U.S. Department of
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**Federal Railroad
Administration**

PTC Radio Desense Mitigation Research, Phase 2: Filter Identification and Testing

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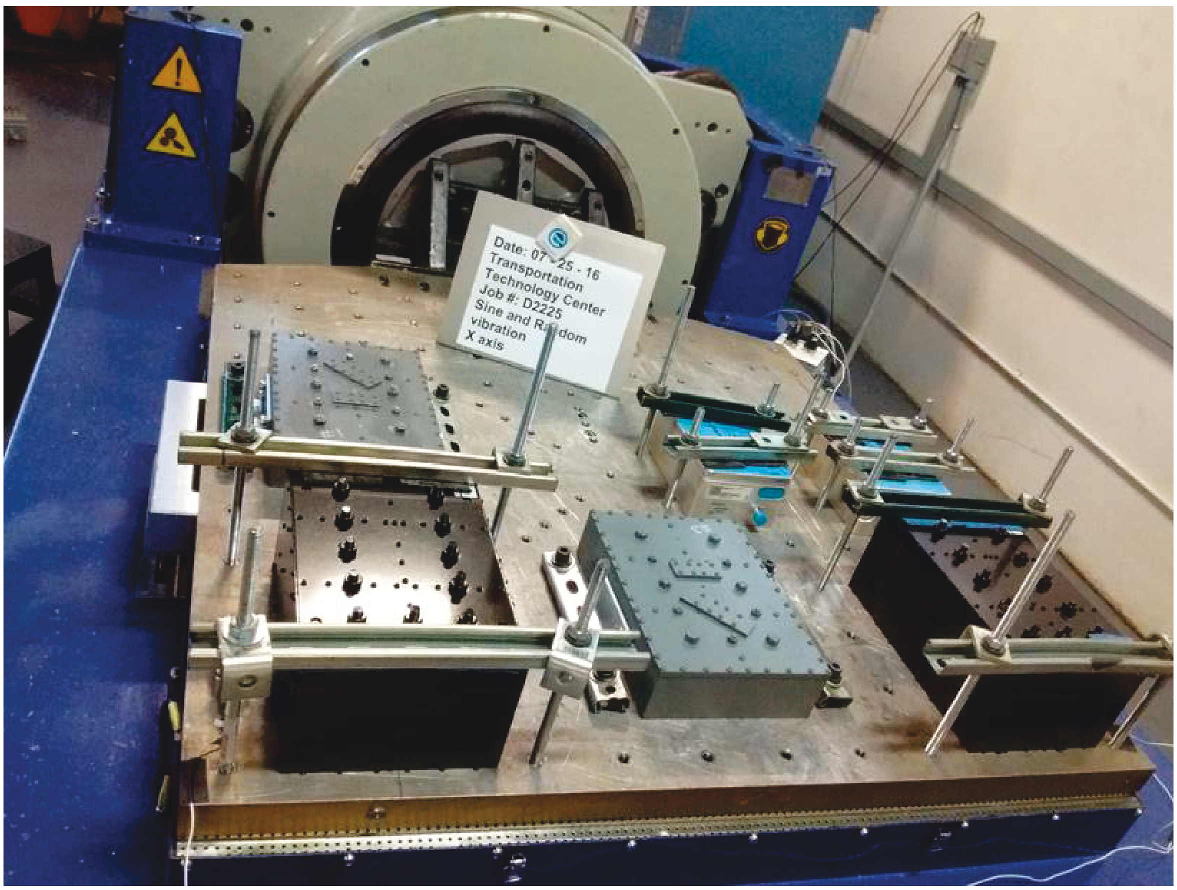
Washington, DC 20590



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13. ABSTRACT (Maximum 200 words)
The Federal Railroad Administration (FRA) sponsored a project, conducted by the Transportation Technology Center, Inc. (TTCI), to identify and evaluate 220 MHz radio filter technologies that are capable of meeting requirements developed for mitigation of 220 MHz Positive Train Control (PTC) radio desense for locomotives operating on and around the Northeast Corridor (NEC). In collaboration with members of the NEC Communications Team, TTCI developed a set of requirements for the 220 MHz locomotive filters. TTCI executed laboratory baseline tests in house as well as laboratory environmental tests at a facility located in Longmont, CO, and installed a subset of the filter samples on a TTCI locomotive for a period of exposure to operations representative of revenue service. Based on the test results, some railroads are moving forward with purchasing and installing filter technologies like those tested. Special consideration and care was suggested for filter installation location and installation methods, as both can affect filter performance.

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1 foot (ft)	=	30 centimeters (cm)	1 centimeter (cm)	=	0.4 inch (in)
1 yard (yd)	=	0.9 meter (m)	1 meter (m)	=	3.3 feet (ft)
1 mile (mi)	=	1.6 kilometers (km)	1 meter (m)	=	1.1 yards (yd)
			1 kilometer (km)	=	0.6 mile (mi)
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1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)	1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)	1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
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MASS - WEIGHT (APPROXIMATE)			**MASS - WEIGHT (APPROXIMATE)**		
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				=	1.1 short tons
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1 tablespoon (tbsp)	=	15 milliliters (ml)	1 liter (l)	=	2.1 pints (pt)
1 fluid ounce (fl oz)	=	30 milliliters (ml)	1 liter (l)	=	1.06 quarts (qt)
1 cup (c)	=	0.24 liter (l)	1 liter (l)	=	0.26 gallon (gal)
1 pint (pt)	=	0.47 liter (l)			
1 quart (qt)	=	0.96 liter (l)			
1 gallon (gal)	=	3.8 liters (l)			
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)	1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)	1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)
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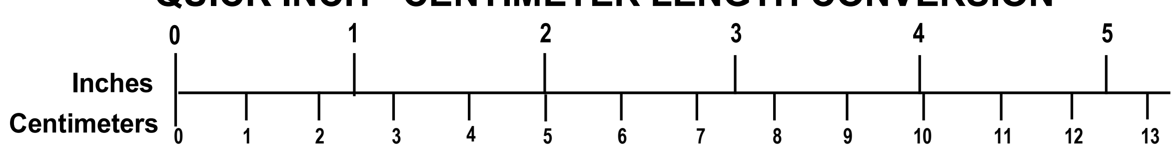

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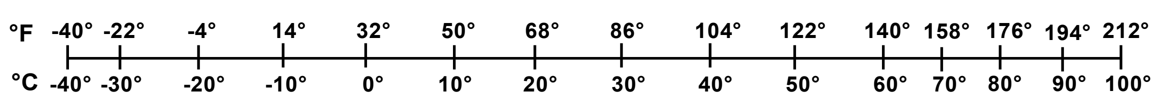

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Executive Summary

The Federal Railroad Administration (FRA) sponsored a project, conducted by Transportation Technology Center, Inc. (TTCI) on December 2015, to identify and evaluate 220 MHz radio filter technologies that are capable of meeting the requirements developed by TTCI for mitigation of 220 MHz Positive Train Control (PTC) radio desense for locomotives operating within the Northeast Corridor (NEC). The operation of dissimilar 220 MHz radio systems in close proximity was shown to cause performance degradation of both radio systems due to a desensitization phenomenon referred to simply as "desense."

The tasks performed in this project included:

- Development of requirements for 220 MHz filters for use on locomotives operating within the NEC
- Acquisition of test samples of 220 MHz filters from five filter vendors
- Preparation of test plans and procedures to characterize filter performance and feasibility of each filter technology to operate without degradation in performance within the shock, vibration, and thermal conditions of locomotives
- Execution of locomotive filter tests
- Reporting on test results and findings

The NEC has additional complexity compared with other areas because of the geographic co-location of dissimilar PTC systems. Throughout this project, TTCI collaborated with the NEC Communications Team, from here on referred to as the Advisory Group (AG), which was composed of telecommunication experts from railroads and the railroad supply industry, to perform project tasks. With the AG, TTCI developed requirements for the 220 MHz filters and issued a request for proposal (RFP) to 12 filter vendors identified by the AG. Ten proposals were received and evaluated; five vendors were selected for environmental testing. Each vendor provided two filter samples, one for the Interoperable Train Control (ITC) system and one for the Advanced Civil Speed Enforcement System (ACSES). Baseline measurements were completed for the 10 filters, and then the filter samples were subjected to environmental tests representative of the potential conditions associated with operation in a locomotive environment. Just as filters may be applied to ACSES and ITC fixed radio sites to mitigate mutual desense between the two radio systems, filters may also be applied to locomotives to reduce the impact of desense between ACSES and ITC mobile radios.

These tests included:

- Sinusoidal vibration
- Thermal exposure (Temperature Cycling and Temperature Extremes)
- PTC signal testing during random vibration
- Random vibration

The environmental requirements used in development of the test plan and procedures for the PTC 220MHz filters were developed on the basis of "Railroad Electronic Environmental Requirements" by the Association of American Railroad (AAR). [1]

Following environmental laboratory testing, a subset of the filter samples were installed on a TTCI locomotive for exposure to operations representative of revenue service. Post-test measurements were collected at the conclusion of all testing.

Of the 10 filters tested, 2 incurred permanent damage during testing. Due to timing, these filters were unable to be repaired and returned to repeat testing. For the remaining eight filter samples, six met the passband insertion loss requirement of 2.5 decibels (dB) or less, across the entire passband, during the post-test measurements. The other two exhibited small deviations from the passband requirement; these were ACSES filter samples and deviated at the 219 MHz passband corner. In discussions of the results with the filter manufacturers, the manufacturers anticipate these minor deviations can be addressed and improved upon.

All filter samples met the Tier II isolation requirements for the stopband, which are 45.6 dB for ACSES and 42.7 dB for ITC. Post-test measurements of five filters, two ACSES samples and three ITC samples, met the more stringent Tier I isolation requirements of 60.8 dB for ACSES and 57.7 for ITC.

During testing, it was identified that special consideration should be given to the method of filter installation and the location of installation. Improper securement may result in drastic changes to the filter response. Rapid change of temperature may cause the responses of the filter to shift, and should be avoided if possible. Consideration of these factors will help prevent unexpected degradations in PTC radio communications.

From the test results gathered during this project, members of the AG concluded that industry needs can be met with filter technologies similar to those tested. As a result, some railroads have already ordered and begun installing filters.

1. Introduction

The Federal Railroad Administration (FRA) sponsored a project, conducted by Transportation Technology Center, Inc. (TTCI), to identify and evaluate 220 MHz radio filter technologies that are capable of meeting requirements developed for mitigation of 220 MHz Positive Train Control (PTC) radio desense for locomotives operating within the Northeast Corridor (NEC).

1.1 Background

The Rail Safety Improvement Act of 2008 requires the implementation of interoperable PTC on rail lines identified therein. The scope of PTC implementation covers a significant portion of the national railroad network.

The NEC has additional complexity compared with other areas because of the geographic co-location of dissimilar PTC systems. Advanced Civil Speed Enforcement System (ACSES) is the PTC system being deployed by passenger and commuter railroads operating on and around the NEC, such as Amtrak, Long Island Rail Road (LIRR), and Metro-North Railroad (MNR). ACSES utilizes the General Electric (GE) TD220 data radios. The Class I freight railroads are deploying the Interoperable Train Control (ITC)-compliant PTC system, with ITC-compliant 220 MHz data radios developed by MeteorComm (MCC). The operation of dissimilar 220 MHz radio systems in close proximity was shown to cause performance degradation of both radio systems due to a desensitization phenomenon referred to simply as “desense.” In territories within the NEC, in which trains transition between ACSES and ITC, and in territories where ACSES and ITC trains operate over parallel track, the degradation in radio system performance may result in a degradation of PTC system performance that typically manifests as an increase in unnecessary onboard warning or enforcements.

An external filter may be inserted between the antenna port of a radio receiver and the antenna to reduce the effective bandwidth of the receiver. In the case of PTC deployments on the NEC, ITC deployments currently use channels in the 220 MHz to 222 MHz band, and many of the ACSES deployments use channels in the 217 MHz to 219 MHz band. The minimum 1 MHz spectral separation between ITC and ACSES channels allows for the use of passive cavity high pass filters at fixed sites, with a cutoff frequency of 220 MHz to protect ITC radios from ACSES transmissions, and passive cavity low pass filters with a cutoff frequency of 219 MHz to protect ACSES radio installations from ITC transmissions. Bandpass filters may be used instead of high pass or low pass filters.

Passive cavity filters are typically used in radio base station installations because they have a high-power handling capability (i.e., high power transmissions will not damage the filters), relatively low insertion loss, and a high-quality factor, Q. Filters that do not have a high-power handling capability, such as active crystal filter assemblies, require separate transmit and receive ports at the radio, so that the filter can be applied only to the receive port and avoid damage from higher power transmissions, or a transmit bypass mechanism that will shunt a higher power transmission around the filter.

Commercially available passive cavity filters can provide 80 dB reduction to ACSES signals in the 217 MHz to 219 MHz range received at the ITC radio, and a similar reduction to ITC signals in the 220 MHz to 222 MHz range received at the ACSES radio. Isolation of 80 dB between the ACSES and ITC radios is capable of preventing desense between ITC and ACSES radios installed in close proximity. Just as filters may be applied to ACSES and ITC fixed radio sites to mitigate mutual desense between the two radio systems, filters may also be applied to locomotives to reduce the impact of desense between ACSES and ITC mobile radios. The key differences are, depending on the extent of restrictions on physical size, practical locomotive filters will provide less isolation for the radio being protected than fixed site filters provide, and filter stability has yet to be tested in a locomotive vibration and shock environment. Also, due to the potential closer proximity of dissimilar PTC radios (e.g., on the same or nearby locomotive), greater isolation may be required from onboard filters than those at fixed sites. The risks associated with using filters to mitigate desense between ACSES mobile radios operating between 217 MHz and 219 MHz and ITC mobile radios operating between 220 MHz and 222 MHz are:

- The ability for filters to endure locomotive environmental conditions
- The ability for filters to be compact enough to fit within available locomotive space, particularly on crowded commuter locomotives
- The significant reduction or loss of filter effectiveness if any ACSES deployments use channels between 220 MHz and 222 MHz

The NEC railroads, in cooperation with PTC220 LLC, have worked with the Federal Communications Commission (FCC) to swap ACSES radio channels in the 220 MHz to 222 MHz range with channels in the 217 MHz to 219 MHz range to reduce the complexity of mitigating radio desense problems between ACSES and ITC. Those efforts resulted in reallocation of the spectrum used by PTC systems in the NEC to provide a minimum of 1 MHz spectral separation between ACSES and ITC radio channels.

At the time this project was initiated, the Amtrak ACSES deployment in New England, north of New Haven, CT, was planned to use channels in the 220 MHz to 222 MHz band, while using channels in the 217 MHz to 219 MHz band elsewhere on the NEC. To support Amtrak operations in both the NEC and in New England, a filter bypass would be required so that Amtrak does not filter out its own radio signals. The filter bypass would need to be automatically activated when the ACSES radio uses channels in the 220 MHz to 222 MHz band, and deactivated when the ACSES radio uses channels in the 217 MHz to 219 MHz band. Over the past year, PTC 220 LLC and Amtrak have worked with the FCC to identify and acquire channels in the 217 MHz to 219 MHz band in New England. That acquisition process is in progress, and once completed, Amtrak will not need a filter bypass in its locomotive deployments.

Two basic types of filters are commercially available that might be suitable for use in locomotives: passive cavity filter and active crystal filter assemblies. Any filters to be used on locomotives must be hardened against locomotive environmental conditions such as vibration, shock, and temperature extremes. Passive cavity filters are the type of filter commonly used in base station and fixed site radio installations. Passive cavity filters are typically larger than active crystal filters. Passive cavity filter implementations may employ proprietary design techniques to minimize the physical size.

Active cavity filters require a clean power source and offer a high level of isolation. They may include an active amplifier ahead of the actual crystal filter to compensate for their high insertion loss. A radio signal passing through an active crystal filter's passband may show an increase in signal strength (gain), due to the amplifier. The insertion loss of an active crystal filter may be masked by the amplifier gain, therefore the maximum noise figure (NF) is specified rather than insertion loss. The NF is the ratio of the signal-to-noise ratio (SNR) of the signal at the input of the filter to the SNR of the signal at the output of the filter, and is expressed in dB. The NF represents the degradation of the SNR caused by the filter. Also, the maximum input signal of an active crystal filter is limited by the amplifier which may be damaged or saturated, resulting in signal degradation when exposed to high power radio frequency (RF) signals.

1.2 Objectives

The objective of this project was to demonstrate the feasibility of using RF filters within the locomotive environment to provide mitigation of radio desense resulting from the use of PTC radios for ACSES and ITC operating in the same band on the NEC.

1.3 Overall Approach

To determine the suitability of RF filters as a solution for mitigating PTC locomotive radio desense on the NEC, TTCI did the following:

- Analyzed the transmission characteristics of the ITC and ACSES radios, and planned spectrum use on the NEC
- Determined the use cases in which ACSES and ITC locomotive radios may desense one another on the NEC
- Defined the functional and environmental requirements for a 220 MHz PTC locomotive filter
- Issued a request for proposal to RF filter suppliers
- Acquired test samples of 220 MHz filters
- Developed 220 MHz PTC locomotive filter test plan and procedures
- Executed 220 MHz PTC locomotive filter tests
- Documented and reported test results and findings

TTCI conducted this project in close cooperation with an Advisory Group comprised of the NEC Communications Team, further referred to as the AG. This AG consisted of representatives of railroads operating in the NEC, such as CSX Transportation, Inc., Norfolk Southern Corporation (NS), National Railroad Passenger Corporation (Amtrak), New Jersey Transit (NJT), LIRR, MNR, the FRA, and suppliers of PTC communication systems and equipment, such as Wabtec Railway Electronics, GE, and MCC.

1.4 Scope

The scope of the project included the identification and evaluation of filter technologies that may be suitable for mitigation of PTC locomotive radio desense between ACSES and ITC locomotive radios utilized on the NEC. Characterization of desense and mitigation approaches between two fixed radios have been addressed on other TTCI projects. Mitigation of desense for operational cases outside of the NEC were not considered. Multiple filter technologies were selected for evaluation, with each of five vendors providing an ACSES sample and an ITC sample. TTCI collaborated with the AG to:

- Define the functional and environmental requirements to be tested
- Identify operational cases to be considered in development of the test plan and procedure
- Select filter vendors for acquisition of test samples

Locomotive filter environmental tests focused on the demonstration of filter operation within the temperature extremes and shock/vibration environment of a locomotive, but were not intended to be exhaustive Association of American Railroads' (AAR) acceptance tests. The project was not intended to certify or endorse products, or provide pass/fail determination results for any specific test samples.

1.5 Organization of the Report

This report is organized into four major sections as follows:

- Section 1 provides background information on the project to aid in setting the context for the work performed.
- Section 2 provides an overview of the project tasks.
- Section 3 presents an overview of test results.
- Section 4 provides a summary of project findings and recommendations for next steps.

2. Project Overview

The PTC Filter Identification and Testing project consisted of the following four major technical tasks:

- Development of 220 MHz locomotive filter requirements
- Acquisition of filter test samples
- Preparation of filter test plans and procedures
- Execution of 220 MHz filter test

The following sections provide a summary of the listed project tasks.

2.1 220 MHz Locomotive Filter Requirements Development

Requirements were developed to define the functional, interface, and environmental requirements for filters to protect ACSES and ITC locomotive radios from desense. To identify the 220 MHz locomotive filter functional requirements, TTCI documented and analyzed:

- The physical transmission characteristics of the ITC and ACSES radios.
- The spectrum used with the ACSES and ITC deployments on the NEC.
- The use cases in which ACSES and ITC radios may desense one another.

The functional requirements for the 220 MHz locomotive filters include definitions of:

- The frequency band in which radio signals are passed with minimum loss (passband).
- The frequency band in which radio signals are rejected (stopband).
- The minimum amount that rejected signals are attenuated.
- The amount of RF power the filters need to withstand without damage.

To mitigate mutual desense between an ACSES radio and ITC radio installed on a single locomotive, TTCI determined an estimated minimum of 60.8 dB attenuation to the ITC radio transmission is required to prevent an ACSES radio from being desensed, and an estimated minimum of 57.7 dB attenuation to the ACSES radio transmission is required to prevent the ITC radio from being desensed. These required attenuation values assume that the ACSES and ITC antennas are spaced 2 to 5 feet apart and each radio transmits at full power. Greater separation between the ACSES and ITC radio antennas on a locomotive would reduce the required attenuation provided by filters. Practical considerations associated with mounting antennas upon the roof of a locomotive may prevent greater antenna separation.

Some PTC deployments on the NEC, particularly commuter railroad ACSES deployments, only require that locomotives be equipped with a single PTC radio. In this case, locomotive radio filtering is still beneficial in the mitigation of desense between two locomotives operating on adjacent track and mitigation of desense between a fixed site radio and a locomotive. In this scenario, the required amount of isolation to protect the dissimilar 220 MHz PTC radios would be reduced as the antenna would be spaced 12 or more feet apart, as opposed to being co-located on a single locomotive. In this case, propagation and link budget analysis showed that a minimum amount of needed attenuation to the ITC radio transmissions is 45.6 dB, and the estimated minimum amount of needed attenuation to the ACSES radio transmissions is 42.7 dB.

At the time that this project was initiated, the Amtrak ACSES deployment in New England, north of New Haven, CT, was planned to use channels in the 220 MHz to 222 MHz band, while using channels in the 217 MHz to 219 MHz band elsewhere on the NEC. To support Amtrak operations in both the NEC and in New England, a filter bypass would be required so that Amtrak does not filter out its own radio signals. The filter bypass would need to be automatically activated when the ACSES radio uses channels in the 220 MHz to 222 MHz band, and deactivated when the ACSES radio uses channels in the 217 MHz to 219 MHz band. Over the past year, PTC 220 LLC and Amtrak have worked with the FCC to identify and acquire channels in the 217 MHz to 219 MHz band in New England. That acquisition process is in progress, and once completed, Amtrak should not need a bypass for the desense filter in its locomotive deployments.

Two sets of functional requirements were defined: one set for filters to be used with ITC radios, and another set for filters to be used with ACSES radios. The key difference between the two sets of requirements is the passband for the filters. A filter with a passband of 217 MHz to 219 MHz would need to be installed on all ACSES locomotives operating on the NEC. Since ITC radios utilize a two-input diversity receiver to improve performance, two units of a filter with a passband of 220 MHz to 222 MHz would be needed on all ITC locomotives operating on the NEC. Installation of filters will not typically require modification to existing ACSES or ITC radio hardware, but will require additional cabling between the PTC radio and antenna, which would result in signal strength loss in addition to the filter insertion loss.

Two tiers of functional requirements were identified. Tier I requirements define 220 MHz filters capable of mitigating desense in the case where the ACSES and ITC radio antennas are both installed on a single locomotive at separation distances as close as 2 feet apart. As previously noted, filters satisfying Tier I requirements are needed on locomotives that are equipped to operate within both ACSES and ITC territories. Tier II requirements define 220 MHz filters capable of protecting an ACSES or ITC radio from desense in the situation where the other type of radio is transmitting on a locomotive located on an adjacent track. Distance between adjacent track centers is assumed to be as close as 12 feet. Locomotives equipped to operate with only ACSES or ITC may use filters satisfying only Tier II requirements. Tier I requirements are more stringent, and filters satisfying Tier I requirements also satisfy Tier II requirements.

The filter interface requirements include connector type at each port, characteristic impedance at each port, and maximum radio signal loss (insertion loss) or SNR degradation (noise factor) caused by the filter. In the case of connector type and characteristic impedance, the interface requirements for the 220 MHz locomotive filters were driven by the physical characteristics of the ACSES and ITC radios. The filter insertion loss or noise factor was driven by the signal link budget understood to be used in the radio network deployment design.

The environmental requirements for the 220 MHz locomotive filters were developed based on the AAR Manual of Standards and Recommended Practices (MSRP), Section K Part V, Standard S-9401, "Railroad Electronics Environmental Requirements" [1]. The focus of this project was to demonstrate the feasibility of RF filters to operate properly within the locomotive environment. As such, the key operation environmental requirements were the temperature range, vibration conditions, and mechanical shock.

Appendix A, "220 MHz PTC Locomotive Radio Filter Requirements," contains details of the information from which the functional requirements were derived, as well as the minimum requirements for both the ACSES and ITC 220 MHz locomotive filters. Table 1 provides a summary of the requirements for PTC locomotive radio filters. Note that these requirements are based on testing a limited number of radio samples, and therefore, do not account for potential variations in radio performance from sample to sample. Consequently, it is advised that those designing and implementing a PTC system add margin to the filter requirements, especially regarding the amount of isolation each filter is to provide.

Table 1. PTC Locomotive Radio Filter Minimum Requirements Summary

<table>
<tr><th colspan="2">Requirement</th><th>ITC Filter</th><th>ACSES Filter</th></tr>
<tr><td colspan="2">Passband</td><td>220 MHz to 222 MHz</td><td>217 MHz to 219 MHz</td></tr>
<tr><td colspan="2">Stopband</td><td>217 MHz to 219 MHz</td><td>220 MHz to 222 MHz</td></tr>
<tr><td rowspan="3">Tier 1</td><td>Minimum Stopband Attenuation</td><td>57.7 dB</td><td>60.8 dB</td></tr>
<tr><td>Radio Transmit Power</td><td>50 W</td><td>20 W</td></tr>
<tr><td>Receive Power</td><td>0.6 W</td><td>1.2 W</td></tr>
<tr><td rowspan="3">Tier 2</td><td>Minimum Stopband Attenuation</td><td>42.7 dB</td><td>45.6 dB</td></tr>
<tr><td>Radio Transmit Power</td><td>50 W</td><td>20 W</td></tr>
<tr><td>Receive Power</td><td>20 mW</td><td>40 mW</td></tr>
<tr><td rowspan="4">Interface</td><td>Connectors</td><td colspan="2">N-Type Receptical</td></tr>
<tr><td>Impedance</td><td colspan="2">50 Ohm</td></tr>
<tr><td>Maximum Insertion Loss or Noise Figure</td><td colspan="2">2.5 dB</td></tr>
<tr><td>Maximum Variable Standing Wave Radio</td><td colspan="2">1.5:1</td></tr>
<tr><td colspan="2">Environmental</td><td colspan="2">Per AAR MSRP S-9401</td></tr>
</table>

2.2 Acquisition of Filter Test Samples

TTCI issued a Request for Proposal (RFP) for 220 MHz locomotive filters on November 12, 2015. This RFP was sent to 12 filter vendors identified by the project AG. Proposals from 10 vendors were received by the December 18, 2015, response deadline, with 2 vendors declining to offer proposals. Since the purpose of this project was to demonstrate the feasibility of using filters to protect against mutual desense between dissimilar PTC radios, and not to qualify any specific products for use in the railroad industry, the specific vendors are not identified within this report.

The RFP indicated that proposals would be evaluated based on compliance of proposed filters to the requirements, and cost of acquisition of test samples. Evaluation criteria were selected to provide a comparative measure of each vendor's proposed solutions for ACSES and ITC 220 MHz locomotive filters. Each filter vendor proposal was scored to identify the filters to be acquired for the test. Filter proposal scores used the following criteria:

- 2 points awarded if proposed filter satisfies Tier I functional requirements.
- 2 points awarded if proposed filter satisfies Tier II functional requirements.
- 2 points awarded if proposed filter satisfies interface requirements.
- 1 point awarded for each aspect of the environmental requirements satisfied (operating temperature range, temperature extreme, vibration, and mechanical shock), for a maximum total of 4 points.
- Estimated development cost for each test sample filter. The following scale of 0 to 5 was used to assess the sample unit cost on the candidate solution's score:
  - 0 indicates that the cost to acquire test samples exceeds $20,000 per unit.
  - 1 indicates that the cost to acquire test samples is greater than $10,000 per unit, but does not exceed $20,000 per unit.
  - 2 indicates that the cost to acquire test samples is greater than $5,000 per unit, but does not exceed $10,000 per unit.
  - 3 indicates that the cost to acquire test samples is greater than $2,000 per unit, but does not exceed $5,000 per unit.
  - 4 indicates that the cost to acquire test samples is less than $2,000 per unit.
  - 5 indicates that the test samples may be acquired at no cost as loaned evaluation samples.

Table 2 provides a summary of each received proposal for ITC filters, and Table 3 is a summary of each received proposal for ACSES filters. TTCI, with concurrence from the project AG, obtained test samples of ITC and ACSES locomotive filters from the five offerors with the highest scores.

Table 2. Summary of ITC Locomotive Filter Proposal Evaluation Scores

ITC Filter Requirements		Vendor A	Vendor B	Vendor C	Vendor D	Vendor E	Vendor F	Vendor G	Vendor H	Vendor I	Vendor J
Tier 1 Functional		2	2	No	2	2	2	No	2	2	2
Tier 2 Functional		2	2	2	2	2	2	No	2	2	2
Interface		2	2	2	2	2	2	2	2	No	Undefined
Environmental	**Operating Temperature Range**	1	1	No	1	1	1	No	1	1	Undefined
	Temperature Extreme	1	Undefined	Undefined	1	1	1	Undefined	1	Undefined	Undefined
	Vibration	1	1	Undefined	1	1	1	Undefined	1	1	Undefined
	Mechanical Shock	1	1	Undefined	1	1	1	Undefined	1	1	Undefined
Test Sample Cost		3	4	4	5	0	4	4	5	4	3
Proposal Score		**13**	**13**	**8**	**15**	**10**	**14**	**6**	**15**	**11**	**7**

Table 3. Summary of ACSES Locomotive Filter Proposal Evaluation Scores

ACSES Filter Requirements		Vendor A	Vendor B	Vendor C	Vendor D	Vendor E	Vendor F	Vendor G	Vendor H	Vendor I	Vendor J
Tier 1 Functional		2	2	No	2	2	2	No	2	2	2
Tier 2 Functional		2	2	2	2	2	2	No	2	2	2
Interface		1	1	1	1	1	1	1	1	No	Undefined
Environmental	Operating Temperature Range	1	1	No	1	1	1	No	1	1	Undefined
	Temperature Extreme	1	Undefined	Undefined	1	1	1	Undefined	1	Undefined	Undefined
	Vibration	1	1	Undefined	1	1	1	Undefined	1	1	Undefined
	Mechanical Shock	1	1	Undefined	1	1	1	Undefined	1	1	Undefined
Test Sample Cost		3	4	4	5	0	4	4	5	4	3
Proposal Score		**12**	**12**	**7**	**14**	**9**	**13**	**5**	**14**	**11**	**7**

After analysis of filter proposals, samples from Vendors A, B, D, F, and H were obtained for testing. Vendors B, D, F, and H provided passive cavity filters, and Vendor A provided an active cavity filter.

2.3 Preparation of Filter Test Plan and Procedures

TTCI prepared a 220 MHz locomotive filter test plan and procedures document, which defined the tests that were to be conducted, test sequence, and measurements to be collected to determine whether a filter sample met the requirements. Appendix A contains the “220 MHz PTC Locomotive Filter Test Plan and Procedures” document. The test plan defined three stages of tests: laboratory baseline tests, laboratory environmental tests, and field tests. The laboratory baseline tests consisted of collecting a set of measurements for each filter to create a baseline characterization of each filter. The set of laboratory environmental tests was developed in collaboration with the AG, from what were considered to be the key operating environmental conditions in a locomotive environment: temperature variation, vibration conditions, and mechanical shock. Measurements were collected during and after the environmental testing for comparison to the baseline measurements. Field testing included the installation of a subset of filters on a TTCI locomotive for exposure to routine locomotive operating conditions. All measurements gathered during the baseline testing were repeated after each filter completed testing.

2.3.1 Laboratory Baseline Tests

The purpose of the laboratory baseline tests was to establish the characteristics and performance of each filter test sample before exposure to environmental testing. Baseline filter test results were used as a means of comparison to determine the impact of the exposure of the test samples to conditions defined within the environmental test and field test procedures.

The following baseline filter characteristics were recorded:

- 220 MHz Band Amplitude Response — measurement of the signal level that passed through the filter (in dB) with respect to frequency (in MHz) from 216 MHz to 223 MHz.
- Phase Response — relative measurement (in degrees) of the phase of the input signal to the phase of the signal output from the filter, with respect to frequency (in MHz).

- Voltage Standing Wave Ratio (VSWR) — measure of how efficiently RF power passed through the filter. VSWR is the ratio of the maximum and minimum voltages that resulted from RF power being reflected back to the source due to several factors, such as connectors, components, loads, and/or impedance mismatch of transmission lines. In an ideal system, in which 100 percent of the power is successfully transmitted through the filter, the VSWR would be 1.
- Impedance — internal impedance (in Ω) of the filter with respect to frequency (in MHz).
- 160 MHz Band Amplitude Response — amplitude response from 160 MHz to 162 MHz. This was collected to measure the isolation levels in the frequency ranges utilized for railroad handheld radios.
- 210 MHz Band Amplitude Response — amplitude response from 210 MHz to 216 MHz. This was requested by the AG, on the basis of expected incumbents within this frequency range.
- 450 MHz Band Amplitude Response — amplitude response from 451.1 MHz to 458.5 MHz. This was collected to measure the isolation levels in the frequency ranges utilized by end-of-train devices.
- 900 MHz Band Amplitude Response — amplitude response from 896 MHz to 922 MHz. This was collected to measure the isolation levels in the 900 MHz frequency range utilized for some ACSES operations on the NEC.
- Broadband Amplitude Response — amplitude response from 150 MHz to 950 MHz.

2.3.2 Laboratory Environmental Tests

TTCI collaborated with members of the AG to determine which environmental tests were most critical in determining the suitability of a filter for use on a locomotive. The following tests were selected in alignment with the key environmental operating conditions of concern, which were temperature variation and vibration/ mechanical shock:

- Sinusoidal Vibration
- Thermal Exposure (Temperature Cycling and Extremes)
- PTC Signal Testing During Random Vibration
- Random Vibration

In accordance with the AAR MSRP Standard S-9401.V1.0, Section 3.2.4, random vibration testing may be performed as an alternative to drop tests to demonstrate device tolerance to mechanical shock [1]. TTCI and the AG chose to have random vibration testing performed.

2.3.2.1 Sinusoidal Vibration

The purpose of sinusoidal vibration testing was to collect filter performance measurements after exposure to a range of frequencies that reflected the fundamental and harmonic frequencies that may be present within an operating locomotive environment. The vibration profile (frequencies and associated acceleration levels) and duration of the test were defined in accordance with the AAR MSRP Standard S-9401.V1.0 Section 3.2.4.1. [1]. Each filter was subjected to sinusoidal vibration for 4 hours on each of the three mutually perpendicular axes, totaling 12 hours of sinusoidal vibration per filter.

2.3.2.2 Thermal Exposure

Together, the AG and TTCI determined that the most pertinent thermal testing to be conducted was exposure of the filters to temperature extremes and temperature cycling.

2.3.2.2.1 Temperature Cycling

The temperature cycling was intended to collect filter performance measurements after exposure to the rapid temperature change that can occur in a locomotive environment. The temperature cycling test consisted of placing the filter in a thermal chamber set to -45 °C until the surface temperature of the filter reached -45 °C. The filter was transferred, in less than a minute, to a thermal chamber set to 105 °C, and the amplitude response was captured approximately every 10°C until the filter reached 75 °C. Once the filter surface temperature reached 75 °C, the filter was removed. Post-test measurements were completed after the filters were exposed to room temperature for a minimum of 1 day, thereby having internal and surface temperatures of approximately 23 °C.

The temperature cycling test was developed based on the AAR MSRP Standard S-9401.V1.0, Section 3.2.2.3.2, with the exception of conducting only 2 temperature cycles, rather than 75 cycles, as identified in the MSRP [1]. The AG and TTCI chose to perform abbreviated temperature cycling, as the intent was to assess if exposure to rapid temperature change resulted in permanent changes to the filter response, not to perform exhaustive acceptance testing.

2.3.2.2.2 Temperature Extremes

The intent of the temperature extreme test was to collect filter performance measurements at high and low temperature extremes that may exist in a locomotive environment. The test consisted of soaking the filters in a thermal chamber overnight to ensure that both the internal and surface temperature of the filter had reached the extreme temperature before taking measurements. The minimum temperature was -45 °C, and the maximum temperature was 75 °C. The temperature extreme test was developed based on the AAR MSRP Standard S-9401.V1.0 Section 3.2.2.3.1 [1].

2.3.2.3 PTC Signal Testing

The completed PTC signal test assessed if PTC message loss occurred as a result of the filter being exposed to vibration representative of a locomotive environment. The filter was secured to the vibration table and placed in line between a transmitting PTC radio and a receiving PTC radio. The test was set up such that only the filter was exposed to vibration, and the vibration profile was in accordance with the random vibration frequency profile defined in the AAR MSRP Standard S-9401.V1.0 Section 3.2.4.2 [1].

For ACSES filters, the transmitting and receiving radios utilized were the GE TD220x radios, and the transmitted signal level was attenuated to achieve a received signal strength of -85dBm at the receiving TD220x radio. For ITC filters, the transmitting radio utilized was the ITC MCC Base radio, and the receiving radio was the ITC MCC Locomotive radio. The transmitted signal level was attenuated to achieve a received signal strength of -94dBm at the receiving ITC Locomotive radio. A noise generator was included in the RF network to inject white noise at a level resulting in the receiving radio having an approximate packet error rate of 2 to 3 percent, before vibration. Received signal strength and noise levels were measured with a calibrated spectrum analyzer.

With the receiving radio experiencing a packet error rate of 2 to 3 percent, it would be more sensitive to additional message loss that could be induced if filter performance was degraded during vibration. During each test run, the radios were allowed to transmit and receive for 5 minutes while white noise was injected into the RF network. Transmit and receive message logs, noise signal measurements, and RF signal measurements at the receive radio were collected for each test run. Five test runs were completed without vibration, followed by five test runs while the filter was exposed to random vibration.

2.3.2.4 Random Vibration

The purpose of the random vibration test was to collect measurements of the filter performance during and after exposure to vibration conditions that may exist in a locomotive environment. The random vibration test subjected the filters to 4 hours of random vibration on each of the 3 axes, totaling 12 hours of random vibration. The vibration profile for this test was in accordance with the AAR MSRP Standard S-9401.V1.0 Section 3.2.4.2 [1].

2.3.3 Field Test

After the conclusion of environmental laboratory testing, a subset of filters was mounted on a shelf in the nose of one of TTCI's Facility for Accelerated Service Testing (FAST) locomotives. The FAST train runs Monday through Thursday on a 2.7-mile loop at an average operating speed of 40 miles per hour. This test subjected the filters to a locomotive environment for 144 hours and 37 minutes over a 6-week period.

2.3.4 Post Test

A full set of baseline measurements was repeated to serve as a set of post-test measurements for each filter. The measurements were collected at the conclusion of environmental laboratory testing or after field testing for applicable filters.

2.4 220 MHz Filter Test Execution

The baseline laboratory testing was performed at TTCI for each filter. Following the baseline laboratory testing, the filters were moved to a certified environmental test facility located in Longmont, CCO. The environmental testing began July 25, 2016, and concluded October 12, 2016. The 10 filter samples were separated into 2 groups determined by the filter samples available to begin testing in July 2016. The first group tested contained filters from Vendor D, Vendor F, and Vendor H. The second group contained filters from Vendor A and Vendor B. Once environmental testing was concluded, 4 filters were placed on a locomotive at TTCI's FAST facility for 144 hours of operation over a 6-week period. Selection of the filters to participate in field testing was limited to the first group of filters, as FAST operations began while the second group of filters was completing environmental testing. Due to space constraints, only four filters could be tested, and after a discussion with members of the AG, Vendors D and F were selected. Final post-test measurements for all filters were collected by repeating the set of measurements taken during the baseline testing.

3. Overview of 220 MHz PTC Locomotive Filter Test Results

As discussed in Section 2.3, throughout environmental testing, measurements were collected before, during, and after testing of each filter. Table 4 contains a list of the measurements collected for baseline testing, after each environmental test, and at the conclusion of all testing.

Table 4. Test Sequence and Artifacts

Sequence	Test	Artifacts
1	Baseline	Filter Amplitude Response raw data and instrument screen capture files
		Filter Phase Response raw data and instrument screen capture files
		Filter Passband Voltage Standing Wave Ratio raw data and instrument screen capture files
		Filter Passband Impedance raw data and instrument screen capture files
		Filter Amplitude Response 160 MHz Band raw data and instrument screen capture files
		Filter Amplitude Response 450 MHz Band raw data and instrument screen capture files
		Filter Amplitude Response 900 MHz Band raw data and instrument screen capture files
		Broadband Filter Amplitude Response raw data and instrument screen capture files
		Filter Amplitude Response 210 MHz Band raw data and instrument screen capture files
2	Sinusoidal Vibration Test	Filter Amplitude Response raw data and instrument screen capture files
		Filter Phase Response raw data and instrument screen capture files
		Filter Passband Voltage Standing Wave Ratio raw data and instrument screen capture files
		Filter Passband Impedance raw data and instrument screen capture files
		Broadband Filter Amplitude Response raw data and instrument screen capture files
3	Thermal Extremes Test	Filter Amplitude Response raw data and instrument screen capture files

Table 5. Test Sequence and Artifacts Continued

Sequence	Test	Artifacts
4	Thermal Cycling Test	Filter Amplitude Response raw data and instrument screen capture files
		Filter Phase Response raw data and instrument screen capture files
		Filter Passband Voltage Standing Wave Ratio raw data and instrument screen capture files
		Filter Passband Impedance raw data and instrument screen capture files
		Broadband Filter Amplitude Response raw data and instrument screen capture files
5	PTC Signal Test	Message Radio Logs
		PTC Test Sheet
		Signal Level raw data and instrument screen capture files
6	Random Vibration Test	Filter Amplitude Response raw data and instrument screen capture files
		Filter Phase Response raw data and instrument screen capture files
		Filter Passband Voltage Standing Wave Ratio raw data and instrument screen capture files
		Filter Passband Impedance raw data and instrument screen capture files
		Broadband Filter Amplitude Response raw data and instrument screen capture files
7	Post Environmental (After environmental laboratory tests, or after field tests, for applicable filters)	Filter Amplitude Response raw data and instrument screen capture files
		Filter Phase Response raw data and instrument screen capture files
		Filter Passband Voltage Standing Wave Ratio raw data and instrument screen capture files
		Filter Passband Impedance raw data and instrument screen capture files
		Filter Amplitude Response 160 MHz Band raw data and instrument screen capture files
		Filter Amplitude Response 450 MHz Band raw data and instrument screen capture files
		Filter Amplitude Response 900 MHz Band raw data and instrument screen capture files
		Broadband Filter Amplitude Response raw data and instrument screen capture files
		Filter Amplitude Response 210 MHz Band raw data and instrument screen capture files

To provide a summary of filter performance in a concise manner, amplitude response traces for each filter are presented and discussed in Sections 3.1.1 through 3.4.2. The amplitude response provides a measurement of the signal level that passed through the filter (in dB) with respect to frequency (in MHz). Red dashed vertical lines on each plot correspond to the limits of the passbands and stopbands, while the horizontal red dashed lines indicate the requirements for Tier I and Tier II isolation levels, and insertion loss.

Results for the ITC filters are presented in Section 3.1, and results for the ACSES filters are presented in Section 3.2. Section 3.3 provides a summary of all test results, and Section 3.4 discusses additional observations from testing.

3.1 ITC Test and Results

The requirements for the ITC filters are:

- Passband: 220-222 MHz
- Stopband: 217-219 MHz
- Tier I Isolation: 57.7 dB
- Tier II Isolation: 42.7 dB
- Maximum Insertion Loss: 2.5 dB

Summaries of the test results for each vendor's ITC filter sample are provided in the following subsections.

3.1.1 Vendor A

Figure 1 shows the baseline and post environmental amplitude responses for the Vendor A ITC filter. The baseline measurement was the initial measurement of the filter before testing, and the post environmental measurement was taken after all testing was completed. Amplitude response traces above the green-shaded rectangle indicate filter conformance to passband and insertion loss requirements. Amplitude response traces below the red-shaded rectangles indicate filter conformance to the requirements for stopband and Tier I and II isolation levels.

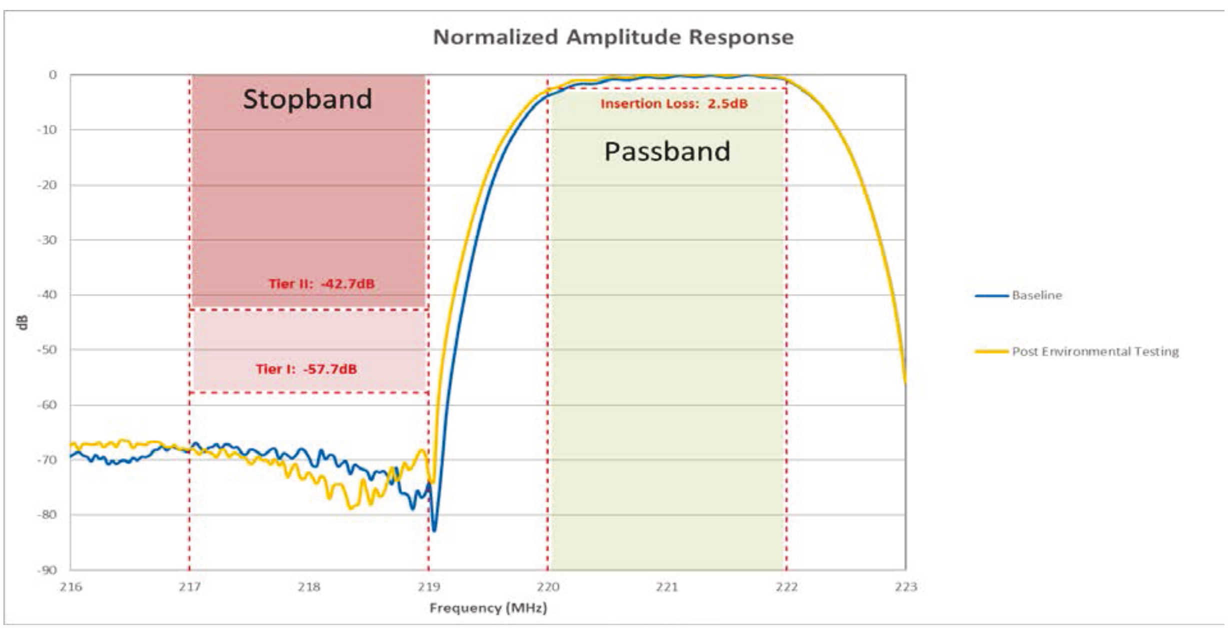

Figure 1. Vendor A Amplitude Response ITC Filter Characterization

Table 6 shows the results of the baseline and post environment amplitude response for the passband, split into 250 kHz steps, for the Vendor A ITC filter. The first step begins at the lowest ITC channel, channel 101, with a center frequency of 220.1125 MHz, and the last step ends at the highest ITC channel, channel 174, with a center frequency of 221.9375 MHz. Consequently, the first step spans 150 kHz and the last step spans 200 kHz. Displaying results in frequency steps allows for an evaluation of filter performance in frequency ranges of interest, based on the planned channel usage. For each step, the "Percent in Spec" column indicates the percentage of passband frequencies within the range represented by that step that met the insertion loss requirement. If the filter did not meet the requirement for that step, the average and maximum deviation from the requirement, within the frequency step, is provided.

Table 6. Vendor A ITC Passband Results

Vendor A																								
	Passband (MHz)																							
	220.100 - 220.250			220.250 - 220.500			220.500 - 220.750			220.750-221.000			221.1125 - 221.250			221.250 - 221.500			221.500 - 221.750			221.750-221.950		
Test	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)
Baseline	75%	0.2	0.2	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-
Post	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-

Table 7 shows the percentage of the stopband that met the Tier I and Tier II isolation requirements for the Vendor A ITC filter. If the filter did not meet the requirement, then the average and maximum deviation from the requirement, across the entire stopband, is provided. Table 7 also provides the physical dimensions of the filter, and the percentage of the passband in which the VSWR met the requirement of 1.5:1 or lower. The VSWR is a measure of how efficiently RF power passed through the filter.

Table 7. Vendor A ITC Filter Characteristics, Stopband, and VSWR Results

Vendor A									
	Tier I			Tier II			VSWR		
	217.0-219.0			217.0-219.0			220.0-222.0		
Test	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Filter Dimensions	Filter Weight
Baseline	100%	-	-	100%	-	-	72%	8" x 8" x 8"	12 lbs
Post	100%	-	-	100%	-	-	32%		

Figure 2 shows the amplitude response from the temperature extremes testing for the Vendor A ITC filter. The blue trace shows the response at the cold extreme temperature of -45 °C, and the red trace shows the response at the hot extreme temperature of 75 °C. The green trace shows the baseline taken before environmental testing.

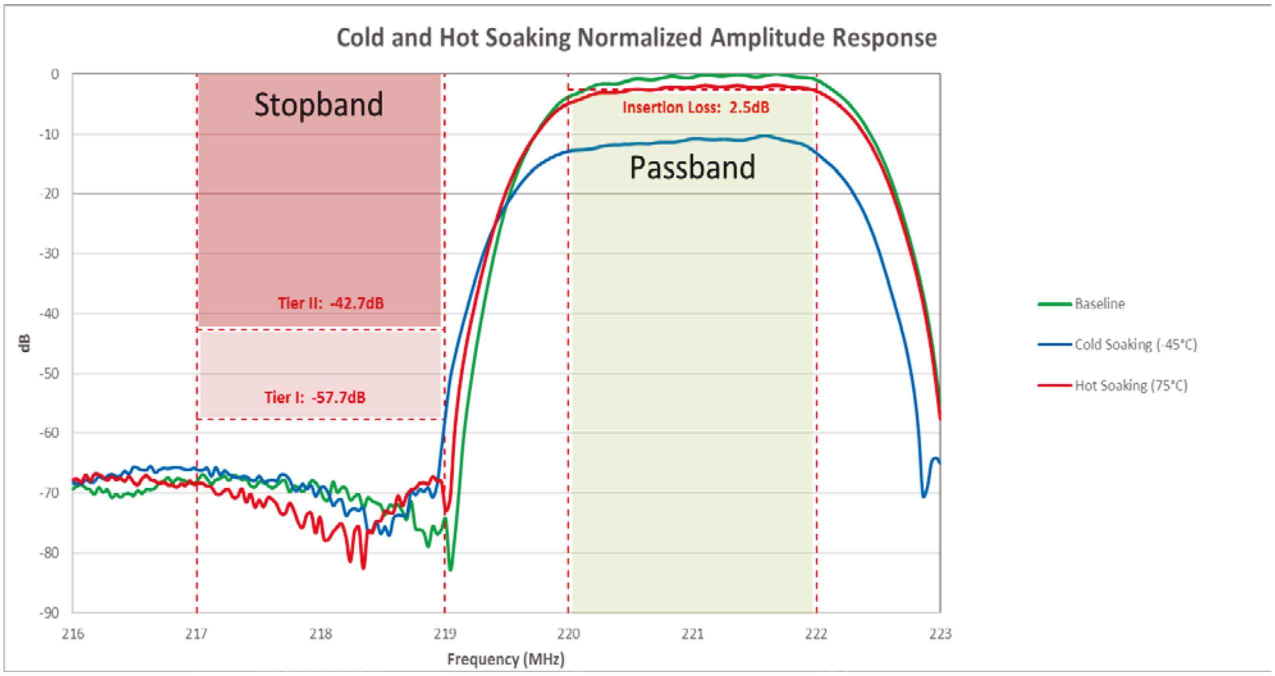

Figure 2. Vendor A ITC Amplitude Response for Temperature Extreme Tests

The ITC filter sample from Vendor A had a severe drop in amplitude, approximately 6dB, when soaked overnight at -45 °C, as shown in Figure 2. The filter's amplitude response returned to baseline levels as the temperature was increased. This filter did not experience a similar response during the hot extreme temperature of 75 °C. The Vendor A ACSES filter also experienced a similar drop. No other filters had similar amplitude response changes when exposed to the minimum or maximum temperatures overnight.

3.1.2 Vendor B

Figure 3 shows the baseline and the post environmental amplitude responses. The baseline was the initial measurement of the filter, and the post environmental measurement was taken after all testing was concluded. Amplitude response traces above the green-shaded rectangle indicate filter conformance to passband and insertion loss requirements. Amplitude response traces below the red-shaded rectangles indicate filter conformance to the requirements for stopband and Tier I and II isolation levels.

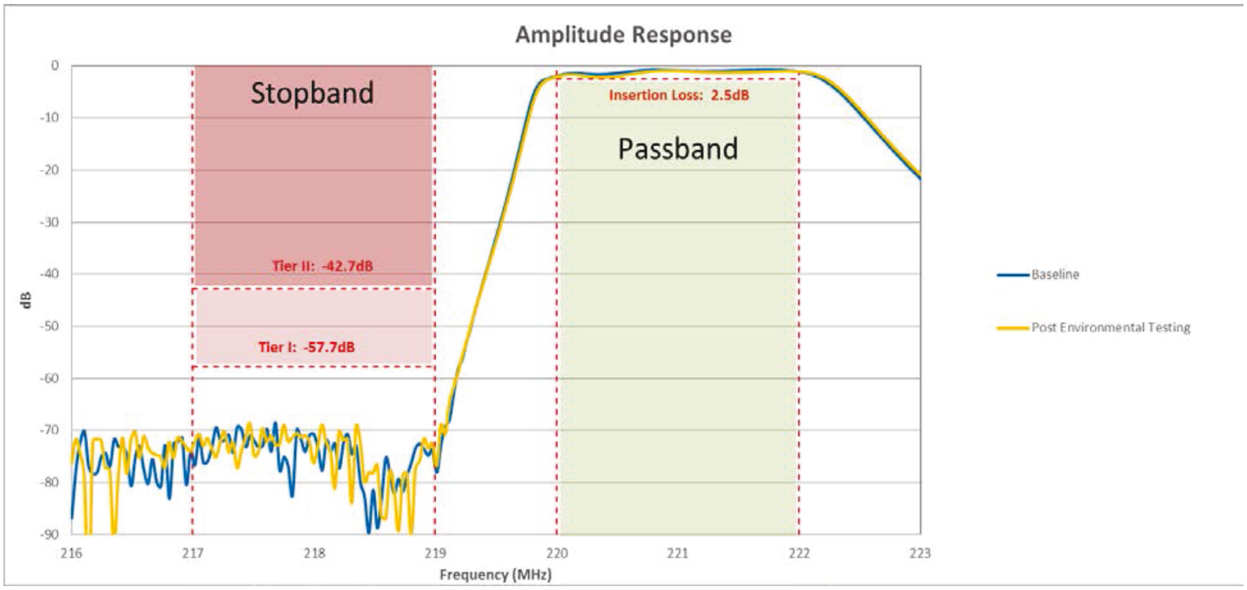

Figure 3. Vendor B Amplitude Response ITC Filter Characterization

Table 8 shows the results of the baseline and post environment amplitude response for the passband, split into 250 kHz steps, for the Vendor B ITC filter. The first step begins at the lowest ITC channel, channel 101, with a center frequency of 220.1125 MHz, and the last step ends at the highest ITC channel, channel 174, with a center frequency of 221.9375 MHz. Consequently, the first step spans 150 kHz and the last step spans 200 kHz. Displaying the results in frequency steps allows for evaluation of filter performance in frequency ranges of interest, based on planned channel usage. For each step, the "Percent in Spec" column indicates the percentage of passband frequencies within the range represented by that step that met the insertion loss requirement. If the filter did not meet the requirement for that step, the average and maximum deviation from the requirement, within the frequency step, is provided.

Table 8. Vendor B ITC Passband Results

	Vendor B																							
	Passband (MHz)																							
	220.100 - 220.250			220.250 - 220.500			220.500 - 220.750			220.750- 221.000			221.1125 - 221.250			221.250 - 221.500			221.500 - 221.750			221.750- 221.950		
Test	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)
Baseline	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-
Post	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-

Table 9 shows the percentage of the stopband that met the Tier I and Tier II isolation requirements for the Vendor B ITC filter. If the filter did not meet the requirement, then the average and maximum deviation from requirement, across the entire stopband, is provided. Table 9 also provides the physical dimensions of the filter, and the percentage of the passband in which the VSWR met the requirement of 1.5:1 or lower.

Table 9. Vendor B ITC Filter Characteristics, Stopband, and VSWR Results

Vendor B									
	Tier I 217.0-219.0			Tier II 217.0-219.0			VSWR 220.0-222.0		
Test	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Filter Dimensions	Filter Weight
Baseline	100%	-	-	100%	-	-	100%	12.6" x 8.5" x 5.7"	14.2 lbs
Post	100%	-	-	100%	-	-	95%		

Figure 4 shows the amplitude response from the temperature extremes testing for the Vendor B ITC filter. The blue trace shows the response at the cold extreme of -45 °C, and the red trace shows the response at the hot extreme of 75 °C. The green trace shows the baseline taken before environmental testing.

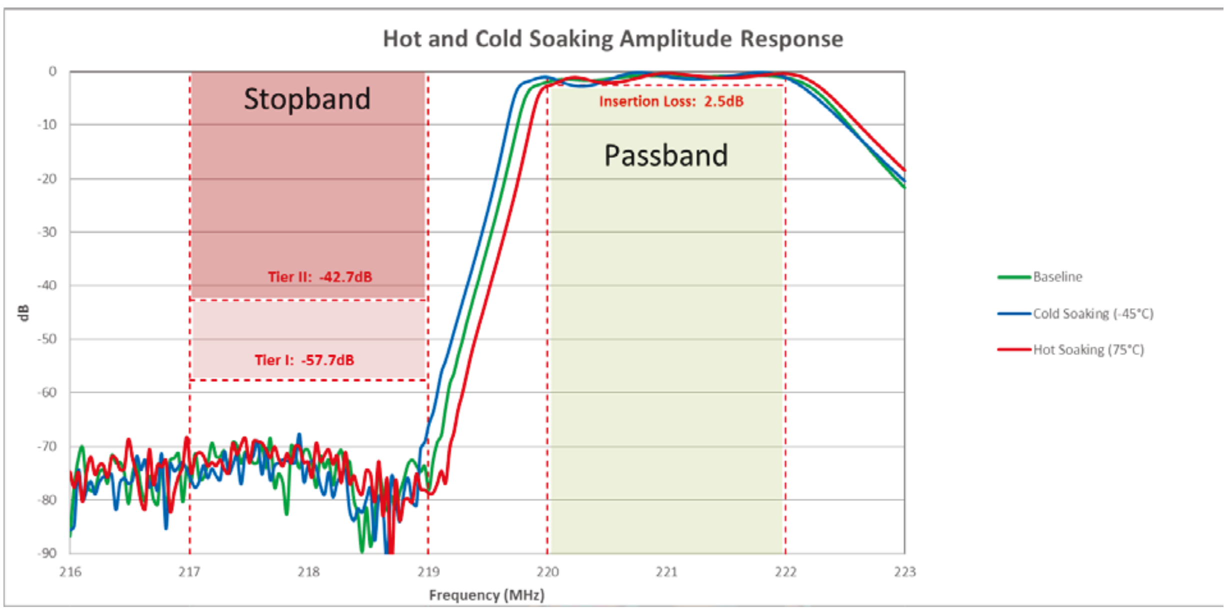

Figure 4. Vendor B ITC Amplitude Response for Temperature Extreme Tests

Approximately 2 hours into sinusoidal vibration, the Vendor B ITC filter was found to have an audibly loose internal component. As a result, both of the Vendor B filters were removed from vibration testing and sent back to the vendor for repair. The filters were repaired and returned in time to fully participate in the testing.

3.1.3 Vendor D

Figure 5 shows the baseline and the post environmental amplitude responses. The baseline was the initial measurement of the filter, and the post environmental measurement was taken after all testing was completed. Amplitude response traces above the green-shaded rectangle indicate filter conformance to passband and insertion loss requirements. Amplitude response traces below the red-shaded rectangles indicate filter conformance to the requirements for stopband and Tier I and II isolation levels.

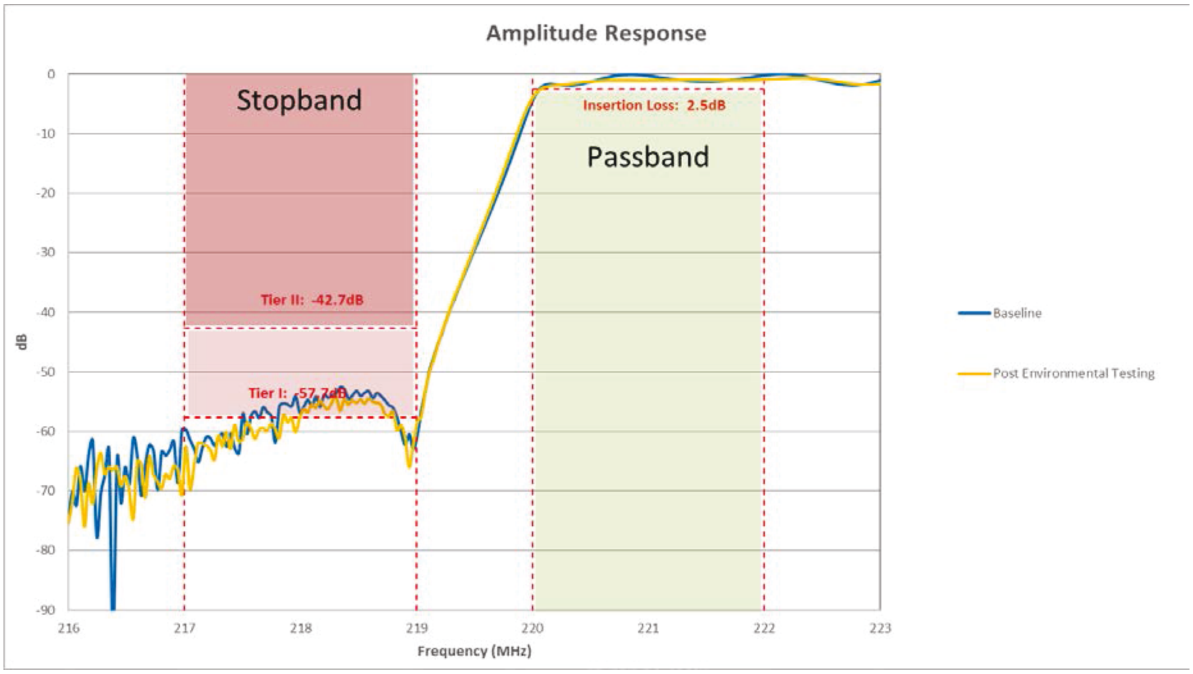

Figure 5. Vendor D Amplitude Response ITC Filter Characterization

Table 10 shows the results of the baseline and post environment amplitude response for the passband, split into 250 kHz steps, for the Vendor D ITC filter. The first step begins at the lowest ITC channel, channel 101, with a center frequency of 220.1125 MHz, and the last step ends at the highest ITC channel, channel 174, with a center frequency of 221.9375 MHz. Consequently, the first step spans 150 kHz and the last step spans 200 kHz. Displaying results in frequency steps allows for an evaluation of filter performance in frequency ranges of interest, based on planned channel usage. For each step, the “Percent in Spec” column indicates the percentage of passband frequencies within the range represented by that step that met the insertion loss requirement. If the filter did not meet the requirement for that step, the average and maximum deviation from the requirement, within the frequency step, is provided.

Table 10. Vendor D ITC Passband Results

	Vendor D																							
	Passband (MHz)																							
	220.100 - 220.250			220.250 - 220.500			220.500 - 220.750			220.750- 221.000			221.1125 - 221.250			221.250 - 221.500			221.500 - 221.750			221.750- 221.950		
Test	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)
Baseline	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-
Post	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-

Table 11 shows the percentage of the stopband that met the Tier I and Tier II isolation requirements for the Vendor D ITC filter. If the filter did not meet the requirement, then the average and maximum deviation from the requirement, across the entire stopband, is provided. Table 11 also provides the physical dimensions of the filter, and the percentage of the passband in which the VSWR met the requirement of 1.5:1 or lower.

Table 11. Vendor D ITC Filter Characteristics, Stopband, and VSWR Results

	Vendor D								
	Tier I			Tier II			VSWR		
	217.0-219.0			217.0-219.0			220.0-222.0		
Test	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Filter Dimensions	Filter Weight
Baseline	37%	1.40	5.14	100%	-	-	100%	3.5" x 12.42" x 8.75"	31.7 lbs
Post	58%	0.95	3.61	100%	-	-	100%		

Figure 6 shows the amplitude response from the temperature extremes testing for the Vendor D ITC filter. The blue trace shows the response at the cold extreme temperature of -45 °C and the red trace shows the response at the hot extreme temperature of 75 °C. The green trace shows the baseline taken before environmental testing.

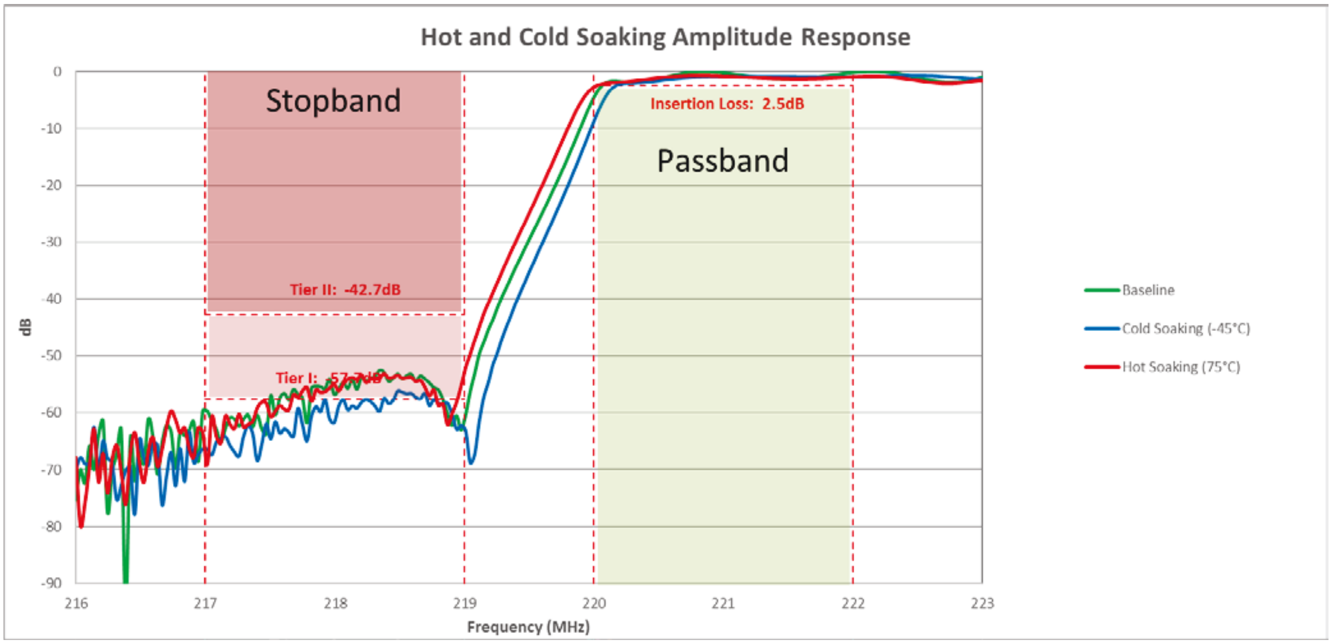

Figure 6. Vendor D ITC Amplitude Response for Temperature Extreme Tests

3.1.4 Vendor F

Figure 7 shows the baseline and the post environmental amplitude responses. The baseline was the initial measurement of the filter, and the post environmental measurement was taken after all testing was completed. Amplitude response traces above the green-shaded rectangle indicate filter conformance to passband and insertion loss requirements. Amplitude response traces below the red-shaded rectangles indicate filter conformance to the requirements for stopband and Tier I and II isolation levels.

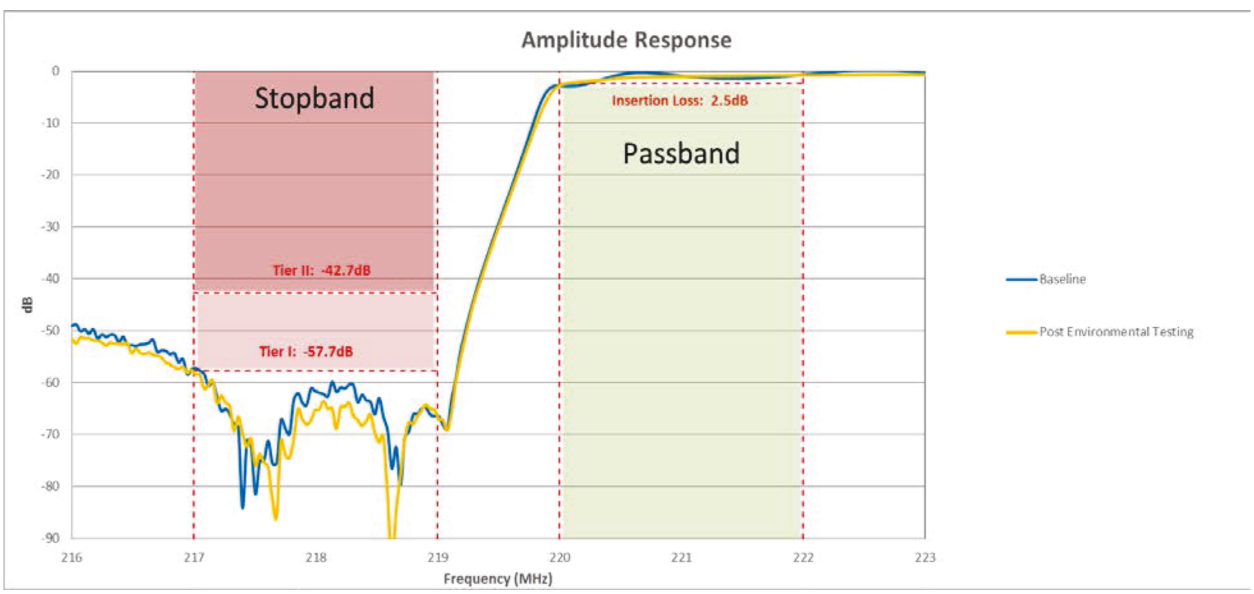

Figure 7. Vendor F Amplitude Response ITC Filter Characterization

Table 12 shows the results of the baseline and post environment amplitude response for the passband, split into 250 kHz steps, for the Vendor F ITC filter. The first step begins at the lowest ITC channel, channel 101, with a center frequency of 220.1125 MHz, and the last step ends at the highest ITC channel, channel 174, with a center frequency of 221.9375 MHz. Consequently, the first step spans 150 kHz and the last step spans 200 kHz. Displaying results in frequency steps allows for an evaluation of filter performance in frequency ranges of interest, based on planned channel usage. For each step, the "Percent in Spec" column indicates the percentage of passband frequencies within the range represented by the step that met the insertion loss requirement. If the filter did not meet the requirement for that step, the average and maximum deviation from the requirement, within the frequency step, is provided.

Table 12. Vendor F ITC Passband Results

Vendor F																								
	Passband (MHz)																							
	220.100 - 220.250			220.250 - 220.500			220.500 - 220.750			220.750- 221.000			221.1125 - 221.250			221.250 - 221.500			221.500 - 221.750			221.750- 221.950		
Test	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)
Baseline	20%	0.21	0.37	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-
Post	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-

Table 13 shows the percentage of the stopband that met the Tier I and Tier II isolation requirements for the Vendor F ITC filter. If the filter did not meet the requirement, then the average and maximum deviation from the requirement, across the entire stopband, is provided. Table 13 also provides the physical dimensions of the filter, and the percentage of the passband in which the VSWR met the requirement of 1.5:1 or lower.

Table 13. Vendor F ITC Filter Characteristics, Stopband, and VSWR Results

Vendor F									
	Tier I			Tier II			VSWR		
	217.0-219.0			217.0-219.0			220.0-222.0		
Test	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Filter Dimensions	Filter Weight
Baseline	96%	0.32	0.57	100%	-	-	100%	5.9" x 3.6" x 8.6"	11.2 lbs
Post	100%	-	-	100%	-	-	100%		

Figure 8 shows the amplitude response from the temperature extremes testing for the Vendor F ITC filter. The blue trace shows the response at the cold extreme temperature of -45 °C, and the red trace shows the response at the hot extreme temperature of 75 °C. The green trace shows the baseline taken before environmental testing.

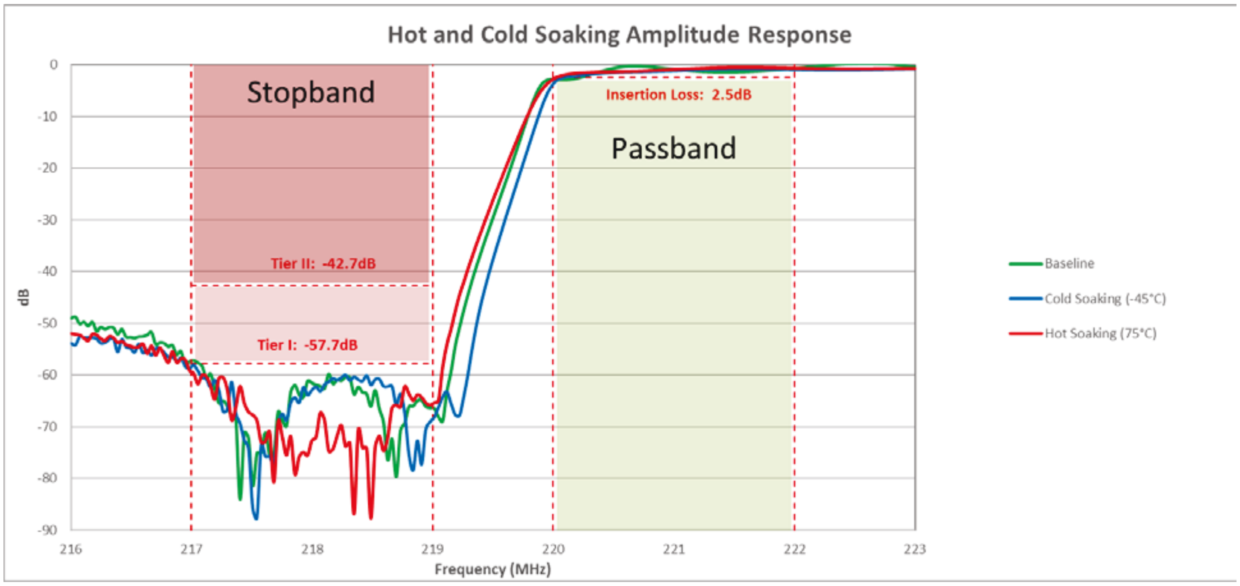

Figure 8. Vendor F ITC Amplitude Response for Temperature Extreme Tests

3.1.5 Vendor H

Figure 9 shows the baseline and the post environmental amplitude responses. The baseline was the initial measurement of the filter, and the post environmental measurement was taken after all testing was completed. Amplitude response traces above the green-shaded rectangle indicate filter conformance to passband and insertion loss requirements. Amplitude response traces below the red-shaded rectangles indicate filter conformance to the requirements for stopband and Tier I and II isolation levels.

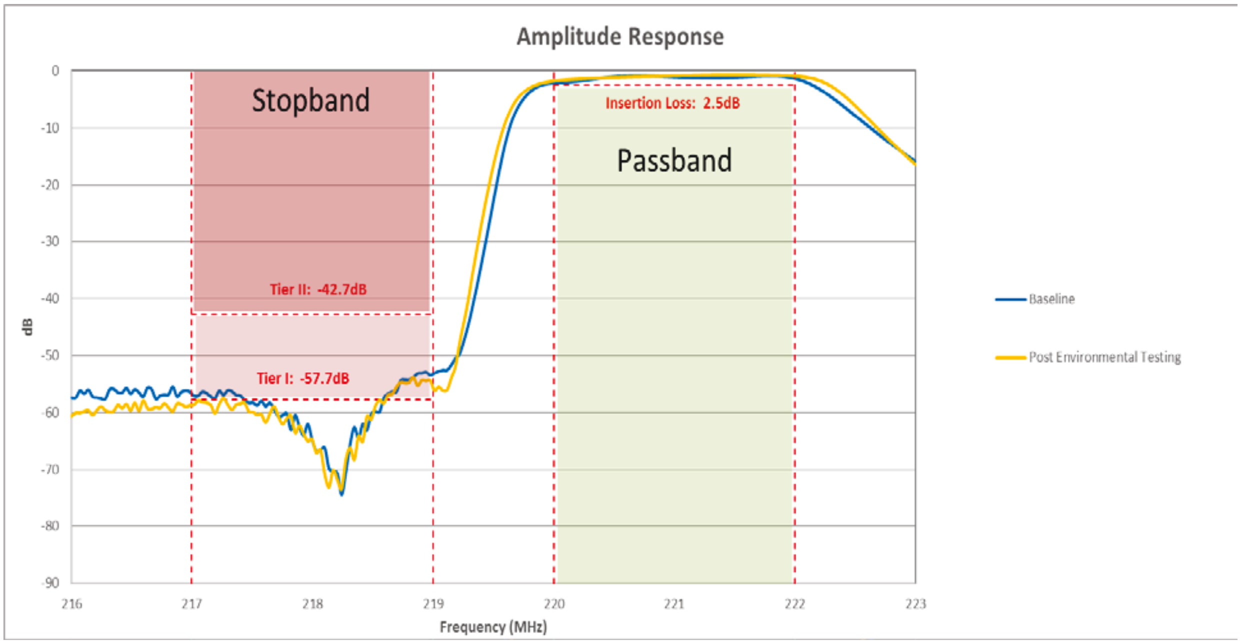

Figure 9. Vendor H Amplitude Response ITC Filter Characterization

Table 14 shows the results of the baseline and post environment amplitude response for the passband, split into 250 kHz steps, for the Vendor H ITC filter. The first step begins at the lowest ITC channel, channel 101, with a center frequency of 220.1125 MHz, and the last step ends at the highest ITC channel, channel 174, with a center frequency of 221.9375 MHz. Consequently, the first step spans 150 kHz and the last step spans 200 kHz. Displaying results in frequency steps allows for an evaluation of filter performance in frequency ranges of interest, based on planned channel usage. For each step, the "Percent in Spec" column indicates the percentage of passband frequencies within the range represented by that step that met the insertion loss requirement. If the filter did not meet the requirement for that step, the average and maximum deviation from the requirement, within the frequency step, is provided.

Table 14. Vendor H ITC Passband Results

	Vendor H																							
	Passband (MHz)																							
	220.100 - 220.250			220.250 - 220.500			220.500 - 220.750			220.750- 221.000			221.1125 - 221.250			221.250 - 221.500			221.500 - 221.750			221.750- 221.950		
Test	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)
Baseline	100%	-	-	100%			100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-
Post	100%	-	-	100%			100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-

Table 15 shows the percentage of the stopband that met the Tier I and Tier II isolation requirements for the Vendor H ITC filter. If the filter did not meet the requirement, then the average and maximum deviation from the requirement, across the entire stopband, is provided. Table 15 also provides the physical dimensions of the filter, and the percentage of the passband in which the VSWR met the requirement of 1.5:1 or lower.

Table 15. Vendor H ITC Filter Characteristics, Stopband, and VSWR Results

Vendor H									
	Tier I			Tier II			VSWR		
	217.0-219.0			217.0-219.0			220.0-222.0		
Test	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Filter Dimensions	Filter Weight
Baseline	57%	1.56	4.81	100%	-	-	65%	13" x 7" x 5"	9.6 lbs
Post	79%	1.18	3.88	100%	-	-	63%		

Figure 10 shows the amplitude response from the temperature extremes testing for the Vendor H ITC filter. The blue trace shows the response at the cold extreme temperature of -45 °C, and the red trace shows the response at the hot extreme temperature of 75 °C. The green trace shows the baseline taken before environmental testing.

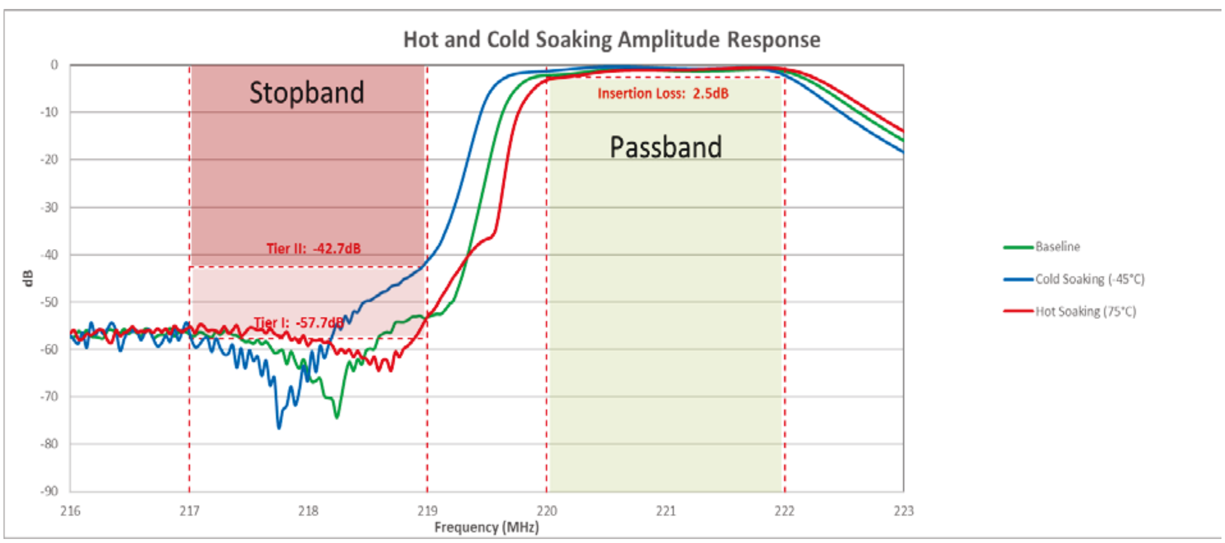

Figure 10. Vendor H ITC Amplitude Response for Temperature Extreme Tests

3.2 ACSES Test and Results

The requirements for the ACSES filters are:

- Passband: 217-219 MHz
- Stopband: 220-222 MHz

- Tier I Isolation: 60.8 dB
- Tier II Isolation: 45.6 dB
- Maximum Insertion Loss: 2.5 dB

Summaries of the tests for each vendor's ACSES filter sample are provided in the following subsections.

3.2.1 Vendor A

Figure 11 shows the baseline and the post environmental amplitude responses. The baseline was the initial measurement of the filter, and the post environmental measurement was taken after all testing was completed. Amplitude response traces above the green-shaded rectangle indicate filter conformance to passband and insertion loss requirements. Amplitude response traces below the red-shaded rectangles indicate filter conformance to the requirements for stopband and Tier I and II isolation levels.

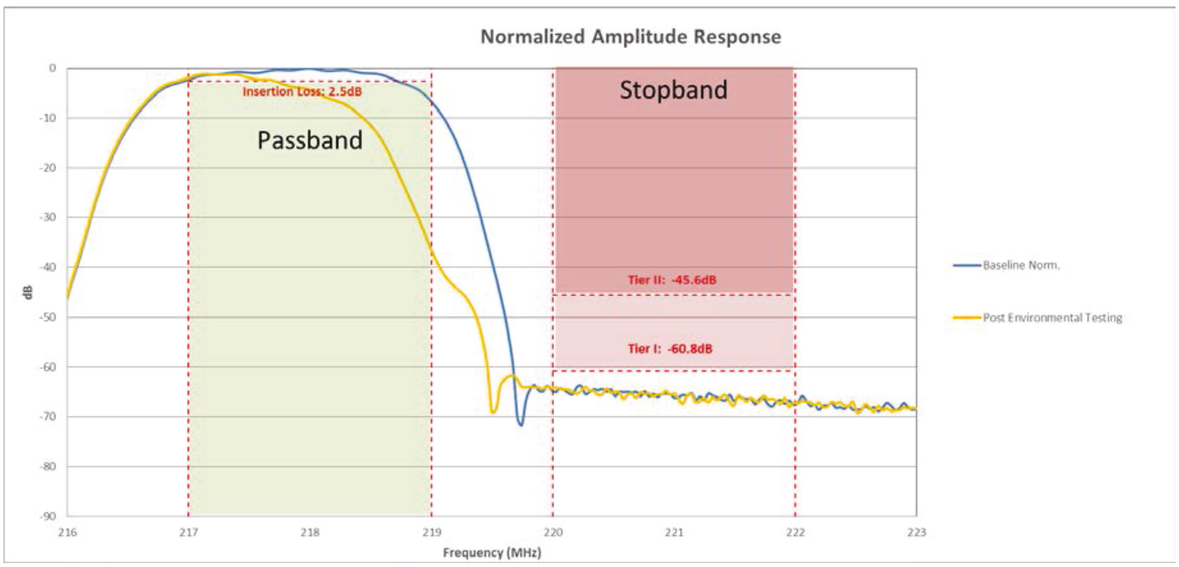

Figure 11. Vendor A Amplitude Response ACSES Filter Characterization

A drop in the amplitude response, within the passband, for the post environmental trace can be seen in Figure 11. This occurred during temperature cycling and is discussed in further detail below.

Table 16 shows the results of the baseline and post environment amplitude response for the passband, split into 250 kHz steps from 217 MHz to 219 MHz, for the Vendor A ACSES filter. Displaying results in frequency steps allows for an evaluation of filter performance in frequency ranges of interest, based on planned channel usage. For each step, the "Percent in Spec" column indicates the percentage of passband frequencies within the range represented by the step that met the insertion loss requirement. If the filter did not meet the requirement for that step, the average and maximum deviation from the requirement, within the frequency step, is provided.

Table 16. Vendor A ACSES Passband Results

Vendor A																								
	Passband (MHz)																							
	217.000-217.250			217.250-217.500			217.500-217.750			217.750-218.000			218.000-218.250			218.250-218.500			218.500-218.750			218.750-219.000		
Test	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)
Baseline	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	86%	0.12	0.12	0%	1.69	3.45
Post	100%	-	-	100%	-	-	75%	0.20	0.35	0%	1.28	1.76	0%	3.22	4.17	0%	6.38	8.55	0%	13.63	18.68	0%	26.33	32.42

Table 17 shows the percentage of the stopband that met the Tier I and Tier II isolation requirements for the Vendor A ACSES filter. If the filter did not meet the requirement, then the average and maximum deviation from the requirement, across the entire stopband, is provided. Table 17 also provides the physical dimensions of the filter, and the percentage of the passband in which the VSWR met the requirement of 1.5:1 or lower.

Table 17. Vendor A ACSES Filter Characteristics, Stopband, and VSWR Results

Vendor A									
	Tier I			Tier II			VSWR		
	220.0-222.0			220.0-222.0			217.0-219.0		
Test	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Filter Dimensions	Filter Weight
Baseline	100%	-	-	100%	-	-	60%	8" x 8" x 8"	12 lbs
Post	100%	-	-	100%	-	-	39%		

Figure 12 shows the amplitude response from the temperature extremes testing for the Vendor A ACSES filter. The blue trace shows the response at the cold extreme temperature of -45 °C and the red trace shows the response at the hot extreme temperature of 75 °C. The green trace shows the baseline taken before environmental testing.

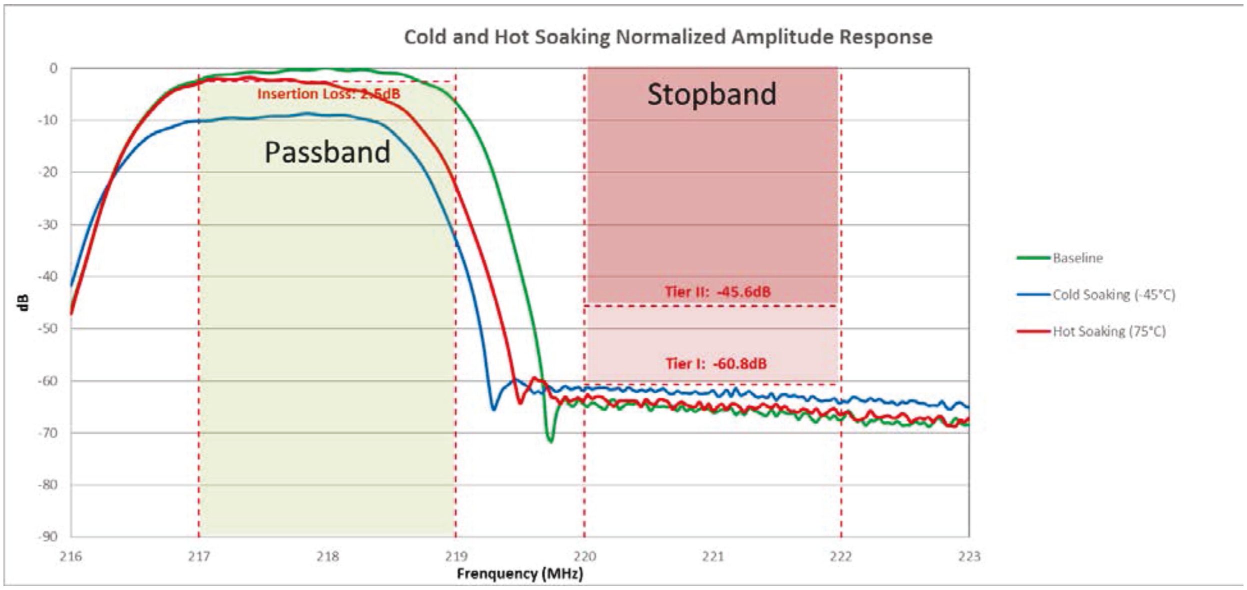

Figure 12. Vendor A ACSES Amplitude Response for Temperature Extreme Tests

The ACSES filter sample from Vendor A had a severe drop in amplitude, approximately 8 dB, when soaked overnight at the cold extreme temperature of -45 °C, see Figure 12. The filter's amplitude response returned to baseline levels as the temperature was increased. This filter did not experience a similar response during the hot extreme temperature test at 75 °C. The Vendor A ITC filter also experienced a similar drop. No other filters had similar amplitude response changes when exposed to the minimum or maximum temperatures overnight.

During thermal testing, a permanent alteration of the amplitude response occurred with the Vendor A ACSES filter sample. During the second thermal cycling run, over half of the passband dropped below the requirement. Beginning at approximately 217.7 MHz, the passband began to noticeably deviate from the baseline trace, with a maximum loss of 32 dB at 219 MHz. This change remained for the duration of testing. Figure 13 shows a comparison of the post temperature cycling amplitude response and the baseline amplitude response.

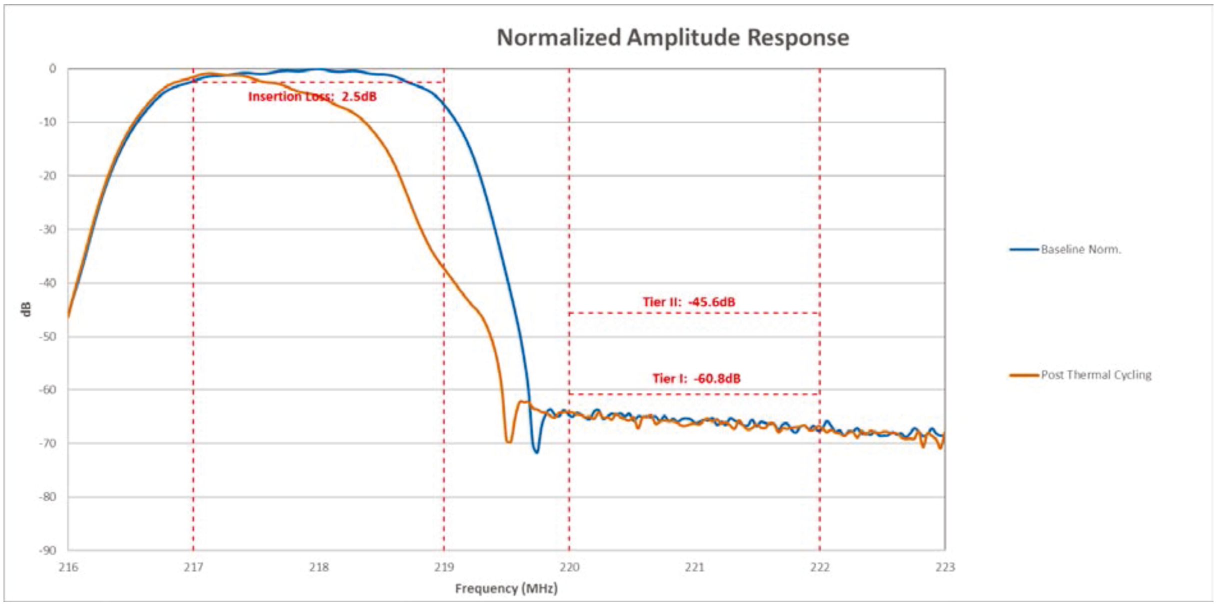

Figure 13. Amplitude Response of Baseline and Post Thermal Testing of the Vendor A ACSES Filter

3.2.2 Vendor B

Figure 14 shows the baseline and the post environmental amplitude responses. The baseline was the initial measurement of the filter, and the post environmental measurement was taken after all testing was completed. Amplitude response traces above the green-shaded rectangle indicate filter conformance to passband and insertion loss requirements. Amplitude response traces below the red-shaded rectangles indicate filter conformance to the requirements for stopband and Tier I and II isolation levels.

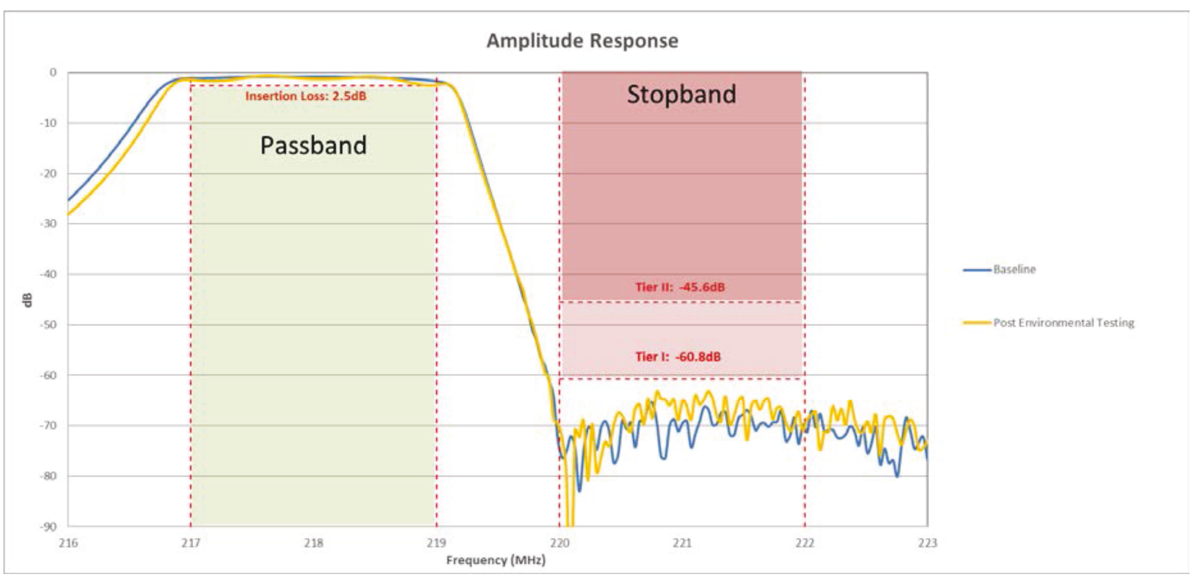

Figure 14. Vendor B Amplitude Response ACSES Filter Characterization

Table 18 shows the results of the baseline and post environment amplitude response for the passband, split into 250 kHz steps from 217 MHz to 219 MHz, for the Vendor B ACSES filter. Displaying results in frequency steps allows for an evaluation of filter performance in frequency ranges of interest, based on planned channel usage. For each step, the "Percent in Spec" column indicates the percentage of passband frequencies within the range represented by that step meeting the insertion loss requirement. If the filter did not meet the requirement for that step, the average and maximum deviation from the requirement, within the frequency step, is provided.

Table 18. Vendor B ACSES Passband Results

Vendor B																								
	Passband (MHz)																							
	217.000-217.250			217.250-217.500			217.500-217.750			217.750-218.000			218.000-218.250			218.250-218.500			218.500-218.750			218.750-219.000		
Test	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)
Baseline	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-
Post	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	71%	0.01	0.02

Table 19 shows the percentage of the stopband that met the Tier I and Tier II isolation requirements for the Vendor B ACSES filter. If the filter did not meet the requirement, then the average and maximum deviation from the requirement, across the entire stopband, is provided. Table 19 also provides the physical dimensions of the filter, and the percentage of the passband in which the VSWR met the requirement of 1.5:1 or lower.

Table 19. Vendor B ACSES Filter Characteristics, Stopband, and VSWR Results

Vendor B									
	Tier I			Tier II			VSWR		
	220.0-222.0			220.0-222.0			217.0-219.0		
Test	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Filter Dimensions	Filter Weight
Baseline	100%	-	-	100%	-	-	100%	12.6" x 8.5" x 5.7"	14.2 lbs
Post	100%	-	-	100%	-	-	100%		

Figure 15 shows the amplitude response from the temperature extremes testing for the Vendor B ACSES filter. The blue trace shows the response at the cold extreme temperature of -45 °C and the red trace shows the response at the hot extreme temperature of 75 °C. The green trace shows the baseline taken before environmental testing.

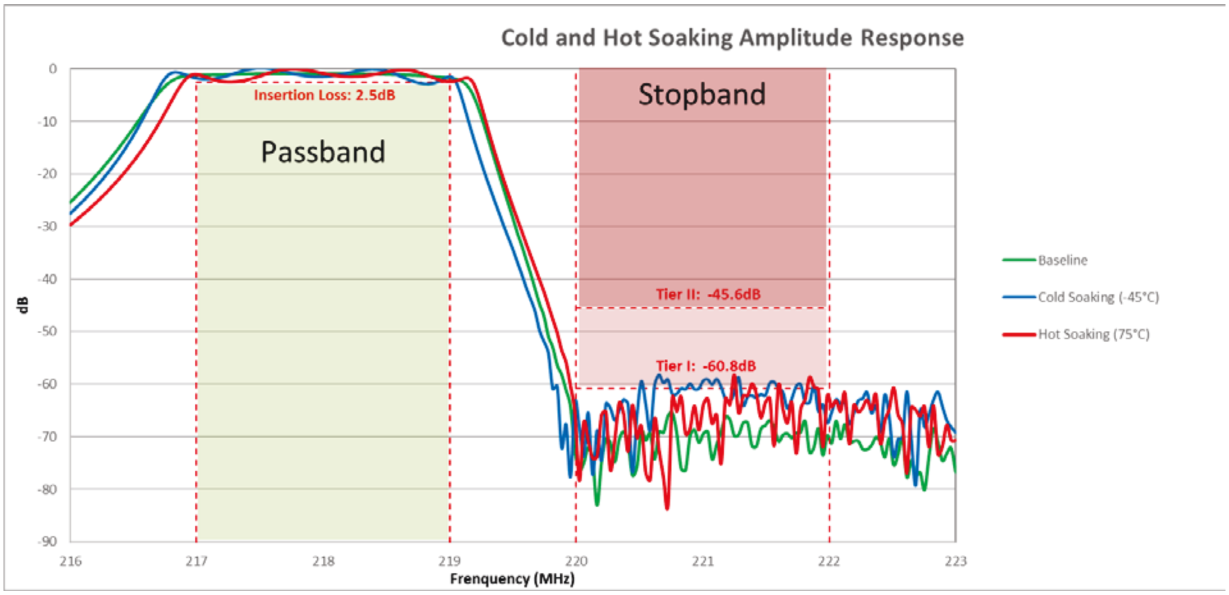

Figure 15. Vendor B ACSES Amplitude Response for Temperature Extreme Tests

Approximately 2 hours into sinusoidal vibration, the Vendor B ITC filter sample was found to have an audibly loose internal component. As a result, both of the Vendor B filters were pulled from vibration testing and sent back to the vendor for repair. The filters were repaired and returned in time to fully participate in testing.

3.2.3 Vendor D

Figure 16 shows the baseline and the post environmental amplitude responses. The baseline was the initial measurement of the filter, and the post environmental measurement was taken after all testing was completed. Amplitude response traces above the green-shaded rectangle indicate filter conformance to passband and insertion loss requirements. Amplitude response traces below the red-shaded rectangles indicate filter conformance to the requirements for stopband and Tier I and II isolation levels.

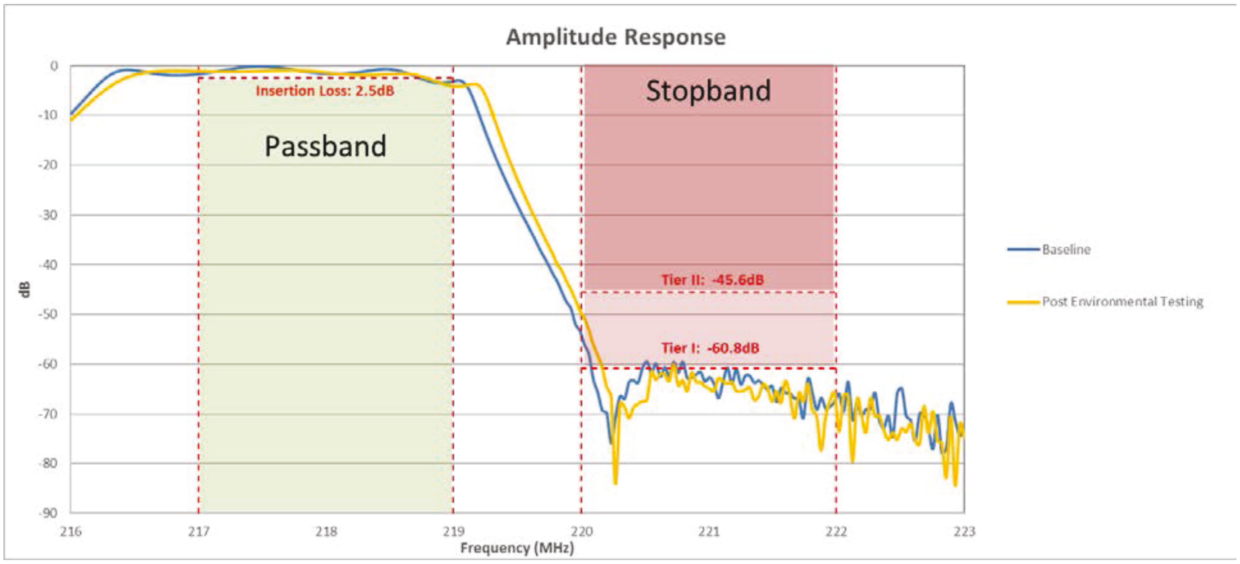

Figure 16. Vendor D Amplitude Response ACSES Filter Characterization

Table 20 shows the results of the baseline and post environment amplitude response for the passband, split into 250 kHz steps from 217 MHz to 219 MHz, for the Vendor D ACSES filter. Displaying results in frequency steps allows for an evaluation of filter performance in frequency ranges of interest, based on planned channel usage. For each step, the "Percent in Spec" column indicates the percentage of passband frequencies within the range represented by that step meeting the insertion loss requirement. If the filter did not meet the requirement for that step, the average and maximum deviation from the requirement, within the frequency step, is provided.

Table 20. Vendor D ACSES Passband Results

Vendor D																								
	Passband (MHz)																							
	217.000-217.250			217.250-217.500			217.500-217.750			217.750-218.000			218.000-218.250			218.250-218.500			218.500-218.750			218.750-219.000		
Test	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)
Baseline	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	0%	0.71	0.70
Post	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	14%	0.86	1.54

Table 21 shows the percentage of the stopband that met the Tier I and Tier II isolation requirements for the Vendor D ACSES filter. If the filter did not meet the requirement, then the average and maximum deviation from the requirement, across the entire stopband, is provided. Table 21 also provides the physical dimensions of the filter, and the percentage of the passband in which the VSWR met the requirement of 1.5:1 or lower.

Table 21. Vendor D ACSES Filter Characteristics, Stopband, and VSWR Results

Vendor D									
	Tier I			Tier II			VSWR		
	220.0-222.0			220.0-222.0			217.0-219.0		
Test	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Filter Dimensions	Filter Weight
Baseline	89%	1.72	4.74	100%	-	-	100%	3.5" x 12.42" x 8.75"	31.7 lbs
Post	89%	4.29	10.03	100%	-	-	93%		

Figure 17 shows the amplitude response from the temperature extremes testing for the Vendor D ACSES filter. The blue trace shows the response at the cold extreme temperature of -45 °C and the red trace shows the response at the hot extreme temperature of 75 °C. The green trace shows the baseline taken before environmental testing.

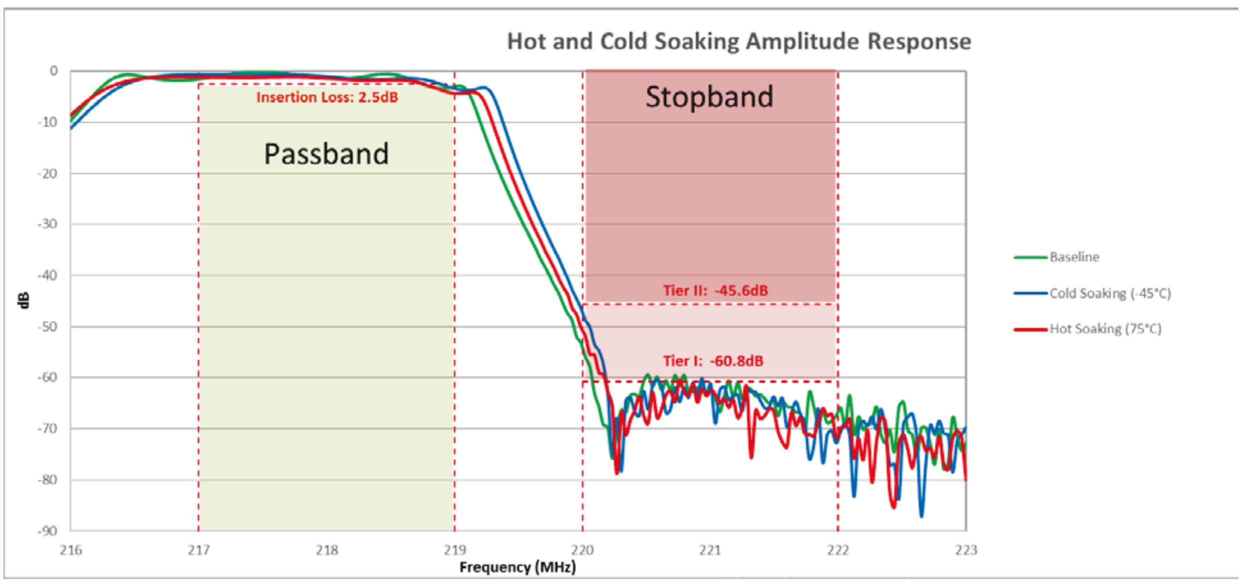

Figure 17. Vendor D ACSES Amplitude Response for Temperature Extreme Tests

3.2.4 Vendor F

Figure 18 shows the baseline and the post environmental amplitude responses. The baseline was the initial measurement of the filter, and the post environmental measurement was taken after all testing was completed. Amplitude response traces above the green-shaded rectangle indicate filter conformance to passband and insertion loss requirements. Amplitude response traces below the red-shaded rectangles indicate filter conformance to the requirements for stopband and Tier I and II isolation levels.

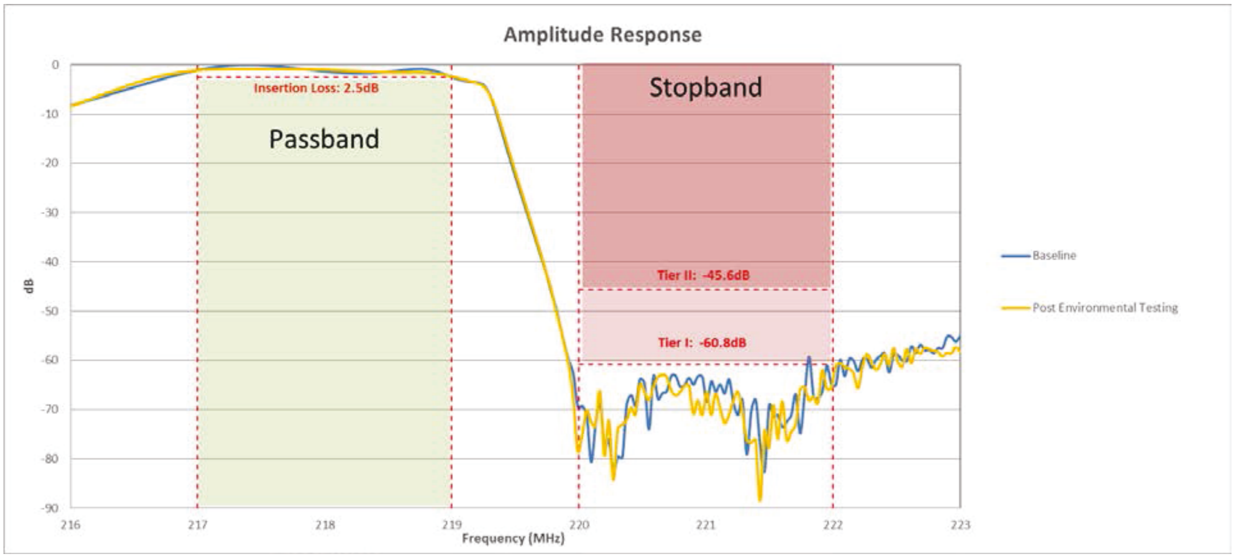

Figure 18. Vendor F Amplitude Response ACSES Filter Characterization

Table 22 shows the results of the baseline and post environment amplitude response for the passband, split into 250 kHz steps from 217 MHz to 219 MHz, for the Vendor F ACSES filter. Displaying results in frequency steps allows for an evaluation of filter performance in frequency ranges of interest, based on planned channel usage. For each step, the "Percent in Spec" column indicates the percentage of passband frequencies within the range represented by that step meeting the insertion loss requirement. If the filter did not meet the requirement for that step, the average and maximum deviation from the requirement, within the frequency step, is provided.

Table 22. Vendor F ACSES Passband Results

Vendor F																								
	Passband (MHz)																							
	217.000-217.250			217.250-217.500			217.500-217.750			217.750-218.000			218.000-218.250			218.250-218.500			218.500-218.750			218.750-219.000		
Test	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)
Baseline	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-
Post	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-	100%	-	-

Table 23 shows the percentage of the stopband that met the Tier I and Tier II isolation requirements for the Vendor F ACSES filter. If the filter did not meet the requirement, then the average and maximum deviation from the requirement, across the entire stopband, is provided. Table 23 also provides the physical dimensions of the filter and the percentage of the passband in which the VSWR met the requirement of 1.5:1 or lower.

Table 23. Vendor F ACSES Filter Characteristics, Stopband, and VSWR Results

Vendor F									
	Tier I			Tier II			VSWR		
	220.0-222.0			220.0-222.0			217.0-219.0		
Test	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Av Dev from Spec (dB)	Max Dev. from Spec (dB)	Percent in Spec	Filter Dimensions	Filter Weight
Baseline	98%	1.52	1.52	100%	-	-	100%	5.9" x 3.6" x 8.6"	11.2 lbs
Post	100%	-	-	100%	-	-	100%		

Figure 19 shows the amplitude response from the temperature extremes testing for the Vendor F ACSES filter. The blue trace shows the response at the cold extreme temperature of -45 °C, and the red trace shows the response at the hot extreme temperature of 75 °C. The green trace shows the baseline taken before environmental testing.

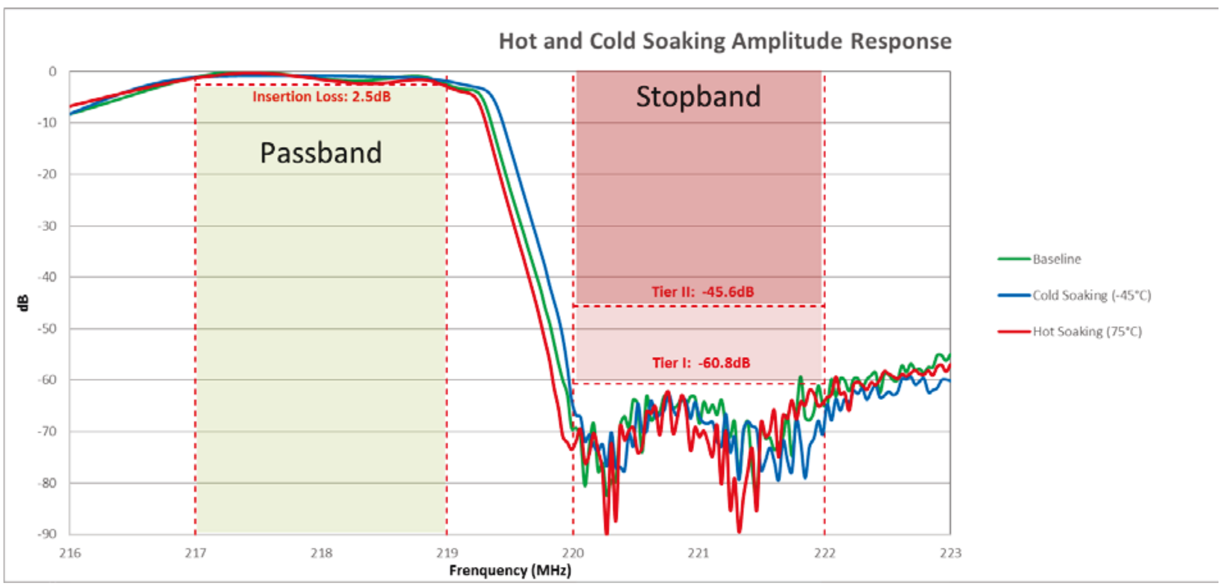

Figure 19. Vendor F ACSES Amplitude Response for Temperature Extreme Tests

3.2.5 Vendor H

An internal component came loose from the Vendor H ACSES filter after approximately 10 hours of sinusoidal vibration. This was noticed because of a permanent alteration in the amplitude response of the filter. This alteration is shown in Figure 20. As a result, the ACSES filter was sent back to the vendor for repair, but the filter was unable to be returned in time to participate in additional testing. The Vendor H ITC filter did not experience similar issues, and completed testing as described in Section 3.1.5.

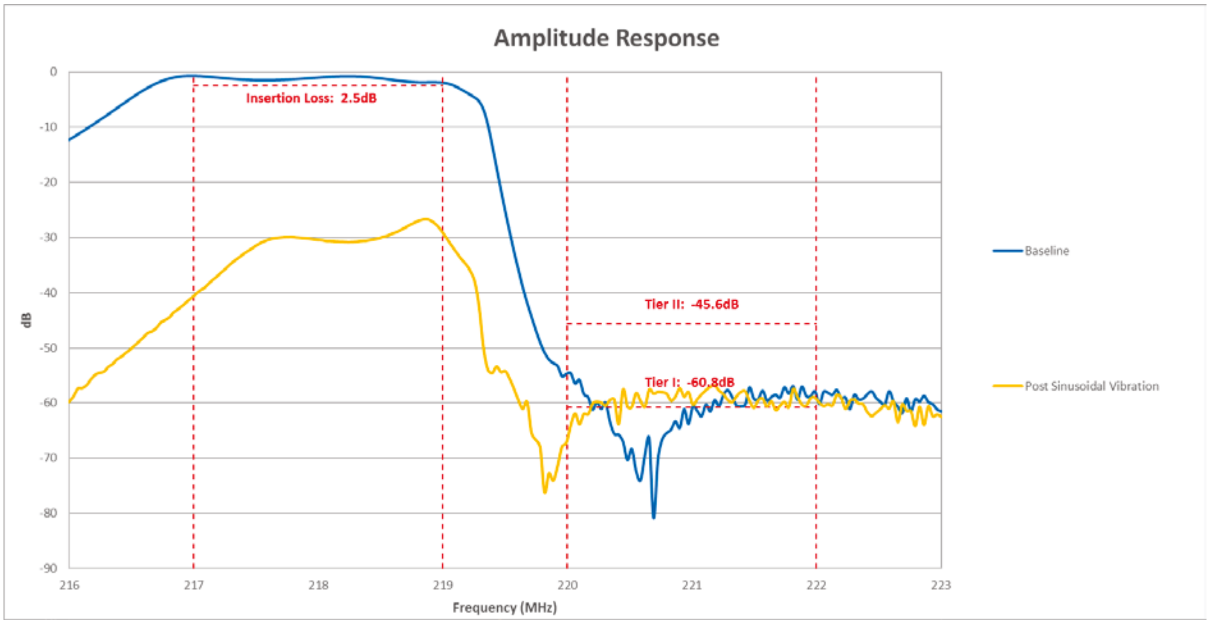

Figure 20. Vendor H Amplitude Response ACSES Filter Characterization

3.3 Summary of Test Results

Table 24 and Table 25 show a summary of ITC filter results and ACSES filter results, respectively, that were presented in the tables in Sections 3.1.1 through 3.2.5. Each table provided:

- The percentage of the passband that met the insertion loss requirement of 2.5dB or less, with the passband split into 250 kHz steps, as described in previous sections. If the filter did not meet the requirement, then the average and maximum deviation from the requirement is provided.
- The percentage of the stopband that met the Tier I and Tier II isolation requirements. If the filter did not meet the requirement, then the average and maximum deviation from the requirement is provided.
- The dimensions of the filter.
- The weight of the filter.

3.3.1 Summary of ITC Filter Test Results

From Table 24 it is clear that all ITC filter samples met the passband insertion loss requirement of 2.5 dB or less across the entire passband during the post environment measurement. The minor deviations present during the baseline measurements for the filters from Vendors A and F may be attributed to measurement variation associated with the cable calibration function of the vector network analyzer (VNA), or with cable position during measurement.

All filters met the Tier II isolation requirement of 42.7 dB for the stopband. Filters from Vendors A, B, and F met the more stringent Tier I isolation requirement of 57.7 dB for the stopband during the post-test measurement. Filter samples from Vendor D and Vendor F participated in field testing. No signs of corrosion or rust were identified upon removal of the filters from the locomotive.

Table 24. ITC Filter Testing Summary

		Filter	Vendor A		Vendor B		Vendor D		Vendor F		Vendor H	
		Test	**Baseline**	**Post**	**Baseline**	**Post**	**Baseline**	**Post**	**Baseline**	**Post**	**Baseline**	**Post**
Passband (MHz)	220.100 - 220.250	Percent in Spec	75%	100%	100%	100%	100%	100%	20%	100%	100%	100%
		Av Dev from Spec (dB)	0.20	-	-	-	-	-	0.21	-	-	-
		Max Dev. from Spec (dB)	0.20	-	-	-	-	-	0.37	-	-	-
	220.250 - 220.500	Percent in Spec	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
		Av Dev from Spec (dB)	-	-	-	-	-	-	-	-	-	-
		Max Dev. from Spec (dB)	-	-	-	-	-	-	-	-	-	-
	220.500 - 220.750	Percent in Spec	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
		Av Dev from Spec (dB)	-	-	-	-	-	-	-	-	-	-
		Max Dev. from Spec (dB)	-	-	-	-	-	-	-	-	-	-
	220.750- 221.000	Percent in Spec	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
		Av Dev from Spec (dB)	-	-	-	-	-	-	-	-	-	-
		Max Dev. from Spec (dB)	-	-	-	-	-	-	-	-	-	-
	221.1125 - 221.250	Percent in Spec	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
		Av Dev from Spec (dB)	-	-	-	-	-	-	-	-	-	-
		Max Dev. from Spec (dB)	-	-	-	-	-	-	-	-	-	-
	221.250 - 221.500	Percent in Spec	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
		Av Dev from Spec (dB)	-	-	-	-	-	-	-	-	-	-
		Max Dev. from Spec (dB)	-	-	-	-	-	-	-	-	-	-
	221.500 - 221.750	Percent in Spec	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
		Av Dev from Spec (dB)	-	-	-	-	-	-	-	-	-	-
		Max Dev. from Spec (dB)	-	-	-	-	-	-	-	-	-	-
	221.750- 221.950	Percent in Spec	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
		Av Dev from Spec (dB)	-	-	-	-	-	-	-	-	-	-
		Max Dev. from Spec (dB)	-	-	-	-	-	-	-	-	-	-
Tier I Stopband (MHz)	217.0- 219.0	Percent in Spec	100%	100%	100%	100%	36.84%	57.89%	96.49%	100%	57.90%	78.94%
		Av Dev from Spec (dB)	-	-	-	-	1.40	0.95	0.32	-	1.56	1.18
		Max Dev. from Spec (dB)	-	-	-	-	5.14	3.61	0.57	-	4.81	3.88
Tier II Stopband (MHz)	217.0- 219.0	Percent in Spec	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
		Av Dev from Spec (dB)	-	-	-	-	-	-	-	-	-	-
		Max Dev. from Spec (dB)	-	-	-	-	-	-	-	-	-	-
Filter Dimensions (in)			8" x 8" x 8"		12.6" x 8.5" x 5.7"		3.5" x 12.42" x 8.75"		5.9" x 3.6" x 8.6"		13" x 7" x 5"	
Filter Weight (lbs)			12		14.2		31.7		11.2		9.6	

3.3.2 Summary of ACSES Filter Test Results

From Table 24, it is clear that the ACSES filter sample from Vendor F met the passband insertion loss requirement of 2.5 dB or less across the entire passband. The filters from Vendors B and D met the passband insertion loss requirement, except near the 219 MHz passband corner. Of these two filters, the maximum deviation of the insertion loss from the requirement in the 218.750 MHz to 219.000 MHz frequency step was 1.54 dB for Vendor D during the post-test measurement. For the same filter measurement and frequency step, 14 percent of passband for the filter from Vendor D met the requirement. As discussed in Section 3.2.1, the Vendor A ACSES filter sample incurred permanent damage during the temperature cycling testing, and this is reflected in six of the eight frequency steps for the post amplitude response measurement.

All filters met the Tier II isolation requirement of 45.6 dB for the stopband. The filters from Vendors A, B, and F met the more stringent Tier I isolation requirement of 60.8 dB for the stopband during the post-test measurements. The minor deviations present during the baseline measurements for the filter from Vendor F may be attributed to measurement variation associated with the cable calibration function of the VNA, or with cable position during measurement. Filter samples from Vendor D and Vendor F participated in field testing. No signs of corrosion or rust were identified upon removal of the filters from the locomotive.

Table 25. ACSES Filter Testing Summary

		Filter	Vendor A		Vendor B		Vendor D		Vendor F	
		Test	**Baseline**	**Post**	**Baseline**	**Post**	**Baseline**	**Post**	**Baseline**	**Post**
Passband (MHz)	217.000-217.250	Percent in Spec	100%	100%	100%	100%	100%	100%	100%	100%
		Av Dev from Spec (dB)	-	-	-	-	-	-	-	-
		Max Dev. from Spec (dB)	-	-	-	-	-	-	-	-
	217.250-217.500	Percent in Spec	100%	100%	100%	100%	100%	100%	100%	100%
		Av Dev from Spec (dB)	-	-	-	-	-	-	-	-
		Max Dev. from Spec (dB)	-	-	-	-	-	-	-	-
	217.500-217.750	Percent in Spec	100%	75%	100%	100%	100%	100%	100%	100%
		Av Dev from Spec (dB)	-	0.20	-	-	-	-	-	-
		Max Dev. from Spec (dB)	-	0.35	-	-	-	-	-	-
	217.750-218.000	Percent in Spec	100%	0%	100%	100%	100%	100%	100%	100%
		Av Dev from Spec (dB)	-	1.28	-	-	-	-	-	-
		Max Dev. from Spec (dB)	-	1.76	-	-	-	-	-	-
	218.000-218.250	Percent in Spec	100%	0%	100%	100%	100%	100%	100%	100%
		Av Dev from Spec (dB)	-	3.22	-	-	-	-	-	-
		Max Dev. from Spec (dB)	-	4.17	-	-	-	-	-	-
	218.250-218.500	Percent in Spec	100%	0%	100%	100%	100%	100%	100%	100%
		Av Dev from Spec (dB)	-	6.38	-	-	-	-	-	-
		Max Dev. from Spec (dB)	-	8.55	-	-	-	-	-	-
	218.500-218.750	Percent in Spec	86%	0%	100%	100%	100%	100%	100%	100%
		Av Dev from Spec (dB)	0.12	13.63	-	-	-	-	-	-
		Max Dev. from Spec (dB)	0.12	18.68	-	-	-	-	-	-
	218.750-219.000	Percent in Spec	0%	0%	100%	71%	0%	14%	100%	100%
		Av Dev from Spec (dB)	1.69	26.33	-	0.01	0.71	0.70	-	-
		Max Dev. from Spec (dB)	3.45	32.42	-	0.02	0.95	1.54	-	-
Tier I Stopband (MHz)	220.000-222.000	Percent in Spec	100%	100%	100%	100%	89.47%	89.47%	98.25%	100%
		Av Dev from Spec (dB)	-	-	-	-	1.72	4.29	1.52	-
		Max Dev. from Spec (dB)	-	-	-	-	4.74	10.03	1.52	-
Tier II Stopband (MHz)	220.000-222.000	Percent in Spec	100%	100%	100%	100%	100%	100%	100%	100%
		Av Dev from Spec (dB)	-	-	-	-	-	-	-	-
		Max Dev. from Spec (dB)	-	-	-	-	-	-	-	-
Filter Dimensions (in)			8" x 8" x 8"		12.6" x 8.5" x 5.7"		3.5" x 12.42" x 8.75"		5.9" x 3.6" x 8.6"	
Filter Weight (lbs)			12		14.2		31.7		11.2	

3.3.3 VSWR Results

Table 25 summarizes the VSWR results for the ACSES filters and for the ITC filters that were presented in Sections 3.1.1 through 3.2.5. The table provides the percentage of the passband that met the VSWR requirement of 1.5:1 or less for each filter.

Table 26. Summary of VSWR Results

		Filter	Filter A		Filter B		Filter D		Filter F		Filter H	
		Test	Baseline	Post	Baseline	Post	Baseline	Post	Baseline	Post	Baseline	Post
VSWR	ACSES 217.000-219.000	Percent in Spec	60%	39%	100%	100%	100%	93%	100%	100%	N/A	N/A
	ITC 220.000-222.000	Percent in Spec	72%	32%	100%	95%	100%	100%	100%	100%	65%	63%

The ACSES filter samples from Vendors B and F met the requirement for VSWR across the entire passband during the post environment measurement. Similarly, ITC filter samples from Vendors D and F met the VSWR requirement across the entire passband.

3.4 Additional Observations

During environmental laboratory testing, it was observed that the method for (a) mounting filters to the vibration table and (b) temperature cycling both impacted the amplitude response of all filters.

3.4.1 Filter Mounting

During the first environmental laboratory test conducted, sinusoidal vibration testing, a component came loose on the Vendor B ITC filter sample approximately 2 hours into vibration. Consequently, the test was stopped, and all filters were analyzed while mounted to the vibration table. Each filter sample was initially mounted on the vibration table on its base, as shown in Figure 21. Analysis showed changes in amplitude response compared to the original baseline in all filters. As an example, Figure 23 shows the amplitude response for the ITC filter from Vendor F from the baseline testing compared to that measured when mounted on the vibration table on its base. Further investigation into the issue identified the initial mounting method caused the changes to the amplitude response. Measurements taken after unmounting the filters were similar to the original baseline measurements.

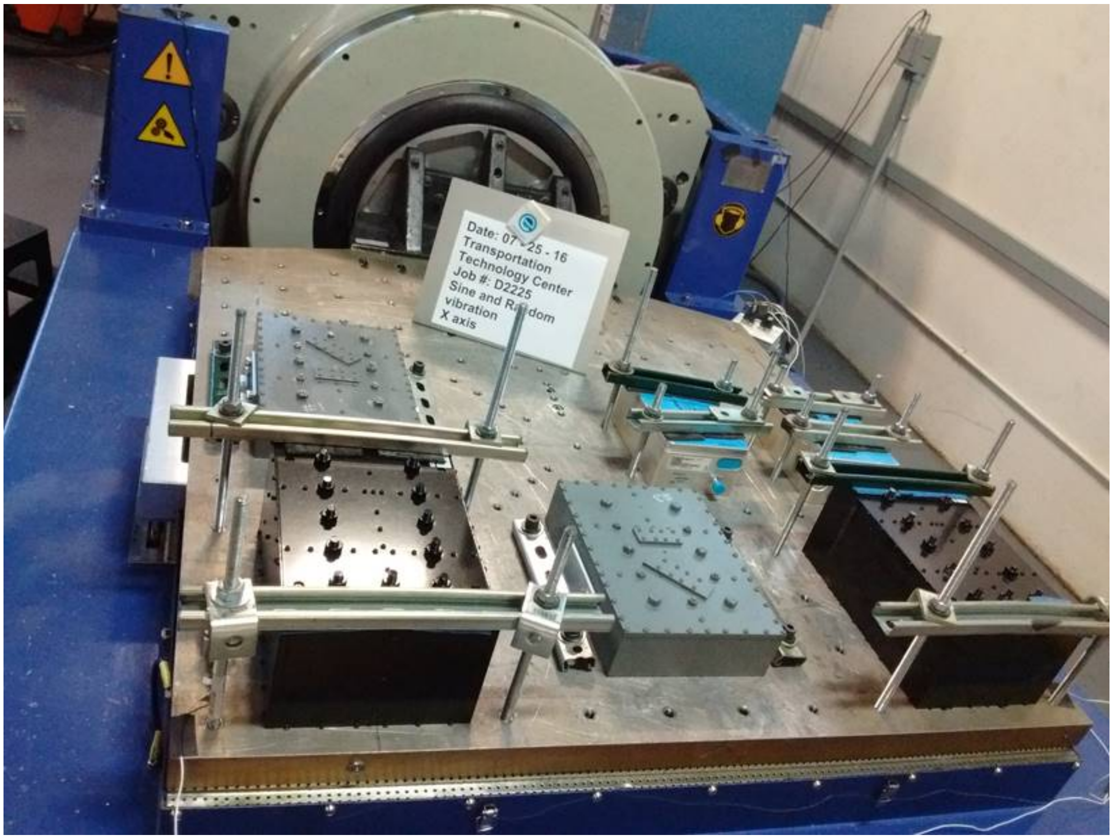

Figure 21. Base Mounting Filter Configuration

After experimentation with different mounting methods, it was determined, for the purpose of testing, that the filters should be mounted on their sides. Figure 22 shows this mounting configuration, which prevented undesired effects to the amplitude responses of the filters. It was also noted that the amount and uniformity of the pressure applied by the brackets, over the filters, affected the amplitude response. As a result, the amount of pressure was regulated by tightening the nuts in the clamping assembly used to secure the filters, as indicated by the red arrows in Figure 22, with a torque wrench to ensure uniformity in pressure on each bracket. A torque level of 55 inch-pounds (in-lbs) was used for all filters, except for Vendor D. Due to the greater weight of the Vendor D filters, there was concern for the filters to potentially shift out of place during vibration. Shifting during vibration could potentially cause filter damage, and does not allow for accurate filter exposure to the intended frequency and acceleration levels. After experimentation, it was identified that a torque level of 75 in-lbs could be utilized for securing the Vendor D filters without causing amplitude response changes.

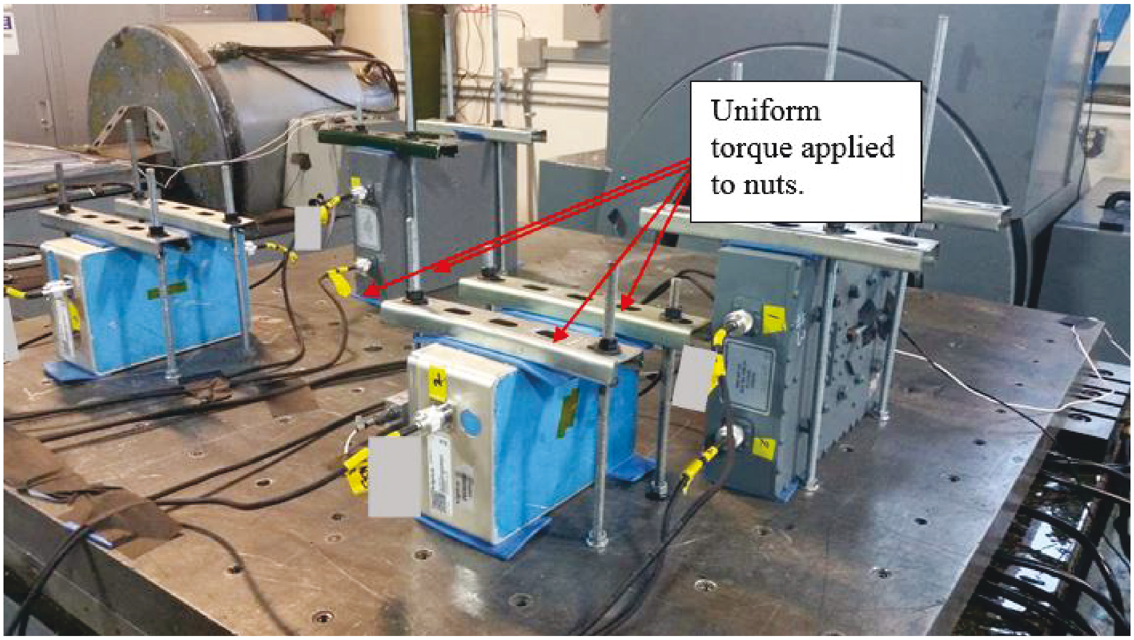

Figure 22. Side Mounting Used for Testing

Figure 23 shows the amplitude responses for the Vendor F ITC filter sample at baseline, when secured in the original mounting configuration, and when secured in the side-mounted configuration. The sensitivity of the filters to mounting practices is of significant interest to the rail industry. Collaboration with filter vendors, and/or special attention to installation of filters in the locomotive environment is suggested to ensure the filter mounting method does not compromise the performance of the filter. If improperly mounted, the performance of the filter could result in degraded radio communications.

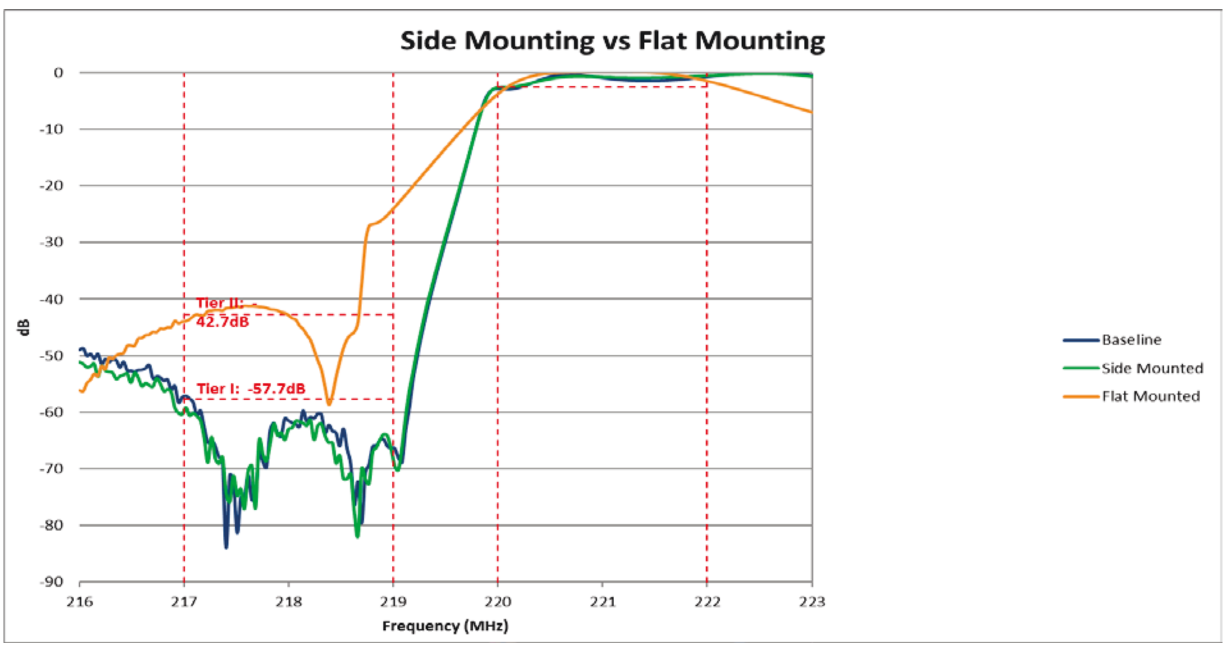

Figure 23. Vendor F ITC Orientation Comparison

3.4.2 Impact of Thermal Conditions

Impact of Rapid Thermal Change (Thermal Shock)

During temperature cycling, each filter exhibited some amount of amplitude response shifting compared to the baseline. The amount of amplitude response shift differed for each filter, and ranged from 0.2 MHz to 1.2 MHz. Figure 24 shows the amplitude responses collected during temperature cycling for the Vendor B ACSES filter. The shifting observed for this filter was the most significant of all the filters. Figure 24 includes all traces collected, four traces of interest are bolded in the plot, and represent the following:

- Blue trace – the baseline amplitude response
- Black trace – the first amplitude response collected after the filter was transferred to the hot chamber
- Green trace – the amplitude response that deviated most from the baseline as the filter surface temperature increased
- Brown trace – the amplitude response collected once the surface temperature of the filter reached 75 °C

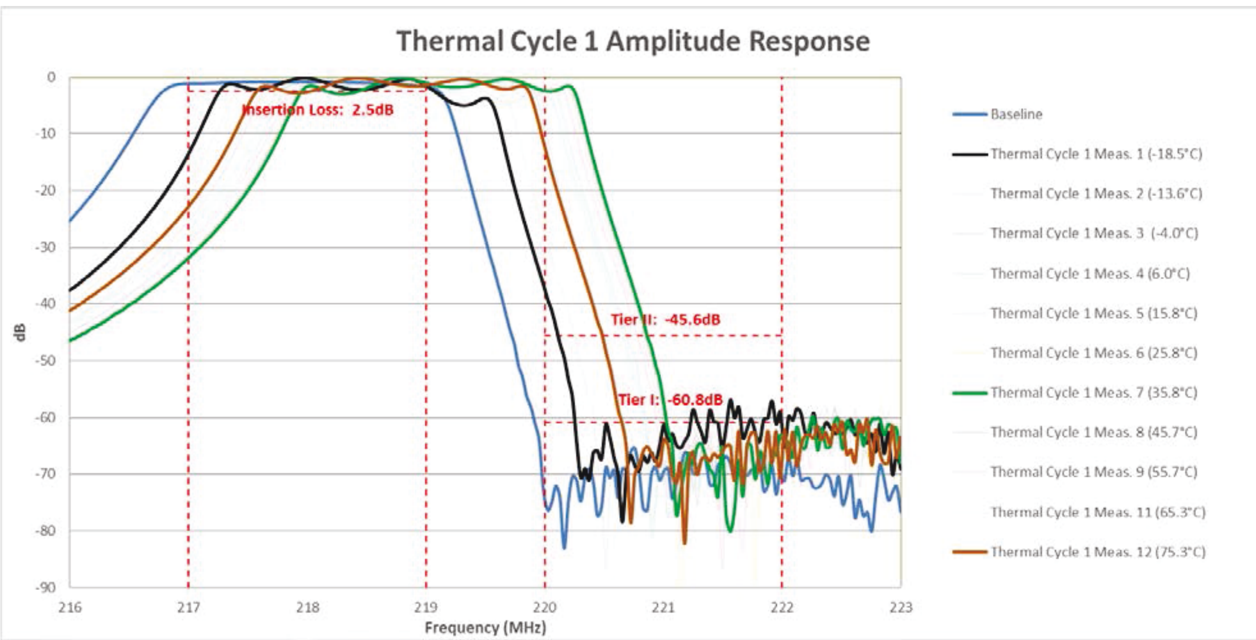

Figure 24. Frequency Shifting Caused by Thermal Cycling

By the end of the thermal cycle, most of the filters settled back to their baseline. Those filters that had not settled back to their baselines by the end of the cycle did return to baseline after returning to room temperature. During temperature cycling, the filters were removed from a -45 °C thermal chamber and transferred immediately to a 105 °C thermal chamber to rapidly heat each filter. The surface temperature of the filter increased faster than the internal temperature, and may have resulted in changes to the surface area and volume within the filter. These changes to the filter may be the cause of the changes to the amplitude responses. Temperature cycling conditions may occur in revenue service operation or in storage, however, they are not expected to be representative of a typical locomotive environment.

Due to the changes in filter response observed during the rapid thermal changes, it is suggested that filters not be placed in areas where rapid temperature change would typically occur. Exposure to such dynamic thermal conditions may cause the filters to perform unexpectedly, and could potentially result in permanent damage to the filter.

4. Conclusion

The purpose of this project was to develop 220 MHz locomotive filter requirements, acquire filter samples, develop tests for the acquired samples, and test the samples. Working with members of the Advisory Group (AG), Transportation Technology Center, Inc. (TTCI) developed a set of requirements for the 220 MHz locomotive filters. Using these requirements, a request for proposal (RFP) was developed and sent out to 12 filter vendors. Proposals were received from 10 vendors, and 5 of which were selected for environmental testing. TTCI, in collaboration with the AG, developed a set of tests to perform on all the acquired samples. TTCI proceeded to test all the samples at an environmental testing facility located in Longmont, CO. Table 27 and Table 28 show summaries of the results of the environmental testing.

Note that the filter requirements developed on this project are from testing a limited number of radio samples, and therefore, do not account for potential variations in radio performance from sample to sample. Consequently, it is advised that those designing and implementing a Positive Train Control (PTC) system add margin to the filter requirements, especially regarding the amount of isolation each filter is to provide.

Table 27. ACSES Filter Results

		ACSES								
		Filter	Vendor A		Vendor B		Vendor D		Vendor F	
		Test	Baseline	Post	Baseline	Post	Baseline	Post	Baseline	Post
Passband (MHz)	217.000-219.000	Percent in Spec	86%	33%	100%	96%	88%	89%	100%	100%
		Av Dev from Spec (dB)	1.49	9.63	-	0.01	0.71	0.86	-	-
		Max Dev. from Spec (dB)	3.45	32.42	-	0.02	0.95	1.54	-	-
Tier I Stopband (MHz)	220.000-222.000	Percent in Spec	100%	100%	100%	100%	89%	89%	98%	100%
		Av Dev from Spec (dB)	-	-	-	-	1.72	4.29	1.52	-
		Max Dev. from Spec (dB)	-	-	-	-	4.74	10.03	1.52	-
Tier II Stopband (MHz)	220.000-222.000	Percent in Spec	100%	100%	100%	100%	100%	100%	100%	100%
		Av Dev from Spec (dB)	-	-	-	-	-	-	-	-
		Max Dev. from Spec (dB)	-	-	-	-	-	-	-	-
VSWR	217.000-219.000	Percent in Spec	60%	39%	100%	100%	100%	93%	100%	100%
Filter Dimensions (in)			8" x 8" x 8"		12.6" x 8.5" x 5.7"		3.5" x 12.42" x 8.75"		5.9" x 3.6" x 8.6"	
Filter Weight (lbs)			12		14.2		31.7		11.2	

Table 28. ITC Filter Results

		ITC										
		Filter	Vendor A		Vendor B		Vendor D		Vendor F		Vendor H	
		Test	Baseline	Post	Baseline	Post	Baseline	Post	Baseline	Post	Baseline	Post
Passband (MHz)	220.100-221.950	Percent in Spec	98%	100%	100%	100%	100%	100%	94%	100%	100%	100%
		Av Dev from Spec (dB)	0.2	-	-	-	-	-	0.2	-	-	-
		Max Dev. from Spec (dB)	0.2	-	-	-	-	-	0.32	-	-	-
Tier I Stopband (MHz)	217.000-219.000	Percent in Spec	100%	100%	100%	100%	37%	58%	96%	100%	58%	79%
		Av Dev from Spec (dB)	-	-	-	-	1.40	0.95	0.32	-	1.56	1.18
		Max Dev. from Spec (dB)	-	-	-	-	5.14	3.61	0.57	-	4.81	3.88
Tier II Stopband (MHz)	217.000-219.000	Percent in Spec	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
		Av Dev from Spec (dB)	-	-	-	-	-	-	-	-	-	-
		Max Dev. from Spec (dB)	-	-	-	-	-	-	-	-	-	-
VSWR	220.000-222.000	Percent in Spec	72%	32%	100%	95%	100%	100%	100%	100%	65%	63%
Filter Dimensions (in)			8" x 8" x 8"		12.6" x 8.5" x 5.7"		3.5" x 12.42" x 8.75"		5.9" x 3.6" x 8.6"		13" x 7" x 5"	
Filter Weight (lbs)			12		14.2		31.7		11.2		9.6	

Passband results shown in Table 28 are from 220.100 MHz to 221.9375 MHz. This reflects the lowest interoperable train control (ITC) channel (channel 101 with a center frequency of 220.1125 MHz) and the highest ITC channel (channel 174 with a center frequency of 221.9375 MHz). Of the 10 filters tested, 2 incurred permanent damage during testing, which were the Advanced Civil Speed Enforcement System (ACSES) filter samples from Vendor A and Vendor H. Due to timing, these filters were unable to be repaired and returned to repeat testing. For the remaining eight filter samples, six met the passband insertion loss requirement of 2.5 dB or less across the entire passband during the post-test measurements. The other two filter samples exhibited small deviations from the passband requirement, which were ACSES filter samples and they deviated at the 219 MHz passband corner. In discussions regarding the results with the filter manufacturers, the manufacturers anticipated these minor deviations and noted that they can be addressed and improved.

All filter samples met the Tier II isolation requirements for the stopband, 45.6 dB for ACSES and 42.7 dB for ITC. Post-test measurements of five filters, two ACSES samples and three ITC samples, met the more stringent Tier I isolation requirements, 60.8 dB for ACSES and 57.7 dB for ITC. During testing, it was identified that special consideration should be given to the method and location of filter installation. Improper installation may result in drastic changes to the filter response. Rapid change of temperature may cause the response of the filter to shift, and should be avoided if possible. Consideration of these factors will help prevent unexpected degradations in PTC radio communications.

From the test results gathered during this project, members of the AG concluded that industry needs for mitigating desense between dissimilar PTC locomotive onboard radios can be met with filter technologies of the types tested. As a result, some railroads have already ordered and begun installing filters.

Locomotives equipped with the filter technologies like those tested will require the onboard PTC radio communications to operate on frequencies within the passband of the filter. If such locomotives operate outside of the passband frequencies (e.g., outside of the Northeast Corridor [NEC]), the filters may degrade PTC radio communications. Development of a filter bypass could be considered for such scenarios, as discussed Section 1.1.

5. References

1. Association of American Railroads. (2009). *Manual of Standards and Recommended Practices.* Section K-V. Electronics Environmental Requirements and System Management. Standard S-9401.V1.0. "Railroad Electronics Environmental Requirements."

Appendix

- Appendix A – Requirements for Positive Train Control 220 MHz Locomotive Radio Filter, (*internal document from TTCI)*. Available at: https://www.fra.dot.gov/eLib/details/L19334#p1_z5_gD.
- Appendix B – 220 MHz PTC Locomotive Filter Test Plan and Procedures, (*internal document from TTCI).* Available at: https://www.fra.dot.gov/eLib/details/L19335#p1_z5_gD.

Abbreviations and Acronyms

AAR	American Association of Railroads
ACSES	Advanced Civil Speed Enforcement System
AG	Advisory Group
AMTRAK	National Railroad Passenger Corporation
dB	Decibel
CSV	Comma Separated Values
FAST	Facility for Accelerated Service Testing
FCC	Federal Communication
FRA	Federal Railroad Administration
GE	General Electric
In-lb	Inch-pounds
ITC	Interoperable Train Control
LIRR	Long Island Railroad
MCC	Meteorcomm Communications
MHz	Megahertz
MNR	Metro-North Railroad
MSRP	Manual of Standards and Recommended Practices
NJT	New Jersey Transit
NEC	Northeast Corridor
NF	Noise Figure
NS	Norfolk Southern Corporation
PER	Packet Error Rate
PLY	Polyphaser
PNG	Portable Network Graphics
PTC	Positive Train Control
RF	Radio Frequency
RFS	Radio Frequency Systems
RFP	Request for Proposal
SNR	Signal-to-Noise Ratio
TTCI	Transportation Technology Center, Inc. (the company)
TNL	Tunnel Temperature
VNA	Vector Network Analyzer
VSWR	Voltage Standing Wave Ratio