COMPREHENSIVE NUCLEAR-TEST-BAN TREATY ORGANIZATION

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Analysis of CTBT IMS Hydroacoustic hydrophone station underwater system electronics calibration sequences

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Introduction

- IMS Hydroacoustic (HA) hydrophone station overview

(For useful videos introducing the IMS and its HA network, visit https://www.ctbto.org/verification-regime/ and https://www.ctbto.org/verification-regime/monitoring-technologies-how-they-work/hydroacoustic-monitoring/)

- IMS HA hydrophone station calibration
  - Pre-deployment end-to-end calibration
  - Calibration of underwater system (UWS) digitizer electronics after deployment
- Overview of HA hydrophone station end-to-end system response
- Analysis of UWS digitizer electronics calibrations found in the CTBTO International Data Centre (IDC) database to date
- H10S fault – example of large changes in UWS digitizer response
- Conclusions, Ongoing Work and Outlook

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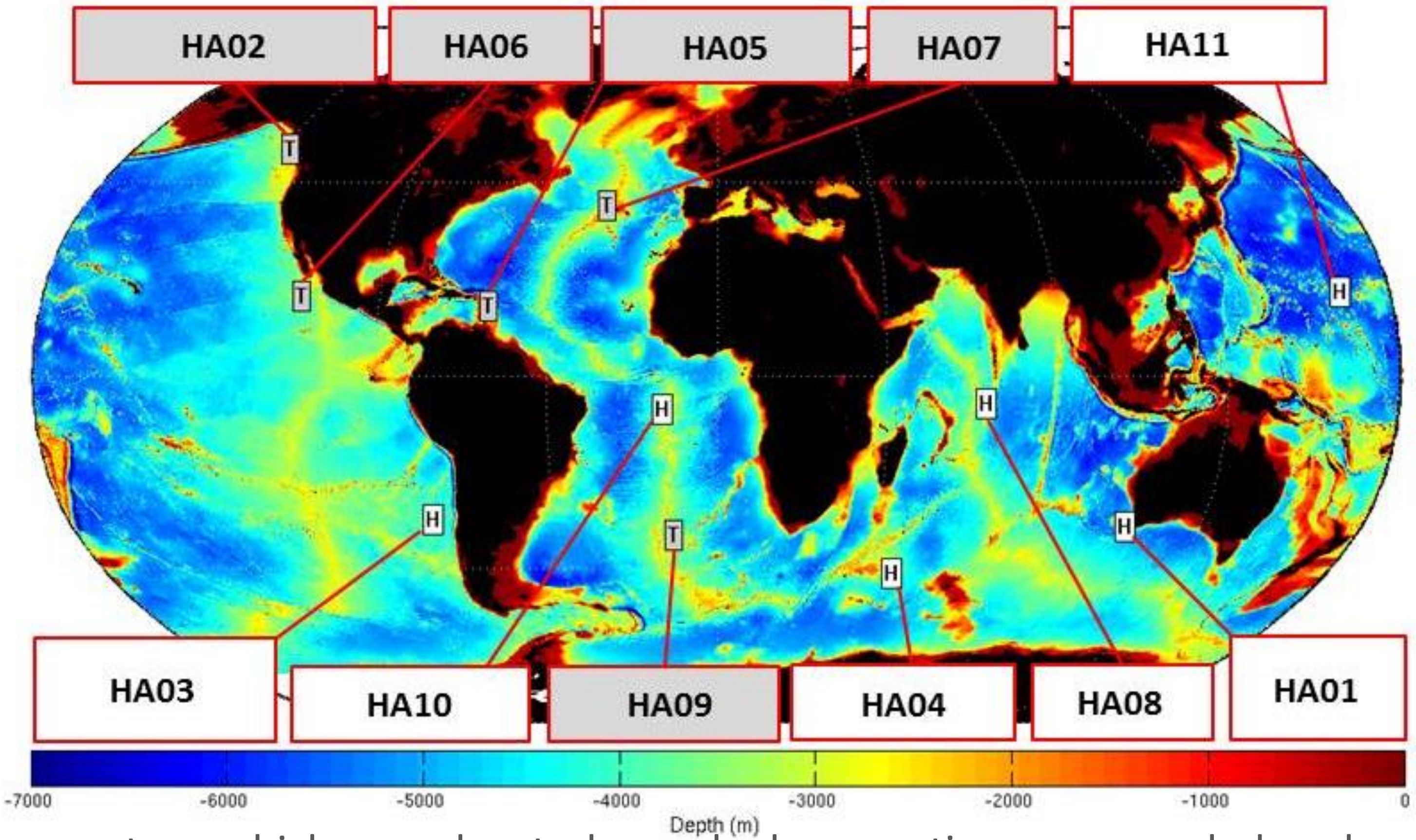
The CTBT IMS HA Network

Hydrophone Station		Water depth (m)	Hydrophone depth (m)
HA01	**W**	**1550**	**1100**
HA03	**N**	**1866**	**824**
	S	**2071**	**830**
HA04	**N**	**1310**	**541**
	S	**1309**	**535**
HA08	**N**	**2300**	**1250**
	S	**1800**	**1350**
HA10	**N**	**2000**	**850**
	S	**1700**	**850**
HA11	**N**	**1400**	**750**
	S	**1150**	**750**



- (Grey boxes) 5 T-phase stations: near-shore seismometers, which record waterborne hydroacoustic waves coupled upslope into the earth's crust.
- (White boxes) 6 Hydrophone stations: moored hydrophones pick up hydrocaoustic waves in the water column. Each hydrophone station has two triplets of hydrophones to prevent shadowing from the island, except for HA01 (Australia) which has only one triplet.

HA hydrophone station UWS (one triplet and trunk cable)

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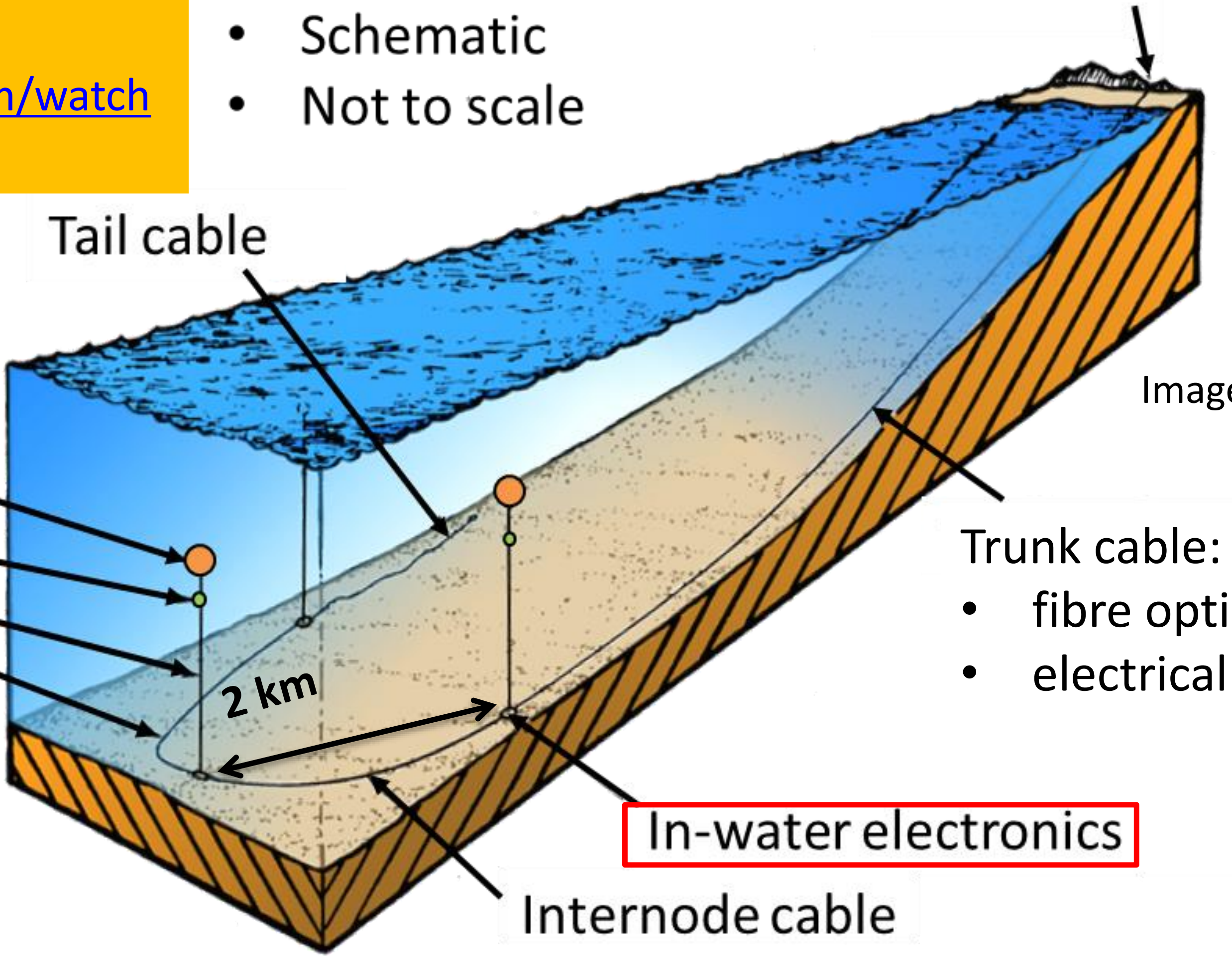
If you want to know more about how an IMS HA hydrophone station is installed, see this short documentary: https://www.youtube.com/watch?v=wKUiNIvOvug

Note
- Schematic
- Not to scale



Shore facility (power to the triplet & control, sends hydrophone data to CTBTO in Vienna via satellite link)

Image adapted from L3-MariPro, Inc.

Trunk cable:
- fibre optic data link
- electrical power to triplet.

Note: Each IMS HA hydrophone station has two triplets, except for HA01 (Australia)

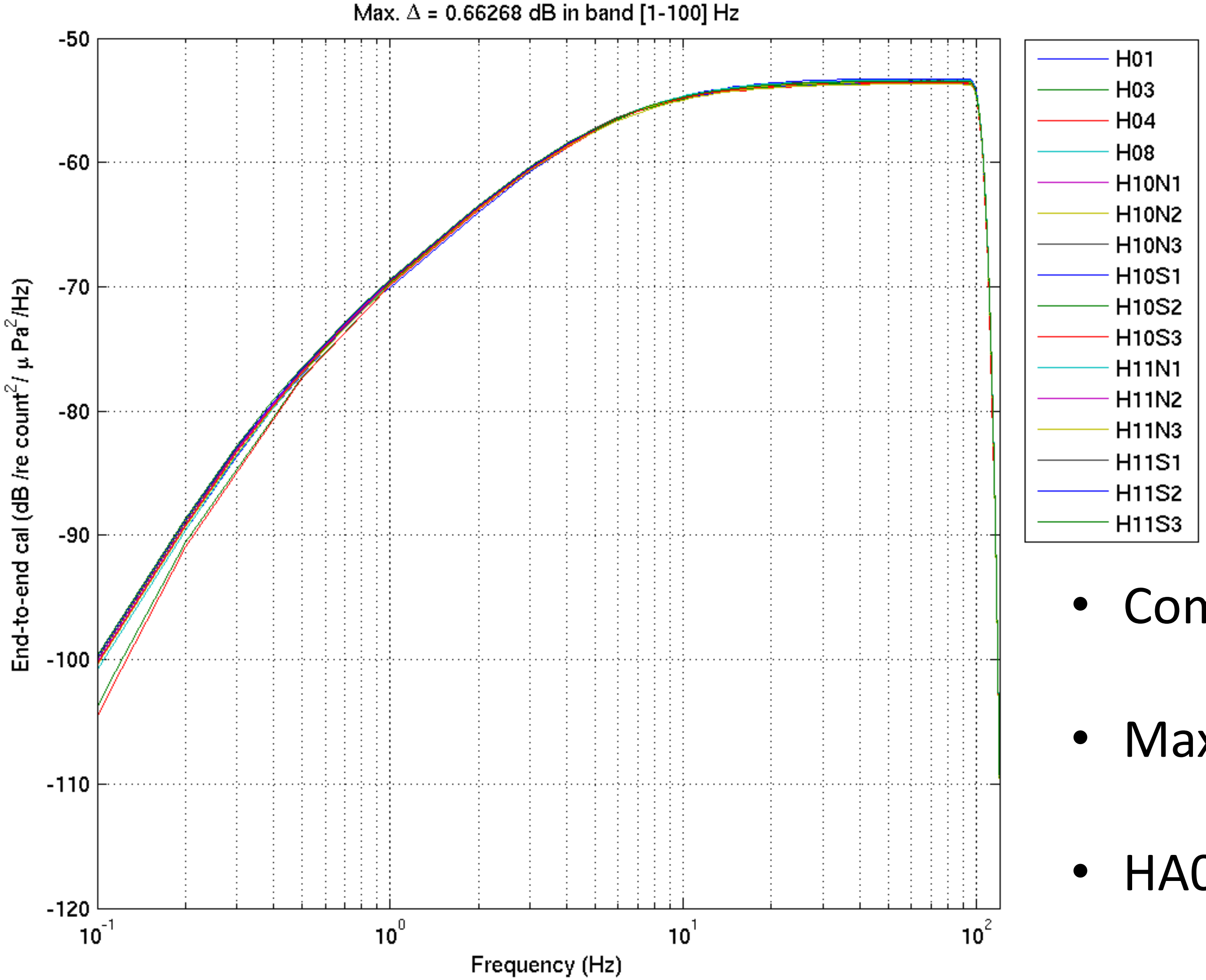
IMS HA hydrophone Station Calibration

- Comprehensive Nuclear-Test-Ban Treaty requirement:
  - amplitude calibration must be measured in the band 1 – 100 Hz
  - accuracy within 1 dB amplitude, no requirements on the phase

- Before deployment: full end-to-end system calibration at Factory Acceptance Test (FAT) / System Integration Test (SIT)
  – Hydrophone sensing element & pre-amp in low-frequency tank facility
  – UWS digitizer electronics: input from riser cable to laser output in the lab

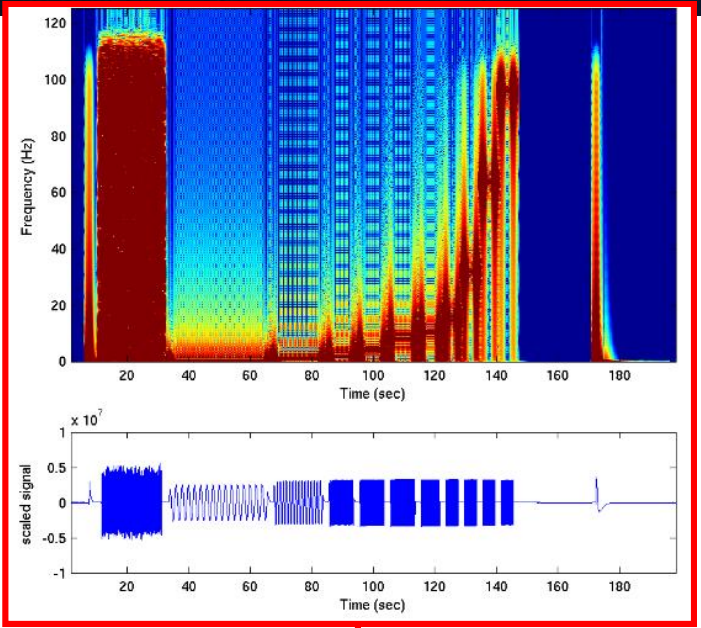
- After deployment: UWS digitizer electronics calibration, triggered by a command from the shore facility

Full end-to-end calibration before deployment

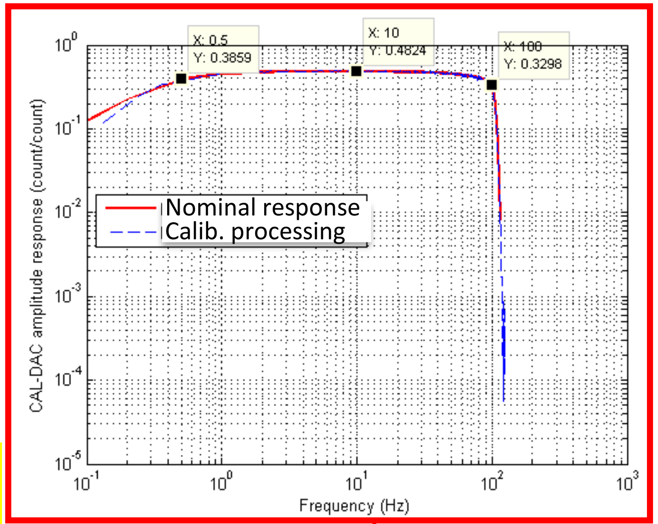


- Comparison between all stations
- Max. spread in 1 – 100 Hz band = 0.66 dB
- HA03 (2014) is shown here

UWS Digitizer Electronics Calibration



3) Data received at the shore and sent to Vienna via the satellite link. Processed to check if there are changes in the response over time.



Hydrophone (ceramic capacitance and resistor)

Pre-amplifier

1) Command from shore opens a relay switch in the UWS electronics bottle.

2) Known pre-stored analog waveform is injected via a Digital-to-Analog converter (DAC). Sequence consists of:

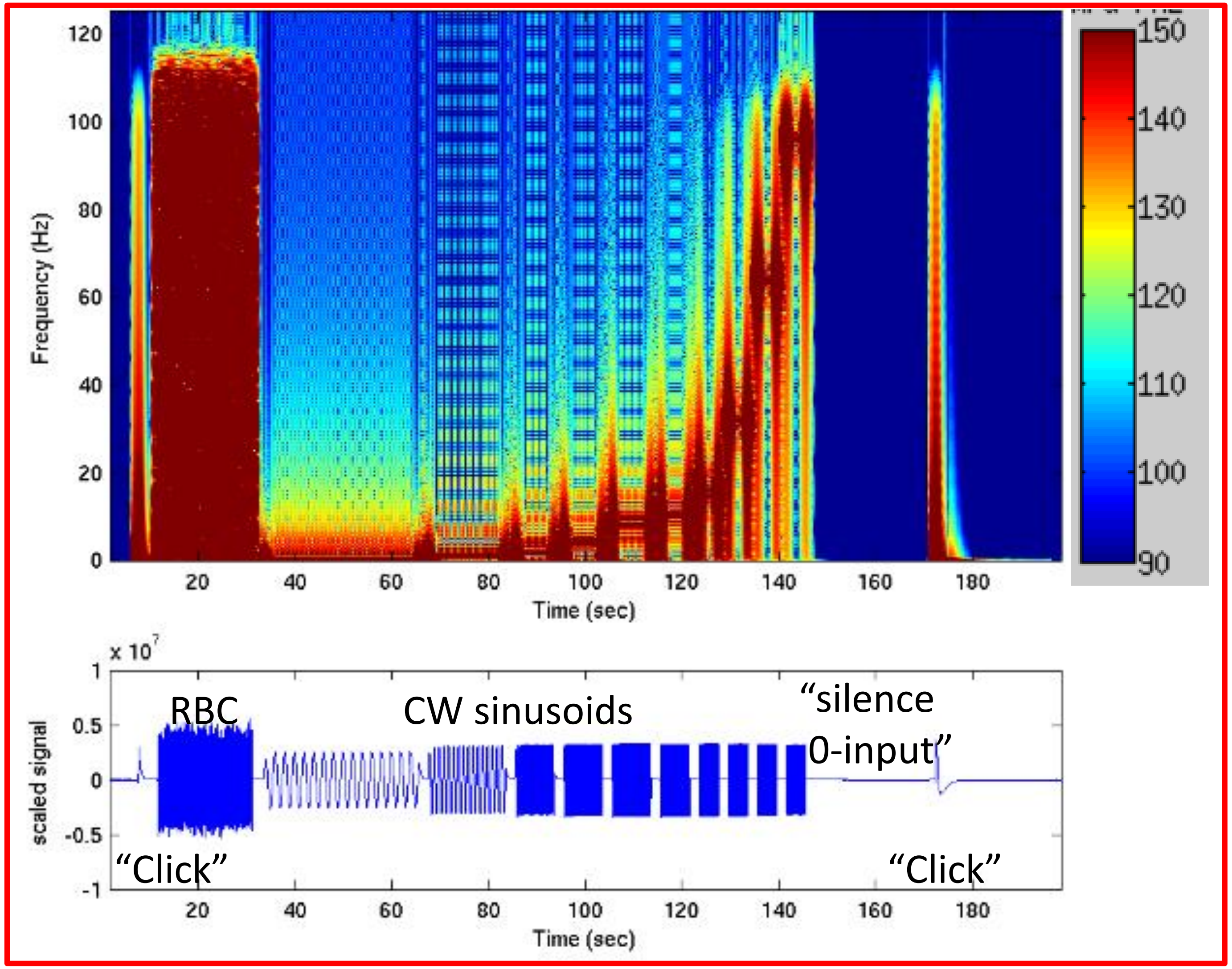
- ***Pseudo-random noise: random broadband code (RBC)***
- ***CW sinusoid chirps***

Analog High-pass filter [to compensate for low-frequency ocean noise curve]

Analog Anti-Aliasing Low-pass filter [***Nyquist*** : bandwidth < $f_{sampling}/2$]

Analog-to-Digital Converter (ADC)

UWS electronics calibration sequence



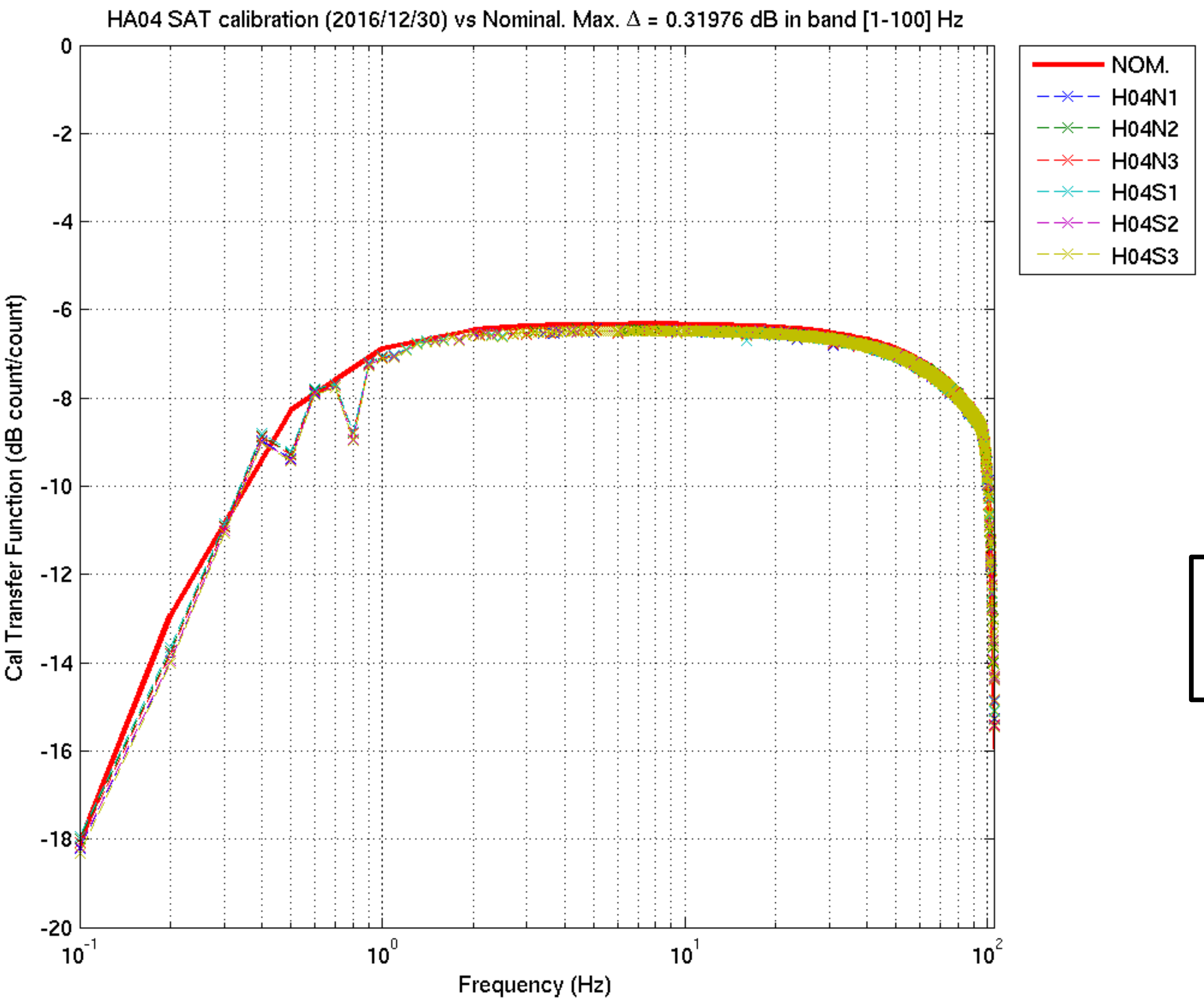
Colorscale: signal amplitude squared in dB /re arbitrary reference

- Calibration data recorded at the shore.
- While one channel is calibrating, the others continue to acquire acoustic data.
- Data received & stored at the CTBTO International Data Centre (IDC).
- Transfer function from Digitizer input to ADC output (fiber/laser) computed using a replica of the analog calibration waveform and some key processing parameters recommended by the manufacturer.

UWS electronics calibration sequence processing

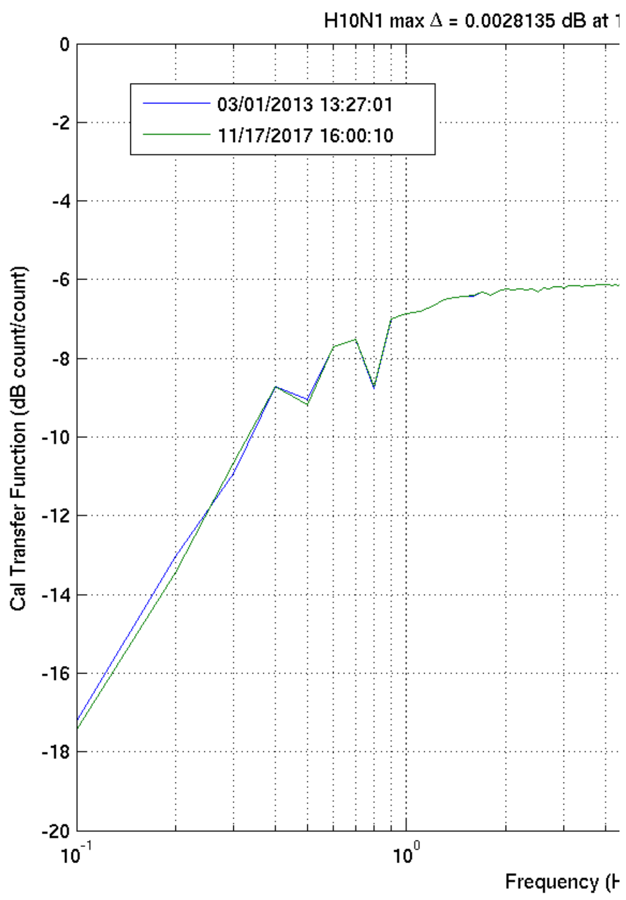
- Table from the CTBTO International Data Centre (IDC) with start/end times when calibration flag bit is set
- Remove DC bias from raw signal.
- Use raw signal squared magnitude w/ threshold to reliably detect beginning of RBC sequence.
- Cut out RBC sequence signal with fixed # of samples.
- Compute transfer function using RBC input sequence replica.

HA04 Crozet UWS digitizer electronics calibration

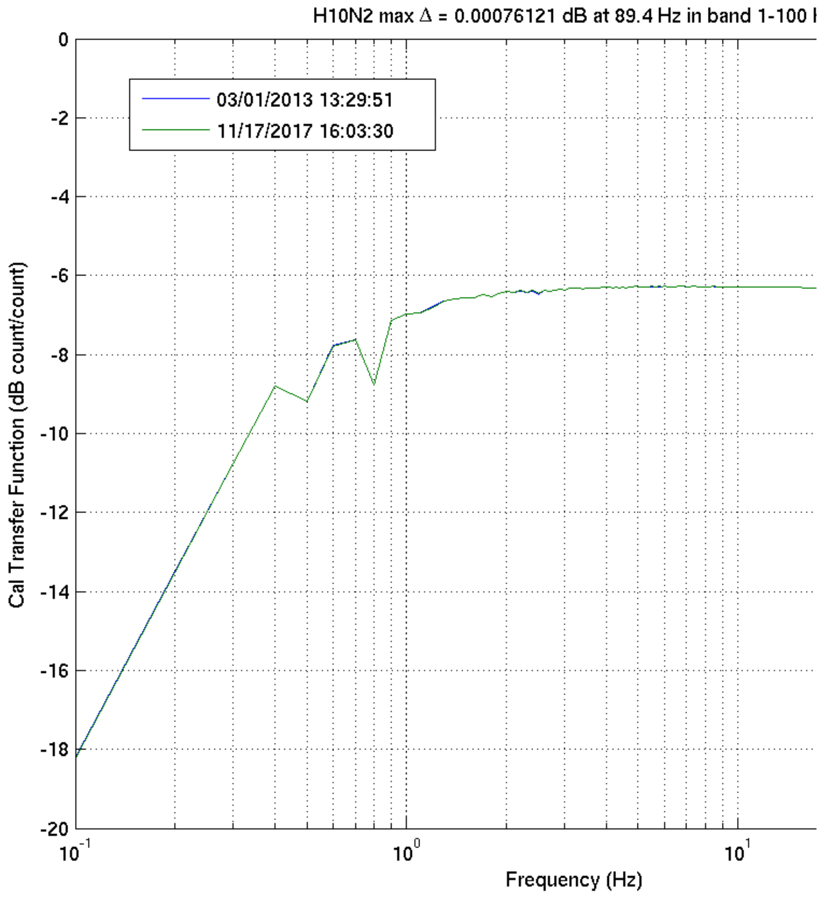


- Transfer functions for all 6 HA04 Crozet Hydrophone digitizers.
- Data from HA04 Crozet System Acceptance Test (SAT) 2016/12/30.
- Compared to Nominal curve (NOM) from UWS FAT measurements.
- Max. deviation from nominal response = 0.32 dB in 1-100 Hz band.
- The bumpy features (below 1 Hz) are considered to be data processing artefacts not related to the actual system response.

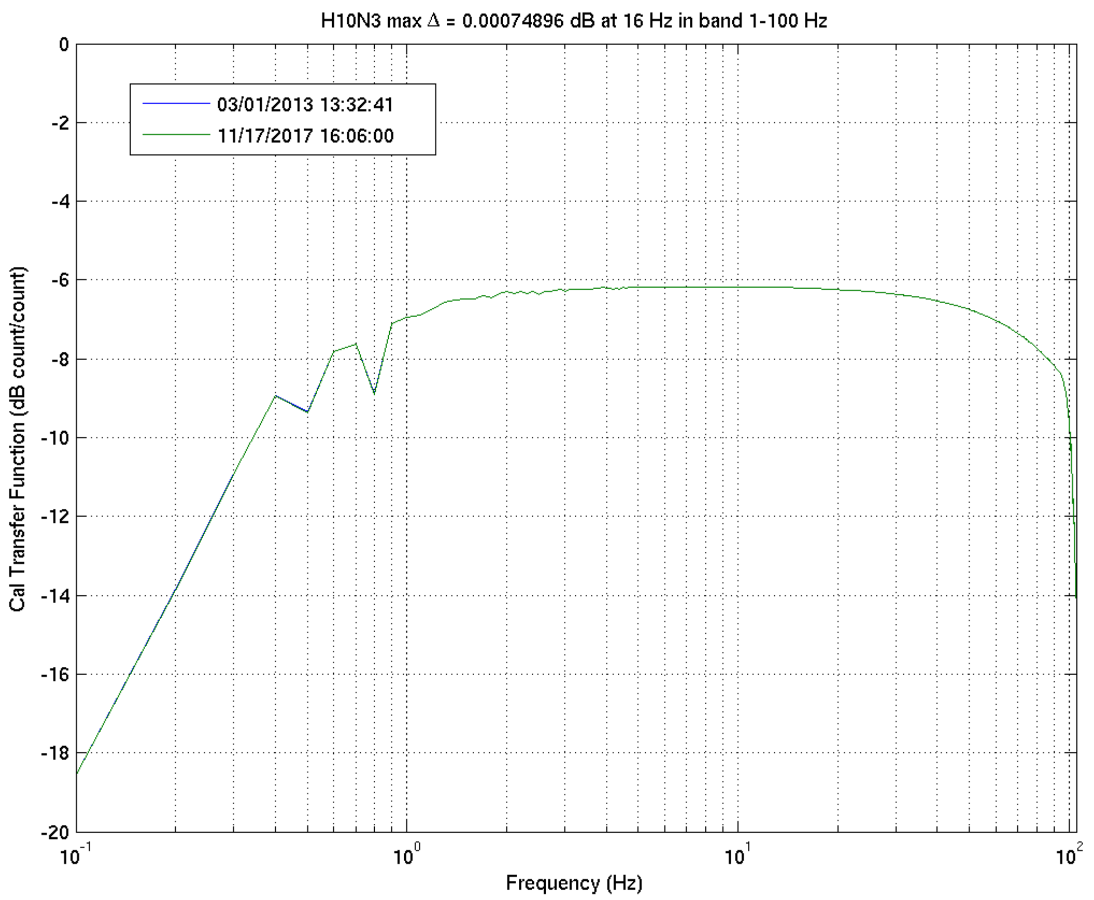
H10N 2013 vs. 2017



Max Δ = 0.00281 dB, 1 – 100 Hz

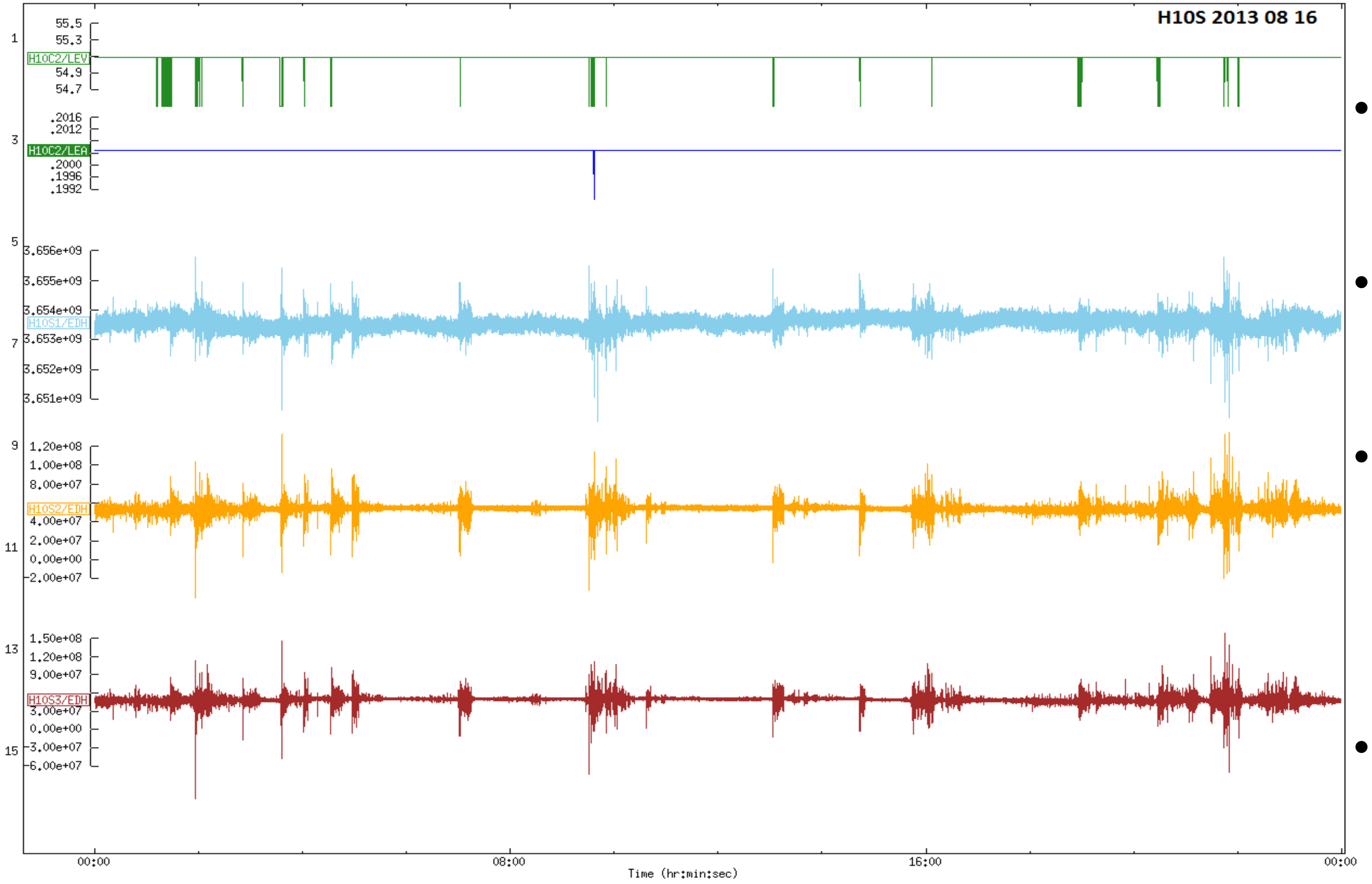


Max Δ = 0.00076 dB, 1 – 100 Hz



Max Δ = 0.00075 dB, 1 – 100 Hz

H10S electronic noise since 2013



- Electrical noise spike found 2013/07/19, channel H10S1.
- Evolved to strong permanent noise with cross-talk to H10S2 and H10S3.
- Since then, varying levels of noise H10S1 w/ cross-talk to H10S2 & S3.
- H10S1 out of CTBTO IDC Operations (OPS) because of large number of spurious detections caused by electrical spikes in the signal.
- However many events are still detected by H10S (e.g. airgun surveys)
- Present interpretation: possible riser cable failure.

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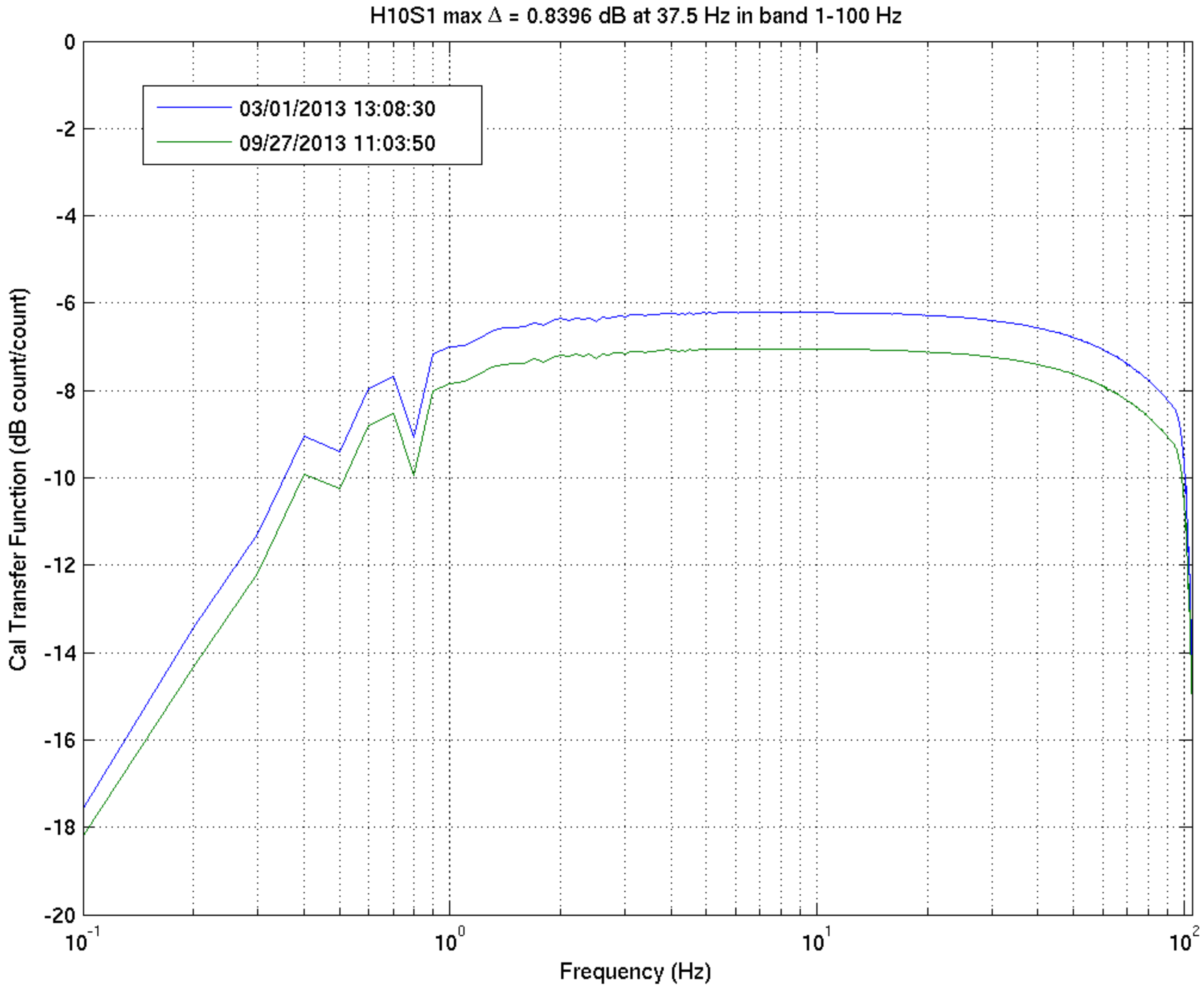
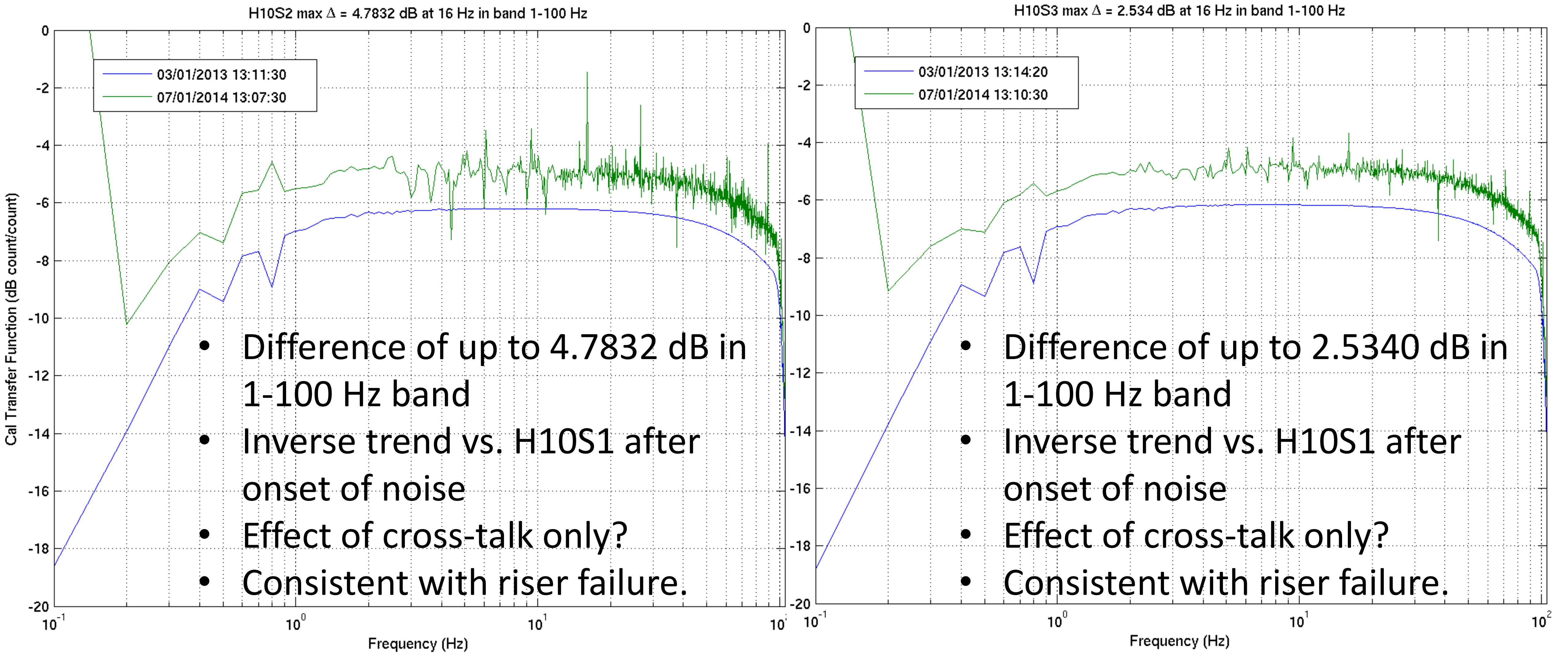
H10S1 before and after onset of electrical noise



- H10S1 shift by 0.8396 dB in 1-100 Hz band between MAR 2013 and SEP 2013.
- Otherwise UWS transfer function shows no major change in shape.

H10S2&3 before and after onset of electrical noise



- Difference of up to 4.7832 dB in 1-100 Hz band
- Inverse trend vs. H10S1 after onset of noise
- Effect of cross-talk only?
- Consistent with riser failure.

- Difference of up to 2.5340 dB in 1-100 Hz band
- Inverse trend vs. H10S1 after onset of noise
- Effect of cross-talk only?
- Consistent with riser failure.

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Comparison between early and recent UWS calibrations

Channel	1st date found	Last date found	Delta max 1-100 Hz
H01W1	2018/07/07	2018/07/11	0.00044 dB
H01W2	2018/07/07	2018/07/11	0.00066 dB
H01W3	2018/07/07	2018/07/11	0.00051 dB
H03N1	2017/12/18	2018/08/13	0.10369 dB
H03N2	2017/12/18	2018/13/08	0.20510 dB
H03N3	2017/12/18	2018/13/08	0.10510 dB
H03S1	2016/07/27	2018/08/22	0.23072 dB
H03S2	2016/07/27	2018/08/22	0.12456 dB
H03S4	2016/07/27	2018/08/22	0.11435 dB
H08N1	2012/11/13	2014/03/01	0.00942 dB
H08N2	2012/11/13	2014/03/01	0.00172 dB
H08N3	2012/11/13	2014/03/01	0.00124 dB
H08S1	2012/11/13	2017/12/24	0.00506 dB
H08S2	2012/11/13	2017/12/24	0.00132 dB
H08S3	2012/11/13	2017/12/24	0.00074 dB

Channel	1st date found	Last date found	Delta max 1-100 Hz
H10N1	2013/03/01	2017/11/17	0.00281 dB
H10N2	2013/03/01	2018/07/11	0.00076 dB
H10N3	2013/03/01	2017/11/17	0.00075 dB
H10S1	2013/03/01	2013/09/27	0.83960 dB
H10S2	2013/03/01	2013/09/27	4.78320 dB
H10S3	2013/03/01	2013/09/27	2.53400 dB
H11N1	2013/07/02	2017/09/06	0.00247 dB
H11N2	2013/07/02	2017/09/06	0.00050 dB
H11N3	2013/07/02	2017/09/06	0.00128 dB
H11S1	2013/07/02	2017/09/06	0.01160 dB
H11S2	2013/07/02	2017/09/06	0.00054 dB
H11S3	2013/07/02	2017/09/06	0.00088 dB

Onset of electrical noise JUL 2013 (H10S1–H10S3)

- Mostly small differences, no clear indication of drift w/ time.
- HA04 only UWS calibration available 2016/12/30.
- New HA04 UWS calibration to be conducted soon.

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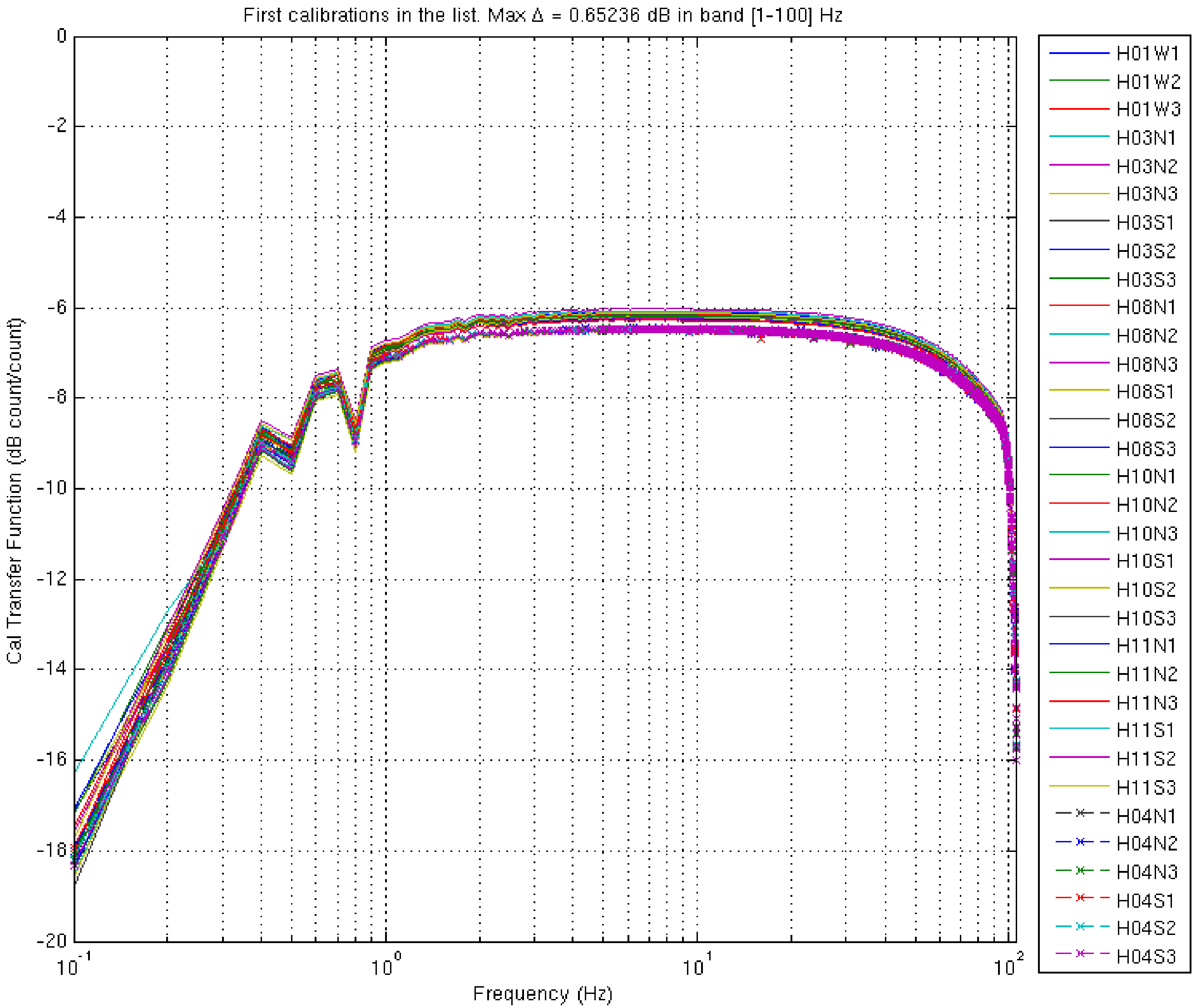
Comparison of first UWS calibration responses



- Earliest calibration responses found with the calibration bit flag in the IDC database (2013).
- Max. spread between all hydrophones and stations is 0.653 dB in the frequency band 1 – 100 Hz.
- Max spread is H03 and H04 (new generation UWS) vs. the other stations.

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Conclusions

- HA hydrophone station end-to-end responses match closely among different stations spread around the globe.

- UWS digitizer electronics calibrations show small variations over time, which do not affect the performance w.r.t. Treaty monitoring;

  no clear trend with time → more likely measurement fluctuations rather than actual sensor drift? Can this hypothesis be tested?

- What is known about possible drift over time of ceramics + pre-amp? Lab tests?

Ongoing Work/Outlook

- Further analysis of available calibration data (e.g. variations vs. freq.&time, CW waveforms and the "sound of silence" at the end of the calibration sequence), statistics to verify if there is a trend over time.
- Detailed analysis of calibration responses including review of electronics designs and early manufacturing and installation calibration responses where available.
- Models of IMS HA hydrophone station calibration responses also below 1 Hz, to provide more accurate estimation of system response at very low frequencies. Of interest for scientific studies in hydroacoustics & geophysics.
- Yearly calibration schedule for HA01, HA03 and HA04.

- Full at-sea calibrations could be useful vis-à-vis pre-installation calibrations → investigation of at-sea calibration **concepts**.