This documents contains the three deliverables

2.3.1 Common methodology developed for stability and temperature sensitivity tests of ECUs

2.3.9 Report on the stability of and temperature effects on ECUs

2.3.10 Good Practice Guide for the recalibration of ECUs.

from the EMRP project

SIB62 HFCircuits

July 2013 to June 2016

Version July 2016

Electronic Calibration Units

Stability and Temperature Tests

Version 17.04.2014

Introduction

This document presents methods to test short and long term stability of electronic calibration units (ECU), including sensitivity to temperature variations and connector repeatability. It is expected that primarily national metrology institutes, manufacturers of ECUs and eventually calibration laboratories are interested to conduct this type of tests. The results of these tests should help to give advice to end users of ECUs on typical recalibration intervals of ECUs and best practice in measurements with ECUs.

The following effects are considered:

- Effects caused by the fact that ECUs contain an internal heater and the resulting heat flow between ECU and VNA.
- Issues related to stress on the connection between ECU and VNA (connector repeatability, connector orientation stability)
- Stability of the states of the ECU during operation (short term) and due to ageing (long term)

The instabilities related to ECUs show effects at different levels: The electrical characteristics of the states of the ECUs, the error terms of the VNA or the S-parameters of a DUT. For the temperature effects one can assume that the characteristics of the VNA are primarily affected. It therefore makes sense to study the variations in the error terms of the VNA over time. For the studies related to changes in the ECU states it is better to directly study the variations in the S-parameters of the ECU states if it is technically feasible. The resulting changes in error terms of the VNA or the S-parameters of a DUT can always be derived. The other way around is generally not unambiguously possible.

The described stability tests partially necessitate control of the switching states of the ECU under test as well as the ability to calculate the VNA error term from a set of ECU switching state measurements.

Basic preparations

1. Use VNA test ports with recessions that are large enough to avoid connector resonance effects. Consider the use of adapters with shimmed inner connectors to satisfy this requirement.
   The center conductor of the test port should be centered. Verification by visual inspection is sufficient.
2. Check basic stability of system and setup: Perform three raw measurements of a high reflect standard, as an open or short, at three different connector orientations and verify that the spread of the results is regular .
3. Measurement setup: Avoid cable movement during measurements where possible. For one port measurements keep the test port cable in a fixed clamped position.
4. VNA setup: This will depend on the type of VNA. Set the IF BW of the VNA to a small value that keeps the noise level down and set the average to 1. Set the source power to a value that avoids compression effects. The default power is usually a good choice. This is however

not always the case, e.g. for the Rohde & Schwarz ZVA a source power of -10 dBm is advised instead of the default 0 dBm. A reasonable number of frequency points should be selected to achieve the desired time resolution in the short term tests.

5. ECU setup: If the ECU should have electro-mechanical switches, it is advised to cycle them several times before use.

Temperature stability (TS) tests

The purpose of these tests is to determine the influence of temperature variations on the electrical properties of the ECU states and on the error terms of the VNA. There are different tests proposed to investigate variations in ambient temperatures and temperature differences between test port and ECU.

Test port and ECU can be at different temperatures. Once the connection between test port and ECU is established, changes can occur until temperature equilibrium is reached. It is assumed that this primarily affects the VNA error terms and to a lesser extent the states in the ECU. One needs to distinguish between measurements directly made at the VNA test port and measurements with a test port cable between VNA and ECU. Tests TS1a and TS1b address these effects, looking directly at the change in the error terms over time. TS2 is another way to look at the same effect. After a calibration with an ECU, a mechanical DUT at nominal temperature is measured repeatedly. In TS2 the heat source is removed and a change in the error terms might be observed indirectly in the change of the measured S_{11} of the mechanical standard.

Changes of the room temperature might influence the characteristics of the ECU states. Test TS3 investigates the sensitivity of the ECU to external temperature variations. A temperature controlled chamber is needed for that test.

ECU test TS1a

A test port cable is installed between the VNA port and the ECU.

The following procedure is carried out at one single frequency or a reduced number of frequencies to keep the time interval between measurements reasonably short.

1. ECU is turned on and ready.
2. Connect ECU and immediately start measuring ECU states repeatedly. Use the measurements of the ECU states to determine the VNA error terms and record their drift over time. t = 0 is the moment when the electrical contact between ECU and test port is established (visible from VNA response).

ECU test TS1b

The same as TS1a but without test port cable. Measurements are directly done at the VNA test port.

ECU test TS2a

A test port cable is installed between VNA port and ECU.

The following procedure is done at one single frequency or a reduced number of frequencies to keep the time interval between measurements reasonably short.

1. Connect ECU and wait until the system is in temperature equilibrium.
2. Perform a one port VNA calibration with the ECU.
3. Disconnect ECU and immediately connect a mechanical short standard.

4. Immediately start measuring mechanical standard repeatedly and record drift over time. t = 0 is the moment when ECU and VNA test port are electrically separated (visible from VNA response).

Repeat for mechanical load and open standard. Heating from human skin contact of the mechanical standards should be avoided as far as possible. Avoid unnecessary touching and/or use insulating gloves if feasible.

ECU test TS2b

The same as TS2a but without test port cable. Measurements are directly done at the VNA test port.

ECU test TS3

1. Place the ECU inside a temperature controlled chamber while the VNA stays outside. One port of the ECU is connected through a test port cable to the VNA. The test port cable should be kept outside the chamber, to be affected by temperature changes in the chamber as little as possible.
2. Perform a one port calibration of the VNA with the connected ECU at nominal lab temperature $T_0 = 23C$ in chamber.
3. Set temperature in chamber to $T_0 + \Delta T$. Wait until temperature equilibrium is reached in chamber.
4. Make measurements for all states of the ECU.
5. Repeat 4 to 5 for different ΔT. Record changes as a function of ΔT.

Connector Repeatability (CR) Tests

The purpose of these tests is to determine the influence of the connection between ECU and test port on the characteristics of the ECU states. It is unavoidable that the properties of the test port connectors influence the results of this test.

ECU test CR1

1. Directly connect ECU to VNA test port cable in horizontal orientation, wait until temperature equilibrium is reached
2. Do measurements of all ECU states to determine VNA error terms $\mathbf{E_1}$
3. Repeat measurements of all ECU states at different connector orientations and determine new VNA error terms $\mathbf{E_2}, \mathbf{E_3}, \ldots$.
4. De-embed the mean of all error terms $\langle \mathbf{E} \rangle$ from all subsequently determined error terms to calculate the change in S-parameters of the connector $\mathbf{C_1}, \mathbf{C_2}, \mathbf{C_3}, \ldots$.

   $$\mathbf{E_i} = \langle \mathbf{E} \rangle \oplus \mathbf{C_i} \;\longrightarrow\; \mathbf{C_i} = \mathbf{E_i} \ominus \langle \mathbf{E} \rangle$$

   The operators $\oplus$ and $\ominus$ denote cascading and decascading, respectively.

Alternatively it is possible to look at pairwise differences: $\mathbf{C_i} = \mathbf{E_i} \ominus \mathbf{E_{i-1}}$. This is less prone to drift.

Long term Stability (LS) Tests

To test the long term (months to years) stability of an ECU, a calibration of the VNA is performed using a mechanical calibration kit, assuming that the components of the mechanical kit are stable. The calibration is verified using a set of mechanical verification standards. The states of the ECU are measured.

The test LS is based on a mechanical SOL calibration. It keeps the cables first fixed to measure one port states and only at the end the two port states are measured using the Unknown Thru calibration.

ECU test LS1

Keep both test port cables fixed. Leave enough space between test ports that ECU terminated with short(s) on the not used port(s) can be connected to both, but not more.

1. Perform VNA Calibration on port 1: Mechanical SOL.
2. Perform verification measurements with previously characterized components (Open, Short, Load which were not used during the calibration) on port 1.
3. Connect ECU to port 1 and terminate the not used ports with a load. Wait until temperature equilibrium is reached.
4. Measure S-parameters of ECU one port states.
5. Remove ECU from port 1 and repeat steps 1 to 4 for the other ECU ports.
6. Leave ECU connected to port 2 (in case of 2-port ECU) and move test port cable 2 to connect ECU also to port 1. Wait until temperature equilibrium is reached.
7. Measure all ECU two port states. Use the ECU Thru state showing the lowest attenuation to perform an Unknow Thru calibration.
8. Verification: Remove ECU. Connect a known 10 dB attenuator, wait until 23 deg temperature equilibrium is reached and measure it. Establish mechanical Thru and measure it. During all these operations keep text port cable 1 fixed and just move test port cable 2.
9. Record drift of one port and two port ECU states over time.

Alternatively one could use the ECU measurements to determine the VNA error terms and record their variation with respect to the error terms determined in the mechanical calibration.

Short term Stability (SS) Tests

Tests of short term (minutes, hours) stability face two challenges:

1. How to distinguish between the stability of ECUs and the stability of the VNA.
2. How to avoid reconnections of the ECU. The connector repeatability likely shadows short term stability effects of the ECU

Because of these eventually dominating effects it might be difficult to determine the short term stability of the ECU states.

Two tests are proposed that should be able to separate VNA drift from ECU drift, at least to a certain extent, while avoiding reconnections of the ECU. At this stage it is unclear if these tests will provide conclusive results. Practical investigations are needed to come up with an exact procedure.

Test SS1 uses two ECUs in series and measures the stability relative to each other. Correlated drifts are interpreted as drifts of the VNA. This assumption can obviously be wrong, if e.g. environmental influences lead to the same changes in both ECUs. It is further assumed that the Thru state of the first ECU is reasonably stable.

Test SS2 uses one ECU and measures the stability of states relative to each other. Again correlated drifts are attributed to the VNA. This assumption is prone to be wrong because correlated drift of the ECU states is likely.

ECU test SS1

Connect two ECUs in series to the test port: VNA - ECU1 - ECU2.

The following procedure should be done at one single frequency or a reduced number of frequencies to keep time intervals between measurements reasonably short.

1. Measure all ECU1 one port states → Raw S-parameters: $M_{11}^{ECU1}(t_1)$
2. Set ECU1 to Thru and measure all one port states of ECU2 → Raw S-parameters $M_{11}^{ECU2}(t_2)$
3. Keep repeating steps 1 and 2.
4. Determine error terms of the VNA for each of the ECU measurement: $\boldsymbol{E}(t_i)$
5. Error correct the raw S-parameter measurements using the error terms from the previous measurement. E.g. calculate $S_{11}^{ECU2}(t_i)$ from $M_{11}^{ECU2}(t_i)$ and $\boldsymbol{E}(t_{i-1})$.
6. Calculate differences $\Delta S_{11}(t_i) = S_{11}^{ECU1}(t_i) - S_{11}^{ECU2}(t_{i-1})$.
7. Record changes in $\Delta S_{11}(t_i)$ over time.

ECU test SS2

Connect a single ECU to a test port.

The following procedure should be done at a single frequency or a reduced number of frequencies to keep time intervals between measurements reasonably short.

1. Measure all ECU states repeatedly.
2. Calibrate the VNA based on all states with an over-determined technique where all states have the same weight.
3. Record the changes of the error corrected values of all ECU states with respect to the first measurement.

Analysis of tests

All tests produce a series of measured S-parameters or error correction terms, either as a function of time or as a function of ambient temperature change. The analysis is discussed here for measured S_{11} at different times t_1, t_2, t_3, …. For all other cases the analysis remains in principle the same.

From the measured series of S_{11}

$$S_{11}(t_1), S_{11}(t_2), S_{11}(t_3), \ldots$$

calculate the vector differences with respect to the reference measurement

$$\Delta S_i = S_{11}(t_i) - S_{11}(t_1)$$

For the graphical representation it might be preferable to reduce the two dimensional quantity to a scalar by calculating the magnitude $|\Delta S_i|$.

The measurement uncertainty is a criterion to distinguish between variations coming from the stability effects of the ECUs and variations coming from the other measurement errors.

Use uncertainty propagation to determine the standard uncertainty covariance matrix $\mathbf{V}$ of the complex-valued ΔS_i(to be explained in more detail). It can be expanded with a factor of $(2.45)^2$ for 95% coverage. If the elliptical region defined by the expanded uncertainty does not contain the origin of the coordinate system the deviation might be attributed to ECU effects.

For the magnitude $|\Delta S_i|$ linear uncertainty propagation might provide a wrong result due to the non-linear relation between $|\Delta S_i|$ and ΔS_i. Monte Carlo propagation will only produce positive values. The distribution does not include zero and is therefore not suitable to make the above mentioned distinction. An alternative is to calculate a more heuristic uncertainty based on a graphical interpretation of the elliptical region defined by V, see M. Zeier, CPEM 2006, Conf. Digest p. 458-459, 2006.

$$u(|\Delta S_i|) = \sqrt{(\Delta S_i' V^{-1} \Delta S_i)^{-1} \chi^2_{2,1-p}} |\Delta S_i|, \; |\Delta S_i| \neq 0$$

ΔS_i represents in this equation a row vector of length two, containing the real and imaginary part.
$\chi^2_{2,1-p}$ denotes the chi square factor for a coverage probability p.
$\chi^2_{2,1-p} = (2.45)^2$ for $p = 0.95$.

Analysis of residual errors

As an alternative to analyze the S-parameters of each ECU state we can instead analyze the drift or difference in VNA error terms. This could be viewed as an investigation of the drift in residual error. For the LS case we would deembed the mechanical error terms from the ECU error terms at each measurement occasion. The residual errors would then be analyzed using the same approach as the S-parameters above.

Measurement Protocol

ECU Inventory

METAS:

Shortcut	Model	S/N
M:E01	ECU Agilent N4690C, 2 x Type-N (f-m), 300 kHz - 18 GHz	
M:E02	ECU Agilent N4691B, 2 x 3.5 mm (f-m), 300 kHz – 26.5 GHz	
M:E03	ECU Agilent N4693A, 2 x 2.4 mm (f-m), 10 MHz - 50 GHz	
M:E04	ECU Agilent N4694A, 2 x 1.85 mm (f-m), 10 MHz - 67 GHz	
M:E05	ECU Agilent N4694A, 2 x 1.85 mm (f-m), 10 MHz - 67 GHz	

PTB:

Shortcut	Model	S/N
P:E01	Rohde&Schwarz ZV-ZV52, 4 x 3.5 mm (f-f-f-f), 10 MHz – 24 GHz	
P:E02	Anritsu 36585V, 2 x 1.85 mm (f-f), 70 kHz - 70 GHz	
P:E03	Anritsu 36585V, 2 x 1.85 mm (f-f), 70 kHz - 70 GHz	
P:E04	Agilent N4694A, 2 x 1.85 mm (f-m), 10 MHz - 67 GHz	
P:E05	Agilent N4694A, 2 x 1.85 mm (f-m), 10 MHz - 67 GHz	

SP:

Shortcut	Model	S/N
S:E01	Agilent N4690B 2 x Type-N (f-m), 300 kHz – 18 GHz	
S:E02	ECU Agilent N4691B: 2 x 3.5 mm (f-m), 300 kHz – 26.5 GHz	

Longterm stability tests

ECUs:

1. M:E04
2. P:E01
3. S:E02

Frequency List:

every 100 MHz up to maximum frequency

Sequence:

1. 15. Nov 2013: METAS and PTB perform first LS1 test.
2. 30. Nov 2013: Discuss experience and make adjustments to LS1
3. Perform LS1 every 4 to 8 weeks.
4. 30. April 2014: METAS, PTB and SP provide 1st data set of LS1 tests
5. Reduce measurement frequency gradually afterwards, based on the experience made in the previous measurements. In case of irregular behavior an increase in frequency might be advised.

6. 28. Feb. 2015: Provide 2nd data set of LS1 tests
7. 31. Dec.2015: Provide final data setoff LS1 tests

Short term stability tests

ECUs:

Use all available ECUs

Frequency List:

Not defined for first tests

Sequence:

1. 30. Nov. 2013: METAS and PTB perform first TS and CR tests on a subset of the available ECUs. First data sets collected.
2. 5. Dec. 2013: Workshop: First results are discussed. Adjustments to test procedures are made
3. 15. March 2014: Repeat TS and CR tests for adjusted procedures and the remaining ECUs. Perform SS tests on a subset of ECUs. Adjust SS tests if necessary.
4. Complete short term tests on remaining ECUs
5. June 2014: Provide final data set

Exchange data format:

The exchange data format is a common format that allows participants to analyze test data taken by another laboratory. The data does not contain measurement uncertainties.

For each frequency sweep (even if it is just a single frequency) a single file is created in the Touchstone format, see http://www.eda.org/ibis/connector/touchstone_spec11.pdf, containing the frequencies and the measured S-parameters. The S-parameters should be stored in Cartesian coordinates with real and imaginary components.

The files are organized in folders, each folder corresponding to a single short term test (TS, CR, SS) or to a single session of the long term test (LS).

The folder names have the following structure:

<test>_<date>_<counter>

Field	Definition
<test>	Name of the test. Use shortcuts defined in this document, e.g. TS1a
<date>	Date in the format yyyymmdd
<counter>	Two digit number: 01, 02, 03, …

The files in the folder have the following name structure:

data_<time stamp>_<kit/ecu>_<standard/state>.s2p

Field	Definition
<time stamp>	Time in the format yyyymmddhhmmss
<kit/ecu>	Identifier of ECU or mechanical kit used. Use the shortcuts in the inventory above for the ECUs, e.g. P:E01. For the test SS1, where two ECUs are used in series, use e.g. M:E04-M:E05 Participants declare identifiers for the mechanical kits they use using the same scheme, e.g. P:M01
<standard/state>	Identifier of the mechanical standard or the ECU state used. For the ECU one port states the identifier has the form <Port><StateNum>.

	<Port> can be A, B, C etc. <StateNum> is a single digit number. Using state 1 on port A is therefore coded as A1. For ECU two port states use e.g. AB1 if ECU port A is connected to VNA port 1 or BA1 if ECU port B is connected to VNA port 1. For the test SS1, where two ECUs are used in series, specify e.g. AB1-A1. For the mechanical standards use the following names: Open, Short, Load, Thru, SLoad, MMatch, Att, Line. Each of these can be followed by a number, e.g. Short1

Additional information about the measurement should be written in a plain text file named Info.txt

Some of the tests require S-parameter data of the ECU states or the mechanical standards to perform VNA calibration and error correction. This data is provided by the participants in the same file format as the experimental data. The naming scheme is
caldata_<kit/ecu>_<standard/state>.s2p
with the same definitions as above.

Deliverable 2.3.9 - Report on the stability of and temperature effects on ECUs

Version 2016-03-18

Introduction

This report summarizes results of stability and temperature effect investigations of electronic calibration units (ECU). It is subdivided into short-term measurements in the time frame of seconds and minutes and long-term measurements in the range of months and years. Short-term measurements give insight into effects related to thermal heat flow until the thermal equilibrium has been reached, while long-term measurements give information about a recommended re-calibration time interval of an ECU.

Parameters

Two ECUs from different manufacturers have been monitored for a time period of month and years to determine the long-term stability of the ECUs. To identify slight changes of the ECU switching states versus time, always the same VNA setup and the same mechanical calibration standards have been used. Prior to all stability measurements, sufficient heat-up time was given until both VNA and ECU had fully reached thermal equilibrium. Furthermore, the laboratory environmental conditions were very stable (±0.2 K). The IF bandwidth of the VNA was set to 10 Hz. Cable movement was avoided where possible.

ECU1 is a four port ECU equipped with PC3.5mm connectors for frequencies up to 24 GHz. Each port can be switched to the three one port states Open, Short, and Match. Furthermore, a through connection between all ports is switchable. Here, all 1-port states and the 2-port states 1-4 and 3-2 have been analyzed between 1 GHz and 24 GHz in 1 GHz steps.

ECU2 is a 2-port ECU for frequencies up to 67 GHz. Each port can be switched to the seven one port states, and a through connection between the ports is possible. Here, all states have been analyzed for 45 MHz to 67 GHz.

Short-term stability measurements

The purpose of short-term measurements is to determine the influence of temperature variations on the electrical properties of the ECU (-switching states) and on the VNA error terms.

Test TS1a

This test investigates the change of VNA error terms after connecting the ECU to the VNA test port cable until the thermal equilibrium is reached.

Procedure:

- Install test port cables between ECU and VNA
- Choose a limited number of frequency points (in order to accelerate the VNA sweep rate)
- Let ECU reach thermal equilibrium
- Connect ECU and immediately start measuring ECU states repeatedly
- Calculate VNA error terms from ECU switching states raw data
- Calculate VNA error term drift (vector difference)

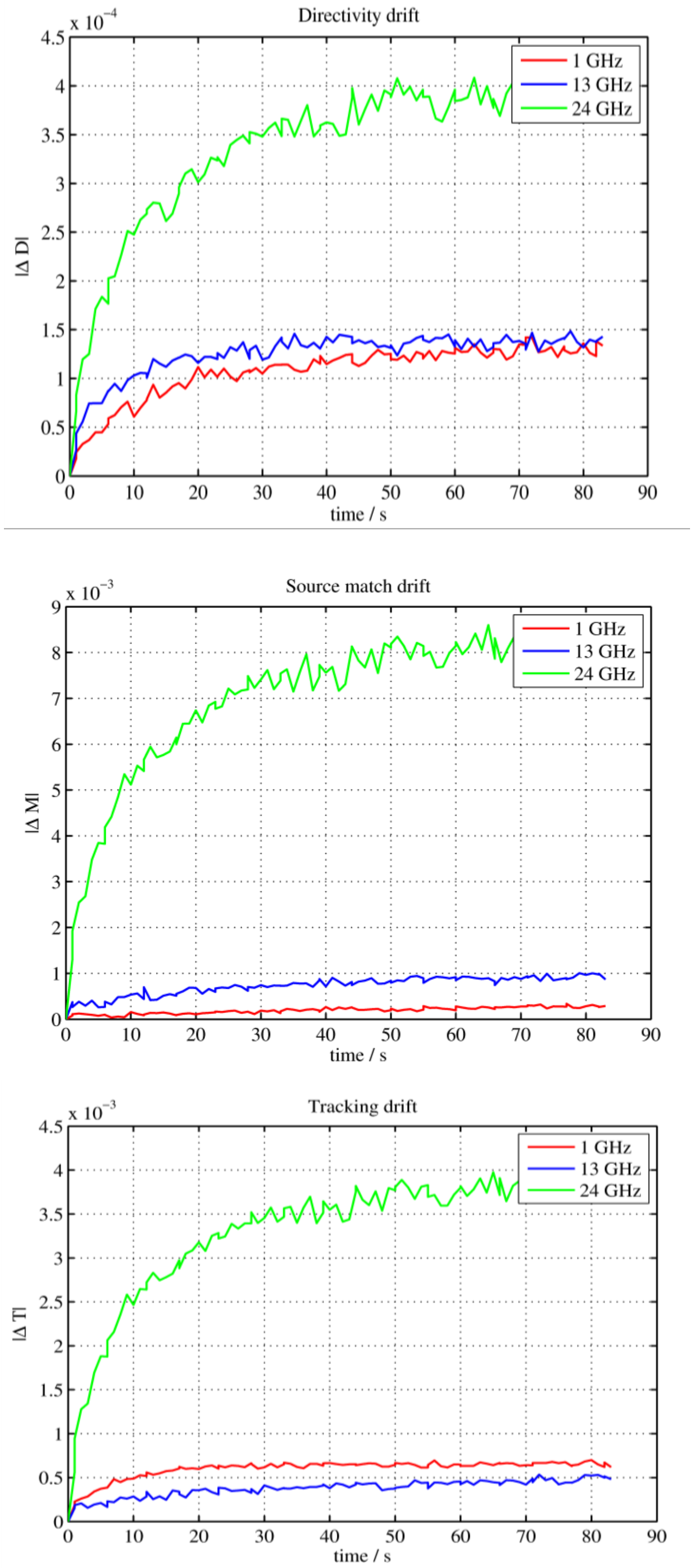


Fig. 1. Drift of VNA error terms after connecting ECU to test port cable.

Test TS1b

This test investigates the change of VNA error terms after connecting the ECU directly to the VNA test port until the thermal equilibrium is reached.

Procedure:

- Same procedure as for TS1a, while directly connecting ECU to VNA test port

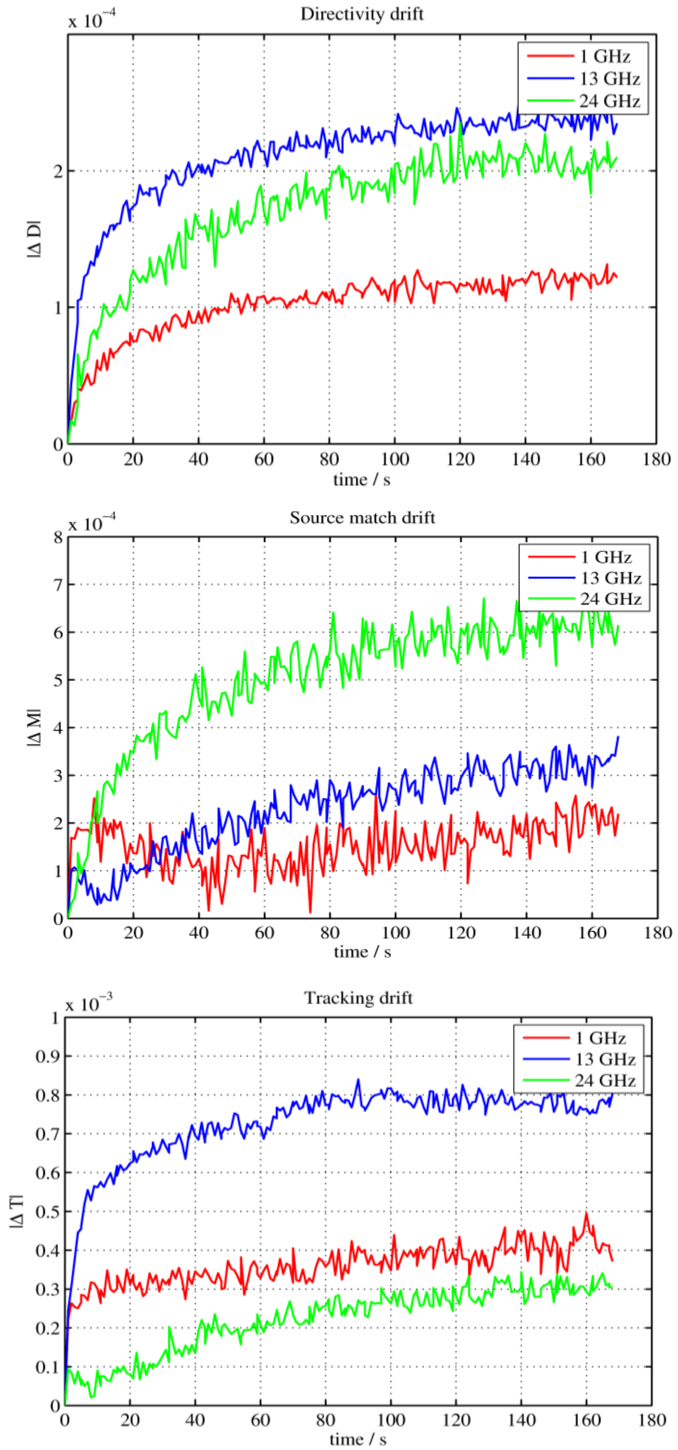


Fig. 2. Drift of VNA error terms after connecting ECU directly to VNA test port.

Test TS2

This test investigates the change of DUT S-parameters immediately after performing a VNA calibration using an ECU.

Procedure:

- Install test port cables between ECU and VNA
- Connect ECU and wait for thermal equilibrium
- Perform 1-port VNA calibration using ECU
- Disconnect ECU and immediately connect mechanical 1-port standards (open short, load)
- Measure S-parameters of mechanical standard repeatedly
- Calculate drift (vector difference)

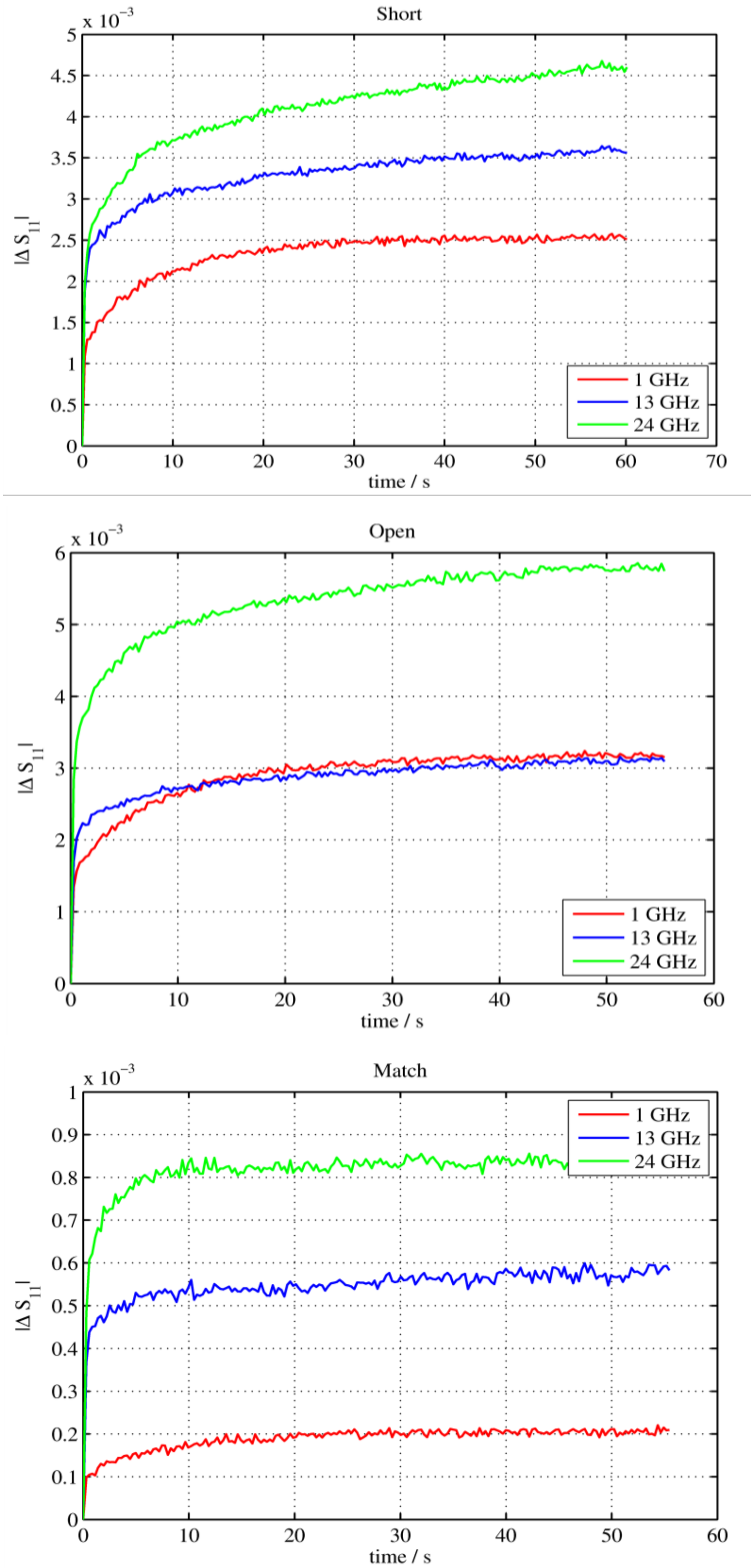


Fig. 3. Drift of DUT S-parameters immediately after performing an VNA calibration using an ECU .

Test TS3

This test investigates the change of ECU switching states due to change of ambient temperature.

Procedure:

- Place ECU inside a temperature-controlled chamber
- Perform a 1-port ECU calibration at laboratory temperature
- Increase chamber temperature stepwise up to 40°C

- Measure all ECU switching states after thermal equilibrium has been reached
- Calculate drift of ECU states (vector difference)

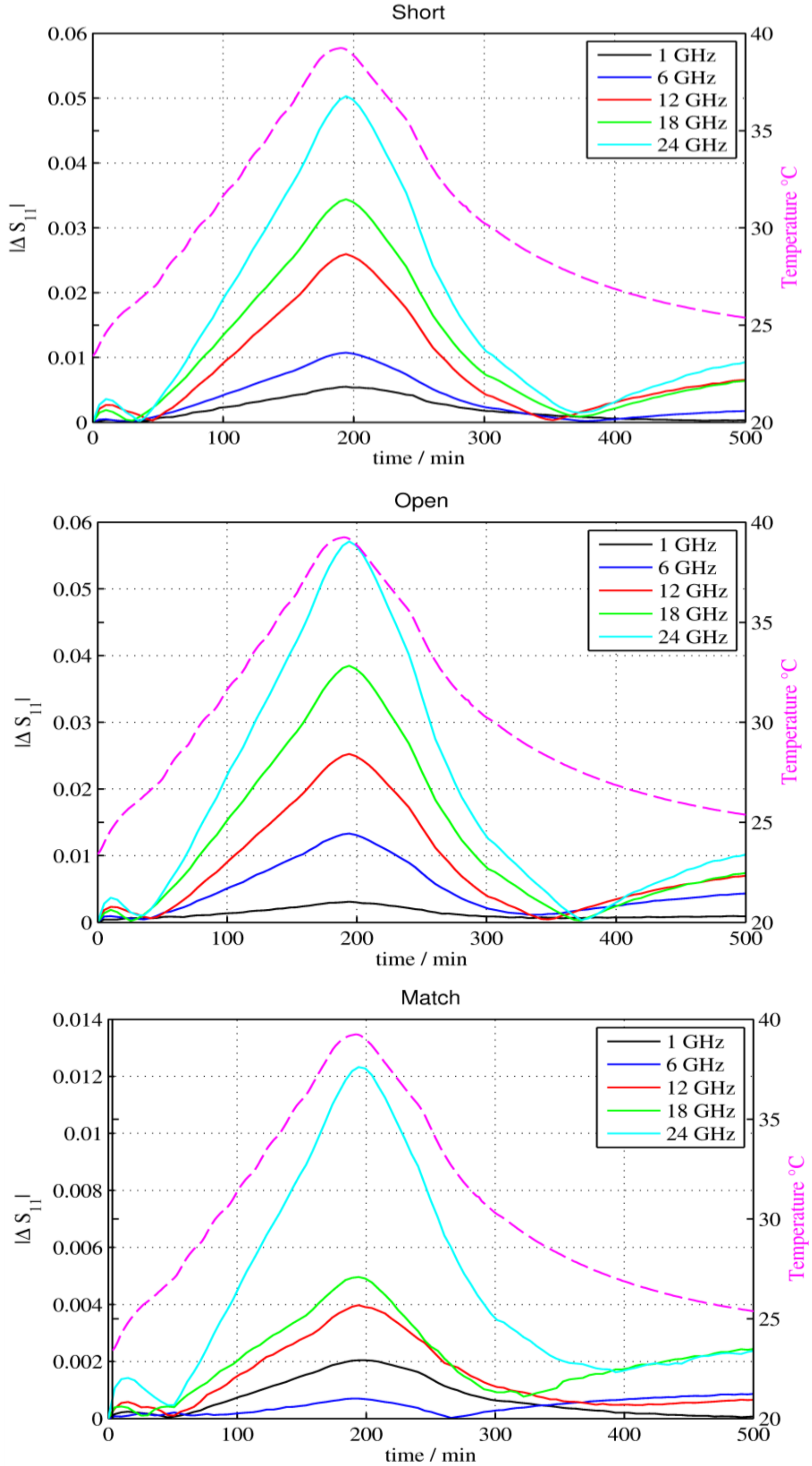


Fig. 4. Change of ECU switching states due to change of ambient temperature.

Long-term stability measurements

Results of 1-port stability: ECU1

For all measurements, the complex scattering parameters have been monitored and analyzed. Only the magnitude results are shown here. The twelve different 1-port states are depicted in Fig. 5 to Fig.

16. In all diagrams the magnitude of the reflection coefficient Γ versus frequency (left) and the magnitude of the reflection coefficient Γ normalized to the first measurement (right) are plotted.

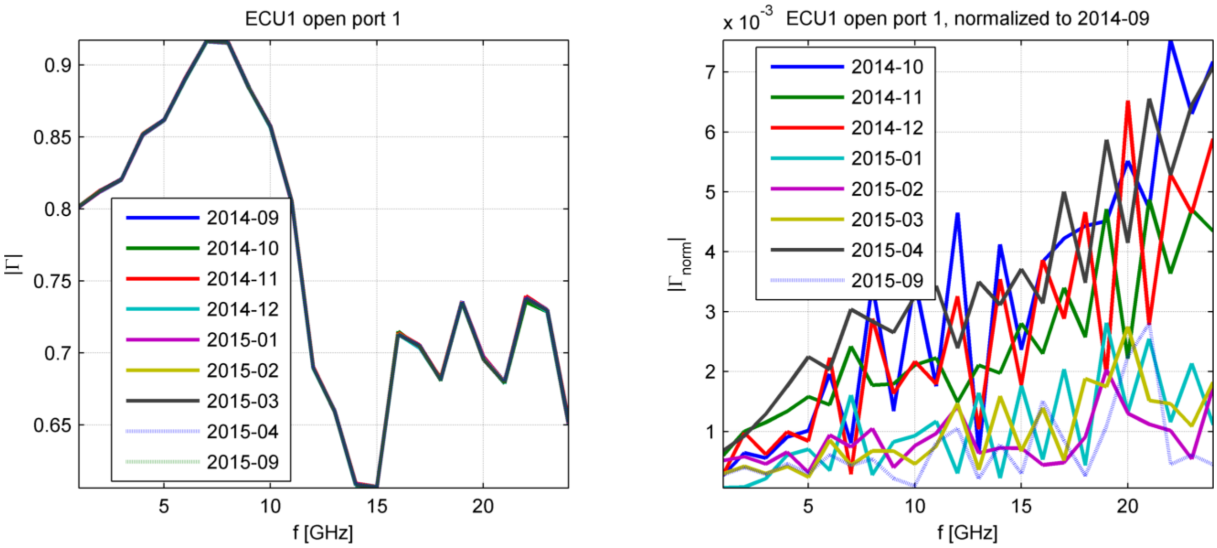


Fig. 5. Open state port 1 of ECU1.

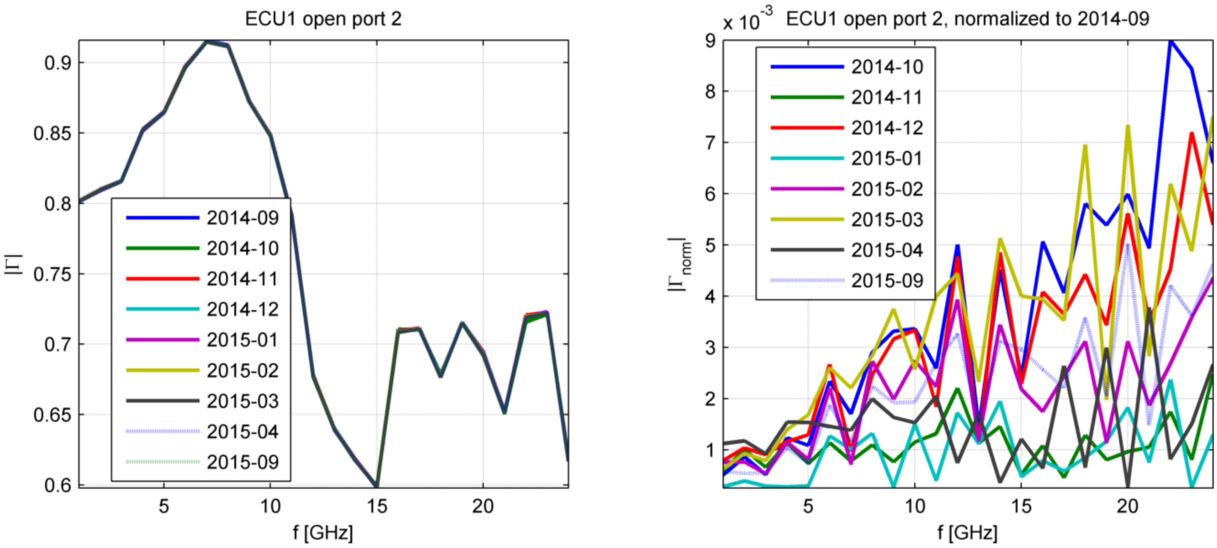


Fig. 6. Open state port 2 of ECU1.

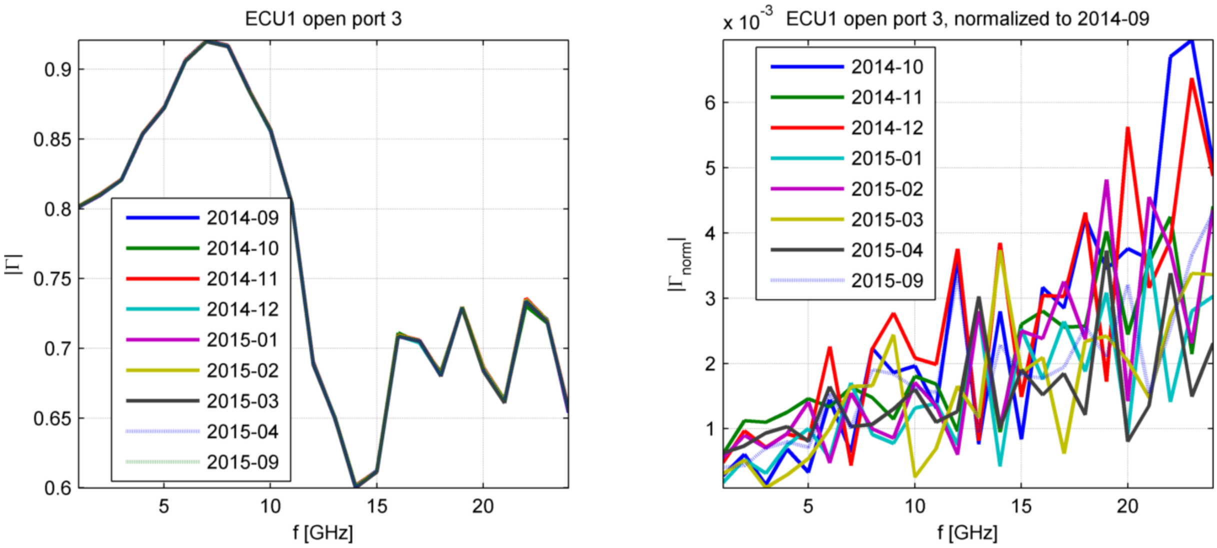


Fig. 7. Open state port 3 of ECU1.

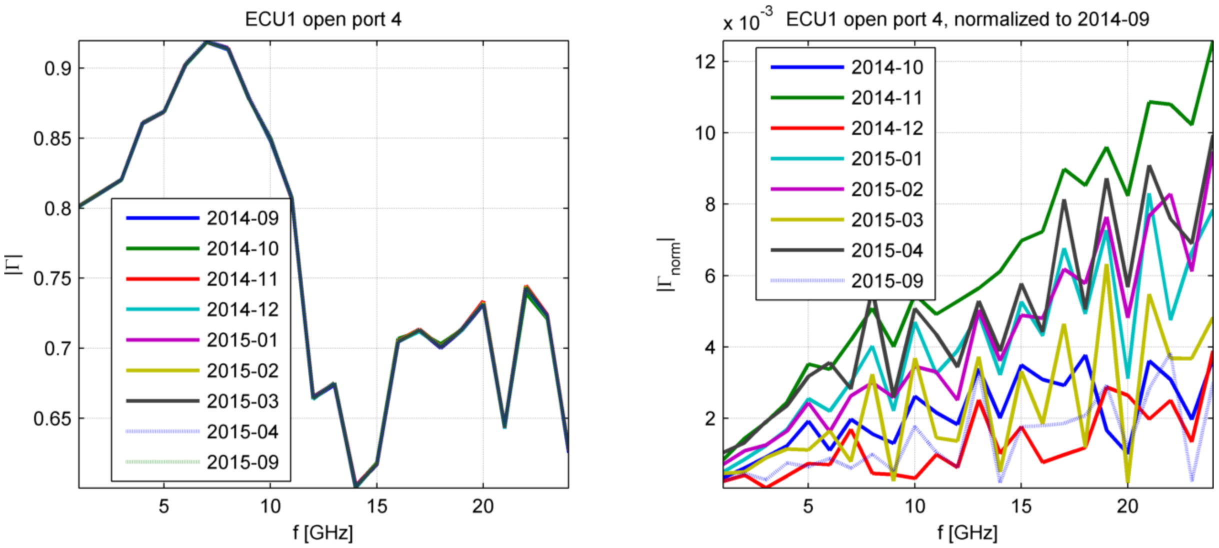


Fig. 8. Open state port 4 of ECU1.

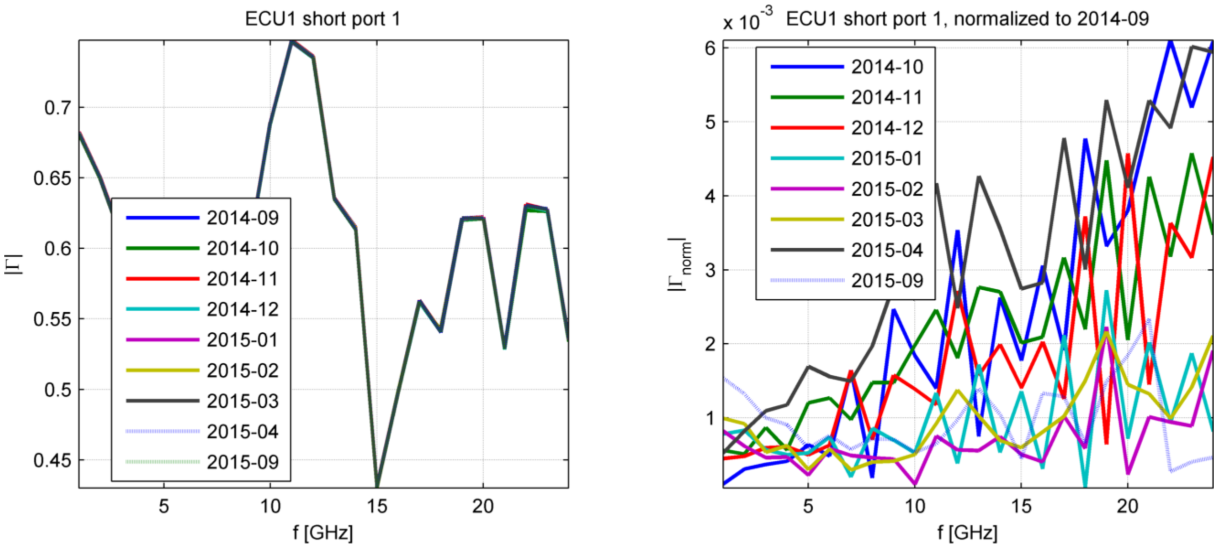


Fig. 9. Short state port 1 of ECU1.

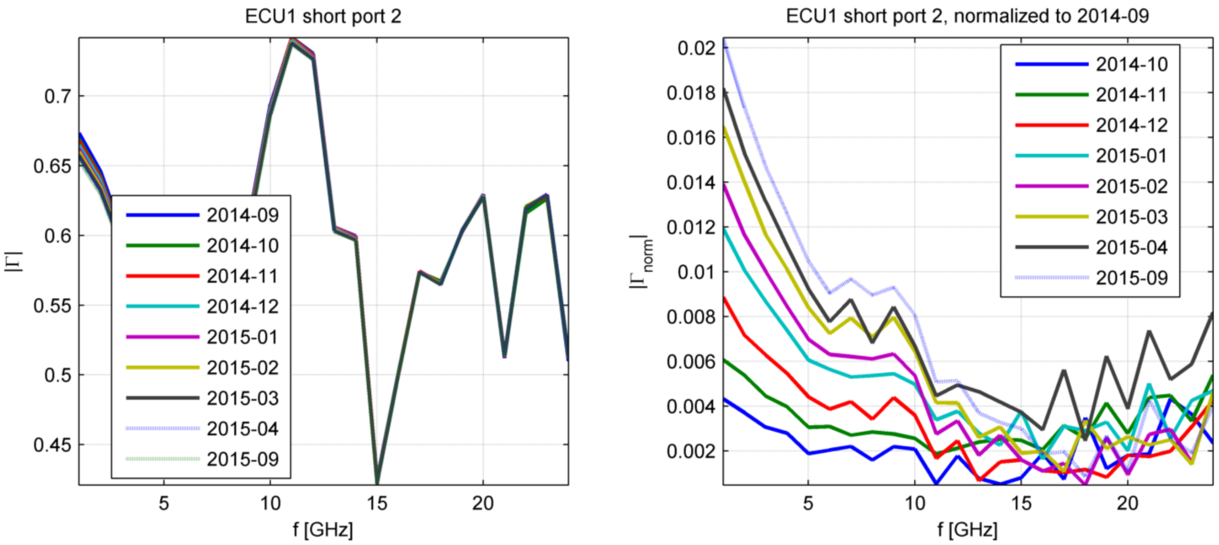


Fig. 10. Short state port 2 of ECU1.

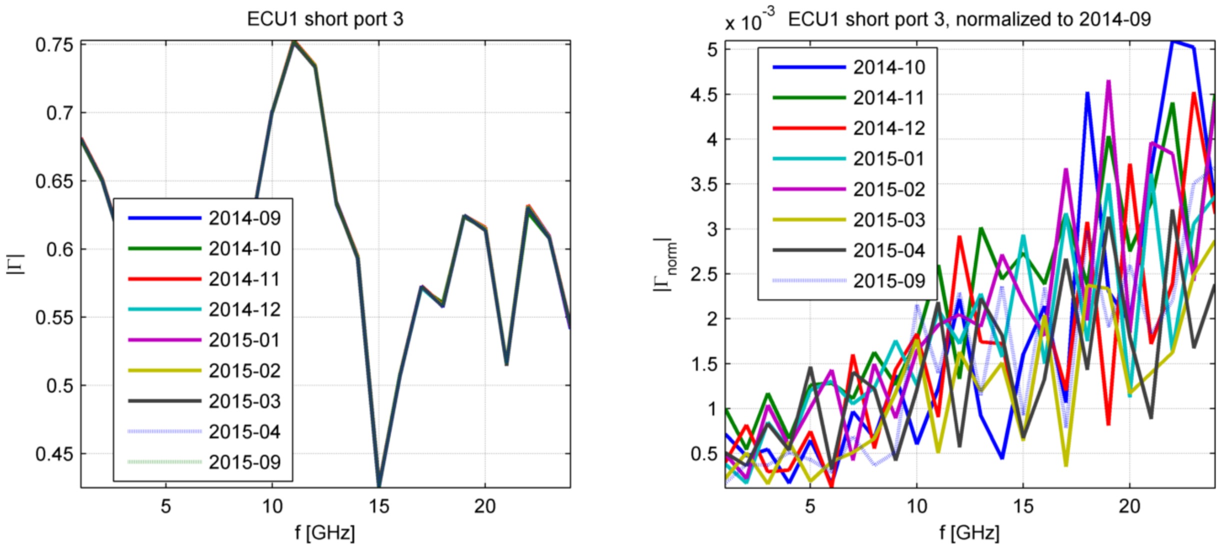


Fig. 11. Short state port 3 of ECU1.

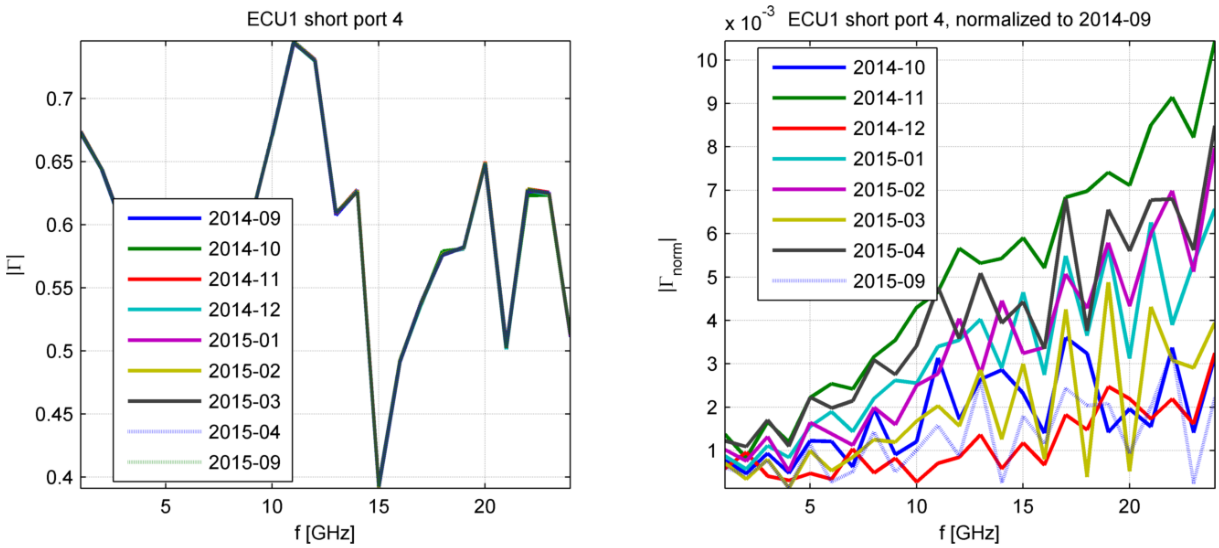


Fig. 12. Short state port 4 of ECU1.

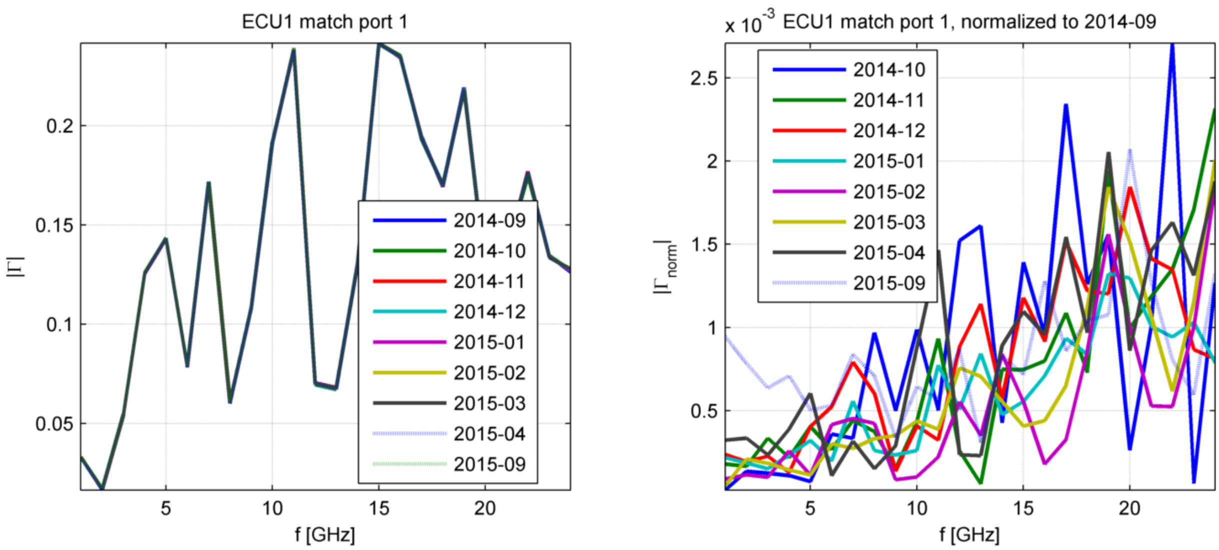


Fig. 13. Match state port 1 of ECU1.

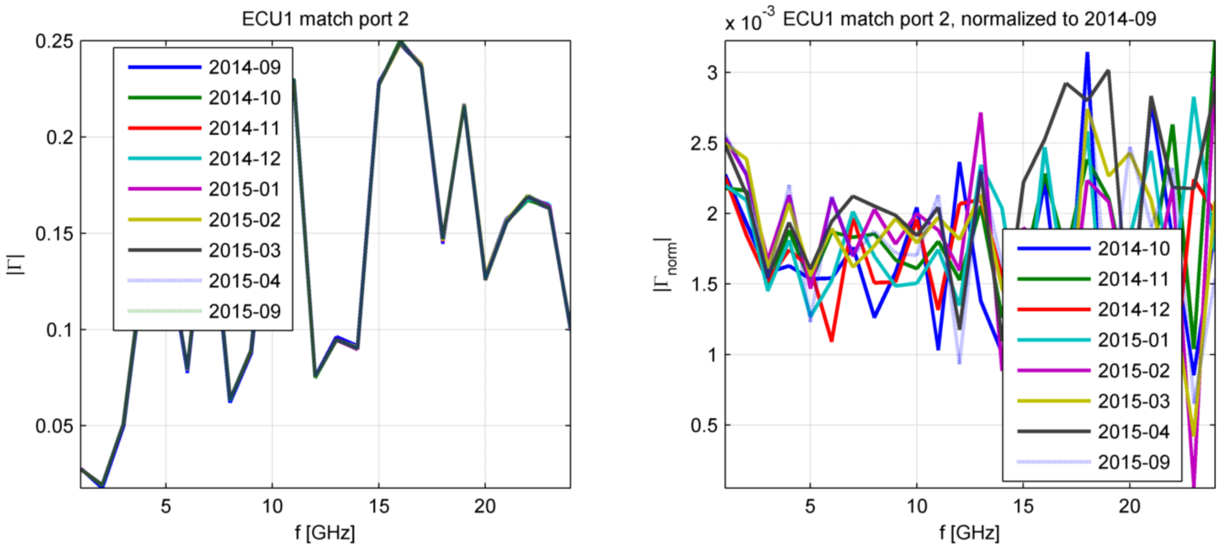


Fig. 14. Match state port 2 of ECU1.

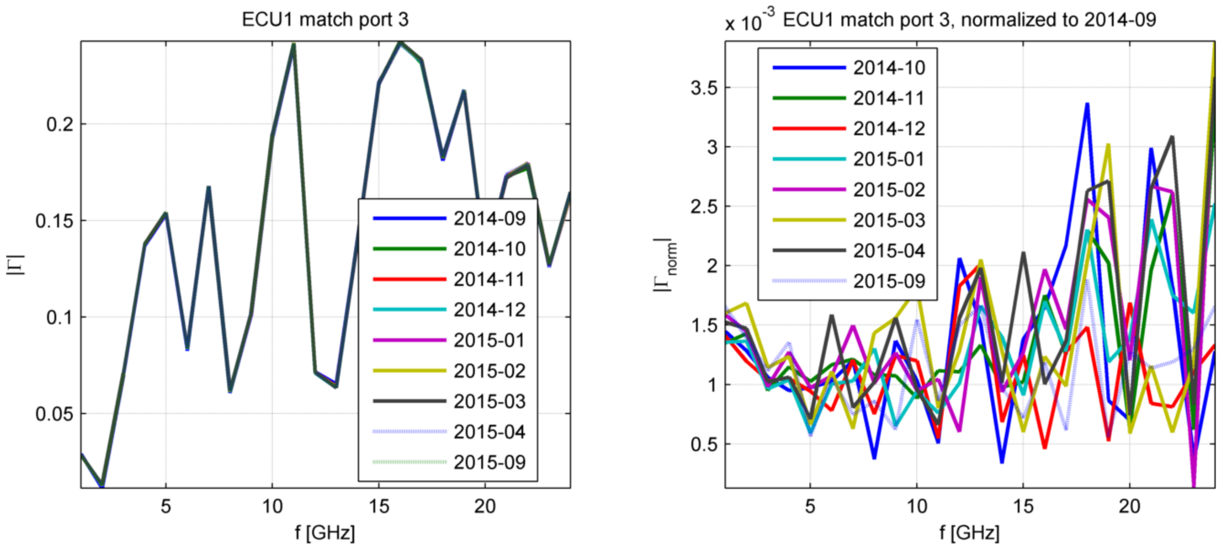


Fig. 15. Match state port 3 of ECU1.

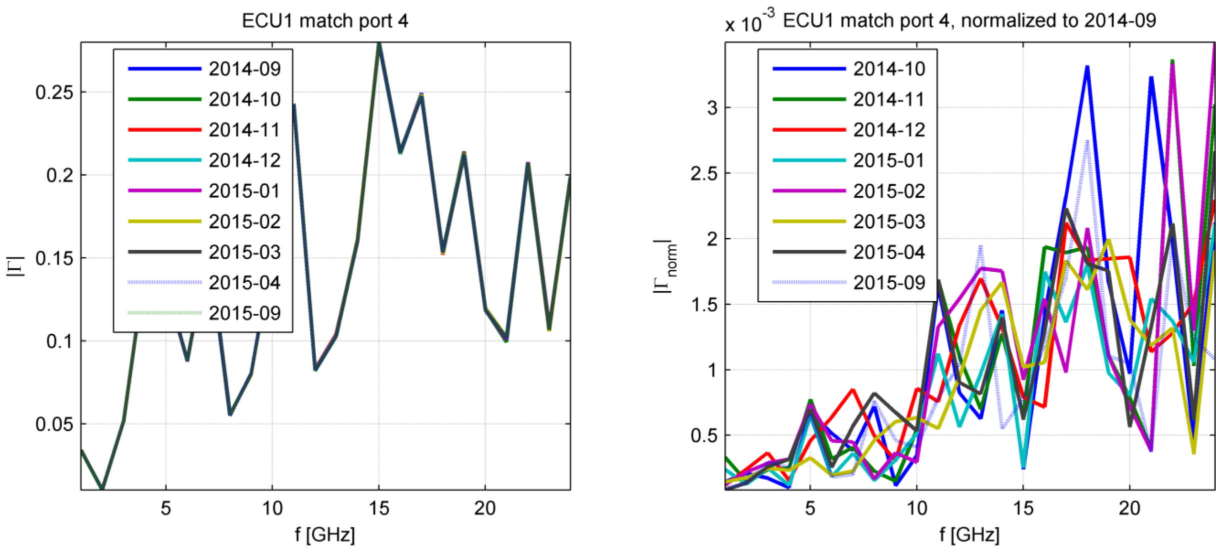


Fig. 16. Match state port 4 of ECU1.

Results of 2-port stability: ECU1

For all measurements, the complex scattering parameters have been monitored and analyzed. Only the magnitude results are shown here. The two 2-port states 1-4 and 3-2 are depicted in Fig. 17 to

Fig. 24. In all diagrams the magnitude of the scattering parameters versus frequency (left) and the magnitude of the scattering parameters normalized to the first measurement (right) are plotted.

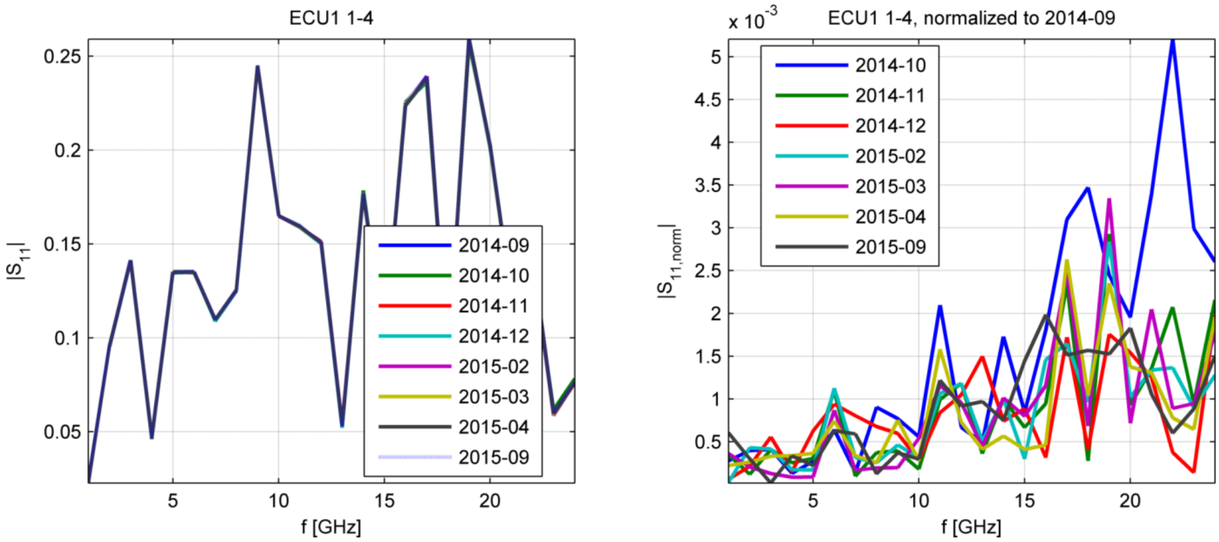


Fig. 17. Reflection coefficient S_{11} 2-port state 1-4 of ECU1.

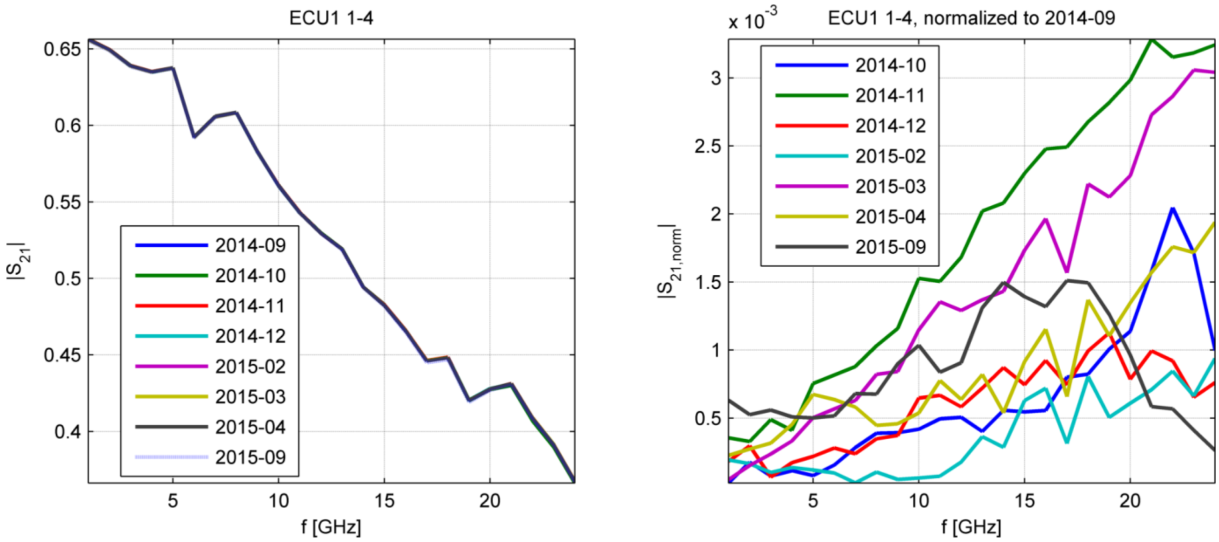


Fig. 18. Transmission coefficient S_{21} 2-port state 1-4 of ECU1.

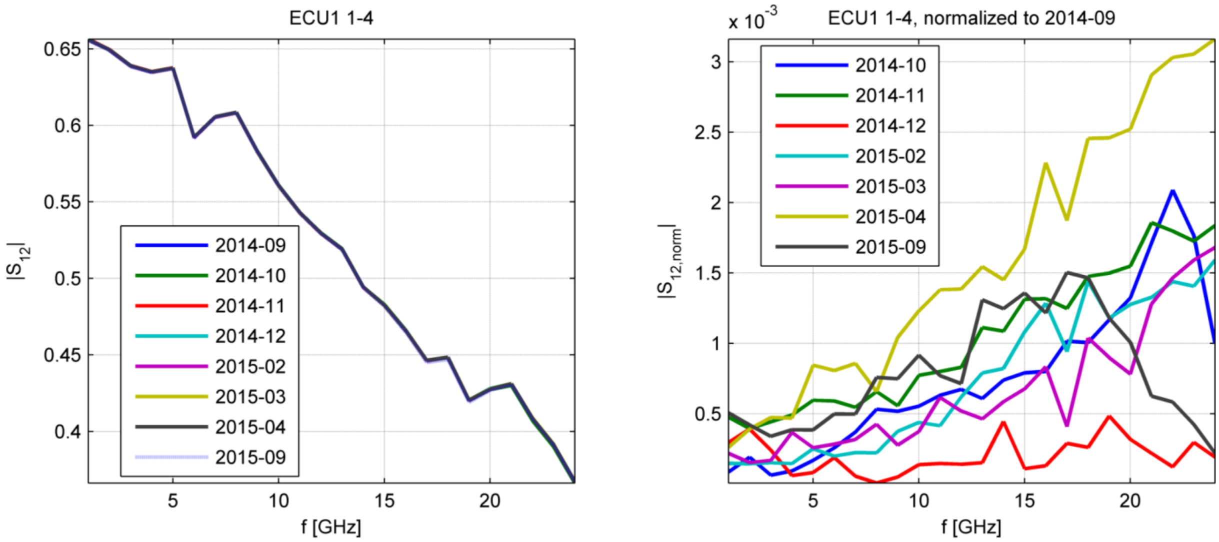


Fig. 19. Transmission coefficient S_{12} 2-port state 1-4 of ECU1.

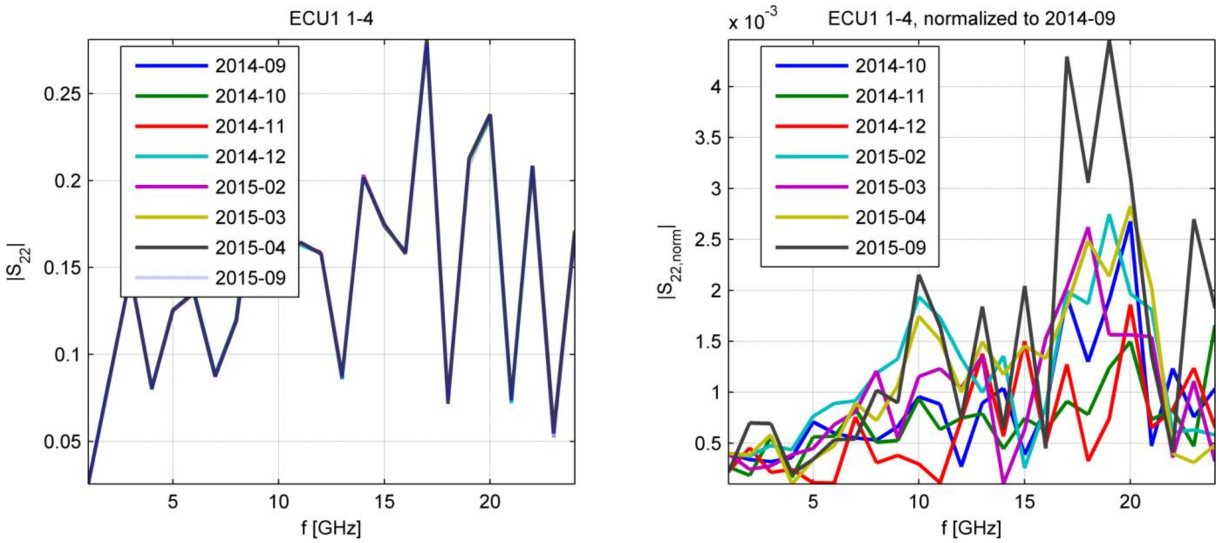


Fig. 20. Reflection coefficient S_{22} 2-port state 1-4 of ECU1.

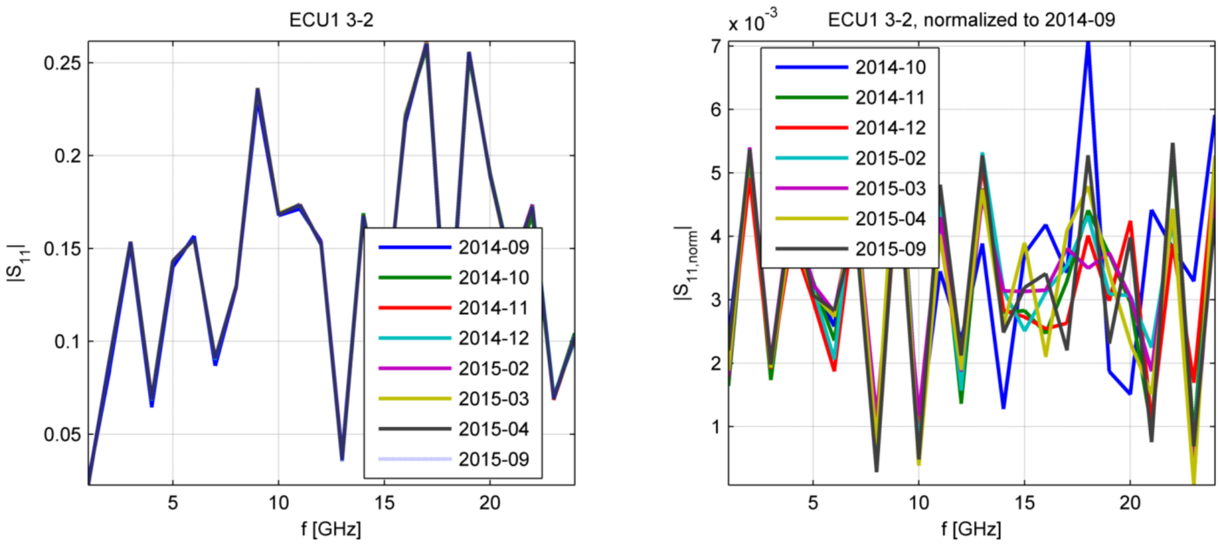


Fig. 21. Reflection coefficient S_{11} 2-port state 3-2 of ECU1.

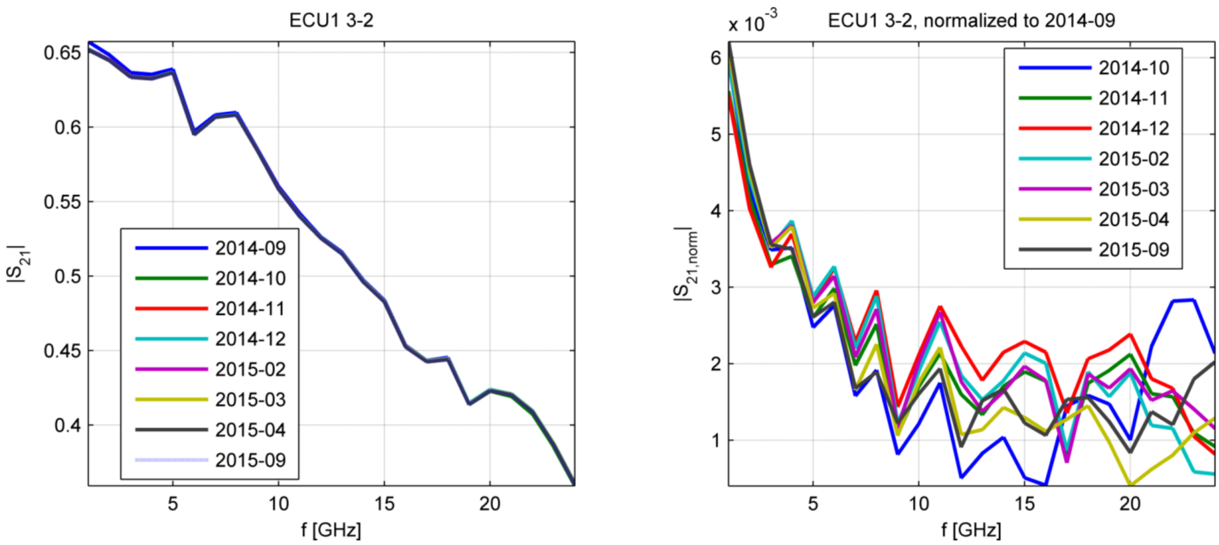


Fig. 22. Transmission coefficient S_{21} 2-port state 3-2 of ECU1.

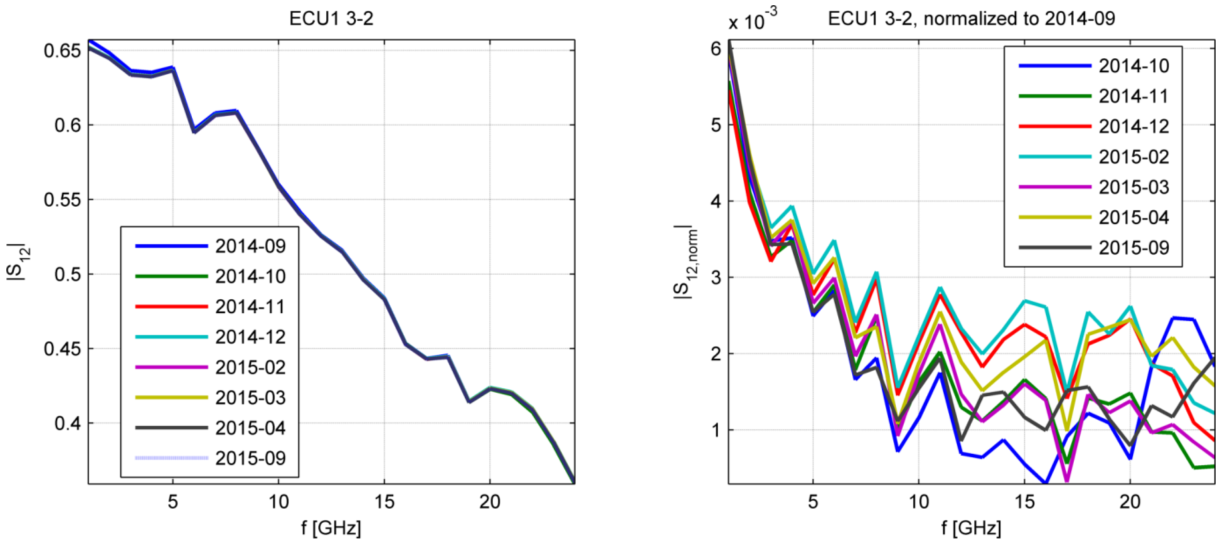


Fig. 23. Transmission coefficient S_{12} 2-port state 3-2 of ECU1.

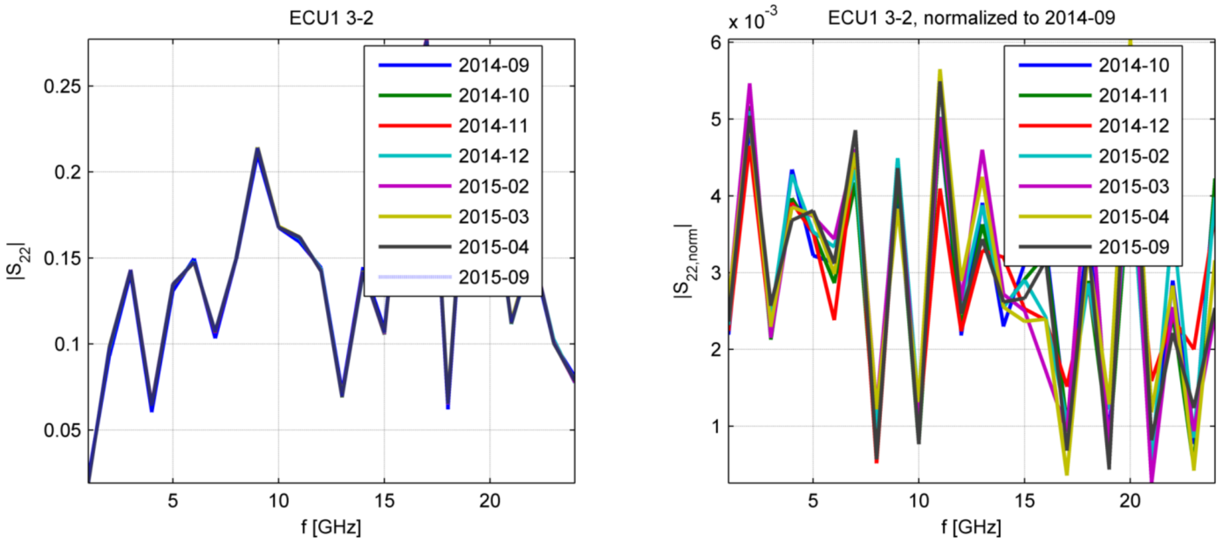


Fig. 24. Reflection coefficient S_{22} 2-port state 3-2 of ECU1.

Discussion of long-term stability: ECU1

The stability results for ECU1 show an ambivalent behavior. The 2-port states seem to be quite stable, though e.g. for an unknown thru calibration (UOSM) the actual scattering parameter of the thru standard is not needed. Some of the 1-port states also show very stable behavior within a time period of month and years, especially the match states, while the open and short states are stable at ports 1 and 3 but somewhat unstable at ports 2 and 4. As the actual internal termination is identical for all ports, there is evidence that one of the ECU switches introduces unstable behavior. The drift results are summarized in Table 1 and Table 2.

Table 1. Drift of 1-port states of ECU1.

State	Port	Drift Magnitude [10^{-3}]
Open	1	7.5
	2	9.0
	3	7.0
	4	12.5
Short	1	6.0
	2	21.0

	3	5.0
	4	10.2
Match	1	2.8
	2	3.2
	3	3.8
	4	3.5

Table 2. Drift of 2-port states of ECU1.

State	S-Par.	Drift Magnitude [10^{-3}]
1-4	S_{11}	5.1
	S_{21}	3.3
	S_{12}	3.2
	S_{22}	4.4
3-2	S_{11}	7.0
	S_{21}	6.1
	S_{12}	6.1
	S_{22}	5.6

Results of 1-port stability: ECU2

For all measurements, the complex scattering parameters have been monitored and analyzed. The two 2-port states AB1 and AB2 are depicted in Fig. 25 to Fig. 42. In all diagrams the magnitude of the scattering parameters versus frequency (on top) and the magnitude and phase of the scattering parameters normalized to the first measurement (on bottom) are plotted. The normalized data are showing in addition the combined uncertainty regions (U95) from each of the measurements.

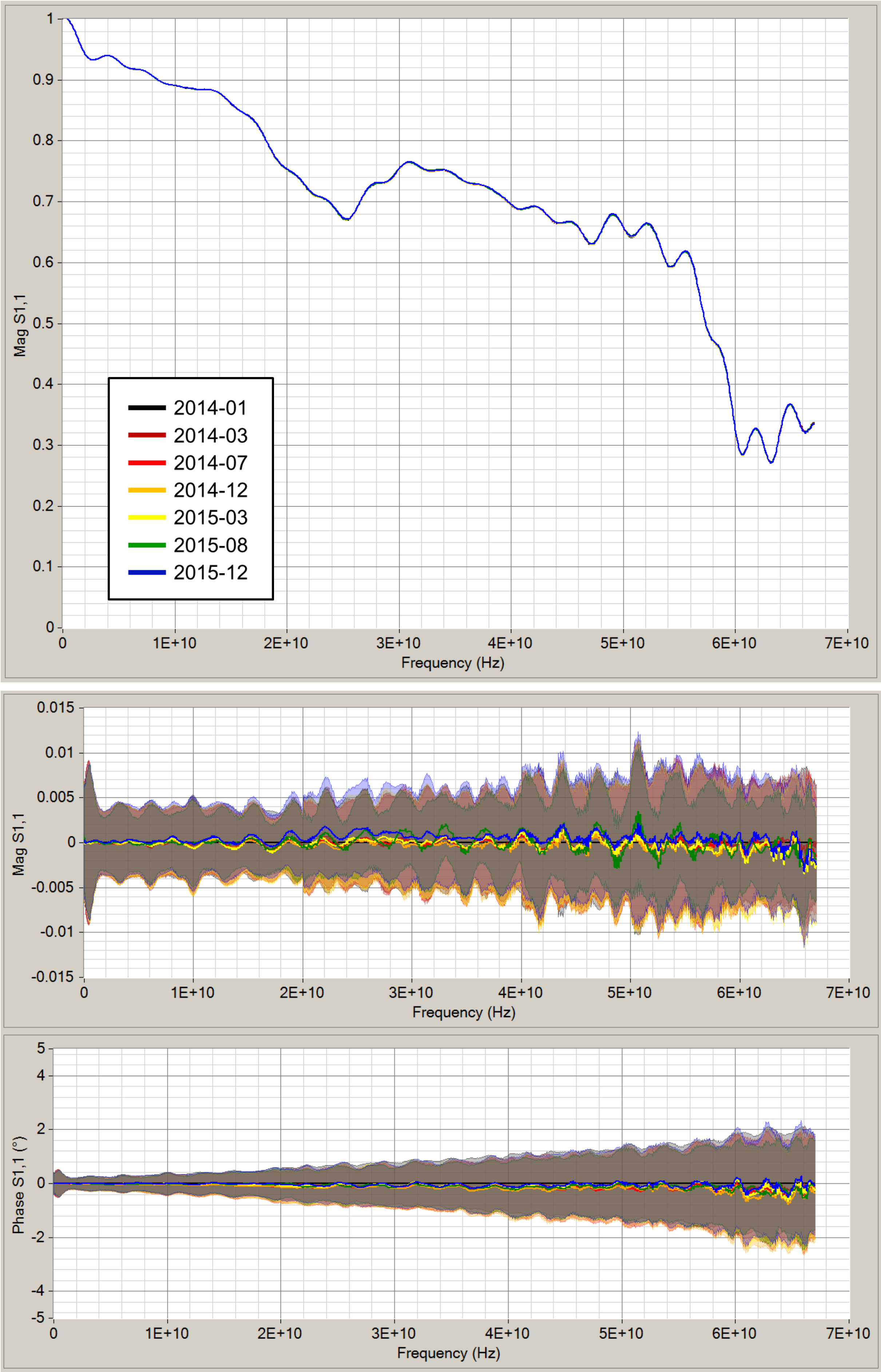


Fig. 25. Reflection coefficient S_{11} 1-port state A1 of ECU2.

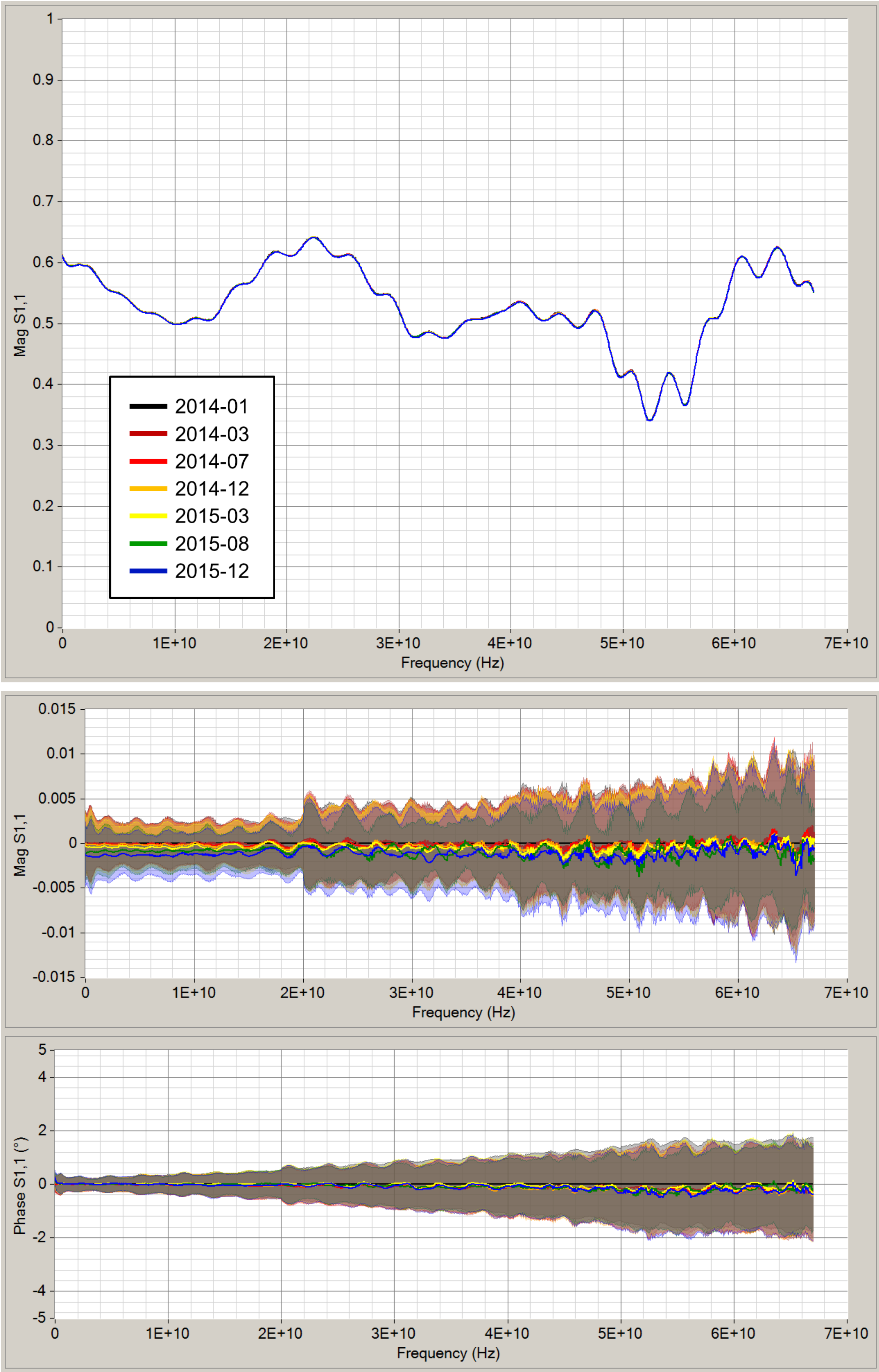


Fig. 26. Reflection coefficient S_{11} 1-port state A2 of ECU2.

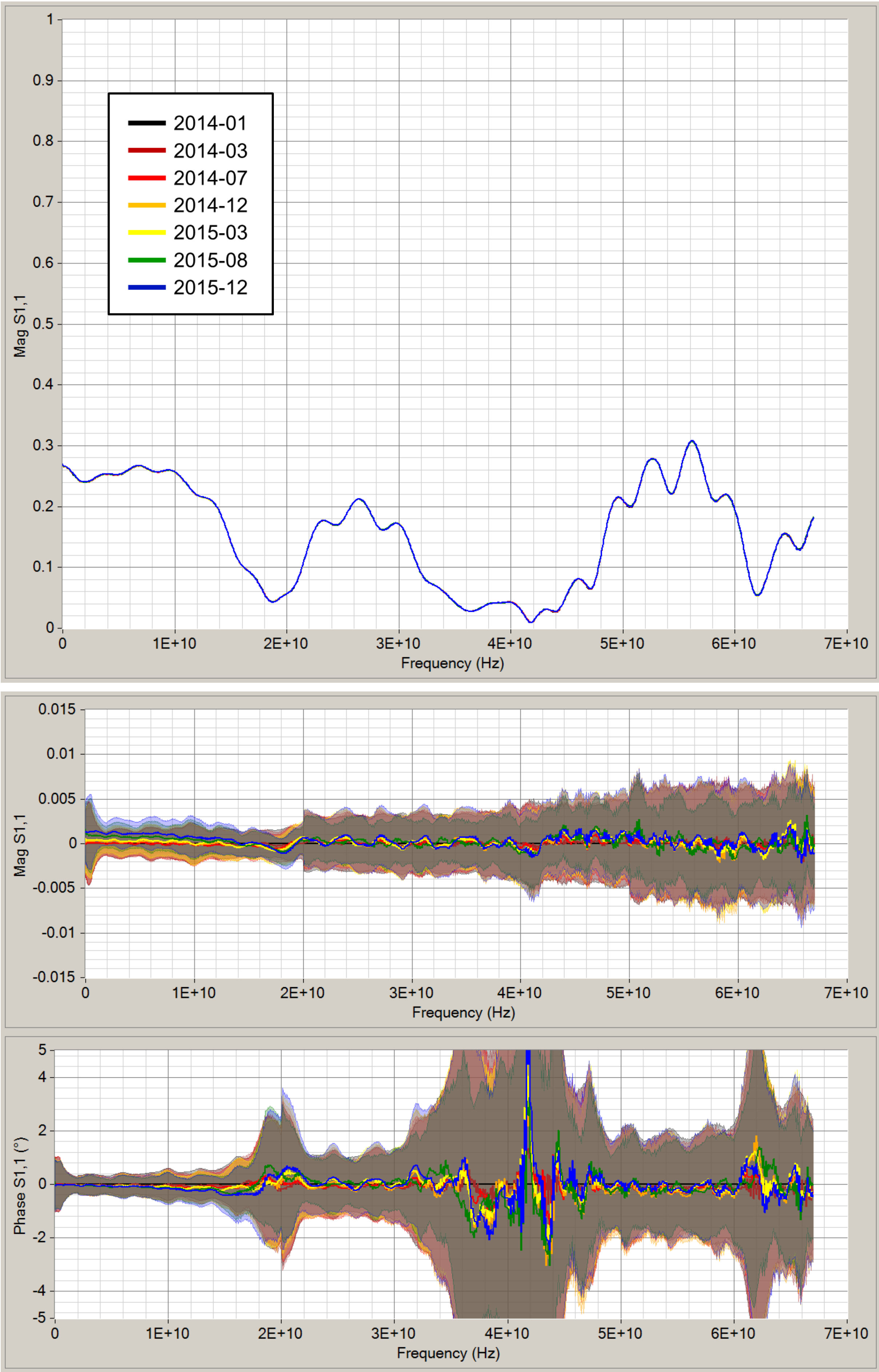


Fig. 27. Reflection coefficient S_{11} **1**-port state **A3** of ECU**2**.

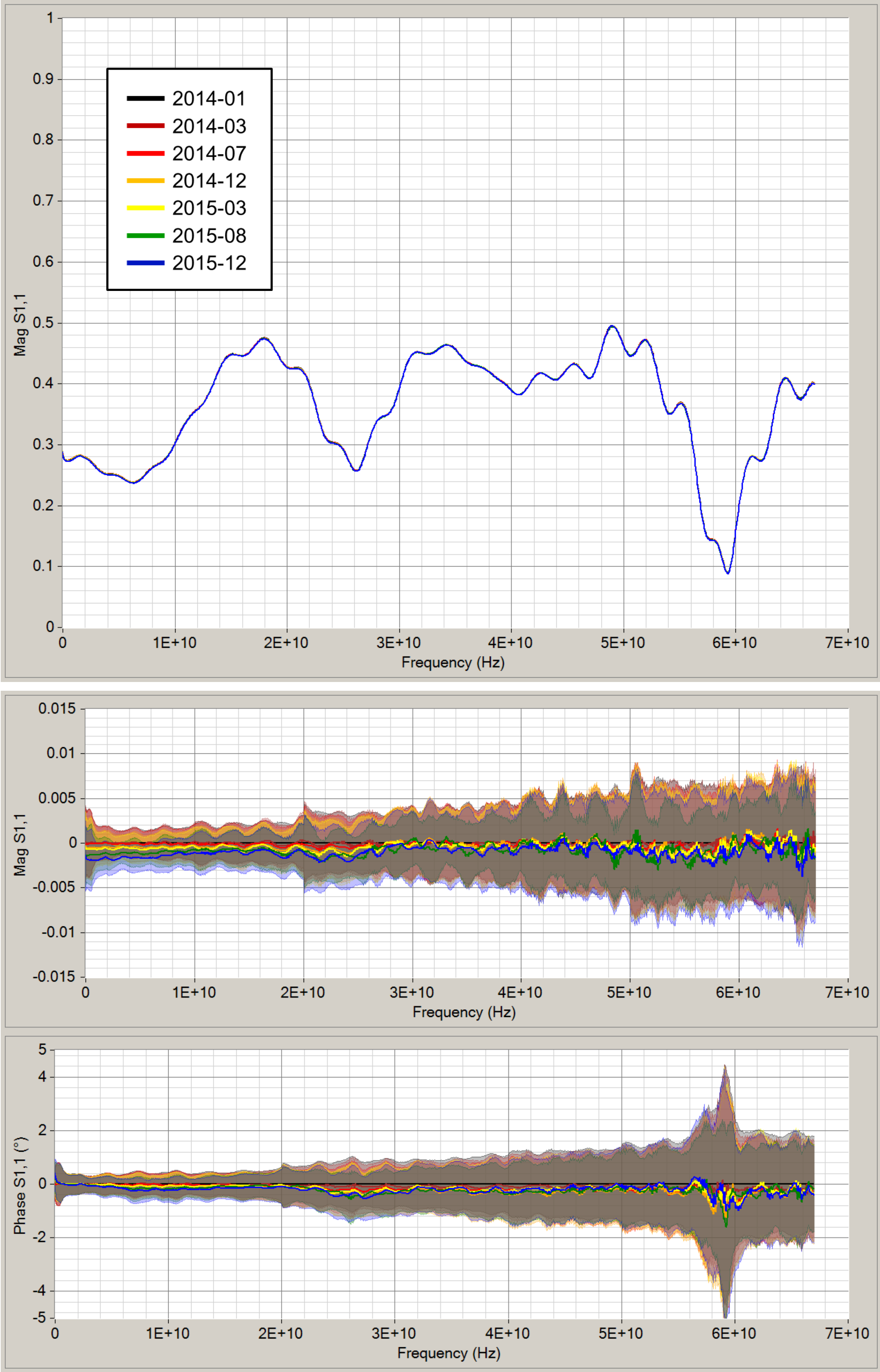


Fig. 28. Reflection coefficient S_{11} **1**-port state **A4** of ECU**2**.

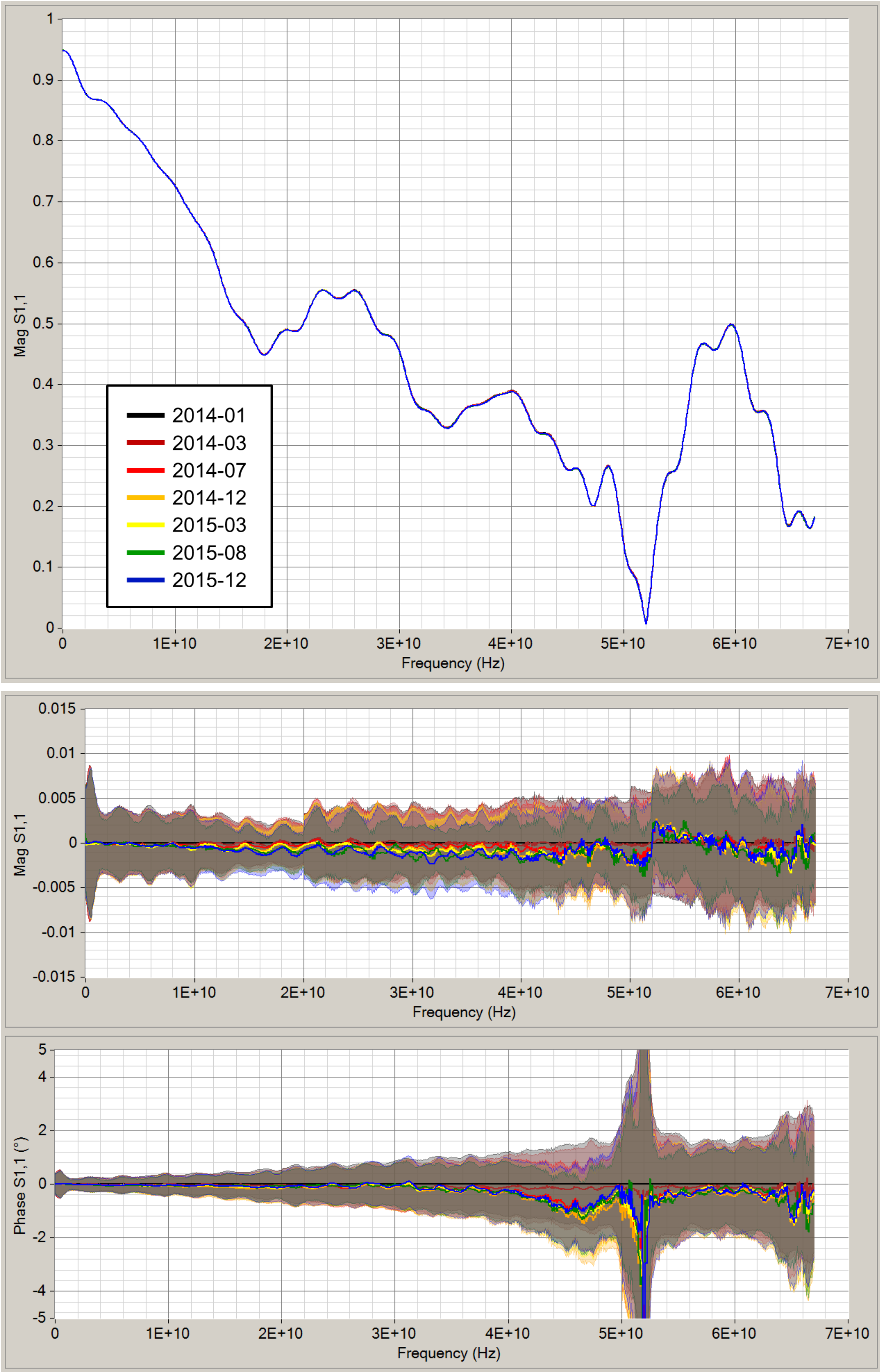


Fig. 29. Reflection coefficient S_{11} **1**-port state **A5** of ECU**2**.

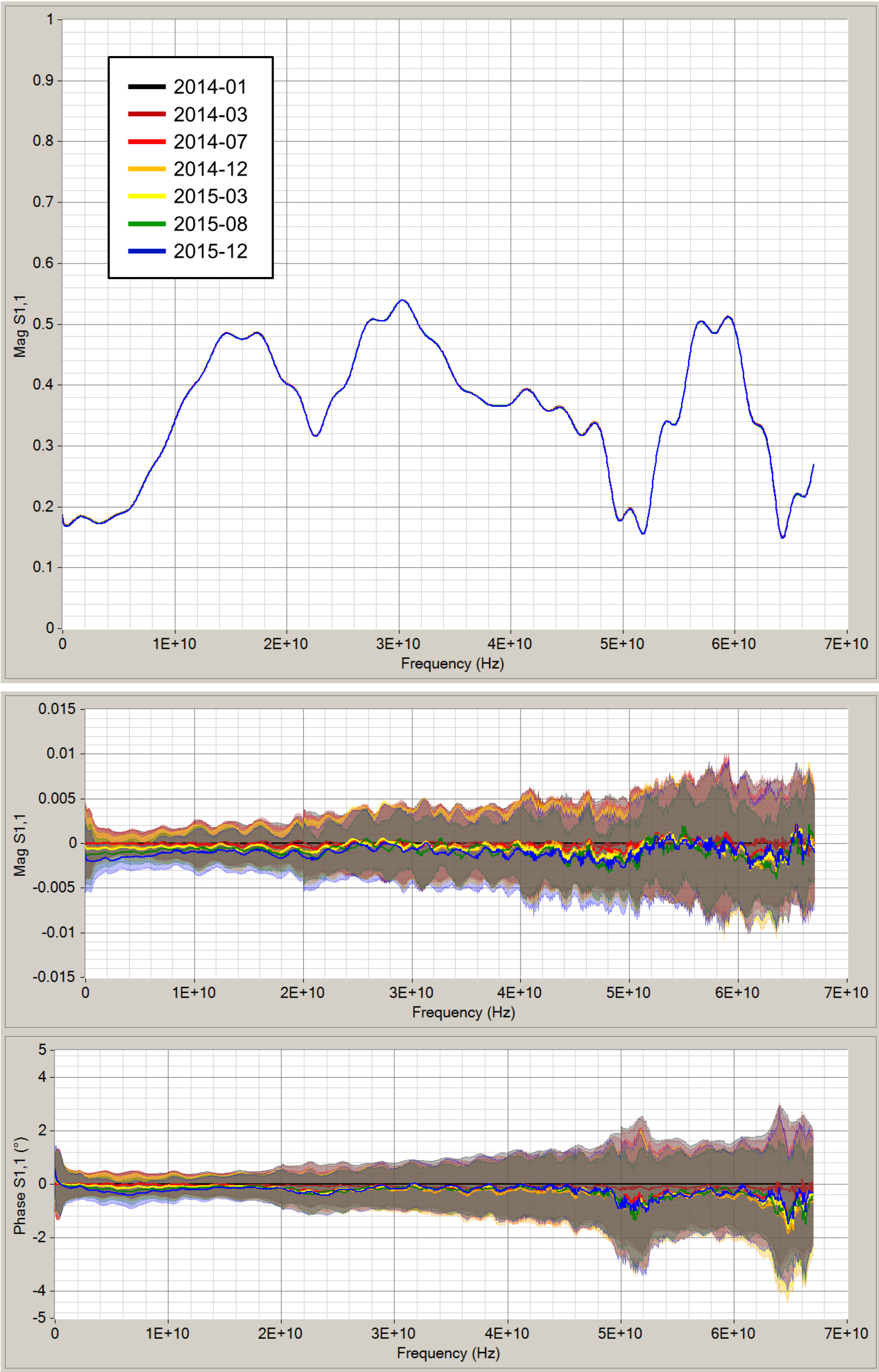


Fig. 30. Reflection coefficient S_{11} **1**-port state **A6** of ECU**2**.

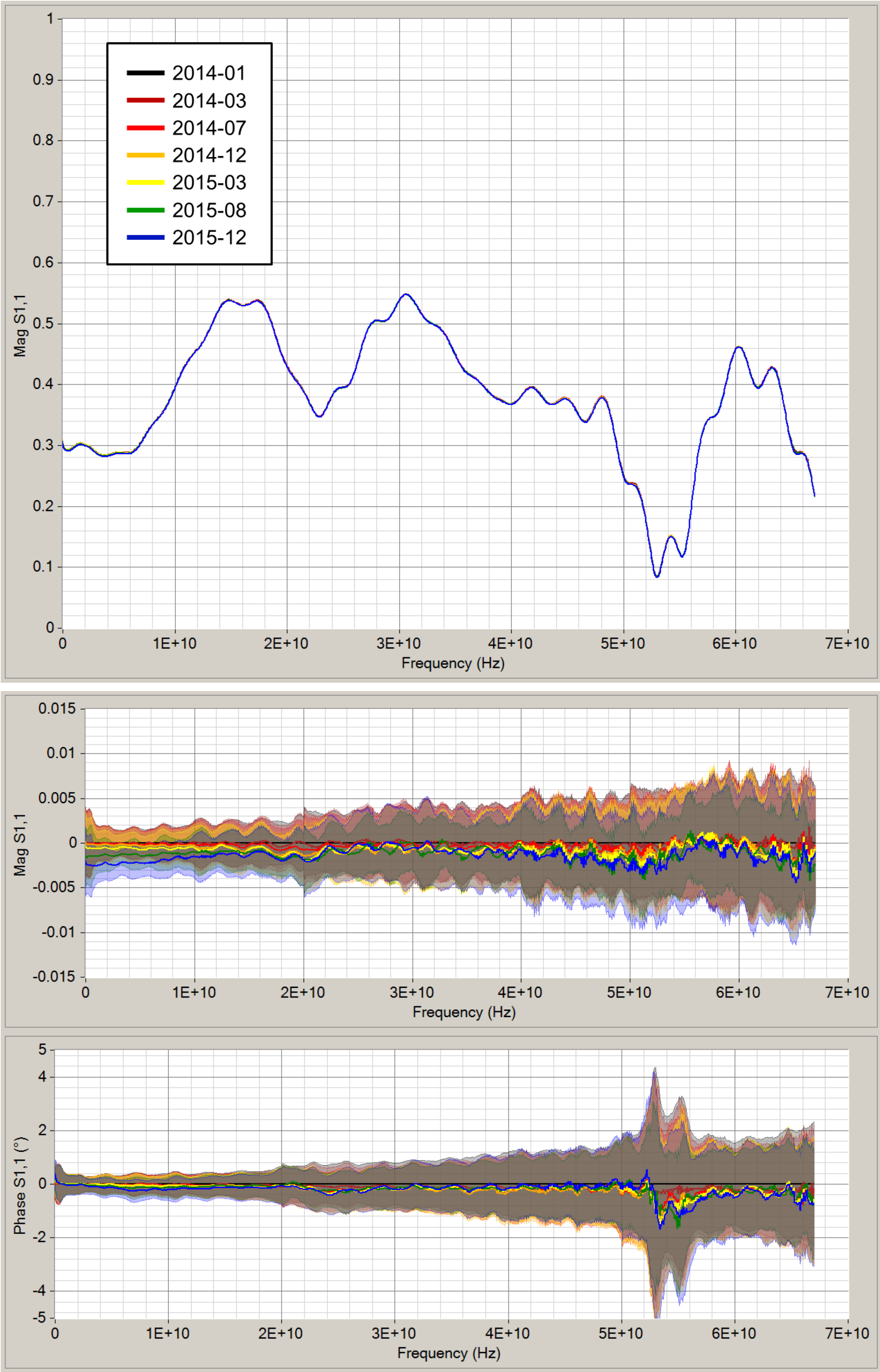


Fig. 31. Reflection coefficient S_{11} **1**-port state **A7** of ECU**2**.

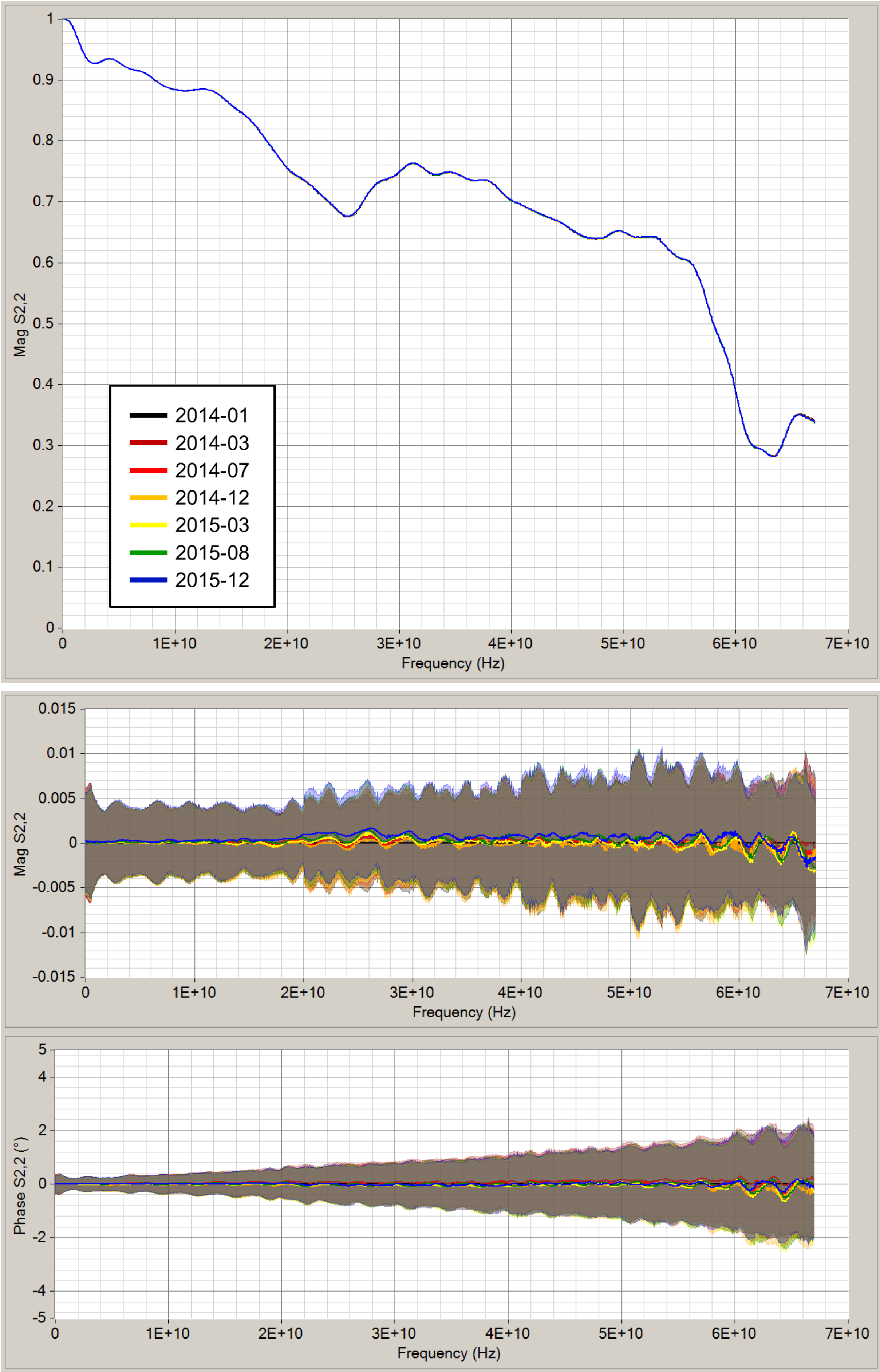


Fig. 32. Reflection coefficient S_{22} **1**-port state **B1** of ECU**2**.

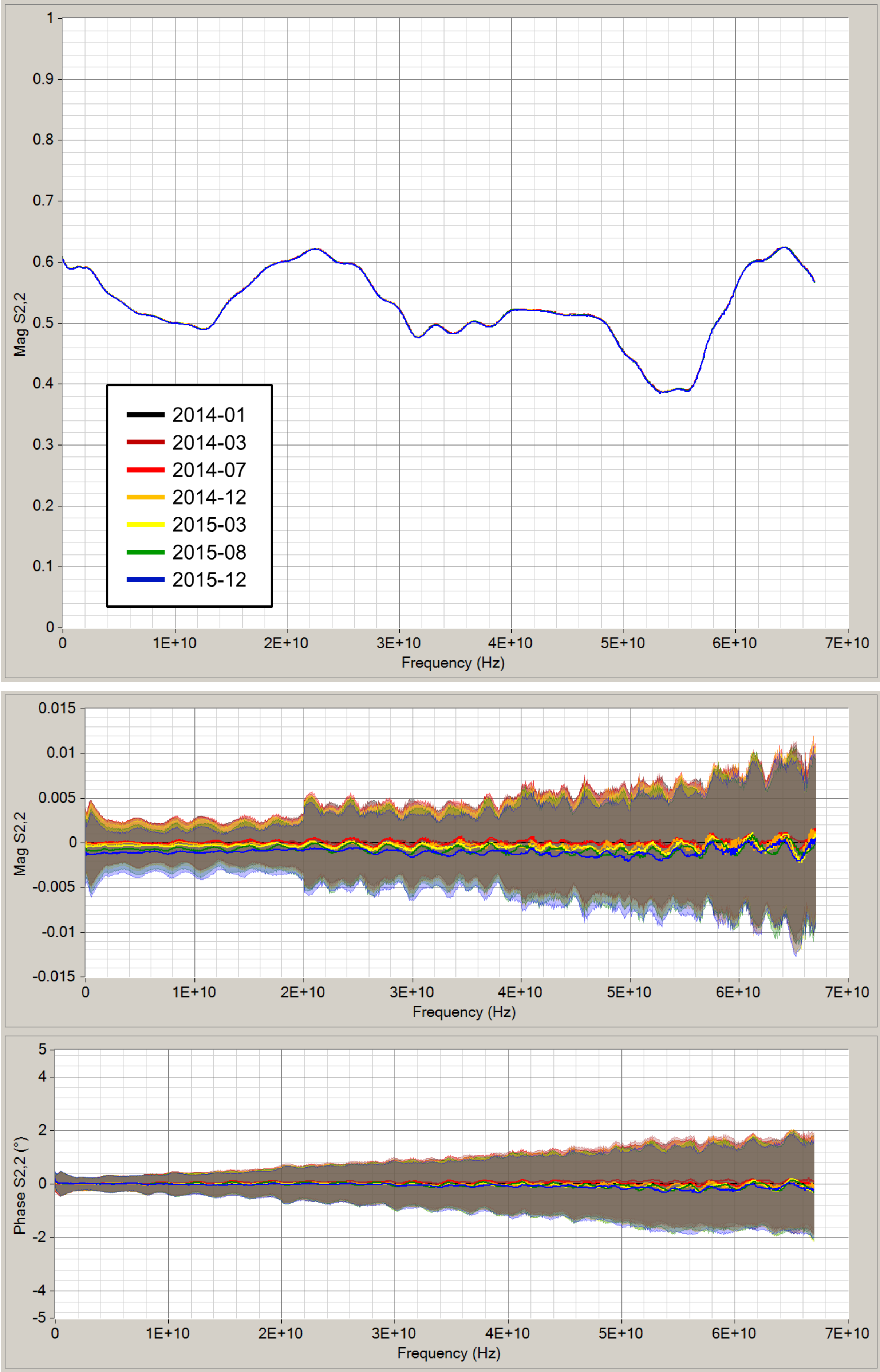


Fig. 33. Reflection coefficient S_{22} **1**-port state **B2** of ECU**2**.

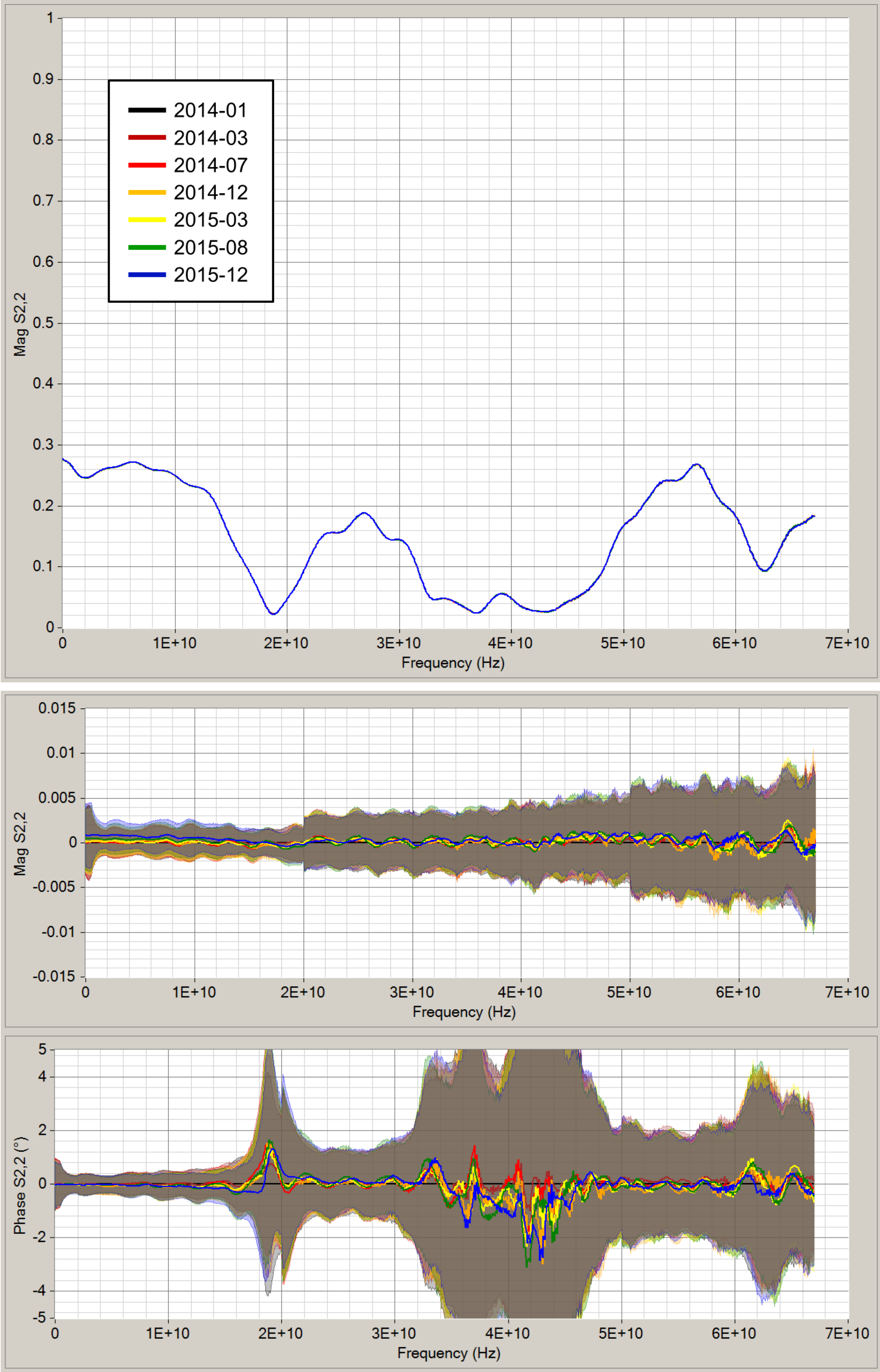


Fig. 34. Reflection coefficient S_{22} **1**-port state **B3** of ECU**2**.

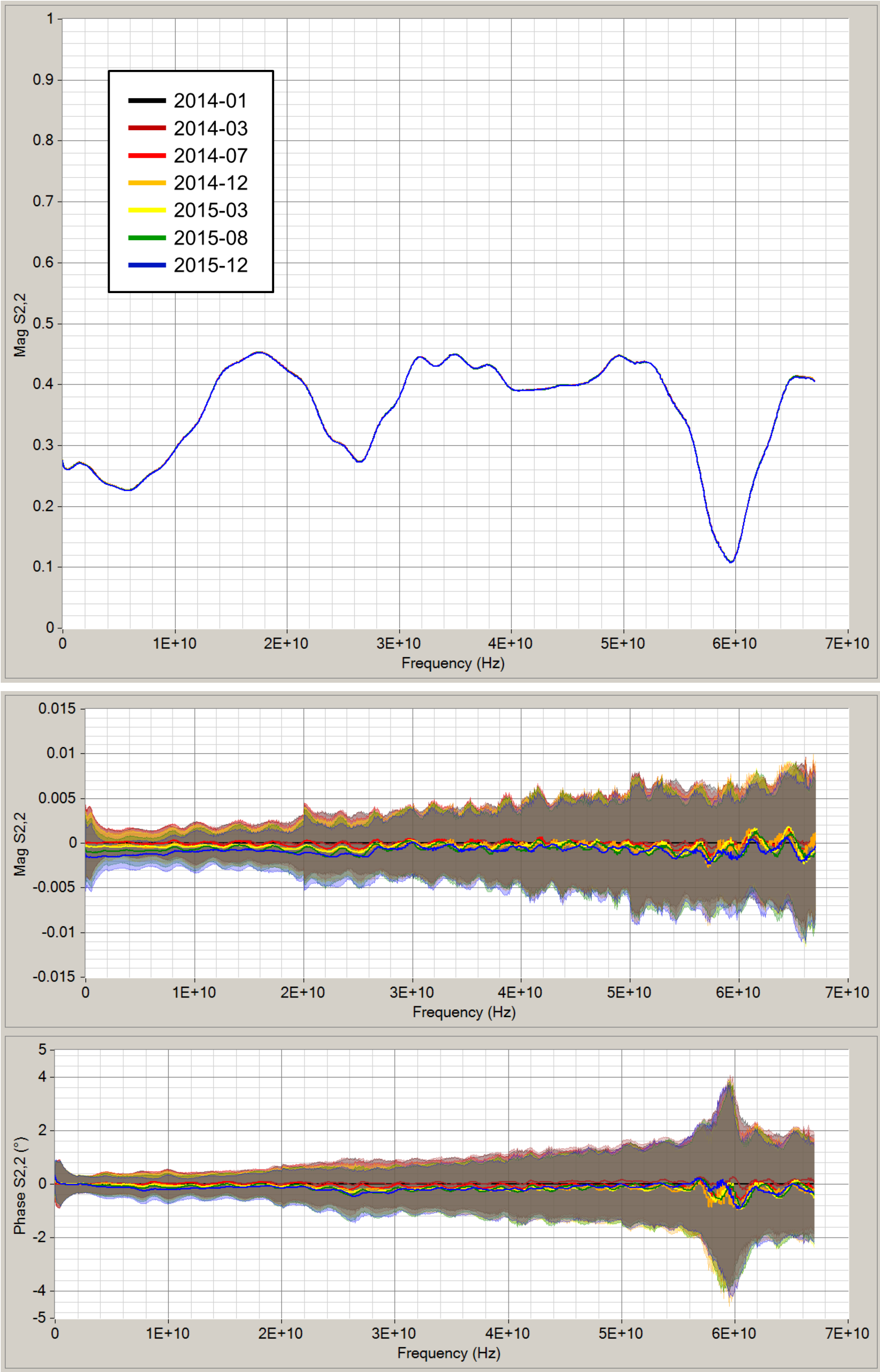


Fig. 35. Reflection coefficient S_{22} **1**-port state **B4** of ECU**2**.

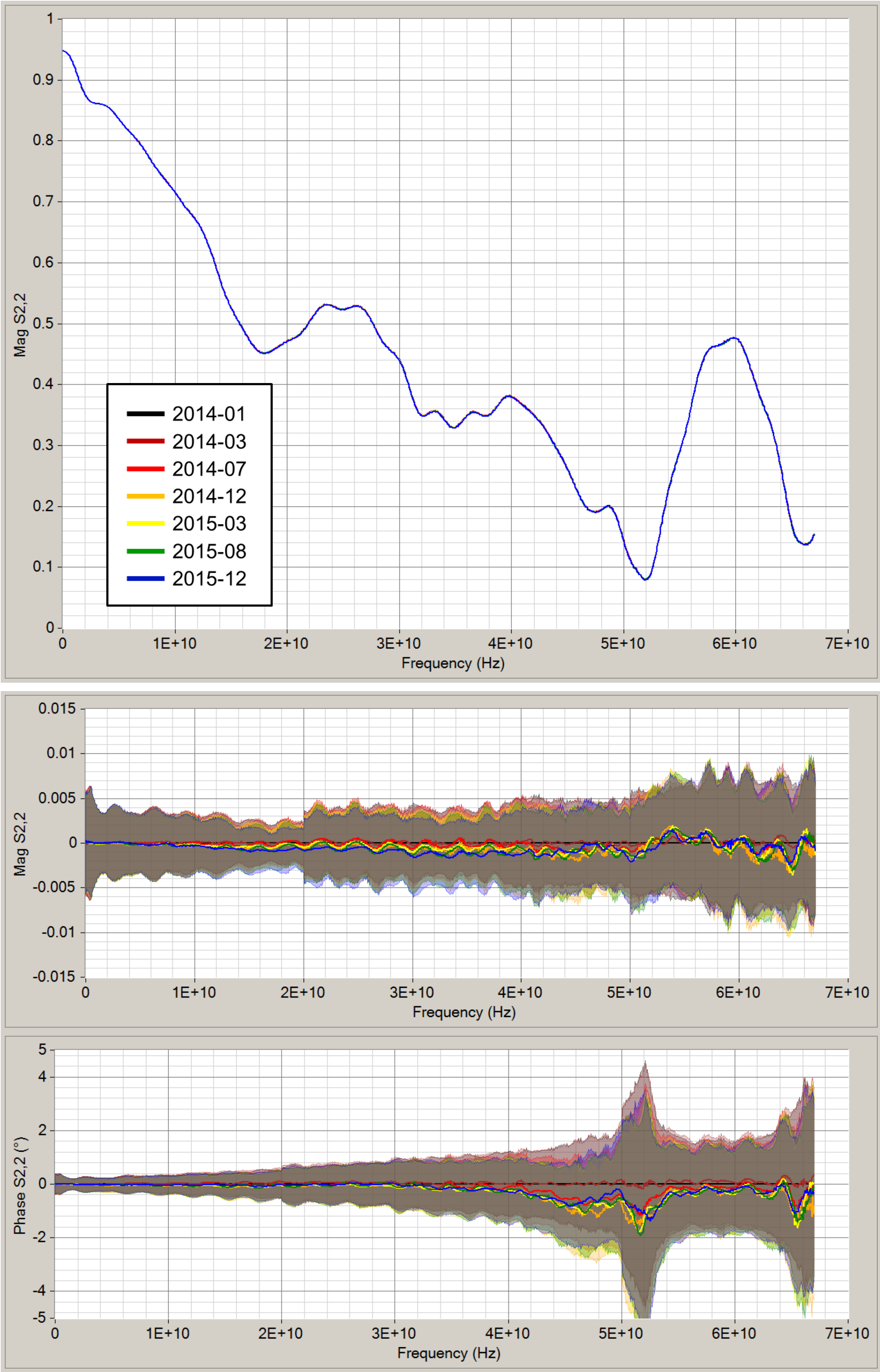


Fig. 36. Reflection coefficient S_{22} **1**-port state **B5** of ECU**2**.

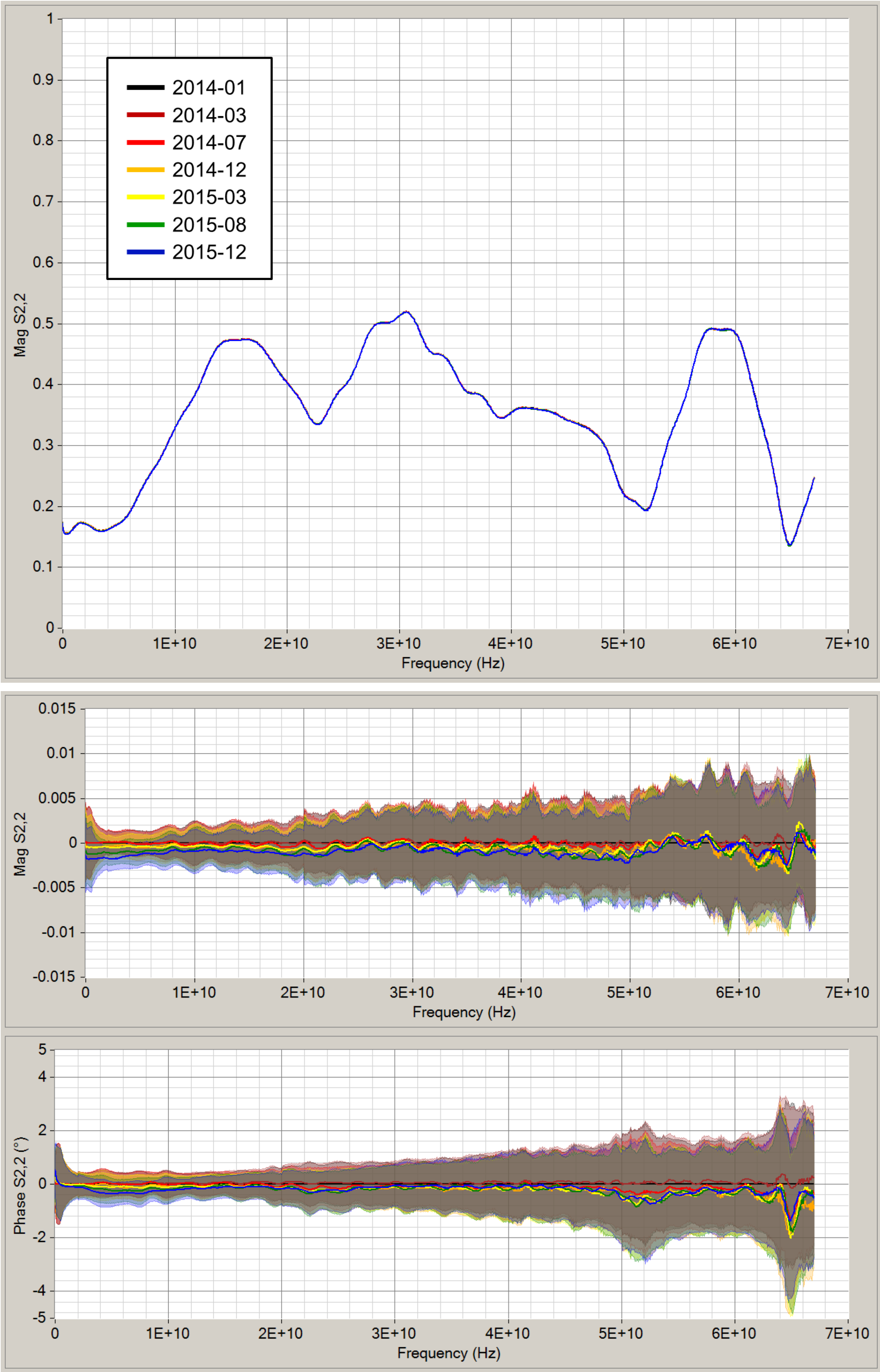


Fig. 37. Reflection coefficient S_{22} **1**-port state **B6** of ECU**2**.

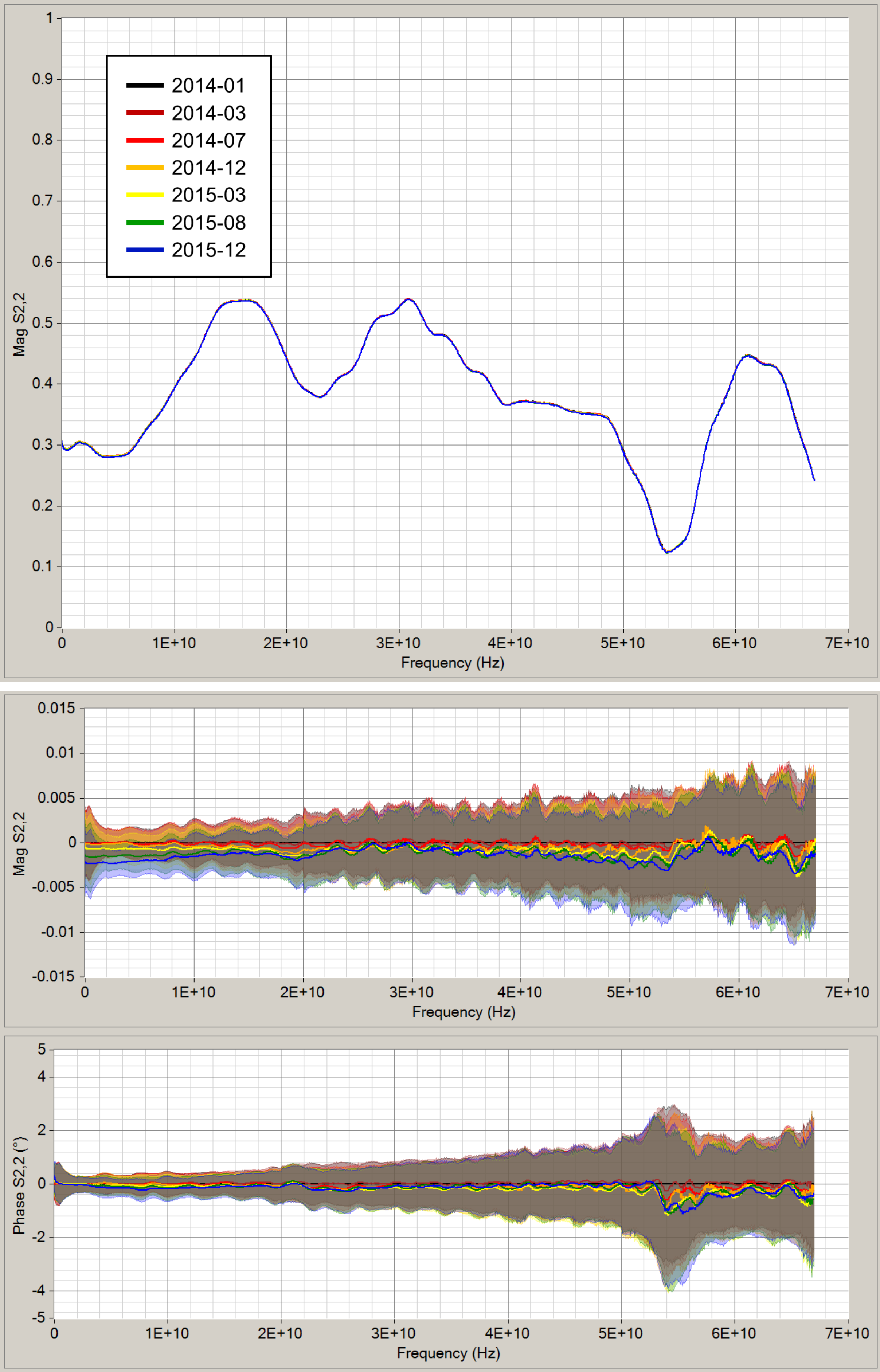


Fig. 38. Reflection coefficient S_{22} **1**-port state **B7** of ECU**2**.

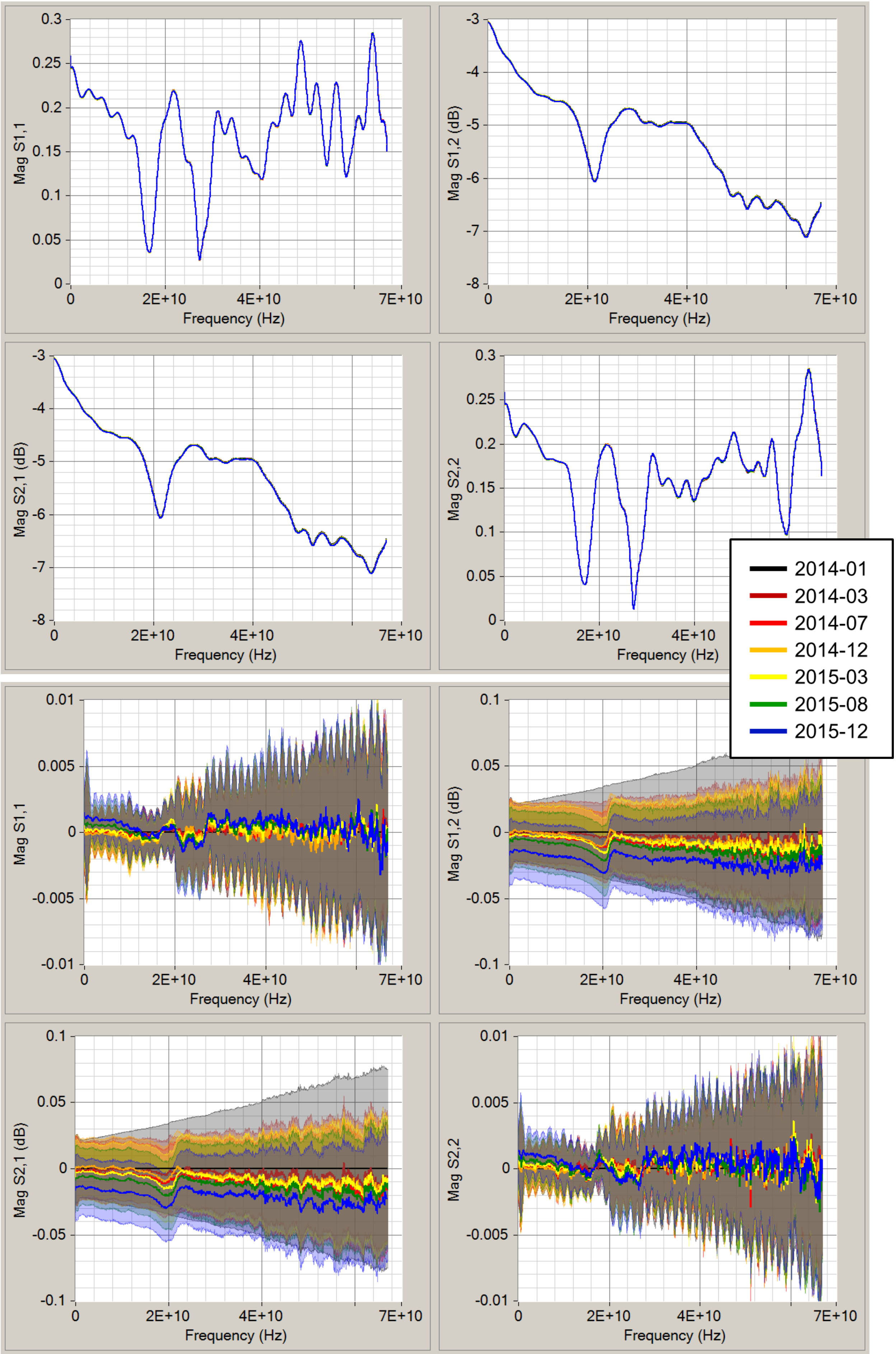


Fig. 39. Reflection and transmission coefficients (magnitude) **2**-port state **AB1** of ECU**2**.

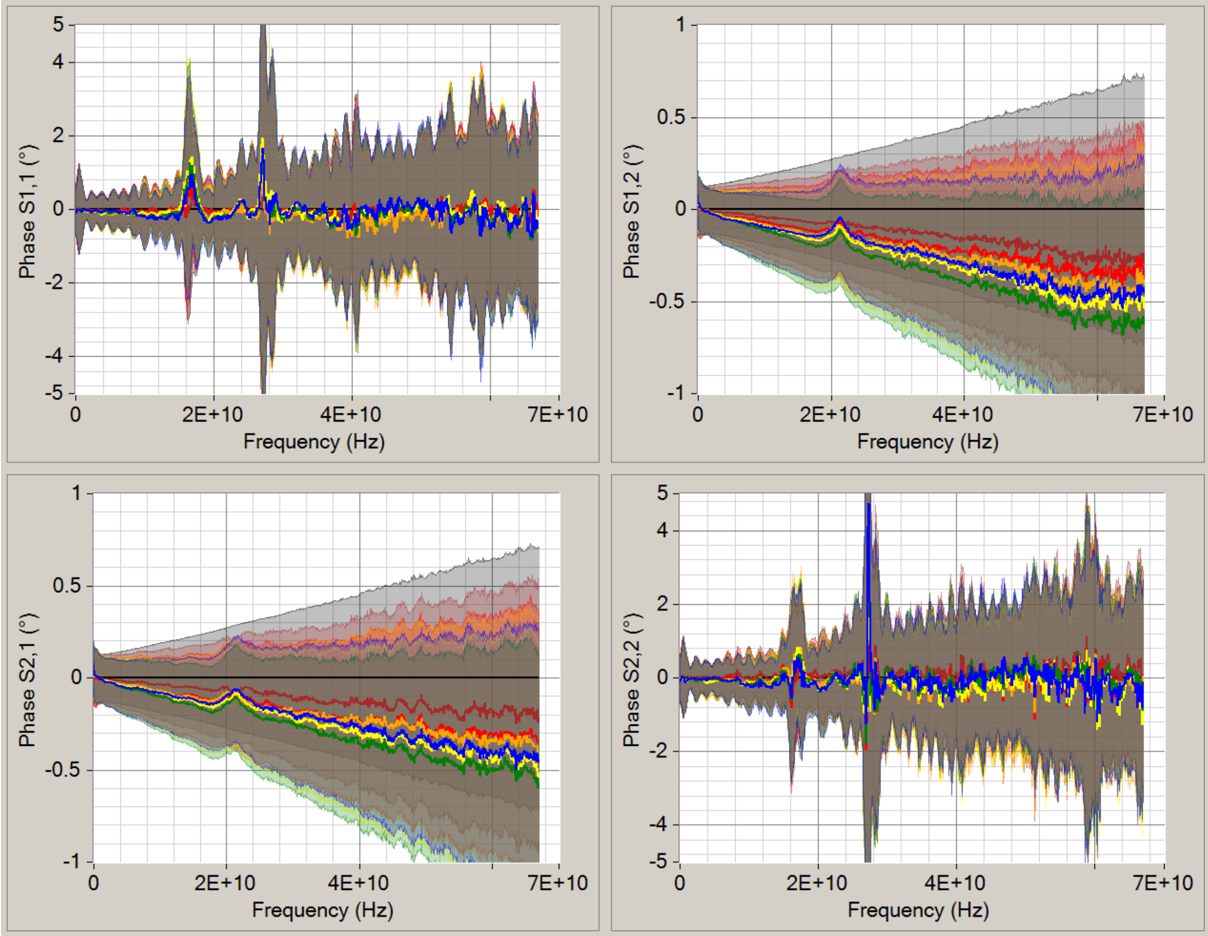
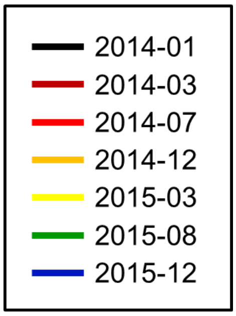


Fig. 40. Reflection and transmission coefficients (phase) **2**-port state **AB1** of ECU**2**.



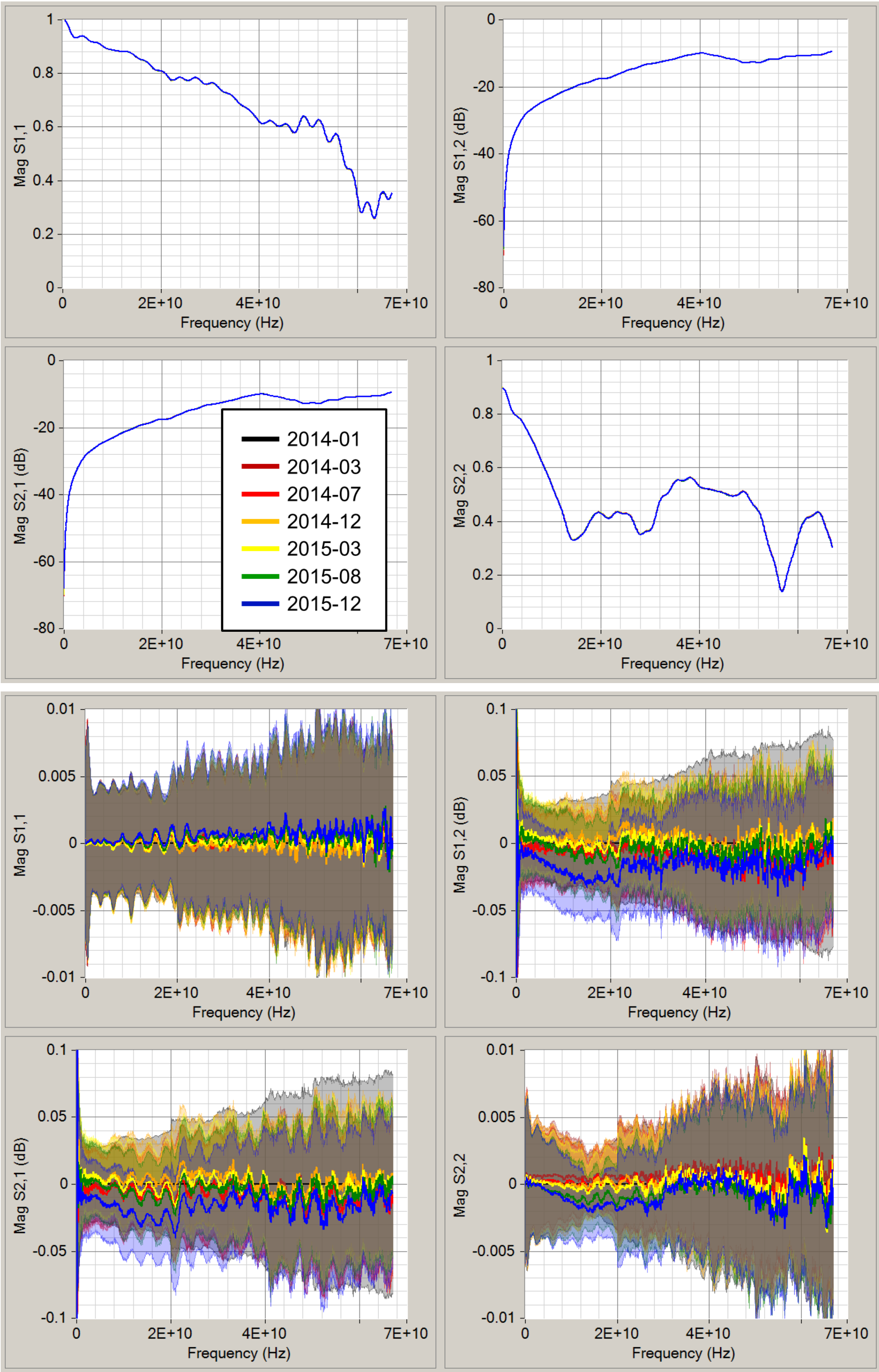


Fig. 41. Reflection and transmission coefficients (magnitude) **2**-port state **AB2** of ECU**2**.

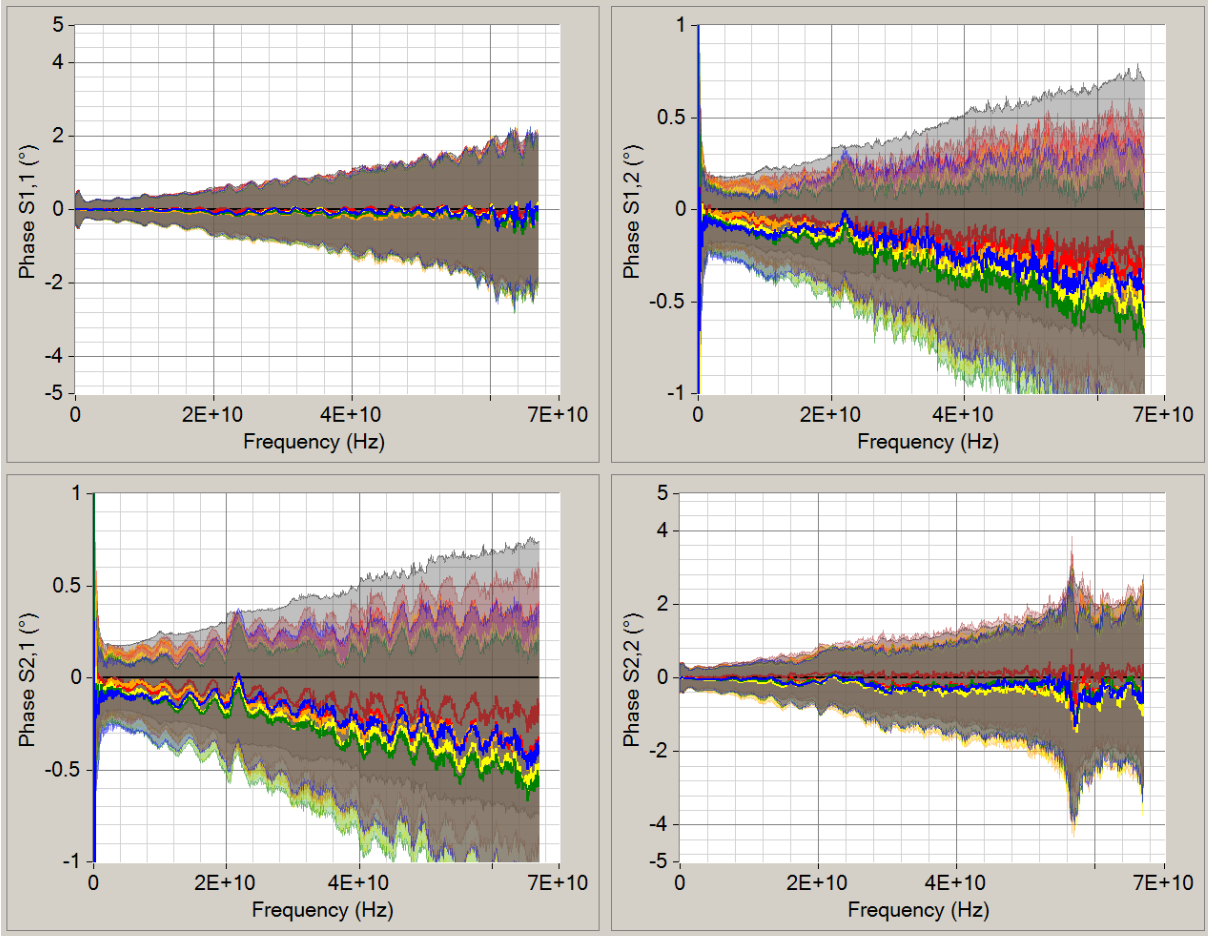
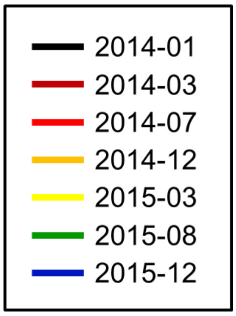


Fig. 42. Reflection and transmission coefficients (phase) **2**-port state **AB2** of ECU**2**.



Discussion of long-term stability: ECU2

The stability results for ECU2 show a drift behavior inside the claimed measurement uncertainty regions up to 67 GHz. The 2-port states seem to be quite stable, though e.g. for an unknown thru calibration (UOSM) the actual scattering parameter of the thru standard is not needed. Some of the 1-port states show an increased drift behavior towards then end of the observation period. There is evidence that one of the ECU switches introduces unstable behavior as some of the states showing a similar behavior. The drift results are summarized in Table 3 and Table 2.

Table 3. Drift of 1-port states of ECU2 in the frequency range up to 67 GHz.

State	Port	Drift Magnitude [10^{-3}]
A1	1	4.0
B1	2	3.5
A2	1	4.0

B2	2	2.5
A3 B3	1 2	3.5 3.0
A4 B4	1 2	4.0 2.5
A5 B5	1 2	4.0 4.0
A6 B6	1 2	4.0 3.5
A7 B7	1 2	4.5 4.0

Table 4. Drift of 2-port states of ECU2 in the frequency range up to 67 GHz.

State	S-Par.	Drift Magnitude [10^{-3}]
AB1	S_{11} S_{21} S_{12} S_{22}	3.3 2.0 1.9 3.6
AB2	S_{11} S_{21} S_{12} S_{22}	2.8 1.0 1.2 3.6

Deliverable 2.3.10 - Good Practice Guide for the re-calibration of ECUs

Version 2016-05-29

Introduction

This document is intended to give advice for the recalibration (procedures and intervals) of electronic calibration units (ECUs). Investigations (D2.3.9) have revealed that ECUs show, dependent on manufacturer and model, different behavior. Thus, recommendation for re-calibration intervals cannot be generalized for all kinds of ECU. Instead, an approach is outlined here to firstly determine the important characteristics of ECUs and secondly the recalibration.

For all stability tests, it is important to follow the instruction of the ECU manufacturer (e.g. heat up time).

Thermal stability

To set the different impedance states, ECUs usually utilize semiconductor components (switches, etc.) rather than mechanical devices like e.g. MEMS (microelectromechanical systems). The electrical characteristic of semiconductor components is by nature highly sensitive to heat changes. Consequently, the electronic circuits of an ECU are thermally stabilized by e.g. active heating to ensure a stable behavior for all 1-port and 2-port ECU states independently of environmental temperature changes.

On the other hand, if an ECU is used in testing or calibration laboratories, the environmental conditions have to be stated in the test report or the calibration certificate. Usually, for VNA (vector network analyzer) measurements a room temperature of 23°C (and associated uncertainty) is common practice. Since the laboratory temperature is significantly lower than the internal ECU temperature, heat flows out of the ECU towards the reference plane, resulting in a change of environmental measurement conditions. To determine the influence of this temperature change on the measurement results, the following test procedures (D2.3.1) can be applied:

- **Test TS1a**
  This test investigates the change of VNA error terms after connecting the ECU to the VNA test port cable until the thermal equilibrium is reached.
- **Test TS2**
  This test investigates the change of DUT S-parameters immediately after completing a VNA calibration using an ECU.

The outcome may be classified into two cases:

1. The temperature influence on the measurement results is negligible (much smaller than measurement uncertainty).
2. The temperature influence on the measurement results is not negligible (similar scale as or larger than measurement uncertainty).

While for the first case the ECU may be considered for VNA calibration, for the second case the measurement uncertainty has to be increased or another ECU should be used.

One may reduce the heat influence by connecting adapters to the ECU. In this case, the adapters must be connected to the ECU during recalibration.

Long-term stability

After the investigation of the thermal stability is satisfactory carried out, a meaningful study of the long-term stability may start.

Investigations (see D2.3.9) have revealed the following two important outcomes:

- An ECU can be stable on timescales of month and years.
- Even if the majority of ECU states is stable on timescales of month and years, one or more states of the same unit may show instable behavior.

To understand the behavior of an ECU, one should start measuring all ECU states on a monthly basis for a 6-12 month period. To exclude other influences, one should use the same measurement setup (VNA, cables, adapters, mechanical calibration kit with fixed standards, calibration routine, etc.).

If no instabilities are observed, one may set the recalibration interval to 12 month. This limit may be extended, if more data about the ECU has been collected in timescales of several years. However, the recommended recalibration interval also depends on how often the ECU is used in a laboratory, as the connectors of the reference plane wear out over time.

If the ECU shows unstable behavior in a 12 month timeframe, one has to increase the measurement uncertainty and should decrease the recalibration interval. The use of another ECU might be preferable.

Conclusion

To apply an ECU for VNA measurements in testing or calibration laboratories (or wherever a statement on uncertainty is needed) investigation of the individual unit is generally required. It would be desirable that manufacturers will provide thermal and long-term stability data as discussed in this document and recommend recalibration intervals.