LF-LF Demonstration System Calculations

With Ferrite Base Station Antenna

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1 Purpose

This document describes the calculations for the **LF-LF Demonstration System,** consisting of:

- **RI-ACC-ADR2** Reader (Base Station) including the TMS3705A [1] and the UCC27424 driver [2]
- **10cm ferrite coil a**ntenna of the 12cm Transponder (50017-A-00)
- LF-LF Dual Antenna Demonstration Board with **TMS37F128** [3]
- **NEOSID 3 x 4.7mH** Transponder receive antenna
- **NEOSID 3 x 2.47mH** Transponder transmit antenna

2 Scope

This information contains TI Internal Data classified information and is intended for the development team and its management on a strict need-to-know base only. Prior to distribution of classified information as contained in this specification to other parts of the organization or under NDA to external persons or companies, approval of the Engineering Manager is required.

3 References

[1] TMS3705A Transponder Base Station IC Rev. 1.1(01/03)

[2] MOSFET Driver Data Sheet UCC27424D

[3] CRAID – TMS37F128 Reference Guide, 11-07-21-003

4 Responsibilities

The Engineering Manager or his designee is responsible to maintain this document.

4.1 Base Station Calculations

4.1.1 Base Station Parameters

The Base Station (RI-ACC-ADR2) using the ASIC TMS3705A [1], is typically equipped with a small 440µH air coil antenna, must be changed to either a bigger 2.5mH air coil or ferrite antenna, to achieve a one meter communication distance. In the calculation example a 10cm ferrite coil antenna (50017-A-00) is used, with the following typical parameters (see Table 1):

PARAMETER	ABBREVIATION	VALUE	UNIT
Length of Antenna Rod	lrant	0.1	m
Radius of Antenna Rod	rrant	0.0039	m
Length of Coil	lcant	0.015	m
Inductance	Ltx	2.54	mH
Turns	Ntx	163	
Nominal Receive Resonance Frequency	f0	127.25	kHz
Antenna Quality Factor	Qant	194	
Receiver input Resistance	Rin	47	kOhm
Supply Voltage (due to serial diode)	Usup	12 (11.3)	V
Full Bridge Drain Source Receive Resistance [2]	Rdson	2 x 2.6= 5.2	Ohm
Full Bridge Drain Source Transmit Resistance [2]	RdsonTX	18+ 2.6= 20.6	Ohm
Filter resistors	Rs	2 x 4.7= 9.4	Ohm

Table 1: Parameters of Base Station RI-ACC-ADR2 with 10 cm Ferrite Coil

4.1.2 Determination of Receive Quality Factor

The minimum required bandwidth to receive the two FSK-frequencies is,

$$fL - fH = 133.3 - 121.2 = 12.1kHz$$

And the nominal receive resonance frequency is,

$$f0 = \frac{(fL + fH)}{2} = 127.25kHz$$

The receive Quality factor should, therefore, be,

$$QRX = \frac{f0}{fbw} = \frac{127.25k}{12.1k} = 10.5$$

The desired Receive Resistance is, therefore,

$$RRX = \frac{2 \cdot \pi \cdot f0 \cdot Ltx}{QRX} = \frac{2 \cdot \pi \cdot 127250 \cdot 0.00254}{10.5} = 193\Omega$$

The Receive Resistance, RRX, is the sum of internal and external resistances such as:

- Driver Stage On-resistance (Rdson= RonN1 + RonN2)
- Filter Resistors (Rs= Rs1 + Rs2)
- Antenna Resistance (Rant)
- Antenna Damping Resistor (Rdmp)
- Receiver Input Resistance (Rin)

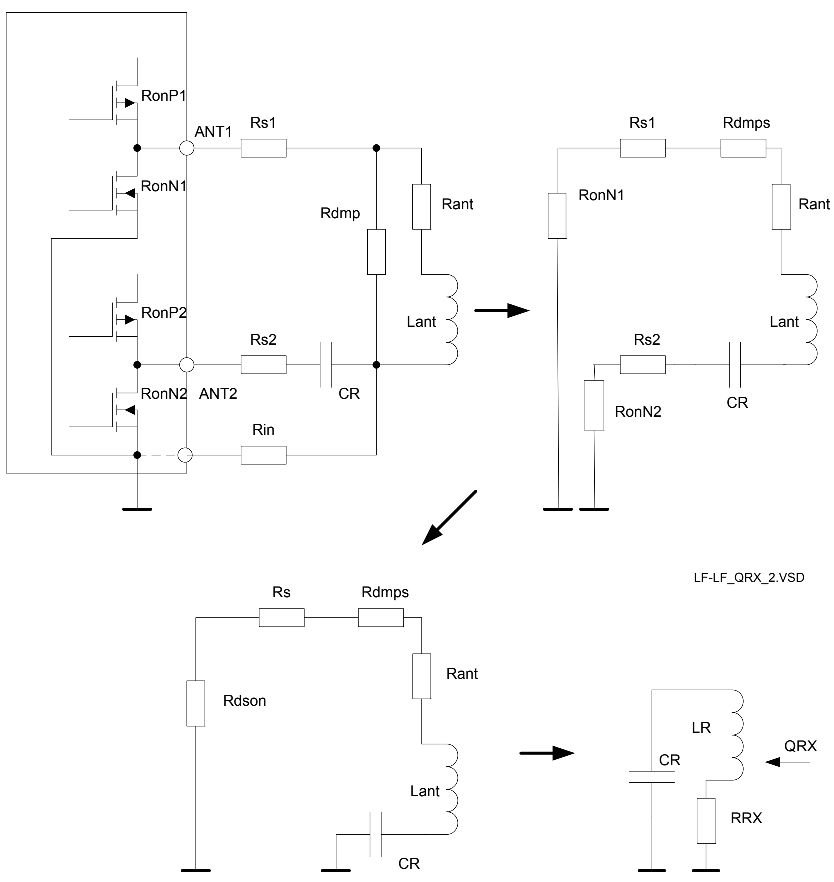

Figure 1: Determination of Receive Quality Factor

The antenna resistance (Rant) is calculated for given antenna quality factor (Qant) and antenna inductance (Lant):

$$Rant = \frac{2 \cdot \pi \cdot f0 \cdot Lant}{Qant} = \frac{2030.8}{194} = 10.5\Omega$$

The required total series damping resistor is, therefore,

$$Rdmps = RRX - Rdson - Rs - Rant = 193 - 5.2 - 9.4 - 10.5 = 167.9\Omega$$

The maximum equivalent total parallel resistance to the antenna (Rp) is,

$$Rp = \frac{(2 \cdot \pi \cdot f0 \cdot Lant)^2}{Rdmps} = 24.5k\Omega$$

And the resulting damping resistor is,

$$Rdmp = \frac{1}{\left(\frac{1}{Rp} - \frac{1}{Rin}\right)} = \frac{1}{\left(\frac{1}{24.5k} - \frac{1}{47k}\right)} = 51.4k\Omega$$

The next lower value is selected:

$Rdmp = 47k\Omega$ (The physical resistor in parallel with the coil)

We now need to solve the above equations in reverse to obtain the actual receive quality factor, QRX.

The actual parallel resistance is, therefore,

$$Rp = \frac{1}{\left(\frac{1}{Rdmp} + \frac{1}{Rin}\right)} = \frac{1}{\left(\frac{1}{47k} + \frac{1}{47k}\right)} = 23.5k\Omega$$

$$Rdmps = \frac{(2 \cdot \pi \cdot f0 \cdot Lant)^2}{Rp} = 175.5\Omega$$

The total receive resistance (RRX) is, therefore,

$$RRX = Rdson + Rs + Rdmps + Rant = 5.2 + 9.4 + 175.5 + 10.5 = 200.6\Omega$$

And the actual receive quality factor is,

$$QRX = \frac{2 \cdot \pi \cdot f0 \cdot Lant}{RRX} = 10.1$$

4.1.3 Determination of Antenna Current

Due to the characteristics of UCC driver, the transmit quality factor (QTX) is slightly lower than the receive quality factor (QRX). The full-bridge drain-source resistance (RdsonTX) includes the P-channel and N-channel Rdson and the influence of the bipolar transistors, parallel to the MOSFET drivers; therefore, the transmit resistance is,

$$RTX = RdsonTX + Rs + Rdmps + Rant = 216\Omega$$

The maximum theoretical antenna peak current is the quotient of supply voltage and RTX,

$$Itx[p] = \frac{V\sup}{RTX} \cdot \frac{4}{\pi} = 70.8mAp$$

Remark: The serial diode in the supply path must in this case be short circuit or compensated by higher input voltage.

The maximum theoretical peak-to-peak antenna voltage, Utxmax[Vpp], at resonance is,

$$Utx\max[Vpp] = Itx[p] \cdot 2 \cdot \sqrt{\left(Rant^2 + \left(2 \cdot \pi \cdot f0 \cdot Lant\right)^2\right)} = 287.4V$$

As the TMS3705A driver has a duty cycle of 80 / 20%, a factor of 0.8 must be taken into account for calculation of the peak-to-peak antenna voltage (Utx) and RMS antenna current (Itx),

$$Utx[Vpp] = Utx\max \cdot 0.8 = 229.9V$$

Because the transmit frequency is 134.45 kHz, the amplitude is typically damped by approximately 3dB due to the resonant circuit bandwidth. Including the serial diode, the real maximum antenna voltage of the demonstration system will be less than 200Vpp (~160V).

Important Note: Nevertheless, the resonance capacitor must still have a rated voltage of at least 250V!

The maximum theoretical RMS antenna current, required for the field strength calculation is,

$$Itx = \frac{Itx[p]}{\sqrt{2}} \cdot 0.8 = 40mA$$

4.1.4 Field Strength Calculation

The transmit antenna rod permeability (µrodant) can be determined using the chart shown in Figure 2, after calculation of the length-of-rod (lrant) to rod diameter (2 x rrant) ratio:

$$lrant/(2 \times rrant) = \frac{0.1}{2 \cdot 0.0039} = 12.82$$

If the rod permeability is above µ = 2000, then the following formula can be used:

$$\mu rodant = 10^{(\log(lrant/2 \cdot rrant) \cdot 1.371926 + 0.441693)} = 91.5$$

In Figure 2 below, the vertical axis is the effective rod permeability, µrodant (μ_{rod} in the graph). The family of curves represents different material permeabilities, µ.

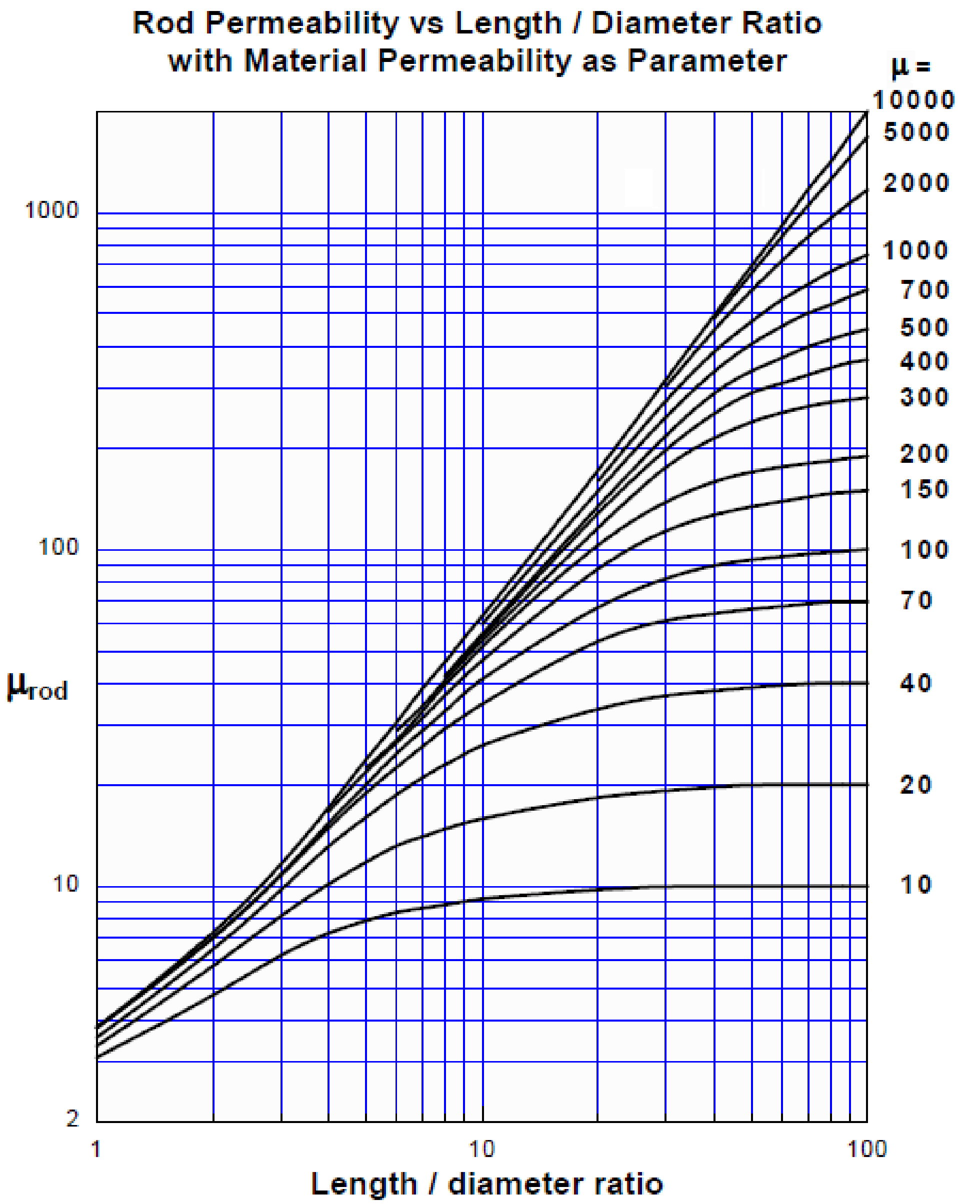

Figure 2: Determination of Rod Permeability

The empirical factor (Fvant) can be determined using Figure 3 after calculation of the length-of-coil (lcant) to length-of-rod (lrant) ratio:

$$\frac{lcant}{lrant} = 0.15$$

$$Fvant = 0.994$$

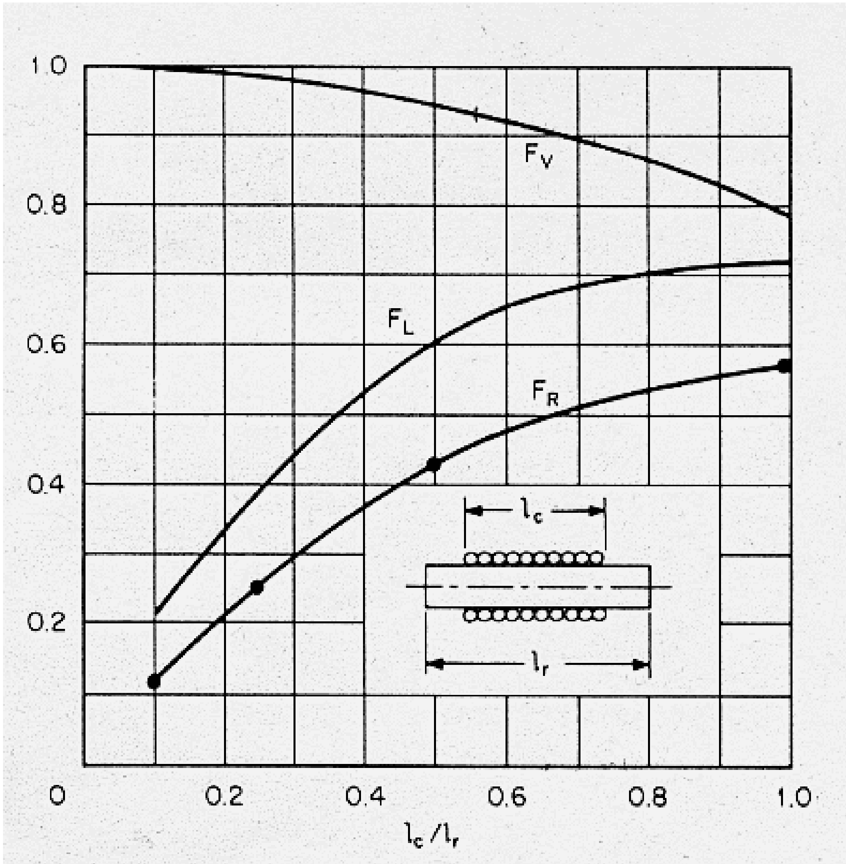

Figure 3: Empirical Factors Fv (or Fvant) and Fl as function of lc/lr

The effective antenna radius (rtx) depends on the radius of the antenna rod (rrant), the rod permeability (µrodant) and an empirical factor (Fvant):

$$rtx = rrant \cdot \sqrt{\mu rodant \cdot Fvant} = 0.0372m$$

The field strength, H, generated by the Base Station at distance, d, in case of a certain antenna current, Itx, is then calculated to be,

$$H[d] = \frac{Ntx \cdot rtx^2 \cdot Itx}{2 \cdot \left(d^2 + rtx^2\right)^{1.5}} \text{ , [A/m]}$$

Where Ntx = 163 is the number of turns of the antenna coil from Table 1.

$$H[dB\mu V/m] = 20 \cdot \log\left(H[A/m] \cdot 10^6\right) + 51.5$$

And 51.5 is the conversion factor from amps to volts in an air medium ($Z_{air} = 377\Omega$)

In Figure 4 the typical calculated field strength over distance, H[d], is shown.

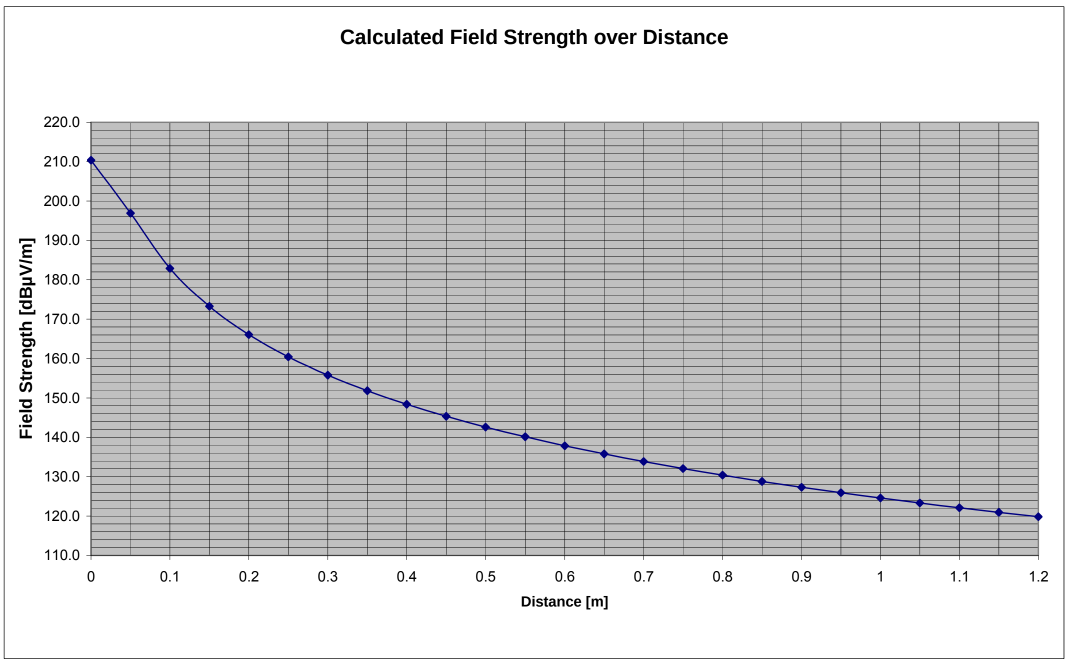

Figure 4: Calculated Base Station Field Strength over distance

4.2 Transponder Parameter

4.2.1 Transponder Receive Antenna

The Transponder receive antenna of the demonstration system is a three-dimensional block shape antenna from NEOSID. Because the inductance of all three coils is equal, the Z-axis typically has higher sensitivity; therefore, the X-axis is calculated here as an example.

4.2.1.1 Receive Antenna Parameter

The X-axis has the following typical parameters, which are known from the antenna data sheet, measured at device, or calculated out of known parameters (see Table 2):

X-AXIS PARAMETER	ABBREVIATION	VALUE	UNIT
Inductance	Ltrp	4.7	mH
Typical Transp. Quality Factor	Qtrp	20	
Coil Sensitivity Specification	S	0.12	V/A/m
Magnetic Field Constant	µ0	$1.25664 \cdot 10^{-6}$	Vs/Am
Material Permeability (assumed)	µ	2000	
Length of Rod (measured)	lr	0.0154	m
Width of Rod (measured)	ar	0.0145	m
Thickness of Rod (measured)	br	0.0031	m
Effective Radius of Rod (calculated)	rr	0.003783	m
Length to Diameter Ratio (calculated)	lr/2rr	2.0356	
Rod Permeability (calculated)	µrod	7.3	
Length of coil to length of rod (calculated)	lc/lr	0.45	
Empirical Factor (Fv=f(lc/lr)	Fv	0.95	
Empirical Factor (Fl=f(lc/lr)	Fl	0.56	
Area of Loop (calculated)	Atrp	$4.495 \cdot 10^{-5}$	m^2
Turns (calculated)	Ntrp	377	

Table 2: Typical Parameter of 4.7mH NEOSID 3D Transponder Antenna

As the formulas are for a cylindrical coil, an effective coil radius (rr) and effective coil area (Atrp) are calculated from the rectangular dimensions,

$$rr = \sqrt{\frac{ar \cdot br}{\pi}} = \sqrt{\frac{0.0145 \cdot 0.0031}{\pi}} = 0.003783m$$

$$Atrp = rr^2 \cdot \pi = 4.495 \cdot 10^{-5} m^2$$

4.2.1.2 Antenna Open Circuit Voltage Based on Antenna Parameters

If the antenna is exposed to a certain field strength (B), the sole, unloaded antenna will show an open circuit voltage (Utrp), which depends on,

- Magnetic field constant (µ0)
- Rod permeability (µrod),
- Effective coil area (Atrp)
- Number of windings (Ntrp)
- Empirical factor (Fv)

$$Utrp = 2 \cdot \pi \cdot f0 \cdot \mu0 \cdot \mu rod \cdot Fv \cdot Ntrp \cdot Atrp \cdot B$$

For rod permeability (µrod), the length-of-rod (lr) to rod diameter (2rr) ratio is required (see Figure 2):

$$lr/2rr = \frac{0.0154}{2 \cdot 0.00378} = 2.0356$$

$$\mu rod = 10^{(\log(\frac{lr}{2 \cdot rr}) \cdot 1.371926 + 0.441693)} = 7.3$$

4.2.1.3 Empirical Factor for Voltage Calculation (Fv)

The empirical factor (Fv) depends on the ratio of length-of-coil (lc) to length-of-rod (lr) and can be determined using Figure 3,

$$\frac{lc}{lr} = 0.45$$

$$Fv = 0.95$$

4.2.1.4 Empirical Factor for Inductance Calculation (Fl)

The empirical factor (Fl) depends on the ratio of length-of-coil (lc) to length-of-rod (lr) and can be determined using Figure 3.

$$\frac{lc}{lr} = 0.45$$

$$Fl = 0.56$$

4.2.1.5 Calculation of Windings

Because the number of windings (Ntrp) is not given for the NEOSID antenna, it must be determined from known and measured parameters,

$$Ntrp = \sqrt{\frac{Ltrp \cdot lc}{\mu 0 \cdot \mu rod \cdot Atrp \cdot Fl}} = 377$$

4.2.1.6 Inductance Control Calculation

To check if the calculated number of windings is valid, the following formula for inductance can be used,

$$Ltrp = \frac{\mu 0 \cdot \mu rod \cdot Fl \cdot Atrp \cdot Ntrp^2}{lc} = 4.7089 mH$$

4.2.1.7 Open Circuit Voltage Based on Coil Parameters

At a distance of 1.1m the calculation showed a field strength of B = 0.00339A/m. The calculation of open circuit voltage results in Utrp = 40.2mV.

4.2.1.8 Open Circuit Voltage Based on Coil Sensitivity Specification

In order to check the calculation result based on antenna parameters, the sensitivity (S = 0.12 V/A/m) specification of the NEOSID antenna can be used as follows,

$$Utrp = S \cdot B = 40.6 mV$$

4.2.1.9 Coupling between Base Station and Receive Transponder Antenna

The coupling factor (K) over distance (d) between the Base Station and the receive Transponder antenna is calculated by the following formula:

$$K = \frac{\mu 0 \cdot (\mu rod \cdot Fv \cdot Atrp \cdot Ntrp) \cdot (rtx^2 \cdot Ntx)}{2 \cdot \left(d^2 + rtx^2\right)^{1.5} \cdot \sqrt{Ltx \cdot Ltrp}}$$

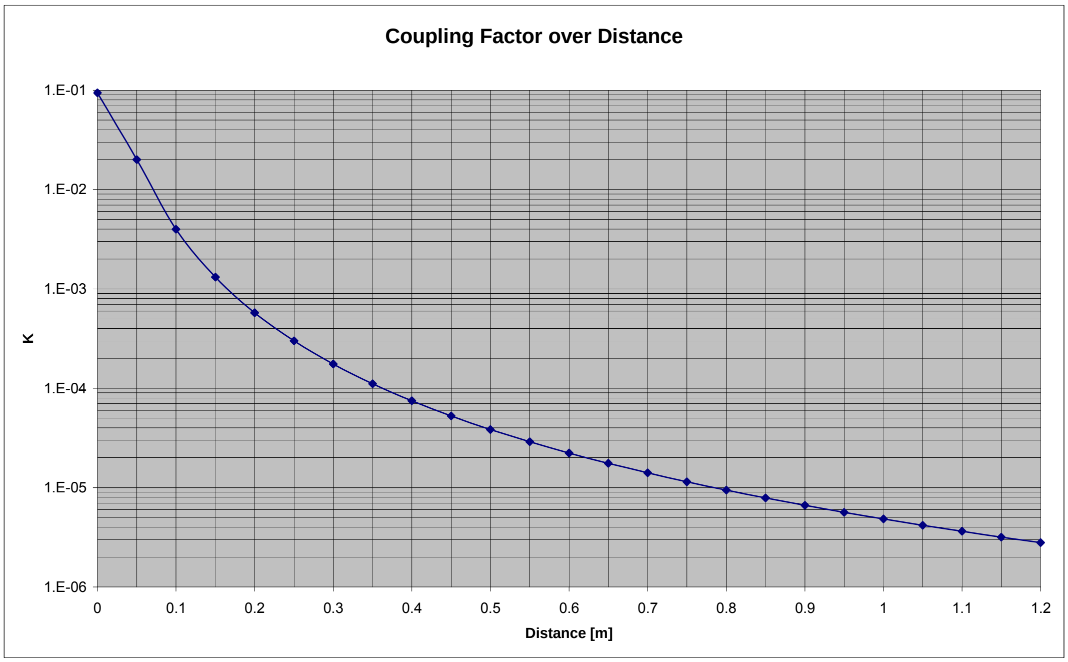

Figure 5: Coupling Factor vs. Distance

4.2.1.10 RF Input Peak-to-Peak Voltage

The effective equivalent voltage source (Ureff) of the system arrangement is calculated by,

$$Ureff = 2 \cdot \pi \cdot f0 \cdot Qtrp \cdot I \cdot K \cdot \sqrt{Ltrp \cdot Lant}$$

The effective equivalent voltage source in a distance of d= 1.1m is Ureff= 8mV

The equivalent source resistance (Req) is calculated by,

$$\mathrm{Re}q = 2 \cdot \pi \cdot f0 \cdot Ltrp \cdot Qtrp = 75.16k\Omega$$

Together with the input resistance for small input voltages of the IC (Ri = 1.2MΩ), the RF input peak-to-peak voltage (VRFpp) at the identification device input can be calculated as,

$$VRFpp = \frac{2 \cdot \sqrt{2} \cdot Ureff \cdot Ri}{(\mathrm{Re}q + Ri)} = 21.4mVpp$$

4.2.1.11 Conclusions

At a distance of d= 1.1m the calculation results in VRFpp= 21.4mVpp. Because the sensitivity of the Write Distance Expander (WDE) is a factor of 10 higher, the Wake Sensitivity should be reduced to avoid undesirable wakeup due to noise.

4.2.1.12 Calculation of Charge Voltage for Batteryless Functionality

In Figure 6, the equivalent circuit for determining the charge voltage (VCL) is given.

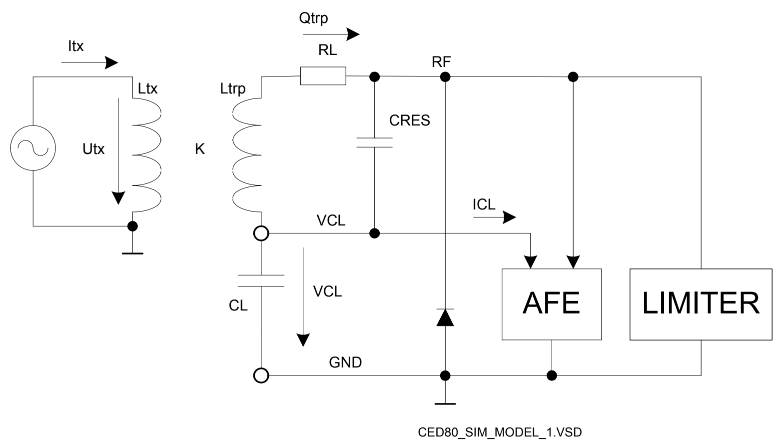

Figure 6: Calculation Model for Charge Voltage

The final charge voltage (VCL) can be calculated with the formula,

$$VCL = \left(Itx \cdot K \cdot \sqrt{Ltx \cdot Ltrp} - ICL \cdot \sqrt{2} \cdot Ltrp\right) \cdot 2 \cdot \pi \cdot fRES \cdot Qtrp \cdot \sqrt{2} + \frac{ICL}{Itx \cdot K \cdot \sqrt{2}} \cdot \sqrt{\frac{Ltrp}{Ltx}} - 0.5$$

,or with the equivalent parameter determined before:

$$VCL = Ureff \cdot \sqrt{2} - 2 \cdot \mathrm{Re}\, q \cdot ICL \cdot (1 - \frac{1}{Ureff \cdot 2 \cdot \sqrt{2}}) - 0.5$$

Whereby it is assumed that,

$$fRES = fTX = 127.25kHz$$

Because the real transmit frequency is 134.45 kHz, VCL will be lower.

ICL is the average DC standby current of the IC during charging and Qtrp is the total Transponder quality factor, represented by RL in the calculation model,

$$Qtrp = \frac{2 \cdot \pi \cdot fRES \cdot Ltrp}{RL}$$

For the charts, the parameters shown in Table 3 are assumed.

PARAMETER	ABBREVIATION	VALUE	UNIT
Transponder Quality Factor	Qtrp	20	
Standby Current during Charge	ICL	4.3	µA
Charge Capacitor	CL	220	nF

Table 3: Parameters for VCL Calculations

In Figure 7 the final, limited charge voltage over distance is shown.

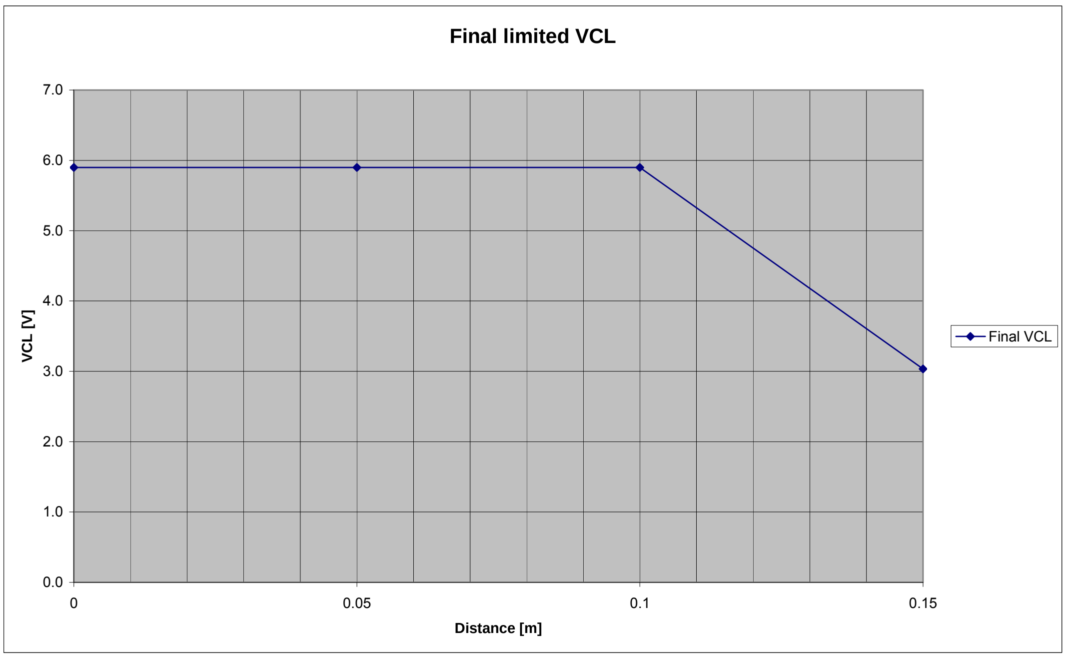

Figure 7: Final Limited Charge Voltage Over Distance

The charge voltage without limitation after 50ms can be calculated by,

$$VCL\_50 = VCL \cdot \left(1 - e^{\frac{-0.05}{4 \cdot \pi \cdot fRES \cdot Qtrp \cdot Ltrp \cdot CL}}\right)$$

In Figure 8, the limited charge voltage over distance for a 50ms charge burst is shown.

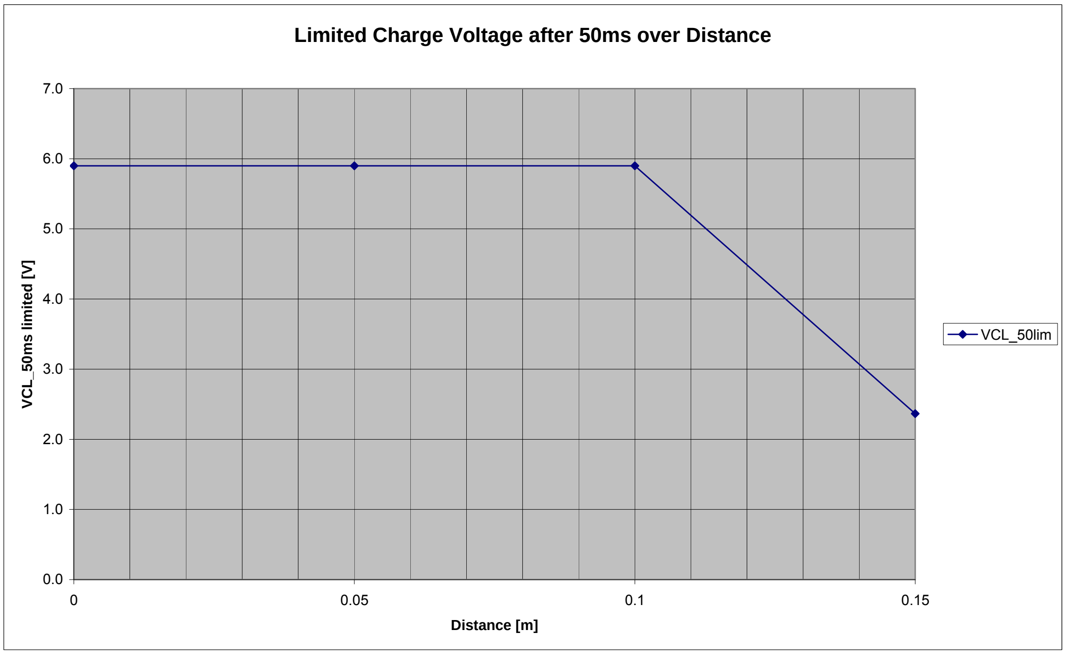

Figure 8: Limited Charge Voltage After 50ms Over Distance

4.2.1.13 Conclusions

The maximum passive (dead battery) communication distance will be about 13cm from the center, or 8 cm from the top, of the transmit antenna.

Important Note: Z- axis of transponder antenna must be in line with axis of transmit antenna. X- and Y- channel are not able to transmit in passive mode!

4.2.2 Transponder Transmit Antenna

The Transponder transmit antenna of the demonstration system is a three-dimensional block shape antenna from NEOSID. Because the inductance of all three coils is equal, the Z-axis typically has higher sensitivity; therefore, the X-axis is calculated here as an example.

4.2.2.1 Parameter of Transponder Transmit Antenna

The X-axis of Transponder Transmit Antenna has the following typical parameters, which are known from the antenna data sheet, from Table 2, or calculated out of known parameters (see Table 4):

X-AXIS PARAMETER	ABBREVIATION	VALUE	UNIT
Inductance	LtrpTX	2.47	mH
Typical Transp. Quality Factor	QtrpTX	30	
Coil Sensitivity Specification	Stx	0.062	V/A/m
Magnetic Field Constant	µ0	$1.25664*10^{-6}$	Vs/Am
Material Permeability (assumed)	µ	2000	
Length of Rod (Table 2)	lr	0.0154	m
Width of Rod (Table 2)	ar	0.0145	m
Thickness of Rod (Table 2)	br	0.0031	m
Effective Radius of Rod (Table 2)	rr	0.003783	m
Length to Diameter Ratio (Table 2)	lr/2rr	2.0356	
Rod Permeability (Table 2)	µrod	7.3	
Length of coil to length of rod (Table 2)	lc/lr	0.45	
Empirical Factor (Fv=f(lc/lr) (Table 2)	Fv	0.95	
Empirical Factor (Fl=f(lc/lr) (Table 2)	Fl	0.56	
Area of Loop (Table 2)	Atrp	$4.495*10^{-5}$	m^2
Turns (calculated)	NtrpTX	273	

Table 4: Typical Parameter of Transponder Transmit Antenna

4.2.2.2 Calculation of Windings

Because the number of windings (Ntrp) is not given for the 2.47mH NEOSID antenna, it must be determined from the calculated windings of 4.7mH antenna:

$$NtrpTX = Ntrp \cdot \sqrt{\frac{LtrpTX}{Ltrp}} = 273$$

4.2.2.3 Effective Antenna Radius

The effective antenna radius of transponder transmit antenna (rrtx) depends on the radius of the antenna rod (rr), the rod permeability (µrod) and an empirical factor (Fv):

$$rrtx = rr \cdot \sqrt{\mu rod \cdot Fv} = 0.00998m$$

4.2.2.4 Peak Antenna Current

The Transponder transmit antenna is driven in a full-bridge mode, supplied by a battery (Vbat = 3V). The peak-to-peak current depends on the transmit antenna quality factor (QtrpTX). For the medium frequency (f0=(fL+fH)/2):

$$RtrpTX = \frac{2 \cdot \pi \cdot f0 \cdot LtrpTX}{QtrpTX} = \frac{1974}{30} = 65.8\Omega$$

$$ItrpTX = \frac{Vbat}{RtrpTX} \cdot \frac{4}{\pi} = 58mAp$$

$$UtrpTX = ItrpTX \cdot 2 \cdot \sqrt{RtrpTX^2 + (2 \cdot \pi \cdot fL \cdot LtrpTX)^2} = 0.116 \cdot 1975 = 229Vpp$$

4.2.2.5 Response Coupling Factor

The response coupling factor (Krx) over distance (d) between the Base Station and the Transponder antenna is calculated as follows,

$$Krx = \frac{\mu 0 \cdot (rtx^2 \cdot \pi \cdot Ntx) \cdot (rrtx^2 \cdot NtrpTX)}{2 \cdot \left(d^2 + rrtx^2\right)^{1.5} \cdot \sqrt{Ltx \cdot LtrpTX}}$$

For a distance of d= 1.1m the response coupling factor is Krx=3.63785e-6.

4.2.2.6 Receiver Input Voltage

The Base Station antenna voltage (URX) at a given coupling factor (Krx), induced by a certain Transponder peak-to-peak antenna voltage (UtrpTX) can be calculated as follows,

$$URX = \frac{Krx \cdot \sqrt{LtrpTX \cdot Ltx} \cdot UtrpTX \cdot 2 \cdot \pi \cdot fres}{2 \cdot \sqrt{2} \cdot 2 \cdot \pi \cdot fres \cdot LtrpTX \cdot \sqrt{\frac{1}{QtrpTX^{2}} + 1}} \approx \frac{UtrpTX \cdot Krx}{2 \cdot \sqrt{2}} \cdot \sqrt{\frac{Ltx}{LtrpTX}}$$

For a distance of d= 1.1m the Base Station antenna voltage is Urx= 298.5µV.

The receiver input voltage is higher due to the quality factor of the receiver resonant circuit, but the amplitude of the receive frequencies (fL= 133.3 kHz, fH= 121.2 kHz) will be damped by approximately 3dB (a factor of 0.7) due to the resonant circuit bandwidth.

$$UIN[Vpp] = URX \cdot QRX \cdot 2 \cdot \sqrt{2} \cdot 0.7 = 6mVpp$$

4.2.2.7 Conclusions

For a distance of 1.1m the receiver input voltage is 6mVpp—sufficient amplitude for the TMS3705A's typical sensitivity of 1.5mVpp. The TMS3705A is the analog front end located in the Base Station.

5 Revision History

Rev.	SCN	Description of Change	Date submitted	By
00		New Issue	02/16/2012	H. Meier