Required Instrumentation

FY20Q1 Update report: WEPG 1.3.4.403 -- Aeroacoustic Assessment of Wind Plant Control

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1 Description of project

The primary goal of the Aeroacoustic Assessment project is to characterize the acoustic emissions of the GE 1.5 SLE MW wind turbine owned by the US Department of Energy (DOE 1.5) to determine the nature and degree of changes of acoustic emissions produced when operating a utility scale wind turbine according to modern wind plant control strategies. Testing will include multiple point-measurements located to sample the acoustic emissions including points required and suggested in the International Electrotechnical Commission (IEC) standard, Wind turbines part 11: Acoustic Noise Measurement Techniques, IEC 61400-11, Edition 3.1, 2018-06, hereafter referred to simply as the Standards. This test plan documents the measurement techniques, test equipment, and analysis procedures for the following quantities at integer wind speeds from 6 to 10 m/s as recommended by the Standards:

- apparent sound pressure level,
- one-third octave band levels,
- optionally, tonality, impulsivity and amplitude modulation (listed as optional as the standards regarding these aspects of wind turbine noise are still in development, details provided below).

Measurement data is intended to be of sufficient quality to determine the change in aeroacoustic emissions from a utility scale turbine under yawed operation and validate aeroacoustics models underlying the Standards and incorporated in a module to interface with NREL's Multiphysics modeling platform, OpenFAST.

2 Measurement locations

During the period of time favorable for wind and acoustic measurements, the wind direction is mostly from the WNW. Figures 1 and 2 show the arrangement of microphones and data acquisition systems (DAS) favorable for sampling the overall sound output of the DOE 1.5. Standard frequency range (SFR) microphones specified to comply with the wind turbine noise measurement standards (20 Hz - 11.2 kHz) will be deployed at the black points. SFR mics will be placed to evenly sample the overall sound pressure level directivity field. Spacing between proximal locations are shown with black lines and annotations. The average sound pressure level difference between neighboring points is expected to be at least 3 dB,

enough to ensure a detectable difference in sound pressure level and quantify the changes induced in the directivity from wind plant control.

Low-frequency (LFR) microphones have also been specified to quantify the noise emissions of the DOE 1.5 in the sub-audible frequency range. Low-frequency noise measurements require specialized equipment, including microphones specifically designed to sample pressure field fluctuations, preamplifiers, and powered signal conditioning units that ensure a flat frequency response below 1 Hz. Due to the requirement of additional power supply to the LFR microphone setups, they will be located near each DAS, indicated as red dots in Figure 1.

To ensure that the acoustic data collected during the project may be accurately analyzed in both the time domain and frequency domain, extra care must be taken with regards to data acquisition. Each microphone will communicate with a DAS over coaxial (BNC) connection. Significant signal degradation is expected for BNC cable runs of length 200 m. Signal degradation is mitigated in the current instrumentation plan by limiting BNC cable lengths to a maximum of 50 m (red dashed lines in Figure 1). Communication from each DAS location to a central data storage server will occur over fiber-optic cables, which can transmit over much longer distances (easily up to 1 km) without signal degradation.

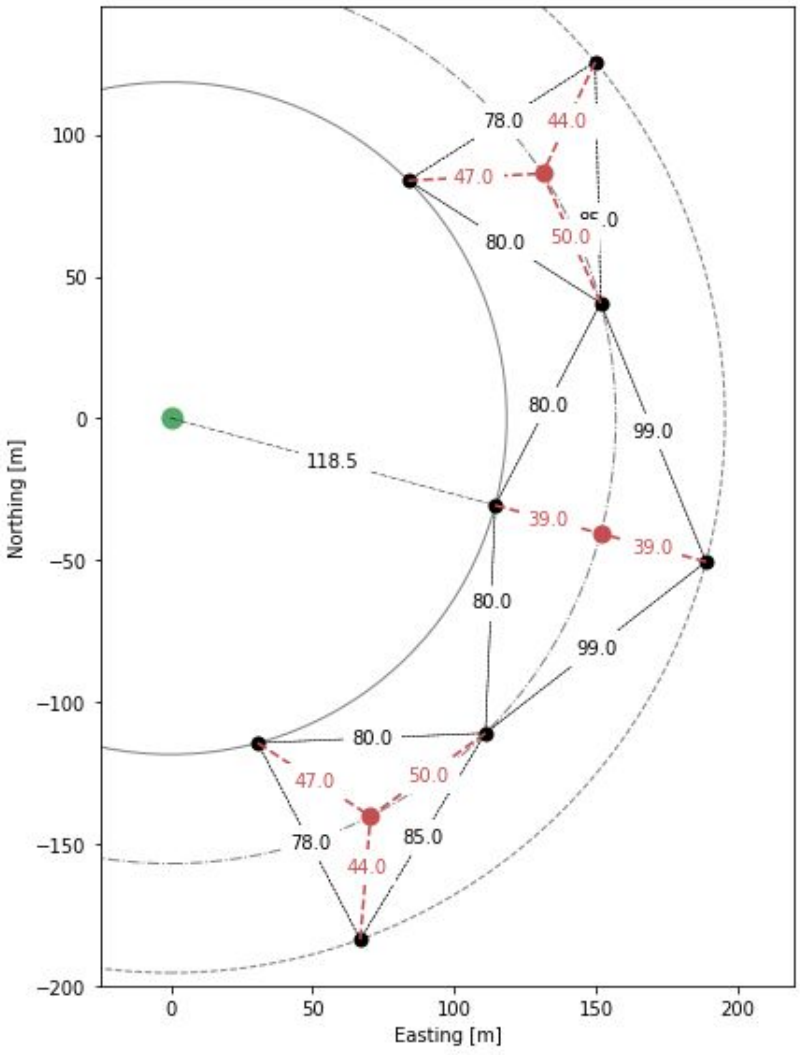

Figure 1: Schematic of measurement (black) and DAS (red) locations and spacing (m).

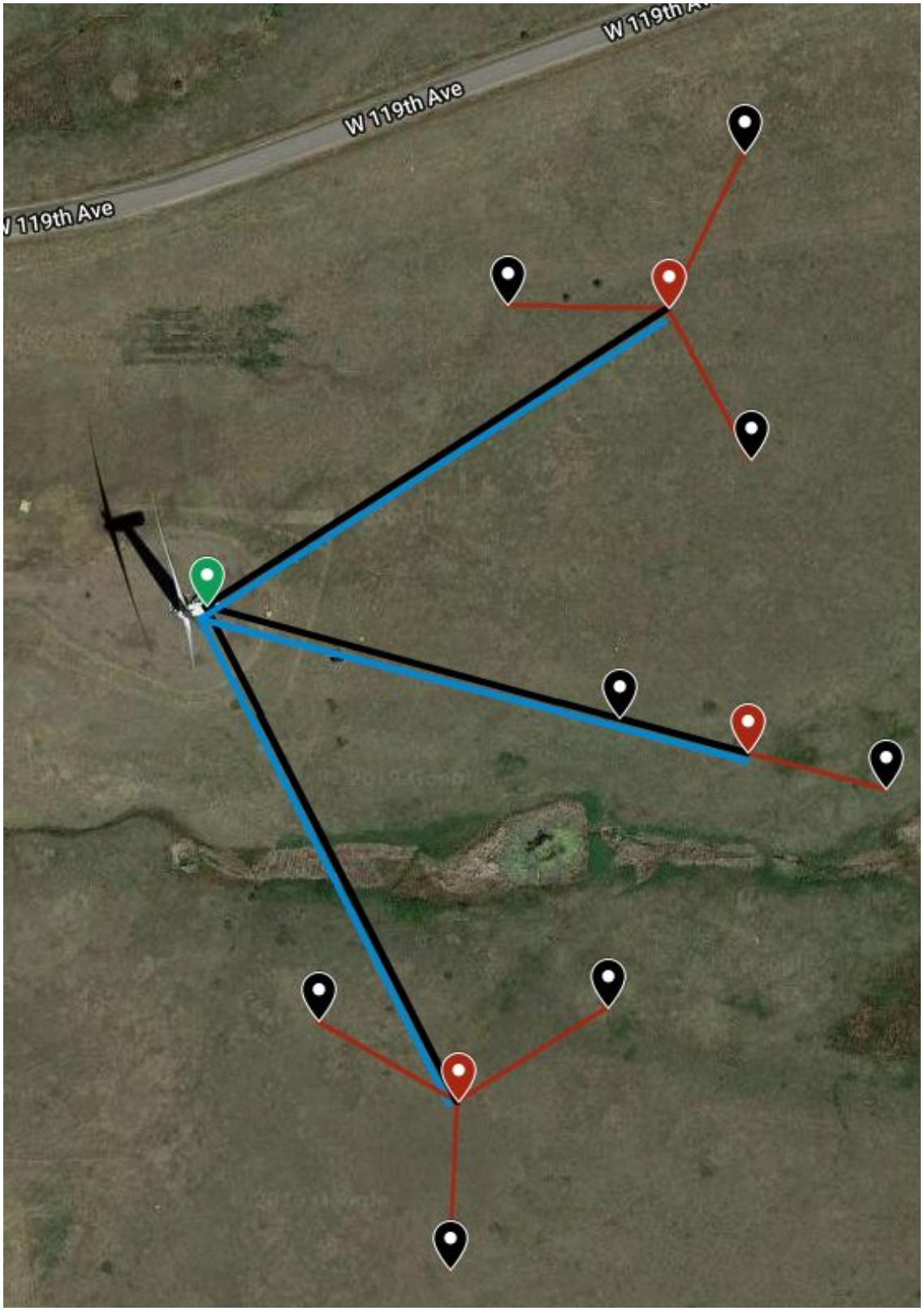

Figure 2: Map of measurement (black points) and DAS subsystem (red points) locations at NREL Flatirons. Power, fiber-optic, and BN cabling are shown in black, blue and red lines, respectively.

3 Summary of measurements

The test will continue until, at a minimum, all requirements listed in Table 1 are fulfilled for each target yaw misalignment. To fulfill the test requirements, each data period must correspond to a mean wind direction within +/-15° of the prevailing wind direction of 285°. Testing will continue until requirements are met according to the IEC Standard and NREL engineers agree that sufficient data will be deemed valid through all quality control procedures.

Table 1: Summary of observations specified in IEC 61400-11.

Measurement Type	Requirements
Overall measurements	At least 30 one-minute averages.
For A-weighted sound pressure level: (for turbine and background measurements)	At least 3 minutes of data with wind speeds ±0.5 m/s of the integer values of 6, 7, 8, 9, and 10 m/s
For octave or third octave band measurements: (for turbine and background measurements)	At least 3 minutes of data with wind speeds ±0.5 m/s of the integer values of 6, 7, 8, 9, and 10 m/s
Narrow band measurements: (for turbine and background measurements)	At least 2 minutes of data with wind speeds ±0.5 m/s of the integer values of 6, 7, 8, 9, and 10 m/s

Additional considerations for data collection, storage and quality control:

- The complete measurement chain shall be calibrated at least at one frequency before and after the measurements, or if the microphones are dis- and reconnected during the measurements.
- All acoustical signals shall be recorded and stored for later inspection.
- Periods with intruding intermittent background noise shall be omitted.
- Background noise (with the wind turbine stopped) will be measured for baseline noise comparison. Every effort shall be made to ensure that the background sound measurements are representative of the noise that occurred during the wind turbine noise emission measurements.
- The measurements shall cover as broad a range of wind speeds as practically possible. To obtain a sufficient range of wind speeds it may be necessary to take the measurements in several measurement series.
- At least 180 measurements shall be made overall for both total noise and background noise covering corresponding wind speed ranges.
- At least 10 measurements shall be made in each wind speed bin for both total noise and background noise.

- Consecutive measurements periods of 10-minutes or longer will be used as often as possible to satisfy the requirements for amplitude modulation quantification described below.

To quantify the incremental changes in wind turbine acoustic emissions induced by operating under the wake steering wind plant control strategy, measurements will be repeated for the prescribed yaw offsets listed in Table 2. The yaw offset controller will cycle between each yaw offset, holding each value for 30 minutes and repeating the schedule every 2.5 hours. The specific order of yaw offsets is intended to reduce the magnitude of the most extreme change in yaw orientation. The first 5 minutes after a new yaw offset is selected will be discarded to account for yaw positioning transients.

Table 2. Yaw Offset Schedule

Yaw Offset	0˚	25˚	18˚	10˚	-18˚
Duration	30 min	30 min	30 min	30 min	30 min

Additional Acoustic Phenomena of Interest

Impulsivity

Impulsivity is defined as the sudden onset of a sound. Noise with prominent impulses is considered to be more annoying than continuous types of noise (without impulses or tones) with the same equivalent sound pressure level, according to the NORDTEST Method Standard (NT ACOU 112). Noise impulse is defined as the combination of onset rate (dB/s) and level difference (Δ dB) for periods when gradient exceeds 10 dB/s.

Hardware requirements

- IEC Class 1 equipment
- Electric background noise 10 dB lower than acoustic background noise

Data processing requirements

- A-weighted SPL
- Time weighting “F” or “Fast” (125 ms time constant)
- 10-25 ms sample period

Amplitude Modulation

Amplitude modulation (AM) is defined as periodic fluctuations in the level of audible noise from a wind turbine (or wind turbines), where the frequency of the fluctuations is related to the blade passing frequency of the turbine rotor(s). AM quantified through peak-to-peak amplitude of fundamental modulation frequency and harmonics over a 10 s period. If energy in the fundamental frequency is more

than 4 times the masking level, AM is deemed significant. AM exists if > 50% of 10 s periods in a 10-minute block meet the above requirement.

Standard: Institute of Acoustics Noise Working Group (Wind Turbine Noise) Amplitude Modulation Working Group Final Report: A method for rating amplitude modulation in wind turbine noise (2016)

Hardware requirements

Measurement should be made according to IOA's Good Practice Guide to the Assessment and Rating of Wind Turbine Noise (IOA NWG, 2013). AM quantification methods are intended to be applied from residential distances, typically greater than 500 m from a utility-scale wind turbine. The current work will make measurements considerably closer to the DOE 1.5 than this guideline, due to limitations in data acquisition feasibility. However, the measurements taken here are expected to be of significant value in terms of validation of numerical models included in the OpenFAST Aeroacoustics Module.

Additional hardware requirements:

- Lower limit of instrument linearity range shall be no higher than 25 dB(A)
- No specific requirements for wind conditions tested under, but as broad as possible for the site and typical of complaint periods if any

Data processing requirements

- A-weighted 1/3 octave band SPL
- 100 ms sample period, 10 consecutive minutes
- 3 filter bands considered: 50-200, 100-400, 200-800 Hz

Low-Frequency and Infrasound

Broadly speaking, low-frequency noise (LFN) describes any acoustic emission at the lower range of or below what is commonly considered the audible frequency range (20-20000 Hz). Low-frequency noise has been associated with wind turbine operation, especially with downwind machines, as far back as the 1980's. For the purposes of wind turbine noise testing, the following frequency ranges are defined:

- Low frequency noise (LFN): 1/3 octave bands centered at 20 – 200 Hz
- Infrasound noise: 1/3 octave bands centered < 20 Hz
- ILFN: Infrasound + LFN (0.5 – 200 Hz)

Hardware requirements

Procedures and instrumentation requirements for low-frequency noise testing for wind energy are specified in Standard: ANSI/ASA S12.9-2016/Part 7: Quantities and Procedures for Description and Measurement of Environmental Sound, Part 7: Measurement of Low-frequency Noise and Infrasound Outdoors and in the Presence of Wind and Indoors in Occupied Spaces. From those requirements, two grades of measurements are specified: *survey grade*, for general or routine-purpose situations, and *precision grade*, for situations requiring the best available precision. Given that the measurements taken in the Aeroacoustic assessment project are intended for scientific research, and will be shared through

journal publications and technical reports, the precision grade standards are to be met for all low-frequency noise recording instrumentation. Requirements are as follows:

- LFN
    - +/- 0.5dB frequency response in 1/3 octave bands from 0.4 – 200 Hz
    - The microphone shall include a 300 mm solid foam (20 ppi) windscreen recommended by the manufacturer or better
    - The microphone shall be at a height of 1.5 m
- ILFN
    - +/- 0.5dB frequency response in 1/3 octave bands from 0.1 – 200 Hz
    - 1 m diameter ground plane (like IEC 61400-11) with 90 mm hemispherical wind screen + 450 mm diameter turbulence/secondary wind screen

Low-frequency microphones noted in Table 1 have been selected to meet the requirements for LFN and ILFN measurements.

Data processing requirements

- Calculate background wind noise for each wind speed bin
- Frequency weighting not specified (C, G, or no weighting are more appropriate)

4 Equipment selection

To meet the requirements for observing wind turbine noise emissions outlined above, specialized equipment has been selected, detailed below.

Microphones

Microphone requirements are specified under the IEC 61400-11 Standard for wind turbine noise (IEC 61400-11) as well as for sound level metering (IEC 61672) and measurement microphones (IEC 61094-4). Standards indicate that microphones must meet the Class 1 requirements for reliable measurement systems and traceable calibration. All the requirements for acoustic instrumentation under the standard are found in Section 6.1: Acoustic Instruments. Relevant excerpts are reproduced below from IEC 61400-11 Edition 3.1 2018-06 (Final Version). The Standards indicate that,

6.1.2 Equipment for the determination of the equivalent continuous A-weighted sound pressure level

"The diameter of the microphone diaphragm shall be no greater than 13mm." (paragraph 6.1.2). The equipment shall meet the requirements relevant to this document of an IEC 61672 class 1 sound level meter.

6.1.3 Equipment for the determination of A-weighted 1/3-octave band spectra

The filters shall meet the requirements relevant to this document of IEC 61260 for class 1 filters.

6.1.4 Equipment for the determination of narrow band spectra

The equipment shall fulfil the relevant requirements for IEC 61672 series class 1 instrumentation in the 20 Hz to 11 200 Hz frequency range.

6.1.6 Acoustical calibrator

The calibrator shall fulfil the requirements of IEC 60942:2003 class 1, and shall be used within its specified environmental conditions.

6.1.7 Data recording/playback systems

A data recording/playback system is a required part of the measurement instrumentation. If used for analysis (other than re-listening), the entire chain of measurement instruments shall fulfil the relevant requirements of IEC 61672 series, for class 1 instrumentation.

Table 1: Acoustic recording instrumentation

Quantity	Component	Description	Cost per unit	Component subtotal
Standard frequency range IEPE microphones				
9	4966-H-041	microphone/preamp combo for measurements down to 6.3 Hz	$1,701.00	$15,309.00
Low-frequency microphones				
4	4964	Microphone for measurements down to 0.1 Hz	$2,409.00	$9,636.00
4	2669-C	Preamp	$900.00	$3,600.00
4	1708	Signal Conditioner	$1,839.00	$7,356.00
4	AO-0414-D-100	Cable, Microphone, circular-1B 7-pin (M) to circular-1B 7-pin (F), 10m (33.3ft), max.+90°C (194°F)	$568.00	$2,272.00
Ancillary gear				
1	4231 Electrodynamic calibrator	Microphone acoustic calibrator	$1,475.00	$1,475.00
				$39,648.00

Standard frequency mics (IEPE)

The requirements for IEC 61400-11 noise measurements are satisfied by the Brüel and Kjæl (B&K) 4966-H-041, which combines a Type 4966 prepolarized, free-field microphone and a Type 1706 microphone preamplifier. Specifically, the 4966-H-041 delivers flat frequency response within the required range of 20 Hz - 11.2 kHz. Additionally, the 4966-H-041 complies with the 'Class 1' specifications in IEC Standard 61672, has an appropriate dynamic range and operating temperature range for all conditions at the NREL Flatirons Campus. Finally, the 4966-H-041 is an integrated electronic piezo-electric (IEPE) microphone, which allows microphones to be powered through BNC cables used for signal transmission.

Low-frequency mics

Specialized microphones are required to take pressure-field measurements as specified in the Standards for LFN and ILFN (ANSI/ASA S12.9-2016). Low frequency noise measurements require additional care in terms of both the acoustic recordings and signal conditioning. To make LFN measurements, the B&K Type 4964 microphone with a nominally flat frequency range below 1 Hz has been selected. These microphones have a similar dynamic range and operating temperature range as the IEPE mics above. However, measuring the low-frequency content of the acoustic emissions requires that the Type 4964 microphones be connected to a Type 2669 preamplifier and a Type 1708 signal conditioner. Because each signal conditioner requires an additional supply of external power (i.e. not powered over the communication line like IEPE microphones), LFN measurements will be made in proximity to the DAS subsystems.

Data Acquisition Systems (DAS)

Quantity	Component	Description	Cost	Subtotal
3	785622-01	cRIO-9042, 1.6 GHz Quad-Core, 70T FPGA, RT, 4-Slot, XT	$4,814.00	$14,442.00
4	779680-01	NI-9234 C Series Sound and Vibration Input Module, 4-Ch, 51.2 kS/s, IEPE and AC/DC	$2,062.00	$8,248.00
4	781632-01	NI 9467, GPS Time Synchronization Module for C Series	$735.00	$2,940.00
3	SRV-CR6075397	STANDARD SERVICE PROGRAM FOR COMPACTRIO SYSTEMS	$608.88	$1,826.64
4	779593-01	NI-9239 C Series Voltage Input Module	$1,241.00	$4,964.00
				$32,420.64

The distribution of measurement points over a large area behind the DOE 1.5 requires a similarly distributed data acquisition system. Reconciling this requirement against the need to keep cable runs short enough to minimize signal degradation points to the assembly of three DAS subsystems. Each DAS is constructed on a National Instruments (NI) CompactRIO (cRIO) chassis that combines a real-time controller with a platform for adding signal input/output modules. The chassis selected for the Aeroacoustics project (cRIO-9042) has sufficient processing power and a modular design to ensure that they will meet the needs for the measurements outlined above and be useable for other measurement campaigns in coming years. Each DAS subsystem will consist of a cRIO outfitted with three NI C-series modules:

- **NI-9234** Sound and Vibration module with 4 BNC input terminals. This module is more than capable of powering the IEPE microphone/preamp combos and processing the acoustic data for the specified frequency range.
- **NI-9239** Analog voltage input module. This module will interface with the B&K signal conditioning unit for each low frequency measurement station. A separate module will be used to ensure that each type of observation can be configured independently.
- **NI-9467** GPS Time Synchronization Module. All data need to be time-stamped locally to ensure that data can be accurately compared for subsequent time-domain analysis.

An example DAS subsystem and measurement devices are shown in a line diagram in Figure 3.

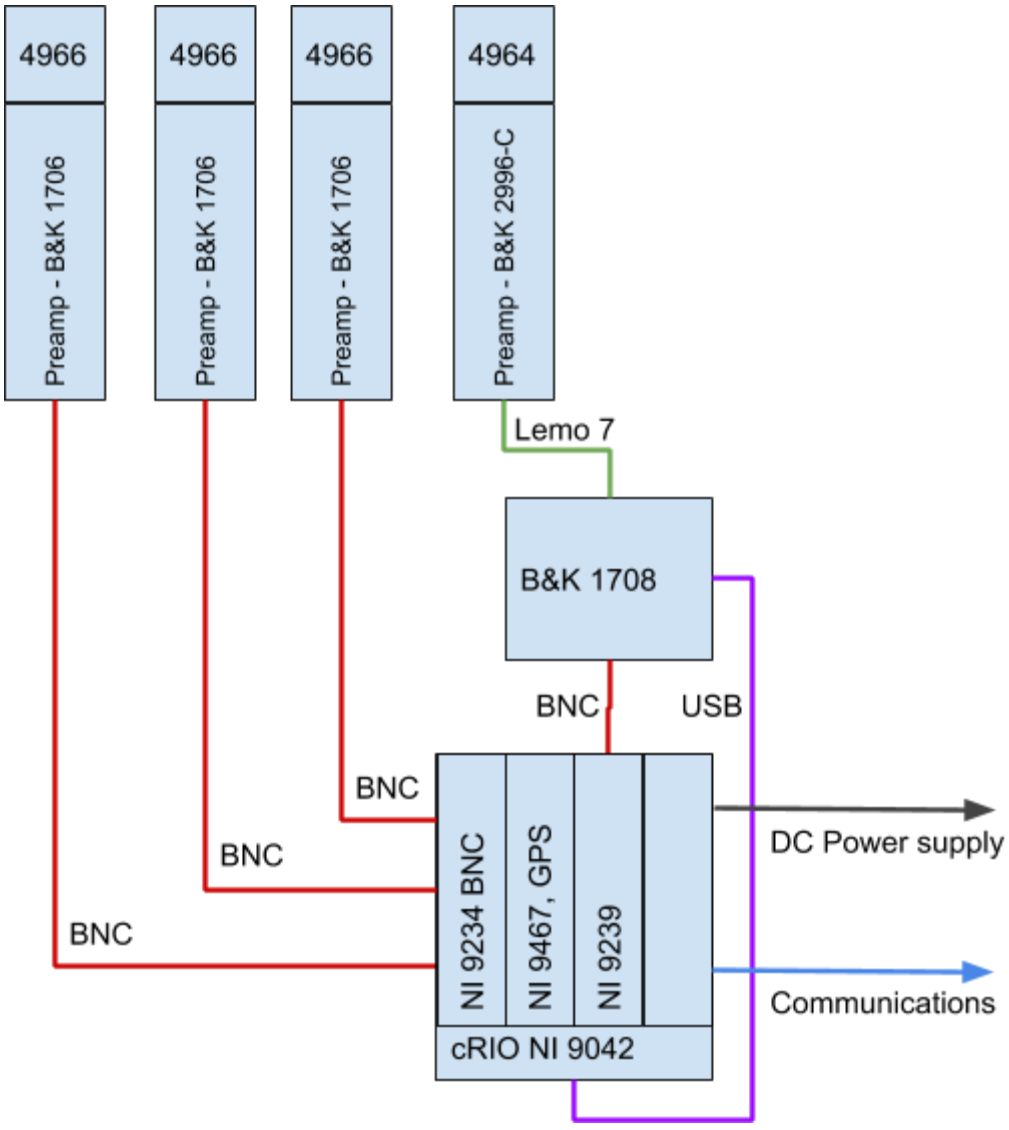

Figure 3: Line diagram of DAS subsystems

Additional memory - Local storage of each DAS will be augmented with an additional memory. Depending on space/power/temperature limitations within environmental enclosures for the cRIO and

signal conditioning modules, either a 32 GB industrial SD card or a USBc external SSD will be added to record raw acoustic data.
Communications - Information collected at each DAS will be communicated to a central data storage system through the base of the DOE 1.5 via fiber-optic cables.
Power - Power to each DAS subsystem will be routed from the base of the DOE 1.5, supplied with a minimum of 14 gauge cable, with an approximate voltage drop of 11% over the run of 150 m. DC power will be run to each DAS subsystem taking into account that the cRIO can be powered between 9 V and 30 V, and that the signal conditioner requires 0.5 A at 5 V.

Calibration

As recommended in the IEC Standards, calibration of the noise measurement system should be undertaken regularly before measurement and while deployed in the field. For calibration before, during and after acoustic measurements, an additional B&K 4231 Sound calibrator will be acquired (one already exists at NREL). Two calibrators will reduce downtime for the measurement system as both calibrators can be used in parallel.

6 Procurement

Two procurement requests (PR) have been submitted to begin the instrumentation acquisition process through NREL. Delivery of acoustic instrumentation (from B&K) and data acquisition hardware (from NI) is expected by January 15, 2020.

<u>B&K</u>
PR #127606
Brüel & Kjær North America, Inc.
Quote Number: QUO-402738-L5S2S6-1
Quote total: $39,706.50

<u>NI</u>
PR #127620
National Instruments
Quote Number: 1757700
Quote Total: $30,350.00
Note: NI procurement to be submitted 12/27/19

Appendix A: Instrument Documentation

Attached documentation:

Instrument	**Filename**
NI 9467 - GPS module	373230c.pdf
NI 9234 - BNC module	374238a_02.pdf
NI 9239 - Analog input module	375939b_02.pdf
NI cRIO 9042 - Data acquisition frame	377159f_02.pdf
B&K Sound Calibrator type 4231	bp1311.pdf
B&K - Microphone preamplifier - Type 2669	bp1422.pdf
B&K - Microphone preamplifier - Type 1706	bp2225.pdf
B&K - Low-frequency mic - Type 4964	bp2478.pdf
B&K - Standard range mic - Type 4966	bp2559.pdf
B&K - Signal conditioner - Type 1708	bp2536.pdf