Reactor noise analysis applications in CANDU NPPs

IMORN-31

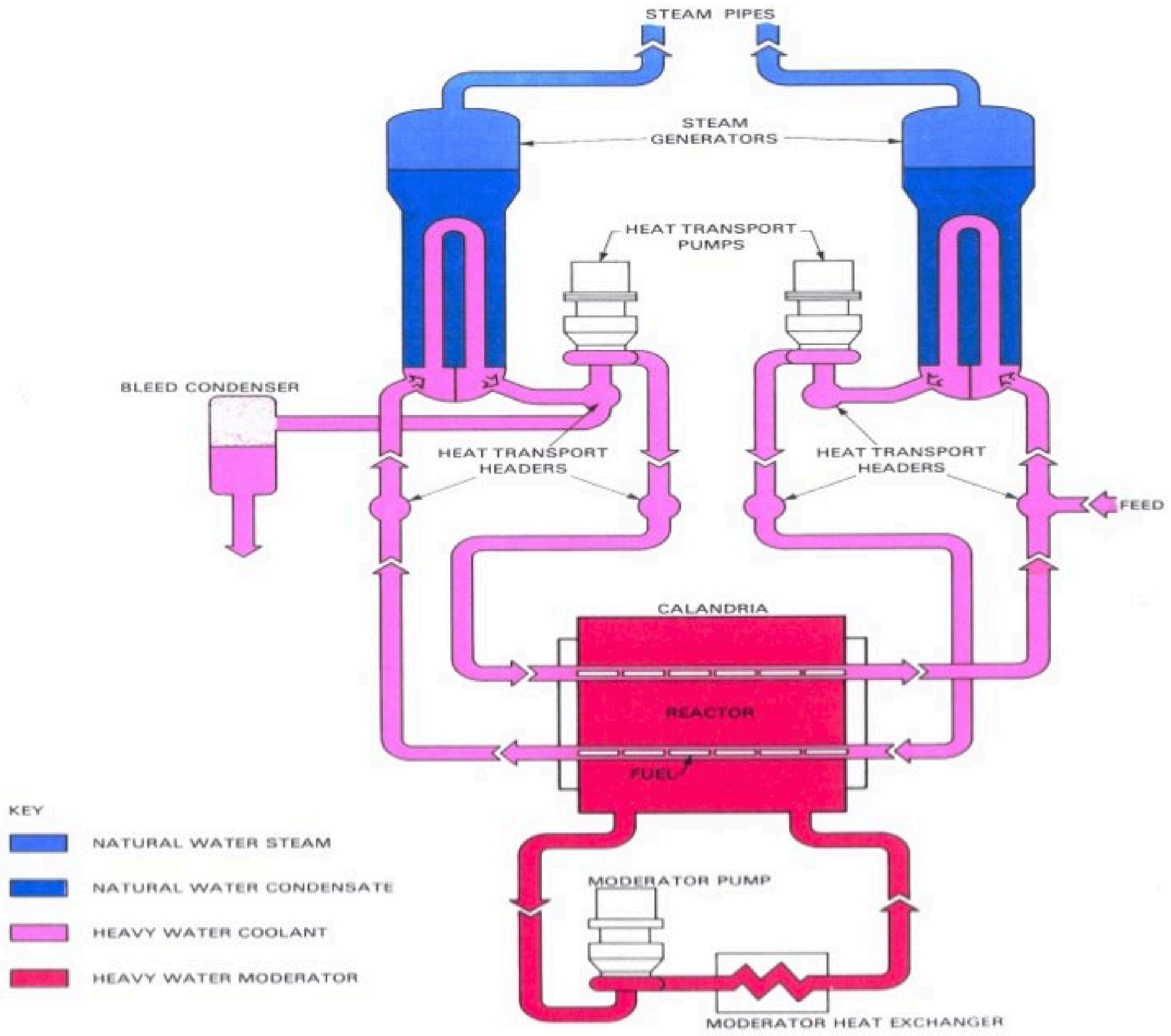
Delft, The Netherlands, September 9-12, 2024

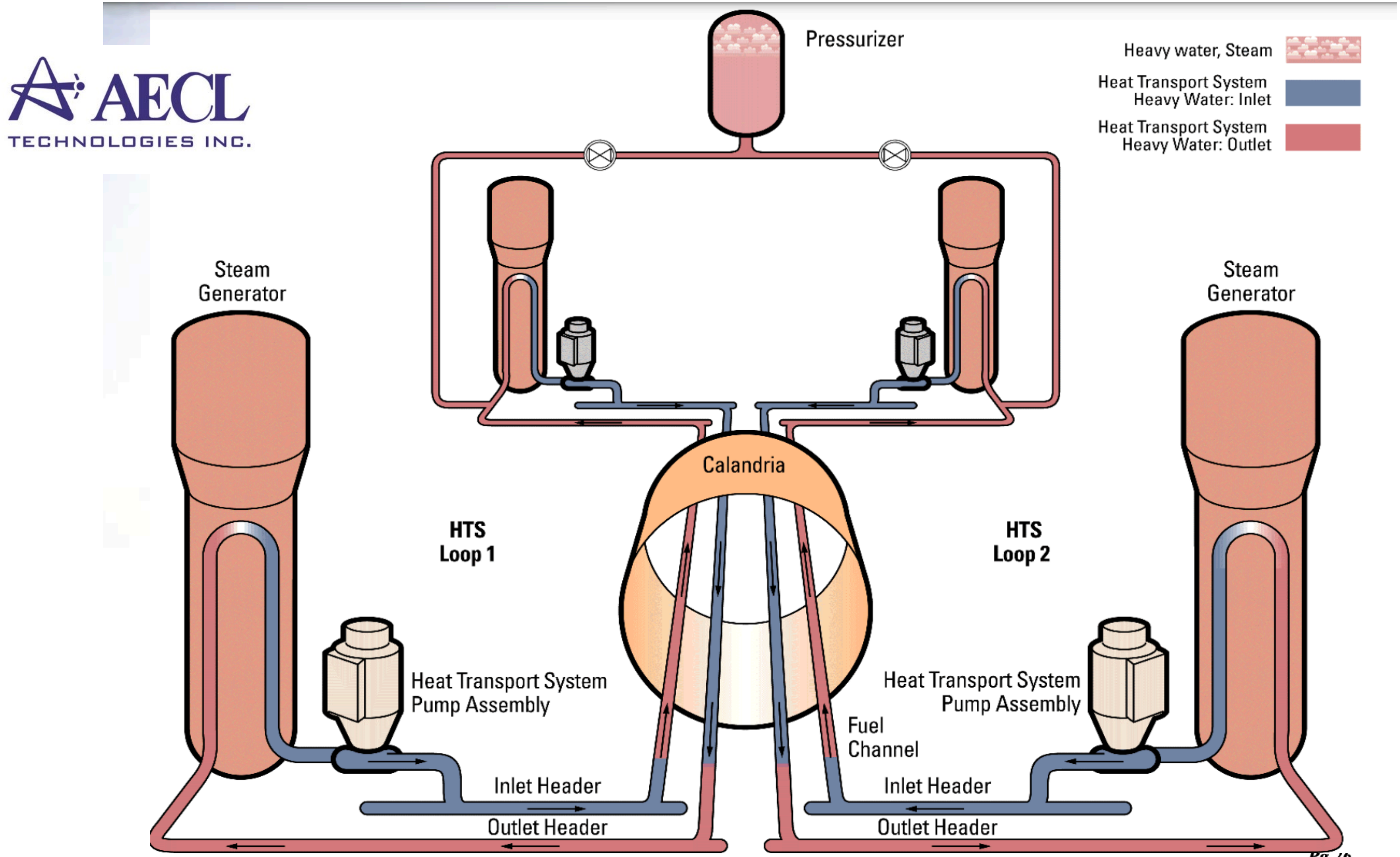
Oszvald Glöckler

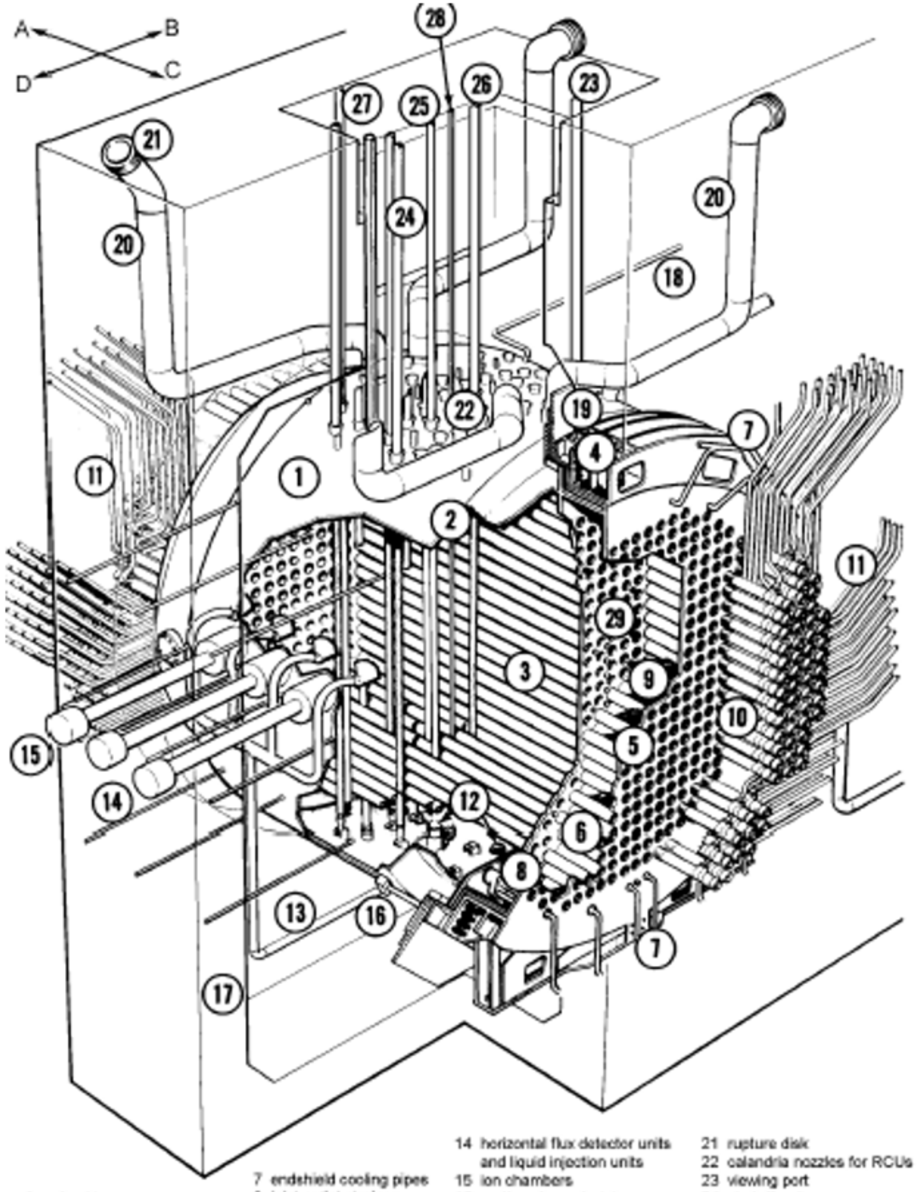
Senior Consultant

Type of signals available to noise analysis in CANDUs:

- In-Core Flux Detectors (ICFDs) – vertical & horizontal SPNDs, 100% prompt
- Ion Chambers (Lin, Log, Loge rate) – outside Calandria
- Flow TXs – Fuel Channel Inlet/Outlet, orifice/venturi, Rosemount/Bailey
- Pressure TXs – Reactor Inlet/Outlet Header Tanks
- Liquid Zone Control level signals – 14 local power distribution controls
- RTDs – Fuel Channel Inlet/Outlet Temperature - coolant
- RTDs – Calandria Inlet/Outlet Temperature - moderator


STEAM PIPES
STEAM GENERATORS
HEAT TRANSPORT PUMPS
BLEED CONDENSER
HEAT TRANSPORT HEADERS
HEAT TRANSPORT HEADERS
FEED
CALANDRIA
REACTOR
FUEL
KEY
NATURAL WATER STEAM
NATURAL WATER CONDENSATE
HEAVY WATER COOLANT
HEAVY WATER MODERATOR
MODERATOR PUMP
MODERATOR HEAT EXCHANGER


AECL
TECHNOLOGIES INC.
Pressurizer
Heavy water, Steam
Heat Transport System Heavy Water: Inlet
Heat Transport System Heavy Water: Outlet
Steam Generator
Steam Generator
Calandria
HTS Loop 1
HTS Loop 2
Heat Transport System Pump Assembly
Heat Transport System Pump Assembly
Fuel Channel
Inlet Header
Outlet Header
Inlet Header
Outlet Header



1 calandria
2 calandria shell
3 calandria tubes
4 endshield embedment ring
5 fuelling tubesheet
6 endshield lattice tube
7 endshield cooling pipes
8 inlet-outlet strainer
9 steel ball shielding
10 fuel channel end fittings
11 feeder pipes
12 moderator outlet
13 moderator inlet pipe
14 horizontal flux detector units and liquid injection units
15 ion chambers
16 earthquake restraints
17 reactor vault wall
18 pipe to moderator expansion head tank
19 curtain shielding slabs
20 moderator discharge pipes
21 rupture disk
22 calandria nozzles for RCUs
23 viewing port
24 shutoff unit
25 adjustor unit
26 control absorber unit
27 liquid zone control unit
28 vertical flux detector unit
29 calandria tubesheet

Major components of the CANDU reactor core

Signals are from the triplicated redundancies in

- RRS – Reactor Regulating System (Channel A, B, C)
- SDS1 – Shut-Down System 1 (Channel D, E, F)
- SDS2 – Shut-Down System 2 (Channel G, H, J)

Temporary connections of multiple DAQ systems to analog station signals

Noise analysis is performed off-line

Trend monitoring and inter-station comparison of noise signatures

Reactor Name	Model	Reactor Type	Net Capacity (MWe)	Construction Start	First Grid Connection
Bruce 1	CANDU 791	PHWR	732	1971-06-01	1977-01-14
Bruce 2	CANDU 791	PHWR	732	1970-12-01	1976-09-04
Bruce 3	CANDU 750A	PHWR	750	1972-07-01	1977-12-12
Bruce 4	CANDU 750A	PHWR	750	1972-09-01	1978-12-21
Bruce 5	CANDU 750B	PHWR	822	1978-05-31	1984-12-02
Bruce 6	CANDU 750B	PHWR	822	1978-01-01	1984-06-26
Bruce 7	CANDU 750B	PHWR	822	1979-05-01	1986-02-22
Bruce 8	CANDU 750B	PHWR	795	1979-07-30	1987-03-09
Darlington 1	CANDU 850	PHWR	881	1982-04-01	1990-12-19
Darlington 2	CANDU 850	PHWR	881	1981-09-01	1990-01-15
Darlington 3	CANDU 850	PHWR	881	1984-09-01	1992-12-07
Darlington 4	CANDU 850	PHWR	881	1985-07-01	1993-04-17
Pickering 1	CANDU 500A	PHWR	508	1966-06-01	1971-04-04
Pickering 4	CANDU 500A	PHWR	508	1968-05-01	1973-05-21
Pickering 5	CANDU 500B	PHWR	516	1974-11-01	1982-12-19
Pickering 6	CANDU 500B	PHWR	516	1975-10-01	1983-11-08
Pickering 7	CANDU 500B	PHWR	516	1976-03-01	1984-11-17
Pickering 8	CANDU 500B	PHWR	516	1976-09-01	1986-01-21
Point Lepreau	CANDU 6	PHWR	660	1975-05-01	1982-09-11

Table 1. Typical CANDU Instrumentation Used in Noise Analysis (Pickering NGS "B" shown)

System	**Type of Sensor**	**Number per System**	**Location of Sensor**
Neutron Power Measurement, Reactor Regulating System (RRS), SDS1 & 2	Platinum / Inconnel in-core flux detectors.	RRS: 28 SDS1: 34 + 34 Spare SDS2: 23 + 23 Spare	Distributed throughout the core to measure local neutron flux.
Neutron Power Measurement, Reactor Regulating System (RRS), SDS1 & 2	Boron Impregnated Ion Chambers	RRS: 3 SDS1: 3 SDS2: 3	At the edge of the neutron reflector to measure bulk neutron power and rate.
Pressure Measurement, Heat Transport Pressure Control System (HTPCS), Emergency Core Injection System (ECIS) and SDS1 & 2	DP Cell	HTPCS: 6 (Outlet Header) ECIS: 4 (Inlet header) 4 (Outlet Header) SDS1: 8 (Outlet Header) SDS2: 12 (Outlet Header)	Distributed throughout the four reactor outlet headers and four reactor inlet headers.
Channel Flow Measurement, RRS and SDS1	DP Cell	RRS: 22 SDS1: 12	Selected inlet feeders
Liquid Zone Level (a system used to control zonal powers within the reactor core)	DP Cell	RRS: 14	Distributed throughout the core.
Temperature Measurement, heat Transport process indication (Process) RRS, SDS1 & 2.	Platinum RTD	RRS: 380 (Outlet Channels) 22 (Inlet Channels) SDS1: 6 (Outlet Header) SDS2: 6 (Inlet Header) Process: 6 (Outlet Header) 4 (Inlet Header)	

Spectral Functions used for “mass-production”

Basics plots:

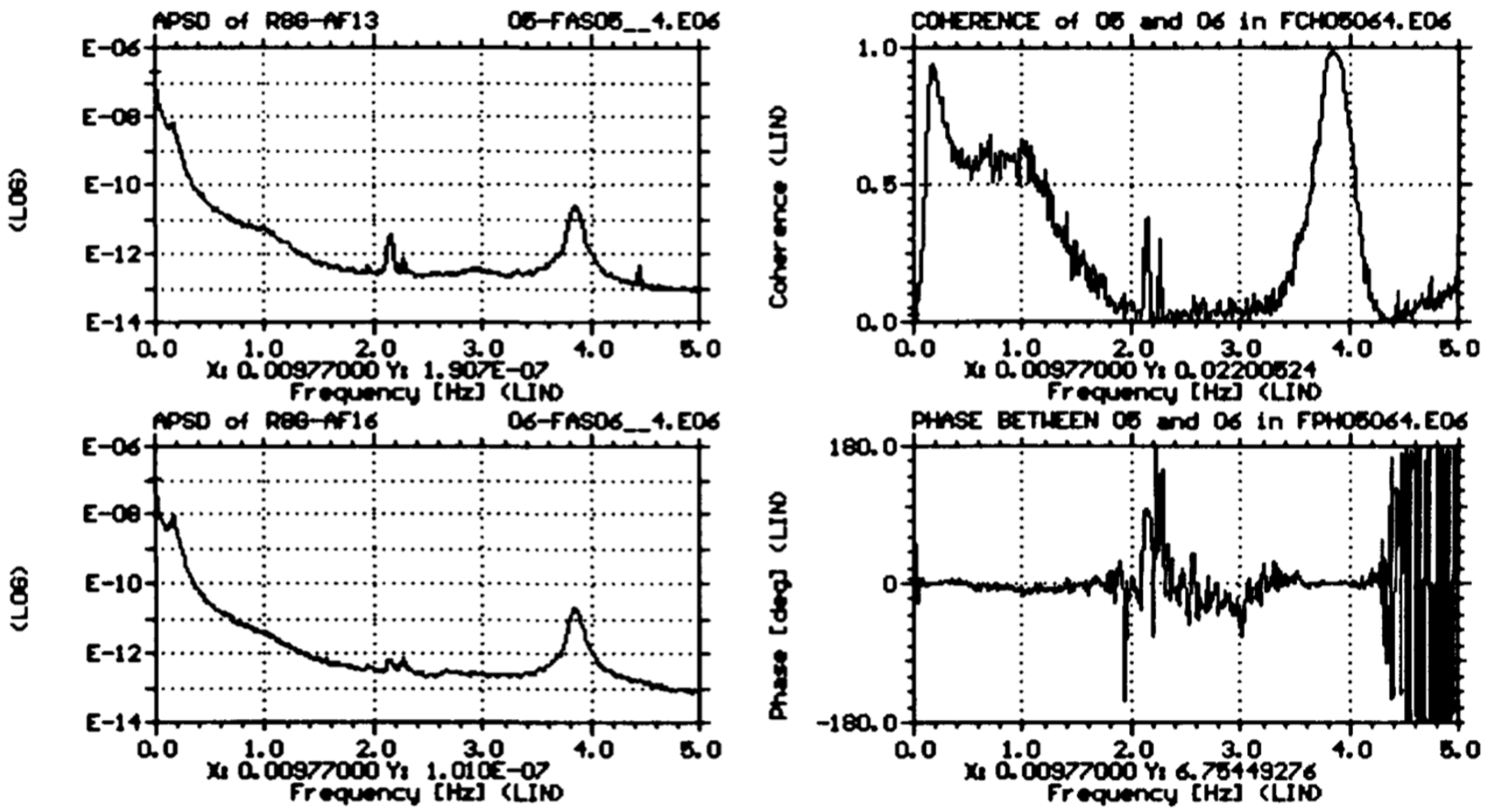
Normalized Auto-Power Spectral Density (APSD), coherence and phase functions of two noise signals

- FFT-based frequency dependent functions
- derived from the complex cross-power spectral density functions – CPSD matrix
- “Quad-plot”: frequency dependent comparison of two noise signals and their connection
- Simple, but powerful, and can be automated

More complex tools:

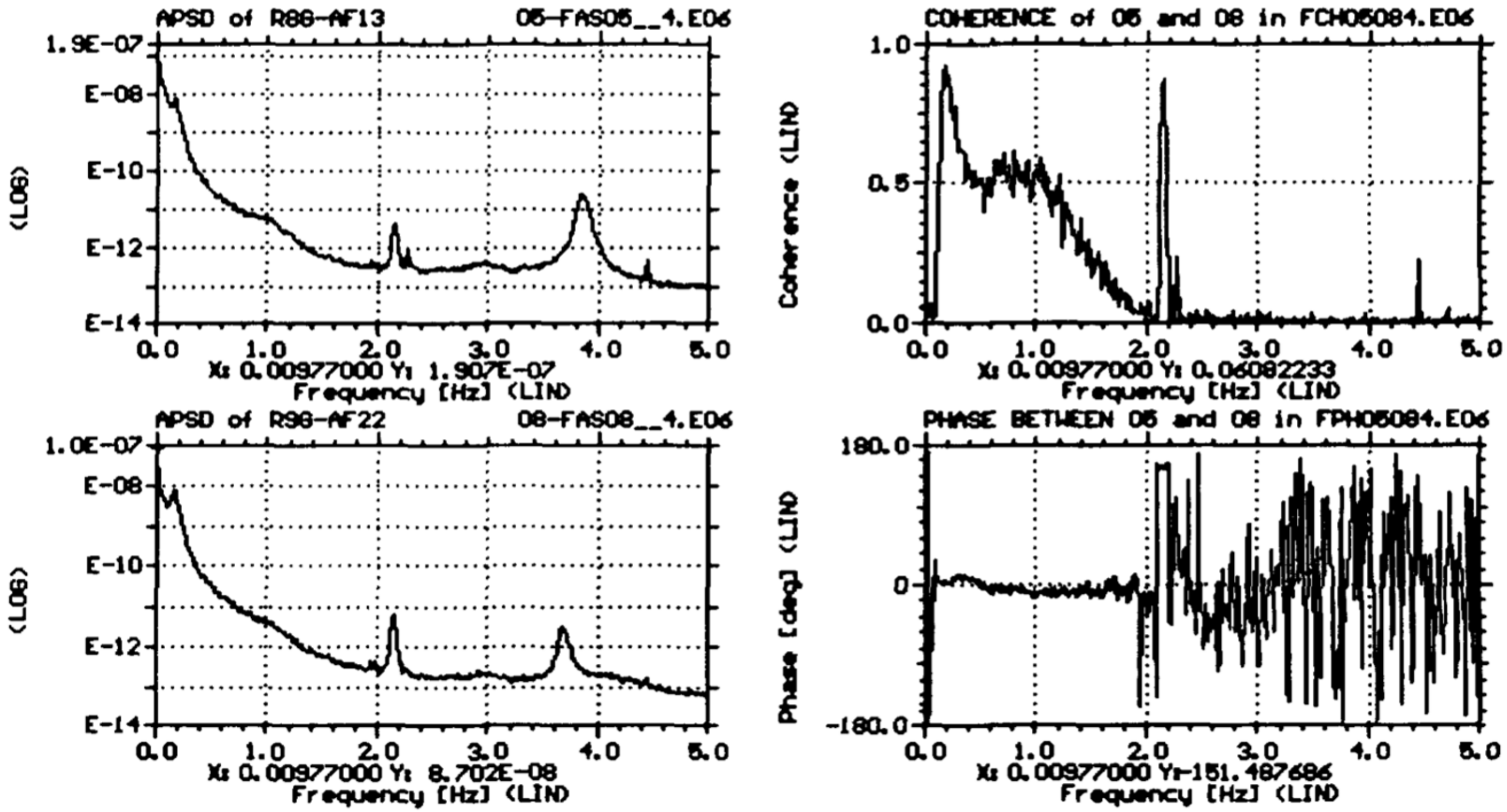
- Multi-signals coherence and phase functions – 3D coherence plots
- Multi-variate autoregressive models – more sophisticated, but works with groups of causally related signals

Vibrations of Horizontal In-Core Flux Detectors (ICFDs) in the same detector tube



Normalized APSD, coherence and phase of two ICFDs

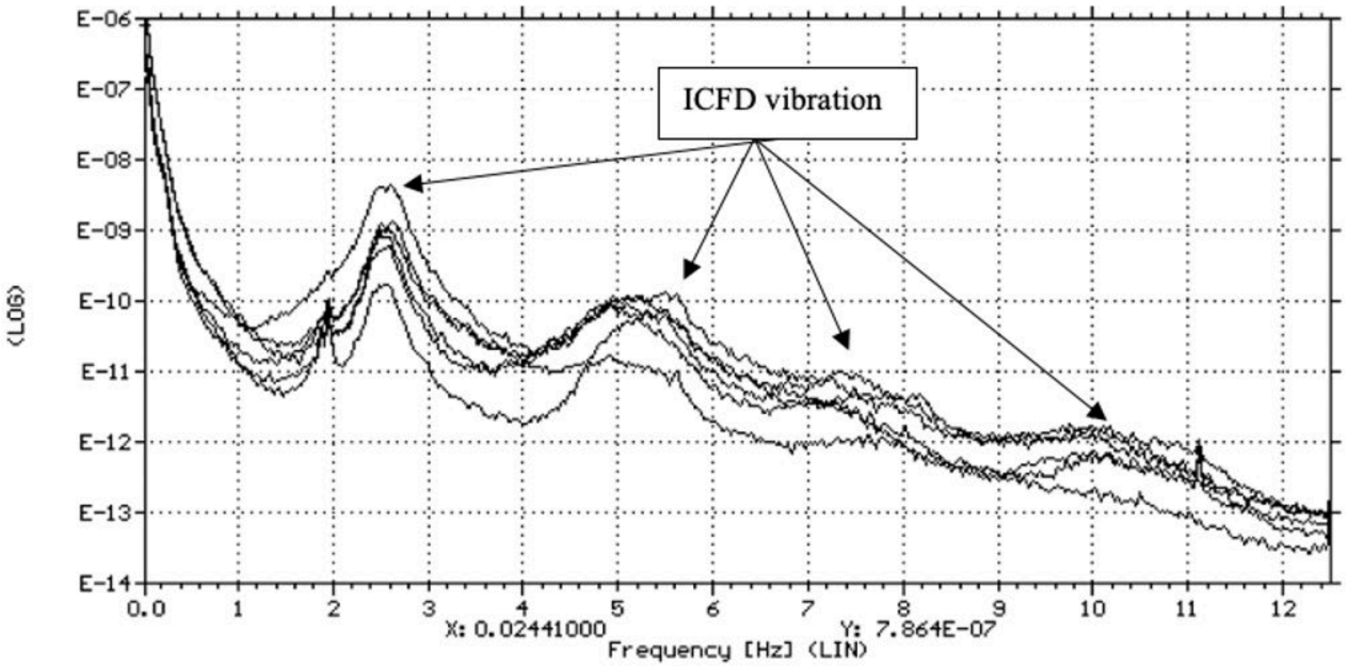
Vibrations of Horizontal In-Core Flux Detectors (ICFDs) in different detector tubes

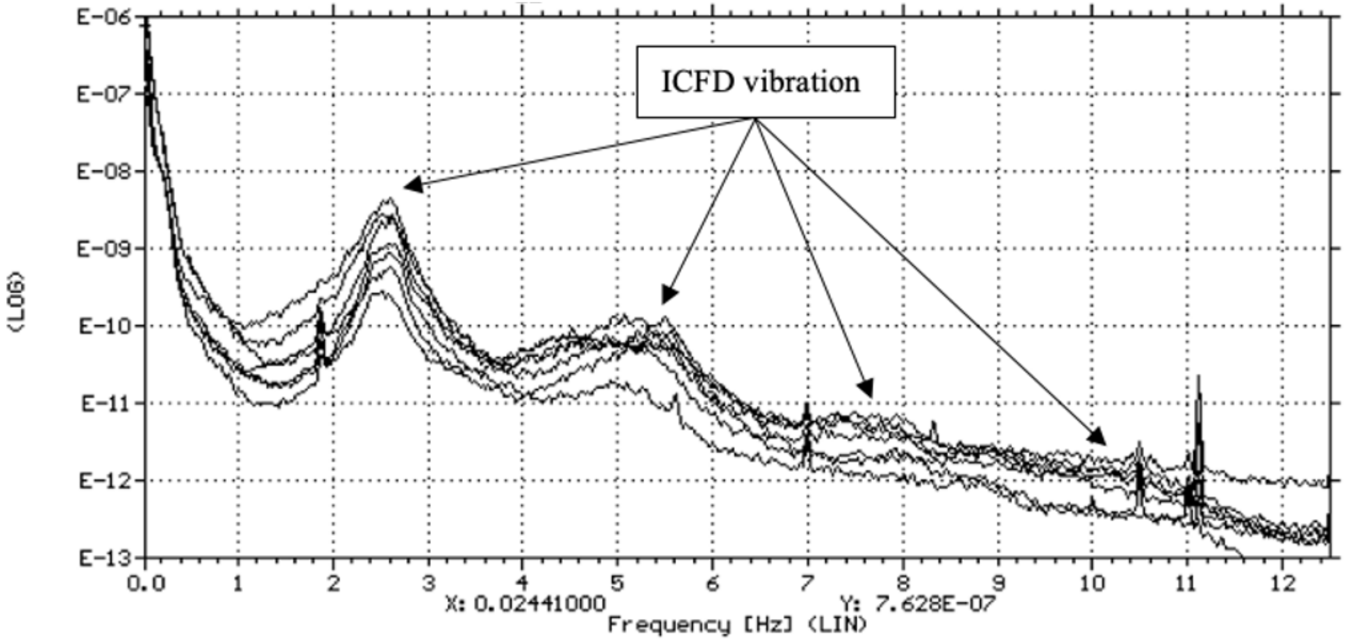


Normalized APSD, coherence and phase of two ICFDs

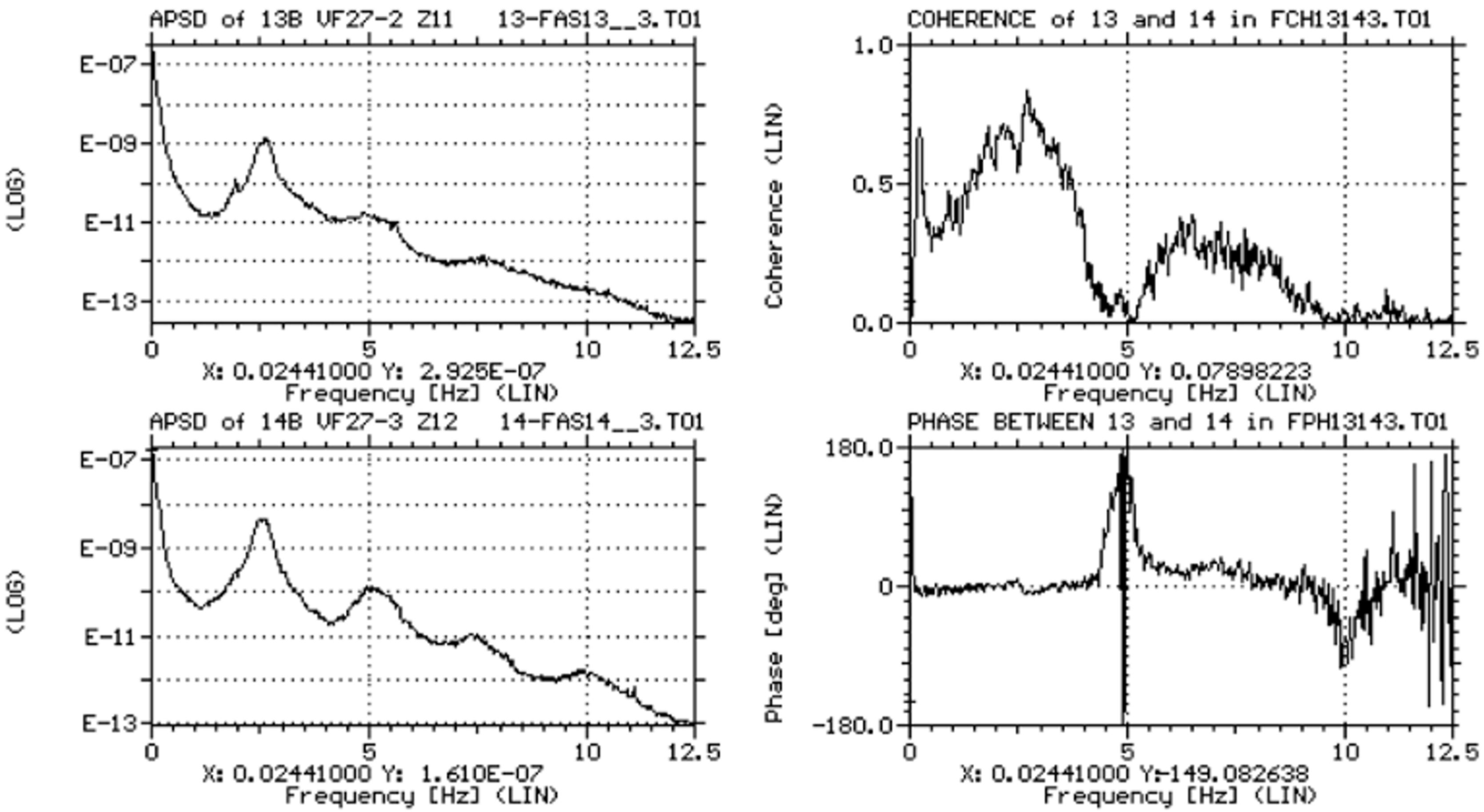
APSDs of 7 vibrating Vertical In-Core Flux Detectors (ICFDs) – in the same detector tube

3 years apart



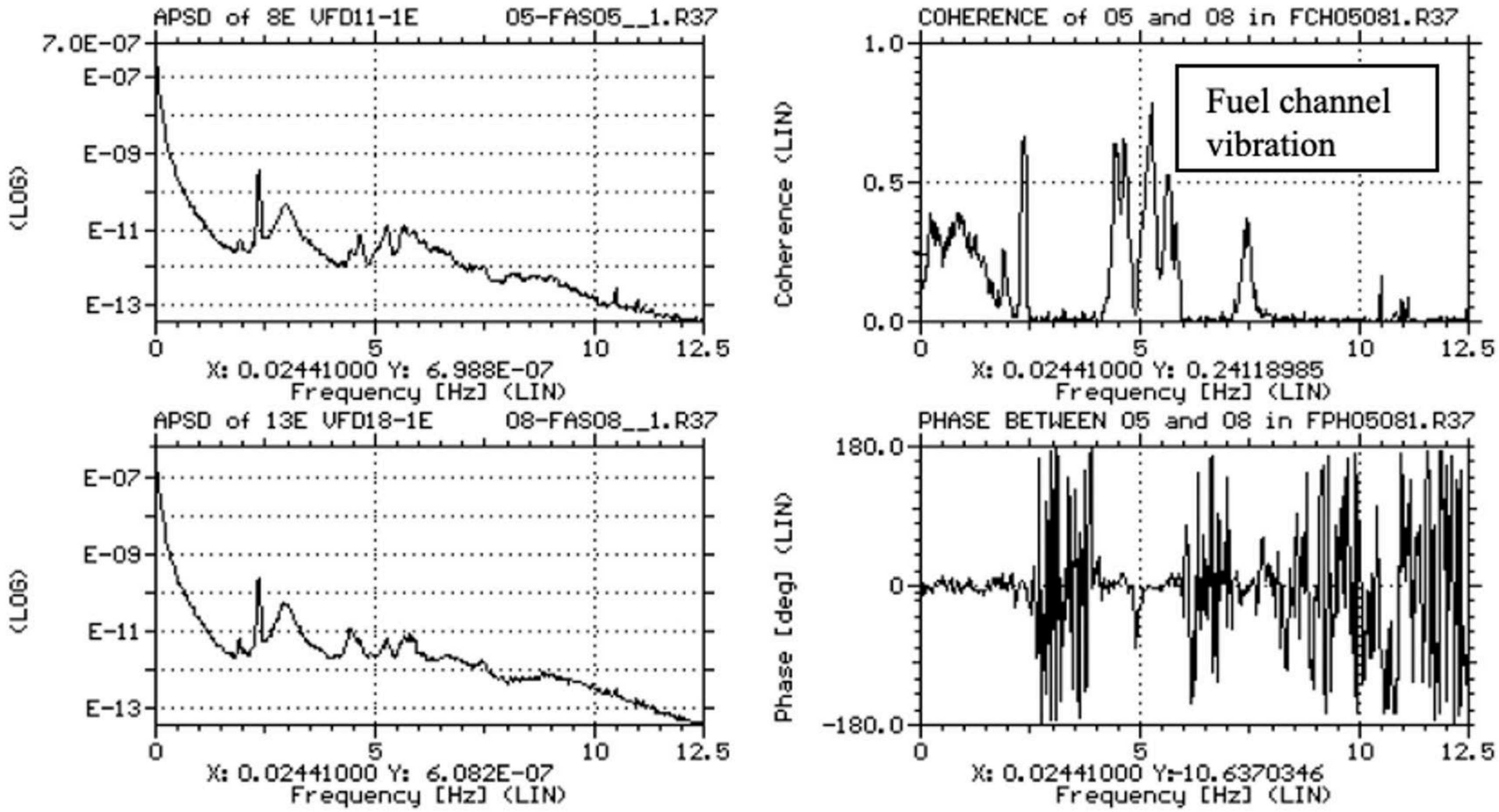


Vibrations of Vertical In-Core Flux Detectors (ICFDs) in the same detector tube



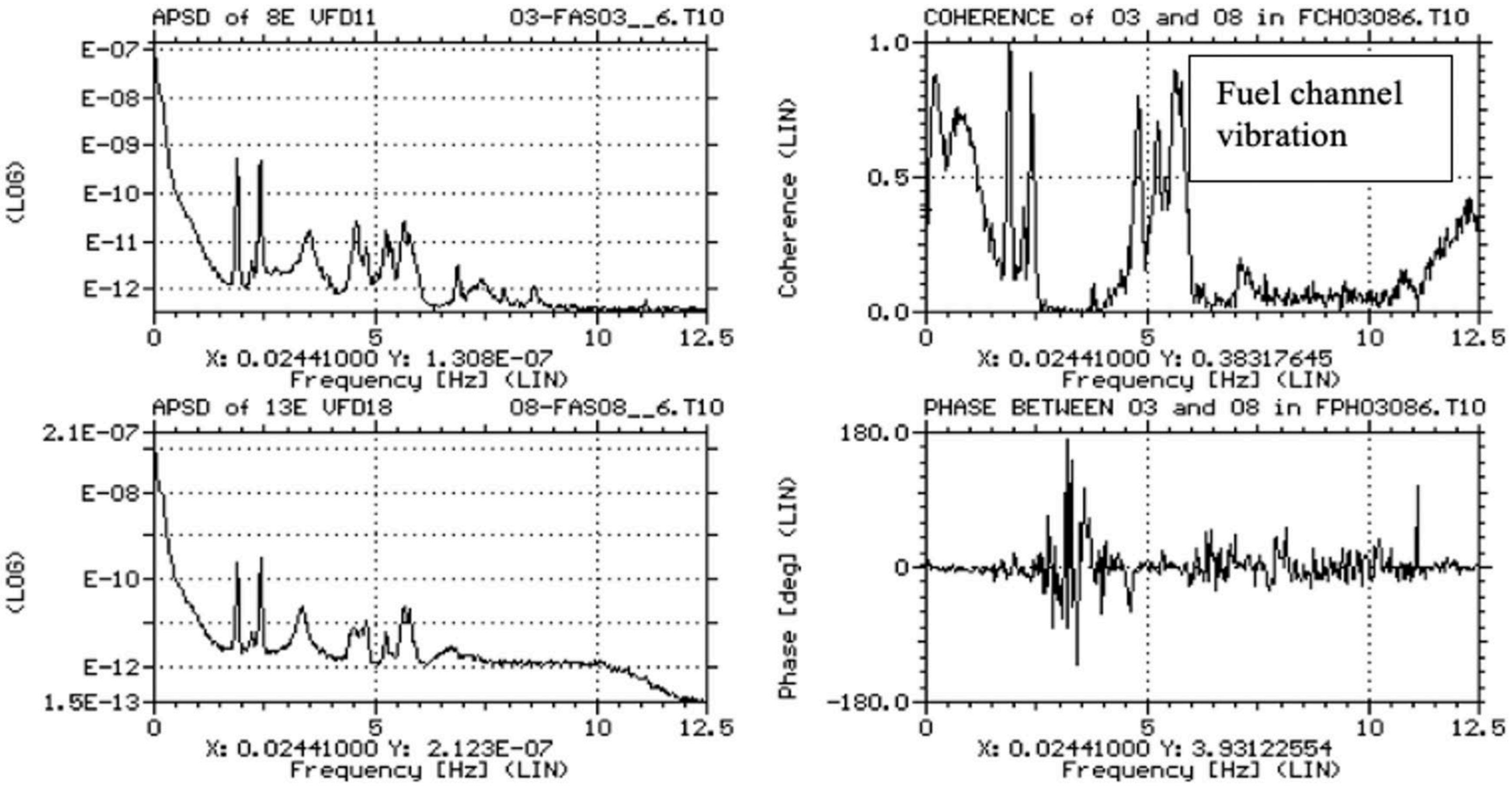
Normalized APSD, coherence and phase of two ICFDs

Fuel Channel Vibrations as detected by In-Core Flux Detectors



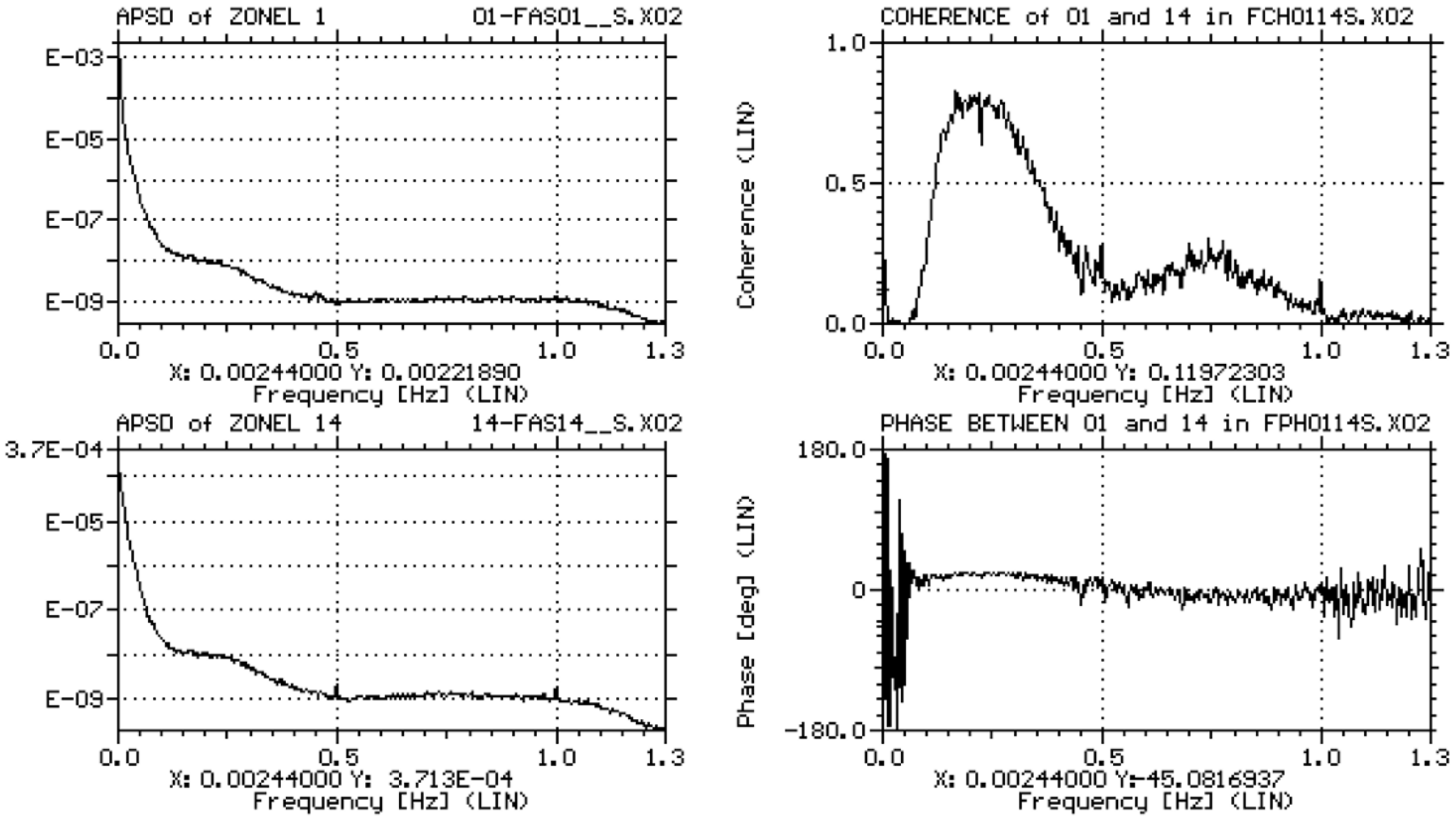
Normalized APSD, coherence and phase of two vertical ICFDs separated by a large distance, but having the same horizontal fuel channel neighbors in D2

Fuel Channel Vibrations as detected by In-Core Flux Detectors



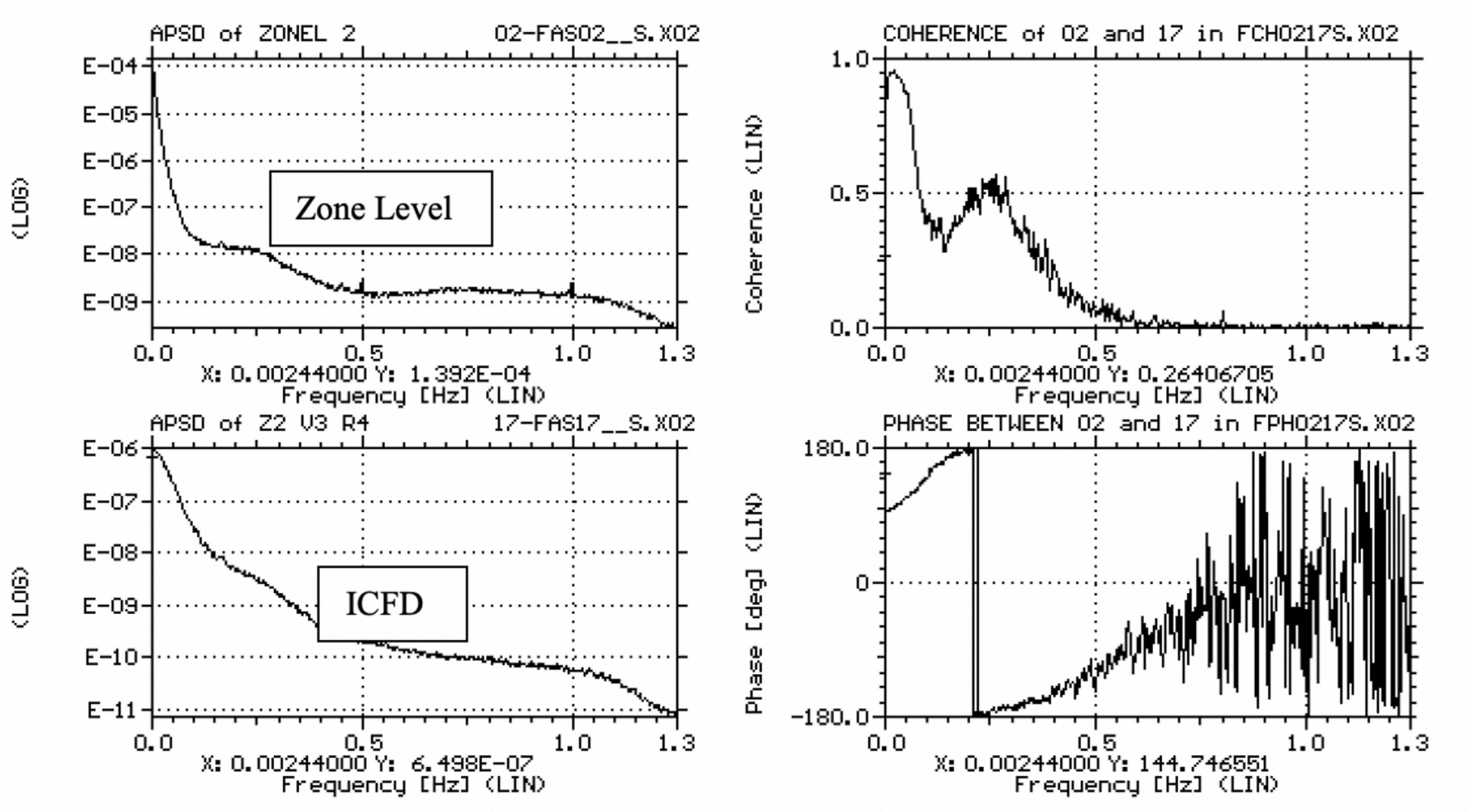
Normalized APSD, coherence and phase of two vertical ICFDs separated by a large distance, but having the same horizontal fuel channel neighbors in D4

Liquid Zone Control Level (LZCL) Fluctuations



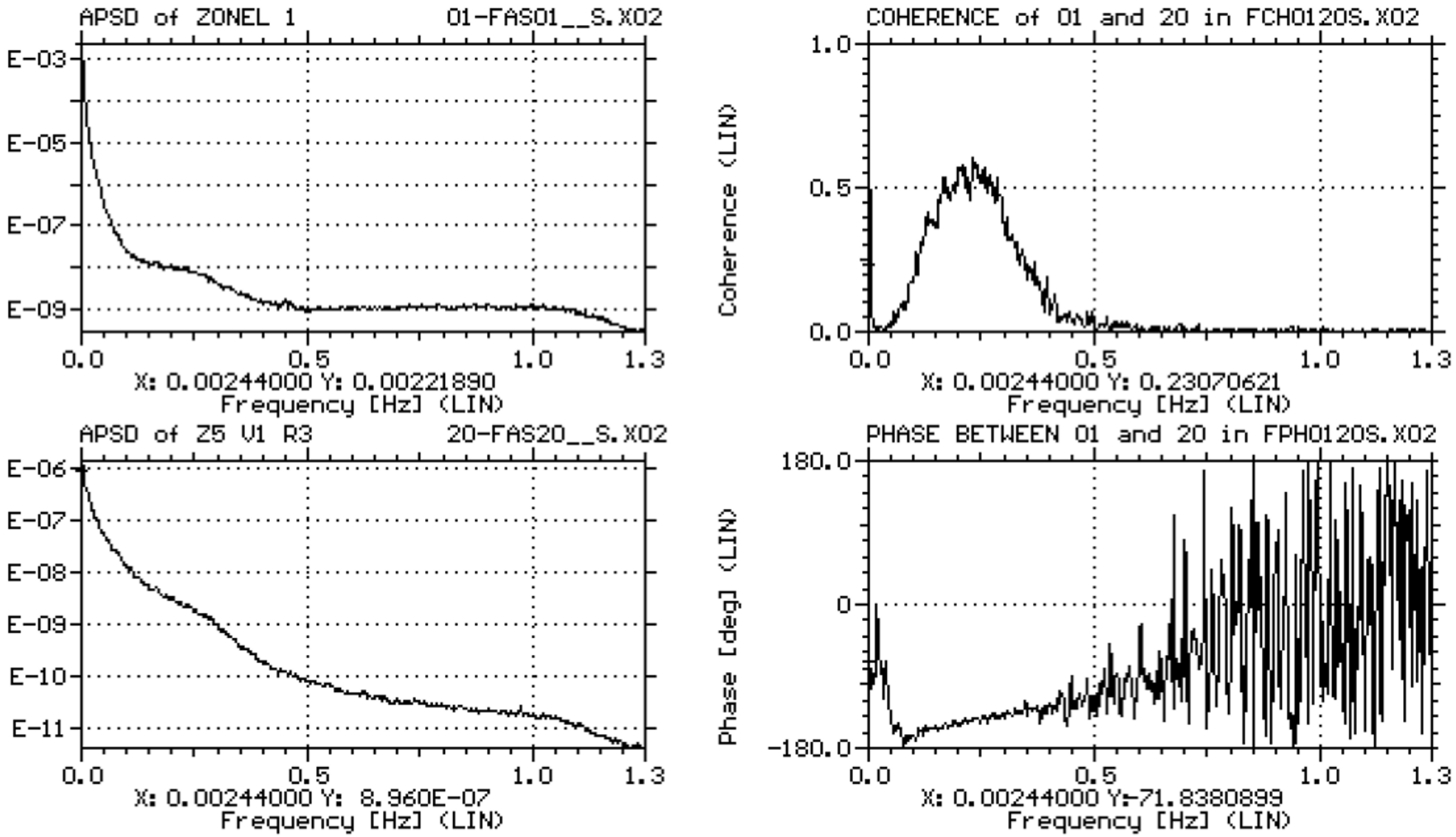
Normalized APSD, coherence and phase of two LZCL 1 and LZCL 14 signals in D3

Coupling between Liquid Zone Control Level and ICFD noise in the same Zone



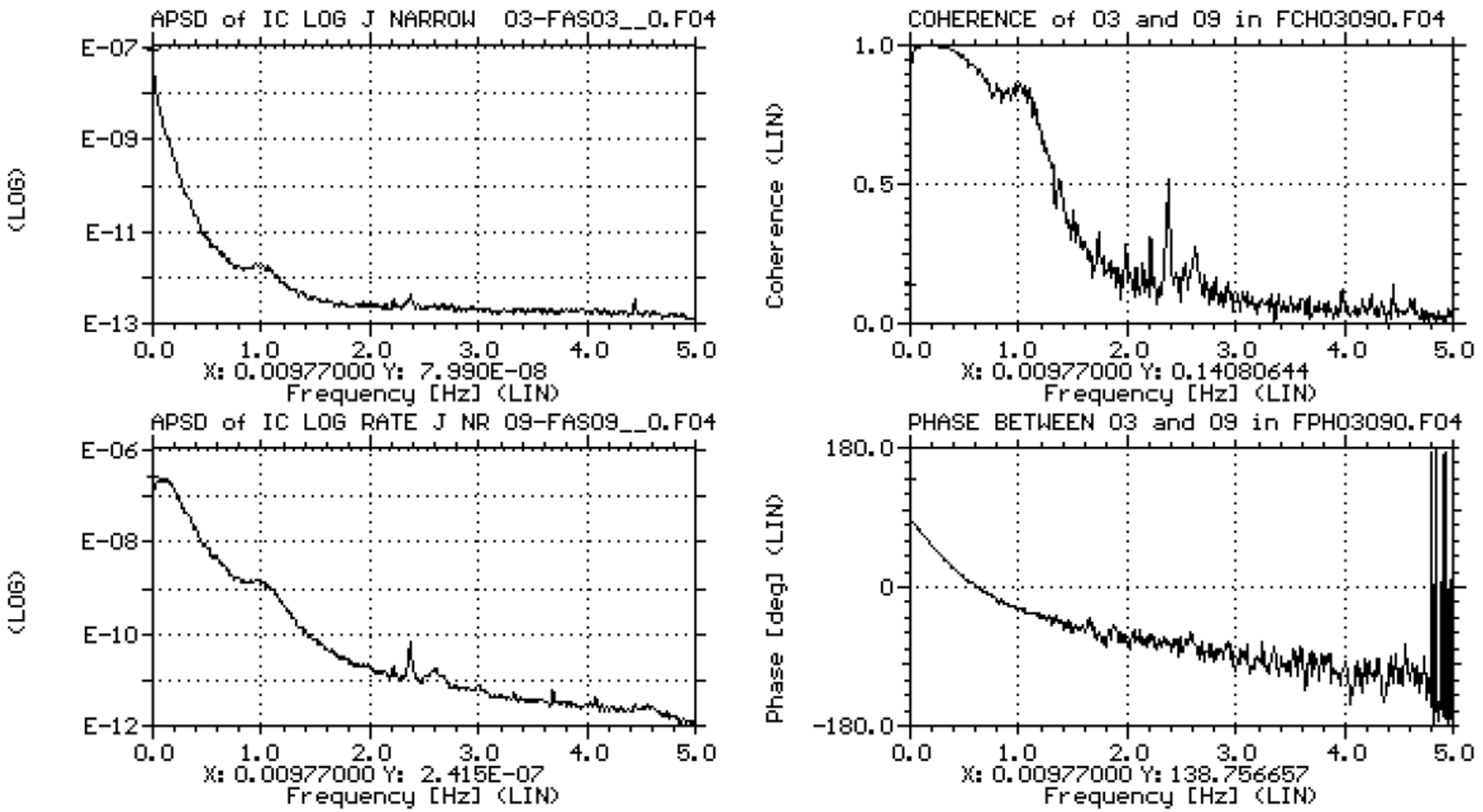
Normalized APSD, coherence and phase of LZCL 2 and ICFD 2 in D3

Coupling between Liquid Zone Control Level and ICFD noise in different Zones



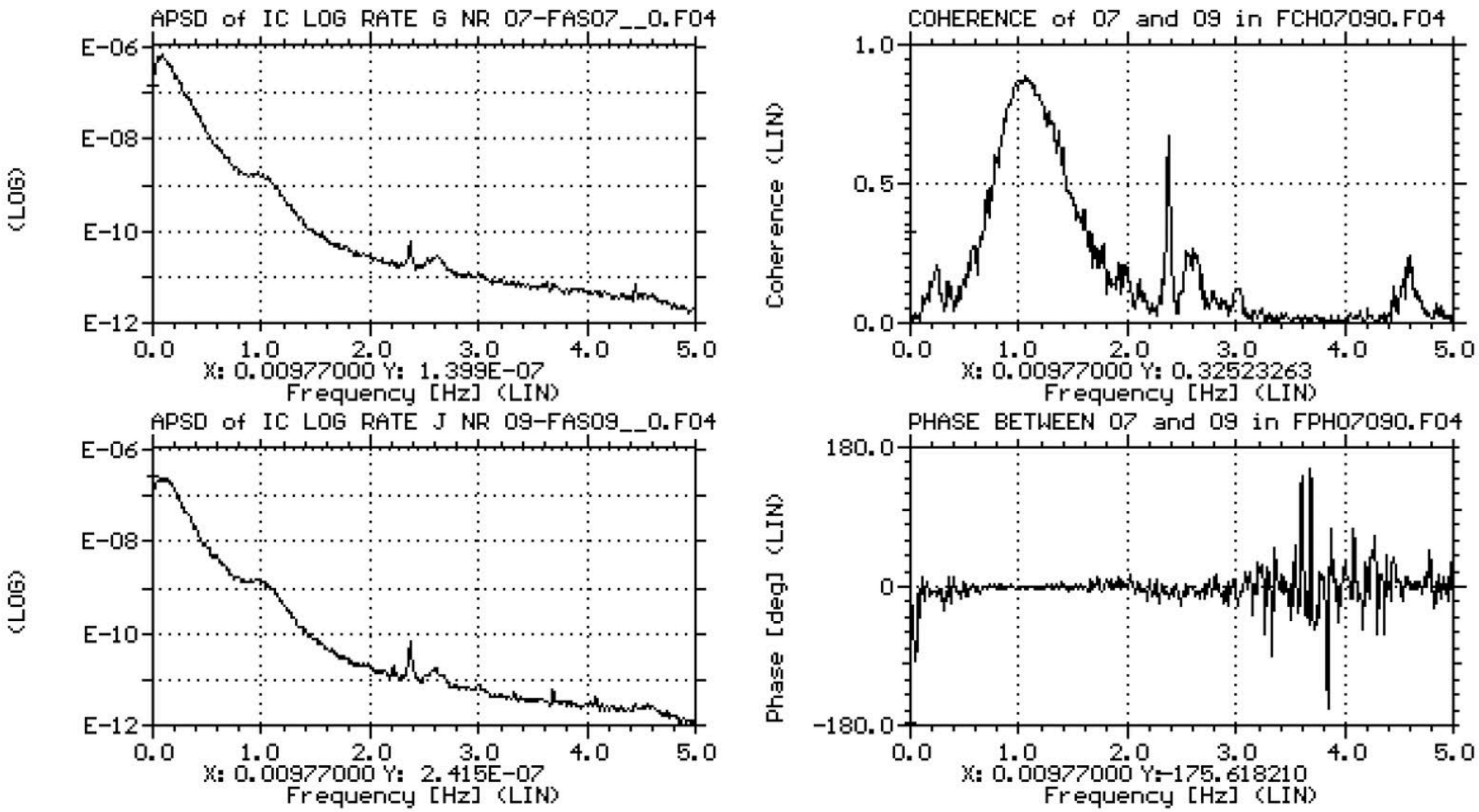
Normalized APSD, coherence and phase of LZCL 1 and ICFD 5 in D3

Ion Chamber noise signals: Log and Log Rate Outputs of the same Ion Chamber



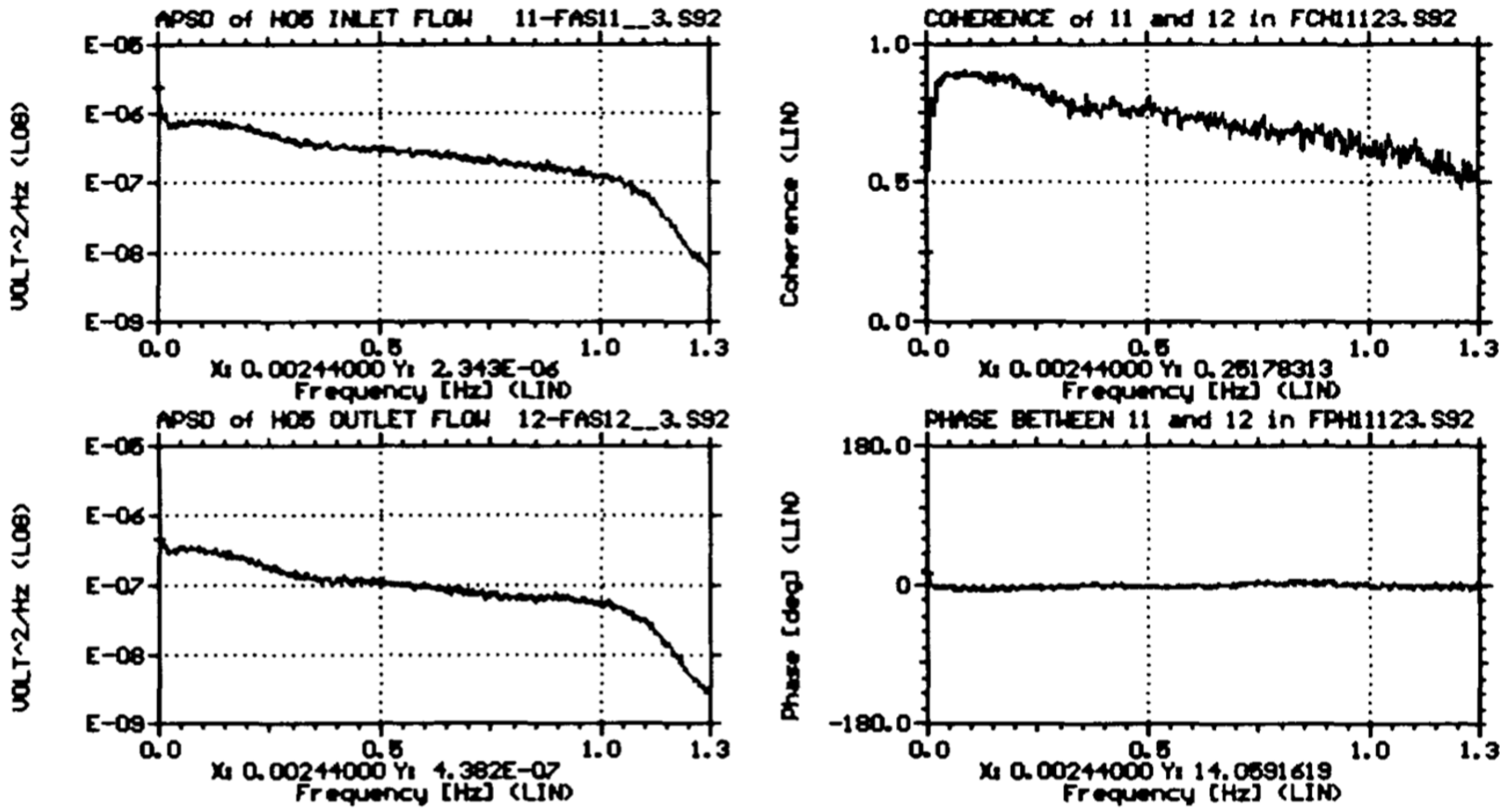
Normalized APSD, coherence and phase of Log and Log Rate Outputs of Safety System Ion Chamber J in P6

Ion Chamber noise signals: Log Rate noise signals from two different Ion Chambers



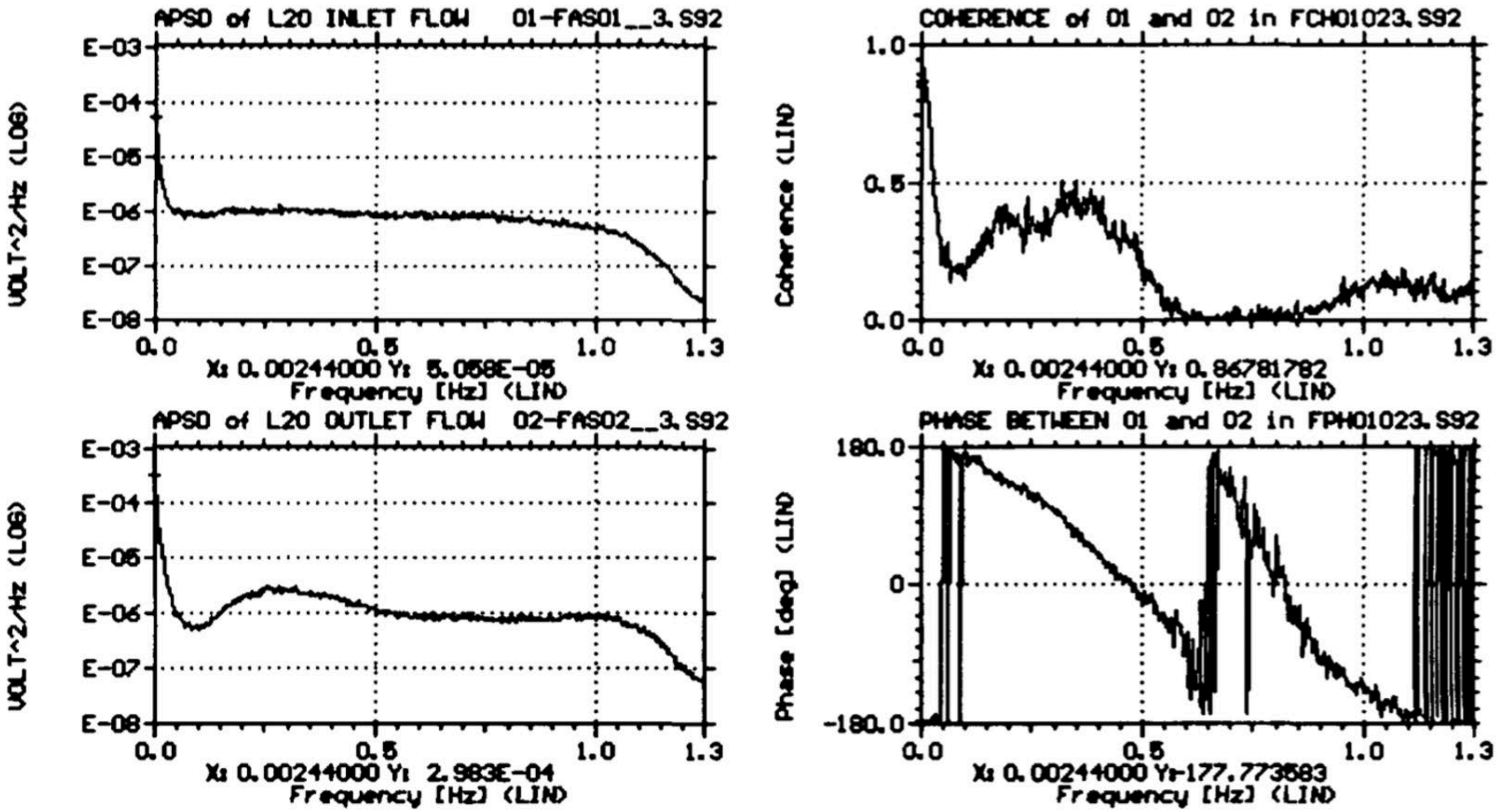
Normalized APSD, coherence and phase of Log Rate Outputs of Safety System Ion Chambers G and J in P6

Inlet and outlet coolant flow noise in Fully Instrumented Fuel Channels (FINCH)



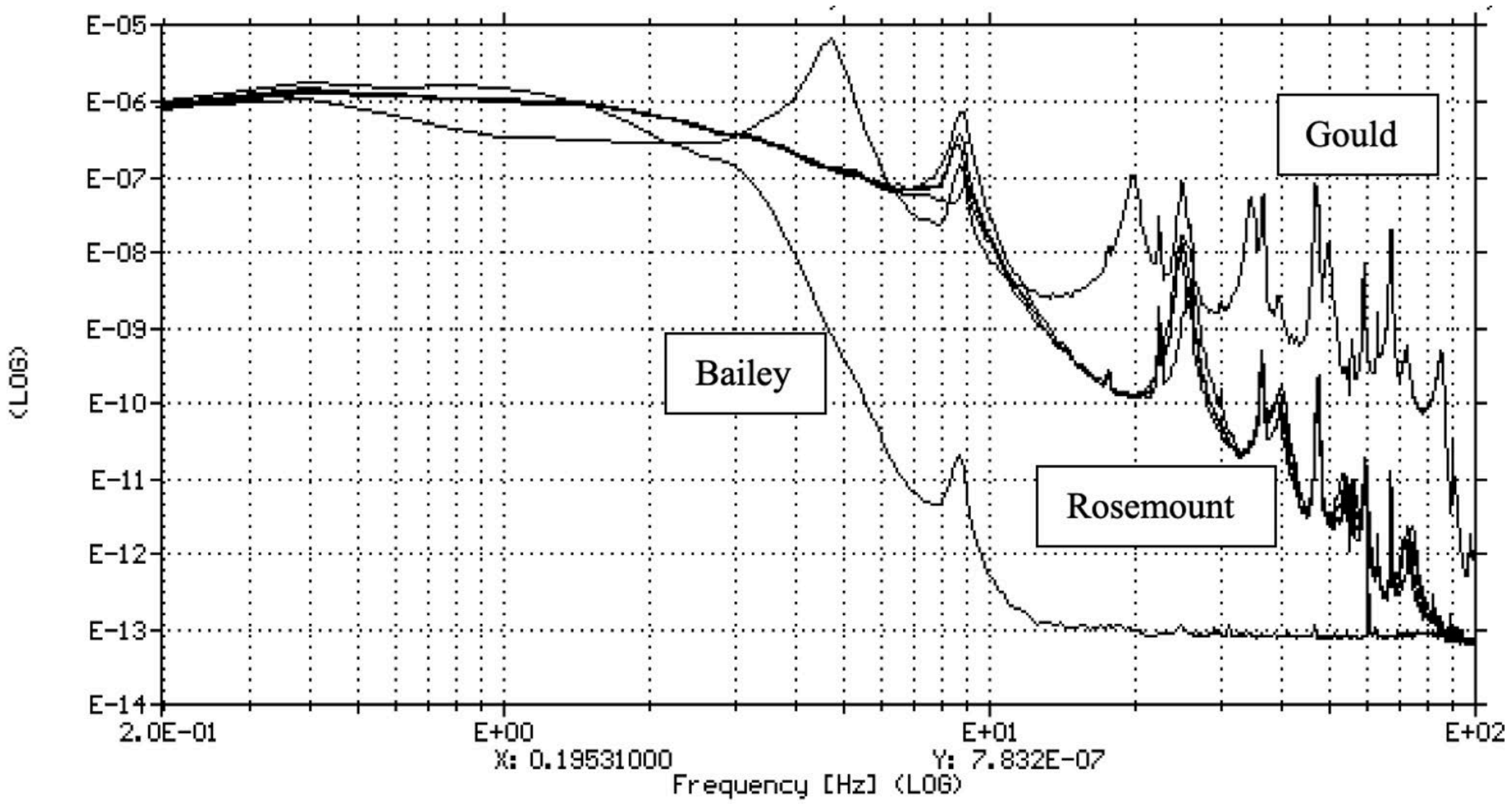
Normalized APSD, coherence and phase of FINCH inlet and outlet flow noise in D3 (low-power fuel channel with 304.5C exit temperature)

Inlet and outlet coolant flow noise in Fully Instrumented Fuel Channels (FINCH)



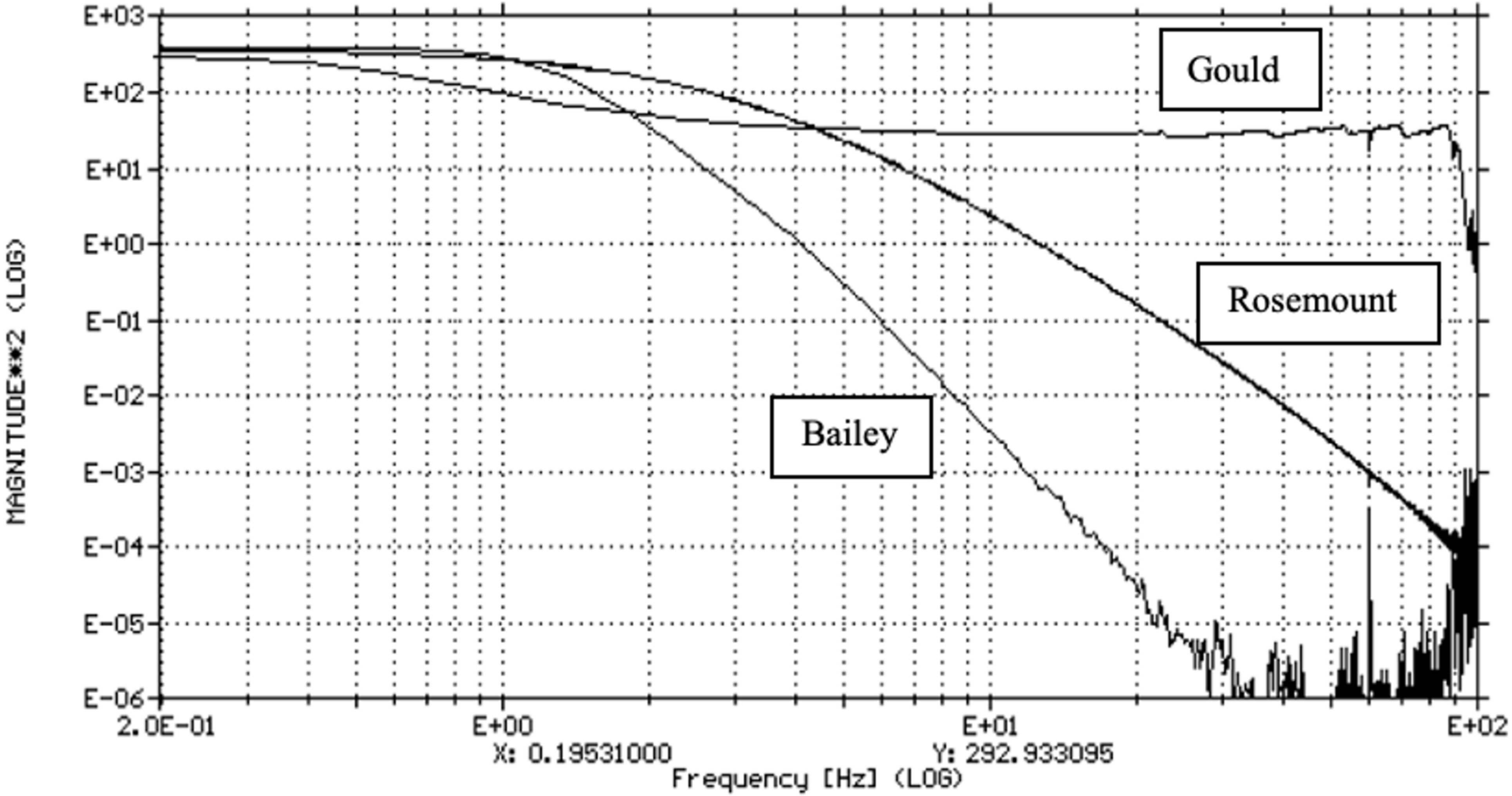
Normalized APSD, coherence and phase of FINCH inlet and outlet flow noise in D3 (high-power fuel channel with 309.0C exit temperature – 830 msec)

Flow transmitter noise analysis – APSDs of TX output noise



Normalized APSDs of safety system flow signals with three different types of flow TXs in D3

Flow transmitter noise analysis – Transfer functions of flow TX



Transfer functions of different types of flow TXs derived from in-situ input-output noise measurements in D3

Flow transmitter noise analysis – APSDs of TX output noise, Bruce-B U6

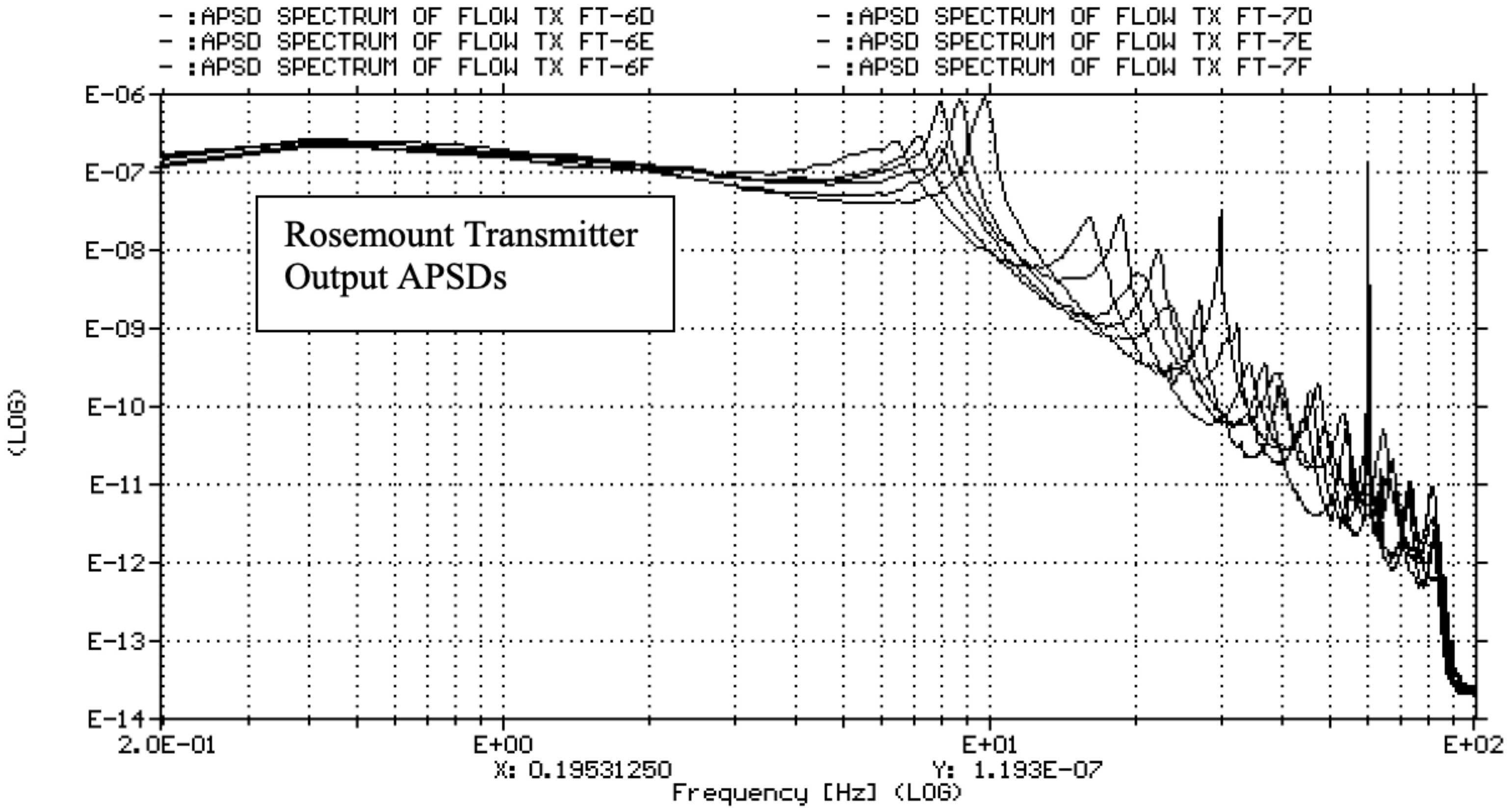


Figure 7.6. APSD spectral functions of the output noise signals of the six SDS1 Rosemount flow transmitters measured in Bruce-B Unit 6 at full power

Flow transmitter noise analysis – noise-based transfer functions, Bruce-B Unit 6

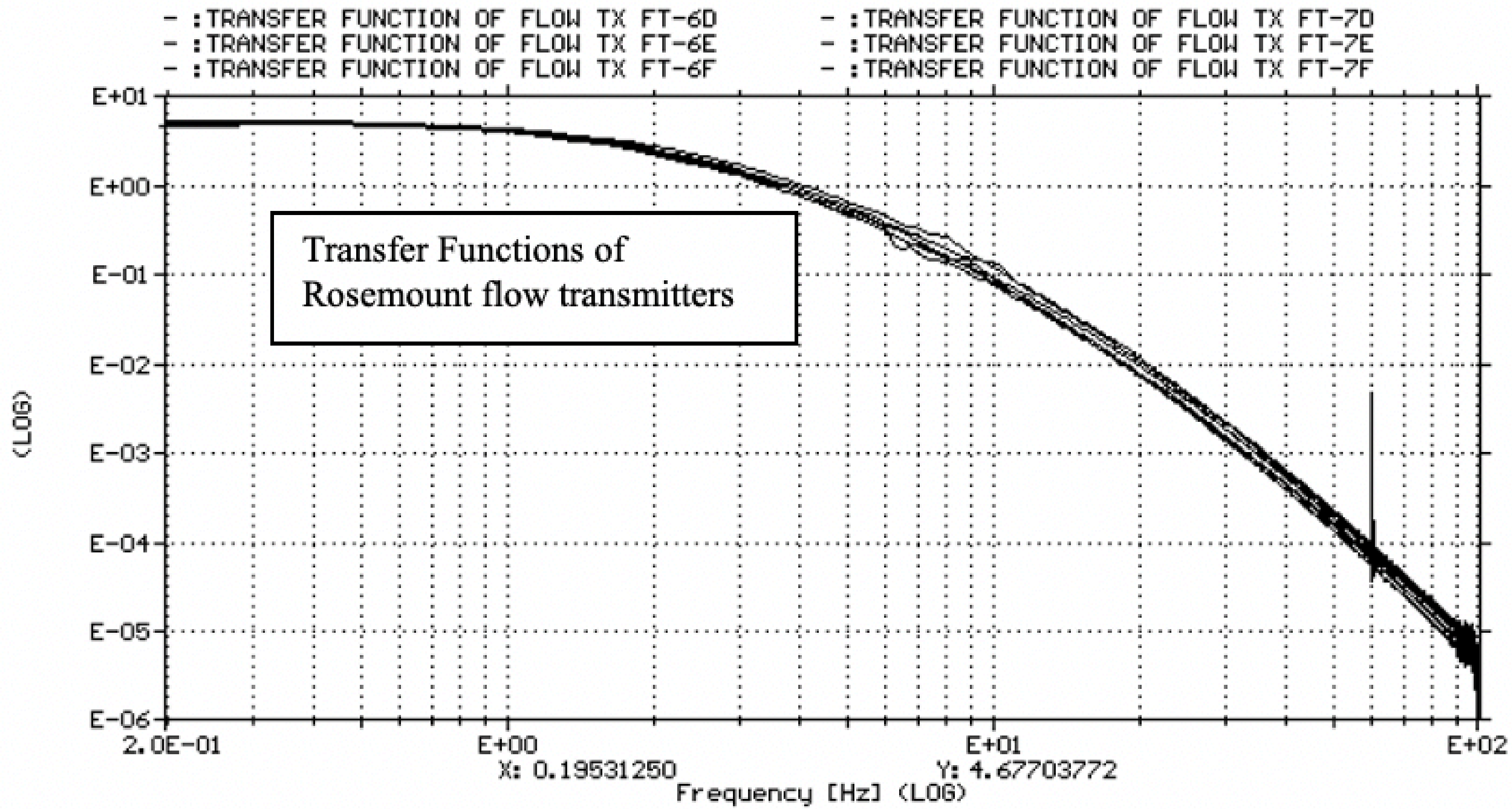


Figure 6.3. Magnitudes of transfer functions of Rosemount flow transmitters derived from in-situ pressure noise measurements in SDS1 flow loops in Bruce-B Unit 6

Flow transmitter noise analysis – curve fitting

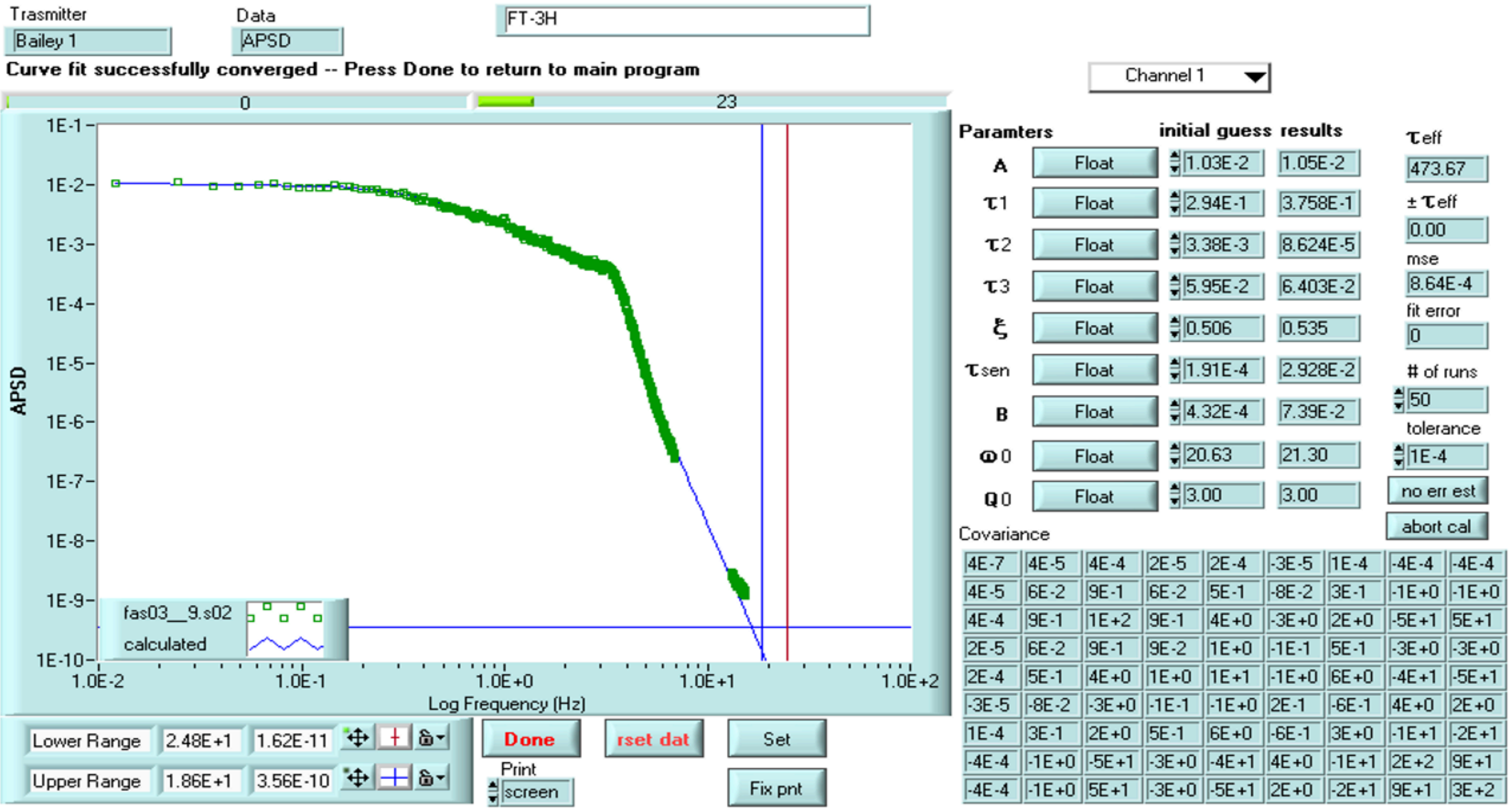
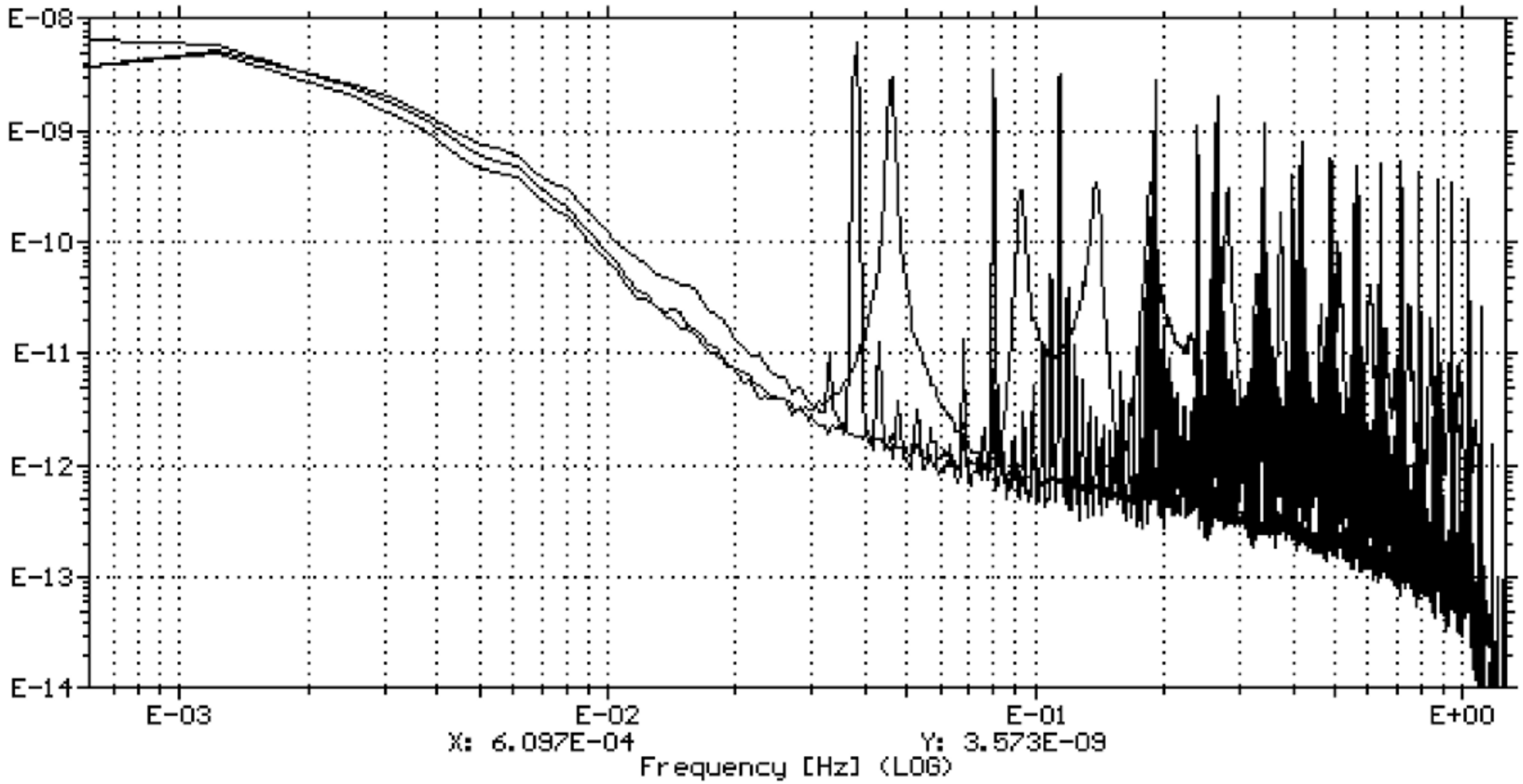


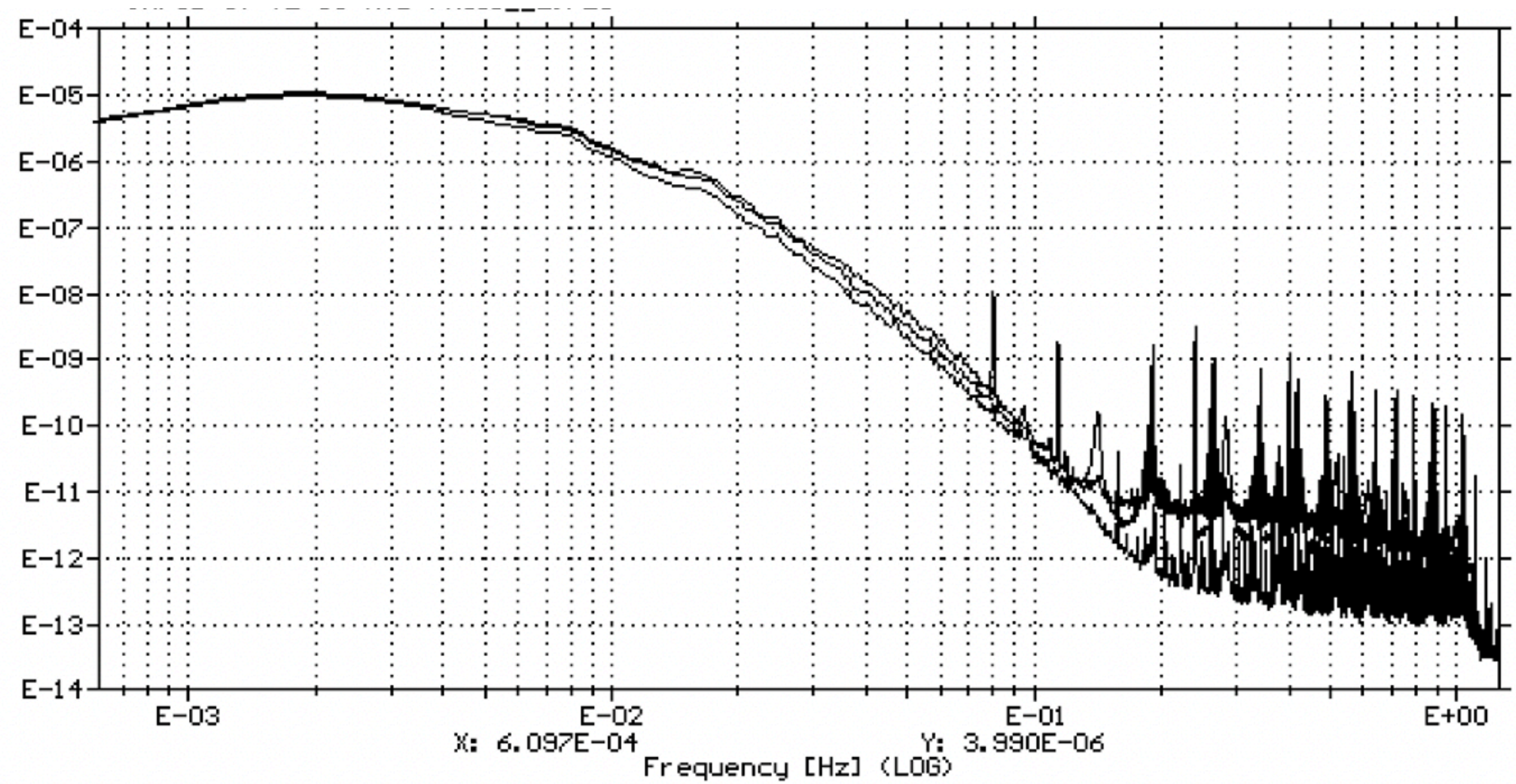
Figure 7.4. Example of the curve fit applied to the measured APSD function of safety system flow loop FT-3H in Darlington Unit 3. The ramp-equivalent response time of the flow loop was estimated in the range of 430 to 475 ms

Temperature noise analysis – Moderator core-exit safety system RTDs (strap-on)

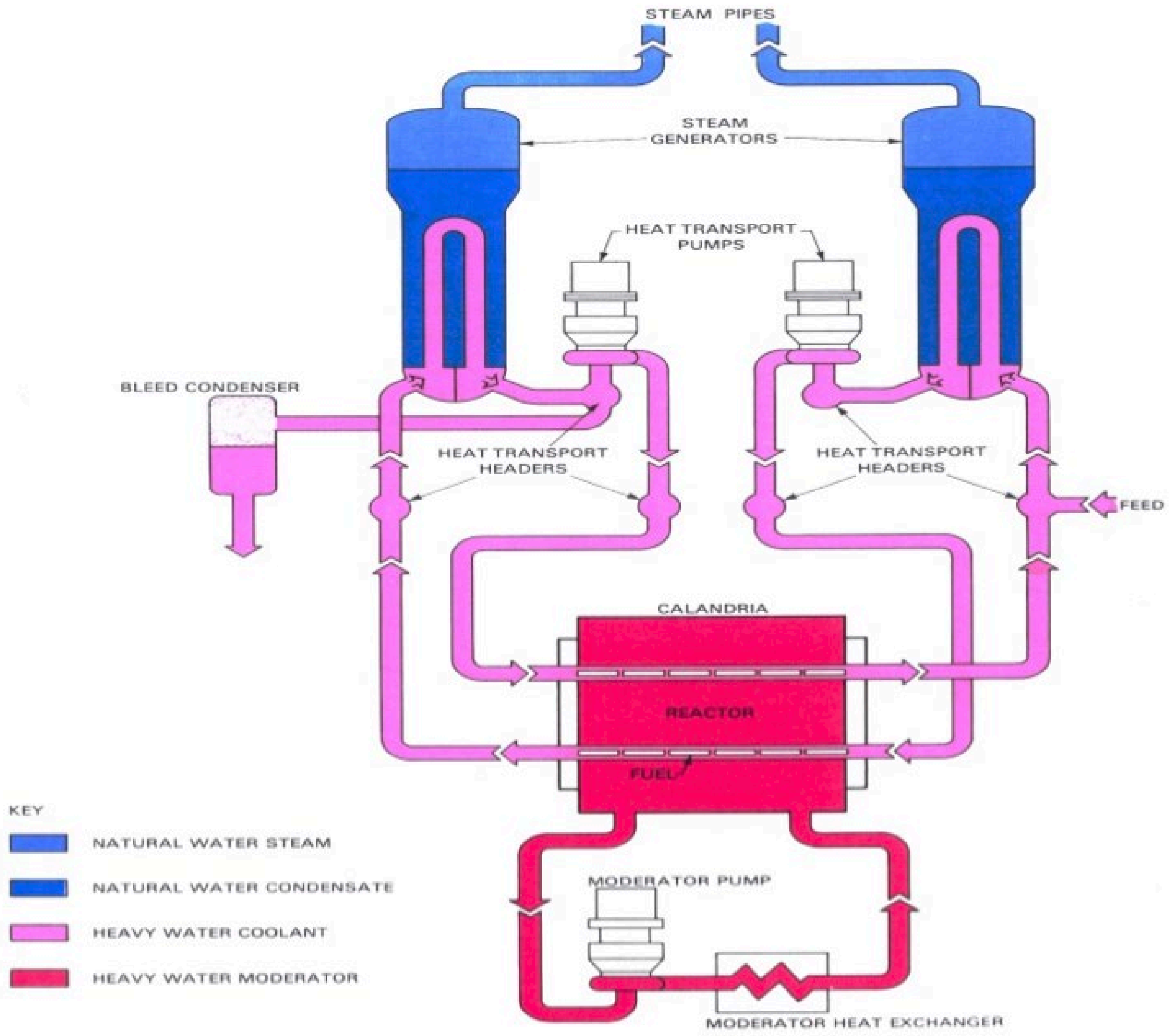


The noise-based response time estimates were in the range of 70 to 90 sec

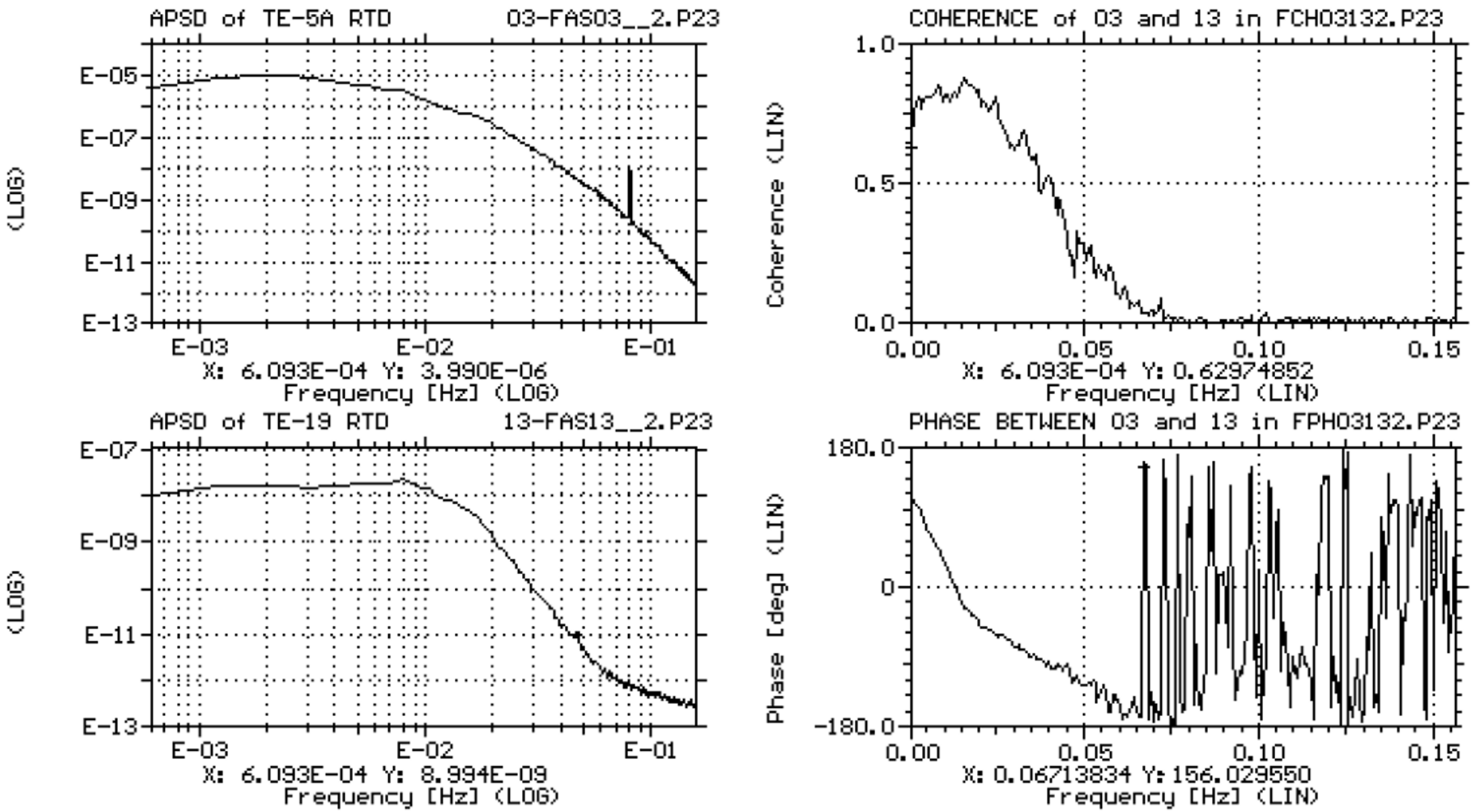
Temperature noise analysis – Moderator core-exit control system RTDs (thermal-well)



The noise-based response time estimates were in the range of 30 to 45 sec

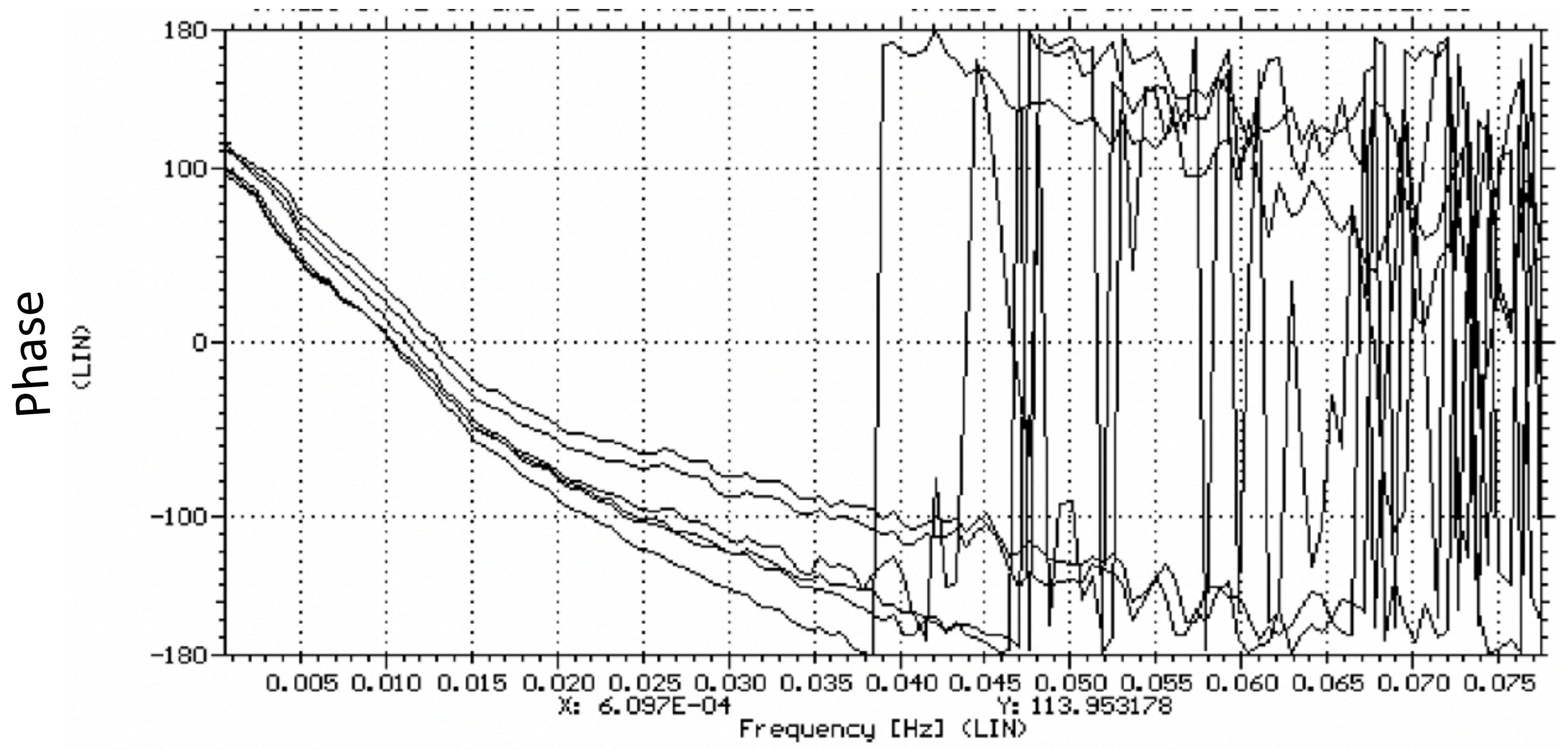

STEAM PIPES
STEAM GENERATORS
HEAT TRANSPORT PUMPS
BLEED CONDENSER
HEAT TRANSPORT HEADERS
HEAT TRANSPORT HEADERS
FEED
CALANDRIA
REACTOR
FUEL
KEY
NATURAL WATER STEAM
NATURAL WATER CONDENSATE
HEAVY WATER COOLANT
HEAVY WATER MODERATOR
MODERATOR PUMP
MODERATOR HEAT EXCHANGER

Temperature noise analysis – Core inlet and outlet regulating system RTDs (thermal-well)



APSD, coherence and phase function of the two RTD noise signals

Temperature noise analysis – Moderator transit time estimates between a core-exit RTD and 6 core-inlet RTDs (thermal-well RTDs in control systems)



The noise-based estimates of transit times varied with distance between RTDs and were in the range of 7 to 13 sec

Conclusion

A large amount of noise measurements were recorded and analyzed over the period of 1992-2004

- from various power units of Ontario Power Generation and Bruce Power
- from various types of safety system and regulating system signals

A new CANDU noise analysis project, funded by COG and CNL, is in its 3rd year focusing on developing noise-based

- estimation of prompt fractions of ICFDs,
- detection of leakage and other anomalies in flow and pressure measurement loops,
- validating the dynamics of signals and detecting signal faults.

Thank you!

Questions?