Motorola Model: XT2061-1
FCC ID: IHDT56YJ1

Power Density Simulation Report

January 2020
Rev. 1.0
AR-20-0001-01.0

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2. Simulation Approach for MPE

This section details the approach taken to identify the worst-case beams and beam pairs for each mm-wave antenna array module for evaluation planes 2 mm away from the mobile device.

2.1. General Approach

The concept of beamforming adds an additional dimension to the test matrix, effectively increasing the number of the exposure test cases to be checked, by a factor equal to the number of beams that the device can form. This makes it impractical to measure every beam in every measurement plane. Because the mm-wave power density measurement is time-consuming per beam and measurement plane, it is necessary to identify a-priori the worst-case beams for each measurement condition (plane) via simulation, so that these beams can then be measured to characterize the worst-case power density of the device.

The Ansys HFSS simulation tool (HFSS 19.3) was used for the simulation of near-field power density for this process.

2.2. Finding Worst-Case Near-Field Results

This process consists of two parts:

1. Finding worst-case surface(s) for each beam, per antenna group and per antenna module in the middle channel of each band for determining worst-case housing influence.
2. Finding worst-case PD value for all three channels of each band for each beam and beam pair, per antenna group and per antenna module for determining the scaling factor for input power limit.

For part 1, only a few measurement planes are considered. The details of selection criteria are as described in a later section. At each x-y-z location on any of the selected measurement planes which are near to a mm-wave module, the simulated PD for each beam from that module is assessed in the middle channel of each band. The test separation distance is 2mm from the device. The worst case of all of these PD results in a worst measurement plane is then identified, and that module and beam configuration is selected for the measurement of PD on the measurement plane in question.

For part 2, only the identified worst-case surfaces are considered as the evaluation planes. At each x-y-z location on any of the selected measurement planes which are near to a mm-wave module, the simulated PD for each beam and beam pair from that module is assessed for all three channels of each band. The test separation distance is 2mm from the device. The worst cases of all these PD results for each individual beam and beam pair are then identified, and that PD value is then compared to PD design target for determining the scaling factor for input power limit as described in RF Exposure Part 0 Report.

For single beams (single-polarization beam generated by transmission from a single Antenna Group, AG0 or AG1 in a module), the PD is simulated directly from the phase weights applied by the modem. For dual beams (beam pairs, i.e. a dual-polarization beam pair generated by transmission from both Antenna Groups in a module), a conservative uncertainty factor was applied based on simulated PD recalculated for every possible group phase relationship between the two beams, to conservatively cover the worst possible combination of relative phase between the two beams (worst-case addition of the fields).

The six measurement planes are named as follows:

- S1 = front
- S2 = back
- S3 = left
- S4 = right
- S5 = top
- S6 = bottom

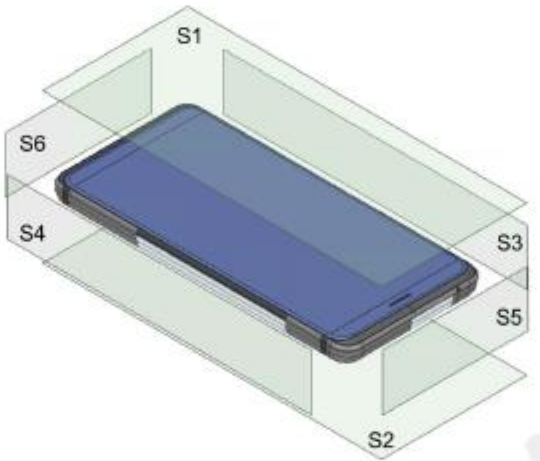

Figure 2.2-1 Identification of the six measurement planes.

2.3. Simulation Tool

2.3.1. Tool Description

For the mm-wave power density simulations, the commercially-available ANSYS Electromagnetics suite version 19.3 (HFSS) is used. The ANSYS HFSS tool is used in the industry for simulating 3D, full-wave electromagnetic fields. Motorola uses this EM simulation tool for mm-wave problems due to its established accuracy, advanced solver, and high-performance computing technology capabilities for doing accurate and rapid characterization of high-frequency components.

2.3.2. Solver Description

HFSS' solver employs the Finite Element Method, which operates in the frequency domain. The HFSS simulation employed a direct solver with first order basis functions.

2.3.3. Convergence criteria and power density calculations

HFSS uses a volume air box containing the simulated area to calculate the EM fields. The box is truncated by an Absorbing Boundary Condition. The simulation uses the adaptive mesh technique to meet the exit criteria of delta S < 0.02. The delta S is the change in the magnitude of the S-parameters between two consecutive passes; if the magnitude and phase of all S-parameters change by an amount less than the Maximum-Delta-S-per-Pass value from one iteration to the next, the adaptive analysis stops. Otherwise, the mesh is refined in higher energy areas, according to proprietary Ansys algorithms, and an additional solution pass is taken. An example of a fully refined mesh through one cross-section of the device is shown in the figure below.

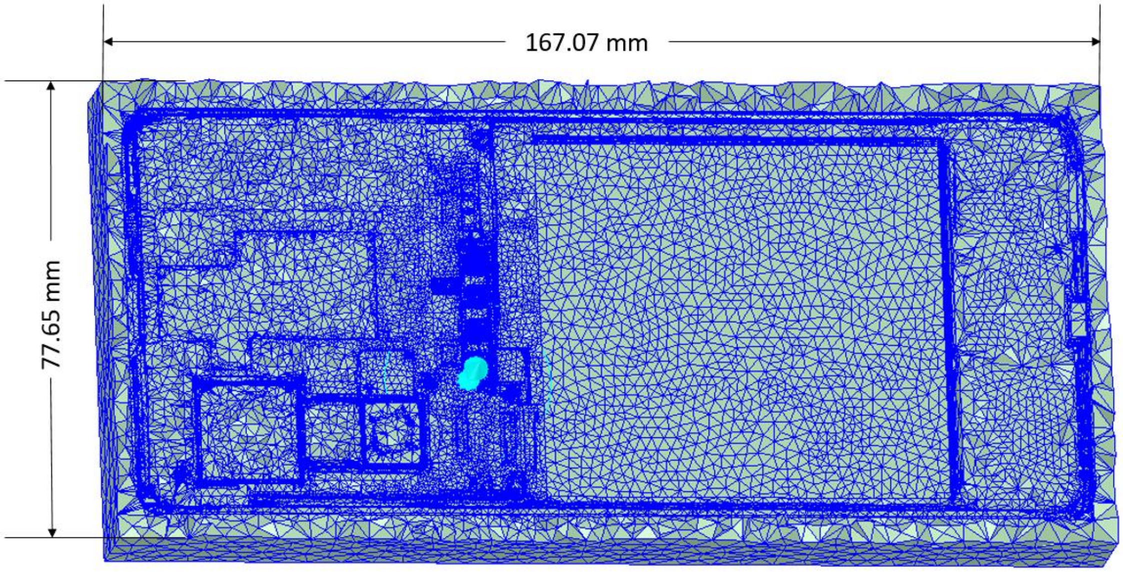

Figure 2.3.3-1: The HFSS mesh in a model of the device. After finding the simulated electric and magnetic (E and H) fields, the Poynting vector is calculated based on "peak" (i.e. non-RMS) field values in a grid with a 1 mm step, on the appropriate measurement planes as defined in previous sections. The Poynting vector at each spatial point is readily available in HFSS through the "Field Calculator" navigation option. The magnitude of the real part of the Poynting vector (all X, Y, Z components) at each spatial point i.e. the point power density is exported from HFSS to do the averaging. The spatially averaged power density at each point on a given surface is then calculated by taking the average of the point power density over a 4 square cm area. Thus the total power density (all X, Y, Z components) through any given surface is used to calculate the averaged power density.

Hence the spatially averaged power density on a given surface is calculated as the surface integral of the Poynting vector over a 4 square cm averaging area A:

$$P_{av} = \frac{1}{2A}\int_A \left|Re(\vec{E} \times \vec{H}^*)\right| \cdot dS$$

Note that E and H are the complex field vectors, and the calculation thus leads to the total power density average.

2.3.4. 3D Models Used in the Simulations

The 3D model simulated consists of the full CAD model of the mobile device that includes all of the significant structure such as PCB, metal frame, battery, cables and legacy antennas as well as mmWave antenna modules called Back module and Top module. Back module is placed at the back side of the device, facing the back side and Top module is placed at the top side of the device, facing the top side. A view of the 3D model variant used in each of the various module simulations is shown in the figures 2.3.4-1 to 2.3.4-2.

Both Back and Top modules consist of 16 ports for source excitation. The antenna ports are divided into 8 ports for 1 x 4 patch array antennas and 8 ports for 1 x 4 dipole array antennas. In the 8 ports included in each patch antenna, 4 ports are divided into V polarization feeding, and the other 4 ports are divided into H polarization feeding.

After 3D full wave electromagnetic simulation of modeling structure is finished, the magnitude and phase information can be loaded for each port by using “Edit Sources” function in ANSYS Electromagnetics suite (HFSS). Figure 2.3.4-3 shows an example of antenna port excitations.

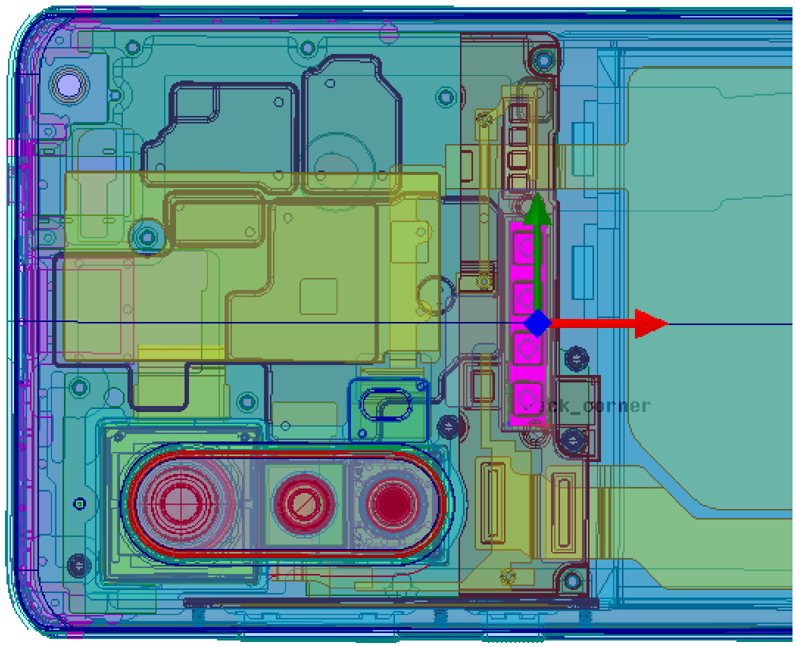

Figure 2.3.4-1: 3D model used for Module 0 (Back module), the antenna array is highlighted

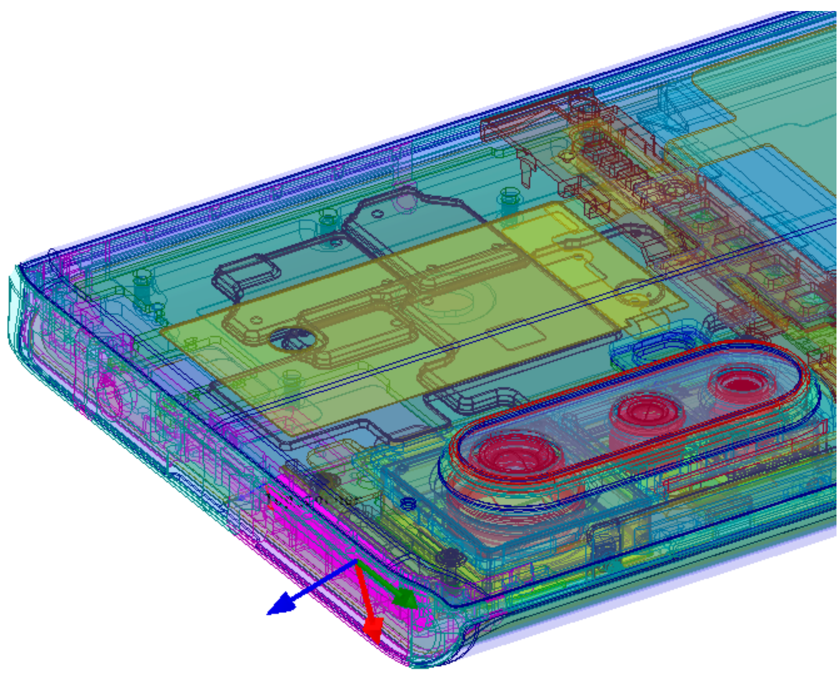

Figure 2.3.4-2: 3D model used for Module 1 (Top module), the antenna array is highlighted

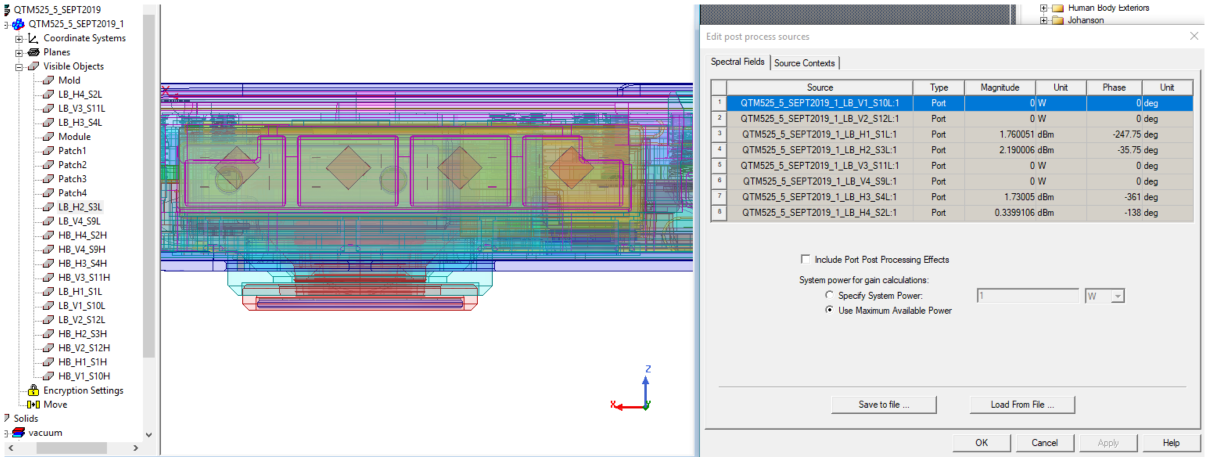

Figure 2.3.4-3: An example of port excitations in HFSS for Top module.

2.3.5. PD evaluation planes

Due to the location of the mmW module and the antenna array orientation relative to the surface of the device, one or more surface(s) might be excluded for PD calculation as they will have no impact for the worst-case PD determination when using Equation below:

$$PD = max\{PD_{s1}, PD_{s2}, PD_{s3}, PD_{s4}, PD_{s5}, PD_{s6}\}$$

Where $PD_{s1}, PD_{s2}, PD_{s3}, PD_{s4}, PD_{s5}, PD_{s6}$ are the highest PD on surface S1,S2,S3,S4,S5 and S6 of the devices respectively.

Table 1 shows the PD evaluation planes for each mmWave antenna module. For the back module case, only S1, S3, S4 are included in PD evaluation planes. The other three planes are excluded from determining the worst case PD because the distance from these planes to the mmWave module is more than a few lambda at 28GHz and 39GHz, resulting in lower PD values on these planes.

Similarly, for the top module the PD evaluation can be conducted on the S1, S5 and S4 surfaces only.

Please note that the ‘Right’ and ‘Left’ edge mentioned in this report are defined from the perspective of looking at the device from the back side with the top of the device pointing up.

Table 1. PD evaluation planes

	Front	Back	Left	Right	Top	Bottom
	S1	S2	S3	S4	S5	S6
Top module	O	X	X	O	O	X
Back Module	X	O	O	O	X	X

Perform EM simulation to characterize PD at low, mid, and high channels for each supported band. We soon realized that the evaluation planes can be further reduced, as shown in Table 2.

Table 2. PD evaluation planes

	Front	Back	Left	Right	Top	Bottom
	S1	S2	S3	S4	S5	S6
Top module	X	X	X	X	O	X
Back Module	X	O	X	X	X	X

It is shown in the RF Exposure Part 0 report that the non-selected surfaces (S3 and S4 for the back module, S1 and S4 for the top module) are not required for the housing material influence determination. The PD on these non-selected surfaces are less than the PD on the selected surfaces for all the beams for both modules for both bands. In other words, these selected evaluation planes correspond to the worst case surface for the PD for each module respectively.

2.3.6. Simulated verification (Spatial-averaged power density)

As mentioned in the previous section, the Poynting vector ($\vec{S}$) can be obtained through cross product of an electric field ($\vec{E}$) and complex conjugate of a magnetic field ($\vec{H}$). The real term of the Poynting vector can be described as the point power density or peak power density. Using the point power density, the spatial-averaged power density can be obtained by the integral of a 4 square cm area at 1 mm intervals of the point power density result. Figure 2.3.6-1 shows examples of the distribution of point power density and the averaged power density.

2.3.7. Simulated and Measured Results

In this section, the simulated power density distribution and measured power density distributions are compared to each mmWave antenna. The input powers per each active port are listed below for both Simulation and Measurement validation and power density characterization. For Simulation, these values were entered directly into the HFSS model. For measurements, using FTM, the phone was configured to set the active port power to these powers in CW modulation.

Table 3 Input power for simulations and measurements

Band	Antenna	Input Power (dBm) SISO	Input Power (dBm) MIMO
n261	Back Module	6	6
	Top Module	6	6
n260	Back Module	6	6
	Top Module	6	6

PD evaluations were performed based on simulation for all the beams on all determined surfaces of the device. The beams that corresponds to the worst PD for each antenna group for each antenna module for both bands with their corresponding worst surfaces are listed in below table:

Table 4 Worst case beams for each antenna group for each antenna module identified through HFSS simulations

Band	Antenna	Beam ID	Surface
n261	Back array	27	Back
		147	Back
	Top array	24	Top
		151	Top
n260	Back array	28	Back
		146	Back
	Top array	23	Top
		142	Top

2.3.7.1 Comparison between simulated and measured Results

The below simulation at measurement results were performed at 2mm evaluation distance and 28GHz/38.5GHz. The input.power.limit was determined based on the results below from the RF Exposure Part 0 Report.

Table 5 Comparison between simulated and measured results

					4 cm^2 avg. PD (W/m^2)	
Band	**Antenna**	**Beam ID**	**Surface**	**Channel**	**Meas.**	**Sim.**
n261	Back array	27	Back	Mid	5.22	12
		147	Back	Mid	5.97	11.8
	Top array	24	Top	Mid	6.39	11.8

		151	Top	Mid	7.28	11.1
n260	Back array	28	Back	Mid	8.97	10.9
		146	Back	Mid	7.18	12.3
	Top array	23	Top	Mid	11.2	12.2
		142	Top	Mid	10.9	12.9

Based on comparison of power density distributions, simulated power density and measured power density have a good correlation. The discrepancy in amplitude between simulated 4cm2 averaged power density and measured 4cm2 averaged power density is considered as housing influence and used in determining input power limit for each beam for RF exposure compliance (see RF Exposure Part 0 Report).

Figure 2.3.7.1-1 to Figure 2.3.7.1-8 show the comparison of the simulated PD distribution and the measured PD distribution. Since this correlation is only for PD distribution correlation, only Point PD distributions are used for comparison.

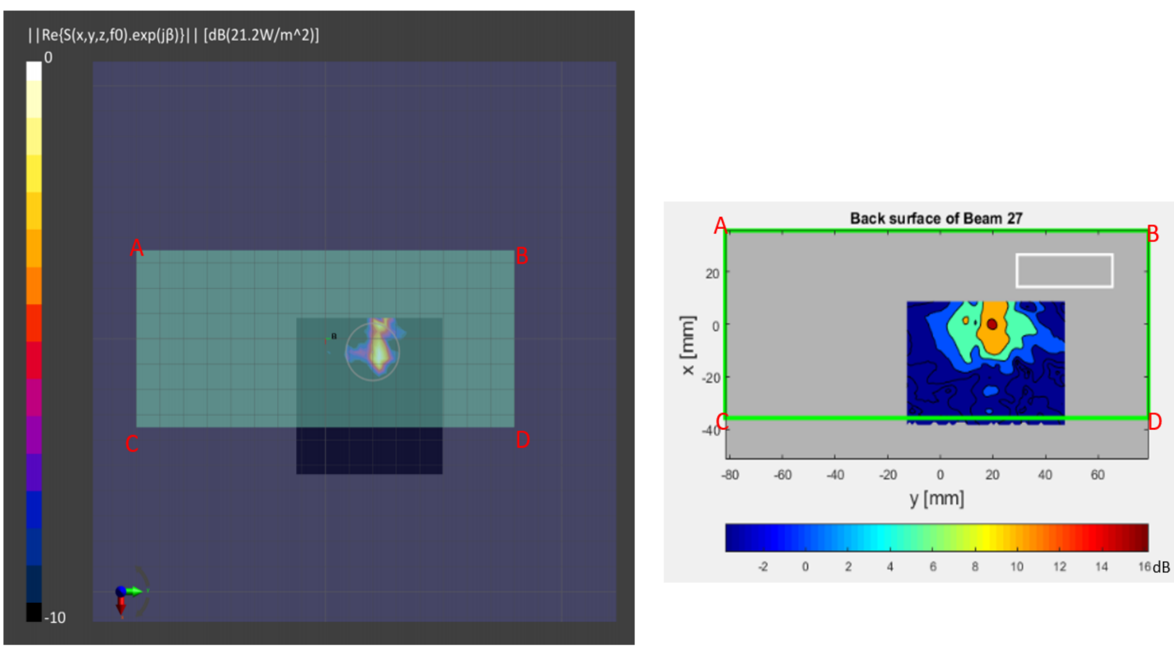

Figure 2.3.7.1-1 Measured (left) and Simulated (right) peak power density distributions for the worst case found in the back surface measurement plane for n261 (**Back module, beam 27, back surface**)

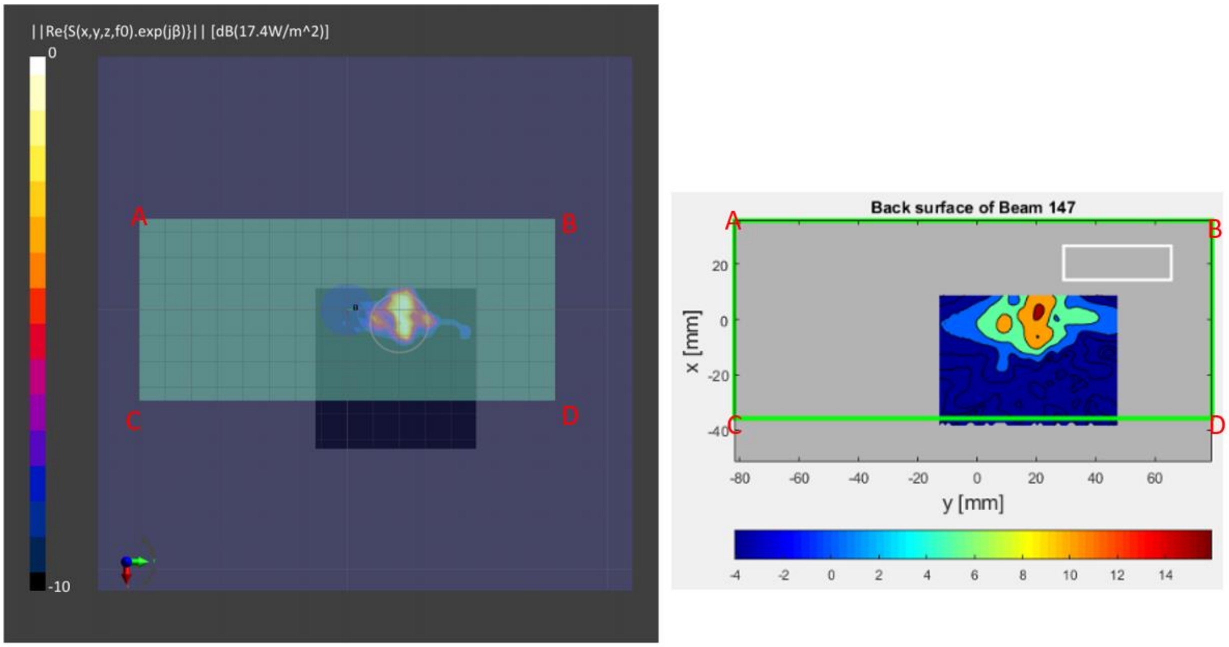

Figure 2.3.7.1-2 Measured (left) and Simulated (right) peak power density distributions for the worst case found in the back surface measurement plane for n261 (**Back module, beam 147, back surface**)

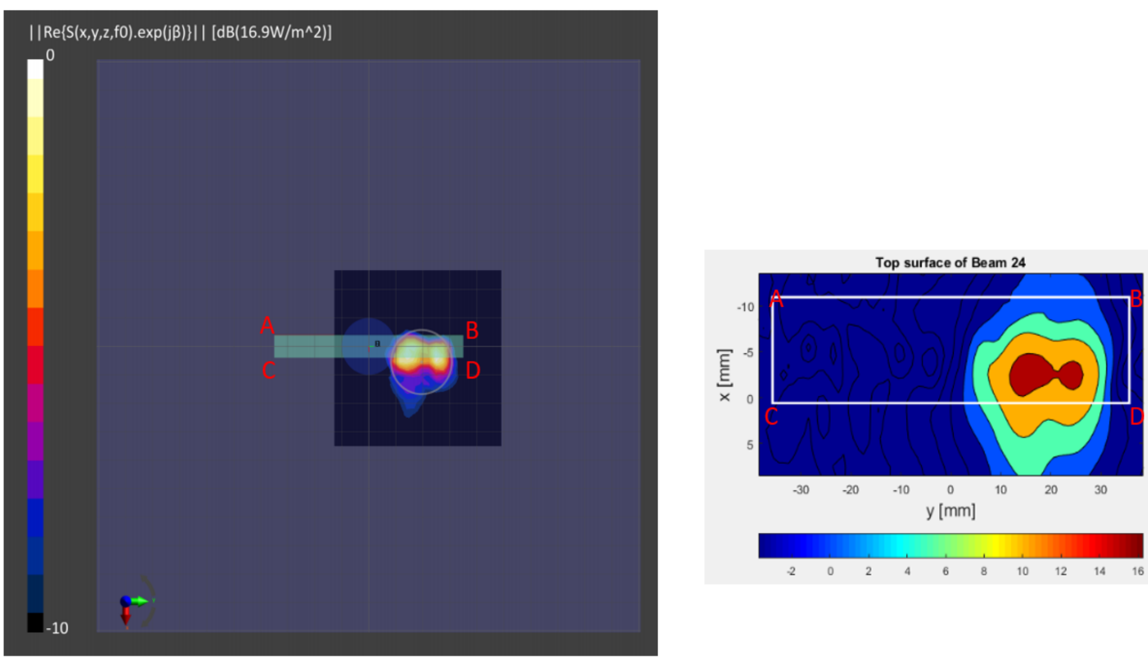

Figure 2.3.7.1-3 Measured (left) and Simulated (right) peak power density distributions for the worst case found in the Top surface measurement plane for n261 (**Top module, beam 24, Top surface**)

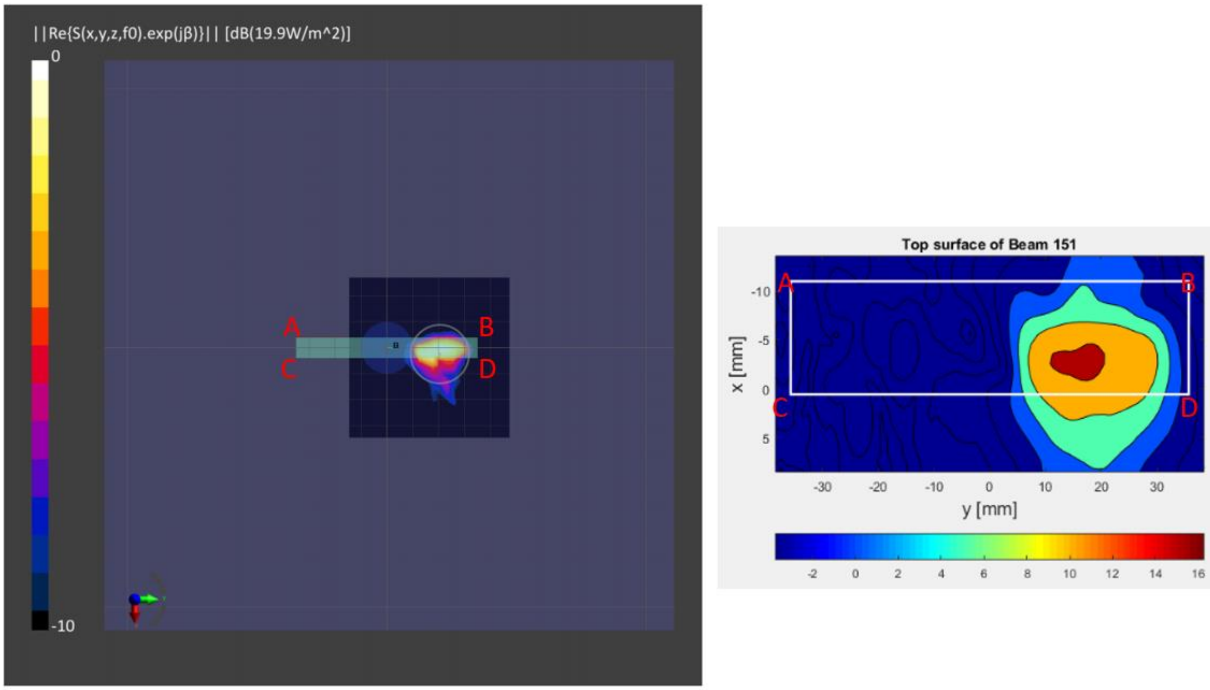

Figure 2.3.7.1-4 Measured (left) and Simulated (right) peak power density distributions for the worst case found in the Top surface measurement plane for n261 (**Top module, beam 151, Top surface**)

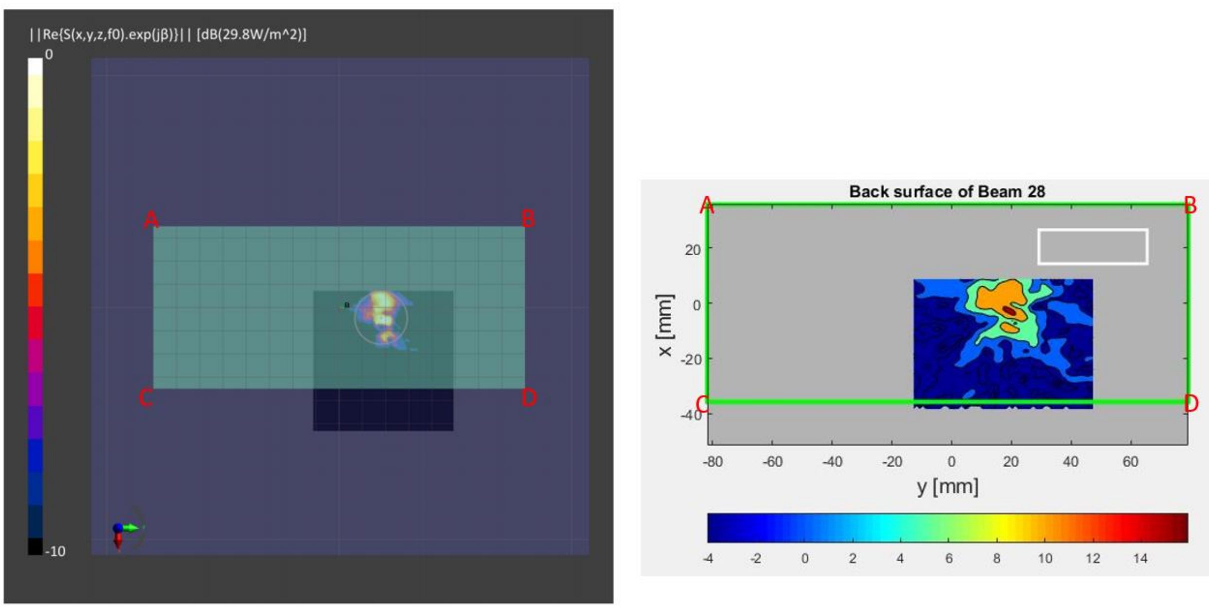

Figure 2.3.7.1-5 Measured (left) and Simulated (right) peak power density distributions for the worst case found in the back surface measurement plane for n260 (**Back module, beam 28, back surface**)

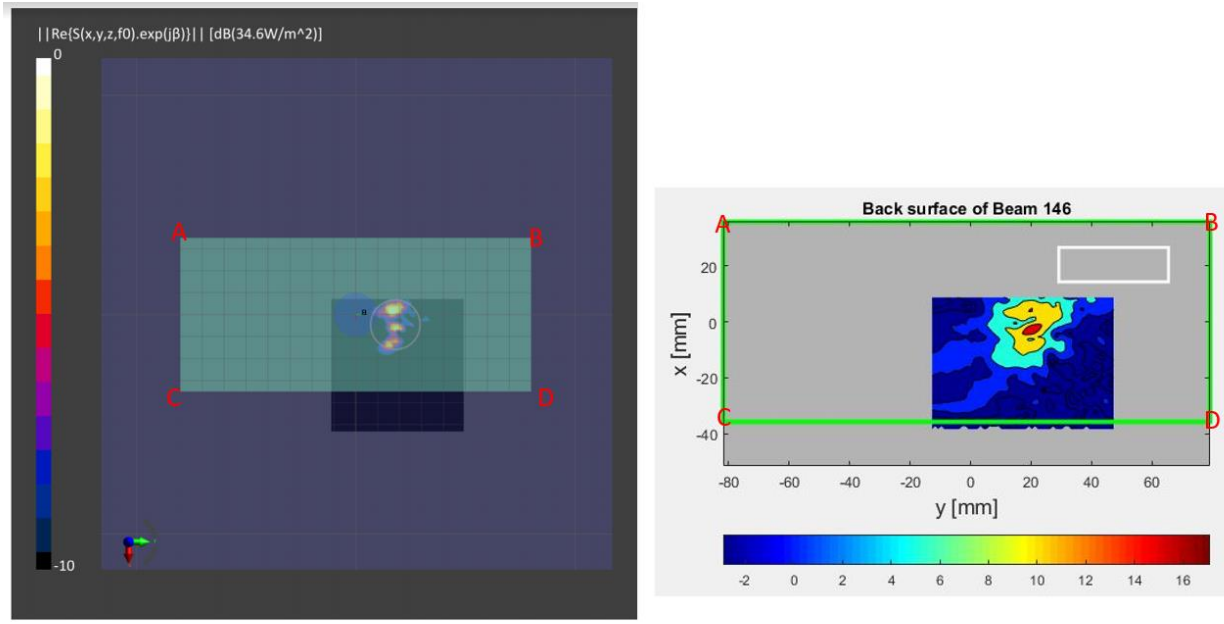

Figure 2.3.7.1-6 Measured (left) and Simulated (right) peak power density distributions for the worst case found in the back surface measurement plane for n260 (**Back module, beam 146, back surface**)

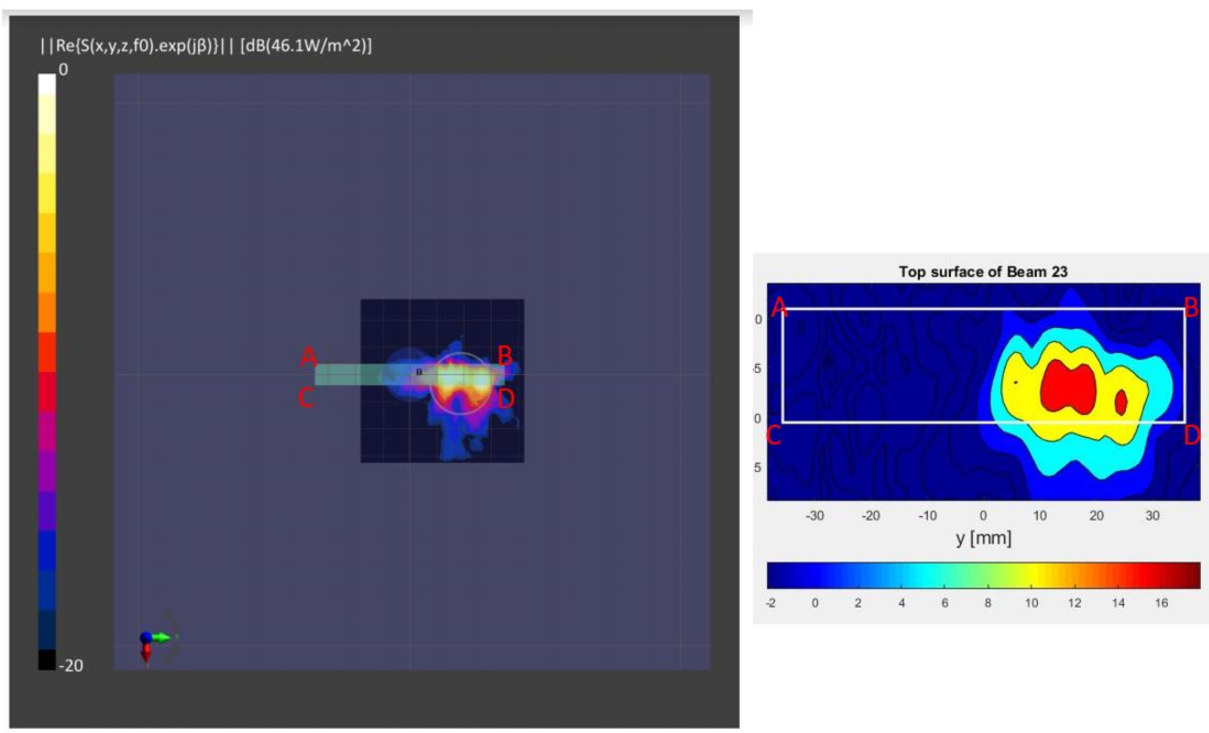

Figure 2.3.7.1-7 Measured (left) and Simulated (right) peak power density distributions for the worst case found in the Top surface measurement plane for n261 (**Top module, beam 23, Top surface**)

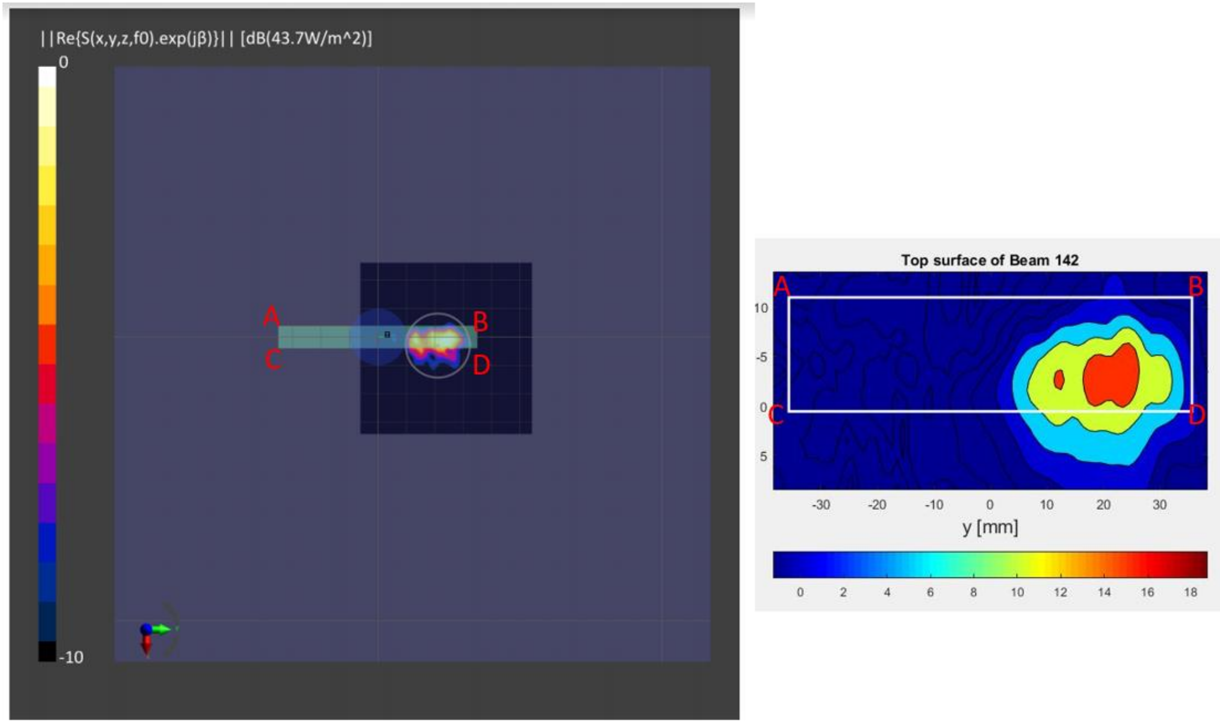

Figure 2.3.7.1-8 Measured (left) and Simulated (right) peak power density distributions for the worst case found in the Top surface measurement plane for n260 (**Top module, beam 142, Top surface**)

2.3.8. Simulation Results

This section shows the PD simulation results of both the back module and the top module at 28 GHz and 39 GHz for each evaluation plane in Table 2 at separation distance of 2mm.

The relative phase between beam pairs is not controlled in the chipset design. Therefore, the relative phase between each beam pair was considered mathematically to identify the worst case conditions. The below MIMO results represent the highest reported MIMO simulation results after a conservative uncertainty factor was applied based on simulated PD recalculated for every group phase relationship between the two beams sweeping from 0° to 360° at a 5° step interval. The worst-case simulated PD determined from the tables in this section were used for conservativeness in input.power.limit determination in RF Exposure Part 0 Report.

2.3.8.1 Back Module

Table 6&7 show the PD simulation evaluation of the back module at 28GHz/39GHz for the corresponding evaluation planes specified in Table 2.

Table 6 PD of Back module (28GHz – n261)

Beam ID 1	Beam ID 2	Antenna Module	4cm2 Average Total PD (W/m^2)			Surface
			low channel	mid channel	high channel	
1		0	3.5	3.5	3.3	S2
5		0	7.2	6.3	6	S2
6		0	5.5	5.2	4.8	S2

7		0	4.1	4	4	S2
10		0	5.3	5.2	4.9	S2
11		0	7	6.6	6.4	S2
17		0	10.3	9.3	8.8	S2
18		0	12.5	11.8	10.9	S2
19		0	12.3	11.4	10.9	S2
20		0	10.9	10.2	9.6	S2
21		0	9.4	8.9	8.5	S2
26		0	11.2	10.5	10.1	S2
27		0	13	12	11.2	S2
28		0	11.5	10.7	9.9	S2
29		0	8.2	7.9	7.8	S2
129		0	2	2	2	S2
133		0	4.6	4.7	4.6	S2
134		0	5.9	5.8	5.5	S2
135		0	4.5	4.5	4.6	S2
138		0	5.2	5.3	5	S2
139		0	5.1	5	5	S2
145		0	10.7	10	9.2	S2
146		0	12.3	11.7	11	S2
147		0	12.5	11.8	10.9	S2
148		0	10.8	9.7	9.1	S2
149		0	8.5	8.1	8	S2
154		0	11.4	10.7	9.8	S2
155		0	12.4	11.8	11.1	S2
156		0	12.1	11.1	10.1	S2
157		0	9.6	8.7	8.4	S2
1	129	0	5.4	5.5	5.3	S2
5	135	0	11.4	10.9	10.5	S2
6	134	0	12.0	11.4	10.9	S2
7	133	0	9.2	9.1	8.8	S2
10	139	0	11.0	10.9	10.8	S2
11	138	0	12.7	12.2	11.5	S2

17	149	0	20.0	19.7	19.6	S2
18	148	0	25.0	22.4	21.3	S2
19	147	0	26.4	24.3	22.0	S2
20	145	0	22.4	20.8	20.2	S2
21	146	0	22.4	21.5	20.8	S2
26	157	0	22.9	20.0	20.1	S2
27	155	0	26.7	24.9	22.9	S2
28	156	0	24.7	22.4	20.2	S2
29	154	0	20.8	19.1	17.9	S2

Table 7 PD of Back module (39 GHz – n260)

Beam ID 1	Beam ID 2	Antenna Module	4cm2 Average Total PD (W/m^2)			Surface
			low channel	mid channel	high channel	
1		0	2.1	3.1	2.9	S2
5		0	3.4	5.8	6.2	S2
6		0	3.3	3.6	2.8	S2
7		0	4.5	7.3	7.4	S2
10		0	3.7	4.9	5.4	S2
11		0	3.2	4.2	5.6	S2
17		0	6.7	9.9	10.7	S2
18		0	6.2	8.2	8.5	S2
19		0	5.5	5.8	5.8	S2
20		0	6.6	9.8	11.0	S2
21		0	6.6	9.9	11.9	S2
26		0	5.6	7.5	6.9	S2
27		0	6.0	8.9	10.4	S2
28		0	6.0	10.9	12.5	S2
29		0	5.7	6.1	6.2	S2
129		0	2.4	2.8	3.1	S2
133		0	4.3	7.0	7.6	S2
134		0	4.1	4.5	3.4	S2
135		0	3.3	4.0	4.4	S2
138		0	3.8	4.8	5.9	S2

139		0	4.3	5.3	4.5	S2
145		0	8.4	11.7	11.7	S2
146		0	8.1	12.3	14.4	S2
147		0	6.5	6.9	6.4	S2
148		0	8.5	12.4	13.9	S2
149		0	6.7	6.6	7.1	S2
154		0	7.0	9.8	9.6	S2
155		0	7.2	11.0	11.6	S2
156		0	8.2	12.1	12.0	S2
157		0	6.8	5.4	6.2	S2
1	129	0	4.6	5.9	6.2	S2
5	135	0	5.6	8.7	9.8	S2
6	134	0	7.2	9.2	8.0	S2
7	133	0	8.9	14.0	14.8	S2
10	138	0	6.7	9.4	10.4	S2
11	139	0	6.7	9.2	10.1	S2
17	145	0	13.8	18.9	21.4	S2
18	146	0	15.1	21.2	23.4	S2
19	149	0	12.1	12.2	11.4	S2
20	147	0	13.5	19.6	19.3	S2
21	148	0	15.3	21.9	23.3	S2
26	156	0	12.9	20.3	17.4	S2
27	154	0	11.5	16.2	18.6	S2
28	157	0	12.8	16.3	17.3	S2
29	155	0	12.5	17.8	14.5	S2

2.3.8.2 Top Module

Table 8&9 show the PD simulation evaluation of the top module at 28 GHz / 39 GHz for the corresponding evaluation planes specified in Table 2.

Table 8 PD of Top module (28GHz – n261)

Beam ID 1	Beam ID 2	Antenna Module	4cm2 Average Total PD (W/m^2)			Surface
			low	mid	high	

			channel	channel	channel	
0		1	3.1	3.2	3.1	S5
2		1	4.6	4.5	4.4	S5
3		1	5.7	5.6	5.5	S5
4		1	4.9	4.8	4.8	S5
8		1	4.6	4.9	5.1	S5
9		1	6.5	6.3	6.1	S5
12		1	7.0	7.2	7.4	S5
13		1	6.2	6.1	6.2	S5
14		1	10.3	10.2	10.0	S5
15		1	10.6	10.4	10.1	S5
16		1	7.5	8.2	8.5	S5
22		1	7.1	7.7	8.1	S5
23		1	7.7	7.8	7.9	S5
24		1	11.9	11.9	11.7	S5
25		1	8.0	8.6	8.7	S5
128		1	2.3	2.2	2.1	S5
130		1	4.8	4.6	4.4	S5
131		1	5.5	5.3	5.1	S5
132		1	4.3	4.4	4.3	S5
136		1	5.3	5.0	4.8	S5
137		1	4.8	4.8	4.7	S5
140		1	7.7	7.3	6.9	S5
141		1	10.5	10.1	9.8	S5
142		1	11.1	10.7	10.2	S5
143		1	7.7	8.1	7.9	S5
144		1	6.0	6.2	6.2	S5
150		1	9.3	8.8	8.4	S5
151		1	11.3	11.1	10.7	S5
152		1	10.0	9.6	9.0	S5
153		1	6.7	7.2	7.2	S5
0	128	1	4.6	4.6	4.5	S5
2	132	1	9.1	9.3	9.4	S5

3	131	1	10.6	10.3	10.0	S5
4	130	1	9.2	9.0	9.0	S5
8	137	1	8.1	8.0	8.0	S5
9	136	1	11.1	10.7	10.5	S5
12	143	1	15.4	16.0	15.6	S5
13	144	1	13.8	14.1	14.3	S5
14	142	1	19.6	19.0	18.3	S5
15	141	1	20.1	19.0	18.4	S5
16	140	1	18.5	18.4	17.6	S5
22	152	1	16.4	16.0	15.8	S5
23	153	1	16.5	17.2	17.4	S5
24	151	1	21.3	21.0	20.6	S5
25	150	1	18.5	18.4	18.1	S5

Table 9 PD of Top module (39GHz – n260)

Beam ID 1	Beam ID 2	Antenna Module	4cm2 Average Total PD (W/m^2)			Surface
			low channel	mid channel	high channel	
0		1	3.1	3.2	3.1	S5
2		1	4.6	4.5	4.4	S5
3		1	5.7	5.6	5.5	S5
4		1	4.9	4.8	4.8	S5
8		1	4.6	4.9	5.1	S5
9		1	6.5	6.3	6.1	S5
12		1	7.0	7.2	7.4	S5
13		1	6.2	6.1	6.2	S5
14		1	10.3	10.2	10.0	S5
15		1	10.6	10.4	10.1	S5
16		1	7.5	8.2	8.5	S5
22		1	7.1	7.7	8.1	S5
23		1	7.7	7.8	7.9	S5
24		1	11.9	11.9	11.7	S5
25		1	8.0	8.6	8.7	S5

128		1	2.3	2.2	2.1	S5
130		1	4.8	4.6	4.4	S5
131		1	5.5	5.3	5.1	S5
132		1	4.3	4.4	4.3	S5
136		1	5.3	5.0	4.8	S5
137		1	4.8	4.8	4.7	S5
140		1	7.7	7.3	6.9	S5
141		1	10.5	10.1	9.8	S5
142		1	11.1	10.7	10.2	S5
143		1	7.7	8.1	7.9	S5
144		1	6.0	6.2	6.2	S5
150		1	9.3	8.8	8.4	S5
151		1	11.3	11.1	10.7	S5
152		1	10.0	9.6	9.0	S5
153		1	6.7	7.2	7.2	S5
0	128	1	6.1	7.6	7.7	S5
2	131	1	8.7	11.0	10.6	S5
3	130	1	9.1	12.0	12.5	S5
4	132	1	9.9	11.8	11.7	S5
8	136	1	9.0	11.3	11.6	S5
9	137	1	11.3	14.4	13.3	S5
12	140	1	16.3	19.7	19.3	S5
13	144	1	18.2	24.1	25.3	S5
14	142	1	16.4	22.9	21.5	S5
15	143	1	16.3	19.3	20.9	S5
16	141	1	16.4	21.0	21.4	S5
22	150	1	17.4	21.2	18.4	S5
23	151	1	15.3	20.4	20.9	S5
24	152	1	16.1	21.7	21.4	S5
25	153	1	16.0	18.3	19.7	S5