CHAOS During an OSI

A prototype system for applying measurement restrictions during On-Site Inspection activities

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An Introduction to CHAOS

(Coincidence-based High-resolution Analysis for OSI Spectrometry)

- An OSI is a complex and chaotic environment
- Time is limited, and ease of use / deployment is crucial
- A key component of an OSI will be the assay of samples for OSI relevant radionuclides
- Measurements may be subject to certain restrictions, limiting the information recorded and presented to the Inspector
- **CHAOS** is a prototype system developed at the UK laboratory GBL15
    - Provides interface for Inspector to perform measurement and analysis
    - Can be configured to provide different levels of restriction
    - Performs automated analysis of both coincidence and singles data
    - Uses multiple analysis streams to increase confidence in the results
    - Can be applied to any detector system (including single detectors)

CTBT Treaty text – Measurement restrictions

89 Pursuant to Article IV, paragraph 57 (b) and paragraph 88 (a) above, the inspected State Party shall have the right throughout the inspection area to take measures to protect sensitive installations and locations and to prevent disclosure of confidential information not related to the purpose of the inspection. Such measures may include, inter alia:

…

(b) Restricting measurements of radionuclide activity and nuclear radiation to determining the presence or absence of those types and energies of radiation relevant to the purpose of the inspection;

(c) Restricting the taking of or analysing of samples to determining the presence or absence of radioactive or other products relevant to the purpose of the inspection;

Rationale

Any measurement restriction system must be designed to:

- Allow calibration and report status
- Minimise the probability of false positive and false negative detections
- Be transparent, use open source software/methodologies wherever possible
- Allow meaningful measurements while preventing release of classified information
- Be suitable for any type of High Purity Germanium detector
- Provide Confidence to ISP / DG concerning the validity of these measurements
- Be suitable for operation by personnel with minimal training

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- **This requires a large degree of automation (including complex analysis)**

Problems

- Level of measurement restrictions required not yet defined
- What is allowed/required – Various scenarios
  - Inspector is allowed to review of full spectra and only OSI relevant Radionuclides reported
  - Inspector is allowed to review windowed spectra in the regions of OSI relevant Radionuclides and these are reported
  - No review of spectra including windowed, fully automated analysis and reporting of OSI relevant Radionuclides

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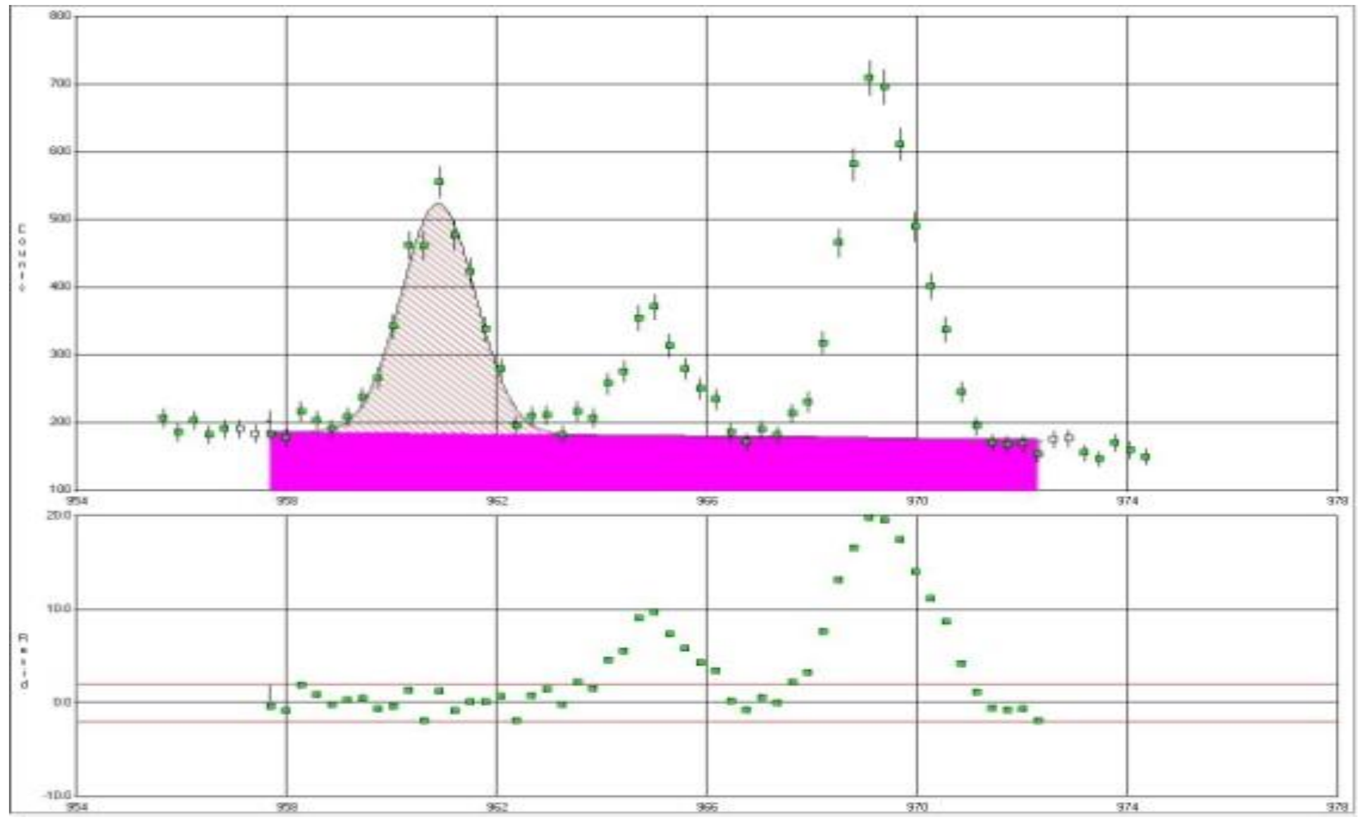
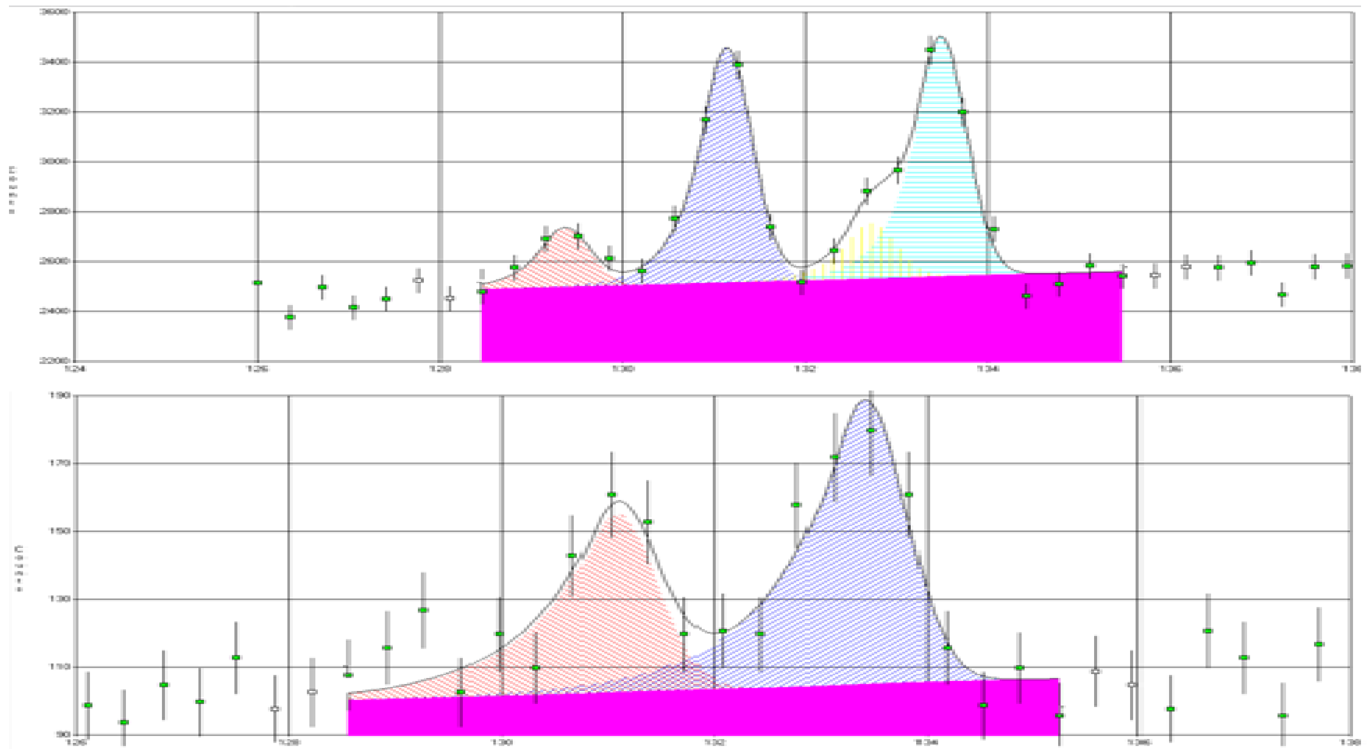
- **An example:** ISP stating that the measurement of gamma energies that relate to actinide signatures would break their NPT commitment, <u>this leaves zero regions available for review by a trained analyst</u>

Problems with an automated solution

- Algorithm has to be very robust to successfully analyse complex spectra
- Analysed 250 spectra for fresh fission products on various detectors using a commercially available optimised automated peak search routine
- All samples required some manual peak fitting
- ~10% of spectra contained severe errors (major peaks poorly fitted or completely missed)



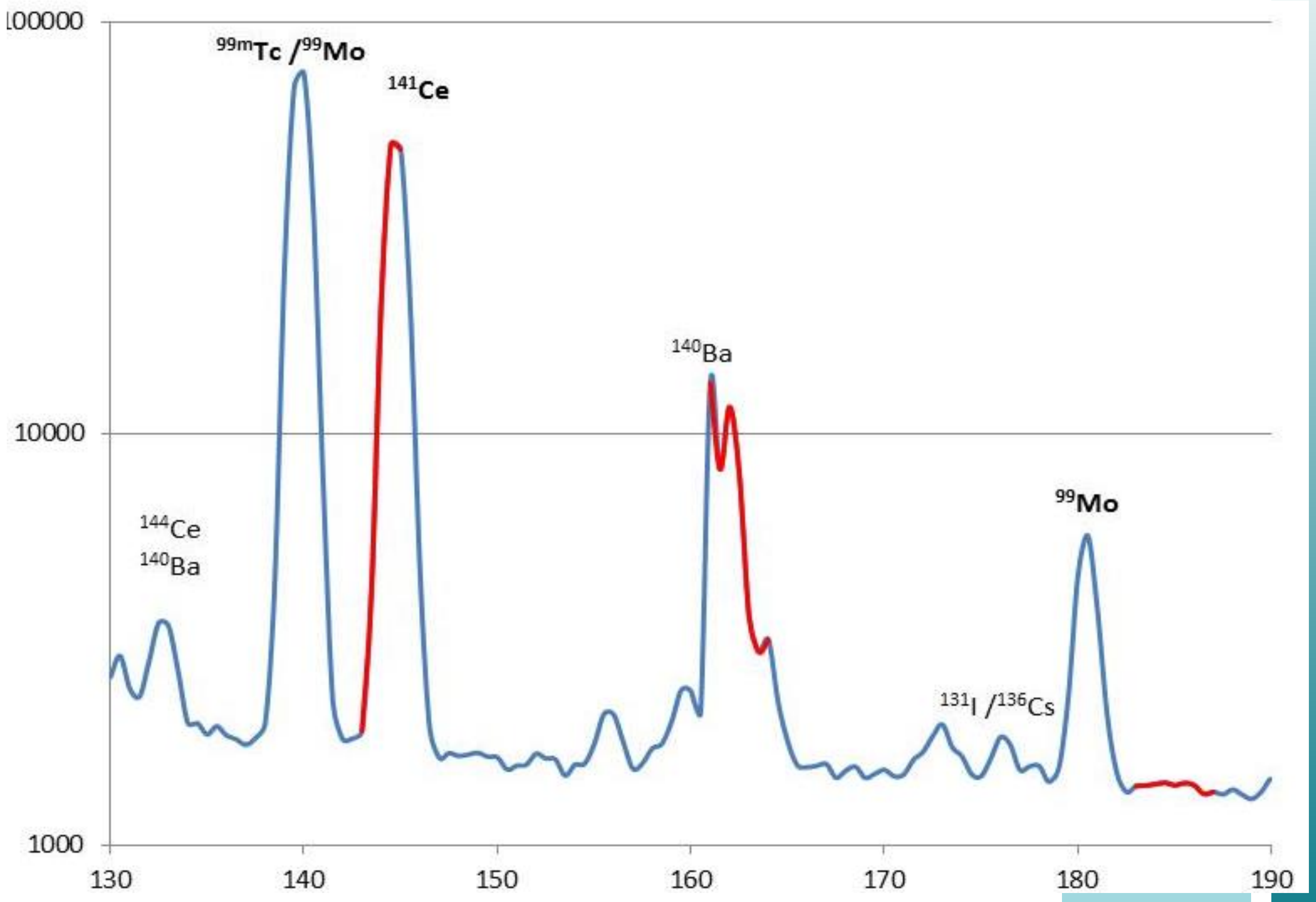
Example – Poor automated peak fitting must be mitigated



Example - ^{144}Ce/^{140}Ba interference deconvolution

Problems with a windowed solution

- Analysis of full/windowed spectra and filter out "classified information"
- Peak fitting routines struggle to deal with 'jumps' in counts from zero to many
- An analyst may be required to de-convolute peaks in a robust way
- Even with a windowed spectra, an analyst could glean information on sensitive nuclides from the Compton continuum, Compton edges, backscatter and escape peaks etc.
- The restrictions mean that little information may be left on possible interferences, resulting in a lack of confidence in the reliability of the result



Example regions (red) of ^{235}U showing proximity to OSI relevant radionuclides

UK Measurement Restrictions Solution (CHAOS)

- Multi-analysis approach
  - Full, Windowed, Coincidence and Anti-coincidence data streams captured in real time
  - 'Smart algorithms'; analysis is completely automated, and only OSI relevant radionuclides reported

- Flexible, list-mode event based recording
  - 14 out of 17 OSI nuclides have coincidence signatures
  - γ-γ coincidence used to independently quantify OSI nuclides alongside traditional / windowed analysis
  - Automated coincidence analysis can establish whether signals suffer from interference
  - Decay during measurement could be used as part of multiple assessments
  - Single emitters can be analysed in anti-coincidence to improve confidence

Zr-95	Te-132	La-140
Nb-95	I-131	Ce-141
Mo-99	I-132	Ce-144
Tc-99m	Cs-134	Pr-144
Ru-103	Cs-137	Nd-147
Rh-106	Ba-140	

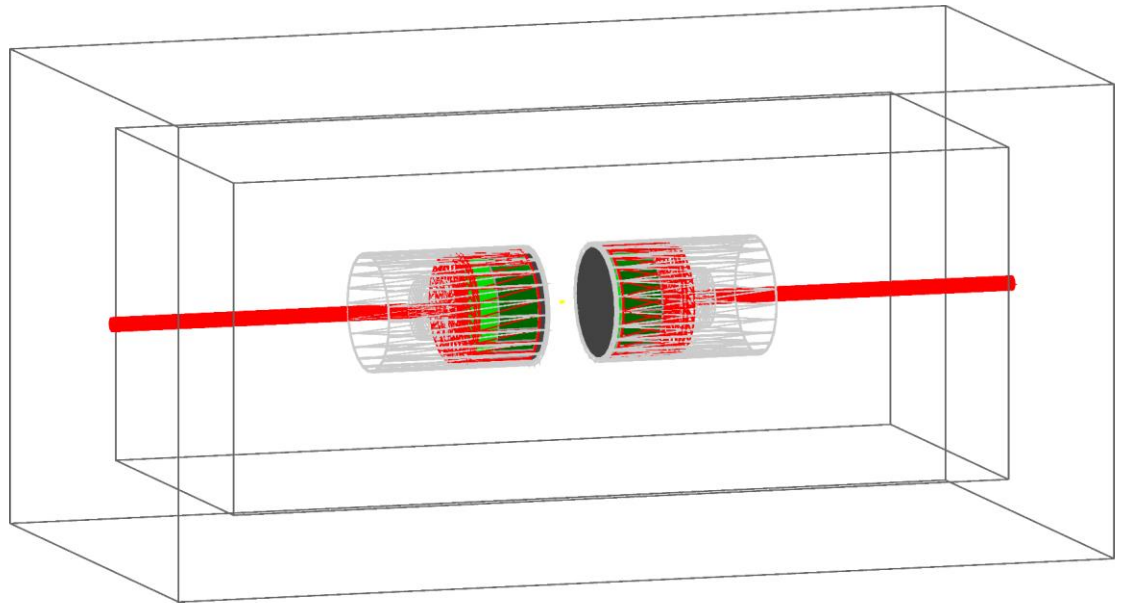
Known as 'Coincidence-based High-resolution Analysis for OSI Spectrometry' (CHAOS)

CHAOS– Packaged in a single electronics unit

- Dual-channel HPGe LV/HV power and DSP
- On-board Linux PC used for real-time data processing
  - Buffer real-time, time synchronised list-mode data in volatile RAM
  - Sort buffered data into histograms, including raw, windowed, and coincidence
  - Internal data storage encrypted
  - All data processing completed within the electronics unit
  - Processing algorithms will be made available
  - Bespoke detector control and data acquisition software based on open-source libraries
  - Communication with unit only via secure protocols
- Unit potentially cheap enough to leave at ISP
- Only ‘filtered’ results available to user, output configurable
- Can be used with any commercial HPGe with pre-amplifier output

Validation – Modelling and Coincidence Quantification

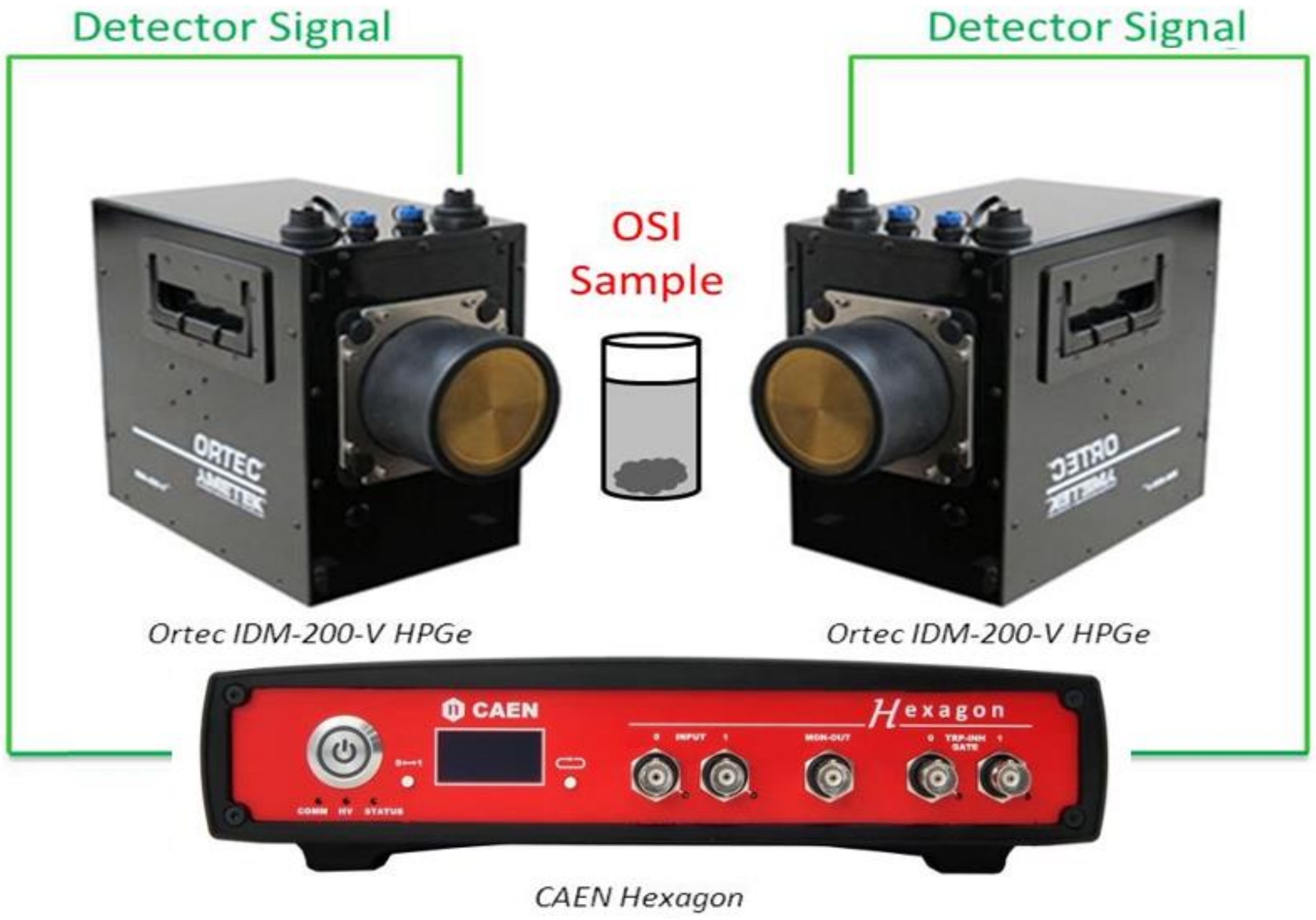
- Various configurations have been modelled to optimize set up
- Close geometry, ‘face-to-face’ configuration most efficient
- Adjustable separation to accommodate different sources
- Analysis code written in c++, and compiled with ROOT libraries for coincidence analysis (in use for > 4 years)
- Coincidence factors calculated using ISOCS and RIMMER
- PTE 2014 / PTE 2015 / PTE 2016
- *Quantifying radionuclide signatures from a γ-γ coincidence system*, Journal Environmental Radioactivity, 149 (2015) 158-163



OSI Relevant Radionuclide	PTE2014	PTE2015	PTE2016	IER-151
Zr-95				
Nb-95				
Mo-99				
Tc-99m				
Ru-103				
Rh-106				
Te-132				
I-131				
I-132				
Cs-134				
Cs-137				
Ba-140				
La-140				
Ce-141				
Ce-144				
Pr-144				
Nd-147				

Validation – Design Considerations

- Software is configurable for different detectors and sample geometries
- Potential to use more robust detector systems for field deployment (once efficiency is characterised)
- All software is verified before deployment to the MCA (at which point it cannot be changed)



UK System – Design

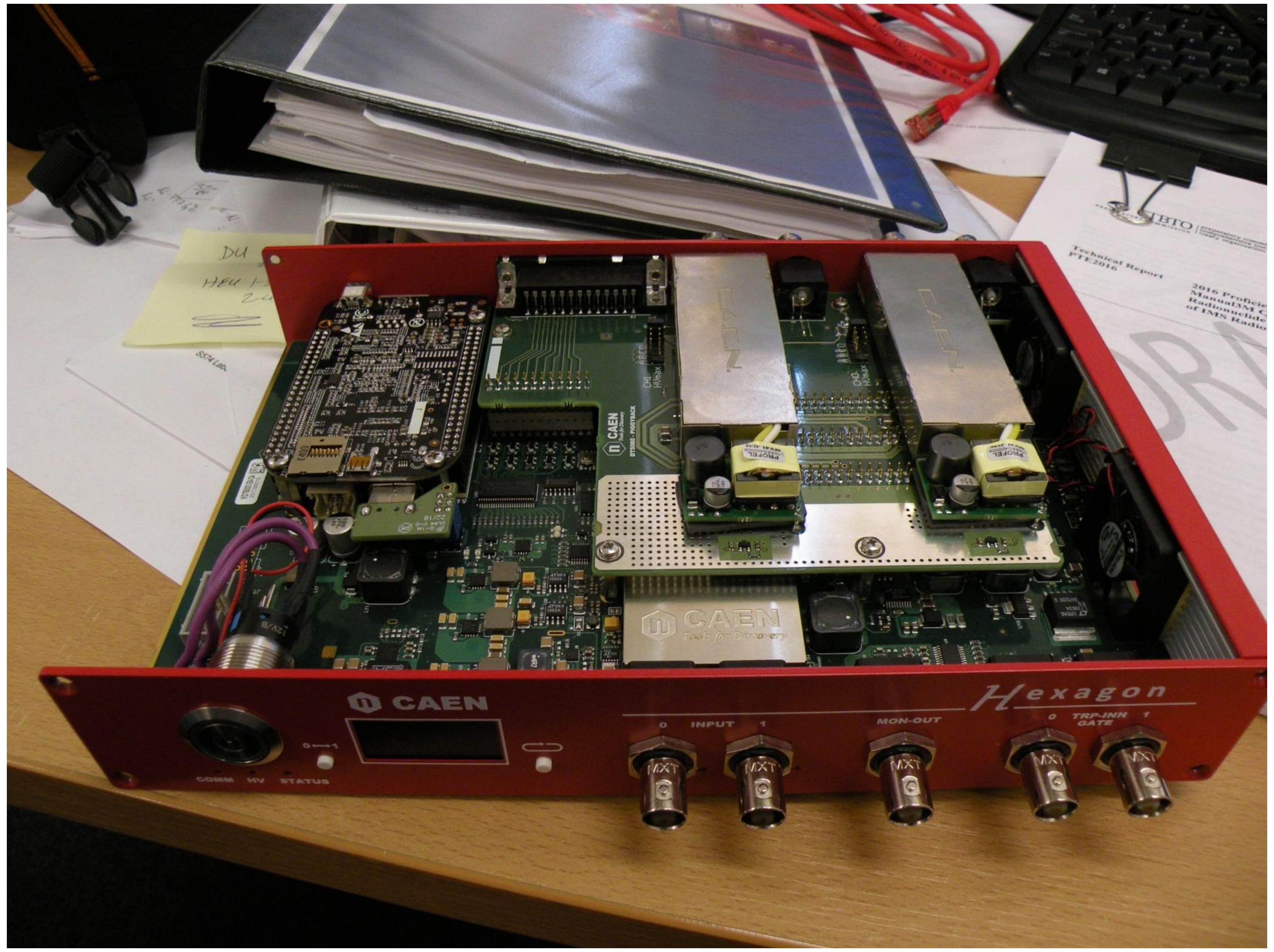
User device (laptop/tablet)

Combined LV / HV / MCA / Processing unit

- Provides a GUI for the user
- Button based control can only issue specific requests
- All comms via SSH (Secure Shell) Protocol

- Code verified via checksum or similar before deployment
- Will only execute approved tasks requested via SSH
- Analysis of all data streams happen in real time
- If ‘analysis’ request received, control software pushes report to User device (ZERO data is pulled from user side)

UK System – Hexagon Electronics



UK System - CHAOS Analysis

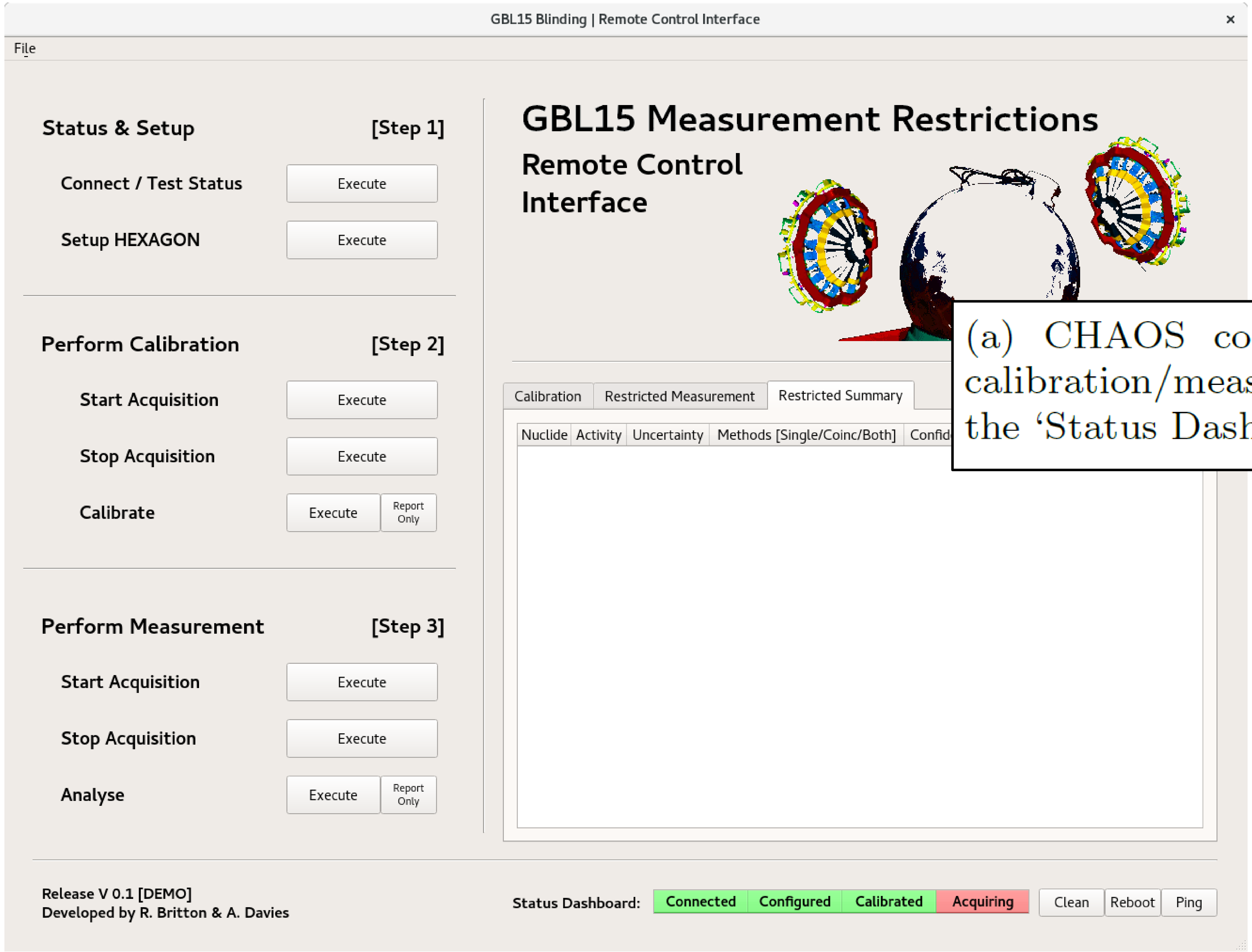
- No commercial solutions or tools available for the processing of list-mode data, so all developed in-house. Software automatically creates raw spectra and coincidence matrices (validated over the past five years, extremely robust and efficient)

- Each detector is calibrated using automated routines plus gain-matched
  - Raw Spectra
  - Restricted (windowed) raw spectra
  - Restricted coincidence spectra
  - Restricted anti-coincidence spectra

- All of these are automatically analysed in the CHAOS system (with up to 200 configurable search regions in the case of restricted spectra), using industry standard peak fitting and nuclide quantification (only for OSI relevant radionuclides)

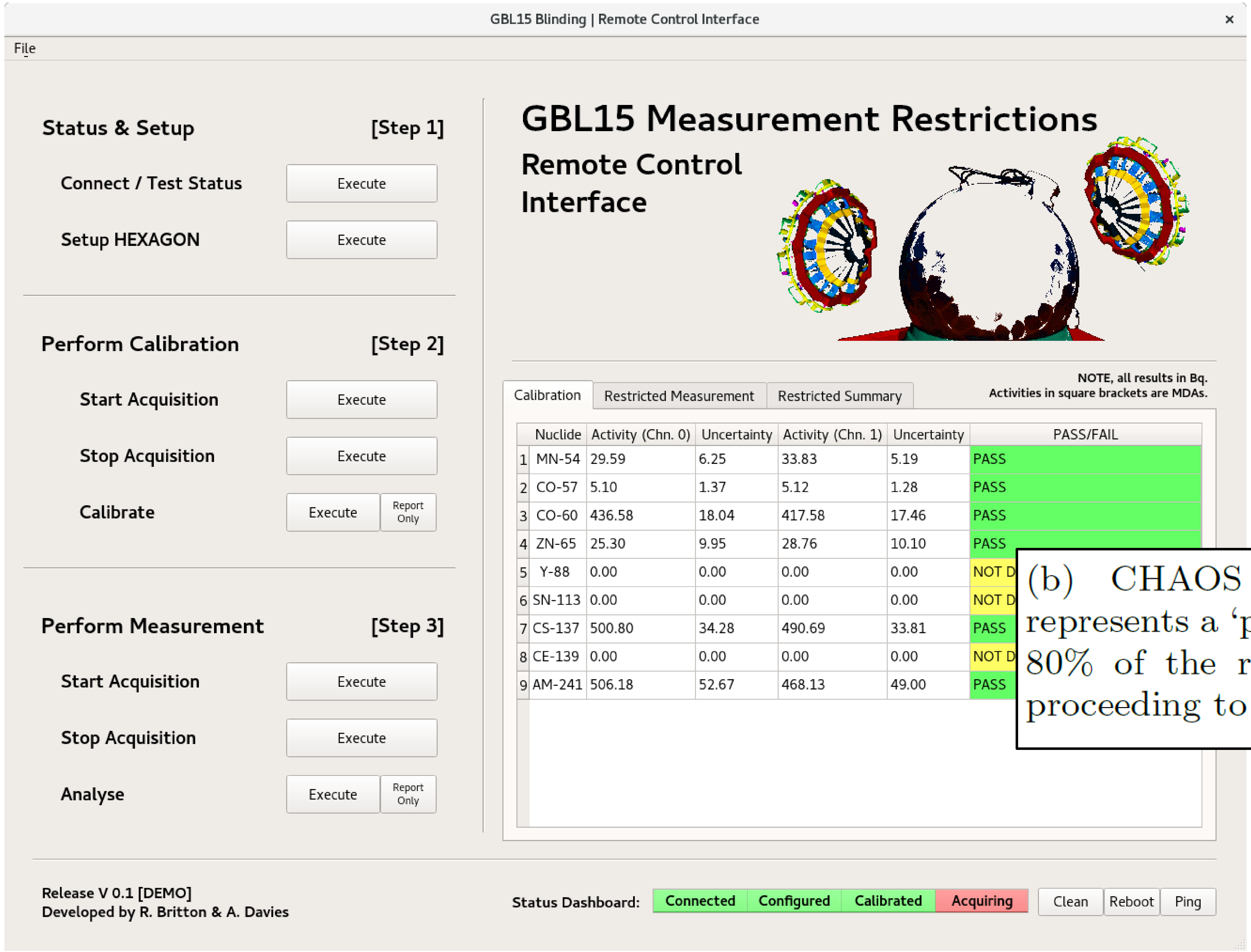
- Four analysis streams give far greater confidence in measurements if spectra not available to inspector

Analysis Example



(a) CHAOS connected to the Hardware, ready for calibration/measurement. System status is shown via the 'Status Dashboard' at the bottom of the GUI.

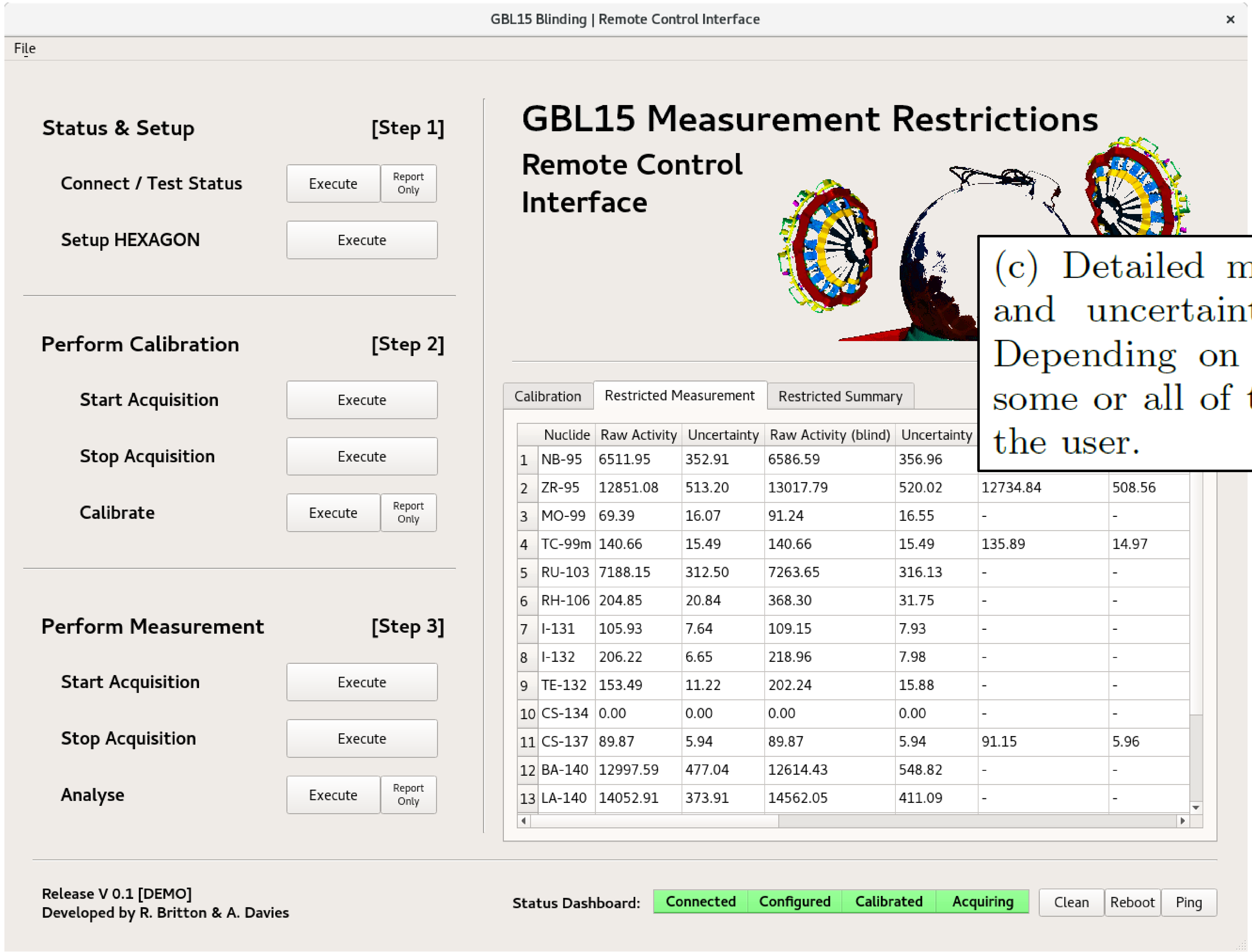
Analysis Example



	Nuclide	Activity (Chn. 0)	Uncertainty	Activity (Chn. 1)	Uncertainty	PASS/FAIL
1	MN-54	29.59	6.25	33.83	5.19	PASS
2	CO-57	5.10	1.37	5.12	1.28	PASS
3	CO-60	436.58	18.04	417.58	17.46	PASS
4	ZN-65	25.30	9.95	28.76	10.10	PASS
5	Y-88	0.00	0.00	0.00	0.00	NOT D
6	SN-113	0.00	0.00	0.00	0.00	NOT D
7	CS-137	500.80	34.28	490.69	33.81	PASS
8	CE-139	0.00	0.00	0.00	0.00	NOT D
9	AM-241	506.18	52.67	468.13	49.00	PASS

(b) CHAOS displaying calibration results; green represents a ‘pass’ for each specificradionuclide. At least 80% of the radionuclides are required to pass before proceeding to the measurement phase.

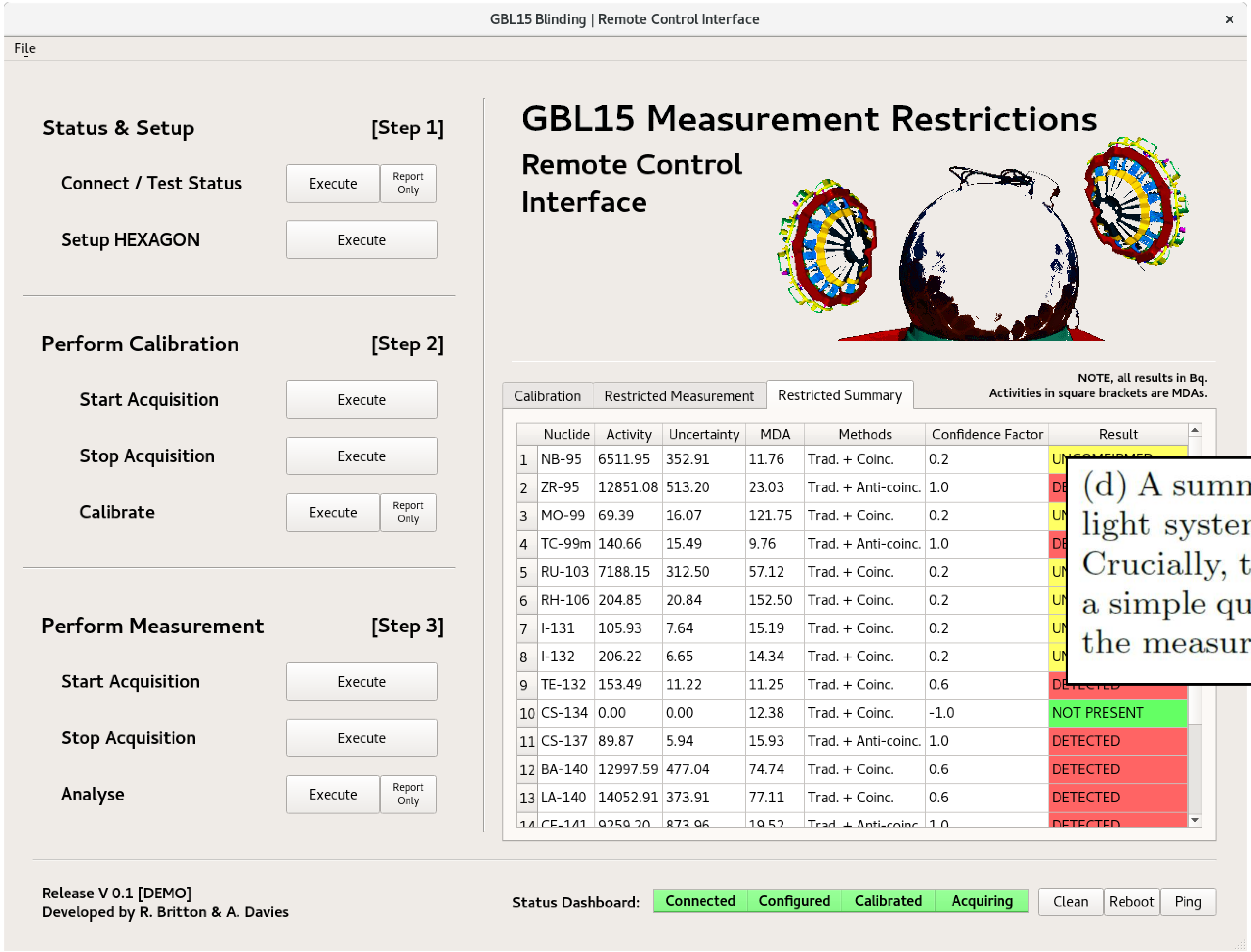
Analysis Example



	Nuclide	Raw Activity	Uncertainty	Raw Activity (blind)	Uncertainty		
1	NB-95	6511.95	352.91	6586.59	356.96		
2	ZR-95	12851.08	513.20	13017.79	520.02	12734.84	508.56
3	MO-99	69.39	16.07	91.24	16.55	-	-
4	TC-99m	140.66	15.49	140.66	15.49	135.89	14.97
5	RU-103	7188.15	312.50	7263.65	316.13	-	-
6	RH-106	204.85	20.84	368.30	31.75	-	-
7	I-131	105.93	7.64	109.15	7.93	-	-
8	I-132	206.22	6.65	218.96	7.98	-	-
9	TE-132	153.49	11.22	202.24	15.88	-	-
10	CS-134	0.00	0.00	0.00	0.00	-	-
11	CS-137	89.87	5.94	89.87	5.94	91.15	5.96
12	BA-140	12997.59	477.04	12614.43	548.82	-	-
13	LA-140	14052.91	373.91	14562.05	411.09	-	-

(c) Detailed measurement results, including activities and uncertainties for each measurement technique. Depending on the measurement restrictions in place, some or all of this information may not be available to the user.

Analysis Example



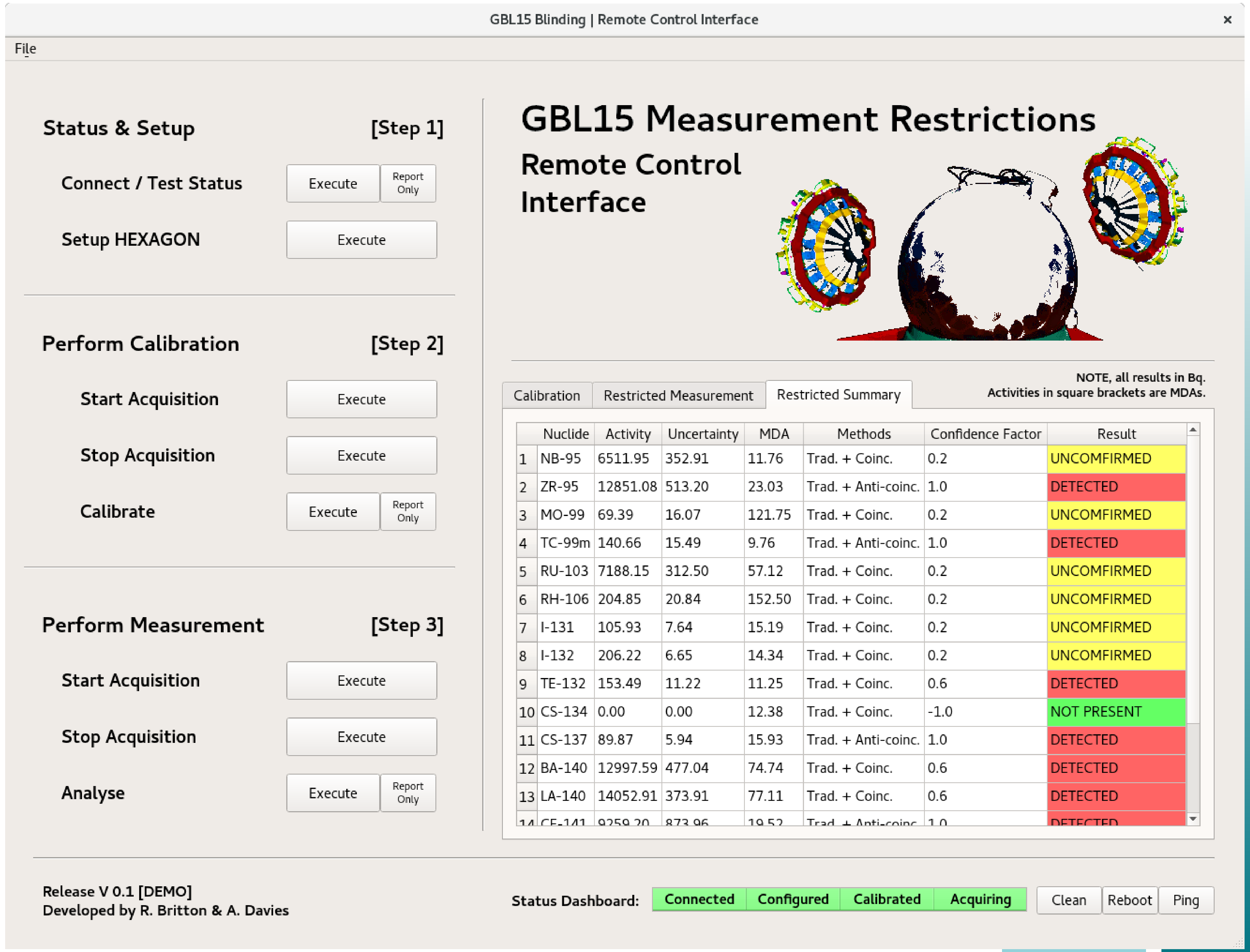
(d) A summary of the measurement results, with a traffic light system for the detection of relevant radionuclides. Crucially, the ‘Confidence Factor’ provides the user with a simple quantitative metric for each radionuclide during the measurement.

Analysis Example – Full restrictions

- Results only contain information on OSI relevant radionuclides with confidence factor based on multiple analysis streams

Confidence Factor Tests	Single Detector		Coincidence System			
	All Emitters		Cascade Emitters		Single Emitters	
	PASS	*FAIL*	*PASS*	*FAIL*	*PASS*	*FAIL*
Nuclide Detection (Traditional)	0.4	-0.4	0.2	-0.2	0.2	-0.2
Nuclide Detection (Windowed)	0.4	-0.4	0.2	-0.2	0.2	-0.2
Nuclide Detection (Coincidence)*	-	-	0.2	-0.2	-	-
Nuclide Detection (Anti-Coincidence)*	-	-	-	-	0.2	-0.2
Traditional vs. Windowed	0.2	-0.2	0.1	-0.1	0.1	-0.1
Detector Consistency*	-	-	0.1	-0.1	0.1	-0.1
Traditional vs. Coincidence*	-	-	0.2	-0.2	-	-
Traditional vs. Anti-Coincidence*	-	-	-	-	0.2	-0.2

Table 1: Confidence Factor weights for each system type. 'Single Detector' refers to a single HPGe detector. 'Coincidence System' refers to a dual–HPGe coincidence system; this has two different schemes depending on the OSI relevant radionuclide. An asterisk '*' denotes those weights which can only be applied to a dual–detector system.



CHAOS – Full System Testing

- Full system "Coincidence-based High resolution Analysis for On-Site-Inspection Spectrometry (CHAOS) tested on "representative" samples that could be collected during an OSI

- **Sample 1** - This solution represents the 'freshest' fission sample likely to be observed during an OSI; traditional analysis identified over 100 radionuclides

- **Sample 2** - This solution represents a realistic age for a fission sample likely to be observed during an OSI. Traditional analysis identified over 20 radionuclides

Sample ID	Nuclides Present		Detections	
	OSI Relevant	Other	OSI Relevant	Other
1	16	100+	16	0
2	8	20+	8	0
3	0	4	0	0
4	0	4	0	0
5	0	0	0	0

- **Sample 3** - This contained no OSI relevant radionuclides, but did contain HEU. This therefore represents a potentially sensitive sample that could be measured during the course of an OSI.

- **Sample 4** - This SRM (100 grams of soil) contained only Naturally Occurring Radioactive Material (NORM), and no OSI relevant radionuclides.

- **Sample 5** - This sample (an exposed high-volume air filter) contained no OSI relevant radionuclides, and as such represents a typical background

Summary

- Science has been validated and published in peer review journals
- All analysis automated, with multiple analysis streams greatly improving confidence in result
- CHAOS is designed for range of restrictions with the most robust option only returning results from OSI relevant radionuclides to users device (PC / tablet)
- Easily configurable (before deployment), options are available to allow access at various levels of restrictions
- Code all open source and human readable
    - Installation Scripts 200 lines (plus external libraries e.g. gnuplot)
    - CAEN acquisition Code 6500 lines
    - Canberra SDK 10000 lines
    - Python control Code (on hexagon) 1000 lines
    - Python remote control Code (on laptop /device) 1000 lines
- User friendly GUI developed for use by OSI inspectors / non-experts

1. **A high-efficiency HPGe coincidence system for environmental analysis** (2015) Britton, Davies, Burnett, Jackson https://dx.doi.org/10.1016/j.jenvrad.2015.03.033
2. **Coincidence corrections for a multi-detector gamma spectrometer** (2015) Britton, Burnett, Davies, Regan https://dx.doi.org/10.1016/j.nima.2014.09.054
3. **Quantifying radionuclide signatures from a γ–γ coincidence system** (2015) Britton, Jackson, Davies https://dx.doi.org/10.1016/j.jenvrad.2015.07.025
4. **CHAOS development** (2019) Britton, Davies https://doi.org/10.1016/j.nima.2019.06.029

Additional Applications

- Multiple analysis stream approach is unique
  - Greatly increases confidence of automated analysis
  - Weightings within CHAOS can be modified for any application
  - Applicable to all isotopes, cascade emitters or not
- Automated coincidence processing and quantification greatly reduces work load
  - Notoriously difficult to operationalise
  - CHAOS can be configured to look for any combination of signatures
  - Coincidence analysis still uses industry standard peak identification and fitting
- Could be automated to analyse large numbers of samples quickly and efficiently
  - Massively reduced analyst workload
  - Flags for spectra of interest can be raised for analyst review
  - Ideal for routine analysis or Forensics programmes

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Highlights

- First measurement system to ever automatically measure environmental radionuclides in both traditional and coincidence modes.
- Unprecedented confidence in the measurement result due to multiple analysis streams.
- Applications are numerous, but this implementation is designed specifically for use during an OSI, measuring 17 key radionuclides to gather evidence of a treaty violation (nuclear test).
- Measurement restrictions fully implemented so the user isn't exposed to sensitive information.
- Represents a crucial advance that is required for effective monitoring, and eventual Entry Into Force (EIF) of the Comprehensive Nuclear Test-Ban-Treaty (CTBT).

CHAOS development (2019) Britton, Davies https://doi.org/10.1016/j.nima.2019.06.029