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Influence of Electric Vehicle High Voltage Electromagnetic Fields on NVH Sensors

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INFLUENCE OF ELECTRIC VEHICLE HIGH VOLTAGE ELECTROMAGNETIC FIELDS ON NVH SENSORS

Abstract

The development of NVH sensors for automotive applications, in the past, has been without regard for HV EM Fields that are now present with EVs and HEVs. Consequently, there are concerns about what influence or effects HV EM Fields impose on microphone and accelerometer signals when implemented for operational testing of EVs or HEVs. To address and understand the influences of EV HV EM Fields on microphone and accelerometer signals a study was performed to asses these effects on an EV. Ten different models of PCB NVH sensors, including several cable types for some of the sensors, were evaluated local to various HV EM Field sources on an EV. The microphone and accelerometer signals were recorded along with signals from adjacent transducers that measure the EM Field strength. Assessment of the influence of the HV EM Fields is based on the coherence function between the NVH sensor signal and the corresponding EM Field transducer signal – where higher coherence values indicate a higher influence of HV EM Fields on the NVH sensor signals.

NOTE: abbreviations are defined at the end of the paper.

NVH Sensors and Cables Subject to EV HV EM Field Evaluations

Ten types of PCB Piezotronics NVH Sensors were evaluated at nine different HV EM Field sources on an EV. Six of the NVH sensors, all of which were an ICP type, were evaluated with two different cables. The sensors and cables that were evaluated are summarized in Table 1.

PCB Piezotronics SENSOR DESCRIPTION					PCB Piezotronics CABLE DESCRIPTION			
TYPE	MODE	FEATURES	AXES	M/N	CABLE A		CABLE B	
					M/N	VARIANTS	M/N	VARIANTS
Microphone	ICP	pre polarized	uniaxial	378B02	003D20	Low Noise Coax	024AC015AC	Twisted Pair
Accelerometer	charge	charge converter	triaxial	356A70	003G10	Low Noise Coax	n/a	**n/a**
Accelerometer	ICP	standard	triaxial	356A02	010AY015NF	Grounded Shield	010S10	Non-grounded Shield
Accelerometer	ICP	filtered	triaxial	HT356A63	010AY015NF	Grounded Shield	010S10	Non-grounded Shield
Accelerometer	ICP	TEDS	triaxial	TLD356A16	010AY015NF	Grounded Shield	078G10	Non-grounded Shield
Accelerometer	ICP	case isolated	triaxial	354A04	010AY015NF	Grounded Shield	036G20	Non-grounded Shield
Accelerometer	ICP	ground isolated	triaxial	J356A43	010AY015NF	Grounded Shield	036G20	Non-grounded Shield
Accelerometer	DC	single ended	triaxial	3713B11200G	037M29	Multi Conductor	n/a	**n/a**
Accelerometer	DC	differential	uniaxial	3741F12100G	integral	Multi Conductor	n/a	**n/a**
Accelerometer	CVLD	case isolated	uniaxial	355M87A	integral	Coax	n/a	**n/a**

Note: All cables are shielded

Table 1 - PCB Piezotronics sensors and PCB Piezotronics sensor cables subject to EV HV EM Field evaluations

Each PCB sensor / cable is evaluated at 9 different HV EM Field locations on the EV (the EV was a 2014 BMW i3 without the Range Extender feature). Table 2 summarizes the EV HV EM Field locations selected for evaluation.

EV HV EM FIELD LOCATIONS FOR SENSOR EVALUATION	
LABEL	DESCRIPTION
EME TOP	Power electronics module with HV inverter, HV converter, DC-DC converter, top surface
ELEC HEAT CABLE	Cable for high voltage heat system
KLE SIDE	Charging electronics module, side surface
KLE TOP	Charging electronics module, top surface
EME KLE CABLE	Cable connecting power electronics module to charging electronics module
LOCAL HV BAT CABLE	Local to high voltage battery cable, offset to one side of the parallel cables
HV BAT CABLE	Immediately adjacent to high voltage battery cable, above but centered between the parallel cables
EKK BOTTOM	Air conditioner compressor motor, bottom surface
EM BOTTOM	Vehicle electric motor, bottom surface

Table 2 – BMW i3 EV HV EM Field locations implemented for NVH sensor / cable evaluations

Operating Data from EV

Operating measurements were obtained for EV conditions that yield a high or maximized EM Field to assess a maximum influence on the NVH sensors / cables. Table 3 summarizes EV operating conditions that were implemented for assessing HV EM Field influences.

VEHICLE OPERATING CONDITIONS FOR HV EM FIELD INFLUENCE ASSESSMENT		
OPERATING CONDITION DESCRIPTION / PARAMETERS	**OBJECTIVE**	**ACTIVE SYSTEMS**
vehicle power off	Baseline EM Field Levels (reference zero)	none
accelerate up-hill	Max Load - DC and AC systems	HV BAT, EME, EM, EKK
air. cond. max		
windows down		
constant speed	Max Load - AC heat system	EME, ELEC HEAT CABLE
max heat		
windows down		

Table 3 – Vehicle operating conditions implemented for HV EM Field influence assessment

Data Analysis – Coherence Function

Assessment of the influence of HV EM Fields on the NVH sensors / cables is accomplished using the coherence function between the NVH sensor signal (system output) and the locally measured EM Field transducer signal (system input) – where the NVH sensor / cable and the corresponding EM Field transducer define a single system.

The coherence function has values that range from 0 (zero) to 1 where a value of 0 indicates no causality between the system output signal and the system input signal, and where a value of 1 indicates causality between the system output signal and the system input signal. As related to the NVH sensor / cable coherence data, frequencies with low coherence indicate less susceptibility of the sensor / cable to the local EV EM Field and frequencies with high coherence indicate more susceptibility of the sensor / cable to the local EV EM Field.

In an ideal situation the coherence function between the sensor signal and the EM Field will be 0 (zero) – no causality. This means the sensor signal only contains information about the desired measured phenomena (acceleration / acoustic pressure) and is not influenced by the EM Field (electrical noise).

Data Analysis – Minimum Achievable Coherence (Practical Noise Floor Level)

As a reference point for the practical achievable minimum coherence, the noise floor of the coherence function is established with measurements taken when the EV and all power systems (HV EM Fields) are switched off but with the NVH sensors powered and operating. The time signals corresponding to this condition are presented in Figure 1; where the upper chart shows the time signal of the NVH sensor (system output) and the lower chart shows the time signal of the EM Field (system input).

Note the accelerometer signal has low frequency content, intentionally, by an induced rocking motion of the vehicle from the vehicle occupant, to confirm the accelerometer is operational. The low frequency content is below 5 Hz, is not related to EM Field signals, nor does it affect coherence functions while the EV electrical systems are switched off (rocking the vehicle does not influence the EV HV EM Fields or the EM Field transducer signals).

Also, note the average magnitude of the EM Field signal is near a value of 0.058 T – which corresponds to the magnitude of Earth's magnetic field near the surface.

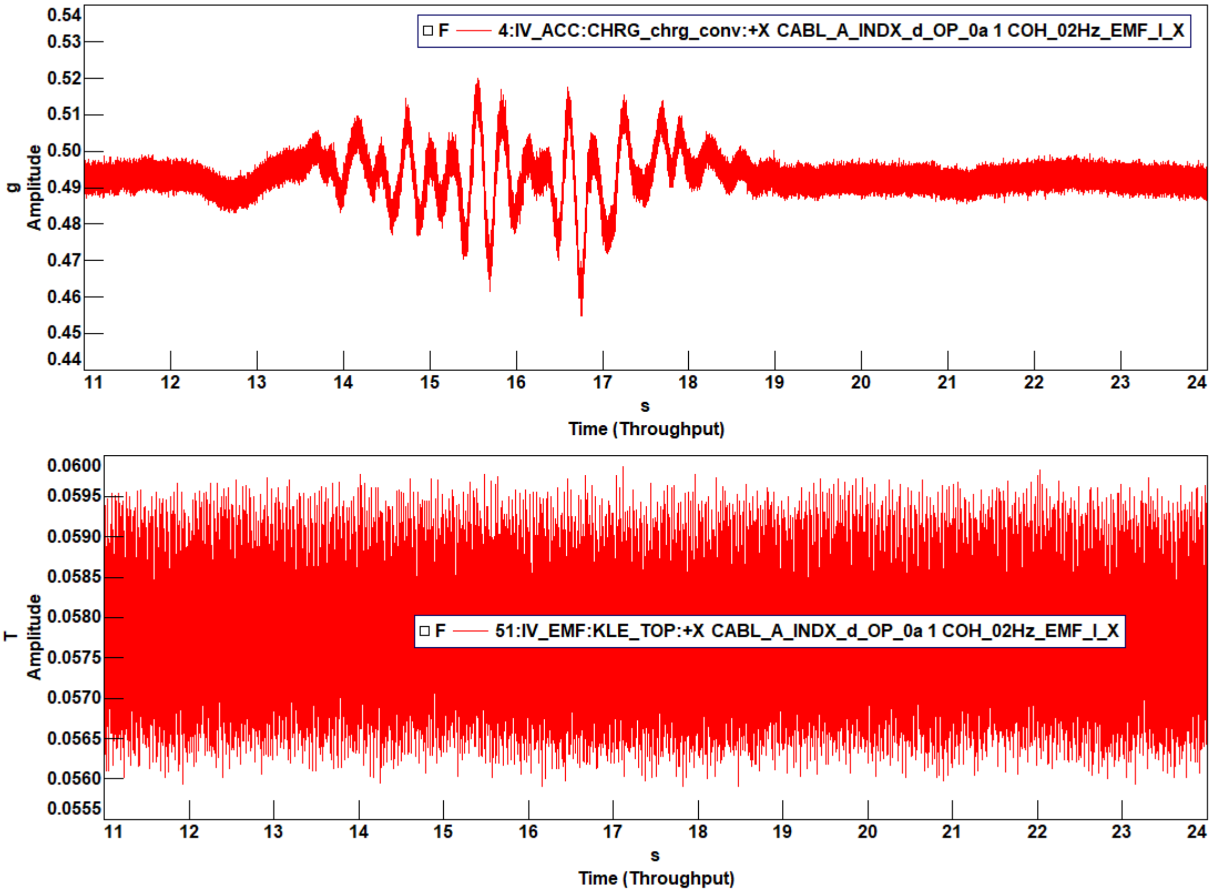


Figure 1 – Time signals of the NVH sensor / EM Field system; measured acceleration is the system output and measured EM Field is the system input for the coherence

Figure 2 shows the resultant coherence function between the output and input time signals from Figure 1; with 2 Hz frequency resolution and up to 9 kHz bandwidth.

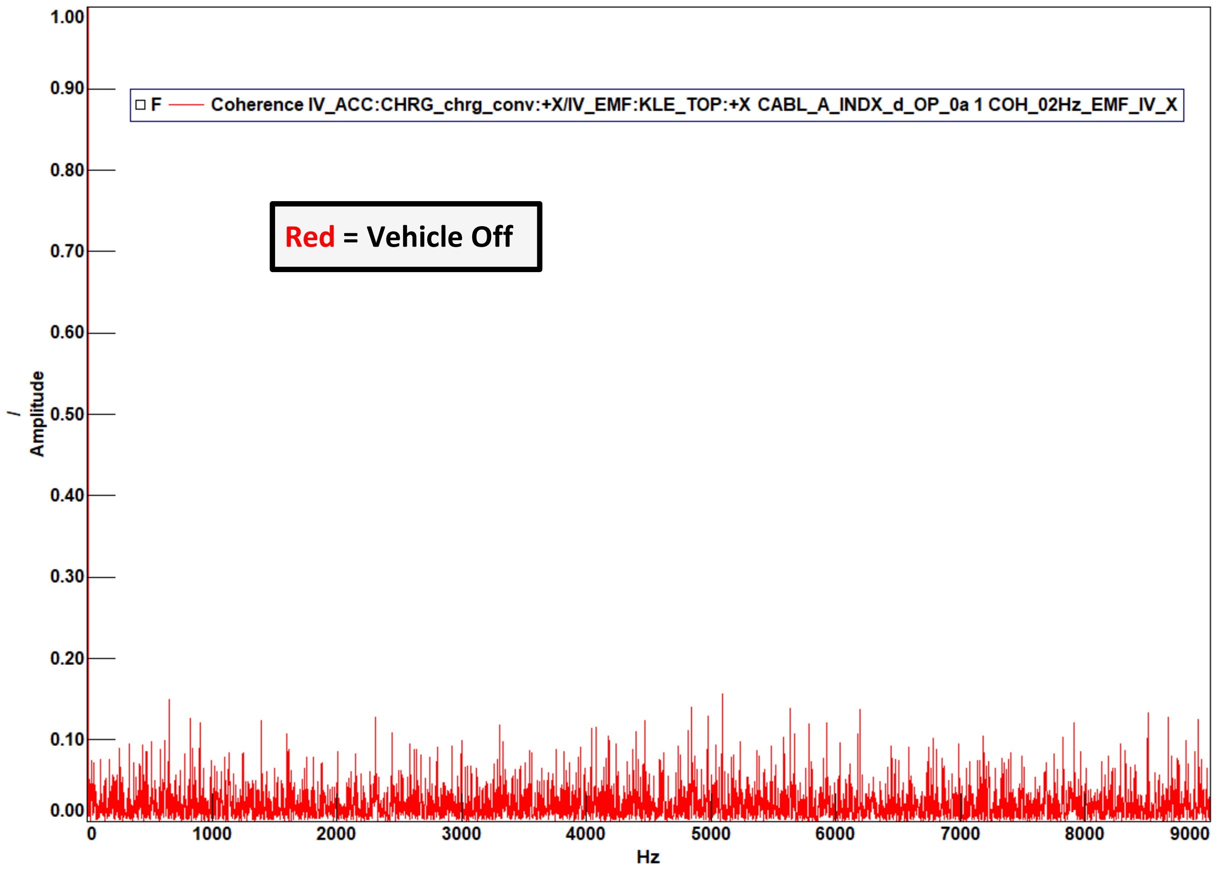


Figure 2 - Coherence function between output signal (accelerometer) and input signal (EM Field)

The coherence functions between the NVH sensor and the EM Field pairs consistently exhibit a coherence level near or below 0.1 (over the frequency range) with the EV HV EM Fields switched off. This establishes a consistent noise floor for all 10 PCB NVH sensors (including different cables) at all 9 EM Field locations. Therefore, for coherence results at discrete frequencies the lowest achievable coherence value is established as 0.1 (using 2 Hz frequency resolution).

Data Analysis – Summarizing, Comparing, Analyzing Coherence Results

The coherence spectrum is useful for assessing the performance characteristics of the NVH sensors / cables at the various EM Field locations or for comparing performance between sensors / cables at the same EM Field location. Figure 3 illustrates the performance characteristic of an NVH sensor / cable subject to an active EV HV EM Field versus the performance characteristic of the same sensor / cable at the same EM Field location with the EV HV EM Field switched off.

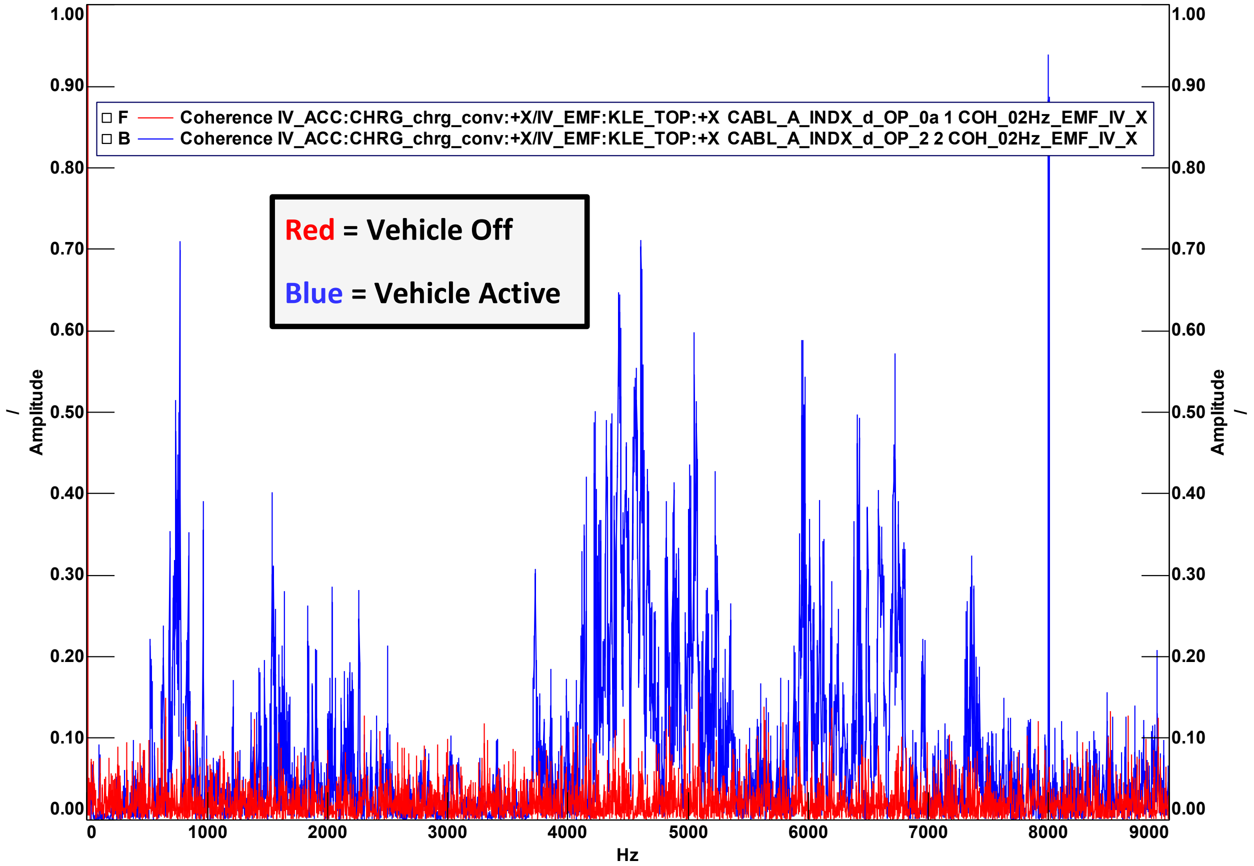


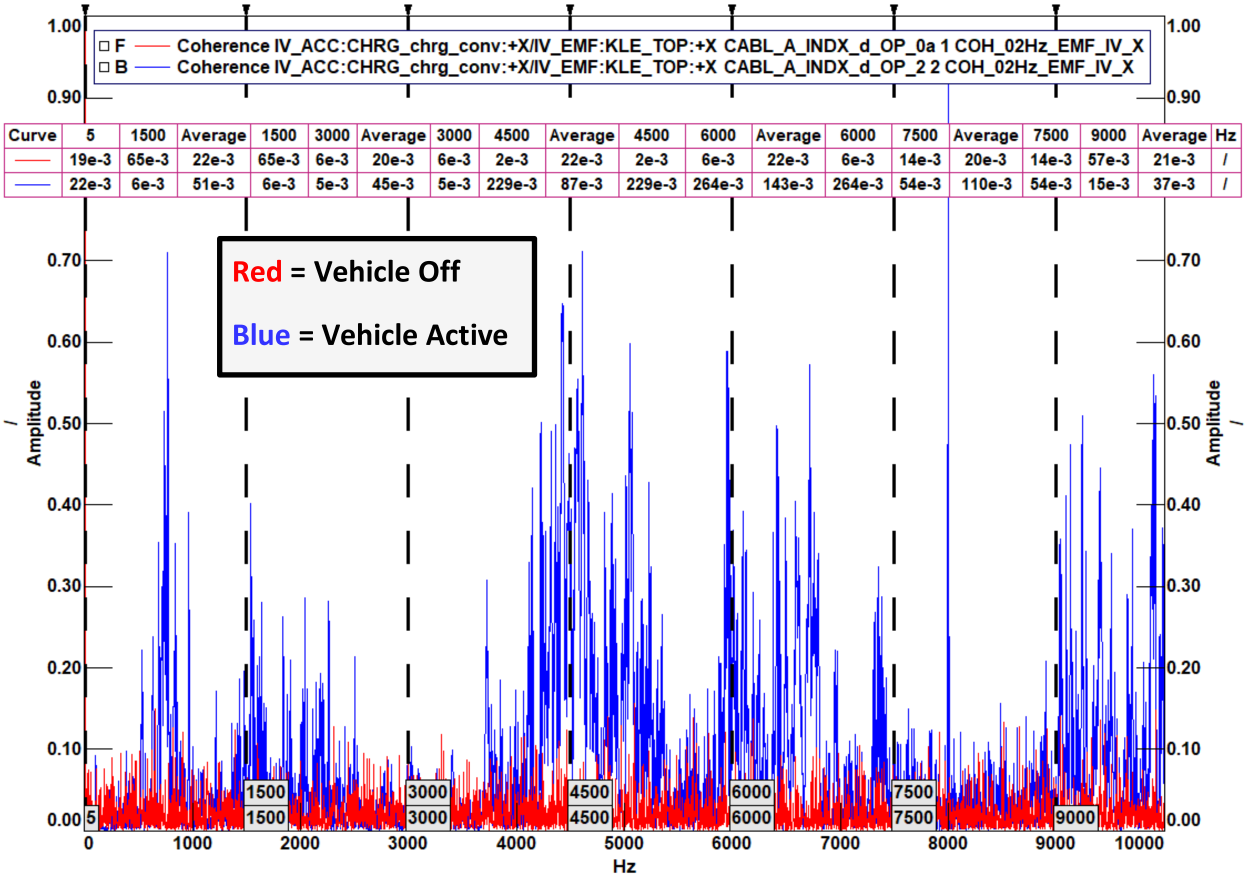
Figure 3 – Coherence functions comparing NVH sensor performance characteristics between an active EV HV EM Field (blue) and the same EV HV EM Field switched off (red)

However, given the large matrix of test results (10 sensors with Cable A, 6 sensors with Cable B, 9 EM Field locations, 3 operating conditions) the method selected to summarize, compare, and analyze the data implements average coherence values for a set of convenient frequency bands.

Six frequency bands were selected with 1.5 kHz bandwidths up to 9 kHz and a seventh frequency band was selected with the full bandwidth up to 9 kHz. Two variations in the selected bandwidths include 1) the first 1.5 kHz bandwidth and 2) the full bandwidth where they each start at 5 Hz instead of 0 Hz. The

5 Hz cut-off allows direct comparison of average coherence results between the AC type sensors and the DC type sensors; where the AC type sensors (charge, ICP, and CVLD) do not have a 0 Hz capability.

Figure 4 presents the same coherence data as in Figure 3 but Figure 4 also includes cursor pairs indicating the frequency bands and a cursor legend showing the average coherence values for the cursor bands.



Curve	5	1500	Average	1500	3000	Average	3000	4500	Average	4500	6000	Average	6000	7500	Average	7500	9000	Average	Hz
🟥	19e-3	65e-3	22e-3	65e-3	6e-3	20e-3	6e-3	2e-3	22e-3	2e-3	6e-3	22e-3	6e-3	14e-3	20e-3	14e-3	57e-3	21e-3	/
🟦	22e-3	6e-3	51e-3	6e-3	5e-3	45e-3	5e-3	229e-3	87e-3	229e-3	264e-3	143e-3	264e-3	54e-3	110e-3	54e-3	15e-3	37e-3	/

Figure 4 - Coherence functions with frequency bands for average coherence value per frequency band

The average coherence per frequency band values are consolidated into data tables. Table 4 is an abbreviated table, for illustration purposes, and contains average coherence data for the two coherence functions from Figure 4.

MEASUREMENT RUN NAME	EM FIELD LOCATION	CHANNEL NAME OF NVH SENSOR	AVG COHERENCE PER FREQUENCY BAND [/]						
			0.005 - 1.5 kHz	1.5 - 3.0 kHz	3.0 - 4.5 kHz	4.5 - 6.0 kHz	6.0 - 7.5 kHz	7.5 - 9.0 kHz	0.005 - 9.0 kHz
CABL_A_INDX_d_OP_0a 1 COH_02Hz_EMF_IV_X	KLE_TOP:+X	ACC:CHRG_chrg_conv:+X	0.022	0.020	0.022	0.022	0.020	0.021	0.021
CABL_A_INDX_d_OP_2 2 COH_02Hz_EMF_IV_X	KLE_TOP:+X	ACC:CHRG_chrg_conv:+X	0.051	0.045	0.087	0.143	0.110	0.037	0.079

Table 4 - Average coherence values per frequency band; Red = Vehicle Off data, Blue = Vehicle Active data

Table 4 also includes the average coherence data for the full frequency band of 5 Hz to 9 kHz in the right most column. Implementing the average coherence value for the full frequency band provides further consolidation of the data – one average coherence value per sensor per cable per axis per EM Field location.

Results – Cable A and Cable B Comparisons with Average Coherence

The average coherence data (5 Hz to 9 kHz) for the sensors with both Cable A and Cable B are plotted side-by-side in charts to assess performance differences between the cables, Figure 5 through Figure 10. A single chart shows average coherence data for a single sensor for a single EM Field reference axis (vertical scale) for each EM Field location (horizontal axis) with Cable A and Cable B data side-by-side. The color bars for Cable A data do not have a border while the color bars for Cable B data are outlined with a bright green border.

The six sensors evaluated with two cables, Cable A and Cable B include:

- Microphone ICP
- Accelerometer ICP, standard
- Accelerometer ICP, filtered
- Accelerometer ICP, TEDS
- Accelerometer ICP, case isolated
- Accelerometer ICP, ground isolated

The side-by-side Cable A and Cable B data in Figure 5 through Figure 10 are organized in the sequence indicated above and include the X, Y, and Z EM Field references as separate charts.

Figure 5 - ICP Mic., X Y Z references, normalized average coherence data for Cable A (003D20) and Cable B (024AC015AC)

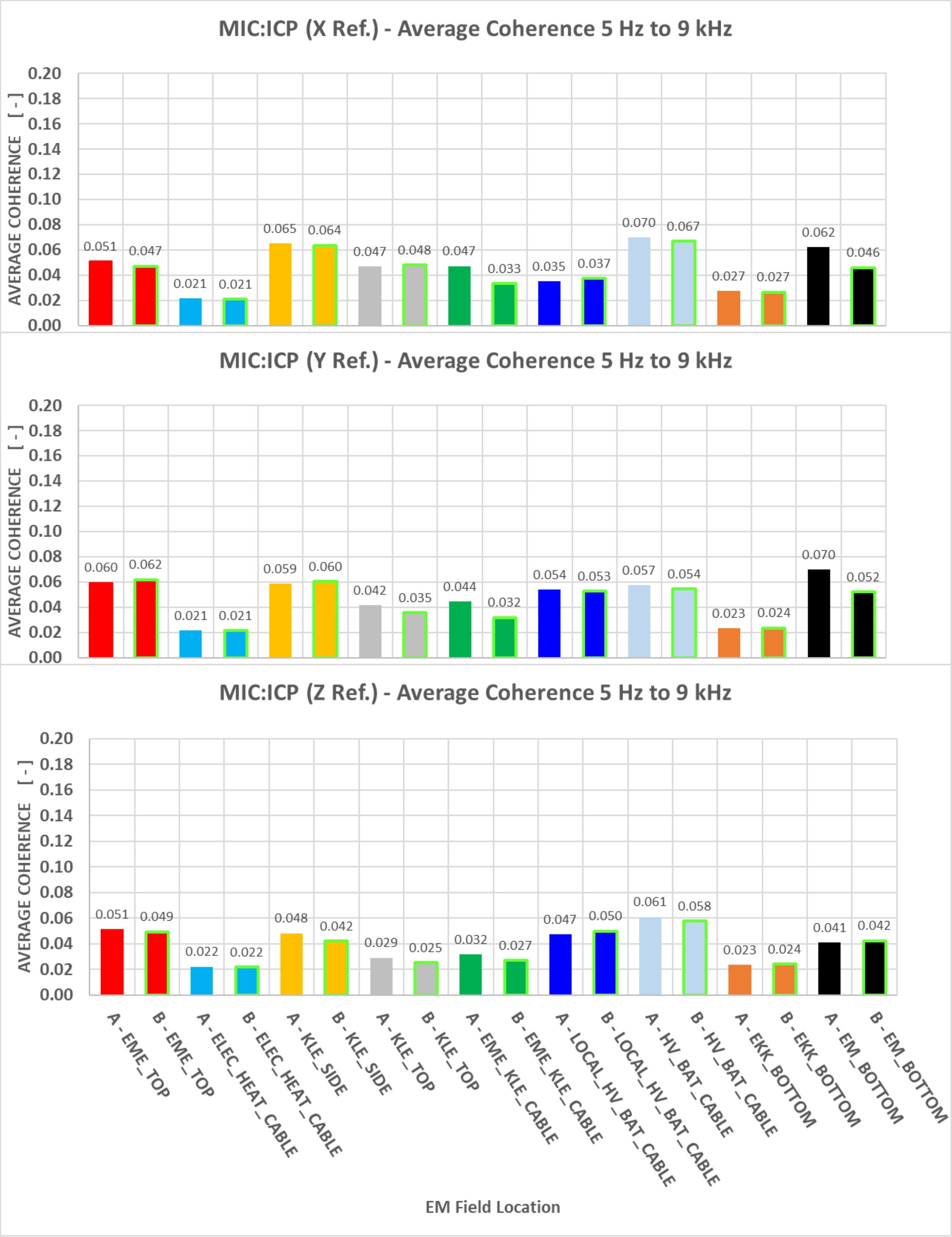


Figure 6 - ICP Accel standard, X Y Z references, normalized average coherence data for Cable A (010AY015NF) and Cable B (010S10)

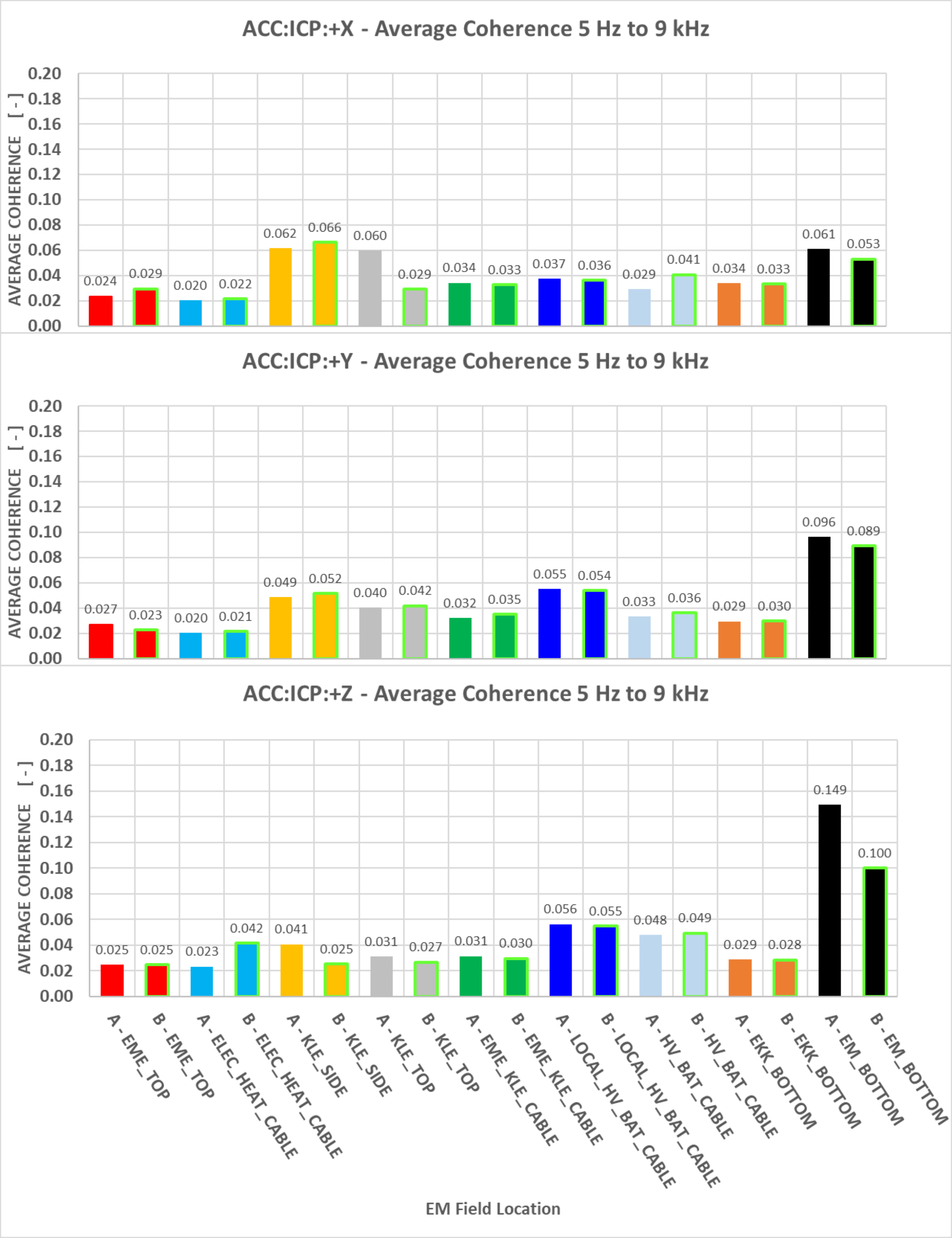


Figure 7- ICP Accel filtered, X Y Z references, normalized average coherence data for Cable A (010AY015NF) and Cable B (010S10)

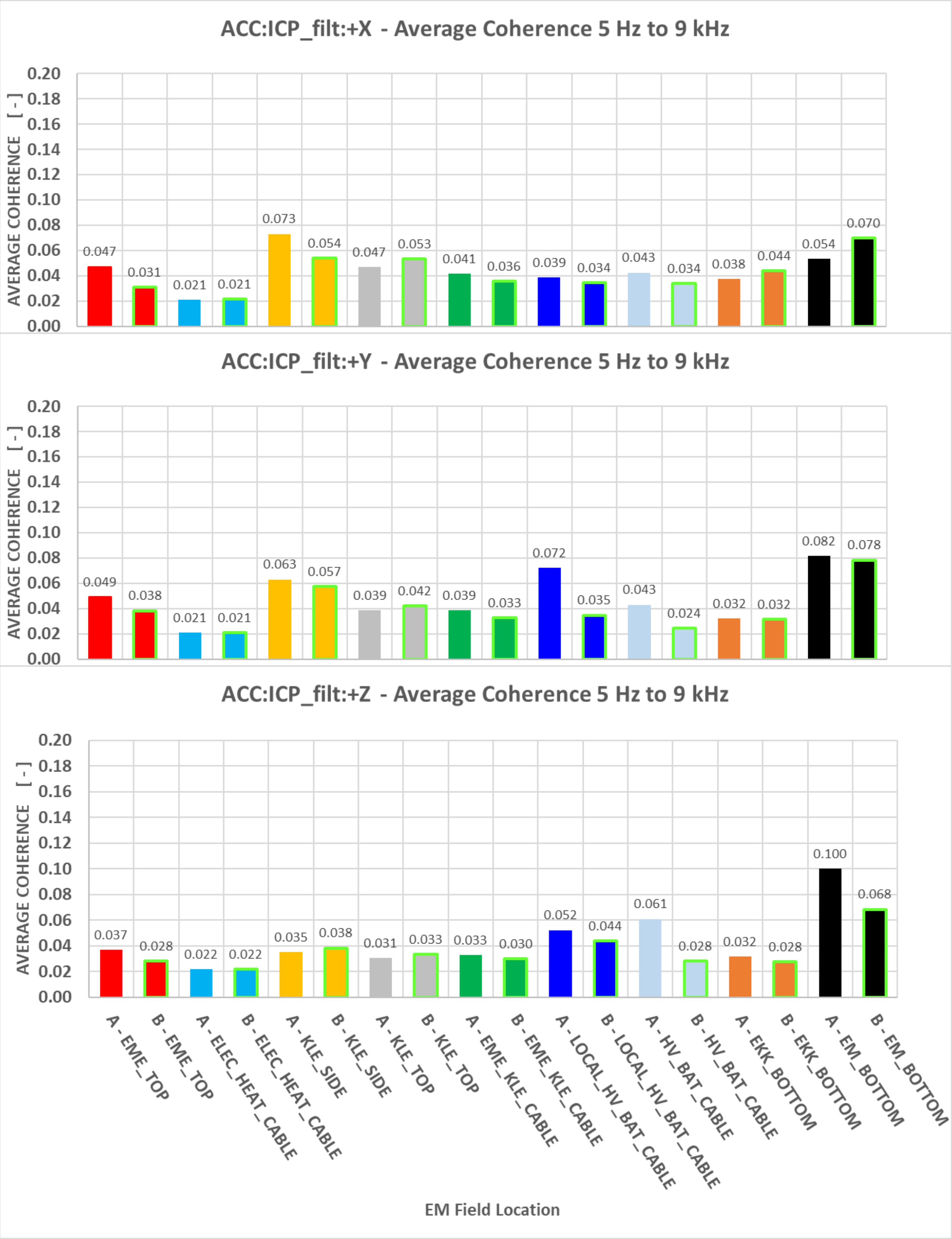


Figure 8 - ICP Accel TEDS, X Y Z references, normalized average coherence data for Cable A (010AY015NF) and Cable B (078G10)

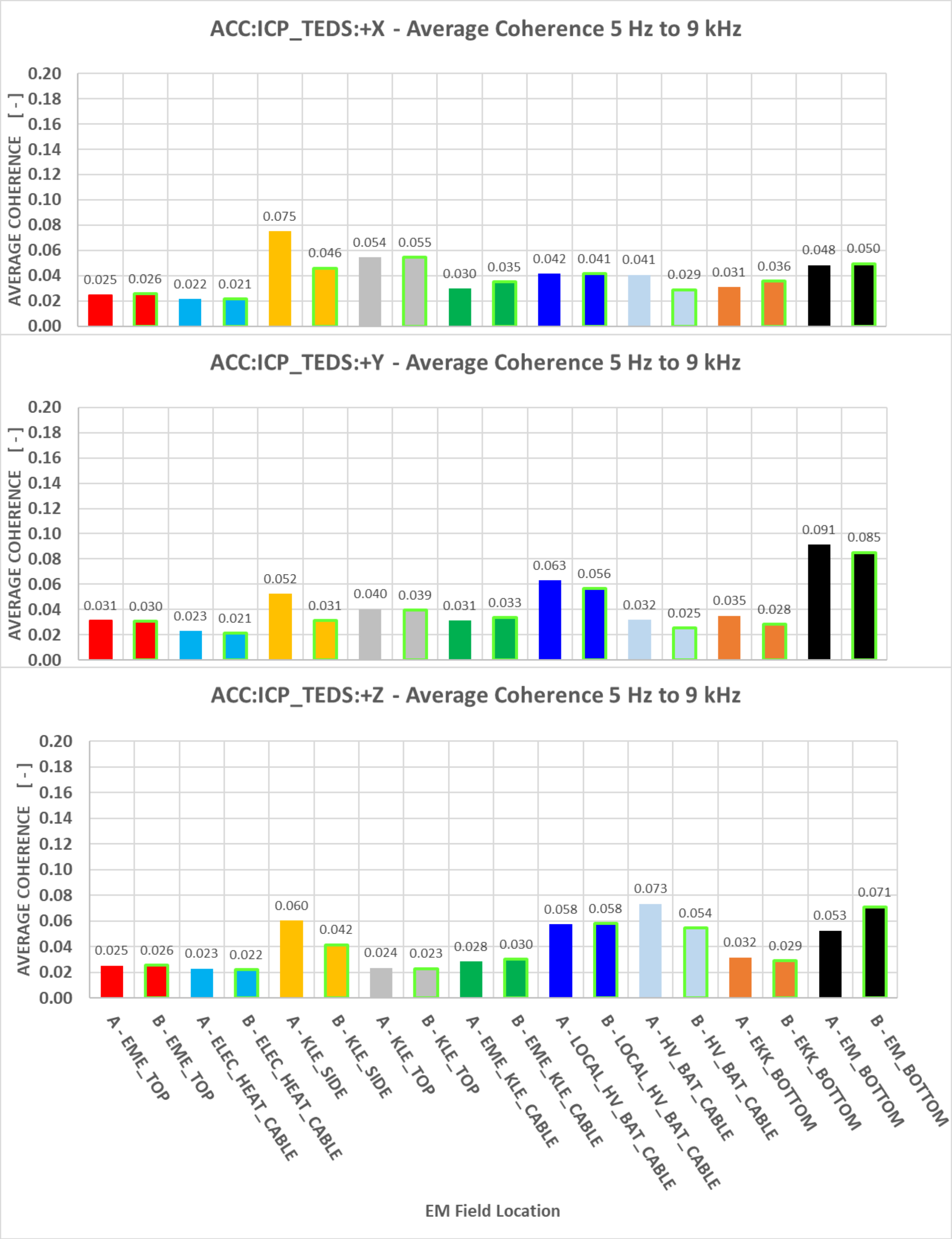
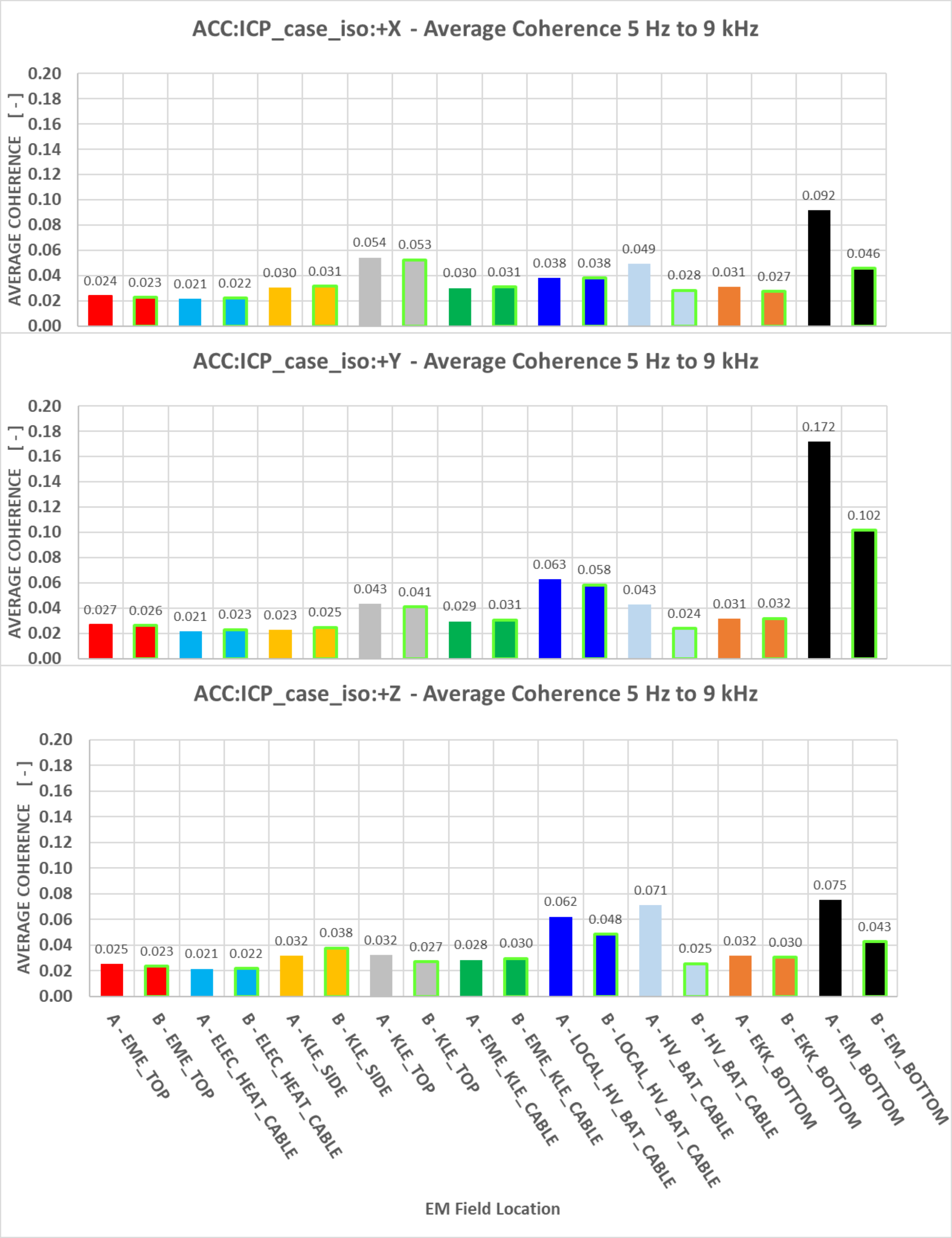


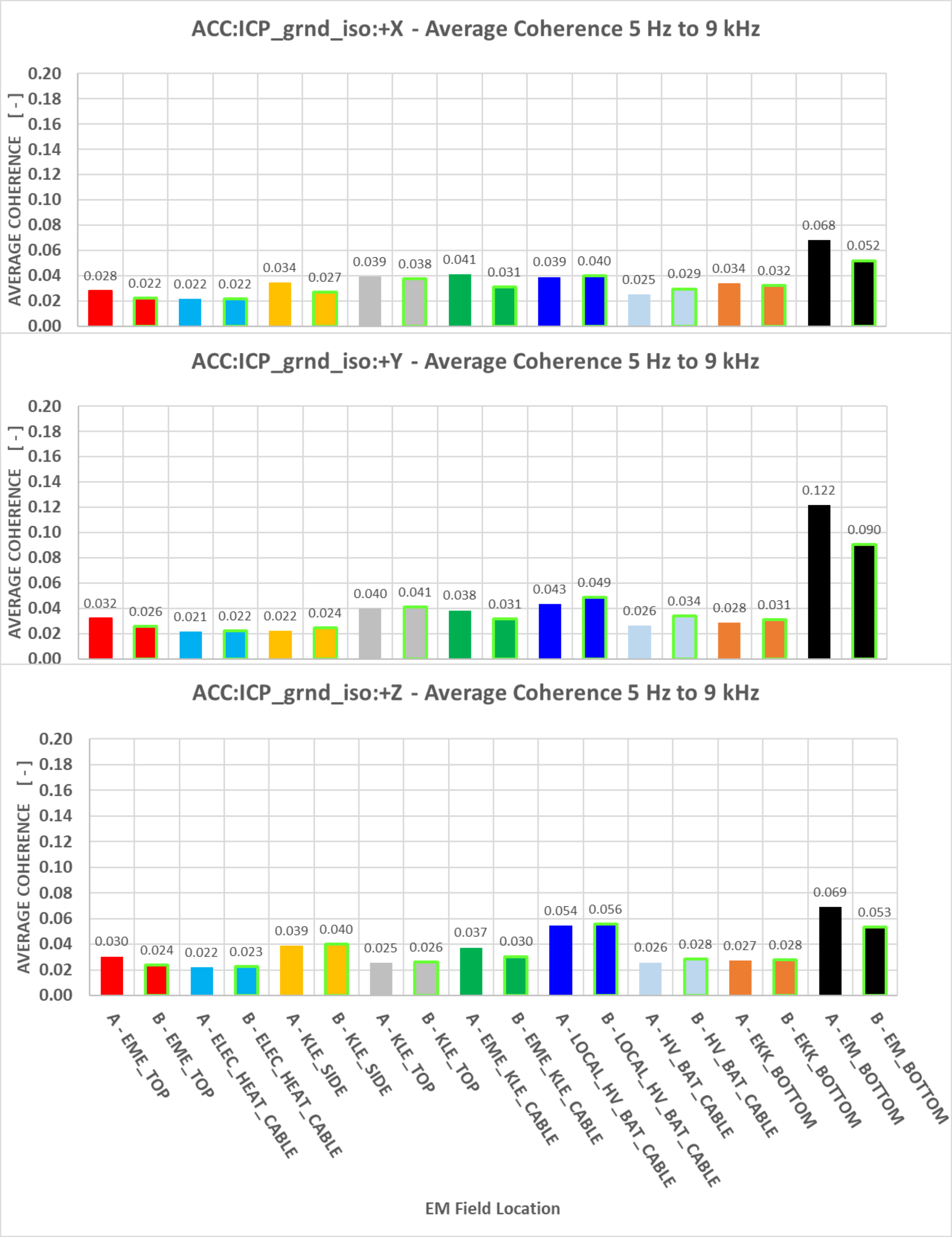
Figure 9- ICP Accel case isolated, X Y Z references, normalized average coherence data for Cable A (010AY015NF) and Cable B (036G20)


ACC:ICP_case_iso:+X - Average Coherence 5 Hz to 9 kHz

ACC:ICP_case_iso:+Y - Average Coherence 5 Hz to 9 kHz

ACC:ICP_case_iso:+Z - Average Coherence 5 Hz to 9 kHz

Figure 10 - ICP Accel ground isolated, X Y Z references, normalized average coherence data for Cable A (010AY015NF) and Cable B (036G20)



The side by side Cable A and Cable B data do not show consistent significant performance differences between the cables.

The side-by-side Cable A and Cable B data do show a general trend in the influence of the EM Field locations on the NVH sensors / cables:

- **Most significant influence** – EM BOTTOM (black color bars) typically exhibits the highest coherence values on the charts
- **Second most significant influence** – KLE SIDE (yellow color bars), KLE TOP (grey color bars), LOCAL HV BAT CABLE (dark blue color bars), and HV BAT CABLE (blue-grey color bars) typically exhibit the next highest coherence values on the charts
- **Moderate influence** – EME TOP (red color bars) typically exhibits a consistent moderate coherence value on the charts
- **Least significant influence** – ELEC HEAT CABLE (light blue color bars), EME KLE CABLE (green color bars), and EKK BOTTOM (orange color bars) typically exhibit the lowest coherence values on the charts

Results – Normalized Average Coherence

The relative ranking of NVH sensor / cable performance at different EM Field locations is not easily assessed with average coherence data given the sensors are not identical (differences include; circuitry, sensitivity, shielding, housing, power source, etc.) and the EM Field sources are not identical (differences include; circuitry, power levels, power functions, switching and duty cycles, etc.). Therefore, the average coherence data for the 5 Hz to 9 kHz frequency bands are normalized to determine a relative ranking performance for the sensors / cables.

The normalized average coherence is determined from ratios between each sensor's average coherence at each EM Field location (for the 5 Hz to 9 kHz band) and the EM Field location with the maximum average coherence for that sensor (one of the nine EM Field locations). Thus, the normalized average coherence values will theoretically range between 0 (zero) and 1. A further consequence of the normalized average coherence process is each sensor / cable will have one EM Field location with a maximum value of 1 (corresponding to the EM Field location that is most influential on a particular sensor / cable).

Consolidating the normalized average coherence values into tables provides an overview for assessing sensor / cable performance at different EM Field locations and for sensor to sensor comparisons. The normalized average coherence data are organized into two tables; Table 5 for the sensors with Cable A and Table 6 for the sensors with Cable B.

A color scale is superimposed on the normalized average coherence values to distinguish between low, moderate, and high values. The color scale fades from green to yellow to orange to red which corresponds to low, low-moderate, moderate-high, and high coherence values, respectively. The color scale applies across the table rows (per sensor performance at each EM Field location), as well as down the table columns (sensor to sensor comparison at each EM Field location), and between the Cable A data and the Cable B data.

Coherence data for the triaxial and uniaxial sensors are provided for the X, Y, and Z axes where the X, Y, and Z axes are references to the local EM Field direction. For the triaxial NVH sensors the coherence functions are determined using the same axis between the sensor and the local EM Field; X sensor to X EM Field, Y sensor to Y EM Field, and Z sensor to Z EM Field. For the uniaxial sensors the coherence functions are determined with the one axis of the sensor (which is a single direction in either X, or Y, or Z) to the three axes of the EM Field; axis of sensor to X EM Field, same axis of sensor to Y EM Field, same axis of sensor to Z EM Field.

NORMALIZED AVERAGE COHERENCE DATA for SENSORS with CABLE A (5 Hz to 9 kHz)

PCB SENSOR DESCRIPTION				EM FIELD LOCATION								
TYPE and M/N	**MODE and AXES**	**FEATURES**	**REF. AXIS**	**EME TOP**	**ELEC HEAT CABLE**	**KLE SIDE**	**KLE TOP**	**EME KLE CABLE**	**LOCAL HV BAT CABLE**	**HV BAT CABLE**	**EKK BOTTOM**	**EM BOTTOM**
MIC 378B02	ICP UNIAX	pre-polarized	X	0.727	0.307	0.931	0.672	0.676	0.500	1.000	0.390	0.887
			Y	0.850	0.305	0.839	0.595	0.635	0.772	0.821	0.331	1.000
			Z	0.842	0.362	0.791	0.477	0.521	0.776	1.000	0.383	0.672
ACCEL 356A70	CHARGE TRIAX	charge converter	X	0.217	0.129	0.273	0.449	0.376	0.527	0.381	0.258	1.000
			Y	0.475	0.181	0.230	0.954	0.331	0.989	0.527	0.332	1.000
			Z	0.503	0.190	0.437	0.756	0.471	0.513	0.542	0.418	1.000
ACCEL 356A02	ICP TRIAX	standard	X	0.382	0.328	1.000	0.966	0.553	0.603	0.470	0.548	0.988
			Y	0.281	0.212	0.505	0.417	0.334	0.570	0.346	0.305	1.000
			Z	0.165	0.156	0.272	0.207	0.210	0.377	0.321	0.191	1.000
ACCEL HT356A63	ICP TRIAX	filtered	X	0.646	0.285	1.000	0.640	0.567	0.532	0.582	0.515	0.733
			Y	0.603	0.255	0.772	0.474	0.474	0.882	0.526	0.392	1.000
			Z	0.367	0.218	0.352	0.306	0.329	0.522	0.609	0.317	1.000
ACCEL TLD356A16	ICP TRIAX	TEDS	X	0.330	0.287	1.000	0.724	0.396	0.554	0.541	0.411	0.644
			Y	0.343	0.252	0.572	0.442	0.344	0.688	0.350	0.383	1.000
			Z	0.344	0.313	0.824	0.322	0.385	0.784	1.000	0.431	0.716
ACCEL 354A04	ICP TRIAX	case isolated	X	0.260	0.233	0.330	0.592	0.328	0.414	0.536	0.340	1.000
			Y	0.157	0.125	0.133	0.252	0.171	0.365	0.249	0.183	1.000
			Z	0.333	0.286	0.421	0.431	0.378	0.827	0.948	0.421	1.000
ACCEL J356A43	ICP TRIAX	ground isolated	X	0.413	0.317	0.506	0.579	0.600	0.572	0.370	0.501	1.000
			Y	0.264	0.175	0.181	0.327	0.314	0.357	0.214	0.233	1.000
			Z	0.443	0.318	0.563	0.370	0.542	0.791	0.375	0.393	1.000
ACCEL 3713B11200G	DC TRIAX	single ended	X	0.368	0.345	0.394	0.355	0.382	0.507	0.447	0.444	1.000
			Y	0.240	0.223	0.247	0.230	0.253	0.318	0.258	0.280	1.000
			Z	0.191	0.176	0.197	0.178	0.183	0.260	0.220	0.235	1.000
ACCEL 3741F12100G	DC UNIAX	differential	X	0.136	0.111	0.223	0.216	0.167	0.196	0.204	0.132	1.000
			Y	0.237	0.108	0.177	0.171	0.158	0.298	0.197	0.134	1.000
			Z	0.232	0.142	0.205	0.177	0.176	0.332	0.254	0.168	1.000
ACCEL 355M87A	CVLD UNIAX	case isolated	X	0.339	0.547	0.580	0.545	0.522	0.426	0.326	0.348	1.000
			Y	0.182	0.238	0.166	0.243	0.232	0.257	0.150	0.153	1.000
			Z	0.434	0.632	0.807	0.421	0.555	0.652	0.374	0.386	1.000

COLOR SCALE for NORMALIZED AVERAGE COHERENCE DATA

NO DATA	low	low - mid	mid	mid - high	high
⬜	🟩	🟩	🟨	🟧	🟥

Table 5 - Normalized average coherence data (5 Hz to 9 kHz) for sensors with Cable A

NORMALIZED AVERAGE COHERENCE DATA for SENSORS with CABLE B (5 Hz to 9 kHz)

PCB SENSOR DESCRIPTION				EM FIELD LOCATION (ID and DESCRIPTION)								
TYPE and M/N	**MODE and AXES**	**FEATURES**	**REF. AXIS**	**EME TOP**	**ELEC HEAT CABLE**	**KLE SIDE**	**KLE TOP**	**EME KLE CABLE**	**LOCAL HV BAT CABLE**	**HV BAT CABLE**	**EKK BOTTOM**	**EM BOTTOM**
MIC 378B02	ICP UNIAX	pre-polarized	X	0.707	0.312	0.953	0.718	0.497	0.561	1.000	0.397	0.689
			Y	1.000	0.344	0.974	0.573	0.514	0.853	0.878	0.380	0.842
			Z	0.856	0.375	0.732	0.434	0.471	0.864	1.000	0.420	0.735
ACCEL 356A70	CHARGE TRIAX	charge converter	X	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
			Y	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
			Z	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
ACCEL 356A02	ICP TRIAX	standard	X	0.445	0.325	1.000	0.442	0.494	0.550	0.615	0.500	0.800
			Y	0.254	0.241	0.578	0.468	0.394	0.603	0.407	0.331	1.000
			Z	0.248	0.417	0.253	0.268	0.297	0.547	0.493	0.285	1.000
ACCEL HT356A63	ICP TRIAX	filtered	X	0.443	0.306	0.773	0.767	0.512	0.493	0.487	0.631	1.000
			Y	0.488	0.265	0.732	0.537	0.416	0.443	0.309	0.404	1.000
			Z	0.413	0.315	0.560	0.485	0.437	0.640	0.412	0.402	1.000
ACCEL TLD356A16	ICP TRIAX	TEDS	X	0.468	0.393	0.844	1.000	0.641	0.759	0.529	0.651	0.908
			Y	0.357	0.251	0.367	0.462	0.392	0.663	0.297	0.333	1.000
			Z	0.365	0.312	0.588	0.326	0.428	0.825	0.771	0.409	1.000
ACCEL 354A04	ICP TRIAX	case isolated	X	0.435	0.420	0.598	1.000	0.593	0.722	0.539	0.520	0.870
			Y	0.259	0.226	0.243	0.402	0.300	0.574	0.235	0.312	1.000
			Z	0.484	0.449	0.781	0.561	0.614	1.000	0.528	0.631	0.885
ACCEL J356A43	ICP TRIAX	ground isolated	X	0.430	0.419	0.520	0.724	0.593	0.768	0.567	0.623	1.000
			Y	0.283	0.243	0.269	0.452	0.346	0.537	0.376	0.343	1.000
			Z	0.424	0.403	0.718	0.468	0.546	1.000	0.507	0.497	0.954
ACCEL 3713B11200G	DC TRIAX	single ended	X	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
			Y	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
			Z	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
ACCEL 3741F12100G	DC UNIAX	differential	X	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
			Y	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
			Z	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
ACCEL 355M87A	CVLD UNIAX	case isolated	X	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
			Y	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
			Z	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

COLOR SCALE for NORMALIZED AVERAGE COHERENCE DATA

NO DATA	low	low - mid	mid	mid - high	high
▨	🟩	🟩	🟨	🟧	🟥

Table 6 - Normalized average coherence data (5 Hz to 9 kHz) for sensors with Cable B

Results – Averaged Normalized Average Coherence

To further distinguish trends and performance differences between the sensors / cables and the influences of the EM Fields the normalized average coherence data were averaged in three ways;

1) Averaged normalized average coherence for X, Y, and Z axes per sensor per EM Field location
2) Averaged normalized average coherence for X, Y, and Z axes for all EM Field locations per sensor
3) Averaged normalized average coherence for X, Y, and Z axes for all sensors per EM Field location

The averaged results described in item 1), item 2), and item 3) above are shown in Table 7 for Cable A data and Table 8 for Cable B data. The averaged data described in item 1) comprise the central portion of Table 7 and Table 8. The averaged data described in item 2) are in the right most column of Table 7 and Table 8 with the heading “Average per Sensor”. The averaged data described in item 3) are in the bottom row of Table 7 and Table 8 with the heading “Average per EM Field Location”.

The color scale that is superimposed on the averaged normalized average coherence is the same as previously described for the normalized average coherence values.

AVERAGED NORMALIZED AVERAGE COHERENCE DATA for SENSORS with CABLE A (5 Hz to 9 kHz)

PCB SENSOR DESCRIPTION				EM FIELD LOCATION									AVERAGE PER SENSOR
TYPE and M/N	**MODE and AXES**	**FEATURES**	**REF. AXIS**	**EME TOP**	**ELEC HEAT CABLE**	**KLE SIDE**	**KLE TOP**	**EME KLE CABLE**	**LOCAL HV BAT CABLE**	**HV BAT CABLE**	**EKK BOTTOM**	**EM BOTTOM**	
MIC 378B02	ICP UNIAX	pre-polarized	X Y Z	0.806	0.325	0.854	0.581	0.611	0.683	0.940	0.368	0.853	0.669
ACCEL 356A70	CHARGE TRIAX	charge converter	X Y Z	0.398	0.167	0.314	0.719	0.393	0.676	0.483	0.336	1.000	0.498
ACCEL 356A02	ICP TRIAX	standard	X Y Z	0.276	0.232	0.592	0.530	0.366	0.517	0.379	0.348	0.996	0.471
ACCEL HT356A63	ICP TRIAX	filtered	X Y Z	0.539	0.253	0.708	0.473	0.457	0.645	0.572	0.408	0.911	0.552
ACCEL TLD356A16	ICP TRIAX	TEDS	X Y Z	0.339	0.284	0.799	0.496	0.375	0.675	0.630	0.409	0.787	0.533
ACCEL 354A04	ICP TRIAX	case isolated	X Y Z	0.250	0.215	0.295	0.425	0.293	0.535	0.577	0.315	1.000	0.434
ACCEL J356A43	ICP TRIAX	ground isolated	X Y Z	0.373	0.270	0.416	0.425	0.485	0.573	0.320	0.376	1.000	0.471
ACCEL 3713B11200G	DC TRIAX	single ended	X Y Z	0.266	0.248	0.279	0.254	0.273	0.362	0.308	0.320	1.000	0.368
ACCEL 3741F12100G	DC UNIAX	differential	X Y Z	0.202	0.120	0.202	0.188	0.167	0.275	0.218	0.145	1.000	0.280
ACCEL 355M87A	CVLD UNIAX	case isolated	X Y Z	0.318	0.472	0.518	0.403	0.436	0.445	0.284	0.296	1.000	0.464
AVERAGE PER EM FIELD LOCATION				0.377	0.258	0.498	0.450	0.385	0.539	0.471	0.332	0.955	

COLOR SCALE for NORMALIZED AVERAGE COHERENCE DATA

NO DATA	low	low - mid	mid	mid - high	high
⬜	🟩	🟩	🟨	🟧	🟥

Table 7 – Averages of normalized average coherence data (5 Hz to 9 kHz) for sensors with Cable A

AVERAGED NORMALIZED AVERAGE COHERENCE DATA for SENSORS with CABLE B (5 Hz to 9 kHz)

PCB SENSOR DESCRIPTION				EM FIELD LOCATION									
TYPE and M/N	**MODE and AXES**	**FEATURES**	**REF. AXIS**	**EME TOP**	**ELEC HEAT CABLE**	**KLE SIDE**	**KLE TOP**	**EME KLE CABLE**	**LOCAL HV BAT CABLE**	**HV BAT CABLE**	**EKK BOTTOM**	**EM BOTTOM**	**AVERAGE PER SENSOR**
MIC 378B02	ICP UNIAX	pre-polarized	X Y Z	0.854	0.344	0.886	0.575	0.494	0.760	0.959	0.399	0.755	0.670
ACCEL 356A70	CHARGE TRIAX	charge converter	X Y Z	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
ACCEL 356A02	ICP TRIAX	standard	X Y Z	0.316	0.328	0.610	0.393	0.395	0.567	0.505	0.372	0.933	0.491
ACCEL HT356A63	ICP TRIAX	filtered	X Y Z	0.448	0.295	0.689	0.596	0.455	0.525	0.402	0.479	1.000	0.543
ACCEL TLD356A16	ICP TRIAX	TEDS	X Y Z	0.397	0.319	0.600	0.596	0.487	0.749	0.533	0.465	0.969	0.568
ACCEL 354A04	ICP TRIAX	case isolated	X Y Z	0.393	0.365	0.540	0.654	0.503	0.765	0.434	0.488	0.918	0.562
ACCEL J356A43	ICP TRIAX	ground isolated	X Y Z	0.379	0.355	0.503	0.548	0.495	0.769	0.483	0.488	0.985	0.556
ACCEL 3713B11200G	DC TRIAX	single ended	X Y Z	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
ACCEL 3741F12100G	DC UNIAX	differential	X Y Z	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
ACCEL 355M87A	CVLD UNIAX	case isolated	X Y Z	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
AVERAGE PER EM FIELD LOCATION				0.464	0.334	0.638	0.560	0.471	0.689	0.553	0.448	0.927	

COLOR SCALE for NORMALIZED AVERAGE COHERENCE DATA

NO DATA	low	low - mid	mid	mid - high	high
⬜	🟩	🟩	🟨	🟧	🟥

Table 8 - Averages of normalized average coherence data (5 Hz to 9 kHz) for sensors with Cable B

Results – Averaged Normalized Average Coherence to Rank Influence of EM Fields

The EM Field locations are ranked by the influence on the sensor / cable signals, from highest to lowest, using the averaged normalized average coherence data in Table 7 and Table 8. These data appear in the bottom row of each table (with heading AVERAGE PER EM FIELD LOCATION as described in item 3 above). The Cable A data in Table 7 and the Cable B data in Table 8 exhibit similar and consistent trends.

- **Most Significant Influence** (orange-red)
  - **EM BOTTOM** (electric motor)
  - ❖ **Cable A / Table 7:** Highest averaged value of 0.955 (bottom row, column 9)
  - ❖ **Cable B / Table 8:** Highest averaged value of 0.927 (bottom row, column 9)
- **Second Most Significant Influence** (yellow, orange)
  - **KLE SIDE** (convenience charging electronics, side)
  - **KLE TOP** (convenience charging electronics, top)
  - **LOCAL HV BAT CABLE**
  - **HV BAT CABLE**
  - ❖ **Cable A / Table 7:** Second highest averaged values between 0.450 and 0.539 (bottom row, columns 3, 4, 6, 7)
  - ❖ **Cable B / Table 8:** Second highest averaged values between 0.553 and 0.689 (bottom row, columns 3, 4, 6, 7)
- **Second Least Significant Influence** (green-yellow)
  - **EME TOP** (electrical machine electronics)
  - **EME KLE CABLE** (electrical machine electronics / convenience charging electronics interconnect cable)
  - **EKK BOTTOM** (air conditioner compressor motor)
  - ❖ **Cable A / Table 7:** Next to lowest averaged values between 0.332 and 0.385 (bottom row, columns 1, 5, 8)
  - ❖ **Cable B / Table 8:** Next to lowest averaged values between 0.448 and 0.471 (bottom row, columns 1, 5, 8)
- **Least Significant Influence** (green)
  - **ELECTRIC HEAT CABLE**
  - ❖ **Cable A / Table 7:** Lowest averaged value of 0.258 (bottom row, column 2)
  - ❖ **Cable B / Table 8:** Lowest averaged value of 0.334 (bottom row, column 2)

Results – Averaged Normalized Average Coherence to Rank Sensor Types (by Cable A Only)

The sensor types are ranked by the influence of the HV EM Fields using the averaged normalized average coherence data from Table 7 in the right most column (with heading AVERAGE PER SENSOR as described in item 2 above). Only the Cable A data in Table 7 is used for ranking the sensor types since Cable B data in Table 8 only includes the ICP sensors.

- **Most Significantly Influenced** (yellow, orange)
    - **ICP**
    - **Charge**
    - **CVLD**
    - **Cable A / Table 7:** Highest averaged values between 0.434 and 0.669 (right most column, rows 1, 2, 3, 4, 5, 6, 7, 10)
    - **Cable B / Table 8:** not available
- **Least Significantly Influenced** (green, yellow)
    - **DC**
    - **Cable A / Table 7:** Lowest averaged values between 0.280 and 0.368 (right most column, rows 8, 9)
    - **Cable B / Table 8:** not available

Results – Averaged Normalized Average Coherence to Rank ICP Sensors

The individual ICP sensors are ranked by the influence of the HV EM Fields using the averaged normalized average coherence data from Table 7 and Table 8 in the right most column (with heading AVERAGE PER SENSOR as described in item 2 above). The Cable A data in Table 7 and the Cable B data in Table 8 exhibit a consistent trend only regarding the ICP microphone which ranks as the most significantly influenced sensor.

- **Most Significantly influenced** (orange)
    - **ICP Microphone**
    - **Cable A / Table 7:** Highest averaged value of 0.669 (right most column, row 1)
    - **Cable B / Table 8:** Highest averaged value of 0.670 (right most column, row 1)
- **Moderately Influenced** (yellow, yellow-orange)
    - **ICP Triaxial, standard**
    - **ICP Triaxial, filtered**
    - **ICP Triaxial, TEDS**
    - **ICP Triaxial, case isolated**
    - **ICP Triaxial, ground isolated**
    - **Cable A / Table 7:** Moderately averaged values between 0.434 and 0.552 (right most column, rows 3, 4, 5, 6, 7)
    - **Cable B / Table 8:** Moderately averaged values between 0.491 and 0.568 (right most column, rows 3, 4, 5, 6, 7)

Results – Averaged Normalized Average Coherence to Rank DC Sensors

The DC sensor types are ranked by the influence of the HV EM Fields using the averaged normalized average coherence data from Table 7 in the right most column (with heading AVERAGE PER SENSOR as described in item 2 above). Only the Cable A data in Table 7 is used for ranking the sensor types since Cable B data in Table 8 only includes the ICP sensors.

- **Moderately Influenced** (green-yellow)
  - **DC Triaxial, single ended**
  - ❖ **Cable A / Table 7:** Moderately averaged value of 0.368 (right most column, row 8)
  - ❖ **Cable B / Table 8:** not available
- **Least Significantly Influenced** (green)
  - **DC Uniaxial, differential**
  - ❖ **Cable A / Table 7:** Moderately averaged value of 0.280 (right most column, row 9)
  - ❖ **Cable B / Table 8:** not available

Significant Findings and Conclusions

The findings and conclusions below, regarding the normalized average coherence (or normalized) and the averaged normalized average coherence (or averaged normalized), take into consideration the realized range of the normalized average coherence values. The normalized average coherence values range from a minimum of 0.108 to a maximum of 1.000 with a corresponding linear color scale that fades from green to yellow to orange to red. A significant change in the normalized values or averaged normalized values is a value greater than 0.1 delta. A delta slightly greater than 0.1 approximately corresponds to the 7 colors in the color scale; green, green-yellow, yellow, yellow-orange, orange, orange-red, and red.

Cable A versus Cable B Performance – No Significant Performance Differences

- Only the ICP type sensors were evaluated with two different cable types where the cables are referred to as Cable A and Cable B. Reference Table 1 for cable model numbers that correspond to Cable A and Cable B for each ICP sensor. The captions in Figure 5 through Figure 10 also reference the Cable A and Cable B model numbers.
- Side by side comparisons of Cable A and Cable B using normalized average coherence data do not show consistent significant performance differences between the cables. Reference Figure 5 through Figure 10 and note that each pair of color bars overwhelmingly exhibit nearly the same values – indicating no significant performance differences between Cable A and Cable B.

HV EM Field Influence on Sensor Signals – EM BOTTOM Exhibits Most Significant Effects

- The EM Field local to the EM BOTTOM (EV electric motor) has the most influence on the NVH sensor signals.
- Regarding the ICP sensors, the side by side comparisons of normalized average coherence for Cable A and Cable B data show a strong trend in the EM BOTTOM as the most significant influence on the NVH sensor signals. Reference Figure 5 through Figure 10 and note the black color bars corresponding to the EM BOTTOM.
- The normalized average coherence data show the EM BOTTOM to consistently exhibit high or the highest normalized values. Reference Table 5 and Table 6 and note the column with the heading EM BOTTOM that exhibits red to orange-red colored cells corresponding to the highest normalized values.
- Similarly, the averaged normalized average coherence data for all sensors local to the EM BOTTOM consistently exhibit high or the highest normalized values. Reference Table 7 and Table 8 and note the column with the heading EM BOTTOM that exhibits red to orange-red colored cells corresponding to the highest averaged normalized values.

HV EM Field Influence on Sensor Signals – ELEC HEAT CABLE Exhibits Least Significant Effects

- The EM Field local to the ELEC HEAT CABLE has the least significant influence on the NVH sensor signals.
- Regarding the ICP sensors, the side by side comparisons of normalized average coherence for Cable A and Cable B data show a consistent trend in the ELEC HEAT CABLE as the least significant influence on the NVH sensor signals. Reference Figure 5 through Figure 10 and note the light blue color bars corresponding to the ELEC HEAT CABLE.
- Regarding all sensors collectively, the normalized average coherence data show the ELEC HEAT CABLE to consistently exhibit low or the lowest normalized values. Reference Table 5 and Table 6 and note the column with the heading ELEC HEAT CABLE that exhibits green to yellow colored cells corresponding to the lowest normalized values.
- Similarly, the averaged normalized average coherence data show the ELEC HEAT CABLE to consistently exhibit low or the lowest averaged normalized values. Reference Table 7 and Table 8 and note the column with the heading ELEC HEAT CABLE that exhibits green to green-yellow colored cells corresponding to the lowest averaged normalized values.

HV EM Field Influence on Sensor Types – DC Sensors Exhibit Least Significant Effects

- The DC sensors exhibit the least significant influence, overall, from the EM Fields.
- The normalized average coherence data for the DC sensors, with Cable A, show consistently low values. Reference Table 5 and note the rows for the DC TRIAX, single ended accelerometer and the DC UNIAX, differential accelerometer with the green and green-yellow cells corresponding to the lowest normalized values. Cable B data was not obtained for the DC sensors.
- Similarly, the averaged normalized average coherence data for the DC sensors, with Cable A, show consistently low values. Reference Table 7 and note the rows for the DC TRIAX, single ended accelerometer and the DC UNIAX, differential accelerometer with the green and green-yellow cells corresponding to the lowest averaged normalized values. Cable B data was not obtained for the DC sensors.
- Note that the DC UNIAX, differential accelerometer performs generally better than the DC TRIAX, single ended accelerometer – Table 5 and Table 7 show lower normalized values and lower averaged normalized values, respectively. However, the difference between the values and the corresponding cell colors is less than the definition of a “significant change”.

HV EM Field Influence on Sensor Types – CVLD Sensor Exhibits Second Least Significant Effects (with Ambiguity)

- The CVLD sensor appears to exhibit the second least significant influence from the EM Fields. However, large differences in the normalized average coherence results between the X, Y, and Z axes makes this conclusion ambiguous.
- The normalized average coherence data for the CVLD sensor, with Cable A, show consistently low values for the Y axis while showing consistently moderate and high values for the X and Z axes. Reference Table 5 and note the Y axis row for the CVLD UNIAX, case isolated accelerometer with the green cells corresponding to the lowest normalized values. Also note in Table 5 the X axis and Z axis rows for the CVLD UNIAX, case isolated accelerometer with the green-yellow to orange cells corresponding to moderate and high normalized values. Cable B data was not obtained for the CVLD sensors.
- The averaged normalized average coherence data for the CVLD sensor, with Cable A, shows consistently low values. Reference Table 7 and note the row for the CVLD UNIAX, case isolated accelerometer with the green-yellow cells corresponding to low averaged normalized values. The averaged normalized values are consistently low, but with ambiguity, due to the low normalized values of the Y axis biasing the average significantly lower than the X axis and Z axis normalized values (compare Table 7 data to Table 5 data). A possible explanation for the differences in EM Field directional sensitivity of the CVLD sensor is the configuration and orientation of the internal circuitry. Cable B data was not obtained for the CVLD sensor.

HV EM Field Influence on ICP Sensors – ICP Microphone Exhibits the Most Significant Influence

- The ICP Microphone exhibits the most significant influence from the EM Fields within the ICP types of sensors.
- The normalized average coherence data for the ICP Microphone, with Cable A and Cable B, show consistently high values. Reference Table 5 and Table 6 and note the rows for the ICP UNIAX Microphone with the primarily yellow, orange, and red cells corresponding to moderate and high normalized values.
- Similarly, the averaged normalized average coherence data for the ICP Microphone, with Cable A and Cable B, show high values. Reference Table 7 and Table 8 and note the rows for the ICP UNIAX Microphone with the orange and red cells corresponding to the higher averaged normalized values.

HV EM Field Influence on ICP Sensors – ICP Accelerometers Exhibit Moderate and Similar Influence

- The ICP Accelerometers exhibit moderate influence from the EM Fields within the ICP types of sensors.
- The normalized average coherence data for the ICP Accelerometers, with Cable A and Cable B, show large variations in coherence levels between the X, Y, and Z axes for each sensor. A consistent trend is not apparent to make a concise conclusion as to which sensor exhibits better performance. Reference Table 5 and Table 6 and note the rows for the ICP TRIAX Accelerometers with varying colors between the axes of the same accelerometer.
- Since the averaged normalized average coherence data, in Table 7 and Table 8, for the ICP Accelerometers, with Cable A and Cable B, is determined from the normalized average coherence in Table 5 and Table 6, and knowing the inter-axis variations of the normalized average coherence, it is not reasonable to make a conclusion whether one ICP accelerometer performs better than another. However, the ICP TRIAX Accelerometers consistently exhibit a trend that shows they perform better than the ICP Microphone.

Definitions of Abbreviations

NVH – Noise, Vibration, and Harshness

HV – High Voltage

* EM – Electromagnetic

EV – Electric Vehicle

HEV – Hybrid Electric Vehicle

ICP – Integrated Circuit Piezoelectric

CVLD – Constant Voltage Line Driver

TEDS – Transducer Electronic Data Sheet

EME – electrical machine electronics (BMW i3 vehicle electrical system)

KLE – convenience charging electronics (BMW i3 vehicle electrical system)

BAT – high voltage BATtery (BMW i3 vehicle electrical system)

EKK – electric motor driven air conditioner compressor (BMW i3 vehicle component)

* EM – Electric Motor (BMW i3 vehicle component)

DC – Direct Current electrical power

AC – Alternating Current electrical power

T – magnetic field measurement unit for Tesla for electromagnetic field strength

* The “EM” abbreviation has two different references that are distinguished by context:

1) when “EM” is succeeded by “Field” then “EM” refers to Electromagnetic

2) when “EM” is succeeded by “BOTTOM” then “EM” refers to Electric Motor

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