WHALE ACOUSTICS LABORATORY

Marine Physical Laboratory of the Scripps Institution of Oceanography University of California, San Diego

SoundTrap ST500 Calibration at the Transducer Evaluation Center (TRANSDEC)

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Executive Summary

Acoustic calibration of the SoundTrap ST500 was conducted at the U.S. Navy's NWIC Pacific Transducer Evaluation Center (TRANSDEC) in San Diego. Recordings were collected from four systems on 4 and 18 October 2019 to measure the sensitivity and transfer function frequency responses in addition to short- and long-axis rotation beam patterns. The full-system sensitivity response was in good agreement with the manufacturer's factory calibration (-175 dB re V/µPa) and relatively flat between one octave above the high pass filter corner frequency and one octave below the low pass filter corner frequency. All four system sensitivities were similar to within +/- 1 dB across the frequency band tested, but all showed higher sensitivity variability at frequencies above 700 Hz, perhaps due to acoustic interference from the data logger pressure housing and its proximity to the hydrophone sensor. Very little receive level variability was observed for the long-axis rotation measurements, but the short-axis measurements showed higher losses and variability with higher frequencies, and the greatest losses at 180° opposite the hydrophone due to acoustic shadowing from the data logger housing between the hydrophone and the source projector. While the sensitivity response describes the signal level upper limit that can be recorded, the electronic noise floor should also be evaluated to better identify the signal level lower limit that can be recorded.

Introduction

Calibrated measurements of sound pressure levels in the ocean are useful for studying underwater sound source levels, acoustic propagation, and ambient soundscapes and noise. Compact autonomous Passive Acoustic Monitoring (PAM) devices currently are capable of providing wideband acoustic recordings over long periods. One such compact PAM recorder is the SoundTrap ST500 by OceanInstruments^{NZ} (http://oceaninstruments.co.nz). In this report, we describe the acoustic calibration of the SoundTrap model ST500 conducted over a wide range of frequencies and orientations.

Methods

Autonomous underwater acoustic recorders typically include hydrophone sensors, amplifiers, filters, digitizers, data storage and a computer to control these components. Individual components and subsystems can be bench-tested to verify design specifications, but a full system, in-water test with calibrated sound sources provides a more complete description of the acoustic recorder's response. For this reason, we conducted an in-water test of the SoundTrap ST500 at the U.S. Navy's Naval Information Warfare Center (NIWC) Pacific Transducer Evaluation Center (TRANSDEC) located in San Diego.

SoundTrap ST500

The SoundTrap ST500 (Appendix A1) is a compact, low-power, self-contained autonomous acoustic underwater recorder used for long-term marine mammal, fish, and noise monitoring. The ST500 specification sheet states that it can record up to 180 days onto 1 TB of data storage (with a compression factor ~3x) sampling 16-bits at 96 kHz and powered by 9x D-cell alkaline batteries due to its very low power consumption (~35 mW). The User Guide is available at: (http://oceaninstruments.co.nz/wp-content/uploads/2018/03/ST500-User-Guide.pdf).

Recordings of calibrated sound sources were made in October 2019 using three SoundTrap model ST500 long-term recorders and four different hydrophone sensors (Table 1).

Table 1. SoundTrap ST500 recorder and hydrophone serial numbers.

Configuration Name	Recorder Serial Number	Hydrophone Serial Number
YellowA	671883305	1054
YellowB	671883305	1066
Blue	671399976	1121
Green	671649831	1077

Factory calibration was provided via an online application for each hydrophone using one tone at 250 Hz and for each recorder using one tone at 1 kHz: (http://oceaninstruments.azurewebsites.net/App/#/%23).

Systems' corner frequencies for a high-pass filter (HPF) and a low-pass filter (LPF) were unavailable online or via email contact with the manufacturer other than having a flat response (+/- 3 dB) from 20 Hz to 60 kHz (personal comms. J. Atkins, 8 October 2019). The four hydrophone calibrations at 250 Hz ranged between 177.0 and 177.2 dB re 1 µPa/V, and all three recorders' system gain calibrations at 1 kHz were -1.8 dB, such that end-to-end system factory calibrations were ~175 dB re 1 µPa/V. To convert wav file recordings with units of volts, the wav file values are scaled by the end-to-end calibration value; for example, 1.0 V (i.e., 0 dB re 1 V) is equal to a sound pressure level of 175 dB re 1 µPa (see ST500 User Guide).

The ST500 can be powered by 9, 6 or 3 D-cell alkaline batteries, and since our calibration tests were only a few hours long, we used just 3 batteries per recorder. Each recorder/hydrophone pair was started manually prior to calibration runs, and recordings were terminated shortly after recovery of the system from the test tank. Data were recorded in a compressed format to the ST500s data storage SD cards, and upon offloading via the system's USB port and manufacturer's software, the recordings were converted into uncompressed wav format files and stored on a data processing computer. While ST500 wav files can be read as floating point values representing voltage, we read the wav files in their native analog-to-digital converter (ADC) 16-bit per sample integer data format such that full-scale (+/- 1.0 V) rail-to-rail values range from -32,768 to 32,767 ADC counts. We chose this approach to allow data processing to be conducted with existing PAM analysis software. All data processing and analysis was conducted using the high-level language technical computing software package MATLAB (The MathWorks Inc., Natick, MA).

Three primary tests were conducted on the ST500s: system sensitivity frequency response, long-axis rotation beam pattern and short-axis rotation beam pattern measurements. All recordings were sampled at 96 kHz, except one which was at 48 kHz to investigate how the LPF frequency responses compare. All four ST500 configurations (Table 1) were calibrated for sensitivity measurements, but only YellowA was used for the two beam pattern measurements.

Two mounting configurations of the ST500s were used during calibrations: vertically mounted for both system sensitivity frequency response and long-axis rotation beam pattern measurements with the hydrophone sensor pointing downward (Figure 1) and horizontally mounted for short-axis rotation beam pattern measurements (Figure 2). Both configurations were at the end of a pole that was lowered into the test pool to horizontally and vertically align the ST500 hydrophone with the calibrated source projector away from reflections caused by the air-water interface.

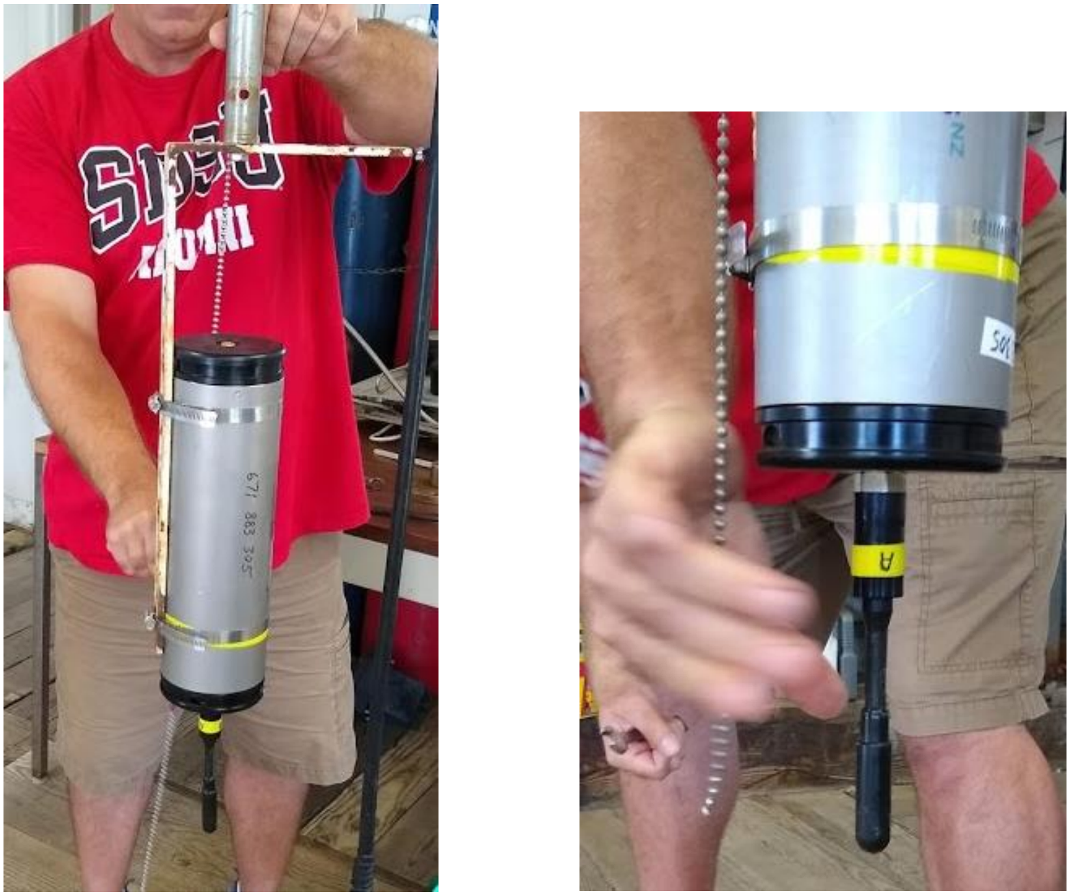


Figure 1. Long-axis vertical configuration. Chain was used to set hydrophone depth.

Figure 2. Horizontally mounted for rotation around the short-axis.

TRANSDEC

The U.S. Navy's NIWC Pacific Transducer Evaluation Center (TRANSDEC) is a controlled environment, low ambient noise transducer calibration and underwater acoustic test facility. The anechoic pool (300 ft x 200 ft x 38 ft deep) contains 6 million gallons of chemically treated fresh water which is continuously circulated to maintain isothermal conditions (Figure 3).

At the center of the pool is a building which houses electronics, computers, calibrated hydrophones and acoustic projectors. In the center of the building, sections of the floor are removed to gain access to the pool for deploying hydrophones and sound sources for calibrated tests.

Figure 3. Aerial view of TRANSDEC anechoic pool with calibration building at the center of the pool on a cross-beam bridge structure. The 'eye' shaped pool was designed for conducting underwater electroacoustic transducer calibrations in the deep center with the contoured shallow perimeter acting as an 'acoustic trap' to eliminate reflections (photo: Google maps).

Three different acoustic projectors were used to transmit pulses at known frequencies, pressure levels and distances to the recorder hydrophones. Different projectors are needed to span the wide band of frequencies that ST500 is capable of recording. All projectors and hydrophones were positioned 6 m below the air/water surface to minimize reflections, and separated horizontally by 1.5 m to avoid near-field effects. The low frequency projector, a custom Lubell VC2C (S/N 22) with lower frequency range than a standard projector, was used to generate continuous wave (CW) pulses either 3 or 4 s duration from 10 Hz to 600 Hz in 10 Hz steps (Appendix A2). An ITC-1007 (S/N 117) projector was used for the mid-frequency range with 10 ms pulses from 500 Hz to 20 kHz in 200 Hz steps (Appendix A3). The projector used for the high frequency calibrations was an ITC-1042 (S/N 919) with 10 ms pulses from 10 kHz to 100 kHz in 1 kHz steps (Appendix A4).

Both the ITC-1007 and ITC-1042 projectors were also used for the long- and short-axis beam pattern measurements (Figures 1 & 2). Pulses were 10 ms duration and at four discrete frequencies using the ITC-1007: 2, 4, 10, and 20 kHz and at three discrete frequencies using the ITC-1042: 10, 20, and 40 kHz. The estimated receive sound pressure levels were held constant for the four ITC-1007 frequencies at 142, 141, 152, and 144 dB re 1 µPa @ 1 m, as were the three ITC-1042 frequencies at 147, 149, and 155 dB re 1 µPa @ 1 m, respectively. The pole on which the ST500 was attached rotated clockwise when viewed from above at the rate of ~1º s^{-1}. Tests were started at 0º relative to hydrophone connector guide pin for the long-axis rotation measurements and relative to dome end of the hydrophone for the short-axis rotation measurements.

The projectors' transmit voltage responses (TVRs) relative to 1 m were measured prior to calibration runs using the calibrated reference hydrophone H52 (S/N 166) (Figure 4). The TVRs (dB re 1 µPa/V @ 1 m), which vary with frequency, were used to estimate transmitted source levels (SL) based on the recorded drive voltage root-mean-squared (rms) levels applied to the projectors at specified frequencies. The source level was then converted to estimated receive sound pressure level (RL) at the hydrophone by applying a transmission loss (TL) based on distance between projector and hydrophone assuming spherical spreading (i.e., $TL = 20*\log_{10}[\text{range(m)}]$). At 1.5 m range, the TL is 3.52 dB re 1 m.

All calibration run settings, resulting drive voltages, TVRs, and component certifications and calibrations were provided by TRANSDEC personnel (S. Pucillo) on a CD-ROM.

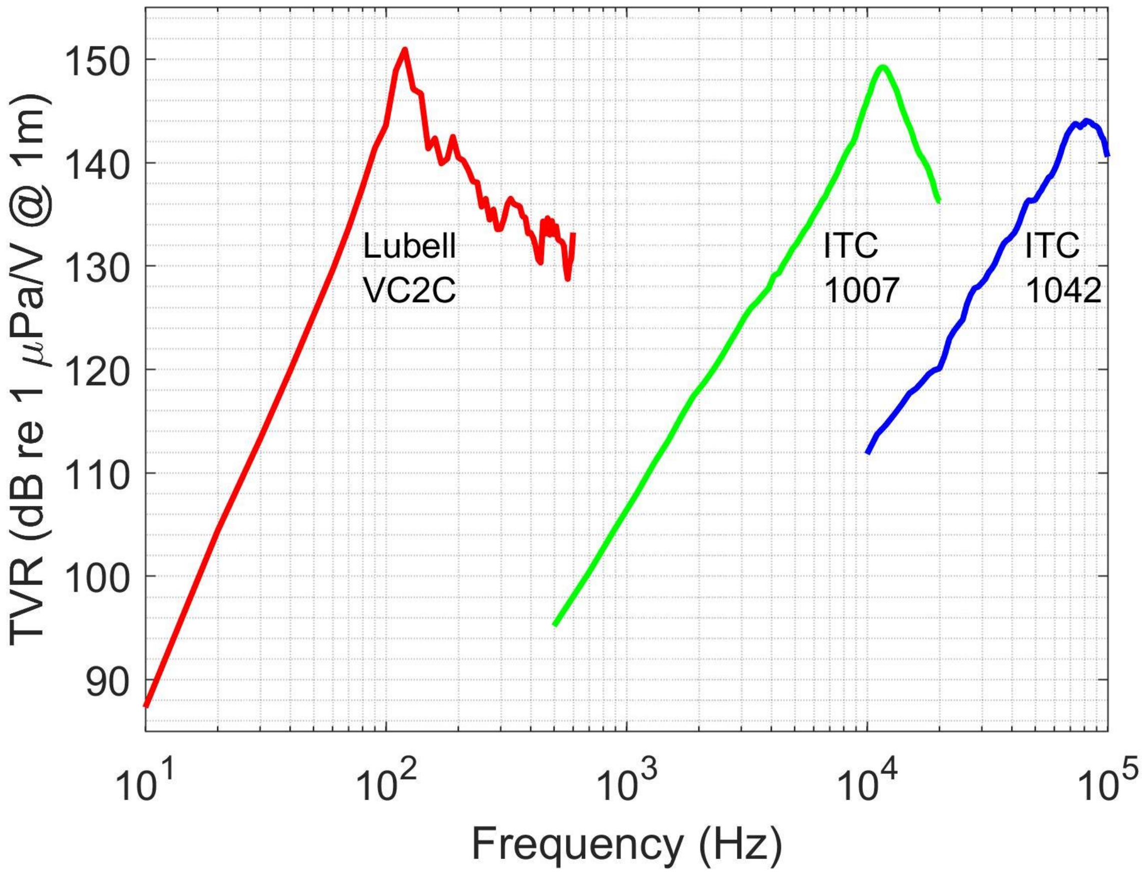


Figure 4. Transmit voltage responses (TVRs) for Lubell VC2C (red), ITC-1007 (green), and ITC-1042 (blue) acoustic projectors measured using calibrated reference hydrophone H52, with peaks at ~110 Hz, ~11 kHz and ~80 kHz, respectively. The drive voltage in dB is added to the TVR to estimate source (projector) sound pressure levels at 1m.

Calibration Processing

On 4 and 18 October 2019, SoundTrap ST500 calibration tests were conducted at TRANSDEC using 29 transmission runs from three projectors ranging from 10 Hz to 100 kHz. In all cases, the received sound pressure level from the 10 Hz tones was too low to be measured above the noise floor, so the system sensitivity response measurements effectively start at 20 Hz.

Each transmission run consisted of a series of pulses with known drive voltages at known source frequencies. These rms source drive voltages (E) were converted into rms receive sound pressure levels (SPL dB re 1 µPa) using the projector TVR values (Figure 4) and the distance TL (i.e., SPL = $20*\log_{10}(E) + TVR – 3.52$).

An automated method was developed to measure the ST500 recorded calibration run waveform amplitudes of the frequency-stepped pulses. The algorithm consisted of a simple time series threshold energy detector in which the amplitude threshold and execution time window were set after reviewing the recorded time series pulses to confirm noise level amplitudes and pulse train start and end times. After the first detection, a temporal offset, based on the pulse rate of the calibration run, provided a lock out time between successive detections. After detection of a pulse, rms receive levels (RL dB re ADC counts) were computed between 0.05 and 0.95 times the pulse duration to avoid transients at the start and end of the pulses. The difference between RL and SPL provided a measured full-system, frequency dependent transfer function (TF dB re count/µPa) which can be used to estimate received levels in future recordings. The ADC volts to counts conversion (-90.3 dB re V/count = $20*\log_{10}(2.0/2^{16})$) was added to the TF to provide the full-system, sensitivity frequency response (dB re V/µPa).

The beam pattern measurements also included the rotation angle for each pulse in a calibration run and dB differences from the maximum RL for the run were plotted on a polar axis.

Results

Sensitivity and Transfer Function Frequency Response

The full-system sensitivity and transfer function frequency responses for the four ST500s calibrated (Table 1) were consistent across the bandwidth with a mean standard deviation of ~1 dB (Appendices 5 & 6), although YellowA, confirmed with a second low frequency calibration run, was less sensitive than the other three below 50 Hz suggesting a slightly different HPF. The four-system average sensitivity and transfer function frequency responses were flat to within +/- 1 dB of the factory calibration value -175 dB re 1 V/µPa over the band from one octave higher than the HPF corner frequency to one octave lower than the LPF corner frequency (Figures 5 & 6). The -3 dB corner frequencies for the HPF and two LPF were 24 Hz, 19 kHz and 31.7 kHz, respectively, with both LPFs causing rapid signal attenuation above their corner frequencies. The greatest amount of variability in the sensitivity and transfer function responses below the HPF corner frequency was at frequencies greater than ~700 Hz.

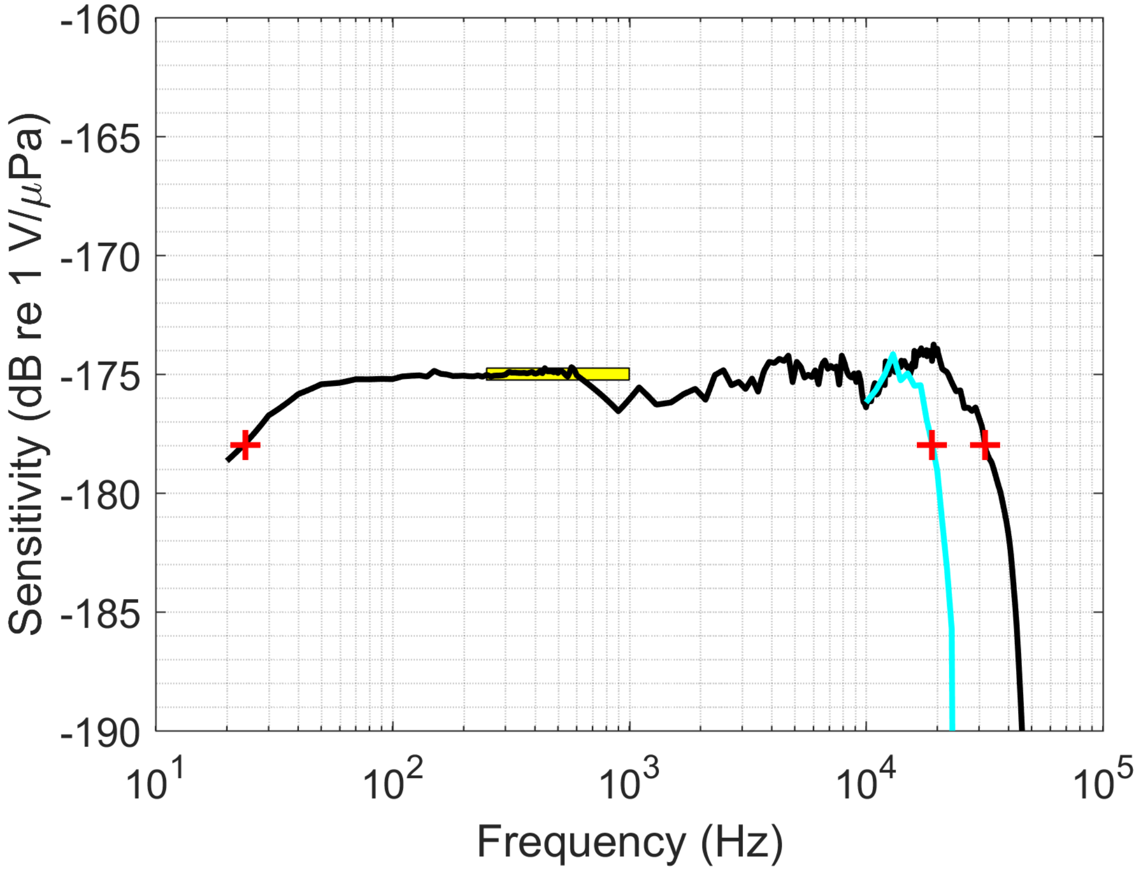


Figure 5. SoundTrap ST500 full-system sensitivity frequency response. The yellow bar is factory calibration sensitivity. The black line is the average sensitivity of four systems calibrated and sampled at 96 kHz; whereas, the teal line is the high frequency stage calibration of Blue system sampled at 48 kHz. Red plus signs are -3 dB corner frequencies for the average HPF (24 Hz), 48 kHz sampled LPF (19 kHz), and 96 kHz sampled average LPF (31.7 kHz).

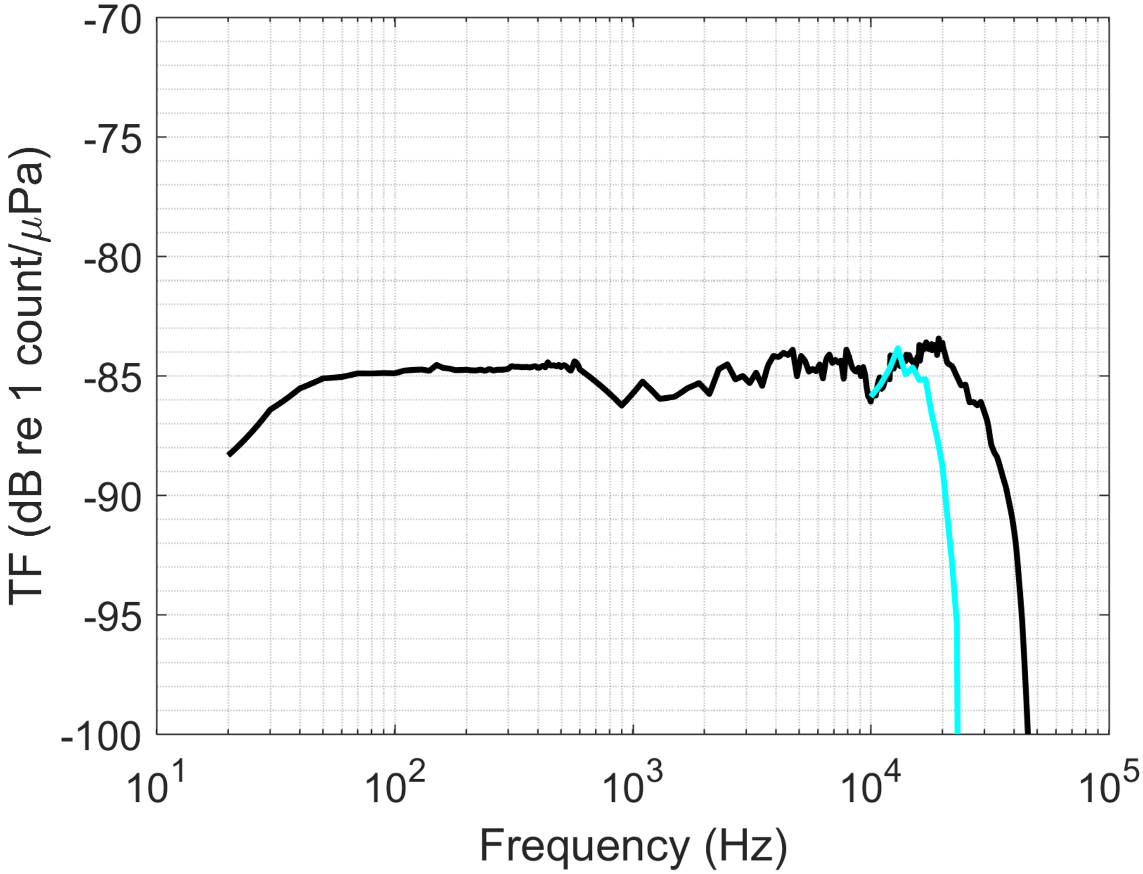


Figure 6. SoundTrap ST500 full-system transfer function frequency response. The black line is the average transfer function of four systems calibrated and sampled at 96 kHz; whereas, the teal line is the high frequency stage calibration of Blue system sampled at 48 kHz.

Beam Patterns

Seven sets of single-frequency beam pattern measurements were made using two different projectors for both short- and long-axis rotation configurations (Figures 7 & 8). The long-axis measurements showed deviations from the maximum RL (0 dB) down to about 1 dB loss for all angles and frequencies; whereas, the short-axis showed RL variability and loss increased with higher frequencies, and was greatest ~180º, when the projector was opposite the hydrophone, facing the blank end of the pressure housing.

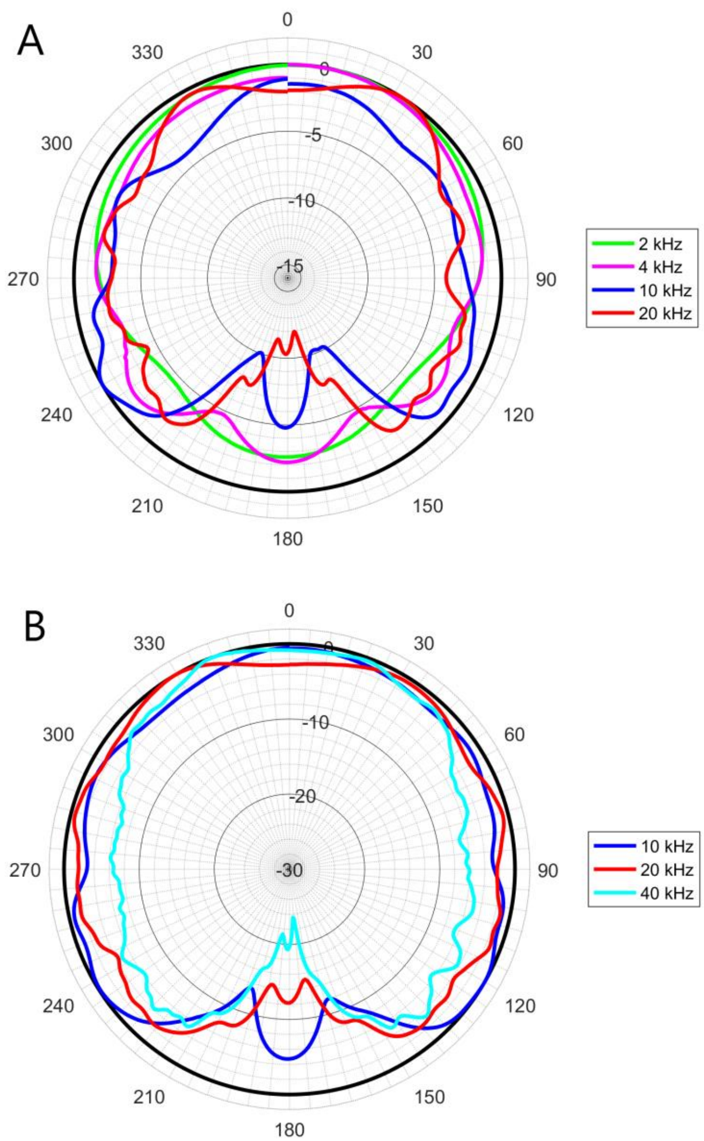
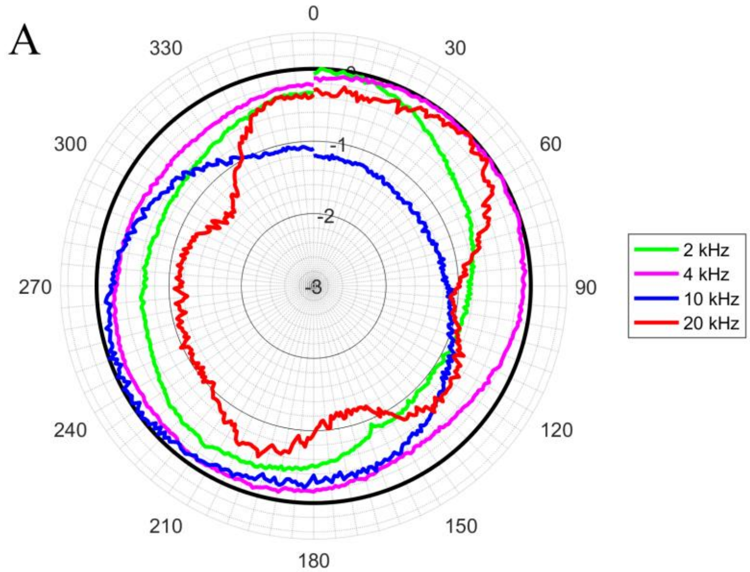


Figure 7. ST500 short-axis rotation beam pattern measurements using projectors (A) ITC-1007 at frequencies: 2, 4, 10, and 20 kHz with constant estimated RLs: 142, 141, 152, and 144 dB re 1 µPa, respectively; and (B) ITC-1042 at frequencies: 10, 20, and 40 kHz with constant estimated RLs: 147, 149, and 155 dB re 1 µPa, respectively. The angle-dependent RL variability and loss increase with frequency, with greatest loss ~180°.



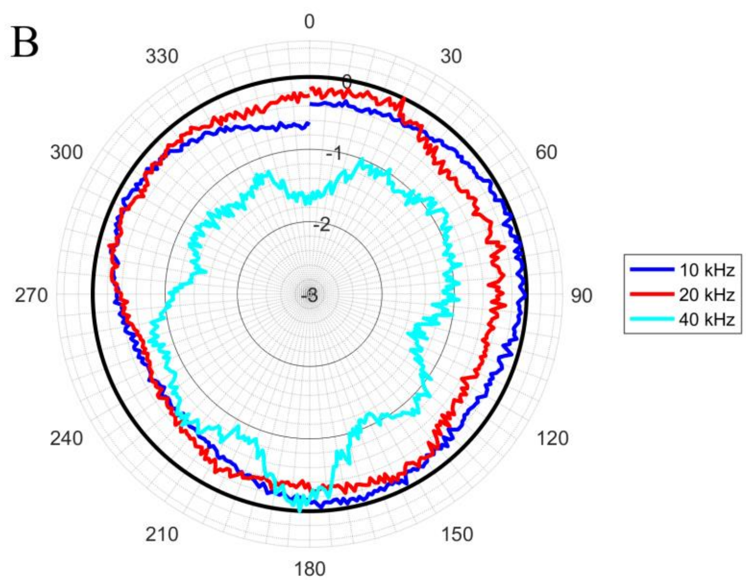


Figure 8. ST500 long-axis beam pattern measurements using projectors (A) ITC-1007 at frequencies: 2, 4, 10, and 20 kHz with constant estimated RLs: 142, 141, 152, and 144 dB re 1 µPa, respectively; and (B) ITC-1042 at frequencies: 10, 20, and 40 kHz with constant estimated RLs: 147, 149, and 155 dB re 1 µPa, respectively.

Discussion and Conclusions

Sensitivity and Transfer Function

The SoundTrap ST500 four data logger/hydrophone pairs were found to have similar sensitivity frequency responses, varying by only ~1 dB across the frequency band tested, although YellowA had ~2 dB lower sensitivity at 20 Hz than the other three systems. Calibrated tones at frequencies lower than about 50 or 40 Hz are traditionally difficult to reliably generate due to their long wavelengths, but the Lubell V2C2 appears to have worked well down to ~20 Hz, based on the frequency response shape measured near the HPF corner which appeared typical for such a filter.

While relatively flat responses were measured for the ST500s sensitivity, the greatest amount of variability was found above ~700 Hz, in the band of the mid-frequency projector ITC-1007; however, we do not attribute the variability to the projector because calibration measurements using other hydrophones and the ITC-1007 did not show similar variability. Alternatively, the sensitivity variability above 700 Hz may be due to acoustic interference from the electronics pressure housing. Supporting this theory is the short-axis beam pattern results which show different RL deviations for different frequencies given a specific angle, such as 90°, which was the geometry used for all of the sensitivity measurements. Based on the short-axis beam pattern measurements, perhaps slightly less sensitivity variability would have occurred if 0° would have been chosen for the sensitivity measurements, but concerns about reflections directly off the endcap for that geometry seemed warranted prior to testing.

Beam Patterns

As one would expect for a cylindrical or spherical hydrophone sensor, there was very little beam pattern in the long-axis rotation measurements; however, this was not the case for the short-axis measurements, presumably due to the size and close proximity of the data logger pressure housing to the hydrophone. The magnitude and variability of the RL losses in the beam pattern were greater at high frequencies due to the shorter wavelengths interfering more with the data logger housing, including the greatest losses ~180° because of acoustic shadowing from the housing. One approach to reducing acoustic interference from the data logger house would be to extend the cable between the hydrophone and the underwater connector into the housing.

While PAM device sensitivity frequency response and beam pattern measurements are important for characterizing recorded sound sources and identifying system signal maximum clip levels, system electronic noise floor frequency response should also be evaluated to provide a more complete description of the system and to determine the smallest signals that can be recorded, especially for studies involving ambient soundscape with low background levels. An estimate of the full-system electronic noise frequency response can be made from recordings with the hydrophone's piezo-electric transducer replaced with an equivalent capacitor to avoid external noise and pressure signal pickup. The TF is applied to the equivalent capacitor recording spectrum levels to display the electronic noise floor in ocean sound pressure spectrum level units dB re 1 μPa^2/Hz.

Appendix

A1a. SoundTrap ST500 brochure with performance specifications (page 1 of 2).

SoundTrap ST500

Underwater Sound Recorder

STD & HF models

OceanInstruments NZ

Applications

- Marine mammal monitoring
- Fish research
- Noise monitoring
- Toothed whale click detection

Features:

- Up to 180 days recording on 9 x regular D cell batteries
- Up to 1TB of data storage (= 3 TB of uncompressed wav data)
- 60 or 150 kHz bandwidth (STD & HF models)
- Very low self-noise
- Extremely low power (~35 mW)
- Toothed whale click detector (HF only)

The SoundTrap ST500 series are compact self-contained sound recorders for underwater acoustic research. SoundTrap recorders are well known for their unique ability to record high quality audio while consuming very little power.

The STD model is intended for general purpose use with 60 kHz of bandwidth while the HF model enables high frequency recording and cetacean click detection with 150 kHz of bandwidth. Both models feature very low self-noise, ensuring beautiful recordings in even the quietest places.

The ST500 series are intended for long term deployments. They are our largest models, thereby allowing them to carry up to 9 regular D cell batteries capable of delivering up to 180 days of continuous recording.

Advanced loss-less audio compression coupled with up to 1TB of memory provides storage for up to 180 days of continuous recording at a 96 kHz sample rate.

Output files use the industry standard WAV format. The included software offers flexible deployment options for sample rate, delayed start and duty cycle.

The HF model includes a toothed whale click detector for memory efficient PAM.

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WWW.OCEANI.NZ

A1b. SoundTrap ST500 brochure with performance specifications (page 2 of 2).

Detailed Specifications

Bandwidth	STD	20 Hz - 60 kHz ± 3dB
	HF	20 Hz - 150 kHz ± 3dB
Self-noise	Better than sea-state 0 (100 Hz - 2 kHz)	
	STD	Less than 36 dB re 1 µPa above 2 kHz
	HF	Less than 37 dB re 1 µPa above 2 kHz
Gain	Max level before clipping: 173 dB re 1 µPa.	
Sample rates	STD	288, 144, 96, 48, 36 & 24 kHz
	HF	576, 288, 192, 96, 72 & 48 kHz
ADC	16-bit SAR	
Calibration	Factory calibration certificate (single point 250Hz)	
Memory	Internal 256 GB (Equivalent to ~1TB due to advanced loss-less compression)	
	3 Slots for up to 3 x 256GB removable SDXC cards for up to 1TB total	
Batteries	9 x D alkaline cell batteries. Provides up to 180 days continuous operation. For recording endurance refer to the calculator on our web site.	
Click Detection	(HF model only) Allows detection and journaling of toothed whale bio-sonar clicks. Detector runs in parallel with normal recording process. Conserves memory by simultaneously using a low sample rate for WAV recording and high sample rate for click detection. See user manual for more information.	
Housing	Titanium. Maximum depth is 200m, or 500m with optional safety valve.	
	Dimensions:	350mm Long x 100mm Diameter (excluding hydrophone)
	Weight:	4.2 kg in air with 9 x D cells loaded

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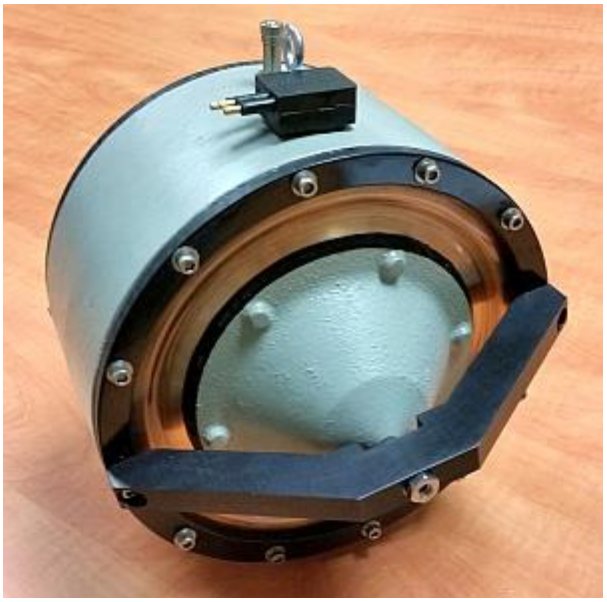
A2. Lubell VC2C Projector Specifications



- **Description:** Axial symmetric double piston radiator with spring copper diaphragms and external stops
- **Frequency Range:** 50 Hz to 1.5 kHz
- **Resonant Frequency:** 115 Hz +/- 5 Hz
- **Impedance:** Varies with frequency (4 ohms minimum @ 50 Hz; 17 ohms @ 1500 Hz)
- **Maximum Output Level:** 174dB/uPa/m
- **Maximum Voltage/Current:** 20 Vrms/2.5A (100% duty-cycle)
- **Q Parameters:** Qtco~2.5 Qmc~5
- **Directivity:** Omnidirectional to 1.5 kHz
- **Cable:** Teledyne Marine LPIL-3-FS on 50 feet of 16/3 SO
- **Operating Depth:** 10 feet (3.05 meters) minimum, 50 feet (15.24 meters) maximum
- **Maximum Air Pressure:** 23 psi (WARNING: use provided hand air pump only!)
- **Piston Stop Gap:** 0.016 inches (Schrader valve pin depressed to equalize internal/external pressure)
- **Dimensions:** 8"D x 9.75"L
- **Weight:** 21 lbs
- **PDF Documents:** Operation manual. Plots: SPL, TVR, broadband Z, and narrow band Z (resonant frequency range)
- **Accessory:** Bogen Classic 100 amplifier (click here for manual)

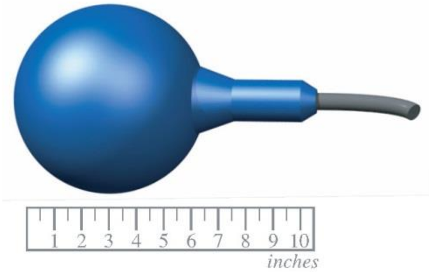
A3. International Transducer Corporation ITC-1007 projector specifications.

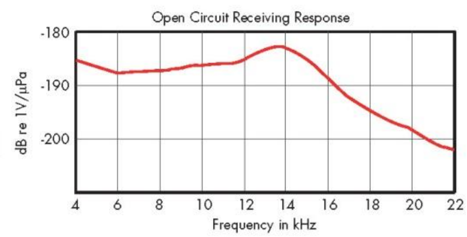
Model ITC-1007

Deep Water Omnidirectional Transducer

Model ITC-1007

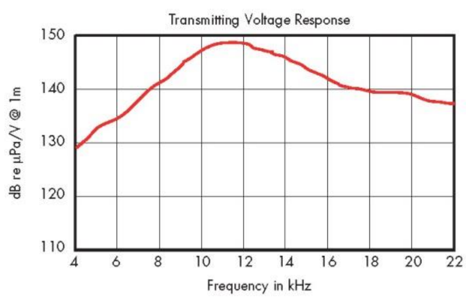
The Model ITC-1007 spherical transducer offers a broadband, omnidirectional transmitting and receiving response with efficiencies greater than 50% over the entire band. This transducer is fabricated of high precision Channelite-5400 and zirconate titanate ceramic hemispheres. It is particularly well suited for high power noise sources and applications where a truly omnidirectional response is required.

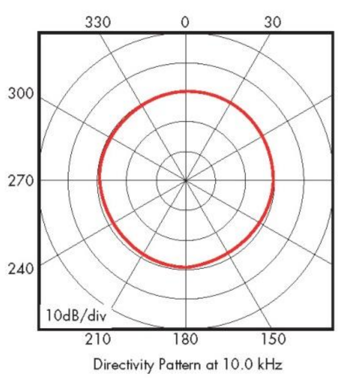




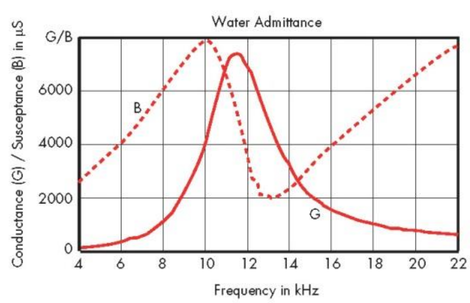
Specifications (Nominal)

Type	Projector/Hydrophone
Resonance Frequency f_r	11.5 kHz
Depth	1250 meters
Envelope Dimensions (in.)	6.5D
TVR at f_r	149 dB//µPa/V@1m
Midband OCV	-188 dB//1V/µPa
Suggested Band	.01 – 20 kHz
Beam Type	Spherical
Input Power	10,000 watts





Directivity Pattern at 10.0 kHz



869 Ward Drive, Santa Barbara, CA 93111
805.683.2575 • 805.967.8199 FAX
International Transducer Corporation
www.itc-transducers.com

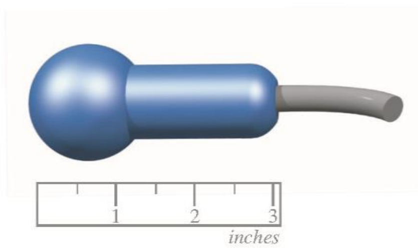
A4. International Transducer Corporation ITC-1042 projector specifications.

Model ITC-1042

Spherical Omnidirectional Transducer

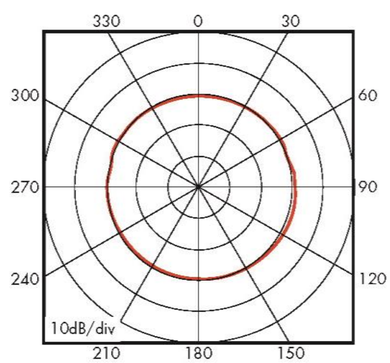
Model ITC-1042

The Model ITC-1042 spherical transducer offers broadband omnidirectional transmitting and receiving response with efficiencies of over 50%. This transducer is fabricated of Channelite-5400 lead zirconate titanate ceramic and is particularly well suited for noise sources as a broadband hydrophone and applications where an omnidirectional response is required. This unit can be supplied with Channelite-5800 for high power applications.

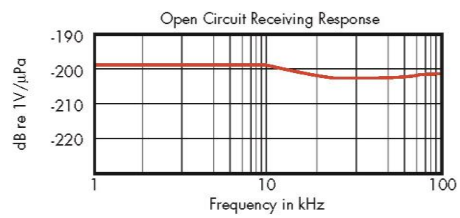


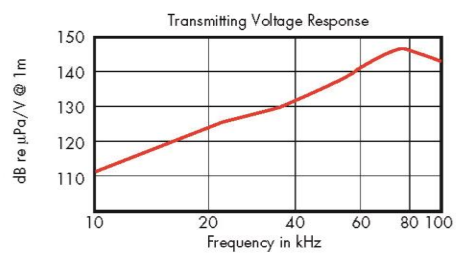
Specifications (Nominal)

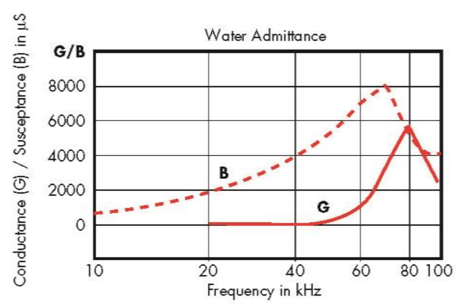
Type	Projector/Hydrophone
Resonance Frequency f_r	79 kHz
Depth	1250 meters
Envelope Dimensions (in.)	1.4D
TVR at f_r	148 dB//μPa/V@1m
Midband OCV	-200 dB//1V/μPa
Suggested Band	.01 - 100 kHz
Beam Type	Spherical
Input Power	100 watts



Directivity Pattern at 20.0 kHz







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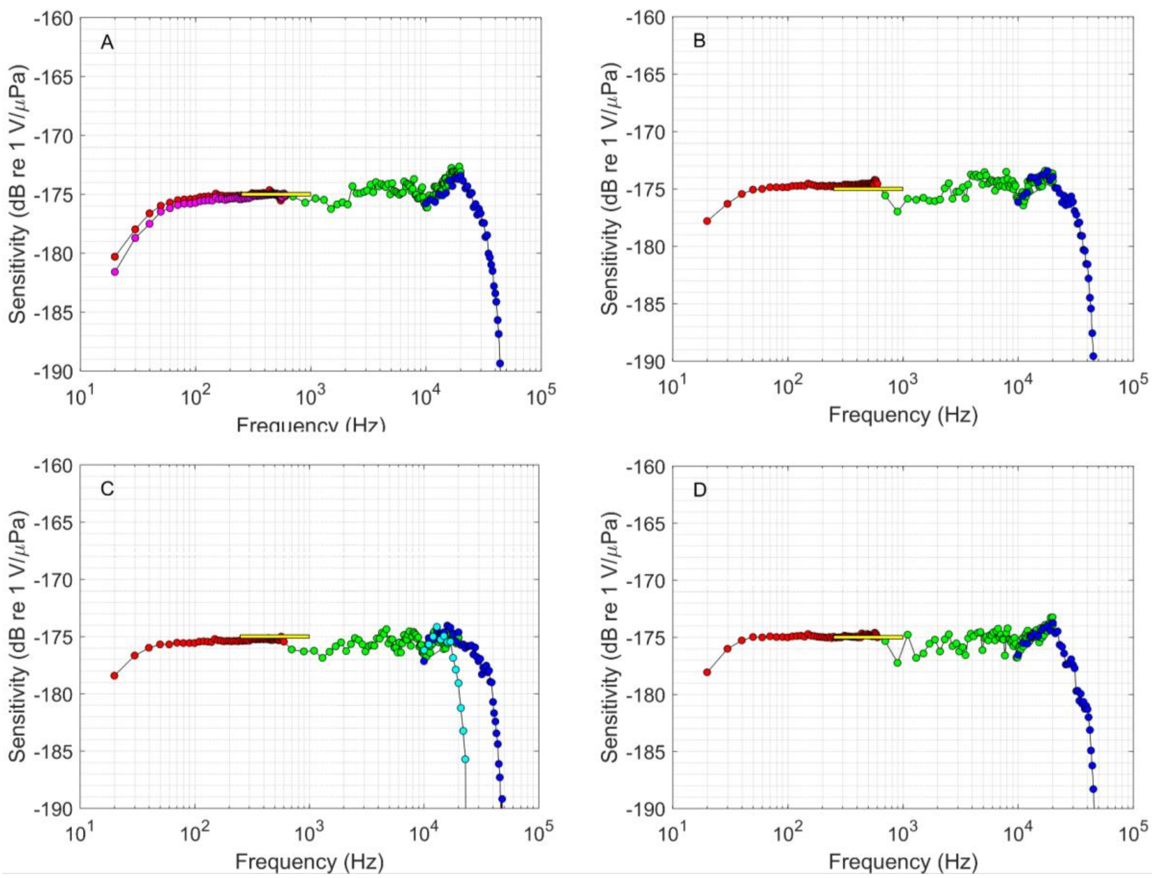
A5. SoundTrap ST500 full-system sensitivity frequency response for four hydrophone/data logger pairs (Table 1). The yellow bar is the factory calibration sensitivity, the red and magenta (a second low frequency run for YellowA) dots are from the Lubell VC2C, the green dots are from the ITC-1007, and the blue (96 kHz sample rate) and cyan (48 kHz sample rate) dots are from the ITC-1042. ST500 individual sensitivities: A = YellowA, B = YellowB, C = Blue, D = Green.



A6. SoundTrap ST500 full-system transfer function frequency response for four hydrophone/data logger pairs (Table 1). The yellow bar is the factory calibration sensitivity, the red and magenta (a second low frequency run for YellowA) dots are from the Lubell VC2C, the green dots are from the ITC-1007, and the blue (96 kHz sample rate) and cyan (48 kHz sample rate) dots are from the ITC-1042. ST500 individual sensitivities: A = YellowA, B = YellowB, C = Blue, D = Green.