Accurate Electromagnetic Field Strength Predictions and Measurements in The Near Field of Activated Antenna Systems on Broadcasting Sites

G.J.J. Remkes¹, W Schröter²
Nozema Broadcast Company, Lopikerkapel, 3412 KB The Netherlands
T-Nova Deutsche Telekom Innovationsgesellschaft mbH, 10589 Berlin, Germany

INTRODUCTION

Accurate methods of electromagnetic field strength predictions of activated antenna systems are of increasing importance for broadcast companies, operators and regulatory governmental bodies. To guarantee the safety of antenna personnel against non-ionising radiation nowadays is increasingly difficult due to the growing number of antenna systems co-located on one broadcasting site. Without a thorough knowledge of the near field effects of antenna exposures, field strengths need to be re-measured after each modification to ensure the safety of personnel. This is a tenuous and costly affair. It is also not a fully satisfactory solution since it provides no knowledge on how to reduce the field strengths. The situation can be even more complicated when some of the companies operating the antenna systems are not willing to reduce power on their systems to allow for maintenance or new construction by other companies. Calculation methods have been optimised and validated to explore the best way of guaranteeing the workers’ safety in the extremely complex near field situation of broadcast towers.

The number of variables in the ‘broadcasting world’ is extremely large. There are many different types of antenna systems and configurations for all purposes and also many types of mast and tower constructions. The full research object has therefore been divided into various sections, which will be dealt with in separate publications. In this paper the near field situation of FM-radio antenna systems on lattice masts will be dealt with.

SET UP

A lattice mast with three (four-fold) FM-antenna layers was specially designed and constructed for research purposes. The mast construction is similar to the standard lattice masts used by the broadcasting industry. Antennae can be rotated to allow for both horizontal and vertical polarisation. Any desired combination of active antenna fields can be used. As a source an non-modulated FM-transmitter was used operating at a frequency of 95 MHz. The total feeding power at the antenna input(s) amounts 450W, regardless of whether 1, 3 or 4 antennae were active.

For research and for standard safety measurement purposes a special elevator construction was designed. A schematic drawing is given in figure (1). The elevator construction consists of two parallel pipes fixed at a distance of 30cm apart. A cart is placed in between the pipes. Cartwheels allow for movement of the cart along the pipes. The wheels prevent movement of the cart in a lateral direction. To obtain a constant velocity the cart is connected to a motor by means of ropes. Measurement equipment can be mounted on the cart in various positions. By moving the cart up and down a series of measurements along the elevator construction can be obtained. To prevent production of undesired EM fields, the entire elevator construction was made of plastic.

EM-safety measurements are usually performed along the climbing routes on locations where the workers may be. Thus, the entire elevator construction is fixed to the ladders on lattice masts or fixed to the reflectors. Then, by moving the cart up and down a series of measurements along the elevator construction can be obtained. To prevent production of undesired EM fields, the entire elevator construction was made of plastic. Three lateral positions of the lines of measurement have been chosen such as to they coincide with the positions of the spinal cord and the left and the right hand side of the body of the worker while climbing on the ladder. This procedure has also been followed in our special research project.

A schematic drawing of the set-up as seen from above is given on the right of figure 1. One antenna layer consisting of four antenna fields can be seen positioned around the mast. The mast is symbolised by the inner square. The diameter of the mast is 1.8 meters and the distance between two opposing reflectors is 3.0 meters. Measurement data were obtained along vertical lines, perpendicular to the plane of drawing. Locations of the vertical lines of measurement are indicated by the letters L, M, R. Curves obtained between the mast and the reflectors (index i) have y-co-ordinates 15, 35 and 57cm for the Rᵢ, Mᵢ and Lᵢ-curve, respectively and are about 35cm away from the reflectors. Lines of measurement obtained between the dipoles and the reflectors (index o) have y-co-ordinates 17, 35 and 53cm for the Rₒ, Mₒ and Lₒ-curve, respectively. The Rₒ and Lₒ-curves are about 35cm away from the reflectors. The Mₒ-curve is 20cm away (x = 130cm). A spatial resolution in the lateral plane of up to 1cm can be attained. Data was obtained each 2.5cm along the lines of measurement. For safety purpose six runs are typically needed for each climbing route, since measurements are performed along three lines, for both the electric and the magnetic field.
Figure 1. Mast and measurement set up for vertical polarisation, side view (left figure). A view from above is given in the right figure. Both drawings are not drawn to scale.

The isotropic E- and H-field sensor EMR 300 made by Wandel and Goltermann was used. This broad band instrument is the standard instrument used in safety measurements in both Nozema and Deutsche Telekom. The absolute accuracy of the E- and H sensors amounts 2.5dB. More accurate selective antennae could not be used because there was not enough space available.

RESULTS OF MEASUREMENTS

Along the dipoles

Electric and magnetic field measurements along the dipoles were carried out for various operational conditions. The results shown in fig. (2) have been obtained for the case of three active antennae located above each other (six dipoles), and horizontal polarisation. All other antennae remained passive. Measurement series were obtained along the active dipoles. As expected, six maxima can be seen at the positions of the six active dipoles for both the electric and the magnetic field. The magnitudes of both maximum 2, and maximum 5, are larger than the other four, especially maximum 1 and maximum 6. This result can be explained by (mutual) coupling of the dipoles. Coupling reduces the impedance of dipoles 2 and 5 with respect to the impedance of dipoles 1 and 6. Consequently, dipoles 2 and 5 have increased output power and consequently increased field strengths, at the cost of the output power of dipoles 1 and 6, respectively. The total power fed to each individual antenna is not affected because the impedance has been adjusted to 50Ω. This also explains that the maxima found near dipoles 3 and 4 have an intermediate value (symmetric situation).
The Ro-curve of the electric field shows a slightly different behaviour. This curve was obtained much
closer to the centre of the (horizontal) dipoles. A more complex interference pattern can be expected near the
dipole centre because the voltage distribution shows a minimum here. The field variations and the maxima of the
magnetic field curve obtained at the position most far away from the centre of the dipoles, the Lo-curve, are
relatively weak. This is to be expected because source current is largest in the centre of the dipoles.

Results of electric and magnetic field measurements for vertical polarisation with only one active
antenna (at the top) are shown in Fig. (3). Measurement series were carried out along the active antenna. Two
maxima can be distinguished at the positions of the top and bottom of the upper two active dipole staves. This
interference pattern is to be expected in the region close to an active dipole. The magnetic field curves show only
one maximum at the position of the centre of the upper dipole staves. This behaviour follows directly from
Ampere’s law because current is largest in the centre of the dipole staves. Ignoring small local maxima and
minima it is clear that electric and magnetic field strengths gradually decrease from 8.5m down to 1m.

Figure 2. The electric and magnetic field as observed along vertical lines between reflector and the active
dipoles. Two dots together with the vertical line symbolise one antenna with horizontal polarisation.

Figure 3. The electric and magnetic field as observed along vertical lines between the reflectors and dipoles.
Two lines within a square symbolise one antenna with vertical polarisation.

Between reflectors and mast

The above experiment was repeated between the mast and the reflectors for a wide range of operational
conditions. The results shown in fig. (4) have been obtained for the same operational conditions as described
with fig. (2). The positions of the vertical measurement lines are given with fig. (1).

Electrical field strengths show similar values all along the measurement lines, except for two maxima
near 4m and 8m in the M\textsubscript{i}-curve. This suggests that the electromagnetic field energy equally spreads out in the
space between the mast structure and the reflectors of the active antennae. The two maxima are found at the
positions of the gaps between the three active antennae. Possibly, the geometry of the gaps is an important factor
for the creation of the two maxima, as the $M_i$-curve was obtained closer to the gaps than the $L_i$ and $R_i$ curve.

Figure 4. The electric and magnetic field as observed along vertical lines between mast and the reflectors, horizontal polarisation.

Looking in more detail at the E-field variation in figure 4, a complex interference pattern can be seen with many local maxima and minima, which do not seem to be consistent with any pattern. For safety assessment the finer details of the E-field variation with position are not relevant.

The magnetic field strength, see fig. (4), shows stronger variations with position than the electric field strength. Although less clear, again two maxima near 4 and 8 meters can be seen for the $M_i$-curve. Ignoring these two maxima the ratio of the largest and the smallest observed field strength value is about 12, which is a huge variation. For the electric field strength this ratio only amounts to 3. The maximum power flux density was calculated as the product of $E$ and $H$ (phase information is not available). The result again shows similar levels at all locations, except for the two locations near 4 and 8 meters, $M_i$-curve. This indicates that the gaps function as a source.

Figure 5. The electric and magnetic field strength between the mast structure and the reflectors, vertical polarisation. The top antenna was active.

The results shown in fig. (5) were obtained behind the reflectors for the same operational conditions as given with figure (3). A complex interference pattern can be seen with strong field variations with location. As a trend field strengths decrease with distance from the active antenna. This decrease is more gradual than that seen near the dipoles, figure (3), implying that electromagnetic energy is better conserved. It demonstrates how electromagnetic energy is transported in the 'wave guide' formed by mast structure and reflectors.

The next experiment was done to determine how electromagnetic energy turns the corner of the mast and penetrates into the space between mast and reflectors. Consider one antenna layer, consisting of four antennae (figure 1). Of this (central) antenna layer three antennae were active, the fourth remained passive. Measurement data was obtained behind the reflector of this passive antenna. In figure (6) the results are shown. Both the electric and magnetic measurement data show complex interference patterns with strong field variations. No straightforward explanation for the position of maxima and minima can be given. The maximum power flux density, $E \times H$ (phase information is not available), has been calculated to determine possible locations of power influx. The result suggests that from 4 to 6 meters and from 7 to 9 meters the power leaks in, because the largest values of the power flux are found there.
Figure 6. The electric and magnetic field between the mast and the reflectors, vertical polarisation. Measurements obtained behind the one antenna of the active layer which was passive.

Through the mast

To determine how electromagnetic energy penetrates from the outside into the mast structure, measurements were performed along horizontal lines through the entire structure from dipole to dipole (vertical polarisation). One antenna layer was active (four antennae, see figure 1). The results are shown in fig 7. Referring to the magnetic field curve, the position of the reflectors is clearly recognisable due to its screening effectiveness. The mast structure can also be identified. As expected, the electric field curves shows a maximum where the dipoles are located. From the results it can be concluded that field strengths inside the mast are relatively low. This is mainly due to the screening effectiveness of the reflectors.

Figure 7. The electric and magnetic field strength through the mast structure, 30cm above the reflector of the active antenna layer (four active antennae, vertical polarisation).

MODELLING

The predictive power of NEC-2D and of I-NAC-3 was tested for the above-described observations. The metallic structure of the entire lattice mast was included in our models. The main question with near-field modelling of broadcast towers is the extent to which constructional details must be included. On the one hand it is desirable to reproduce field strengths which take all observed effects such as resonance and re-radiation in account. On the other hand, due to basic modelling and computer restrictions the number of elements that can be used is limited. Mast structure was modelled as detailed as possible to predict electric and magnetic field strength between the reflector and the dipoles.

Standard segmentation conditions set fundamental restrictions on the extent to which details can be included in the models. Segmentation conditions are [1]:

1) \[ 10 \leq \lambda/L \leq 1000 \]
2) \[ L/d \geq 8 \text{ or } L/d \geq 2, \text{ when the extended kernel is used.} \]
Wavelength is denoted by \( \lambda \), and L and d are the length and diameter of segment, respectively. From conditions (1) and (2) it follows that the length of a segment should be in between 2d and 30cm. Therefore, ‘short thick’ structure elements cannot be included in the models. Approximations concerning lengths and positions of structure elements were used to solve this problem. Consequently, structure elements of our modelling can be shifted up to 10cm.

Another limitation of modelling in NEC is that two structure elements cannot be properly connected if their diameters are very different. In our project, diameters of various structure elements were similar, except for the feeder wiring. Feeder wires were co-located with the mast in such a way that they had a minimum effect on the various electromagnetic field strengths. Therefore, feeder wiring was not included in our models.

NEC-2D and I-NAC-3 use standard procedures to determine the impedances of structure elements. Should the actual impedances of structure elements, and especially the contact impedances of adjoined structure elements, deviate substantially from the calculated values of NEC-2D and of I-NAC-3, then this could lead to errors. Errors in the impedances of exciting elements, e.g. single dipoles, can affect the source field yielding inaccurate predictions, especially in the near field. In safety assessment practice the same problem will be encountered, structure impedance details will be unknown, such errors will have to be accepted and treated as a fundamental limitation of accuracy.

To determine effects of details of modelling, such as position, length, and the presence of metal plate elements on accuracy, these details were altered in order to obtain values as close as possible to the observed ones. It was found that maximum accuracy was required for all calculations except for the calculations along the dipoles. Small errors in screening or coupling effects can significantly affect field strengths at the back of antennae. However, field strengths along the dipoles were hardly affected by the mast structure.

**COMPARISON OF RESULTS OF MEASUREMENT AND OF CALCULATION**

**Along the dipoles**

Observed and calculated electric and magnetic field strengths along the dipoles were compared for all operational conditions used. Good agreement was found for all the cases examined. The magnitude of the maxima of calculated values can be slightly different from the observations as can be seen from the example given in Fig. 8. However, for safety assessment purposes the predictions are sufficiently accurate.

Various calculations have been done using different approximations for details of the inner mast structure. The effect of details of the mast structure on the calculation results for field strengths along the dipoles appeared to be negligible.

![Figure 8. Observed and calculated electric and magnetic field strengths along the dipoles. This example corresponds with fig. (3), one active antenna field with vertical polarisation. Cm denotes the calculated Mo-curve.](image)

**Between the reflector and the mast**

Calculated and observed field strengths between the reflectors and the mast are compared in fig. (9). It can be seen that the order of magnitude of field strength predictions is in agreement with the observations. Considering fig. (9) in more detail, calculated maxima and minima can be found at dislocated positions. This result can be explained as follows. Actual field strengths between the reflectors and mast structure can be seen as the superposition of the many reflected and re-reflected waves. Errors in the phase angles of the superimposed waves will change the interference patterns yielding dislocated maxima and minima.
Figure 9. Observed and calculated electric and magnetic field strengths between the reflectors and the mast. This example corresponds with fig. (4), three active antenna fields and vertical polarisation. Calculated curves are denoted by C, the indices l and r refer to L - and R-curve, respectively.

The interference pattern is further illustrated by a calculated contour diagram, see fig. (10). This contour diagram gives field strengths in the yz-plane, parallel to the reflectors. Lines of observation are parallel with vertical lines in the calculated contour diagram. The contour diagram shows a strongly varying field. Variations in modelling details tend to produce dislocated maxima and minima. However the overall pattern remains the same.

Comparing the envelopes of the three calculated curves and the three observed curves, it can be seen that they show acceptable agreement. This is not surprising, as the power flux is not substantially affected by details. For safety assessment practice this agreement between envelopes is sufficient.

Having compared many observations and calculations it was concluded that exceptions to the above findings remain possible. For safety assessment practice this implies that predicted values should always be verified with a (small) set of measurements.
Figure 10. Calculated contour diagrams of electric and magnetic field strengths between the reflectors and the dipoles, 20 cm behind the reflector and horizontal polarisation (three active antenna fields).
Figure 11. Observed and calculated electric and magnetic field strengths between the reflector nets and the dipoles, horizontal polarisation (three active antenna fields).

The above examination was repeated for the case where three antennae of one antenna layer were active, see figure (6). The antenna behind which the observations were performed was switched off. The result is shown in figure (11). To predict the observations shown in figure (6) that was considered to be the biggest challenge. Neither the envelopes of standard curves, nor the interference pattern could be reproduced accurately. However, the calculation result can be used to predict the order of magnitude of field strengths. The propagation of electromagnetic waves from the active dipoles through (the holes between) reflectors is so sensitive on structure that calculation results cannot be relied upon. For safety assessment procedures this implies that a worst case analysis must be applied. If, for example, only calculation results would have been available, then it could have been concluded that the expected electric field strength is below 50V/m and the magnetic field is maximum 0.2A/m. The measurement data confirm that these conclusions are correct, however, too stringent for the magnetic field.
Through the mast

Calculated and observed field strengths obtained through the entire structure at the position of the dipoles are compared in fig. (12). This example corresponds to fig. (7), one active antenna layer and vertical polarisation. Fairly good agreement between the observed and calculated values was found. The (strong) field variations at the positions of the reflectors and the mast were accurately reproduced by calculations. After many calculations it was found that NEC-models might predict maxima (resonances) inside the mast structure, which were not apparent from observations and vice versa. This effect may be due to resonating structure elements, producing secondary electric and magnetic fields with local maxima and minima. The occurrence of resonances is very sensitive to details of mast structure, especially to length and contact impedance of adjoined structure elements. This statement is valid for both, the calculation model and for the practical situation. Resonances can easily be identified because high electric field strength values correspond to low magnetic field strength values and vice versa. For safety assessment purposes these resonances may not be very relevant because the power flux is relatively low.

Figure 12. Observed and calculated electric and magnetic field strengths through the mast and reflectors, 30 cm above the reflector of the active antenna, vertical polarisation (four active antennae).

The C-curve was calculated, the M-curve measured.

THE VALUE OF SIMPLE ESTIMATES

Simple estimates can be useful before measurements are performed in case detailed calculations cannot be carried out. These rules of thumb apply to specific situations and have no general value. They are based on practical experience and have no thorough physical basis. Electric and magnetic field strengths between reflectors and the mast can be estimated as follows:

\[ E = \sqrt{\sum Z_o P_i / (4\pi R_i^2)} \quad H = \sqrt{\sum P_i / (4\pi R_i^2 Z_o)} \]

where \( P_i \) denotes the electrical source power of antenna field i, and \( R_i \) the distance to the antenna field i. Equation (3) can only be used to get some idea of field strengths present. From a physical point of view, equation (3) states that all electromagnetic energy spreads out equally in space. Because of the directivity of the antennae most energy is directed into the main lobe. In all other directions the assumed gain is 1 referred to an isotropic radiator. Close to the antenna, at the back, this rule of thumb generally over estimates field strengths due to this fact that backward flowing electromagnetic energy is strongly reduced in practice. Equation (3) may fail when the space between the reflector and the mast structure strongly behaves like a wave-guide, thereby conserving more energy then expected. This effect yields a weaker decay of field strength with distance. At locations where re-reflections or strong resonances occur, equation (3) may under-estimate field strength (not the power flux because of the alternate maxima and minima of E and H). Antenna diagrams should not be used to predict field strengths between the reflector and the mast structure, as they are not intended for near field situations.

It is our experience that field strength predictions that were obtained from simple estimates for locations inside masts are not reliable as a rule. This is because in broadcasting practice (bended) feeder cables and dividers may act as sources inside the mast structure. Mast structures can react in such a way as to cause strong resonances. In that case strong field strength maxima can be observed on the inside of the mast in spite of the fact that there is a) no (intended) active antenna and b) the reflectors and masts are very effective at screening. These effects cannot be included in calculation models because the sources cannot be defined. Therefore, field strength measurements will remain necessary inside mast structures.

Antenna diagrams can be used to get some idea of the field strengths along the dipoles. The results may
not always be very accurate because antenna diagrams are valid only for the far field region. NEC modelling
without detailed mast structures will give a better result because mast structure hardly affects field strengths on
the outside.

SUMMARY/CONCLUSIONS

Results of measurements were presented for various representative situations in a broadcast mast
containing a FM-antenna system. These results are compared with calculations using NEC-2D and I-NAC-3. For
most situations a fairly good agreement between calculations and observations was found. For safety assessment
purposes the accuracy of the calculations is satisfactory in general. The best results were obtained along the
dipoles. The least reliable results were obtained when trying to predict how electromagnetic energy turns the
corner and penetrates back into the space between reflectors and mast. Simple estimates are proposed and the
conditions on when to use them.

REFERENCES


Acknowledgement

We would like to thank M. Eppink for the development of the field diagnostic and the computer
programming. Also we would like to thank K.H. Schmidt and S. Schenk for their contribution in the construction
of the set-up and their help with the performance of the measurements.