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**SAR MEASUREMENT REQUIREMENTS FOR 100 MHz TO 6 GHz**

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## 1. Introduction

The SAR measurement procedures for 100 MHz to 6 GHz are described in this document. Field probes, tissue dielectric properties, SAR scans, measurement accuracy and variability of the measured results are discussed. The field probe and SAR scan requirements are derived from criteria considered in IEEE Std 1528-2013. The wireless product and technology specific procedures in applicable KDB publications are required to be used unless further guidance has been provided by the FCC.<sup>1</sup>

SAR measurement requirements have not been fully established for frequencies below 100 MHz. While numerical SAR simulation may be applied in some situations, a combination of other field measurements and analyses, when appropriate, may be considered to demonstrate RF exposure compliance. These are determined on a case-by-case basis through KDB inquiries.

## 2. SAR Measurement Procedures and Requirements

### 2.1. General

The SAR measurement procedures in IEEE Std 1528-2013 were established primarily for testing wireless handsets in the 800 MHz to 1900 MHz bands.<sup>2</sup> Although tissue dielectric parameters are also defined at other selected frequencies, as more products and radio services are introduced in newly allocated spectrums, these previously established measurement procedures have become unclear and insufficient. Because tissue dielectric properties are frequency dependent, the tolerances required by earlier measurement protocols have led to implied frequency intervals within which the dielectric parameters are valid. This has generally worked well for previous generation wireless transmitters in the 800 MHz to 1900 MHz range. As transmission rates continue to push higher, mostly in the 700 MHz to 6 GHz range, wider frequency bands and channel bandwidths are required; for example, devices operating with LTE, WiMax, 802.11ac, etc. The signal and transmission characteristics have become substantially dynamic. The SAR probe calibration, measurement accuracy, tissue dielectric parameters and other SAR measurement procedures required for testing recent generation wireless devices need further examination. In addition, some test laboratories have begun to use multiple SAR probes and multiple measurement systems to perform measurements with multiple test samples to expedite the testing process.<sup>3</sup> This often introduces another level of ambiguity when results must be correlated to determine compliance.

### 2.2. SAR probes

The tip diameter of SAR probes used for earlier SAR systems, intended for measurements below 2 GHz, are typically around 6 mm to 7 mm. These larger probe tips, when used for measurements at closer than 3 mm to 4 mm from the phantom surface, can cause undesirable probe boundary effect error. Field probes with smaller probe tip diameters have been introduced over the last decade to correctly measure the higher SAR closest to the phantom surface, up to 6 GHz, which also provide improved probe performance at lower frequencies. Unless probe boundary effect error compensation is applied, probe tips must be positioned at more than half a probe tip diameter from the phantom surface to minimize probe boundary effect error. Except for a few early generation SAR measurement systems that might still be in

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<sup>1</sup> See *Report & Order* in ET Docket 03-137; OET Bulletin 65 Supplement C 01-01 has been discontinued.

<sup>2</sup> The relevant information in OET Bulletin 65 Supplement C 01-01 has been either imported or duplicated into the *published RF exposure KDB procedures*; see KDB Publication 447498 D01 and references therein.

<sup>3</sup> The next generation of SAR measurement systems and methodologies are expected to shorten the measurement time substantially to expedite SAR testing. These are expected to be available in 1 – 2 years; however, SAR measurement standards will need to be established for these systems.

use, probe boundary effect compensation is generally a standard built-in feature for recent generation SAR systems.

The sensors in SAR probes are physically offset from the probe tip. At higher frequencies, with reduced penetration depths and steeper field gradients in tissue media, the typical sensor to probe tip offset distances of 2.5 mm to 3.0 mm for early generation probes are inadequate for measurements above 2 GHz. Sensor offsets < 1.0 mm to 1.5 mm are necessary for measurements near 6 GHz, to capture the higher fields at 2 mm to 3 mm from the phantom surface. When probe boundary effect compensation is applied, measurements at approximately 2 mm from the phantom surface are possible for probes with a tip diameter < 2.5 mm and sensor offsets  $\leq 1.0$  mm.

When larger probe tips or sensor offsets are used, the closest measurement points are further away from the phantom surface; therefore, the highest SAR in regions closest to the phantom surface must be estimated by extrapolation. When measurement points are further away from the phantom surface at above 3 GHz, the measured SAR could become dominated by noise, due to field attenuations by the tissue medium. This can reduce the reliability of the extrapolation algorithms used to estimate the highest SAR closest to the phantom surface for computing the 1-g SAR.

The probe tip diameter must be  $\leq 8$  mm for measurements  $\leq 2$  GHz; and must be  $\leq 1/3$  of the wavelength in the required tissue-equivalent medium for test frequencies  $> 2$  GHz. The wavelength in tissue-equivalent medium ( $\lambda_T$ ) is calculated according to the following:

$$\lambda_T = \frac{2 \cdot \pi}{\beta}; \quad \beta = \omega \sqrt{\frac{\mu_0 \cdot \varepsilon}{2}} \cdot \sqrt{\sqrt{1 + \left(\frac{\sigma}{\omega \cdot \varepsilon}\right)^2} + 1}; \quad \text{with:}$$

$$\omega = 2 \cdot \pi \cdot f, \quad \varepsilon = \varepsilon_0 \cdot \varepsilon_r, \quad \varepsilon_0 = 8.85 \times 10^{-12}, \quad \mu_0 = 4 \cdot \pi \times 10^{-7}.$$

The calculated values for  $\lambda_T/3$  at 3 GHz, 4 GHz, 5 GHz and 6 GHz for head tissue-equivalent dielectric parameters are 5.28 mm, 4.01 mm, 3.25 mm and 2.74 mm, respectively.

The closest measurement point from the phantom surface is determined by the geometric center of the sensors at the probe tip. This distance is determined by the probe sensor offset and probe tip to phantom separation; therefore, the appropriate probe must be used for the SAR measurement. Depending on whether probe boundary effect compensation is applied, the closest measurement point must be positioned at least  $1/2$  the probe tip diameter plus the probe sensor offset or the probe tip to phantom distance allowed by the probe boundary effect compensation determined during probe calibration plus the probe sensor offset. The closest measurement point from the phantom surface must be  $\leq 5$  mm with  $\leq \pm 1$  mm variation in the required tissue-equivalent medium for measurements  $\leq 3$  GHz; and must be  $\leq 1/2 \cdot \delta \cdot \ln(2)$  mm with  $\leq \pm 0.5$  mm variation for test frequencies  $> 3$  GHz, where:

$$\delta = \frac{1}{\alpha}; \quad \alpha = \omega \sqrt{\frac{\mu_0 \cdot \varepsilon}{2}} \cdot \sqrt{\sqrt{1 + \left(\frac{\sigma}{\omega \cdot \varepsilon}\right)^2} - 1}; \quad \ln(2) = 0.6931.$$

The calculated values for  $1/2 \cdot \delta \cdot \ln(2)$  at 4 GHz, 5 GHz and 6 GHz for head tissue-equivalent dielectric parameters are 3.3 mm, 2.5 mm and 2.2 mm, respectively.

### 2.3. SAR probe calibration considerations

Probes should be calibrated by the manufacturer or a calibration facility authorized by the probe manufacturer, according to IEEE Std 1528-2013 protocols and procedures required by the manufacturer. The effective frequency interval of a probe calibration point can be influenced by deviations in dielectric constant ( $\varepsilon_r$ ) and conductivity ( $\sigma$ ) of the tissue-equivalent media, and differences in tissues recipes used for probe calibration and routine measurements. The required tissue dielectric parameter tolerance and probe calibration methods typically enable probes to be calibrated with an effective frequency of at least

$\pm 50$  MHz, and sometimes up to  $\pm 100$  MHz or more at higher frequencies; for example, above 2 GHz. However, the frequency characteristics of a probe calibration point, associated with a specific tissue medium recipe, can be different when the same tissue recipe is not used for both calibration and routine measurements, especially at offset frequencies away from the calibration frequency; for example  $> \pm 50$  MHz. The useful frequency interval of a probe calibration point can become reduced as the difference in tissue dielectric properties of the media used between probe calibration and routine measurements widens.

Transfer calibrations based on temperature measurements are generally used at frequencies below 1 GHz. Waveguide procedures are required to calibrate probes at above 1 GHz, with respect to theoretically calculated fields. Each probe calibration point must be valid for at least  $\pm 50$  MHz to enable coverage for most frequency bands. For measurements requiring wider frequencies, such as the 5 GHz bands for §§ 15.247 and 15.407 (UNII), the calibration points should be valid for the entire transmission band that requires measurement. If a probe calibration point cannot cover the entire transmission band, multiple probe calibration points are required for measurements in the band. For wireless technologies that operate with substantially wide channel bandwidths, separate probe calibration points centered within the channels may be required. When a single calibration point is used for routine measurements to cover a frequency range larger than  $\pm 100$  MHz, the test lab must verify the valid measurement frequency range supported by the probe calibration point, according to the tissue dielectric parameter requirements and signal modulation characteristics. This is normally performed during SAR system validation. The results must be included in a KDB inquiry to confirm that the frequency range of the probe calibration is acceptable before measurements are performed.

For routine SAR measurements, specific SAR error compensation algorithms may be applied to the measured tissue dielectric parameters to enable the results to have a larger tolerance than normally required. This type of SAR error compensation should be applied only to routine measurements; it does not apply to probe calibrations. The measured  $\epsilon_r$  and  $\sigma$  of the tissue-equivalent medium used during probe calibration must be within 5% of the target parameters specified in Appendix A. The expanded uncertainty for all probe calibrations must be  $\leq 15\%$ , for a confidence interval of  $k = 2$ . The applicable probe calibration and calibration uncertainty information must be included with the SAR report to support the test results.

Probes are normally calibrated with sinusoidal CW signals for measuring the SAR of continuous or periodic pulse-modulated CW equivalent signals. The duty factor of periodic pulse-modulated CW equivalent signals can be easily compensated by existing SAR measurement systems when the amplitude variations within the pulses are insignificant; for example, the constant amplitude modulation used by GMSK in GSM. Although the duty factor is not directly related to the voltage crest factor of a signal, this type of compensation is often called “crest factor” by SAR system manufacturers. The duty factor compensation applied to periodic signals in SAR measurements is not applicable to non-periodic or high peak to average power ratio noise-like signals. The SAR measurement errors for noise-like non-periodic signals are generally expected to vary exponentially with increasing SAR levels. This issue was examined by the IEEE SCC-34 committee during the development of IEEE Std 1528-2003 for a CDMA signal (IS-95). The effects remain to be investigated for other digital modulations with different signal characteristics and different peak to average power ratios. In the meantime, curve-fitting techniques have been applied during probe calibration to enable the SAR error of signals with specific characteristics to be compensated during routine measurement. Until more comprehensive results are available from standards organizations and other relevant sources, the applicable SAR measurement procedures described in this document must be applied, in conjunction with the *published RF exposure KDB procedures*, for specific wireless technologies to minimize measurement concerns.<sup>4</sup>

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<sup>4</sup> See KDB Publication 447498 for *published RF exposure KDB procedures*.

## 2.4. Tissue dielectric parameter requirements

The head and body tissue dielectric parameters specified in Appendix A must be linearly interpolated or extrapolated to the measurement channel frequencies, to determine the tissue-equivalent media dielectric parameters required for testing.<sup>5</sup> Based on the measured tissue dielectric parameters at selected frequencies, some SAR systems have provisions to interpolate and extrapolate the measured dielectric parameters to the test channel frequencies of the device. However, special care is needed so that the test channel frequency is not entered incorrectly in the SAR system, which would lead to the wrong dielectric parameters being applied; for example, using the default mid-band frequency instead of the actual test channel frequency is not acceptable.

The dielectric constant ( $\epsilon_r$ ) and conductivity ( $\sigma$ ) of typical tissue-equivalent media recipes are expected to be within 5% of the required target values for a range of approximately 50 MHz at frequencies below 300 MHz. At above 3 GHz, 5% tolerance can usually be maintained for  $\pm 100$  MHz or more. For signals with a substantially wide channel bandwidth, the tissue-equivalent media dielectric parameters must be within tolerance for the entire channel bandwidth frequency range. For SAR measurement systems that have implemented the SAR error compensation algorithms documented in IEEE Std 1528-2013,<sup>6</sup> to automatically compensate the measured SAR results for deviations between the measured and required tissue dielectric parameters, the tolerance for  $\epsilon_r$  and  $\sigma$  may be relaxed to  $\pm 10\%$ .<sup>7</sup> Unless it is documented in the SAR report that the tissue dielectric parameters used for the measurements are within  $\pm 10\%$  of the required target values for the entire transmission band, and it is also verified and documented that the required SAR error compensation algorithm has been correctly applied to only scale up the measured SAR, and not downward,<sup>8</sup>  $\pm 5\%$  tolerances are required for  $\epsilon_r$  and  $\sigma$ . The target dielectric parameters used by SAR systems to perform the error compensation must also be identified in the SAR report.<sup>9</sup> Regardless of the frequency range and tissue dielectric tolerances supported by a tissue medium recipe, all measurements must be within the constraints of a probe calibration point.

Information on temperature sensitivity and short term stability of the tissue media must also be reported to ensure the tissue dielectric parameters are within tolerance for all measurements.<sup>10</sup> It must be ensured that tissue-equivalent liquid mixtures (suspensions) containing non-polar liquids, such as mineral oil,

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<sup>5</sup> The *Report & Order* in ET Docket 03-137 has discontinued OET Bulletin 65 Supplement C. The tissue dielectric parameters in the former Supplement C 01-01 are now in Appendix A of this document.

<sup>6</sup> The coefficients for conductivity correction are different in IEEE Std 1528-2013 and the publication referenced by it, "Enabling the use of broadband tissue equivalent liquids for specific absorption rate measurements," M. G. Douglas et. al., *IEEE Electromagnetic Compatibility Symposium*, July 2007, due to differences in curve-fitting; however, there are no significant differences in the results.

<sup>7</sup> Depending on the SAR system, there could be frequency restrictions to apply the SAR error compensation; for example, this is limited to  $\leq 3$  GHz for DASY systems.

<sup>8</sup> It is unclear how the SAR error compensation is implemented in different SAR systems; therefore, the test lab must verify this before it is applied to SAR measurements. The SAR system manufacturer may be contacted or SAR measurements using different tissue-equivalent dielectric parameters can be post-processed with and without the error compensation active and verified against the equations listed in IEEE Std 1528-2013 to determine proper implementation.

<sup>9</sup> SAR systems generally require the user to enter or define the target tissue dielectric parameters. The interpolated and extrapolated dielectric values used by the system must be verified against the head and body parameters specified in Appendix A to ensure the correct error compensation is applied.

<sup>10</sup> Temperature sensitivity is generally characterized once for each type of tissue-equivalent medium recipe. When liquids are purchased from SAR system manufacturers, this information is typically available in the data sheets. Short term stability is related to the uniformity (homogeneity) of ingredients in the mixture, which can introduce changes to dielectric parameters during the SAR measurement; for example, mineral oil based mixtures.

glycerol, emulsifier or other agents, that are not fully soluble in water remain thoroughly mixed to maintain the required dielectric properties and within the required temperature range during each SAR measurement. It has been confirmed that sugar-based recipes are typically unable to achieve the required dielectric parameters above 1 GHz to 2 GHz; therefore, such recipes must be limited to measurements below 1 GHz. Several mineral oil based proprietary broadband recipes have been available commercially, which typically require thorough mixing before use. It must be ensured that there are no air bubbles in the mixture before each measurement. Furthermore, some recipes may have a narrow temperature range for the dielectric parameters to be within tolerance; therefore, further documentation is required to use this type of tissue media.

The tissue dielectric parameters of tissue-equivalent media used for SAR measurements must be characterized within a temperature range of 18 °C to 25 °C, measured with calibrated instruments and apparatuses, such as network analyzers and temperature probes. The temperature of the tissue-equivalent medium during SAR measurement must also be within 18 °C to 25 °C and within  $\pm 2$  °C of the temperature when the tissue parameters are characterized. The tissue dielectric measurement system must be calibrated before use. The dielectric parameters must be measured before the tissue-equivalent medium is used in a series of SAR measurements. The parameters should be re-measured after each 3 – 4 days of use; or earlier if the dielectric parameters can become out of tolerance; for example, when the parameters are marginal at the beginning of the measurement series.

## 2.5. Phantom requirements

The SAM phantom specified in IEEE Std 1528-2013 is required for head SAR measurements of devices operating next to the ear. The rationales for the SAM phantom to provide conservative head SAR results are explained in IEEE Std 1528-2013.<sup>11</sup> When a flat phantom is used for other measurements, it must be sufficiently large for the antennas and radiating structures of the transmitters and host device to couple correctly in the intended RF exposure conditions, for both standalone and simultaneous transmission SAR measurements. This generally requires the measurement region, corresponding to the antenna and radiating structures of the device, to be at least 3 cm to 5 cm from the flat phantom boundaries (side walls). When no unusual reflections from the phantom sidewalls are observed in the measured SAR distribution, a margin of at least 3 cm at 6 GHz and 5 cm at 100 MHz is typically acceptable; otherwise, a wider separation is required to minimize the reflection effects. When a test device is larger than the flat phantom, area scan measurements of multiple smaller regions that overlap with adjacent regions by at least 2 cm may be used to determine zoom scan requirements, provided the partial scans do not introduce antenna coupling issues and the overall SAR distribution remains unchanged with the same identical SAR distribution measured in the overlapping regions. These must be clearly explained and fully documented in the SAR report for the results to be acceptable.

The test laboratory must confirm that the following phantom shell dielectric property and thickness tolerance requirements are satisfied:

- $2 \leq \epsilon_r \leq 5$  at  $\leq 3$  GHz
- $3 \leq \epsilon_r \leq 4$  at  $> 3$  GHz
- loss tangent  $\leq 0.05$
- phantom shell thickness is  $2.0 \text{ mm} \pm 0.2 \text{ mm}$  in the measurement regions
- shell thickness at the ear reference point (ERP) location of the SAM phantom, including the ear spacer, is  $6.0 \text{ mm} \pm 0.2 \text{ mm}$

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<sup>11</sup> See ET dockets 13-84 and 03-137 for rule-making and *Report & Order* (FCC 13-39) relating to certain RF exposure testing concerns for cellphones. Further updates to test and compliance requirements will be determined according to the final rules relating to these proceedings.

- the shape of the SAM phantom and thickness of the ear spacer are in accordance with specifications in the IEEE Std 1528-2013 CAD files

The depth of tissue-equivalent liquid in a phantom must be  $\geq 15.0$  cm with  $\leq \pm 0.5$  cm variation for SAR measurements  $\leq 3$  GHz and  $\geq 10.0$  cm with  $\leq \pm 0.5$  cm variation for measurements  $> 3$  GHz. These depths should ensure the SAR probe is immersed sufficiently in the tissue medium while scanning along the curved surfaces of the SAM phantom at various probe angles, with an acceptable separation between the top of the zoom scan volume and the liquid-air boundary above. The required liquid depth for typical SAR measurements is determined at the ERP location of the SAM phantom and at the center of the measurement region for a flat phantom. When a rotated SAM phantom is used, a separation of at least 2.5 penetration depths must be maintained between the top of the zoom scan volume and the liquid surface above. When this is not feasible at the lower frequencies; for example, along curved surfaces near and above the ERP region, a KDB inquiry with specific details should be submitted to determine acceptable measurement requirements.

## 2.6. SAR measurement requirements

To minimize SAR measurement discrepancies due to probe calibration and tissue dielectric parameter concerns, measurements below 300 MHz must be within  $\pm 50$  MHz of the probe calibration point frequency. At 300 MHz to 6 GHz, measurements must be within  $\pm 100$  MHz of the probe calibration point frequency or the valid frequency range supported by the probe calibration, whichever is less. When the measured SAR is within 10% of the SAR limit, the following additional steps are required for measurements exceeding 50% of these intervals, i.e.,  $\pm 25$  MHz at  $< 300$  MHz and  $\pm 50$  MHz at  $\geq 300$  MHz or  $\frac{1}{2}$  the frequency range supported by the probe calibration point, for test results to be acceptable without prior consultation with the FCC Laboratory. The applicable conditions must be clearly identified in the SAR report.

- 1) When the exact tissue dielectric parameters used in the probe calibration are recorded in the calibration data, the measured  $\epsilon_r$  and  $\sigma$  of the liquid used in routine measurements must be
  - within 5% of those recorded in the probe calibration data and also within 5% of the required target dielectric parameters, or
  - within 10% of those recorded in the probe calibration data and also within 10% of the required target dielectric parameters, when the measured SAR is compensated for tissue dielectric deviations (see 2.4)
- 2) When nominal tissue dielectric parameters are recorded in the probe calibration data; for example, only target values and tolerance are reported, the measured  $\epsilon_r$  and  $\sigma$  of the liquid used in routine measurements must be:
  - $\leq$  the target  $\epsilon_r$  and  $\geq$  the target  $\sigma$  values and also within 5% of the required target dielectric parameters, or
  - within +5% and -10% of the target  $\epsilon_r$ , and also within -5% and +10% of the target  $\sigma$  values, when the measured SAR is compensated for tissue dielectric deviations (see 2.4)

## 2.7. SAR scan procedures

### 2.7.1. General

The area and zoom scan resolutions specified in the table below must be applied to the SAR measurements and fully documented in SAR reports, unless further guidance has been provided by the FCC. Probe boundary effect error compensation is required for measurements with the probe tip closer than half a probe tip diameter to the phantom surface. Both the probe tip diameter and sensor offset distance must satisfy measurement protocols; to ensure probe boundary effect errors are minimized and the higher fields closest to the phantom surface can be correctly measured and extrapolated to the phantom surface for computing 1-g SAR. Tolerances of the post-processing algorithms must be verified

by the test laboratory for the scan resolutions used in the SAR measurements, according to the reference distribution functions specified in IEEE Std 1528-2013. The results should be documented as part of the system validation records and may be requested to support test results when all the measurement parameters in the following table are not satisfied.

		$\leq 3$ GHz	$> 3$ GHz	
Maximum distance from closest measurement point (geometric center of probe sensors) to phantom surface		5 mm $\pm$ 1 mm	$\frac{1}{2} \cdot \delta \cdot \ln(2)$ mm $\pm$ 0.5 mm	
Maximum probe angle from probe axis to phantom surface normal at the measurement location		$30^\circ \pm 1^\circ$	$20^\circ \pm 1^\circ$	
Maximum area scan spatial resolution: $\Delta x_{Area}$ , $\Delta y_{Area}$		$\leq 2$ GHz: $\leq 15$ mm 2 – 3 GHz: $\leq 12$ mm	3 – 4 GHz: $\leq 12$ mm 4 – 6 GHz: $\leq 10$ mm	
		When the x or y dimension of the test device, in the measurement plane orientation, is smaller than the above, the measurement resolution must be $\leq$ the corresponding x or y dimension of the test device with at least one measurement point on the test device.		
Maximum zoom scan spatial resolution: $\Delta x_{Zoom}$ , $\Delta y_{Zoom}$		$\leq 2$ GHz: $\leq 8$ mm 2 – 3 GHz: $\leq 5$ mm*	3 – 4 GHz: $\leq 5$ mm* 4 – 6 GHz: $\leq 4$ mm*	
Maximum zoom scan spatial resolution, normal to phantom surface	uniform grid: $\Delta z_{Zoom}(n)$	$\leq 5$ mm	3 – 4 GHz: $\leq 4$ mm 4 – 5 GHz: $\leq 3$ mm 5 – 6 GHz: $\leq 2$ mm	
	graded grid	$\Delta z_{Zoom}(1)$ : between 1 <sup>st</sup> two points closest to phantom surface	$\leq 4$ mm	3 – 4 GHz: $\leq 3$ mm 4 – 5 GHz: $\leq 2.5$ mm 5 – 6 GHz: $\leq 2$ mm
		$\Delta z_{Zoom}(n>1)$ : between subsequent points	$\leq 1.5 \cdot \Delta z_{Zoom}(n-1)$ mm	
Minimum zoom scan volume	x, y, z	$\geq 30$ mm	3 – 4 GHz: $\geq 28$ mm 4 – 5 GHz: $\geq 25$ mm 5 – 6 GHz: $\geq 22$ mm	
Note: $\delta$ is the penetration depth of a plane-wave at normal incidence to the tissue medium; see IEEE Std 1528-2013 for details.				
* When zoom scan is required and the <i>reported</i> SAR from the <i>area scan based 1-g SAR estimation</i> procedures of KDB Publication 447498 is $\leq 1.4$ W/kg, $\leq 8$ mm, $\leq 7$ mm and $\leq 5$ mm zoom scan resolution may be applied, respectively, for 2 GHz to 3 GHz, 3 GHz to 4 GHz and 4 GHz to 6 GHz.				

### 2.7.2. Area scan

All antennas and radiating structures that may contribute to the measured SAR or influence the SAR distribution must be included in the area scan. When applicable, partially overlapping area scans may be considered (see 2.5). The areas of the transmitter(s), antenna(s) and host device, when projected onto the phantom, must be within the area scan measurement region. The area scan measurement resolution must enable the extrapolation algorithms of the SAR system to correctly identify the peak SAR location(s) for subsequent zoom scan measurements to correctly determine the 1-g SAR. Area scans are performed at a constant distance from the phantom surface, determined by the measurement frequencies. When a measured peak is closer than  $\frac{1}{2}$  the zoom scan volume dimension (x, y) from the edge of the area scan region, unless the entire peak and gram-averaging volume are both captured within the zoom scan



volume, the area scan must be repeated by shifting and expanding the area scan region to ensure all peaks are away from the area scan boundary.<sup>12</sup>

When a test device orientation has a small projected area on the phantom; for example, the side edges of a handset or USB dongles, the area scan measurement resolutions must be less than  $\frac{1}{2}$  of the corresponding zoom scan dimensions for the device surface being measured. When the *area scan based 1-g SAR estimation* of KDB Publication 447498 is applied, the area scan resolution must be less than or equal to the corresponding dimensions of the device surface being measured. Regardless of whether zoom scan or *1-g SAR estimation* is used, at least one measurement point must be on the device. Reducing the measurement resolution of a smaller scan region generally requires the similar number of measurement points as compared to applying larger measurement resolutions to larger scan regions.

### 2.7.3. Zoom scan

Except when *area scan based 1-g SAR estimation* applies, a zoom scan measurement is required at the highest peak SAR location determined in the area scan to determine the 1-g SAR. When the 1-g SAR of the highest peak is within 2 dB of the SAR limit, additional zoom scans are required for other peaks within 2 dB of the highest peak that have not been included in any zoom scan to ensure there is no increase in SAR. The zoom scan volume must be larger than the required minimum dimensions described 2.7.1. There must be at least one measurement point within the first 5 mm from the phantom surface for measurements  $\leq 3$  GHz, two measurement points for measurements  $\leq 5$  GHz and three measurement points for measurements above 5 GHz.<sup>13</sup> When graded grids are used, which only applies in the direction normal to the phantom surface, the initial grid separation closest to the phantom surface and subsequent graded grid increment ratios must satisfy the required protocols in 2.7.1 of this document. The 1-g SAR averaging volume must be fully contained within the zoom scan measurement volume boundaries; otherwise, the measurement must be repeated by shifting or expanding the zoom scan volume. The similar requirements also apply to 10-g SAR measurements.

### 2.7.4. SAR measurement drifts

Before an area scan and after the zoom scan, single point SAR measurements are performed at defined locations to estimate the SAR measurement drift due to device output power variations. If a device is known to drift randomly, additional single point drift reference measurements should be performed at regular intervals throughout the area and zoom scan test durations. Substantial drifts, whether positive or negative, can be related to test device setup or other SAR measurement concerns. When the drift is more than 5%, a KDB inquiry should be submitted to determine how to address output power stability issues and to ensure the SAR results are acceptable. If the drift is inherent to the design of the device, the power drift should be characterized to determine if the measured SAR results should be scaled with respect to a nominal time-averaged power level. Drifts that are due to measurement or test setup issues must be resolved before the SAR measurement series can be continued.

### 2.7.5. Post-processing

The interpolation and extrapolation procedures used by the SAR measurement system must be verified against the reference SAR distribution functions described in IEEE Std 1528-2013 to ensure the measurement resolutions used in area and zoom scans are acceptable. SAR values are computed by the reference functions at the required measurement resolutions and processed by the interpolation and extrapolation procedures in the SAR system using different grid offsets. The results from the SAR

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<sup>12</sup> IEEE Std 1528-2013 requires area scans to be repeated when a peak is  $< \frac{1}{2}$  the corresponding zoom scan volume dimension from an area scan boundary. This may not work well for small area scan regions used for USB dongles or device edges.

<sup>13</sup> A measurement point is determined by the geometric center of the probe sensors, which is identified by the probe sensor offset and probe tip to phantom surface distances.

system are compared to the values calculated directly using the reference functions to determine whether the measurement, interpolation and extrapolation resolutions used by the SAR system for routine measurement setups are acceptable. Most SAR systems have built-in provisions to perform these procedures. Unless results for specific SAR measurement resolutions are provided by the SAR system manufacturer, the test laboratory is required to perform these verifications, as a part of the SAR measurement system validation, for the area and zoom scan measurement resolutions, interpolation and extrapolation resolutions used for routine measurements. After hardware upgrades or software updates have been applied to SAR systems or when new measurement resolutions are used in routine measurements, system validation is required. The results should be kept by the test lab as part of the system validation record.

#### 2.7.6. Simultaneous transmission SAR measurement

When simultaneous transmission SAR measurement is required, the following procedures must be considered for test results, unless further guidance has been provided by the FCC. When supported by the SAR system, the normally required area and zoom scan procedures may be applied to measure the SAR of multiple transmitters transmitting simultaneously and continuously without a duty factor, through the same or different antennas, at different frequencies within the same frequency range of a SAR probe calibration point and tissue-equivalent medium. The peak to average power ratio of the aggregate signal may increase; therefore, when SAR is measured with probes calibrated using CW-equivalent signals higher error can be expected for the simultaneous transmission. Measuring multiple signals within the same probe calibration point frequency range may also require some adjustments and adaptation to establish the measurement parameters on the SAR system; for example, SAR error compensation or tissue dielectric parameter adjustments due to dielectric parameter variations may not be easily applied when the transmission frequency is not specific. When transmitters and antennas transmit simultaneously in multiple frequency bands, and multiple SAR probe calibration points or separate tissue-equivalent media are required for SAR measurements, or due to other measurement constraints such as duty factor issues, the transmitters and antennas must be tested separately according to the different SAR probe calibration points and tissue-equivalent media requirements.

- 1) For transmissions in the same frequency band covered by a single probe calibration point:
  - a) The area scan must include all simultaneously transmitting antennas and radiating structures of the device projected onto the phantom.
  - b) The peak to average power ratio of the aggregate signal, according to 99% CCDF (complementary cumulative distribution function) measurements, must be  $\leq 5$  dB; otherwise, separate enlarged zoom scans are required.
  - c) When the simultaneously transmitted signals are coherent, a KDB inquiry must be submitted to determine SAR measurement requirements, with respect to the transmission configurations and SAR system capabilities.<sup>14</sup>
- 2) For transmissions in different frequency bands covered by multiple probe calibration points or in the same frequency band and cannot be tested simultaneously due to measurement constraints:
  - a) When some of the transmitters and antennas in a device are operating in the same frequency band and covered by the same probe calibration point and tissue-equivalent medium, if appropriate, these may be tested together in an enlarged zoom scan measurement. All other transmitters and antennas in the device that operate in different frequency bands, requiring different probe calibration points or tissue-equivalent media, or in a single frequency band due to measurement

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<sup>14</sup> IEC Technical Report 62630 may be considered when the required SAR measurement and post-processing results are accessible to the end user to perform the required additional analysis. SAR and EMC measurement requirements for coherent or correlated signals are different; therefore, the procedures and definitions should not be applied interchangeably.

constraints, such as duty factor and test setup issues, must be tested in separate enlarged zoom scans. All the enlarged zoom scans are processed, by means of superposition, using the volume scan post-processing procedures to determine the 1-g SAR for the aggregate SAR distribution.

- i) Other than a larger measurement volume to enclose all antennas and radiating structures of the test device, the measurement requirements of an enlarged zoom scan are the same as those required by a normal zoom scan; for example, the measurement resolution. An area scan is not required to identify the peak SAR locations; however, if it is necessary or useful, area scans at the different test frequencies may be performed to estimate the extent of the SAR distributions for the different transmitters and antennas. The information can be analyzed to determine the minimum extent of the enlarged zoom scan(s) required to ensure all peak SAR locations are captured and included in the volume scan post-processing.
  - ii) The volume scan post-processing procedures implemented in different SAR systems or particular versions of a system may vary, which can impose different measurement requirements or restrictions to the enlarged zoom scans; for example, identical measurement and/or post-processing spatial resolutions, requirements of identical or overlapping measurement regions, etc.
    - (1) When identical enlarged zoom scan measurement volumes are required, all simultaneous transmitting antennas and radiating structures must be included in the enlarged zoom scan measurement region projected onto the phantom. For larger devices, it may be necessary to determine the minimum enlarged zoom scan measurement region (see 2) a) i)) by performing area scans to reduce the overall measurement time.
    - (2) When the volume scan post-processing procedures in the SAR system require the same enlarged zoom scan measurement spatial resolution, the most stringent and conservative spatial resolution required for measurement, interpolation and extrapolation must be applied to all the enlarged zoom scans. This generally requires the parameters used for the highest frequency measurements to be applied to all enlarged zoom scans.
    - (3) When overlapping enlarged zoom scan regions or varying measurement, interpolation and extrapolation spatial resolutions are supported or required by the volume scan post-processing procedures of the SAR system, all conditions and restrictions required by the measurement system and post-processing algorithms must be satisfied and fully explained in the SAR report to support the test setup and results.
  - iii) For devices where the peak SAR locations of the simultaneously transmitting antennas are spatially separated and not overlapping, performing enlarged zoom scans can be very time consuming. Area scans may be performed for each required enlarged zoom scan configuration to enable the enlarged zoom scan to be replaced with multiple, smaller and less time-consuming normal zoom scans. The normally required zoom scan measurement procedure is applied to the peak SAR locations identified in each of these area scans. For each normal zoom scan required by the peaks determined in the area scan, the same zoom scan is also performed at the same identical location in the other frequency bands that would have required the enlarged zoom scan. The zoom scans required at each peak SAR location, determined by the individual area scans, for all frequency bands that would have required the enlarged zoom scan are combined by superposition using the volume scan post-processing procedures. The simultaneous transmission 1-g SAR is determined by the highest SAR computed by the volume scan post-processing procedures among the peak SAR locations identified by the area scans.
- b) Contour plots for each enlarged zoom scan and aggregate SAR distribution, determined by the volume scan post-processing procedures, must be included in the SAR report. All plots should be shown according to the interpolated results based on points measured closest to the phantom surface, before extrapolation to the phantom surface. The distance between the measured points

and the phantom surface must satisfy the required SAR measurement protocols in 2.7.1. The measurement setup parameters should be clearly identified in both the SAR plots and reported results.

- c) When applying the volume scan post-processing procedures, it is generally assumed that the RF performance and SAR characteristics of transmitters and antennas remain unchanged for standalone and simultaneously transmitting operations; therefore, the SAR can be tested separately using enlarged zoom scans and analyzed through post-processing procedures, by superposition, to determine the aggregate SAR distribution and 1-g SAR. However, this assumption may not always be true for all transmitters due to various device design and implementation requirements. When it is unclear if the volume scan post-processing procedures can be applied, the transmitter manufacturer must be consulted; a KDB inquiry is also required to determine applicable test alternatives.
- 3) When the measured SAR of a simultaneously transmitting transmitter/antenna in the enlarged zoom scan must be scaled, such as WiMax, specific implementations and other considerations are required for the volume scan post-processing procedures. The entire SAR distribution in the enlarged zoom scan must be scaled before applying the volume scan post-processing procedures to determine the aggregate SAR distribution and 1-g SAR. The scaling must be applied to the measured points in the enlarged zoom scan before interpolation and extrapolation. The same requirements also apply to simultaneous transmissions in the same frequency band when the SAR of at least one of the transmitters/antennas needs scaling; therefore, normal zoom cannot be used. This type of implementation may vary among different SAR systems or unavailable for some systems.<sup>15</sup> When unclear, a KDB inquiry is recommended to confirm that the measurement and scaling procedures are acceptable. The details of the implementation and procedures applied must be clearly described in the SAR report for the test setup and results to be acceptable.

## **2.8. SAR measurement variability and uncertainty**

### **2.8.1. SAR measurement variability**

When the highest measured 1-g SAR within a frequency band is  $< 1.5$  W/kg, the extensive SAR measurement uncertainty analysis described in IEEE Std 1528-2013 is not required in SAR reports submitted for equipment approval.<sup>16</sup> The complexity of the measurement uncertainty analysis has often introduced various difficulties for test labs to fully understand and apply the procedures. Similar concerns have also been observed in the TCB review and approval process. The variations in test results observed in most cases are typically related to the test device and measurement setup issues, and are unrelated to basic measurement uncertainty. To minimize equipment approval concerns especially when the SAR results are near the limit, the following procedures are required for each device to verify these types of SAR measurement related variation concerns by repeating the highest measured SAR configuration in each frequency band, unless further guidance has been provided by the FCC. Until SAR test accreditation considerations and other related concerns can be reviewed and addressed effectively, these simple steps are applied to expedite the TCB review and approval process, and to minimize FCC involvement for case-by-case requests, to address measurement variability related compliance concerns.

SAR measurement variability must be assessed for each frequency band, which is determined by the SAR probe calibration point and tissue-equivalent medium used for the device measurements. When both head and body tissue-equivalent media are required for SAR measurements in a frequency band, the variability measurement procedures should be applied to the tissue medium with the highest measured SAR, using

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<sup>15</sup> This could be a hidden feature implemented for manufacturer convenience and not described in the normal procedures of the SAR system.

<sup>16</sup> It should be clearly explained in the test report when SAR measurement uncertainty analysis is not required but included for other purposes (e.g., ISO/IEC 17025 accreditation).

the highest measured SAR configuration for that tissue-equivalent medium. Alternatively, if the highest measured SAR for both head and body tissue-equivalent media are  $\leq 1.45$  W/kg and the ratio of these highest SAR values, i.e., largest divided by smallest value, is  $\leq 1.10$ , the highest SAR configuration for either head or body tissue-equivalent medium may be used to perform the repeated measurement.<sup>17</sup> These additional measurements are repeated after the completion of all measurements requiring the same head or body tissue-equivalent medium in a frequency band. The test device should be returned to ambient conditions (normal room temperature) with the battery fully charged before it is re-mounted on the device holder for the repeated measurement(s) to minimize any unexpected variations in the repeated results. Manufacturers and test labs would typically have some preliminary SAR results of prototypes tested during product development, which can be used to identify the range of SAR levels expected for the exposure conditions in each tissue-equivalent medium used for compliance testing. Based on typical SAR test experiences, test labs can also estimate the exposure condition expected to result in the highest SAR according to maximum output power, test separation distance and other related parameters. This information can be applied to streamline the required variability measurement(s) for either head or body tissue-equivalent medium at the end of the series of measurements without switching liquids.

Repeated measurements are required only when the measured SAR is  $\geq 0.80$  W/kg.<sup>18</sup> If the measured SAR value of the initial repeated measurement is  $< 1.45$  W/kg with  $\leq 20\%$  variation, only one repeated measurement is required to reaffirm that the results are not expected to have substantial variations, which may introduce significant compliance concerns. A second repeated measurement is required only if the measured result for the initial repeated measurement is within 10% of the SAR limit and vary by more than 20%, which are often related to device and measurement setup difficulties. The following procedures are applied to determine if repeated measurements are required. The same procedures should be adapted for measurements according to extremity and occupational exposure limits by applying a factor of 2.5 for extremity exposure and a factor of 5 for occupational exposure to the corresponding SAR thresholds.<sup>19</sup> The repeated measurement results must be clearly identified in the SAR report. All measured SAR, including the repeated results, must be considered to determine compliance and for reporting according to KDB Publication 690783.

- 1) Repeated measurement is not required when the original highest measured SAR is  $< 0.80$  W/kg; steps 2) through 4) do not apply.<sup>20</sup>
- 2) When the original highest measured SAR is  $\geq 0.80$  W/kg, repeat that measurement once.
- 3) Perform a second repeated measurement only if the ratio of largest to smallest SAR for the original and first repeated measurements is  $> 1.20$  or when the original or repeated measurement is  $\geq 1.45$  W/kg ( $\sim 10\%$  from the 1-g SAR limit).
- 4) Perform a third repeated measurement only if the original, first or second repeated measurement is  $\geq 1.5$  W/kg and the ratio of largest to smallest SAR for the original, first and second repeated measurements is  $> 1.20$ .

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<sup>17</sup> All measured SAR values should be rounded to two decimal digits for comparison with the required thresholds.

<sup>18</sup> The measured SAR results do not have to be scaled to the maximum tune-up tolerance to determine if repeated measurements are required. However, compliance must be determined at the maximum tune-up tolerance limit for all measured results, according to procedures in KDB Publication 447498 D01. The *area scan based 1-g SAR estimation* procedure does not apply; zoom scan is required for repeated measurements.

<sup>19</sup> This also applies to the 10-g SAR required for phablets in KDB Publication 648474.

<sup>20</sup> When the measured SAR is lower than normally expected for the range of output power and test separation distance used in a measurement, such concerns must be addressed separately to ensure the results are valid before determining if repeated measurements are required.

### 2.8.2. SAR measurement uncertainty

SAR measurement uncertainty analysis is required in SAR reports only when the highest measured SAR in a frequency band is  $\geq 1.5$  W/kg for 1-g SAR.<sup>21</sup> The equivalent ratio (1.5/1.6) should be applied to extremity and occupational exposure conditions. The procedures described in IEEE Std 1528-2013 should be applied. The uncertainty analysis must be consistent with the measurement parameters used for the frequency band, including penetration depth, tissue-equivalent medium, probe calibration uncertainty and measurement configurations, etc. The SAR equipment manufacturer may have evaluated some of these uncertainty components according to specific measurement conditions, however, additional analyses may be required for the uncertainty components that are dependent on the operating conditions and test configurations of an individual test device. The expanded SAR measurement uncertainty must be  $\leq 30\%$ , for a confidence interval of  $k = 2$ . For this reason, applicants are encouraged to avoid using any equipment or test procedures with large measurement uncertainties to evaluate SAR compliance.<sup>22</sup>

## 3. SAR System Validation and Verification

### 3.1. General

Before a system is deployed and whenever hardware or software changes are made; for example, through system upgrade, software update or when probes and components are recalibrated, the performance specifications of the SAR system must be validated with respect to the probes and components used by the system before routine measurements. After a system is validated, routine verification of system measurement accuracy is required within the measurement frequency range of each probe calibration point required for testing individual devices.

### 3.2. Reference dipoles

#### 3.2.1. General

Reference dipoles are used for SAR system validation and verification.<sup>23</sup> These are available from SAR system manufacturers for users to confirm measurement accuracy. The dipoles are normally tuned to the frequency and tissue-equivalent media characteristics required for transmitter testing; therefore, different dipoles are required for different SAR probe calibration point frequencies. A dipole is normally tuned to and calibrated at the same frequency as a probe calibration frequency. The calibrated SAR target of a dipole is dependent on the measurement setup; for example, dipole to phantom test separation distance and phantom shell dielectric properties and thickness; therefore, the same test setup used to calibrate the dipole must also be used for SAR system validation and verification.

Dipoles are only defined for selected discrete frequencies in IEEE Std 1528-2013. As additional spectrums are introduced these dipoles have become insufficient for covering new frequencies. In some cases, it may be possible for a dipole to cover an adjacent frequency band without substantial degradation from its tuned conditions due to differences in frequency and tissue dielectric parameter requirements; therefore, establishing a SAR target at an adjacent offset frequency may be acceptable. However, when this is not feasible and dipoles are unavailable, it could be difficult to verify SAR measurement accuracy.

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<sup>21</sup> See footnote 15.

<sup>22</sup> The Commission also applies appropriate measurement uncertainty procedures when testing samples for compliance and comparing measured results to applicable limits.

<sup>23</sup> Other reference sources are also defined in SAR measurement standards at selected frequencies; for example, waveguides and current loop sources. Until the procedures for using these other sources are established a KDB inquiry is required.

When dipoles or other equivalent RF sources are developed by SAR equipment manufacturers for new frequencies, the SAR targets must be validated according to the same vigorous numerical simulation and experimental validation protocols used in developing the target values published in IEEE Std 1528-2013. Detailed documentation, similar to those described in IEEE Std 1528-2013, should be available for each dipole. If unclear, test laboratories using newly developed dipoles or other equivalent sources should submit a KDB inquiry to confirm the validity and acceptance of such reference sources before initial use, especially before testing devices.

### 3.2.2. Dipole calibration

It is necessary to re-calibrate reference dipoles at regular intervals to confirm the electrical specifications and SAR targets. A dipole must be calibrated using a fully validated SAR system according to the tissue dielectric parameters and SAR probe calibration frequency required for device testing. It is generally unacceptable to calibrate a dipole using the SAR system that has been validated by the same dipole; therefore, dipoles should be returned to the SAR system manufacturer or its designated calibration facilities for re-calibration. However, instead of the typical annual calibration recommended by measurement standards, longer calibration intervals of up to three years may be considered when it is demonstrated that the SAR target, impedance and return loss of a dipole have remain stable according to the following requirements.

- 1) The test laboratory must ensure that the required supporting information and documentation are included in the SAR report to qualify for the three-year extended calibration interval; otherwise, the IEEE Std 1528-2013 recommended annual calibration applies.
- 2) Immediate re-calibration is required for the following conditions.
  - a) After a dipole is damaged and properly repaired to meet required specifications.
  - b) When the measured SAR deviates from the calibrated SAR value by more than 10% due to changes in physical, mechanical, electrical or other relevant dipole conditions; i.e., the error is not introduced by incorrect measurement procedures or other issues relating to the SAR measurement system.
  - c) When the most recent return-loss result, measured at least annually, deviates by more than 20% from the previous measurement (i.e. value in dB  $\times$  0.2) or not meeting the required 20 dB minimum return-loss requirement.<sup>24</sup>
  - d) When the most recent measurement of the real or imaginary parts of the impedance, measured at least annually, deviates by more than 5  $\Omega$  from the previous measurement.

Dipoles are often optimized individually by manufacturers to provide the best impedance match (50  $\Omega$ ) and return loss (> 20 dB), according to the tissue and phantom shell dielectric property requirements. This may introduce some small variations between the SAR targets specified in IEEE Std 1528-2013 and the dipole calibration results. Therefore, SAR system validation and verification results must be compared to the SAR calibrated for the individual dipole. The 1-g and 10-g SAR measured with a reference dipole, using the required tissue-equivalent medium at the test frequency, must be within 10% of the manufacturer calibrated dipole SAR target. The extrapolated peak SAR at the phantom surface above the dipole feed-point should be within 15% of that reported in the calibration data or specified in IEEE Std 1528-2013 to confirm that the measured SAR distribution is equivalent to that in the dipole calibration record.

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<sup>24</sup> The 20% ensures there is no substantial change or shifts in the frequency characteristics for the dipole.

### 3.3. SAR system validation

#### 3.3.1. Basic system validation requirements

The SAR system must be validated against its performance specifications before it is deployed. When SAR probes, system components or software are changed, upgraded or recalibrated, these must be validated with the SAR system(s) that operates with such components.<sup>25</sup> Reference dipoles are used with the required tissue-equivalent media for system validation, according to the following procedures. Since SAR probe calibrations are frequency dependent, each probe calibration point must be validated at a frequency within the valid frequency range of the probe calibration point, using the system that normally operates with the probe for routine SAR measurements and according to the required tissue-equivalent media. When SAR probes are used interchangeably among identical SAR systems, after the probe has been fully validated on one system, it should be at least selectively verified on each of the other systems for the least desirable results (worst) obtained using the initial system. Other interchangeable components, such as data acquisition modules that are designed to be interchangeable among specific SAR systems and do not need independent verification may be verified collectively in conjunction with the probe(s) during system validation. When SAR system software is updated or upgraded and there is no change in the hardware and probe or dipole calibrations, the validation should be limited to software operational aspects of the SAR system. While SAR probes and other system components are necessary to perform system validation for software changes, it may not be necessary to re-validate the probes and other hardware components that are not related to the software update. When the same software changes are deployed on identical SAR systems, it is acceptable to validate the updated software on one of the identical SAR systems.

Detailed system validation results must be maintained by each test laboratory, which are normally not required for equipment approval. Only a tabulated summary of the system validation status, according to the validation date(s), measurement frequencies, SAR probes, calibrated signal type(s) and tissue dielectric parameters, is required in the SAR report.<sup>26</sup> However, when questions arise or details are required due to probe conversion linearity or other measurement concerns, the relevant system validation results may be required in SAR reports to support the measurement results for equipment approval; for example, due to new probe designs, the specific signal used to calibrate a probe or evolving wireless technologies, and as required by specific KDB inquiries or *published RF exposure KDB procedures*. For signals with very wide channel bandwidths or devices requiring very wide transmission bands, the validity of a probe calibration point must be confirmed through system validation. When the measurement procedures required for these types of new wireless technologies or signal modulation specific probe calibrations are not established, a KDB inquiry is required to determine the applicable SAR measurement and SAR system validation procedures.<sup>27</sup> SAR systems should be validated according to the following procedures for CW and/or signal modulation specific probe calibrations before using a probe calibration point for routine SAR measurement.

#### 3.3.2. System validation for CW probe calibrations

- 1) SAR is measured within the sensitivity range of the SAR probe and measurement system, with a CW signal fed to a reference dipole, at different power levels, for each probe calibration point. The

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<sup>25</sup> The system validation requirements have not changed; however, system validation has become more involved and time consuming due to the increasing complexity of recent generation wireless technologies, more frequency bands and use of SAR probes on multiple SAR systems. Additional investigations are necessary before the system validation procedures can be further streamlined.

<sup>26</sup> The type of signal(s) used to calibrate a probe should be either CW or a wireless technology specific signal modulation according to 3.3.2 to 3.3.4.

<sup>27</sup> The KDB inquiry also determines if a PAG is required; PAG (Pre-Approval Guidance) procedures are described in KDB Publication 388624.



measured 1-g SAR should correspond to approximately 4.0 W/kg. When extremity SAR applies, 10-g SAR is also determined for the 1-g SAR measurement. When occupational exposure limits apply, measurements of 1-g SAR near 8.0 W/kg, and 10-g extremity SAR near 20.0 W/kg are also required. The measured SAR, when normalized to 1.0 W net power, must be within 10% of the calibrated dipole SAR targets.

- 2) SAR probe linearity may be verified by single point SAR measurements at the peak SAR location determined in step 1), without moving the dipole test setup and with the probe tip positioned at  $\frac{1}{2}$  the probe tip diameter from the phantom surface. A single point SAR measurement is performed at the SAR levels required in step 1) for each applicable 1-g and 10-g SAR general population and occupational exposure condition. For each probe calibration point a linear straight line is established between the origin (0) and this single point SAR with respect to the net power applied to the dipole. Additional single point SAR measurements are performed at approximately 0.2 W/kg, 1.0 W/kg and 2.0 W/kg by adjusting the dipole power accordingly. When necessary, single point SAR measurements at additional SAR levels may be added. Alternatively, 1-g SAR measurements may be considered instead of single point measurements. The maximum deviation of the single point or 1-g SAR results should satisfy the SAR probe linearity and system specifications and must be within 10% of the linear straight line.
- 3) Probe isotropy is verified by positioning the geometric center of the probe sensors at the peak SAR location of the reference dipole, with the probe tip located at  $\frac{1}{2}$  the tip diameter from the phantom surface. The probe is rotated around its axis, at the measurement point, and (single point) SAR is measured at  $15^\circ$  intervals, at a SAR level of approximately 1.6 W/kg. When extremity and occupational exposure limits apply, measurements are required at approximately 4.0 W/kg, 8.0 W/kg and 20.0 W/kg, corresponding to the 1-g and 10-g SAR limits. The maximum deviation from the average of all measured values at each SAR level should satisfy the isotropy specifications of the probe and must be  $\leq \pm 0.25$  dB.<sup>28</sup>

### 3.3.3. Additional system validation for using CW probe calibration with other signal types

Rapid changes in wireless technologies and signal characteristics have introduced SAR probe calibration and measurement concerns that have not been fully addressed by existing SAR measurement standards. When SAR systems and associated probes are used to measure modulated signals with high peak to average power ratios or non-periodic characteristics, similar to those used by recent generation wireless transmitters, additional system validation with respect to the operating characteristics of signal(s) transmitted by test devices is necessary for probes calibrated with CW signals.

- 1) For signals with a periodic duty factor and constant pulse amplitude, such as GMSK in GSM, SAR should be measured at the lowest duty factor required for routine device testing. The dipole should be fed with a pulse modulated CW signal at a power level sufficient to achieve approximately 1.6 W/kg for 1-g SAR; and if extremity limit applies, 4.0 W/kg for 10-g SAR. When occupational exposure limits apply, measurements at power levels to achieve approximately 8.0 W/kg and 20.0 W/kg for 1-g and 10-g SAR, respectively, are required. The measured SAR should be duty factor compensated and normalized to 1.0 W net power, and must be within 10% of the calibrated dipole SAR target.
- 2) For signals with high peak to average power ratios ( $> 5$  dB),<sup>29</sup> such as those used in OFDM or similar systems, the procedures in steps 1) and 2) of 3.3.2 should be repeated using the modulated signal with

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<sup>28</sup> Below 1 GHz, instead of 4.0 W/kg, 8.0 W/kg and 20.0 W/kg, 2.0 W/kg may be used when 10-g general population extremity SAR applies; 4.0 W/kg may be used for 1-g occupational SAR and 10.0 W/kg may be used for 10-g occupational extremity SAR to overcome power amplifier limitations.

<sup>29</sup> For SAR measurement purposes, when unclear, CCDF measurements, with less than 1% of the highest peaks in the waveform unaccounted for, should be used to determine peak to average power ratios. The peak to average power ratios of recent generation 3GPP and 3GPP2 uplink signals are considered to be  $< 5$  dB. OFDM signals in

equivalent modulation characteristics as those required for routine device testing, at the same average power levels required for CW signal. When necessary, single point measurements at more SAR levels should be included to generate a smooth curve sufficient to quantify the probe conversion linearity. The linear straight line used to determine linearity deviations must be based on the average power of the CW signal used in step 2) of 3.3.2. The results should be presented in a plot to identify the linearity error as a function of the CW equivalent power fed to the dipole. A summary of the relevant system validation results or a plot with equivalent information must be included in the SAR report to demonstrate probe conversion linearity.

- a) At higher SAR levels (due to higher power), the SAR error can become quite large and unacceptable; therefore, test devices should be measured at a reduced power and results must be scaled to the corresponding higher power levels to minimize probe linearity error. The acceptable error threshold for using a CW calibrated probe in measurements having different signal characteristics is established by the system validation measurements.
  - b) It must be ensured that the SAR error introduced by probe conversion linearity does not underestimate SAR, which could lead to compliance concerns. When the probe conversion linearity error is  $> 10\%$ , SAR should be tested at a reduced power level for probe conversion linearity error to be less than  $10\%$ . Substantial reduction in output power is not recommended because such conditions may not be representative of the normal operating characteristics of a device near maximum output conditions. A reduced power level with probe conversion linearity error at  $5\%$  to  $10\%$  should be considered.<sup>30</sup>
- 3) When both periodic duty factor and high peak to average power ratio are applicable to a signal, the procedures for other non-CW signal types in steps 1) and 2) of this section must be applied to the probes used with the measurement system for system validation.
  - 4) For signals with non-periodic duty factors, such as in TDD systems, SAR must be measured at a fixed periodic duty factor using the highest duty factor representative of conservative normal use conditions; therefore, the procedures for other non-CW signal types in step 1) of this section should be applied. When high peak to average power ratio also applies, step 2) of this section is also required.

#### 3.3.4. System validation for signal modulation specific probe calibrations

The signals used for system validation of signal modulation specific probe calibrations must have the same peak to average power ratio, RF spectral and CCDF characteristics as the signals required for routine SAR measurements. The test lab must verify that the signal modulation specific calibration is suitable for measuring the signals of a test device for the SAR results to be acceptable.<sup>31</sup> For probes calibrated with both CW and signal specific modulations, unless both types of calibrations are used for routine SAR measurements, system validation is required only for the type of calibrations used in routine measurements. The procedures in 3.3.1/3.3.2 and 3.3.3 should be applied independently to the CW and signal modulation specific probe calibration points required for routine SAR measurements. When both CW and signal modulation specific calibrations are applicable to the same calibration frequency point, system validation of probe isotropy for the CW calibration is sufficient. The maximum deviation for

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802.11a/g/n/ac are considered to be  $> 5$  dB. The peak to average power ratio of LTE-Advanced Enhanced SC-FDMA is higher than 5 dB.

<sup>30</sup> This only applies to the power level used by consumer devices. The maximum output power used for SAR testing must satisfy the requirements in KDB Publication 447498; therefore, testing at substantially reduced power levels would not be acceptable for certain high power transmitters. A KDB inquiry is required to resolve the testing issues.

<sup>31</sup> Until standardized procedures are available to make such determination, the applicability of a signal specific probe calibration for testing specific wireless modes and technologies is determined on a case-by-case basis through KDB inquiries, including SAR system verification requirements.

signal specific calibration should satisfy the SAR probe linearity specified for the SAR system and must be within 10% of the linear straight line.

### **3.4. SAR system verification**

#### **3.4.1. General**

SAR system verification is required to confirm measurement accuracy, according to the tissue dielectric media, probe calibration points and other system operating parameters required for measuring the SAR of a test device. The system verification must be performed for each frequency band and within the valid range of each probe calibration point required for testing the device. The same SAR probe(s) and tissue-equivalent media combinations used with each specific SAR system for system verification must be used for device testing.<sup>32</sup> The signal used for SAR system verification must be consistent with the signal characteristics of the probe calibration point used for device testing.<sup>33</sup> When multiple probe calibration points are required to cover substantially large transmission bands, independent system verifications are required for each probe calibration point. A system verification must be performed before each series of SAR measurements using the same probe calibration point and tissue-equivalent medium. Additional system verification should be considered according to the conditions of the tissue-equivalent medium and measured tissue dielectric parameters. Tissue dielectric parameters are typically re-measured every three to four days or sooner when marginal liquid parameters are used at the beginning of a series of measurements. When tissue dielectric parameters are out of tolerance and adjustment to the liquid is necessary, additional system verification is required.

#### **3.4.2. System verification options**

When products are introduced in new frequency bands, reference dipoles may not be available within the probe calibration or test device frequency range. Sometimes the reference dipole, test device and probe calibration frequencies could be substantially misaligned, hence, SAR measurement accuracy may not be easily confirmed.

At above 1.5 GHz to 2 GHz, the reference dipoles can normally maintain return losses of 15 dB or more for approximately 150 MHz to 200 MHz; therefore, additional calibrations at offset frequencies may provide the necessary SAR target values for system verification at nearby frequencies using an existing dipole.

At lower frequencies, below 2 GHz, depending on the frequency range, return losses of 15 dB or more are typically limited to 15 MHz to 100 MHz for reference dipoles; therefore, it may not be feasible or practical to use the dipole outside its resonance frequency range. However, the impact can be much less if the dipole is used at its resonance frequency with the tissue media intended for the nearby offset frequencies. The changes in tissue dielectric parameters within a frequency range of  $\pm 100$  MHz to 250 MHz are usually within  $\pm 10\%$ . Therefore, it would be more practical to establish a new SAR target by operating the dipole at its tuned frequency, but according to the probe calibration and tissue dielectric medium required for device testing at nearby frequencies. The SAR target determined in this manner is only valid for the particular measurement configuration using the specific dipole, SAR probe and calibration point, tissue medium, and the specific phantom; therefore, this alternative should only be considered as the last resort when no other options are available.

These two system verification alternatives are described in the following and should only be used when a required reference dipole or alternative source (defined by SAR standards) is unavailable. All results and

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<sup>32</sup> See footnote 24 and 25.

<sup>33</sup> See 3.3.1, 3.3.2 and 3.3.3 for CW and signal specific probe calibration. As signal specific probe calibration continues to evolve, a KDB inquiry is required to determine the specific signal and procedures required for SAR system verification.

analyses must be included in the SAR report to justify the use of these system verification alternatives, including dipole return loss plots, probe conversion factors, tissue dielectric parameter measurements, coefficient of variation calculations, etc. The same SAR probe and tissue dielectric media used with the dipole for system verification must also be used for device testing. These *interim* procedures may be performed by the test laboratory. When both alternatives are not applicable, a KDB inquiry is required to resolve the system validation and verification issues, before any device testing, to ensure the measurement results are acceptable.

- 1) Establishing a new SAR target for the dipole at an offset frequency
  - a) The SAR probe must be calibrated at the offset frequency.
  - b) The procedures must be repeated when a dipole is recalibrated to re-establish the SAR target at the offset frequency.
  - c) The dipole must have a return loss of 15 dB or more at the offset frequency.
  - d) The differences in target tissue dielectric parameters between the offset and tuned dipole frequencies must be  $\leq 10\%$ .
  - e) The measured SAR at the offset frequency must be within 15% of the manufacturer calibrated SAR at the dipole's tuned frequency.
  - f) The SAR, on a long term basis including all previous measurements after applying these procedures, should have a coefficient of variation  $< 3\%$ ; that is, the standard deviation divided by the mean is  $< 0.03$ .
- 2) Establishing a new SAR target at the tuned dipole frequency according to the probe calibration and tissue dielectric parameters required at an offset frequency for device testing
  - a) When the conditions required in step 1) to establish a new SAR target for the dipole at an offset frequency can be satisfied, this alternative does not apply.
  - b) The tissue dielectric parameters measured at the tuned dipole frequency must be within  $\pm 10\%$  of those required for device testing at the offset frequencies. This tissue parameter tolerance is expected to support an operating range of  $\pm 120$  MHz to 250 MHz or more above 300 MHz and  $\pm 100$  MHz or more below 300 MHz for the typical tissue-equivalent recipes.
  - c) The SAR probe must be calibrated at the offset (device testing) frequency and the probe conversion factors at the tuned dipole frequency and device testing frequencies must be within 10% of each other.
  - d) The new SAR target determined using the probe calibration and tissue-equivalent medium at the offset frequency must be within 15% of the calibrated SAR target at the tuned dipole frequency.
  - e) The new SAR target must be established using 5 or more measurements, each reconfigured separately, with a coefficient of variation  $< 2\%$ ; that is, standard deviation divided by mean  $< 0.02$ . The coefficient of variation for all subsequent system verifications must be less than 3% and the mean must be within 15% of the original tuned dipole SAR target. All previous system verification data must be applied to compute the coefficient of variation; until the probe or dipole is recalibrated or a different tissue recipe is used, which requires the SAR target for the dipole to be reassessed.
  - f) Continued use of this new SAR target and dipole combination for system verification to support SAR measurements required by similar test devices must use the same SAR probe, same probe calibration point and the same tissue-equivalent medium recipe used to establish the SAR target.

### **3.5. SAR system validation and verification requirements below 300 MHz**

When technical requirements are not established, such as applicable limits and evaluation requirements, the provisions of §§ 1.1307 (c) and (d) are considered. Tissue-equivalent dielectric parameters and SAR measurement requirements are both unavailable below 100 MHz; therefore, special considerations are

required. When SAR evaluation is required for a device to show compliance below 100 MHz, a KDB inquiry is required to determine the acceptable test procedures. When appropriate, SAR simulations may be applied to avoid SAR measurement difficulties. A combination of numerical simulation, analytical or measured field strength results may also be considered for more complex situations, as determined through KDB inquiries.

For SAR measurements in the 100 MHz to 300 MHz range, the 150 MHz shielded current loop defined in on-going IEC 62209-2 draft revisions available from selected SAR system manufacturer(s) should be used for SAR system validation and verification. Until the detailed design criteria and SAR target values are fully documented in subsequent IEC 62209 draft or final revisions, test labs should confirm the SAR target values and required measurement setup configurations through KDB inquiry when a shielded current loop is used for the first time. A KDB inquiry must be submitted to determine if any other alternative techniques may be acceptable.

## Appendix A Tissue Dielectric Parameters

The head and body tissue parameters given in this appendix should be used to measure the SAR of transmitters operating in 100 MHz to 6 GHz frequency range. The tissue dielectric parameters of the tissue medium at the test frequency should be within the tolerance required in this document. The dielectric parameters should be linearly interpolated between the closest pair of target frequencies to determine the applicable dielectric parameters corresponding to the device test frequency.

To maintain consistency in using SAR measurement and computational methods to determine compliance, the homogeneous phantom models used for SAR measurements are also recommended for use in SAR computations. When inhomogeneous models are used to compute SAR, tissue dielectric parameters based on the 4-Cole-Cole equation described by Dr. C. Gabriel may be used. Selected tissue parameters are available at the FCC website: <http://transition.fcc.gov/oet/rfsafety/dielectric.html>.<sup>34</sup>

The head tissue dielectric parameters recommended by IEEE Std 1528-2013 have been incorporated in the following table. These head parameters are derived from planar layer models simulating the highest expected SAR for the dielectric properties and tissue thickness variations in a human head. Other head and body tissue parameters that have not been specified in IEEE Std 1528 are derived from tissue dielectric parameters computed from the 4-Cole-Cole equations described above and extrapolated according to the head parameters specified in IEEE Std 1528.

Target Frequency (MHz)	Head		Body	
	$\epsilon_r$	$\sigma$ (S/m)	$\epsilon_r$	$\sigma$ (S/m)
150	52.3	0.76	61.9	0.80
300	45.3	0.87	58.2	0.92
450	43.5	0.87	56.7	0.94
835	41.5	0.90	55.2	0.97
900	41.5	0.97	55.0	1.05
915	41.5	0.98	55.0	1.06
1450	40.5	1.20	54.0	1.30
1610	40.3	1.29	53.8	1.40
1800 – 2000	40.0	1.40	53.3	1.52
2450	39.2	1.80	52.7	1.95
3000	38.5	2.40	52.0	2.73
5800	35.3	5.27	48.2	6.00

( $\epsilon_r$  = relative permittivity,  $\sigma$  = conductivity and  $\rho = 1000 \text{ kg/m}^3$ )

<sup>34</sup> The tissue dielectric properties provided in this Appendix and at the FCC Web Site are based on the 4-Cole-Cole model described by C. Gabriel, "Compilation of the Dielectric Properties of Body Tissues at RF and Microwave Frequencies," Brooks Air Force Technical Report AL/OE-TR-1996-0037.

## Change Notice

**10/24/2012:** 865664 D01 SAR measurement 100 MHz to 6 GHz v01, replaces the previous document SAR 3 to 6 GHz Rev.

**05/28/2013:** 865664 D01 SAR Measurement 100 MHz to 6 GHz v01r01 replaces the previous document 865664 D01 SAR measurement 100 MHz to 6 GHz v01: Relevant comments for 04/05/2013 draft have been taken into consideration. Imported tissue dielectric parameters from Supplement C.

**12/05/2013:** 865664 D01 SAR Measurement 100 MHz to 6 GHz v01r02 replaces the previous document 865664 D01 SAR measurement 100 MHz to 6 GHz v01r01: Discontinued the interim SAR procedures for below 300 MHz due to availability of current loop for SAR system validation and verification.

**02/07/2014:** 865664 D01 SAR Measurement 100 MHz to 6 GHz v01r03 replaces the previous document 865664 D01 SAR measurement 100 MHz to 6 GHz v01r02: Included information from Supplement C 01-01 on handling of pre-grant and post-grant measurement uncertainty and additional clarification for 150 MHz shielded current loop initial use requirements.

**08/07/2015:** 865664 D01 SAR Measurement 100 MHz to 6 GHz v01r04 replaces 865664 D01 SAR Measurement 100 MHz to 6 GHz v01r03, includes updates to reference latest IEEE Std 1528-2013, replacing PBA with PAG and removing reference to Supplement C.