

Thorium-argon spectral lines: emission physics and a measured example

An educational spectroscopy report using privacy-reviewed EXOhSPEC FITS data

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CONTEXT	Curiosity-led report from practical EXOhSPEC work
AFFILIATION	University of Hertfordshire
EXPOSURES	30, 60, 120, and 180 seconds
PUBLIC SCOPE	Detector coordinates; raw FITS and optical details withheld

Central idea. A thorium-argon lamp produces a dense emission-line spectrum: discrete atomic transitions create bright features that can serve as a wavelength ruler in astronomical spectroscopy.

This report distinguishes measured detector morphology from atomic interpretation. No wavelength or species labels are assigned before a validated order trace and dispersion solution.

ABSTRACT Summary

Thorium-argon (Th-Ar) hollow-cathode lamps produce a dense forest of narrow emission features and are established wavelength references for astronomical spectrographs. During practical work on the EXOhSPEC project, several Th-Ar spectra were recorded. Their appearance prompted the questions developed here: what are the bright lines, how does the lamp produce them, how do emission and absorption differ, and why is the spectrum useful? The measured frames provide a real example while private technical details remain unpublished.

The unsaturated integrated response follows exposure time with $R^2 = 0.999276$ and a maximum fractional residual of 1.994%. Pixels at or above 60,000 ADU increase from 1 at 30 s to 121 at 180 s. Phase correlation gives a maximum translation estimate of 0.071 native pixel relative to 120 s under a translation-only model. The 120 s frame is therefore recommended when one exposure must represent the set, while an HDR estimator provides the clearest detector-space visualization.

Keywords: thorium-argon; hollow-cathode lamp; echelle spectroscopy; wavelength calibration; EXOhSPEC; CMOS; exposure optimization

120 s	0.9993	1.994%	0.071 px
recommended single frame	response R^2	largest fit residual	largest estimated shift

1 Purpose, scope, and privacy boundary

The main goal is educational: explain what a Th-Ar source is, why its spectrum consists of emission lines, how thorium and argon contribute, where the materials occur, and how such lamps support astronomical spectroscopy. The supplied exposures are a practical example of how those ideas appear on a detector before wavelength calibration.

This release identifies EXOhSPEC and a generic ZWO CMOS-family detector. It intentionally omits exact hardware configuration, optical prescriptions, laboratory layout, raw detector dimensions, full headers, file paths, and raw images. Public coordinates are normalized. This protects the laboratory while preserving the analysis logic and aggregate evidence.

2 Emission, absorption, and the hollow-cathode source

A Th-Ar lamp is a hollow-cathode discharge source. Argon ions bombard a thorium-bearing cathode and sputter thorium into the discharge. Collisions excite neutral and ionized species. Radiative relaxation produces photons at discrete energies, creating narrow emission features.

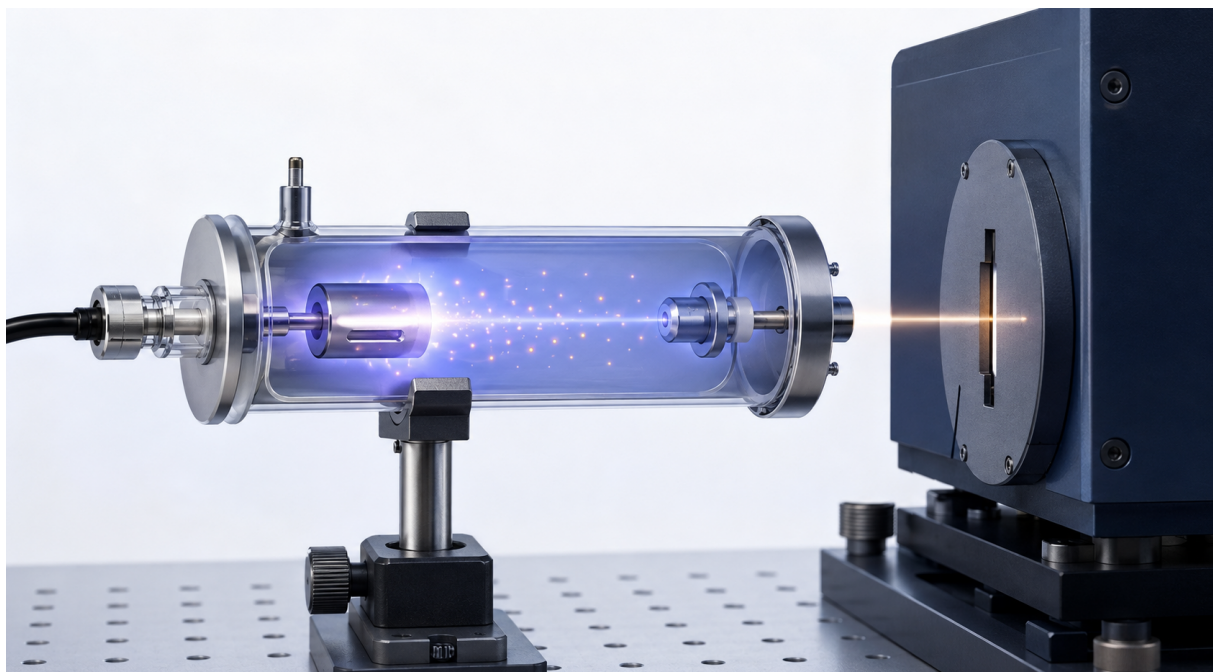


Figure 1. AI-generated conceptual illustration of a Th-Ar lamp feeding a generic spectrograph entrance. It is not a photograph, engineering drawing, or representation of the private EXOhSPEC laboratory.

The fill gas allows a discharge to form at low pressure. Positive argon ions accelerate toward the cathode and transfer momentum to its surface, releasing thorium atoms by sputtering. Electrons and ions then excite and ionize both species. The visible output is therefore a mixture of neutral and ionized thorium and argon transitions.

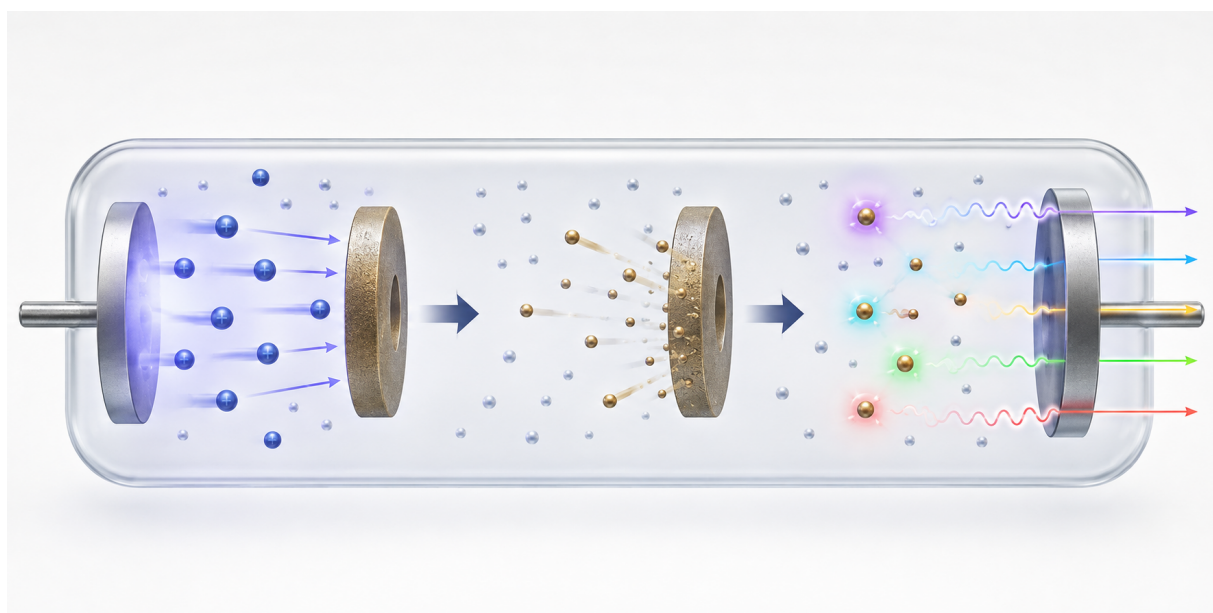


Figure 2. AI-generated conceptual sequence of argon-ion bombardment, thorium sputtering, excitation, and discrete photon emission. The artwork is explanatory rather than a literal cross-section.

2.1 Emission lines versus absorption lines

Emission and absorption are opposite signatures

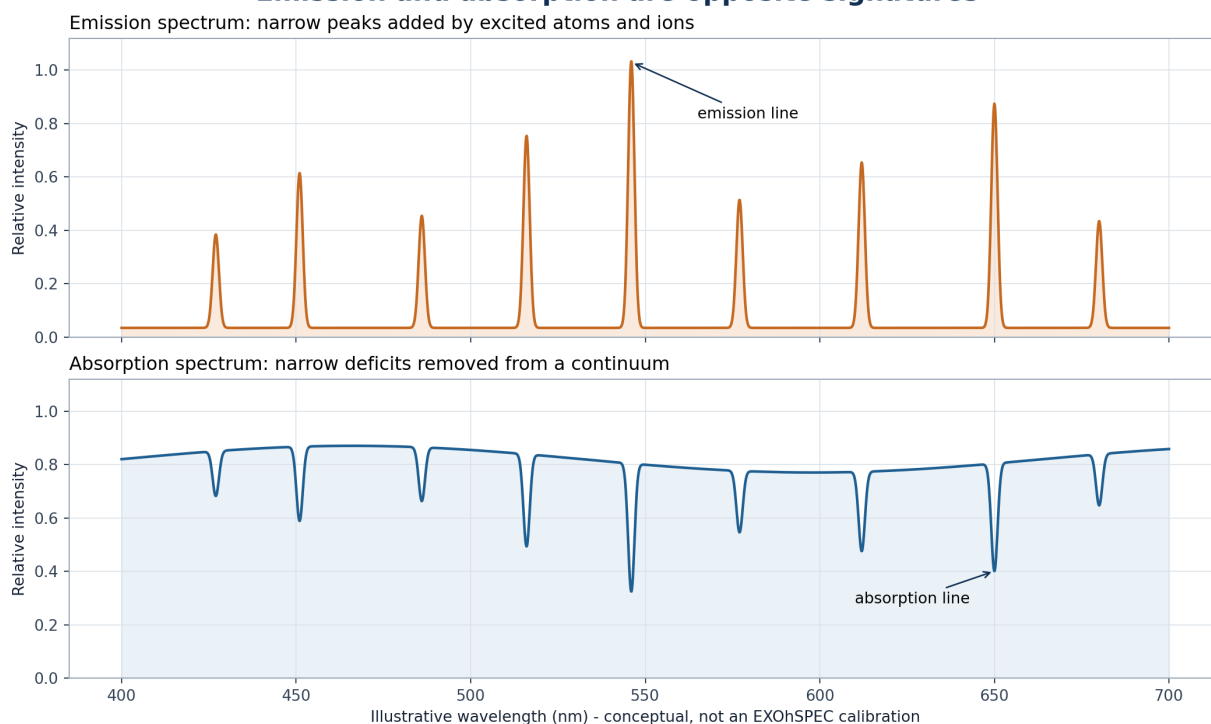


Figure 3. Conceptual distinction between emission peaks and absorption deficits. The wavelength values are illustrative and are not measured EXOhSPEC line assignments.

An emission line is a positive peak because the source adds photons at a transition wavelength. An absorption line is a deficit below a continuum because intervening matter removes photons. The EXOhSPEC lamp frame contains emission-line images; a stellar spectrum commonly contains absorption structure.

A transition from upper energy E_u to lower energy E_l emits a photon satisfying $E_u - E_l = h\nu = hc / \lambda$. Th I, Th II, and Th III denote neutral, singly ionized, and doubly ionized thorium; Ar I, Ar II, and Ar III use the same charge-state convention. Roman numerals do not describe brightness.

The detector records each transition convolved with the spectrograph line-spread function and pixel response. A measured feature therefore has a centroid, width, integrated area, peak height, local background, and uncertainty. Blends, saturation, background gradients, and asymmetry can bias the centroid used for calibration.

3 Why thorium and argon are used

Thorium supplies a dense pattern of narrow transitions. NIST Standard Reference Database 161 contains reference wavelengths for more than 20,000 Th I, Th II, and Th III features together with argon line lists. The dominant terrestrial isotope is thorium-232, whose approximately 1.40×10^{10} year half-life and dominance reduce isotopic complexity.

Argon sustains the discharge and adds Ar I, Ar II, and Ar III features. Some carrier-gas lines are very strong. This is useful for acquisition but challenging for detector dynamic range: faint thorium structure may require an exposure that pushes bright cores toward the ceiling.

USGS estimates about 10.5 mg kg^{-1} thorium in upper continental crust. NOAA gives argon as about 0.934% by volume of dry air, dominated by argon-40. Abundance does not determine calibration quality; reference accuracy, line density, usable intensity, and stability do.

3.1 Thorium and argon from blue to red

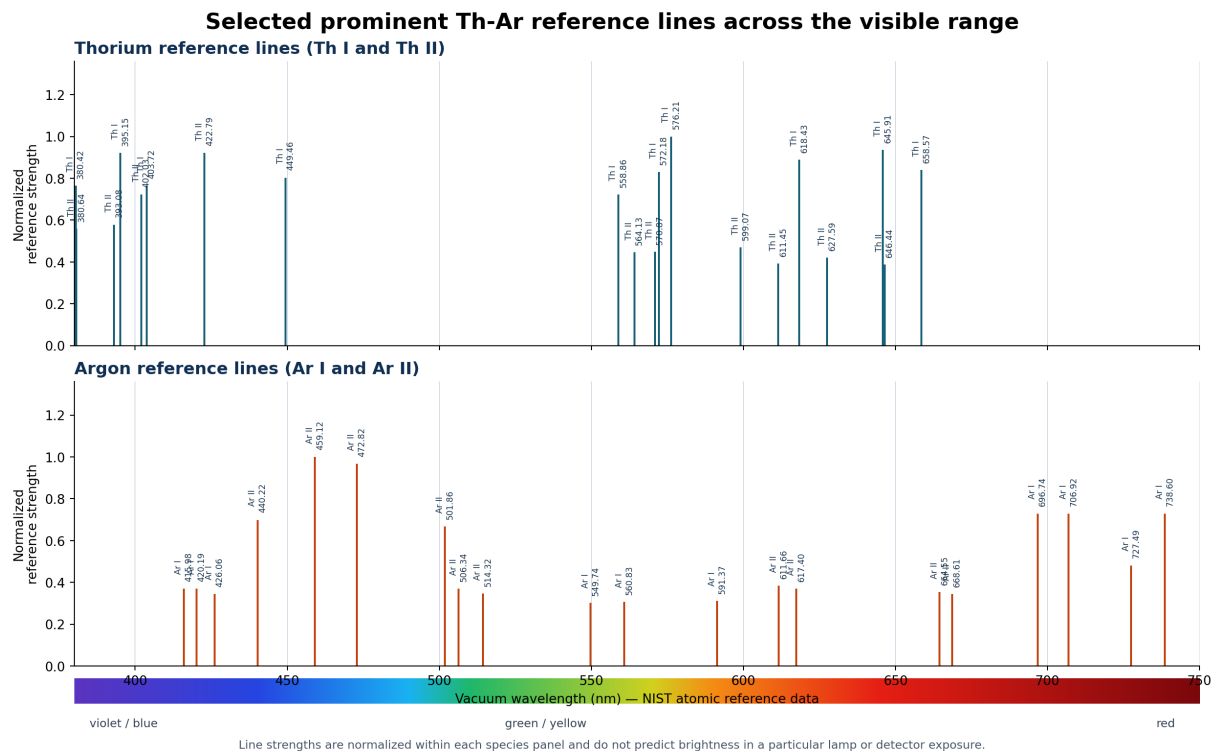


Figure 3b. Selected prominent NIST reference lines from 380 to 750 nm. Thorium and argon are separated by species; the colour strip runs from the violet/blue side to the red side. Strengths are normalized within each panel and do not predict this lamp's measured brightness.

Both thorium and argon contribute lines across the visible interval, so colour alone does not identify the element. Agreement with a laboratory wavelength identifies the species. Th I and Ar I are neutral atoms; Th II and Ar II are singly ionized atoms. Because the supplied FITS files have no validated wavelength solution, this atomic reference guide is kept separate from the measured detector spots.

4 Reading the measured EXOhSPEC detector frame

The supplied FITS exposure is a two-dimensional echellogram, not a finished one-dimensional plot. Dispersion acts along a traced order; cross-dispersion separates neighbouring orders. The landscape presentation below makes these two roles explicit while keeping the sign of increasing wavelength unassigned.

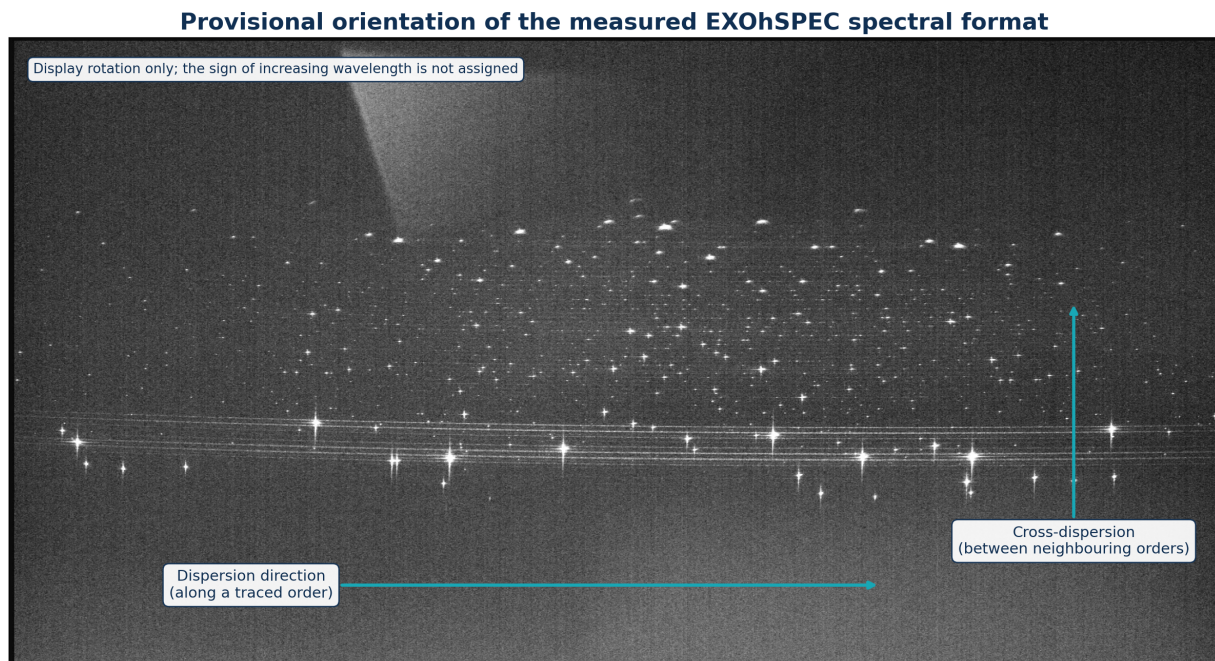


Figure 4. Zoomed-out, rotated measured detector format. The arrows show provisional dispersion and cross-dispersion directions. Rotation changes presentation only; the wavelength-increase direction requires calibration.

The broad pale region is diffuse recorded illumination, not an identified atomic line. Possible contributors include scattered light, order wings, reflections, and a spatially varying background. A final extraction should fit a local two-dimensional inter-order background and propagate its uncertainty.

4.1 Detector morphology in detail

An inverse-hyperbolic-sine display stretch reveals weak structure while retaining bright features. Quantitative calculations use linear detector values; the stretch affects appearance only.

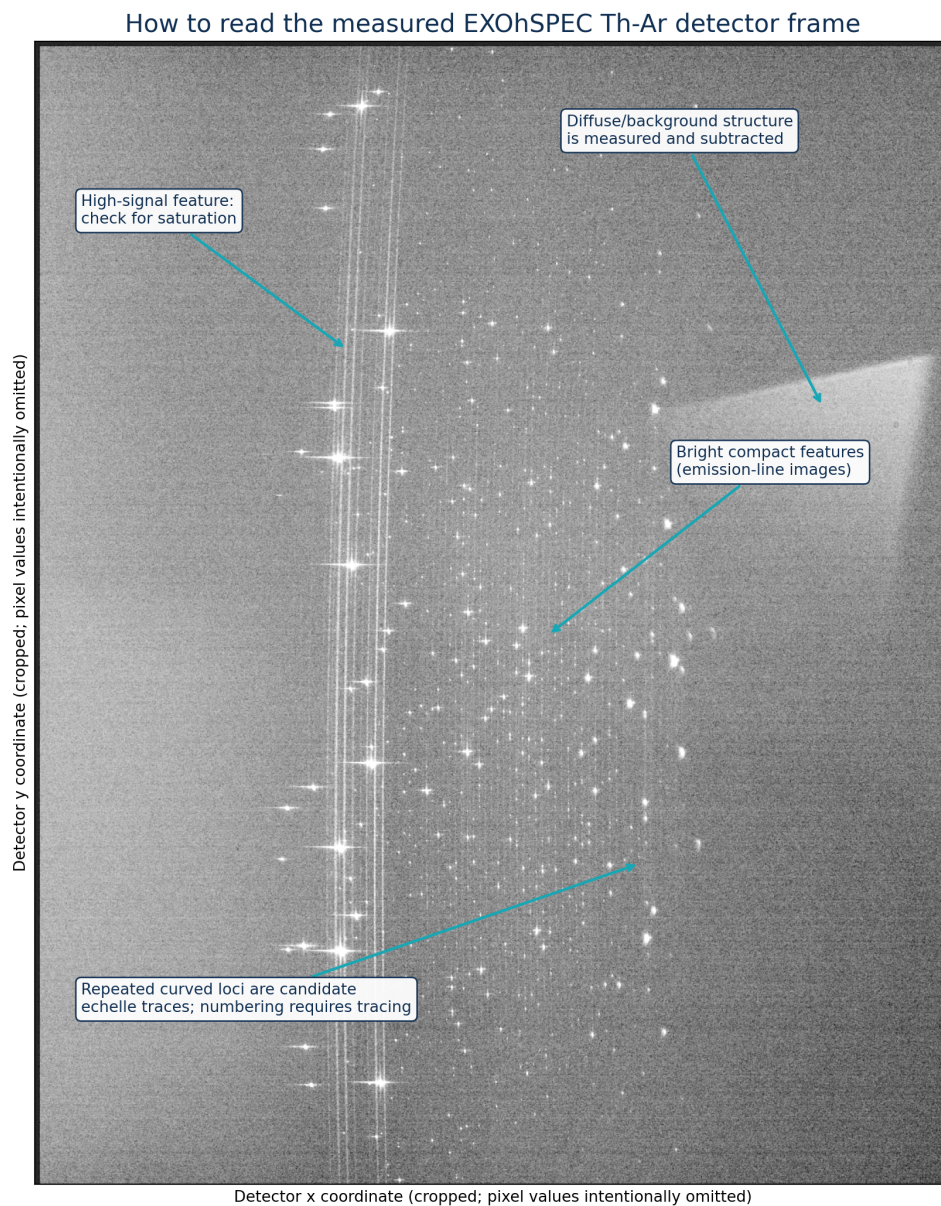


Figure 5. Measured detector morphology with a reading guide. Bright compact features are emission-line images. Repeated loci are candidate echelle traces, but order numbering and wavelengths require calibration.

4.2 Measured features marked in the 120 s frame

Python detects strong local maxima in the measured 120 s array and selects a spatially separated subset for readable callouts. L01-L24 are detector-feature identifiers, not atomic assignments. Their normalized coordinates and relative peak signals are exported as a CSV table.

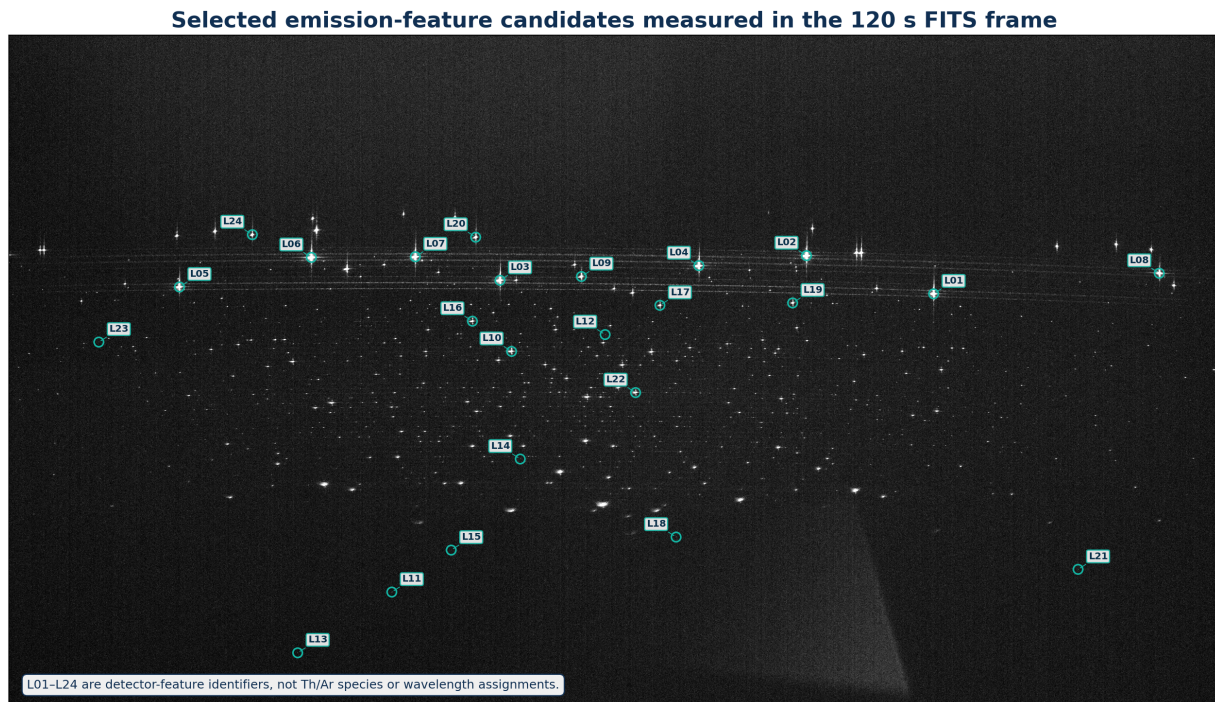


Figure 5a. Selected emission-feature candidates marked directly on the measured 120 s FITS frame. A label identifies a detector feature only; it does not identify thorium, argon, or wavelength.

A valid atomic label requires tracing the containing order, extracting its one-dimensional profile, fitting an unsaturated centroid, and matching several centroids jointly to laboratory wavelengths. Colour and brightness alone cannot distinguish Th I, Th II, Ar I, and Ar II.

4.3 Where are the blue and red ends?

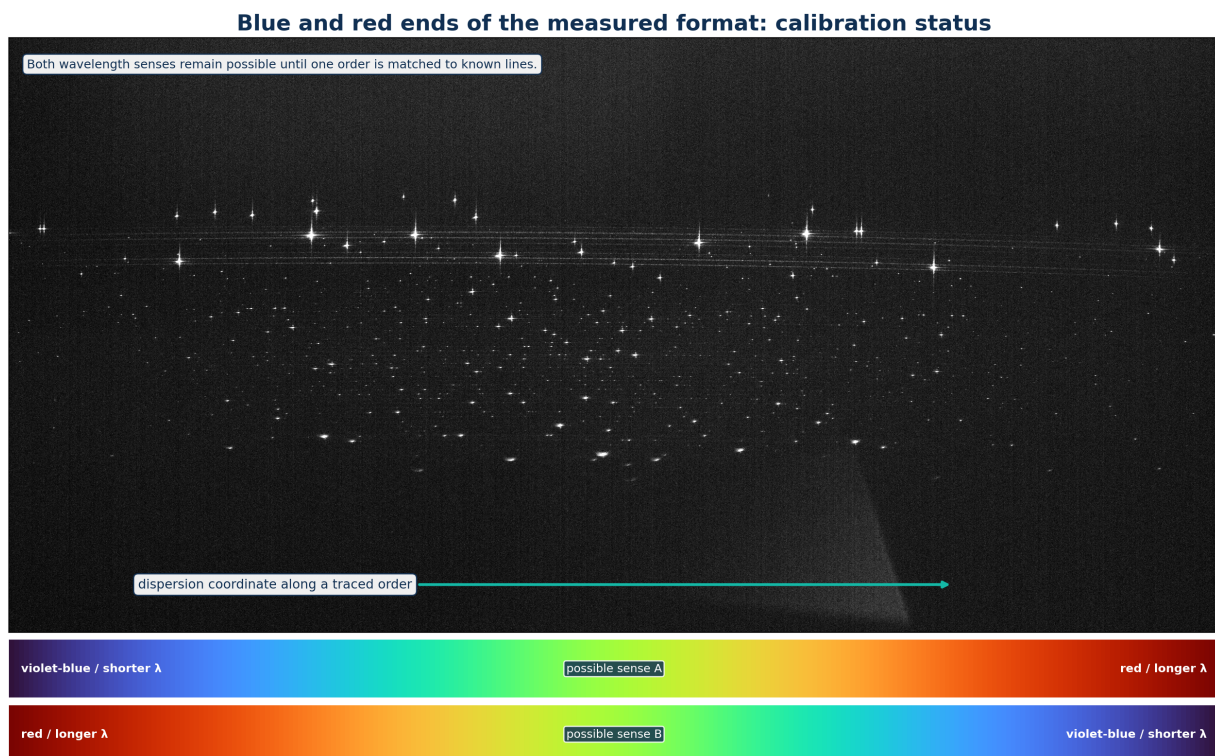


Figure 5b. The measured geometry fixes the dispersion axis but not the sign of increasing wavelength. The two colour bars show the mirror possibilities; a known line/order match is needed to choose one.

The 120 s FITS header contains no WCS, wavelength coordinate, dispersion coefficients, or order numbers. Placing a numerical NIST wavelength on an individual detector spot would therefore be an invented result. The species-coded NIST atlas in Figure 3b supplies the reference wavelengths for the eventual match, while Figures 5a and 5b preserve what this observation itself establishes.

5 Detector-domain methodology

5.1 FITS ingestion

The primary image is memory mapped and FITS scaling keywords are applied so calculations use physical unsigned detector values. Only exposure time is admitted to public metadata.

5.2 Robust background

The pedestal is the median of a sparse full-frame sample. Scatter is 1.4826 times the median absolute deviation, which is resistant to sparse bright features.

5.3 Public crop

Bright-pixel coordinate percentiles define a padded feature-rich region. Published axes are normalized and raw detector dimensions remain private.

5.4 Common mask

The 180 s signal-rate image defines a source mask that is dilated to cover the local feature footprint. Linearity uses only pixels below 55,000 ADU in every exposure.

5.5 Response model

Pedestal-subtracted counts in the common mask are summed and fitted through the origin against exposure time. This is an exposure-response diagnostic, not a complete camera-linearity calibration.

5.6 Registration

Block-averaged log images are compared by phase correlation, with parabolic interpolation around the peak. The model fits translation only, not rotation, scale, or local distortion.

5.7 HDR estimator

At each pixel, the longest exposure below 60,000 ADU is converted to signal per second. Shorter exposures replace longer values near the adopted ceiling.

5.8 Candidates

Local maxima after mild Gaussian smoothing are ranked. The 500 displayed candidates are morphological detections and must not be interpreted as 500 identified atomic lines.

HDR rate estimator

$$R(x,y) = [I_{t^*}(x,y) - B_{t^*}] / t^*$$

where t^* is the longest exposure for which I_{t^*} is below 60,000 ADU.

6 Quantitative exposure results

Exposure	Background	Robust sigma	Bright pixels	>=60,000 ADU	Signal / 30 s
30 s	502	2.965	6,267	1	1.00000
60 s	504	4.448	10,906	15	1.97961
120 s	505	4.448	17,998	75	4.01202
180 s	508	4.448	26,132	121	5.84104

The background pedestal changes by only 6 ADU across the sequence. Visible structure increases with exposure, but the near-ceiling population rises from 1 to 121 pixels. The integrated values remain close to the ideal exposure ratios 1:2:4:6.

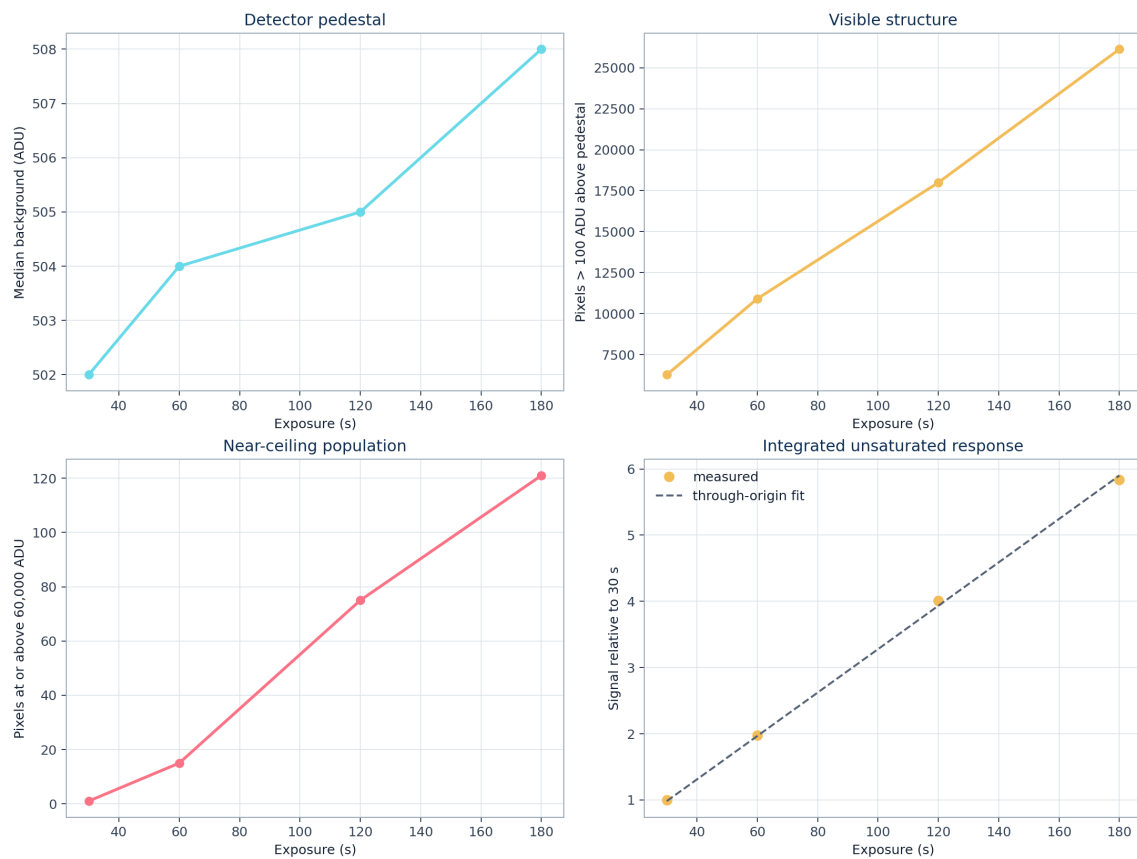


Figure 6. Detector pedestal, visible structure, near-ceiling population, and integrated unsaturated response. The common-mask response gives $R^2 = 0.999276$.

7 Registration and profile structure

Translation estimates relative to the 120 s frame are $(-0.070, -0.012)$, $(-0.065, -0.017)$, $(0, 0)$, and $(-0.045, -0.019)$ pixels in (y, x) for 30, 60, 120, and 180 s. The maximum magnitude is 0.071 pixel. These values show consistency under the algorithm, not a full uncertainty budget.

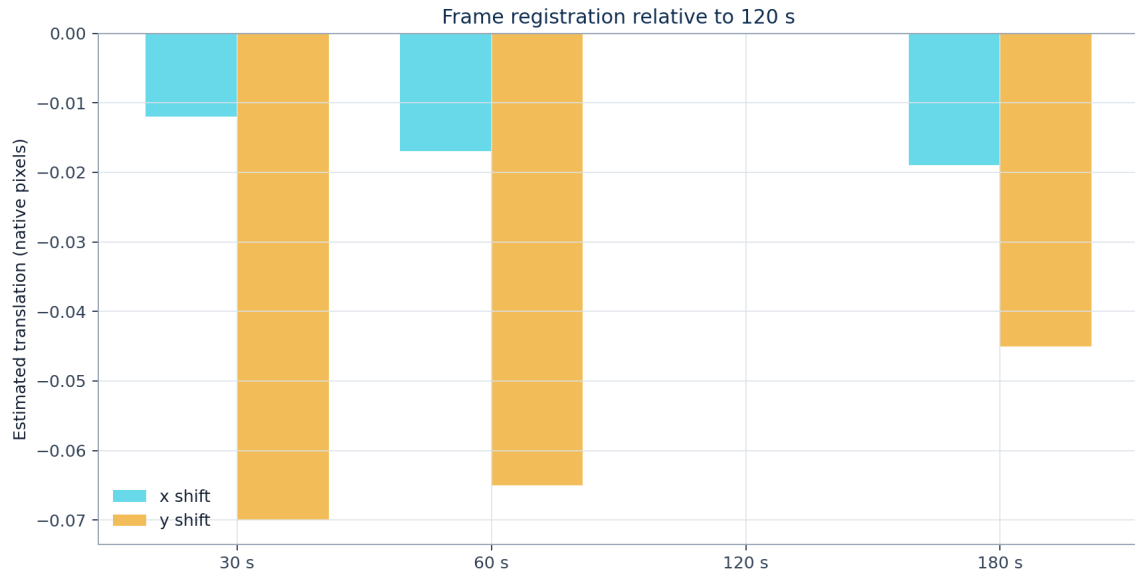


Figure 7. Phase-correlation shifts relative to 120 s after four-pixel block averaging.

Representative extracted detector-space profiles

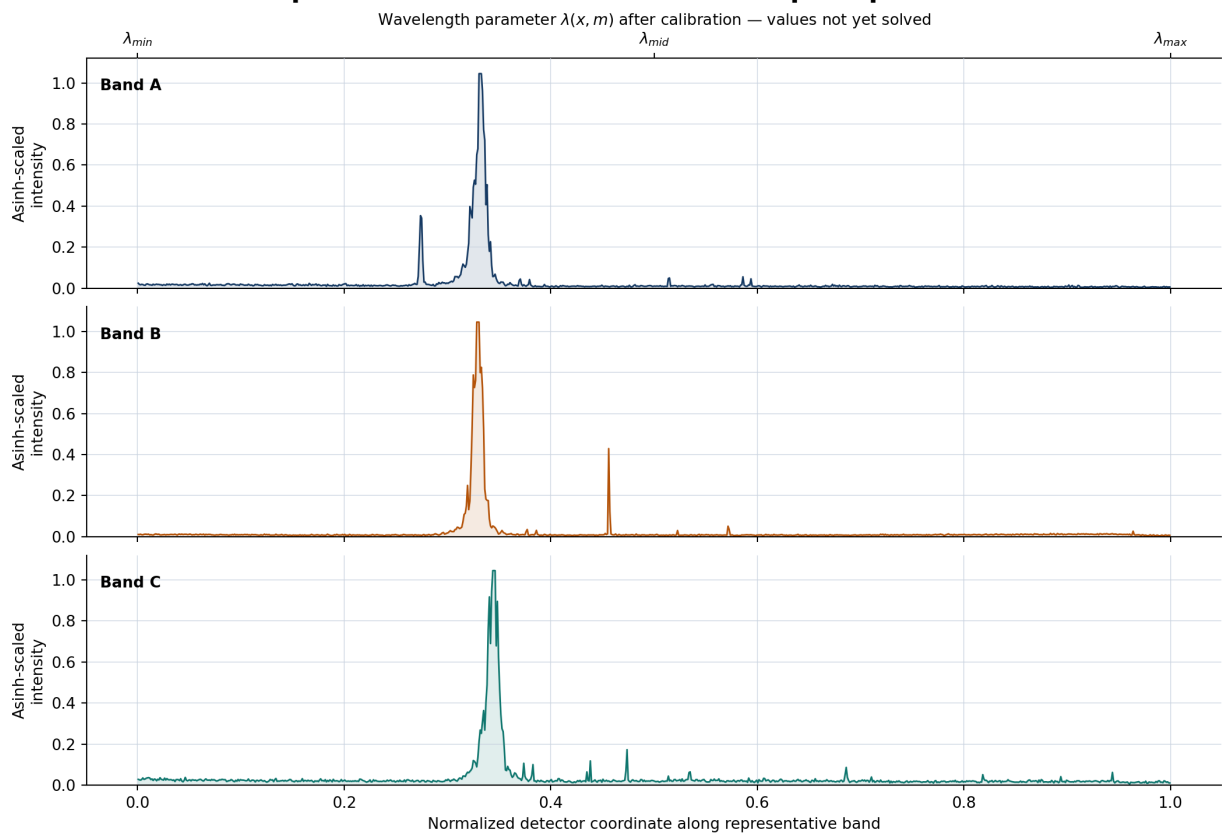


Figure 8. Representative detector-space profiles with asinh-scaled intensity. The lower coordinate is measured detector position; the upper axis names the wavelength parameter, but its numerical values remain unsolved.

8 Interpretation and exposure recommendation

The 120 s exposure is sufficient for a single public example and is the recommended single frame for this sequence. It reveals much more faint structure than 30 or 60 s while retaining more bright-core headroom than 180 s. This result is specific to the acquisition conditions and must not be treated as a universal EXOhSPEC setting.

For HDR construction the 180 s frame supplies 66,279 valid source-mask pixels. The estimator falls back to 120 s for 49 pixels, 60 s for 57 pixels, and 30 s for 14 pixels. The small fallback population carries disproportionately important bright-core information.

Recommended acquisition practice

- Retain 120 s as the main exposure for this configuration.
- Retain a 30 s exposure to protect the strongest feature cores.
- Retain 180 s where faint-feature visibility is important.
- Repeat each duration if temporal repeatability and random uncertainty are required.
- Do not increase beyond 180 s before reviewing near-ceiling behaviour and line-core linearity.
- Keep complete calibration metadata privately even when public derivatives omit it.

The present four frames are enough for this detector-domain report. Additional repeated observations would be needed for cosmic-ray rejection, lamp warm-up characterization, drift versus time, or a statistically defensible repeatability error.

9 Detector coordinate and wavelength

An echelle image is recorded in detector coordinates. Along a traced order, the physical coordinate can be written as $\lambda(x,m)$, where x is detector position and m is order number. Figure 8 therefore shows both the measured normalized position and the wavelength parameter. Numerical wavelength values are absent because the supplied FITS files do not contain a validated pixel-to-wavelength solution. The peaks and smaller fluctuations are genuine Python-derived detector profiles, not illustrative curves.

NIST SRD 161 provides the physical reference wavelengths used in Th-Ar work, including more than 20,000 thorium entries across its constituent spectra. These data explain why Th-Ar is an exceptionally rich wavelength reference; they are cited here as atomic-data provenance rather than attached to uncalibrated detector peaks.

10 Limitations

- Only one frame exists at each duration; fixed-exposure repeatability is unknown.
- The response fit assumes stable lamp output across the sequence.
- Registration models only global translation.
- The 60,000 ADU ceiling is an adopted diagnostic threshold, not an independently calibrated linearity limit.
- The public background treatment is simpler than a full local scattered-light model.
- Feature candidates are not atomic identifications.
- No claim is made about absolute flux, resolving power, line-spread function, or radial-velocity precision.

11 Applications to astronomical spectroscopy

Application	Role of Th-Ar
Absolute wavelength calibration	Reference wavelengths convert detector coordinates into a physical wavelength scale.
Instrument drift	Repeated lamp frames monitor motion of the spectral format.
Radial velocity	Reliable wavelength coordinates are essential before small stellar Doppler shifts are interpreted.
Extraction diagnostics	The line-rich pattern tests trace, background, and order-extraction consistency.
Resolution and line shape	Isolated unsaturated features can constrain widths, asymmetry, and focus variation.
Hybrid calibration	Th-Ar absolute anchors may be paired with a Fabry-Perot etalon or laser-frequency comb.

In exoplanet work the lamp does not detect a planet. It establishes the instrumental wavelength coordinate against which stellar motion or atmospheric structure can be measured. Calibration uncertainty propagates into the astrophysical result.

12 Conclusions

The supplied EXOhSPEC sequence is sufficient for a high-level scientific report. It demonstrates a dense emission-line field and quantitatively captures the exposure trade between faint-feature reach and bright-core headroom. Response is close to proportional over 30-180 s on the common unsaturated mask, and global registration is stable under the stated phase-correlation model.

Use 120 s when only one frame can be shown, but retain the full exposure ladder for HDR display and protection of bright cores. Do not publish atomic labels or wavelengths until trace extraction, line matching, the dispersion solution, and residual validation are complete.

ACKNOWLEDGEMENTS Supervision and contribution

During practical laboratory work on the EXOhSPEC project, **Biswajit Jana** recorded several thorium-argon spectra and became interested in understanding what the bright lines represent, how they are produced, and why they are useful. That curiosity led to the analysis and educational report presented here. The author gratefully acknowledges **Prof. Hugh Jones** for supervision of the EXOhSPEC work and **Prof. Bill Martin** for guidance and supervision during the optics laboratory work at the University of Hertfordshire.

The public release was prepared to communicate the scientific analysis while respecting the privacy of the detector configuration, optical design implementation, laboratory layout, FITS headers, and raw data.

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Reference line databases provide the atomic-data provenance used in Th-Ar spectroscopy. Their existence does not by itself identify peaks in the present detector images.