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UHF RFID tag Delta Radar Cross-Section (ΔRCS) measurement

Proposal for ISO/IEC 18047-6

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1 Abstract

This paper presents a test procedure proposal for delta radar cross-section (ΔRCS) measurement for RFID UHF tags.

2 Introduction

The delta radar cross-section (ΔRCS) of UHF RFID tags shows the difference between the two radar cross-sections in tag return link backscattering for the two modulating states (modulated and non-modulated).

This document presents an experimental method of measuring the delta radar cross-section (ΔRCS) using a vector signal analyzer, based on the measurement of quadrature baseband signals I and Q (in-phase and quadrature). Measurements of I and Q signals allow taking into account the magnitude and the phase of the re-radiated signal from the tag .

Measurements are carried out in an anechoic chamber in bistatic antennas configuration, I and Q signals are measured with and without the tag present in the anechoic chamber that allows measurement of the difference of re-radiated power issued only from the tag, and thus find the ΔRCS.

3 Theory of tag Radar Cross Section

The radar cross-section (RCS) defines the ability of an antenna to backscatter or to re-radiate electromagnetic waves; the RCS is defined by the following formula:

$$P_{re-radiated} = \sigma \cdot S_i$$

Where $P_{re-radiated}$ is the equivalent isotropic power re-radiated by the antenna, σ is the antenna radar cross section in m² and S_i the incident power density on the antenna in (w / m²).

The RCS of an antenna has been expressed by R.B.GREEN as:

$$\sigma = \left(\frac{\lambda^2}{4\pi}\right) G^2 \left|C - \Gamma\right|^2$$

Where

$\Gamma = \frac{Z_c - Z_a^*}{Z_c + Z_a}$ = *Complex reflection coefficient.*

Z_a / Z_c = *Impedance of the antenna / chip.*

G = *Antenna gain.*

λ = *Wavelength.*

C = *Constant.*

There are two components of scattering:

The first being due to the antenna load , this term dependent upon Γ ,called the "antenna mode" ; when conjugate matched $Z_c = Z_a^*$, results in Γ =0 and there is no antenna mode scattering.
The second component of scattering, dependent upon C, is called the "structural mode" and is introduced by the currents induced on the surface of the antenna by the incident filed when the antenna is conjugate-matched, this component solely on the shape and nature of the antenna.

In the case of thin linear dipole antenna (L ≤ λ/2), which is the case with most of UHF RFID tags, the constant C is equal to unity $(C = 1)$, In this case the re-radiation from open-circuited antenna is neglected.
The scattering from this antenna is not zero, since the two wire sections still scatter, but the radar cross-section is relatively very low.

For this particular case the UHF RFID tag antenna can be represented with the Thevenin equivalent circuit below:

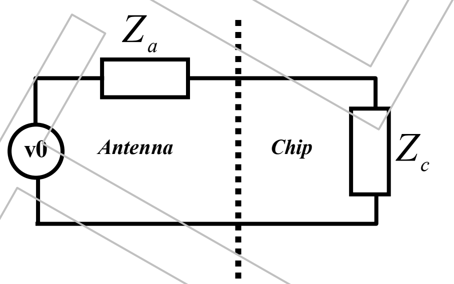

Figure 1: Equivalent circuit of a tag

Where $Z_a = R_a + jX_a$ is the complex antenna impedance and $Z_c = R_c + jX_c$ is the complex chip impedance.

The power P_{ic} available to the tag IC and P_{Ra} dissipated in the radiation resistance of the antenna are given by

$$P_{ic} = i^2 R_c = \frac{v_0^2}{|Z_a + Z_c|^2} R_c \qquad P_{Ra} = i^2 R_a = \frac{v_0^2}{|Z_a + Z_c|^2} R_a$$

Where
P_{ic} = *Power available to the chip (load).*
P_{Ra} = *Power dissipated in the antenna radiation resistance.*
i = *current in the antenna.*
v_0 = *Open-circuit voltage at the antenna terminals.*
Z_a / Z_c = *Impedance of the antenna / chip.*
R_a / R_c = *Resistance of the antenna / chip*

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These two powers expressed using complex reflection coefficient Γ are given by.

$$P_{ic} = \frac{v_0^2}{4R_a}\cdot\left(1-|\Gamma|^2\right) \qquad P_{Ra} = \frac{v_0^2}{4R_a}\cdot|1-\Gamma|^2$$

The power P_{Ra} dissipated in the antenna radiation resistance multiplied by and tag antenna gain, give the equivalent isotopic radiation power , backscattered by the RFID tag.

$$\boxed{P_{re-radiated} = P_{Ra}\cdot G = \frac{v_0^2}{4R_a}\cdot|1-\Gamma|^2\cdot G}$$

The source voltage v_0 is the voltage induced on the open-circuit antenna terminals and it is the result of the scalar product of the incident electric field $\vec{E}$ by the antenna effective length $\vec{l}$.

$$v_0 = \vec{E}.\vec{l}$$

In a far field conditions the module of the incident electric field is given by

$$\left|\vec{E}\right| = \sqrt{S.Z_0}$$

Where S is the incident power density on the antenna which is the Poynting radiation vector as the vector product of E and H, and Z_0 the free space impedance.

And the effective length is given by

$$\left|\vec{l}\right| = 2\sqrt{\frac{\lambda^2}{4\pi}\cdot\frac{R_a G(\theta,\phi)}{Z_0}}$$

Hence,

$$v_0 = \lambda\sqrt{\frac{S.R_a.G(\theta,\phi)}{\pi}}\cdot\left|\vec{\rho}_E.\vec{\rho}_l\right|$$

Where $\left|\vec{\rho}_E.\vec{\rho}_l\right|$ is the scalar product of two polarization unit vectors of the incident electric field and the effective length of the tag antenna.

The value of v_0 *replaced in the equation of* $P_{re-radiated}$ expressed above give

$$\boxed{P_{re-radiated} = \underbrace{\frac{\lambda^2}{4\pi}G^2(\theta,\phi).|1-\Gamma|^2.\left|\vec{\rho}_E.\vec{\rho}_l\right|^2}_{\sigma(RCS)}.S}$$

This value of the radar cross-section based on the Thevenin equivalent circuit agrees with the one expressed by R.B.Green in the case of C=1.

To communicate with the interrogator, the RFID tag modulates its impedance between two states Z_1 and Z_0 (modulated and non-modulated) which in effect create a difference of radar cross section.

Due to the complex form of the antenna radar cross-section the difference between the two radar cross-sections in return link backscattering creates a difference of the re-radiated power level due to the scalar value of radar cross-section, but also a difference in the phase of re-radiated signal.

This result of a backscattered signal which can be modulated with ASK and PSK modulations as shown is the figure 2 below.

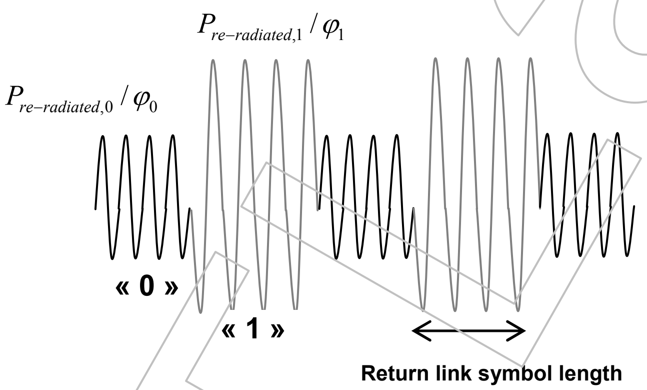


Figure 2 : Re-radiated signal from tag in return link backscattering

The delta radar cross-section is the difference between the two scalar radar cross-sections and it is given by

$$\Delta RCS = |\sigma_1 - \sigma_0| = \sigma_{match} \cdot \left| |1-\Gamma_1|^2 - |1-\Gamma_0|^2 \right|$$

Where $\sigma_{match} = \frac{\lambda^2}{4\pi} G^2(\theta,\phi) \cdot |\vec{\rho}_E . \vec{\rho}_l|$, represents the radar cross section of the tag when loaded by a complex conjugate impedance (Γ =0).

For polarization-matched antennas aligned for maximum directional radiation and reception, σ_{match} can be reduced to $\sigma_{match} = \frac{\lambda^2}{4\pi} G_0^2$.

The figure 3 below shows a 2D curve of the radar cross-section of a tag normalized by the radar cross-section of the same tag when it is complex conjugate matched σ_{match} as a function of the resistances ratio (Rc/Ra) and the reactance ratio (Xc/Xa).

For this example the ratio of antenna reactance to antenna resistance is (Xa/Ra)= -3.

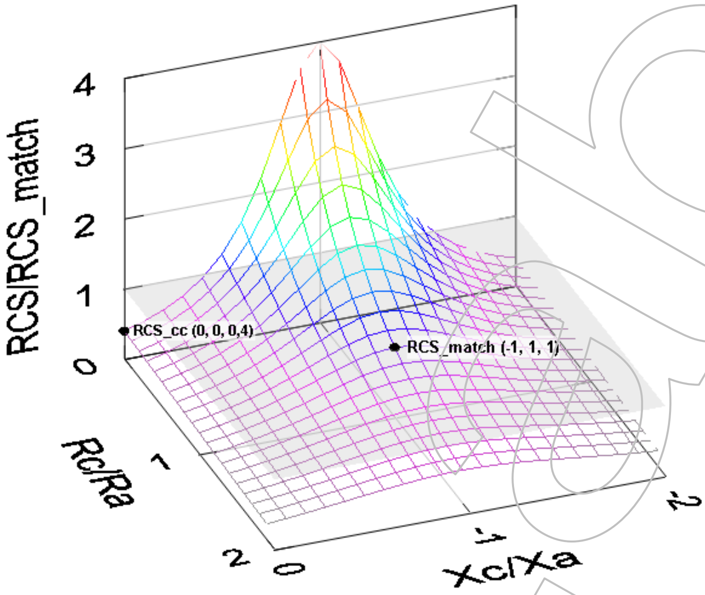


Figure 3 : (RCS/RCSmatch) in function of (Rc/Ra) and (Xc/Xa)

The tag radar cross-section RCS is maximum and equal to 4 * σ_{match} at resonance condition (Xc =-Xa) and when the tag chip resistance is short-circuited Rc=0

When the chip impedance is short-circuited Zc=0 (Rc=0 and Xc=0) the tag RCS is given by

$$\sigma_{short} = \sigma_{match} \cdot \frac{4R_a^2}{R_a^2 + X_a^2}$$

The tag antenna short-circuited will re-radiates less power than complex loaded antenna when ($\left|\frac{X_a}{R_a}\right| > \sqrt{3}$), which is the case with most of UHF RFID tags.

4 ΔRCS measurement methodology:

4.1 Test setup

The delta radar cross-section measurement is carried out using the test setup described in Figure 4 below

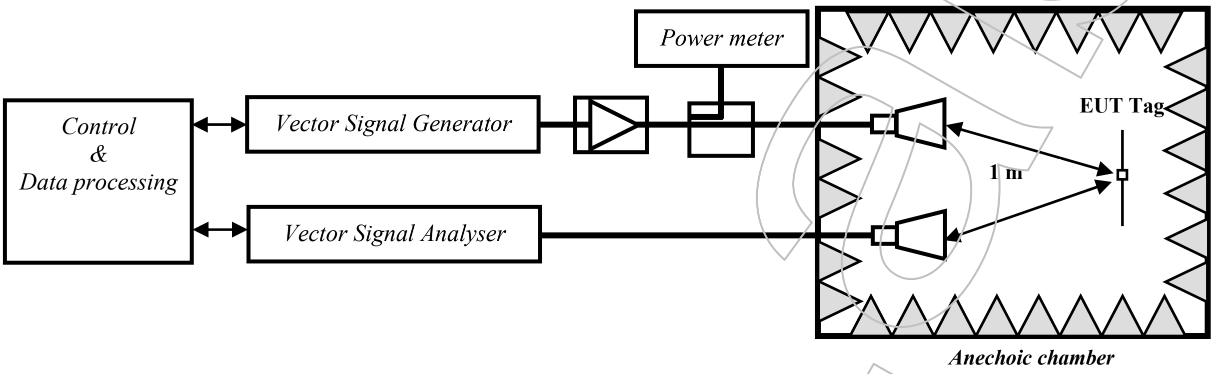


Figure 4 : RFID tag test setup

The test setup include a vector signal generator , a vector signal analyser , an RF amplifer , a directional coupler ,a power meter , and a control and data processing unit.

The measurements are made inside an anecoide chamber in bistatic configuration using two high directivity linearly polarized antennas for RF signals transmition and reception.

The EUT tag is placed at a distance of 1 m from the two test antennas and oriented for maximum reception and re-radiation.

The control and data processing unit is used to drive and configure test equipemt and also to generate protocol baseband commands and analyse EUT tag replys
Baseband commands are transferred to the signal generator where it is modulated , amplified and sent to the EUT tag via transmitting antenna ; in return link the tag reply is collected by the receive antenna and demodulated by the vector signal analyser ,the data are then sent to the control and data processing unit for analysing.

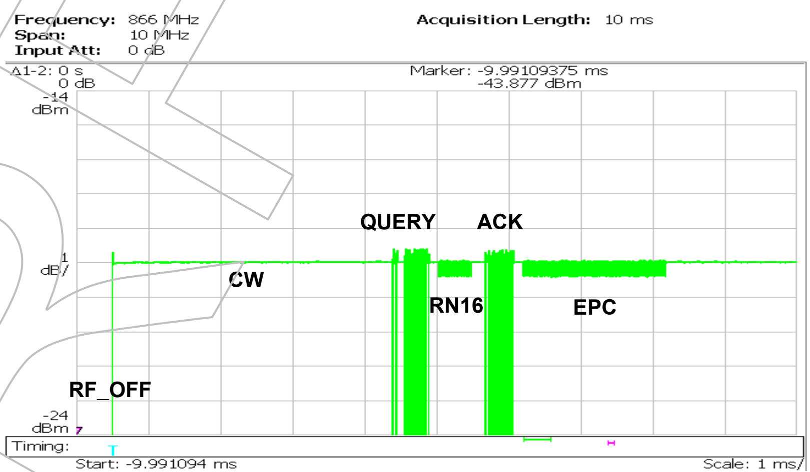


Figure 5 : example of signal generator commands and tag replies demodulated by the signal analyser (ISO 18000-6C)

4.2 Radar equation

The calculation of the radar cross section is made using the radar equation which relates the receive power to the input power, in bistatic antennas configuration is given by

$$\frac{P_r}{P_e} = \sigma \cdot \frac{G_t(\theta_t,\varphi_t)\cdot G_r(\theta_r,\varphi_r)}{4\pi}\cdot\left(\frac{\lambda}{4\pi R_1 R_2}\right)^2 \left|\hat{\rho}_{Tag}\cdot\hat{\rho}_r\right|^2 (1-|\Gamma_t|^2)(1-|\Gamma_r|^2)$$

Where

- σ = *Tag radar cross section (m²).*
- P_r = *Power re-radiated by the tag measured at the receiving antenna (W).*
- P_e = *Power at the entrance of the transmit antenna (W).*
- $G_t(\theta_t,\varphi_t)\,/\,G_r(\theta_r,\varphi_r)$ = *Gain of the transmit antenna / receive.*
- $\hat{\rho}_{Tag}\,/\,\hat{\rho}_r$ = *Vector unit polarization antenna tag / antenna reception.*
- λ = *Wavelength (m).*
- $\Gamma_t\,/\,\Gamma_r$ = *Coefficient reflection of the antenna / reflection.*

For polarization-matched antennas aligned for maximum directional radiation and reception, the radar cross-section is given by

$$\sigma = \frac{P_r}{P_e}\frac{4\pi}{G_{0t}\cdot G_{0r}}\left(\frac{4\pi R_1 R_2}{\lambda}\right)^2$$

In tag return link backscattering the delta radar cross-section is given by

$$\Delta\sigma = |\sigma_1 - \sigma_0| = \frac{\Delta P_r}{P_e}\frac{4\pi}{G_{0t}\cdot G_{0r}}\left(\frac{4\pi R_1 R_2}{\lambda}\right)^2$$

ΔP_r is the difference in power measured at the receiving antenna due to the difference in the power re-radiated by the tag for the two values of RCS.

$$\Delta P_{re-rediated} = |P_{re-radiated,1} - P_{re-radiated,0}| = S_i|\sigma_1 - \sigma_0|$$

In same cases the two scalar radar cross sections can be equal $\Delta RCS = 0$,which result in no difference in the re-radiated power level ($\Delta P_r = 0$), but the tag still backscattering , in this case the information is carried only by the phase of the backscattered signal , which is the case for PSK modulating tags ($\Delta\varphi = \varphi_1 - \varphi_0$).

4.3 Tag re- radiated power ΔP_{tag} measured at receiving antenna

In practice the signal measured at the receive antenna is made up of two signals , the signal (electromagnetic waves) backscattered by the tag and a signal issue from transmitting antenna due to coupling between the two test antennas.

The measured signal is the superposition of the two components as shown in figure 6

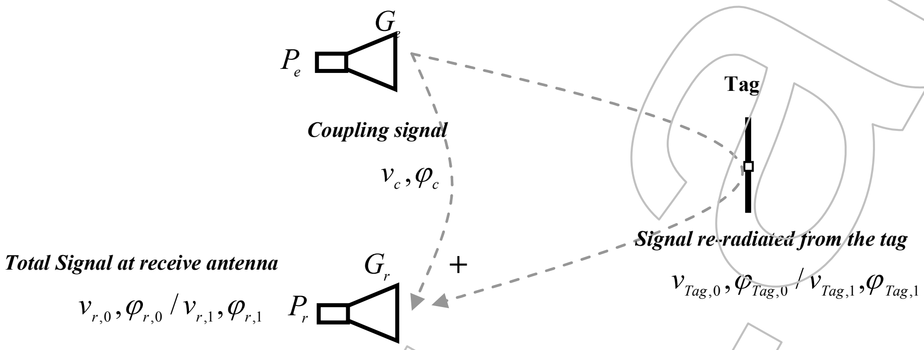


Figure 6 : Total signal measured at receive antenna

The magnitude and phase of the total signal at the receive antenna depend on the magnitude and phase of these two components

The signal collected by the receive antenna has the following form

$$v_{r,0/1}\sin(\omega t+\varphi_{r,0}) = v_{Tag,0/1}\sin(\omega t+\varphi_{Tag,0}) + v_c\sin(\omega t+\varphi_c)$$

The figure 7 below gives the vector representation of the different signals.

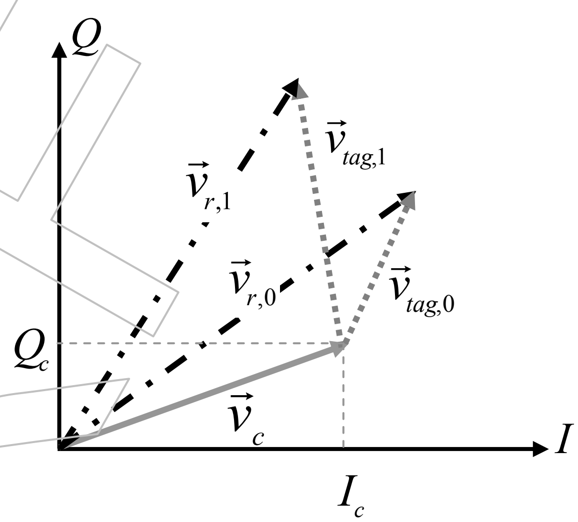


Figure 7 : Vector representation of the signal at receive antenna

The signal measured at receiving antenna represented with the vector $\vec{v}_{r,1/0}$ is the sum of the two vectors $\vec{v}_{tag,1/0}$ and $\vec{v}_c$

$$\vec{v}_{r,1/0} = \vec{v}_c + \vec{v}_{tag,1/0}$$

The measured quadrature baseband Ic and Qc voltages are first measured for empty anechoic chamber without the EUT tag ; the measured values are used as reference and subtracted from the total quadrature baseband Ir and Qr voltages when the EUT tag is present in the anechoic chamber.

From these two measurements and from the vector representation in figure 7 the amplitude of the signals re-radiated from the tag for the two modulation states and measured at receiving antenna are given by

$$\left|v_{tag,1/0}\right| = \sqrt{\left((I_{r,1/0} - I_c)^2 + (Q_{r,1/0} - Q_c)^2\right)}$$

The difference of power and phase of re-radiated signals from the tag measured at the receiving antenna is given by

$$\Delta P_{tag}(rms) = \frac{1}{100} \cdot \left|\left((I_{r,1} - I_c)^2 + (Q_{r,1} - Q_c)^2\right) - \left((I_{r,0} - I_c)^2 + (Q_{r,0} - Q_c)^2\right)\right|$$

And

$$\Delta\varphi_{tag} = Arctg\left(\frac{I_{r,1} - I_c}{Q_{r,1} - Q_c}\right) - Arctg\left(\frac{I_{r,0} - I_c}{Q_{r,0} - Q_c}\right)$$

Where

I_c, Q_c = *Quadrature baseband voltage measured without the EUT tag in empty anechoic chamber*

$I_{r,1}, Q_{r,1}$ = *Quadrature baseband voltage of modulated state measured in tag reply*

$I_{r,0}, Q_{r,0}$ = *Quadrature baseband voltage of non modulated state measured in tag reply*

The figure 8 below shows the EUT tag reply quarature baseband voltages measured at the vector signal analyser.

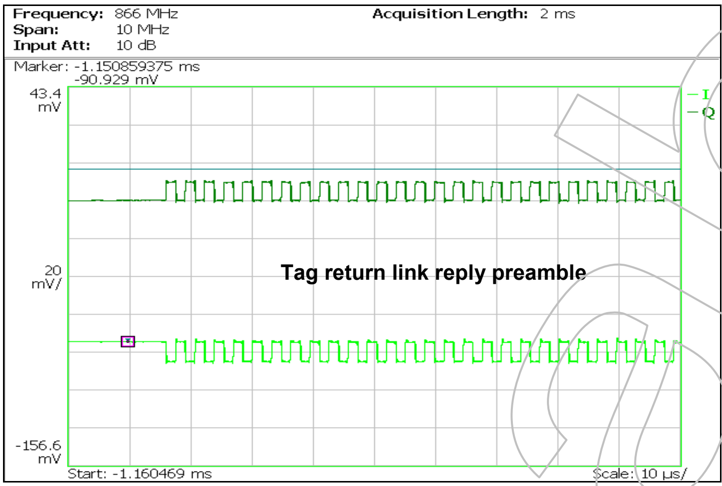


Figure 8 : Quadrature baseband I and Q voltages of tag return link backscattering

4.4 Measurement procedure

Delta radar cross-section measurement procedure:

1) The signal generator shall be set to the required test frequency.

1) The signal generator amplitude shall be set to a value that allows the EUT tag activation..

2) Using the power meter determine the power at the entrance of the transmit antenna **Pe** , which is defined as the average power measured over at least 100µs period during the continues waves signal following the signal generator command .

3) The signal analyser shall be set to measure the quadrature baseband I and Q voltages versus time, with a sampling rate of at least 5Msps.

4) Without the tag placed in the anechoic chamber, the signal analyser shall be set to capture at least 100µs period of I and Q samples at the continues wave just following the signal generator command, determine the Ic and Qc voltages levels.

5) With the tag now placed in the anechoic chamber , the analyser shall be set to capture I and Q voltage samples at least during 10 symbols of tag reply , determine the I and Q voltages corresponding to the two modulation states of tag ($I_{r,0}/Q_{r,0}$) and ($I_{r,1}/Q_{r,1}$). (as shown in figure 8).

6) Measure the difference of power issue from the EUT tag backscattering according the equation below

$$\Delta P_{tag}(rms) = \frac{1}{100} \cdot \left| \left((I_{r,1} - I_c)^2 + (Q_{r,1} - Q_c)^2 \right) - \left((I_{r,0} - I_c)^2 + (Q_{r,0} - Q_c)^2 \right) \right|$$

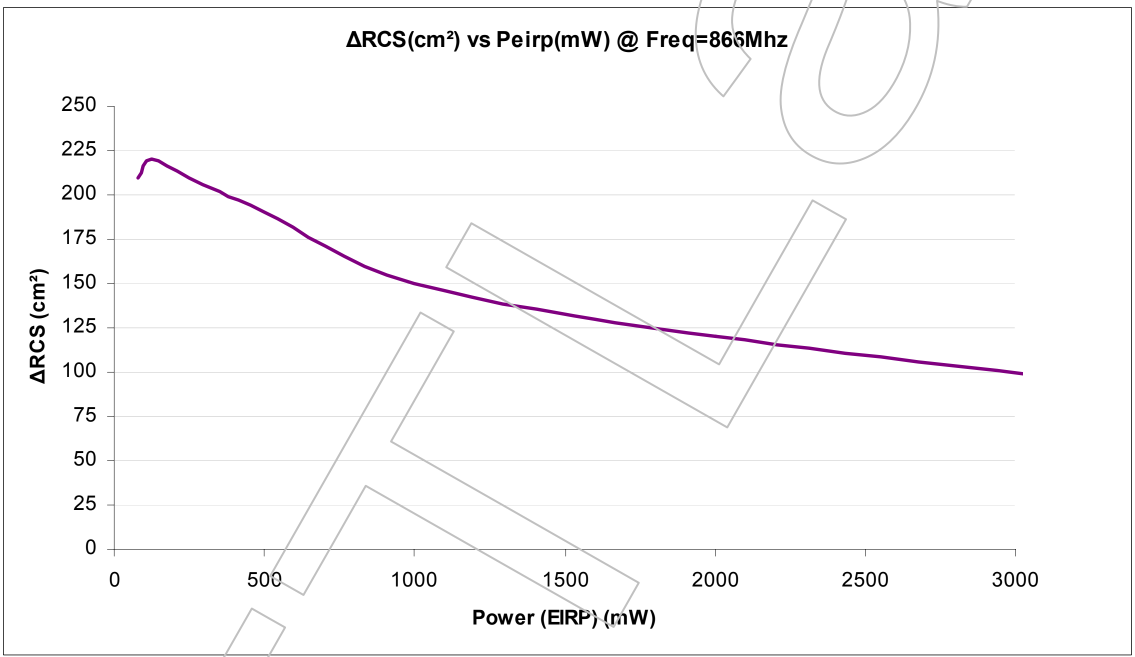
7) Define the ΔRCS of the EUT tag using the radar equation given below

$$\Delta\sigma = \left|\sigma_1 - \sigma_0\right| = \frac{\Delta P_{tag}}{P_e}\,\frac{4\pi}{G_{0t}\cdot G_{0r}}\left(\frac{4\pi}{\lambda}\right)^2$$

(Test setup shall be calibrated to determine antennas gain and mismatch and also cables loss, to be taking into account for power measurements).

4.5 Measurement results:

The curve below shows the measurement of delta radar cross-section of an ISO 18000-6C tag versus Peirp.



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