# ISOTROPY VARIATIONS OF SAR PROBES PRESENTED WITHIN +/- 30 DEGREES TO THE LOCAL FIELD GRADIENT DIRECTIONS

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## Introduction

SAR probes with 3 diode-sensors in an orthogonal arrangement are designed to display an isotropic response when exposed to a uniform field. However, the probes are ordinarily used for measurements in non-uniform fields and isotropy is not assured when the field gradients are significant compared to the dimensions of the tip containing the three orthogonally-arranged dipole sensors.

The uncertainties arising and a new method of correcting for them, were discussed in detail in a previous Indexsar paper [1], IXS0223 (dated 16th May 2003). Another prevalent method of managing the uncertainties arising from field gradient effects is to constrain the probe axis presentation angle to be within 30 degrees to the local normal to the phantom surface.

In this present report, analyses similar to those given earlier [1] are set out for the case where the probe is pointing towards the source to investigate the isotropy control afforded by probe angle restriction schemes.

In the current analysis, the source used will be a balanced dipole aligned along the X-axis of the diagram below. The probe axis is referenced to the normal to the phantom surface (at the bottom) and the source dipole arms are parallel with and below the phantom bottom wall.

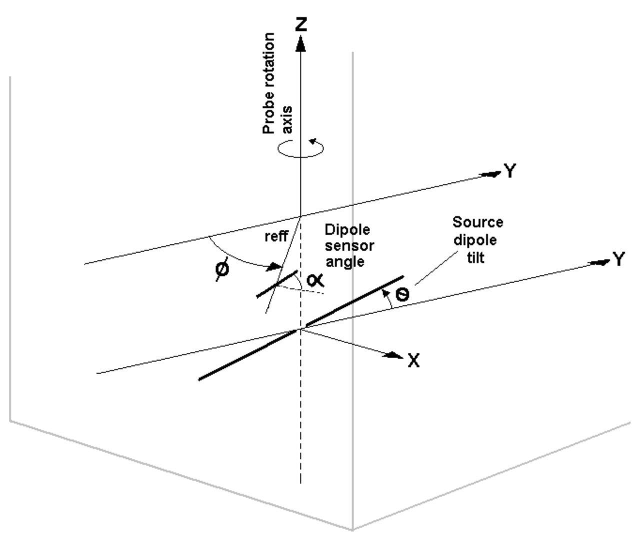


*Figure 1: Coordinate system and angular reference points*

In the Figure 1, θ is the angle of rotation of the source dipole with respect to the Y direction. Φ is the angle between the sensor location and the direction of the source. α is the sensor dipole angle from horizontal (this can be of either sign depending on the probe construction). $r_{eff}$ is the effective sensor radius within the probe tip. Unit direction vectors for the source dipole and for the sensor dipole can be described as below

source dipole unit vector: $X_d = 0$; $Y_d = \cos\theta$; $Z_d = \sin\theta$
sensor dipole unit vector: $X_s = \cos\Phi.\cos\alpha$; $Y_s = \sin\Phi.\cos\alpha$; $Z_s = \sin\alpha$


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The sensor sensitivity is given by the cosine of the angle between them

$$\text{sensor sensitivity} = | X_d\, X_s + Y_d\, Y_s + Z_d\, Z_s |$$

$$= |(0 + \cos\theta.\cos\Phi.\cos\alpha + \sin\theta.\sin\alpha)|$$

where the absolute value is taken since the sensor output is rectified. The magnitude of the local E-field also needs correction for position of the sensor down the field gradient

$$\text{distance correction} = e^{-r_{eff}.dr.\,\sin\theta.\cos\Phi}$$

Where $r_{eff}$ is the effective sensor radius, dr is the attenuation constant (= 1/ skin depth. See definitions in P1528 Section 3) and Φ is the sensor rotation from the source direction. For probe output which is (when linearised) proportional to $E^2$ or SAR,

$$\text{distance correction} = e^{-2.r_{eff}.dr.\,\sin\theta.\cos\Phi}$$

The equations above allow us to calculate the variation of output of a diode sensor, $U_{sensor}$, with probe rotation angle and the angle between the probe axis and the field gradient direction

$$U_{sensor} = U_{centre}\ |(\cos\theta.\cos\Phi.\cos\alpha + \sin\theta.\sin\alpha)|\ e^{-2.r_{eff}.dr.\,\sin\theta.\cos\Phi}$$

where $U_{centre}$ is the value of the field at the centre of the probe tip

This equation can be used three times at angles 2π/3 apart to predict the isotropic response of a 3-channel probe in field gradients of different magnitude as shown in Figure 2.

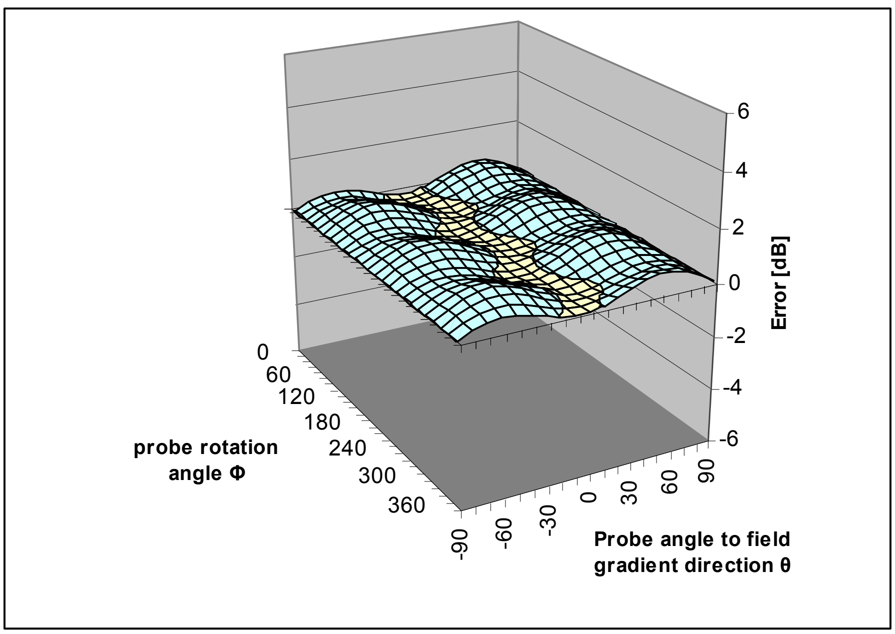


*Figure 2: Predicted isotropic response of 5mm probe with an effective sensor radius of 1.25mm and a sensor angle of 35.3 degrees with the source below the probe. The result shown is for a penetration depth of 9mm corresponding to 2450MHz box testing. The max. spherical isotropy range predicted is + 0.91dB.*


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Figure 2 can be compared with the similar presentation given in [1] for the situation of the source at the side of the probe. This is reproduced as Figure 3.

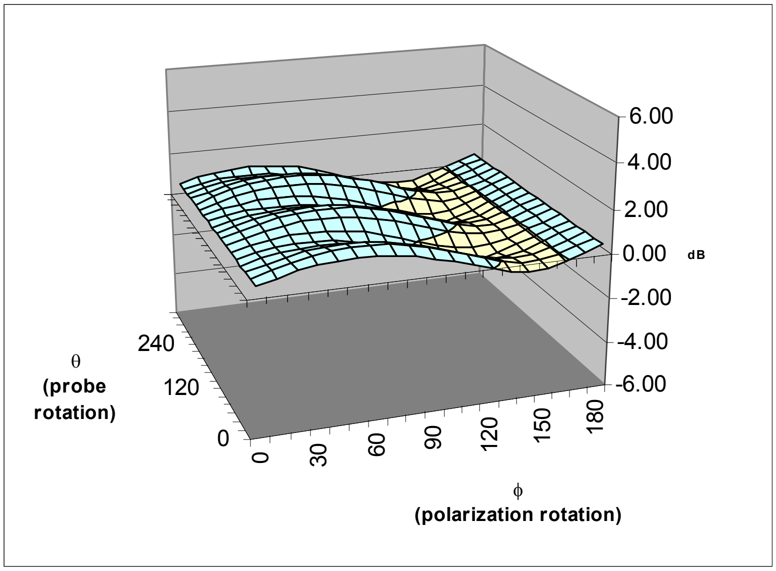


*Figure 3: Predicted isotropic response from [1] of probe with an effective sensor radius of 1.25mm and a sensor angle of 35.3 degrees. The result shown is for a penetration depth of 9mm corresponding to 2450MHz box testing. The probe rotation is offset by 20 degrees to correspond with the measured data. The max. spherical isotropy range predicted is +/- 1.1227dB.*

**Comparison of experimental measurements with the theory**

A measured directivity pattern for a 6.8mm diameter probe is given in [2]. This is reproduced here as Figure 4.

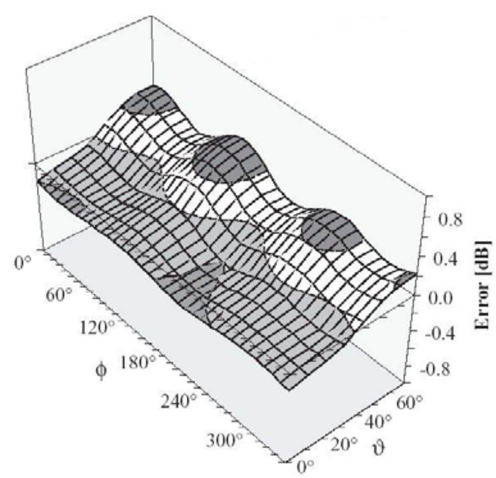


*Figure 4: Measured isotropic response from [2] of a 6.8mm diameter probe in brain tissue simulating liquid at 900MHz. The dipole was positioned normal to the probe axis and then tilted by up to 60 degrees.*

The geometrical theory presented here can be used to make a prediction of the response obtained by Pokovic [2] in Figure 4. Using the same ratio of effective sensor radius to probe diameter, the result obtained is shown in Figure 5.

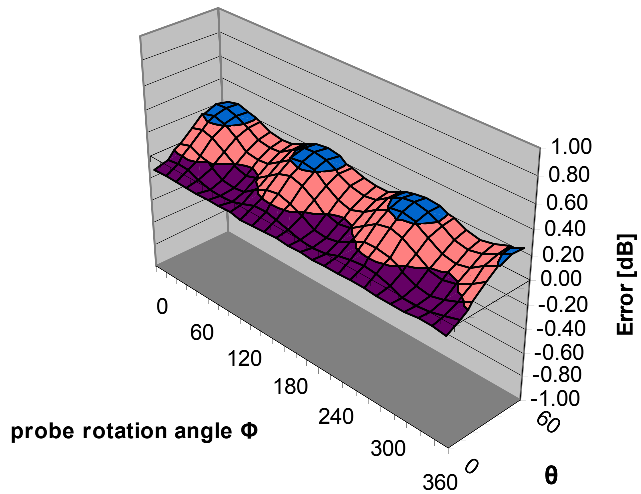


*Figure 5: Theoretical isotropic response of a 6.8mm diameter probe in brain tissue simulating liquid at 900MHz. The dipole is positioned normal to the probe axis and then tilted by up to 60 degrees. The isotropy range from 0 to 60 degrees is 0.39dB.*

Along with the measurements presented in [1], comparison of Figures 4 and 5 leads to the conclusion that the geometrical theory is very capable of predicting probe isotropy in field gradients. The analysis is equally applicable for probes with their axes presented end-on or normal to the field gradient directions.

We can now use the theory to predict the isotropy ranges for different frequencies and the success of angular limitation schemes to limit the uncertainties.

**Table 1: Spherical isotropy range versus frequency for a 6.8mm probe end on to the source direction**

| Frequency (MHz) | Ratio of effective sensor radius to penetration depth of the source decay | Max. anisotropy in field gradient directions -90 to +90 (dB) | Max. anisotropy in field gradient directions -30 to +30 (dB) |
|---|---|---|---|
| 835 | 0.047 | 0.31 | 0.22 |
| 900 | 0.061 | 0.40 | 0.29 |
| 1800 | 0.155 | 1.01 | 0.72 |
| 2000 | 0.170 | 1.10 | 0.79 |
| 2450 | 0.189 | 1.23 | 0.88 |
| 5250 - 5800 | 0.425 | 2.79 | 1.96 |

Computations have been performed using the geometrical model for a 6.8mm probe immersed in liquids at differing frequencies. Compared to Figure 2, the isotropy range rises as the field


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gradients become steeper with frequency. A result equivalent to Figure 2 but for 5GHz is shown as Figure 6.

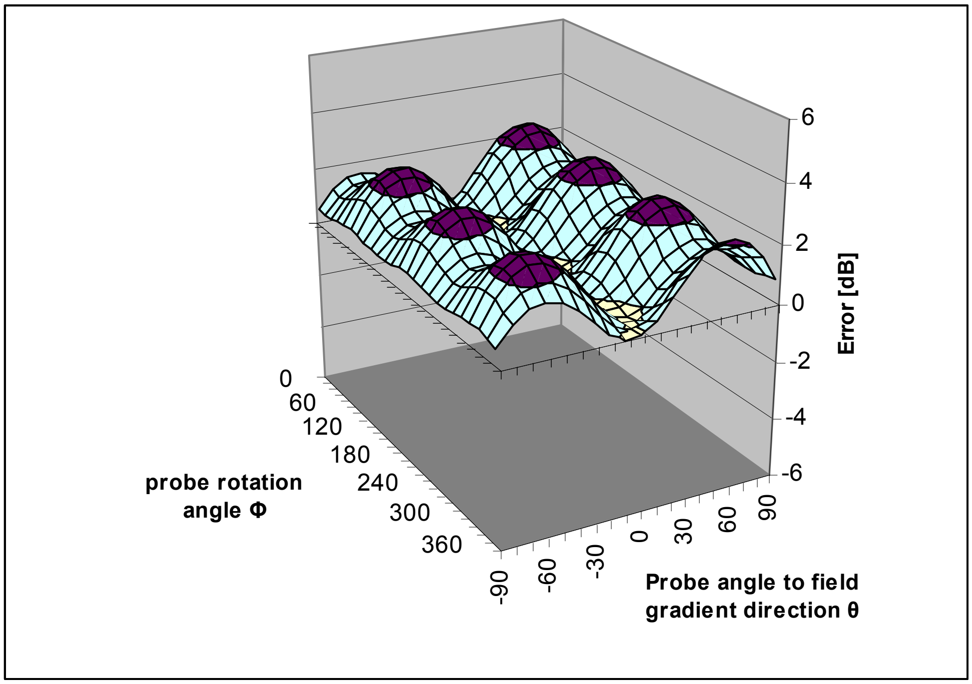


*Figure 6: Predicted isotropic response of 5mm probe with an effective sensor radius of 1.25mm and a sensor angle of 35.3 degrees with the source below the probe. The result shown is for a penetration depth of 4mm corresponding to 5200 MHz box testing. The max. spherical isotropy range predicted is + 2.79dB.*

Table 1 indicates the anticipated isotropy ranges for a probe of 6.8mm diameter immersed in brain liquids appropriate for each frequency as the probe orientation is varied from being normal to the field gradient direction to being inclined at differing angles to the field gradient. This is only equivalent to an angle limitation to the surface normal on the centerline of a symmetrical field distribution having its maximum at a point on the surface.

However, at higher frequencies, significant angles between a probe normal to the surface and the local field gradient will arise. Within a scanned volume, the angles will be greatest when the probe is close to the surface and furthest from the centerline. When scanning with a 6.8mm probe over a 32mm sampling cube, the probe angles to the field gradient could be up to 60 degrees. These will be somewhat less at around 45 degrees within the 1g averaging volume. If you add to this angle the allowance that the probe shaft itself can be within 30 degrees to the surface normal, the range of possible presentation angles between probe and field direction can cover the whole range from 0 to 90 degrees. This means that a 30 degree to the field gradient condition is not assured by maintaining a probe within 30 degrees to the local surface normal and an isotropy reduction cannot easily be claimed for this.

A specific situation in which field gradient will affect the measurements significantly is in the validation of the local at the surface with an offset of 2cm (IEEE 1528 Table 8.1). It is unlikely that this measurement will agree with the reference values within the recommended uncertainty values at higher frequencies.

As indicated in Figures 2, 4 and 5, the variation in probe response for an end-on probe is not distributed on either side of the probe calibration condition, but is all in the same direction. So the


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conclusion is that isotropy error from the calibration condition, if uncorrected, is similar for the two situations where the source is at the side of or underneath the probe.

Without correction, the end-on presentation of the probe characterizes the centerline (maximum) profile arising from most sources in a manner closest to the waveguide calibration geometry. However angular variations from parallelism to the field gradient direction soon build up uncertainties as in Table 1 in a manner dependent on frequency.

In principle, a VPM correction procedure as set out in [1] should correct for all the variation of sensitivity with geometry and is probably the approach with the greatest likelihood of achieving significant uncertainty reductions due to anisotropy at higher test frequencies.

The VPM scheme relies upon the SAR probes having accurate construction in terms of symmetry and of the dipole sensor angle having an effective angle of the correct magnitude. These conditions are met for probes that indicate good isotropy in applications with low field-gradients. The comparison with measurement given above and the additional measurement comparisons given in [1] show that the geometrical theory is successful in predicting the isotropy response for both side and end-on presented sources and, as shown in [1], application of the VPM method removes much of the anisotropy at higher frequencies.

**Conclusions**

A geometrical theory that accounts for the varying sensitivity of the dipole sensors in a SAR probe is successful in explaining the measured isotropic response of such probes in both lateral and end-on field gradients. Consequently, the theory [1] can be applied to measurements to correct for the isotropic variability.

A limitation of +/-30 degrees of the probe presentation to the surface normal does not assure similar angular limitations to the field directions, which is the relevant direction for determining isotropy variations. Variations with angle to the field for a 6.8mm probe have been assessed in this report at different frequencies.

**References**

[1] Manning, MI, 2003, ‘Compensating for the finite size of SAR probes used in electric field gradients’, Indexsar Report IXS0223 dated 16th May 2003.

[2] Pokovic, K. ‘Design and Characterization of E-field probes for lossy media, Dissertation Chapter 3.


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