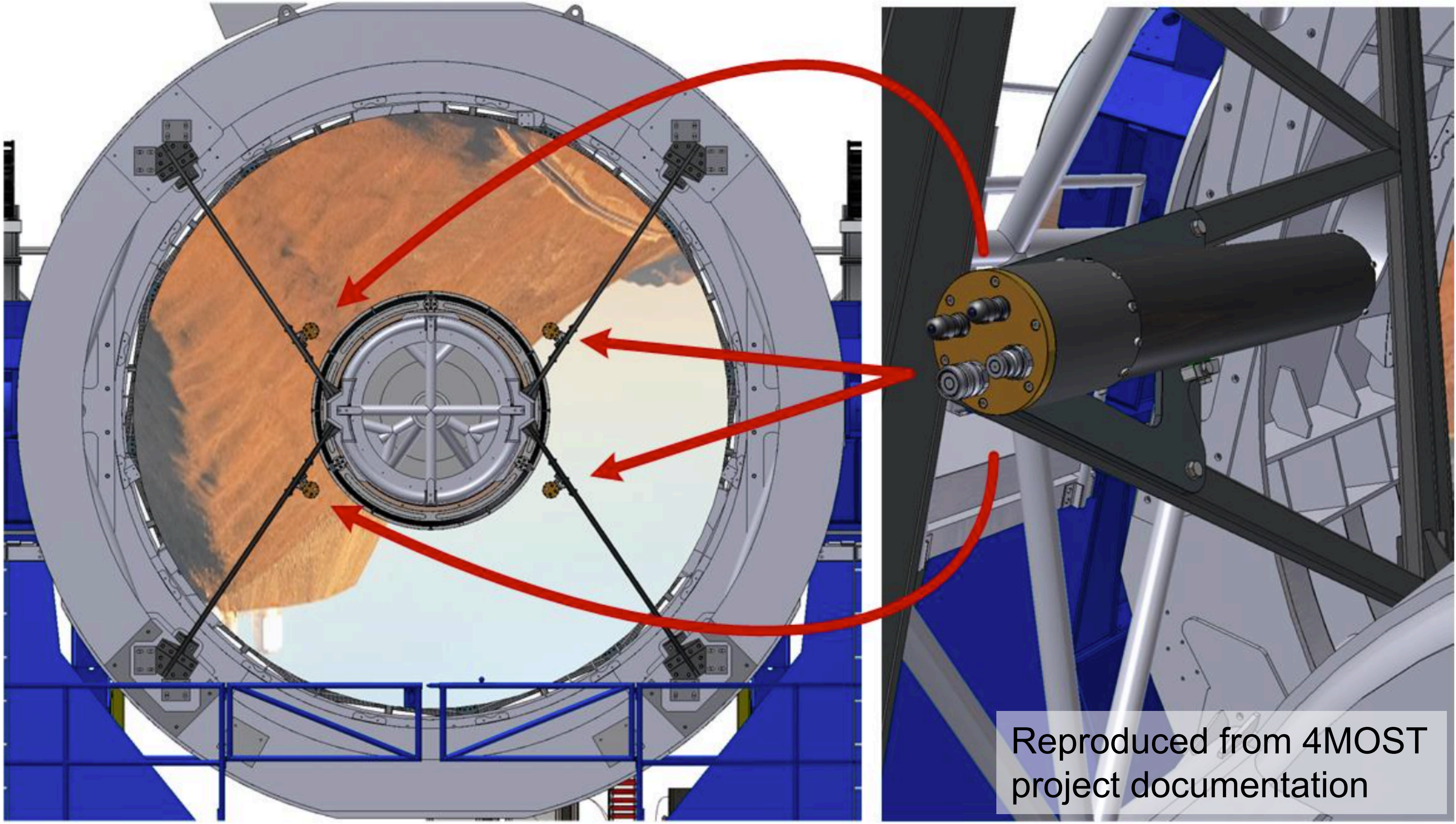
Metrology on VLT Instruments: 4MOST

- **Problem:** Ensure that 2436 science fibre apertures are positioned correctly in the focal plane
- **Timing:** Measurement and repositioning before observation



Reproduced from 4MOST project documentation

Metrology on VLT Instruments: 4MOST



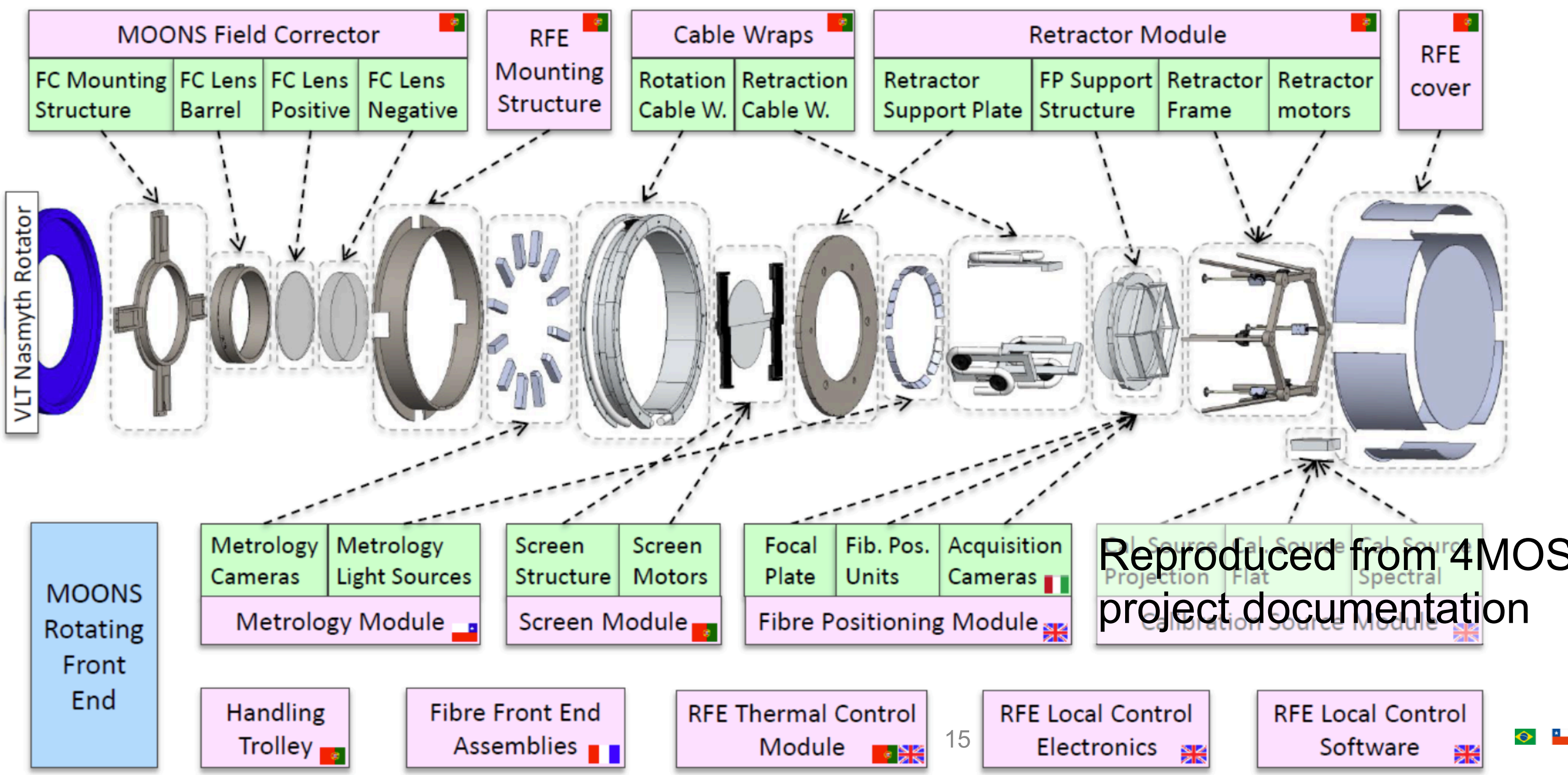
Metrology on VLT Instruments: 4MOST

- **Reference:** Positions of back illuminated fibres on images provided by four dedicated metrology cameras located on the M2 spider assembly are measured relative to images of fiducial and guide fibres.

- The metrology system consists of:
  - imagers for the whole field of fibres
    - 2436 science fibres
    - 24 fiducial fibres
    - 12 guide fibres
  - fiducial markers in the fibre field
  - back illumination for all fibres and fiducial markers
  - software for calculating fibre positions from the acquired images.
  - corrective feedback to the fibre positioning subsystem

Metrology on VLT Instruments: MOONS

- **Problem:** Ensure that ~1000 science fibre positioner units are positioned correctly in the focal plane
- **Timing:** Measurement and repositioning (only if needed) before observation



Metrology on VLT Instruments: MOONS

- **Reference:** Positions of fibre cross-hair markers on images provided by dedicated metrology cameras relative to fiducial reference points.

- Similar solution to 4MOST except:
  - Cross-hairs are used (under illumination)
  - Cameras are located just outside of the rotating front end
  - Should not be necessary for all observations

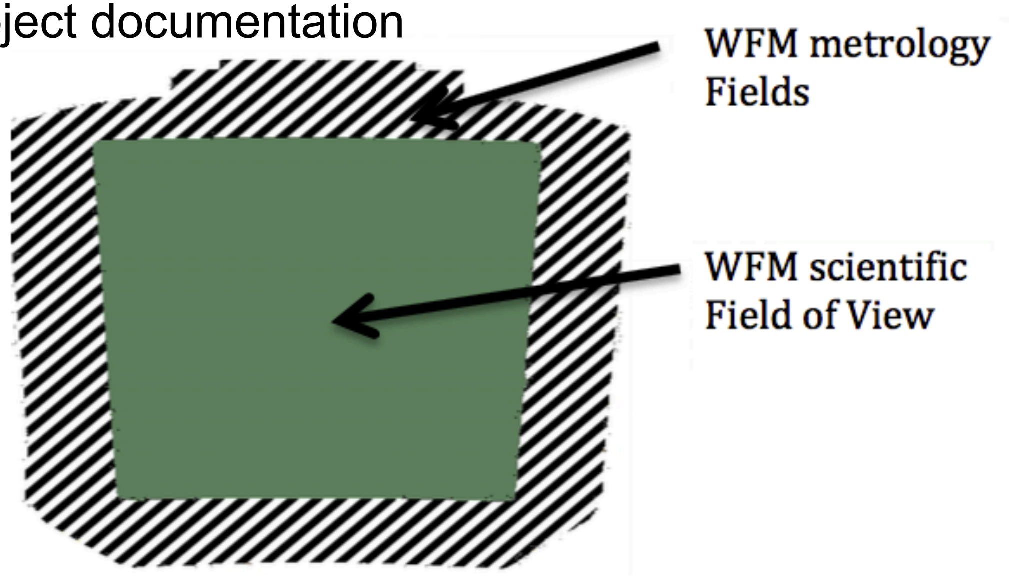
- *See next talk*

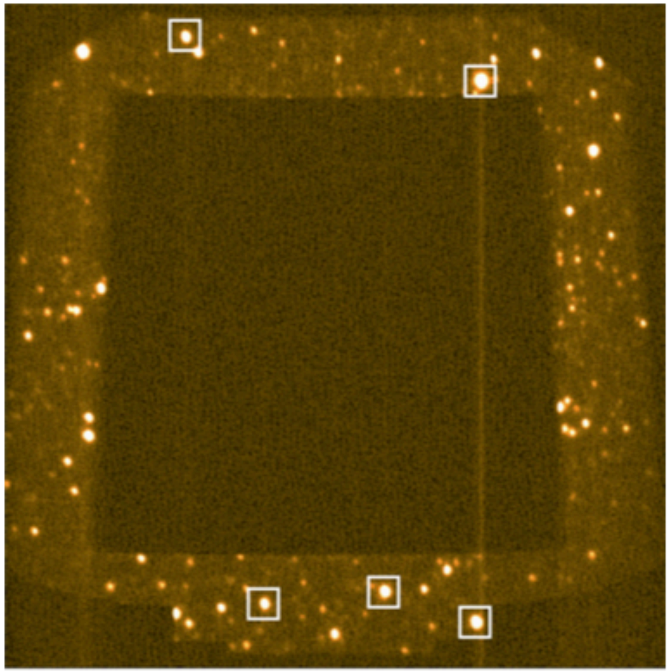
Metrology on VLT Instruments: MUSE

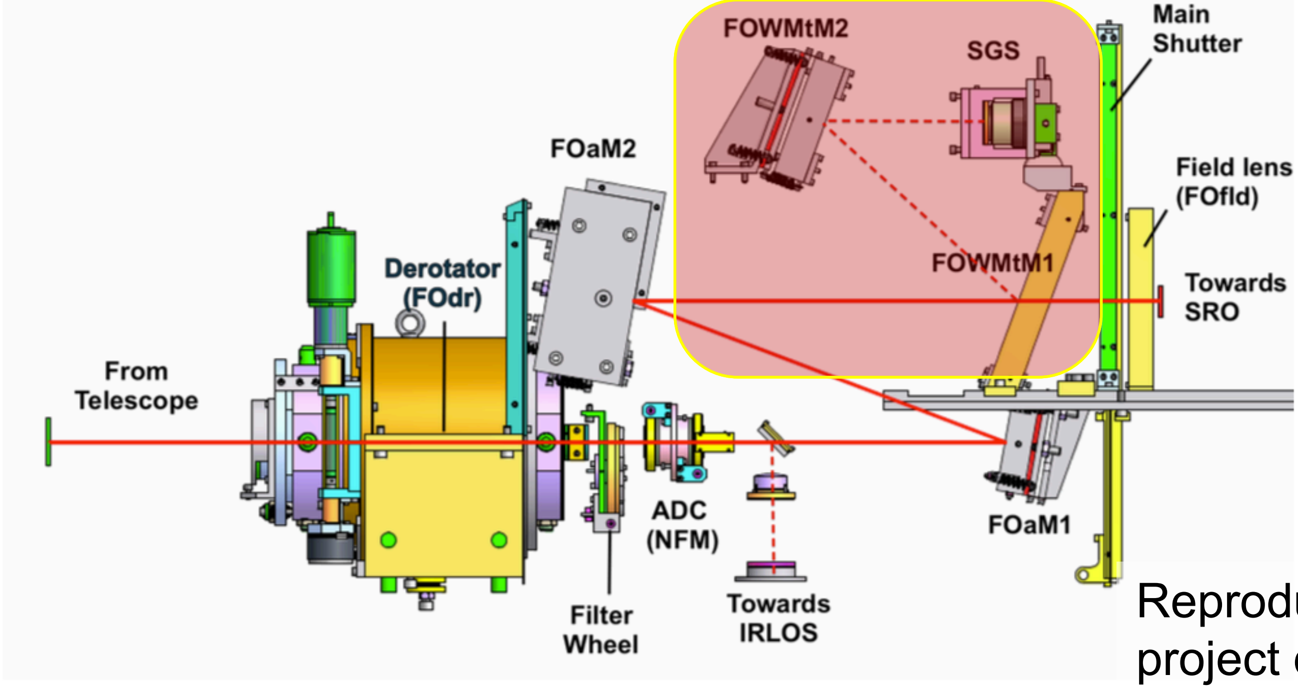
- **Problem:** Derotator and ADC create an image motion at field splitter that exceeds the specified stability during one hour observation. A stabilization of the image at field splitter level is then necessary.

- **Timing:** Feedback correction during observations

Reproduced from MUSE project documentation







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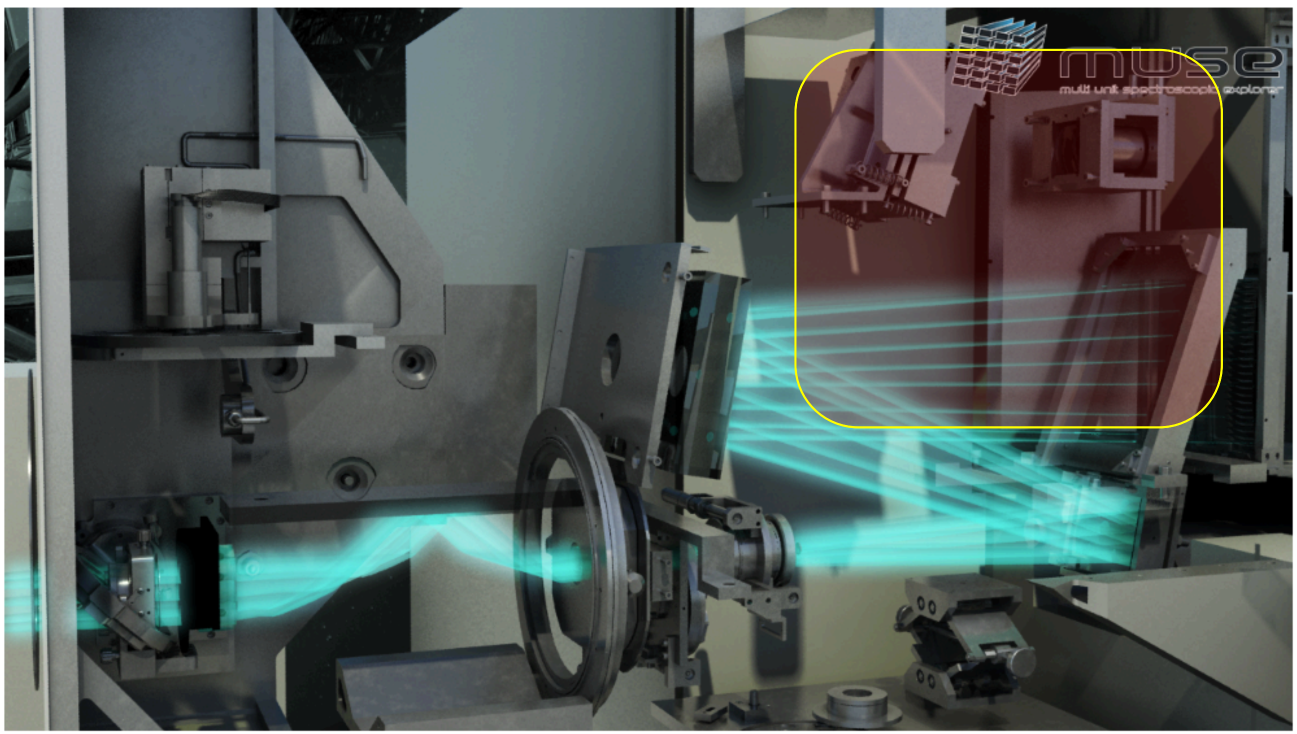


Metrology on VLT Instruments: muse

multi unit spectroscopic explorer

- **Reference:** Motion of automatically detected sources in the metrology fields

- **Slow Guiding**:
  - A dedicated slow guiding camera images the metrology fields
  - Astronomical point source are automatically detected and used as stable references
  - Corrections are sent to the TCS such that the references do not drift, i.e. closed loop control.

Metrology on ESO Instruments: AOF

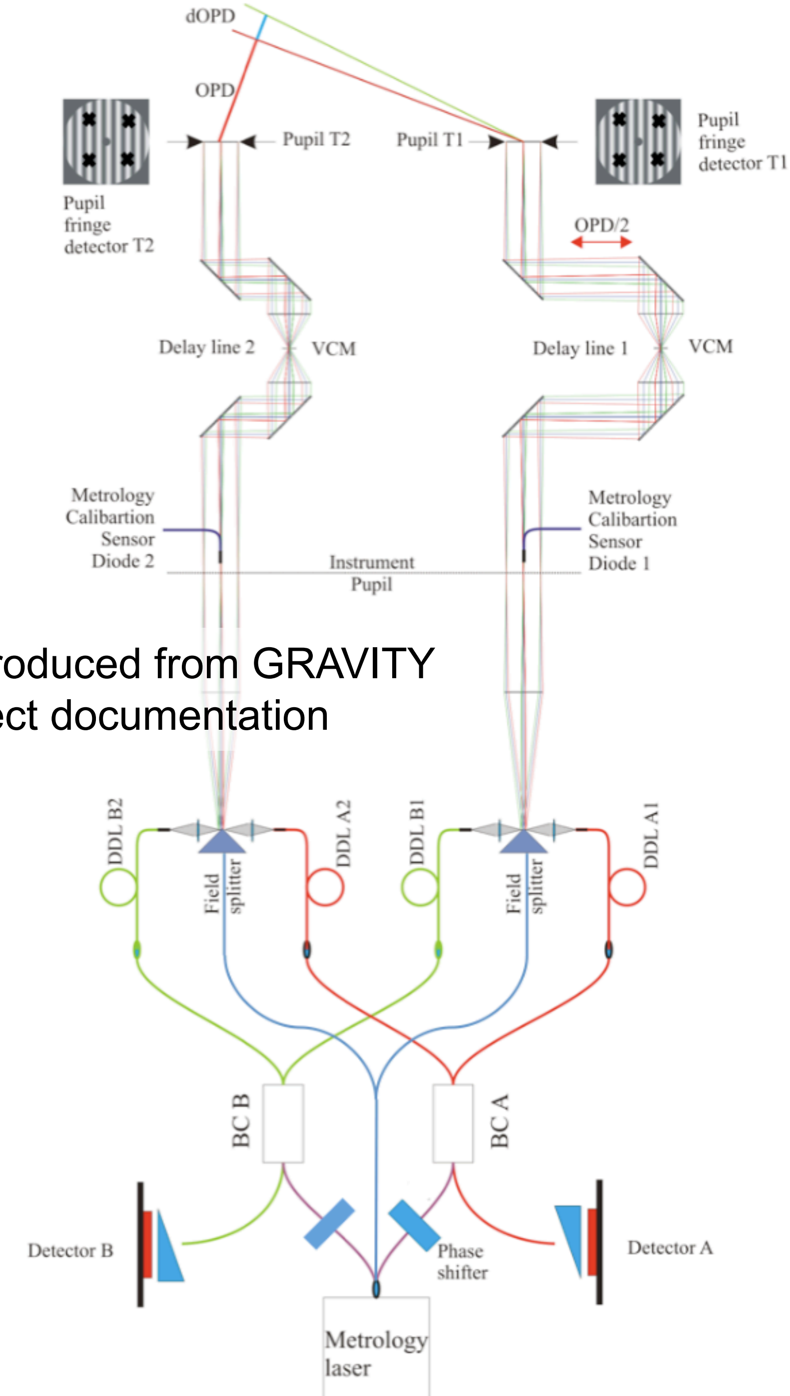
- **Problem:** Creeping mis-registration between the DSM and the WFSs - slow drift on Control Matrix.

- **Timing:** Slow feedback during observations.

- **Reference:** Comparison between the commands sent to the DSM and the measured change in wave front

- The knowledge of the *actually-used* IM is used to retrieve the shifts rotation etc. and update the CM.
- This is computationally intensive, but can be applied on a timescale of minutes.

ALMA Metrology



Reproduced from GRAVITY project documentation

- **VLTI GRAVITY:**
  - The differential OPD between the science and reference beam is measured with a **laser metrology system**.
  - Provides accurate astrometry
  - Absolute path length to a reflector on the spider (UT/AT) is measured
  - PRIMA used a similar approach, but only to M4
- **ALMA:** The antennas use a metrology system to measure internal deflection caused by temperature and wind.

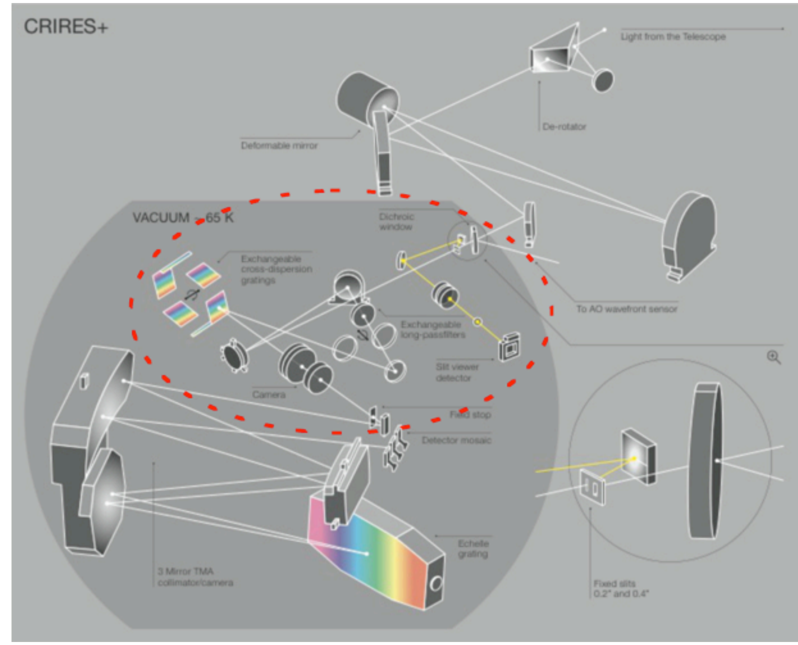
Overview

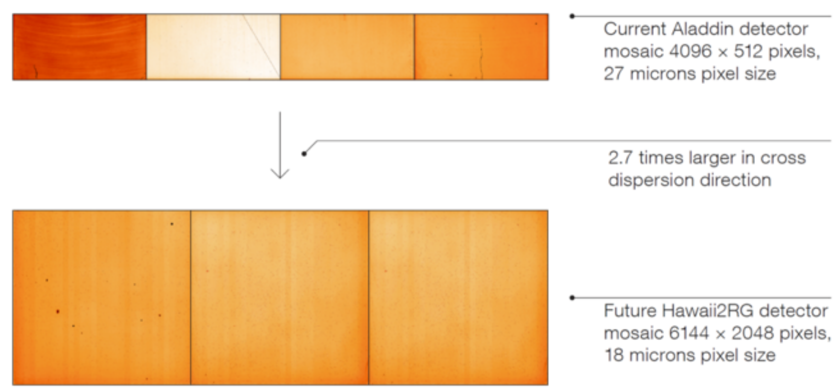
1. Examples of metrology at the La Silla Paranal Observatory
2. CRIRES+ Calibration
3. CRIRES+ Metrology

Original CRIRES → CRIRES+

- 1.0-5.0μm
- R=100,000
- AO assisted
- **Pre-dispersed** → **cross-dispersed**

- Further upgrade activities:
  - New spectro-polarimetric unit
  - **New calibration sources**
  - New ETC
  - Substantially upgraded slit viewer
  - Substantially upgraded ICS
  - Substantially upgraded ICE
  - Substantially upgraded DRS
  - refurbished warm optics (MACAO, derotator)





CRIRES+ Calibration Sources

- Flatfield:
  - Halogen
  - IR emitter
- Pen-Ray lamps:
  - Ne
  - Kr
- HeNe Laser

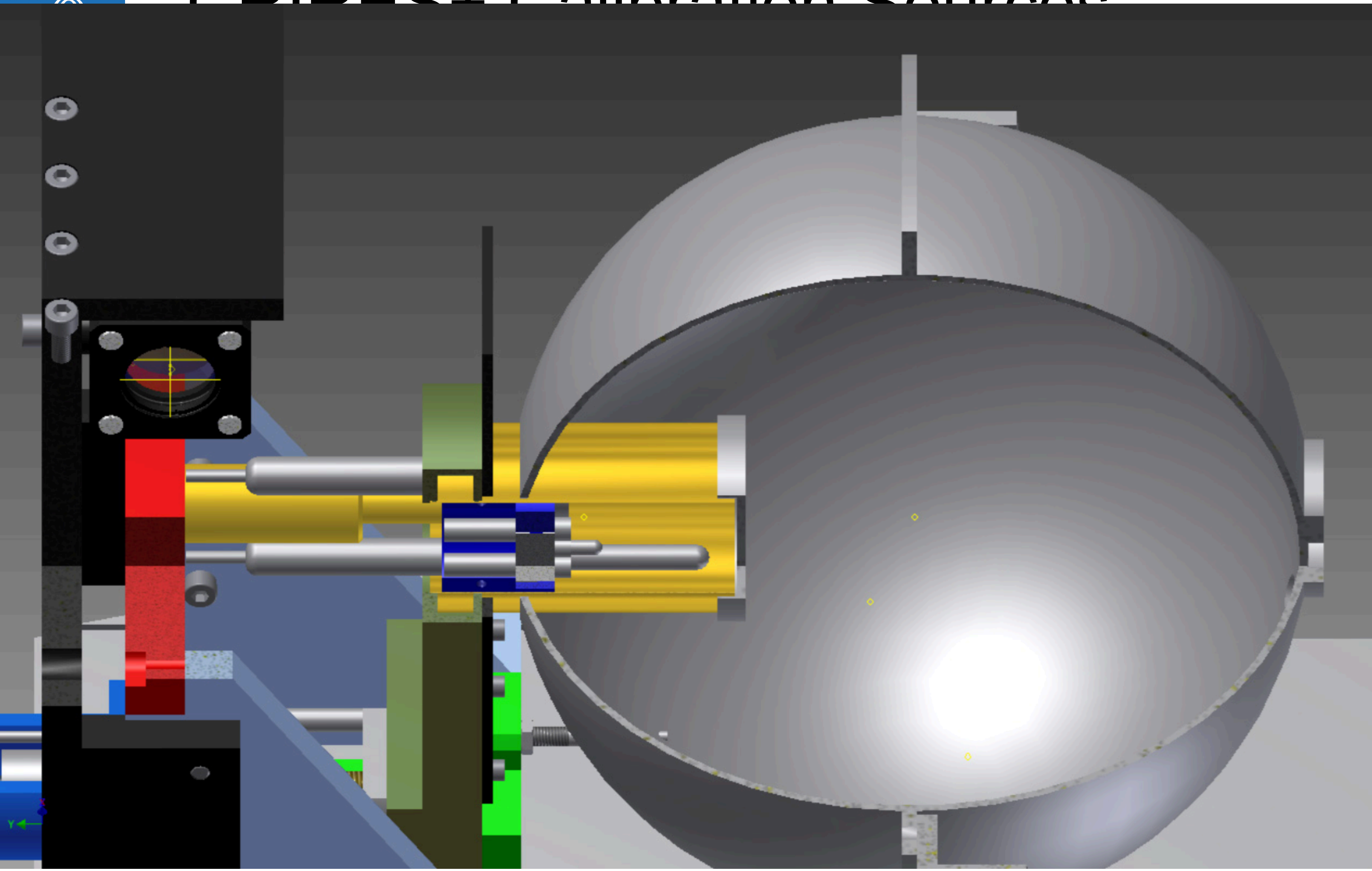
(all above:) oCRIRES, Integrating Sphere

- HCL: *UNe*, replaces ThAr
- *Fabry Perot Etalon, fibre feed to Integrating sphere*

- Absorption Cells:
  - N_2O, retained from oCRIRES
  - *New custom $^{13}CH_4$+$^{14}NH_3$+$^{12}C_2H_2$ (Methane-13, Ammonia, and Acetylene) cell*

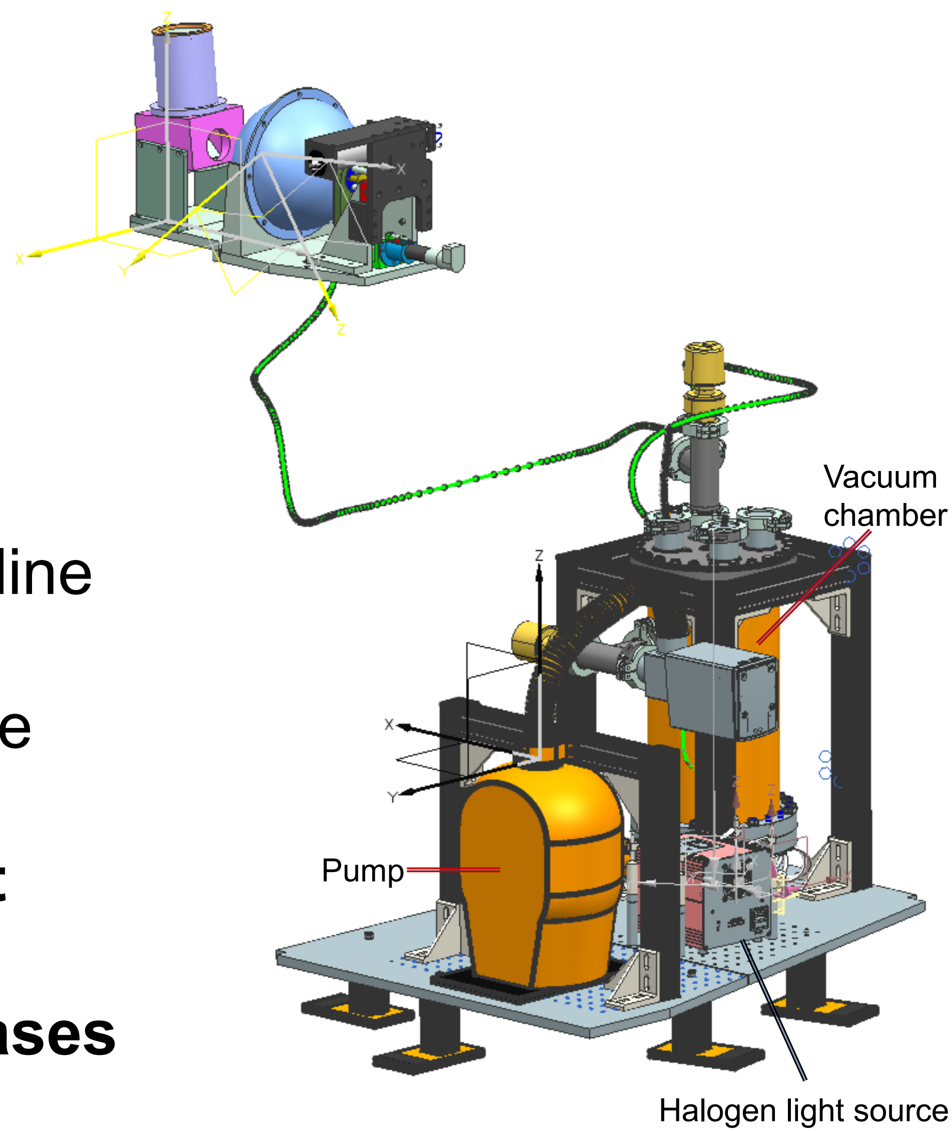
- *Dedicated metrology fibre source: UAr HCL*

CRIRES+ Calibration Sources

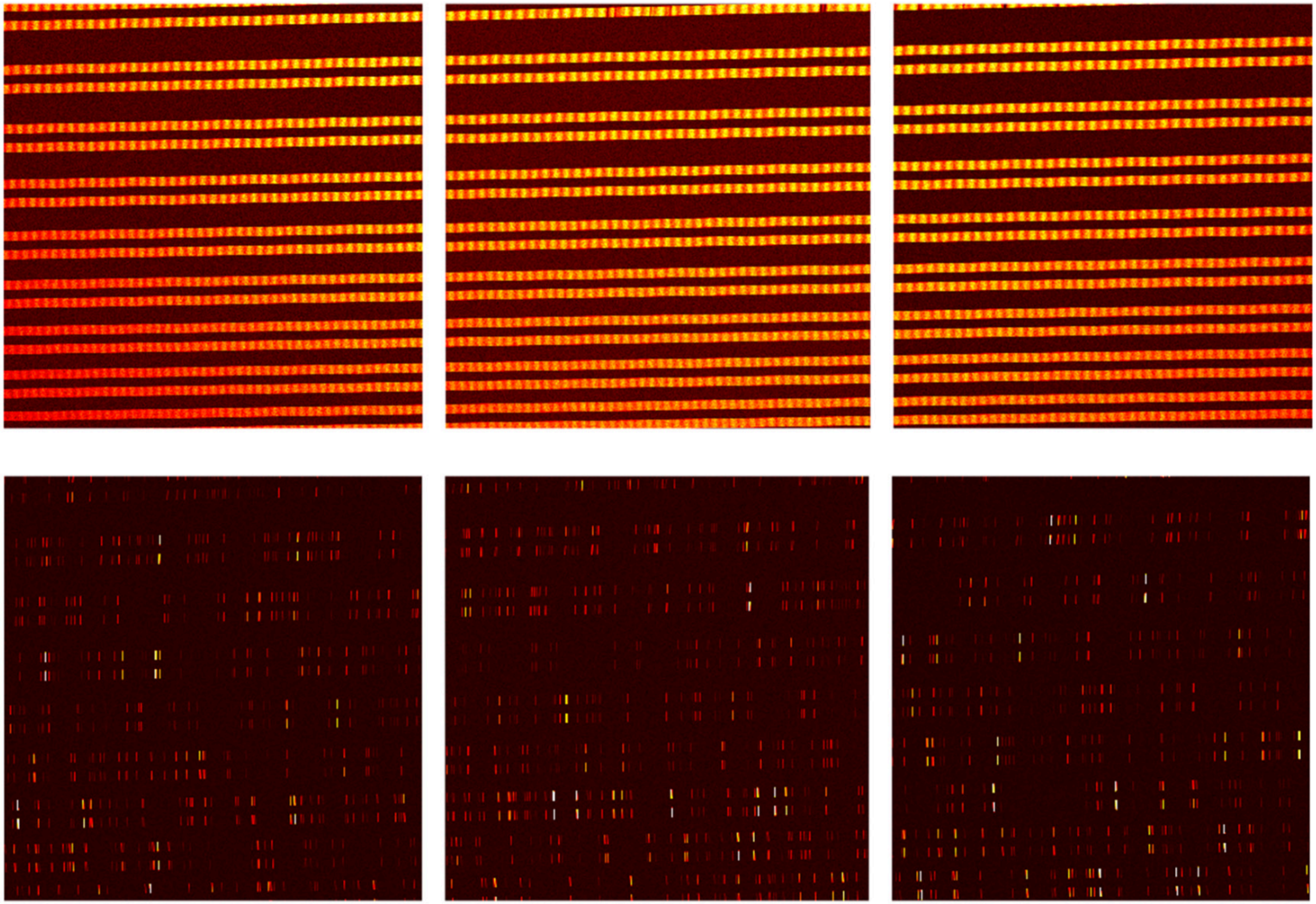


CRIRES+ Etalon

- Single shot *Y-K*
- High, regular line density
- Equally strong spectral features, contrast of 80% in *K*-band
- 10m/s relative wavelength precision
- Zero-pointing with emission line source
- Routed via integration sphere
- Modest vacuum (0.01mbar)
- **Supports exoplanet transit atmosphere and spectro-polarimetry key science cases**



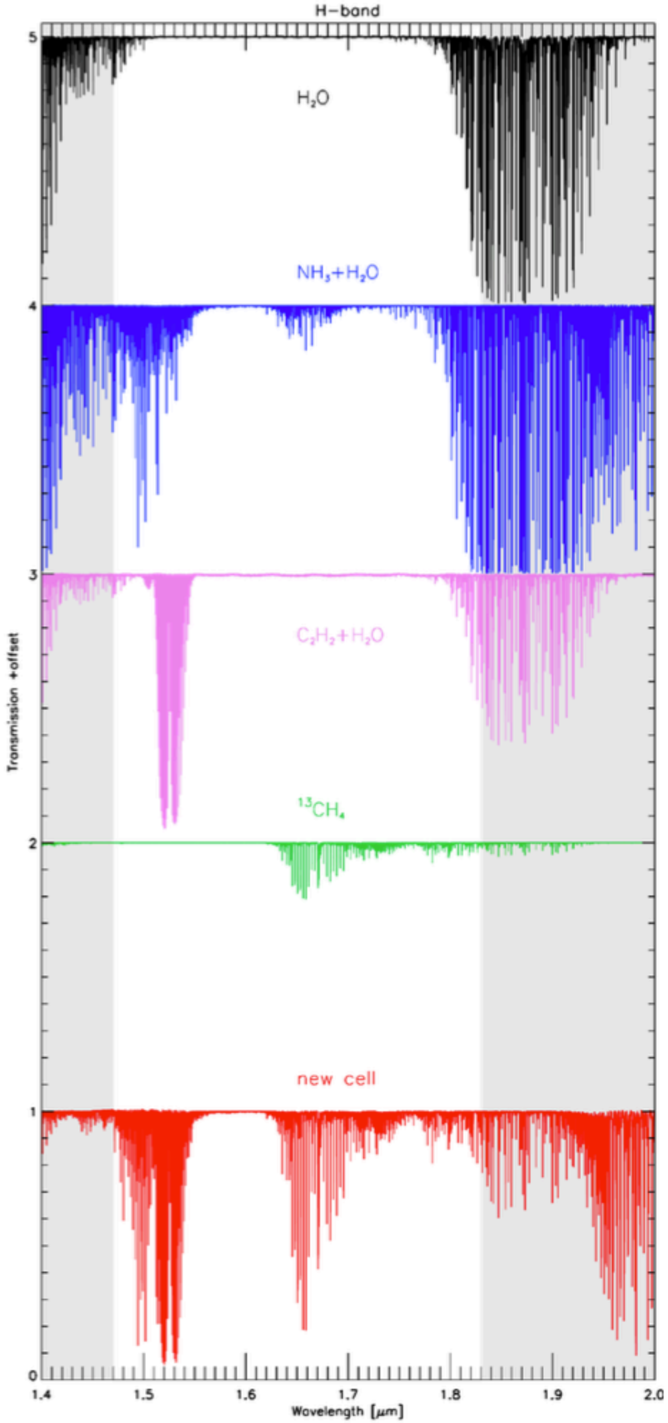
Etalon



CRIRES+ New Gas Cell

New custom **Ammonia, Methane-13 and Acetylene** cell has been developed:

- Simultaneous monitoring of the PSF. (Otherwise tiny changes in the slit illumination would result in huge errors in RV)
- Shown to provide excellent coverage and stability in *H*- and *K*-band, especially in the critical 2250-2450nm range (CO bandheads)
- Will provide <3m/s calibration in *K*-band (remember that CRIRES+ is not an ultra-stable, fibre fed, HARPS-like instrument)
- RV derivation is *not* supported by the pipeline
- First time a custom hybrid gas cell has been developed for IR (as opposed to CO and ammonia)
- Possible future upgrade is a long gas cell that would offer a richer spectrum with better dynamic range
- Also provides some coverage in the *L*- and *M*- bands
- **Supports the CRIRES+ key science driver: search for Super Earths around M-dwarfs**



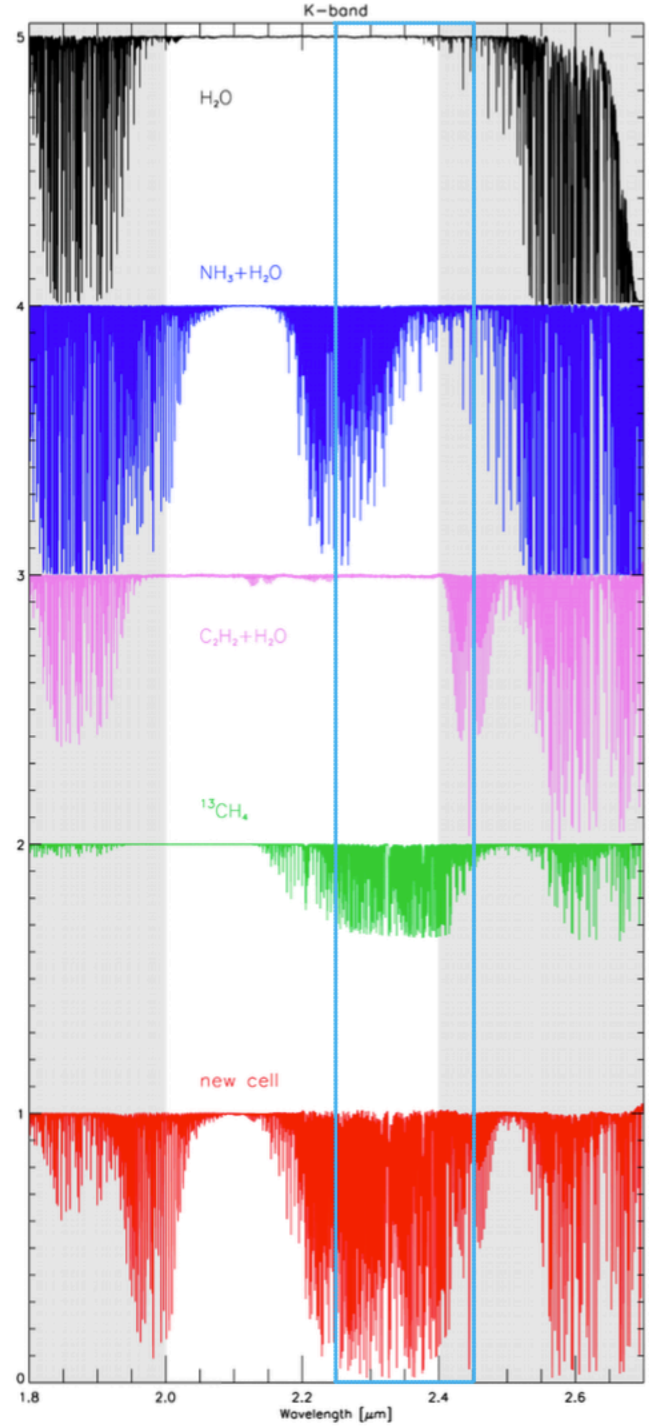
Water

Ammonia
+ water

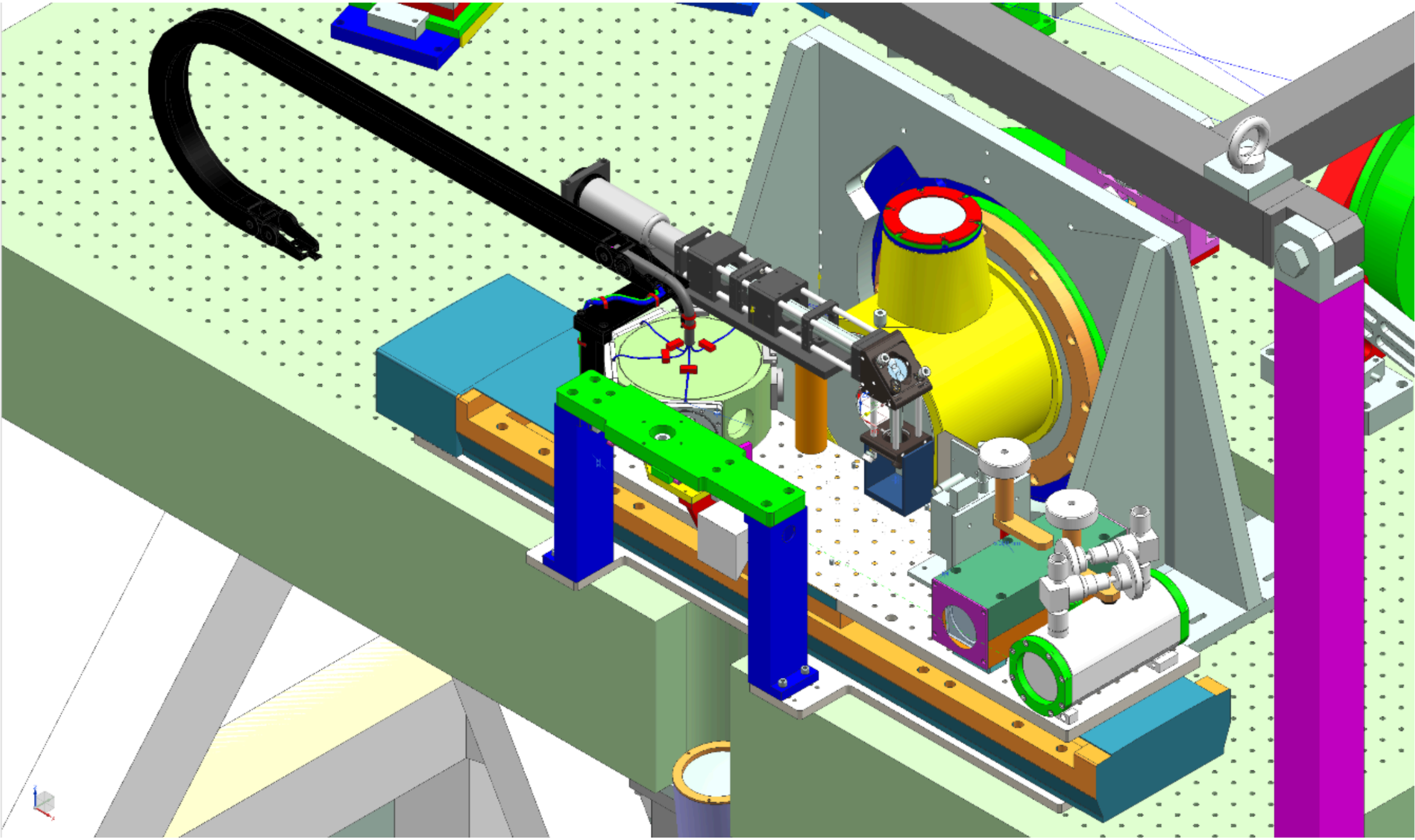
Methane
+ water

Acetylene
+ water

All



CRIRES+ Calibration Slide



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CRIRES+ Metrology

- **Problem:**
  - Stability – Exoplanet atmospheres science case requires long stable exposures
  - Repeatability – Applicability of daytime calibrations

	Dispersion req/goal (pix)	Cross-Dispersion req/goal (pix)
Stability (4hrs)	**0.1 / 0.05**	**0.2/ 0.1**
Repeatability (>24hrs)	**0.5 / 0.2**	**1.0/ 0.5**

- oCRIRES performance was a dispersion stability of ~0.15pix/4hrs and a dispersion repeatability of ~3pix
- *Main Culprit is clearly the echelle grating mechanism retained by CRIRES+*

- **Reference**: Spectral lines on the echellogramme

CRIRES+ Metrology: oCRIRES

- ThAr HCL
- Entrance slit fibres
  - offset from entrance slit to extend the usefulness of the HCL spectrum into settings beyond 2.5μm
    - fibres at two different offsets increase the line density
  - spectral features appear below the science spectrum
  - samples the prism and grating
- Intermediate slit fibre
  - offset from the intermediate slit, no pre-dispersion or order selection (many simultaneous orders)
  - narrow filter selects a region around 750nm that contains two prominent Ar lines (orders 72-74 appear on the FPA)
  - spectral features appear above the science spectrum
  - samples only the echelle grating

Metrology: oCRIRES

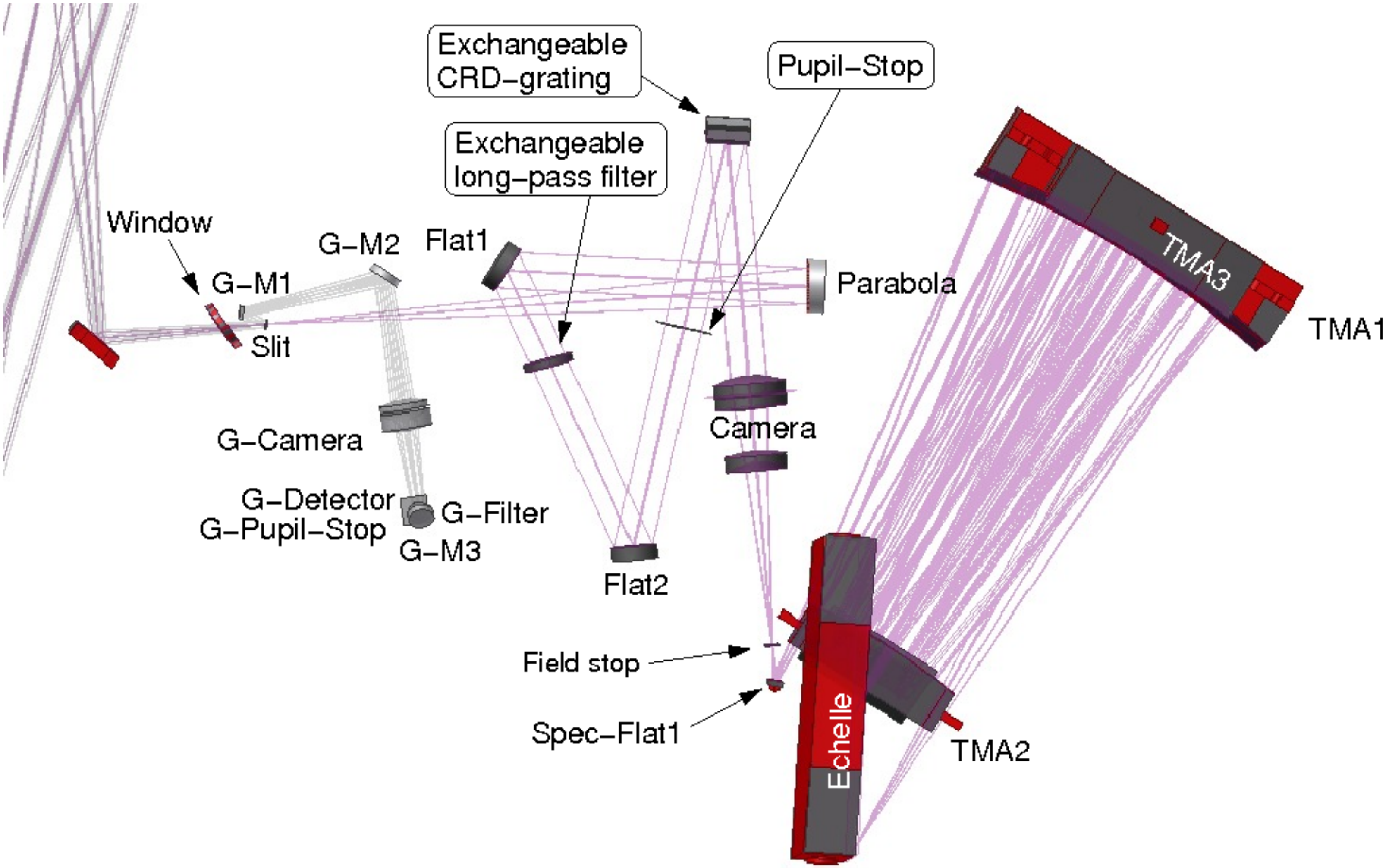
- **Corrective Feedback:** For each of the 200+ oCRIRES standard settings:
  - Identify at least two suitable calibration line from both fibres
  - Determine the exposure time appropriate for the lines in this setting.
  - Record a fiducial location for each line in each setting.
  - Before each science (or daytime flat field) exposure:
  1. Measure the positions of the two intermediate fibre lines.
  2. Compute the grating adjustment required to move them to their fiducial position
  3. Adjust the grating accordingly
  4. Repeat 1-3 above for the slit fibre lines and the prism
  5. Repeat 4 but adjust the piezo actuator instead of the prism
  - *Repeat steps 1-5 until the measured positions of both sets of lines are acceptably close to the fiducial positions.*

CRIRES+ Metrology: oCRIRES

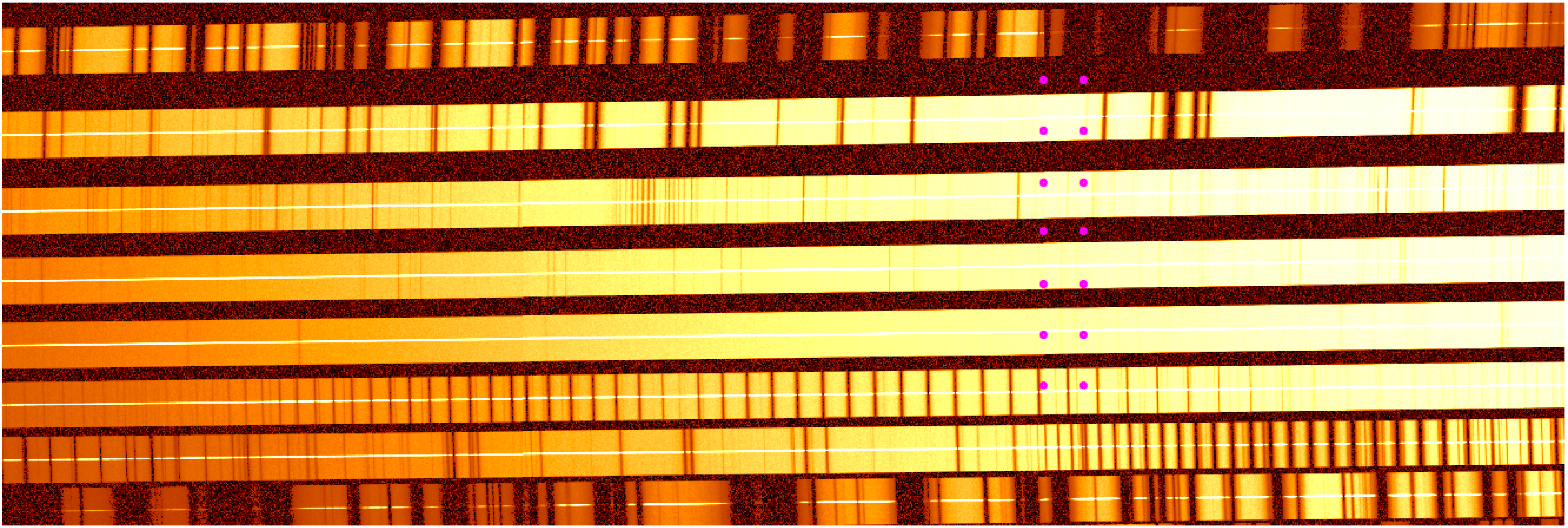
- **Verification in 2012/2013:**
  - All 285 settings tested for convergence to <0.1pix
  - 66 failed to converge
  - Failure was nearly always due to poor reference lines
  - The others:
    - 61/219 = 27% converged in one grating-prism iterations
    - 115/219 = 52% converged in two grating-prism iterations
    - 25/219 = 11% converged in three grating-prism iterations
    - 18/219 = 8% needed four or five grating-prism iterations
  - Mean time to converge was 80s (i.e. could be done during preset)
  - No increase in scattered lights or ghosts was observed as a result of the metrology ⇒ *metrology lines could be included in science spectra*

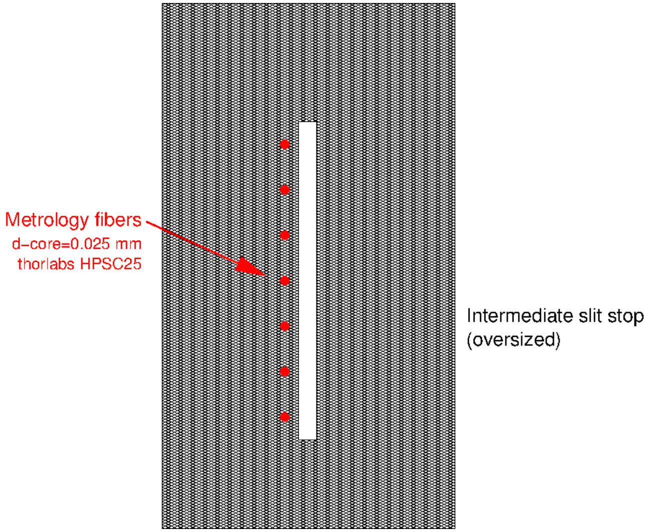
- Never offered to observers because oCRIRES was removed just after the verification was complete

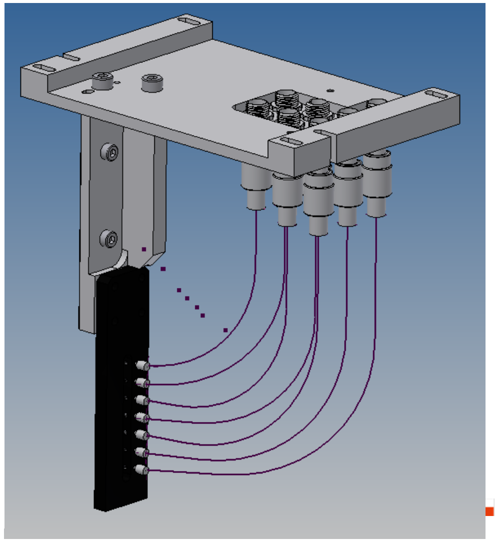
CRIRES+ Metrology: Adaptation



CRIRES+ Metrology: Adaptation







CRIRES+ Metrology: Adaptation

- No dedicated metrology fibre at the entrance slit:
  - The whole echellogramme is illuminated with full slit images of UNe lines
  - Cannot be used for *L*- and *M*-bands
  - Cannot be used simultaneous to science exposures
- A metrology fibre bundle injecting calibration light near to the field stop:
  - 7 fibres aligned parallel to the slit
  - Fed by a UAr HCL (filter extracts 2 prominent Ar lines at ~750nm)
  - Samples only the grating
  - Can be imprinted on science exposures
- A tip/tilt piezo adjustment for the “Flat2” mirror
  - Facilitates cross-dispersion shift of the echellogramme
  - *Not* sampled by the metrology fibre

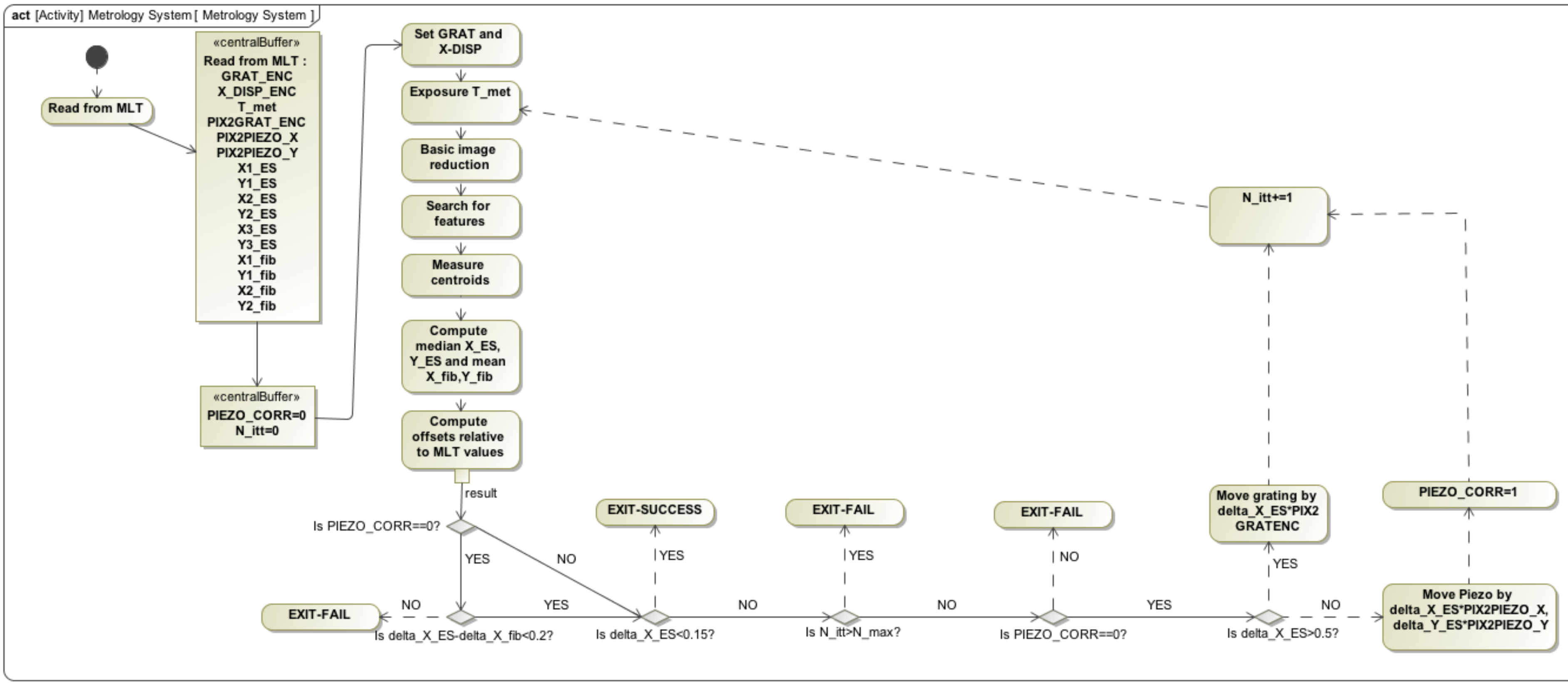
CRIRES+ Metrology: Adaptation

- Modified feedback strategy:
  - Begin with feedback loop on echelle grating mechanism and cross-disperser wheel positions
  - Piezo adjustment is essentially a blind correction that can only be made once, must be the last, sub-pixel adjustment
  - L- and M-band the feedback is done only with the metrology fibre lines

- Metrology Look-Up Table (~25 rows instead of >200):
  - DIT
  - List of suitable entrance slit UNe features (λ, x, y, detector)
  - List of suitable metrology fibre Ar lines (λ, x, y, detector)
  - Translation from pixel shifts
    - cross-disperser wheel encoder value change
    - echelle grating mechanism encoder value change
    - piezo actuator voltage change
  - Convergence statistics

CRIRES+ Metrology: Adaptation

Modified feedback strategy (*Y*- to *K*-band):



CRIRES+ Metrology: Adaptation Issues

- New fibre bundle
- New dedicated UAr lamp
- All processing is done by ICS:
  - Where are basic data reduction files (flats, darks, bad pix) stored?
  - How long would it take to obtain them on-the-fly?
  - Are they even needed?
  - How long does the processing take?
- Warm up time for HCLs
- Remanence from HCLs on H2RGs
- Stick-slip behaviour of echelle grating mechanism
- Reliability of blind piezo adjustments
- Equivalence of piezo mirror tilt and echelle grating tilt
- How many iterations before exiting?
- What to do in the case of no convergence?
- Implementation in templates? (including stability) etc…..

Conclusions

- There are a wide range of clever metrology systems in place on ESO instruments. Probably I have only scratched the surface.
- Metrology:
  - is often the only way to ensures that the raw data is free from the impact of uncontrollable mechanical behaviour
  - may provide additional data for use in data reduction
  - provides diagnostics for instrument monitoring
- The CRIRES+ metrology is simple enough conceptually, but will require significant effort to implement and test