Appendix B

Projects LOTHAR and LOTHAR-fatt

From 2008 to 2011 the National Laboratory "RAdar and Surveillance Systems" (RaSS) of the *National Inter-universitary Consortium for the Telecommunications* (CNIT) and the "Microwave & Radiation Laboratory" (MRL) of the *University of Pisa* co-operated with the "National Institute of Geophysics and Volcanology" (INGV) to the project *"LOTHAR-fatt"* concerning the feasibility study of a ionospheric radar system for the surveillance of the Mediterranean area. The project represents the stage-two of the project "LOTHAR", that is the pre-feasibility study of the same radar system.

Since the project of an entire OTHR-SW apparatus implies an impressive workload, the whole system was virtually divided in subsystems and the work was split among various teams. The MRL, in collaboration with the "Department of Electronics and Telecommunications" (DET) of the University of Florence, was involved in the design of the transmitting and receiving antenna systems, both at the level of the array-system and at the level of the single radiating element. Instead our team (L. Facheris, F. Cuccoli and F. Sermi) developed the proposed Coordinate Registration technique and took active part in the definition of the transmitted signal, in the design of the Tx and Rx sites (with evaluation of the radiated EM field) and in the implementation of a target-tracking algorithm.

In the next sections give a basic description of the characteristics of the LOTHAR radar and some of the solutions selected for: the antenna system; the single antenna element; the model of the radiated EM field.

B.1 Basic characteristics of the LOTHAR system

Some of the main characteristics of the LOTHAR's antenna system are:

- Operative Band: $[7 \div 28]$ MHz;

- Transmitted signal: CHIRP;

- Max Bandwidth: 100 KHz (in stable Ionospheric conditions);

- Pointing Range in elevation: $[5 \div 55]°$;

- Pointing Range in azimuth: $[-90 \div +90]°$;

- Resolution at the centre of the band: $1°$.

These characteristics were obtained through the design of circular-shaped antenna's arrays consisting of wide-band transmission elements and active element in reception.

Since the Coordinate Registration method developed and investigated during the present study was initially proposed to be integrated in the LOTHAR system and consequently we often implicitly consider its geometry and parameters, here in the following we provide a brief description of the LOTHAR and LOTHAR-fatt projects.

B.2 The antenna Array

Due to the overall dimensions of the antenna array of an OTHR-SW system, the entire radiation study needs to be conducted via a simulation tool, without the support of measured data as, instead, it generally happens for microwave radar systems. This theoretical study is fundamental to define the array configuration that better satisfies the project requirements in therms of directivity and dimensions of the radar beam, frequency agility, Side Lobe Level (SSL), etc. During the pre-feasibility stage of the LOTHAR's project several array configurations were tested via the radiation simulator software. Among these it is worth to remember the linear, the "T" shaped, the "Y" shaped, the "inverted π" for what concerns the directive in the horizontal plane and the circular-concentric, the circular-pseudo-random arranged, the Archimedean spiral, etc. for what concerns the isotropic in the horizontal plane.

For what concerns the directive configuration of the antenna array, the best project solution is given by the "Dragonfly" geometry proposed by figure B.2.

This configuration considers a total of 99 elements, 25 of which are located along each arm: 31 along the horizontal axis, 18 along the vertical axis. The elements along the horizontal arm are separated from each other by 12 meters,
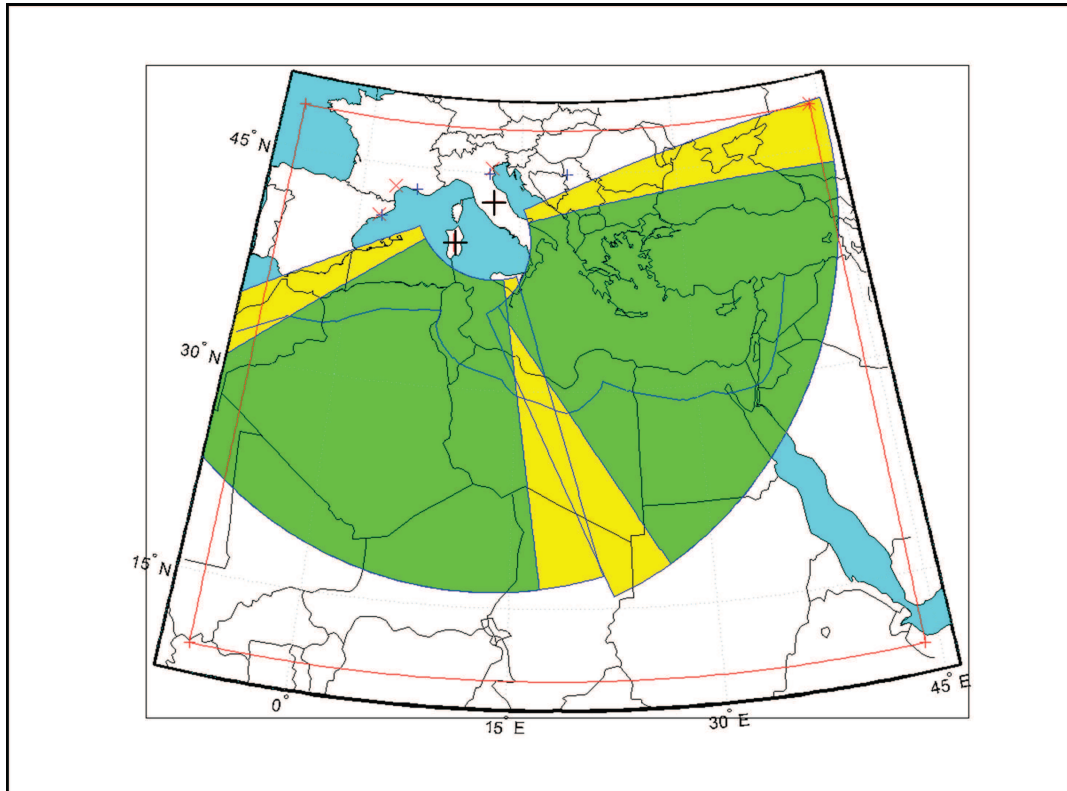
Figure B.1. Surveillance area in the hypothesis of two OTHR-SW systems placed in Sardinia and in the center of Italy, both with $90°$ azimuthal amplitude and a range of 600 to 3000 km.

while the ones along the diagonal arms by 10 meters and those along the vertical arm by 17 meters. The angle between the diagonal and the horizontal arms is 20 degrees. Figure B.3 shows the results of the simulation for the field radiated in the horizontal and in the vertical planes from an antenna with the configuration presented in fig. B.2, assuming a frequency of 15 MHz, an elevation angle equal to $15°$ and azimuth of $0°$.

The "Dragonfly" configuration represents the project solution chosen during the pre-feasibility stage of the LOTHAR project. It manages to balance the requirements in terms of *narrow beam* in both the horizontal and the vertical planes and at the same time ensures a more than acceptable level of side lobes: the average value of SLL is -12 dB but in some configurations it can also reach lower values. The presented configuration also accounts for the problem of the mutual coupling between the single radiating elements.

During the second stage of the project ("LOTHAR-fatt"), different requirements for the radar system emerged, so the directive array geometry was substituted with one that is isotropic in the horizontal plane. It was finally assumed a
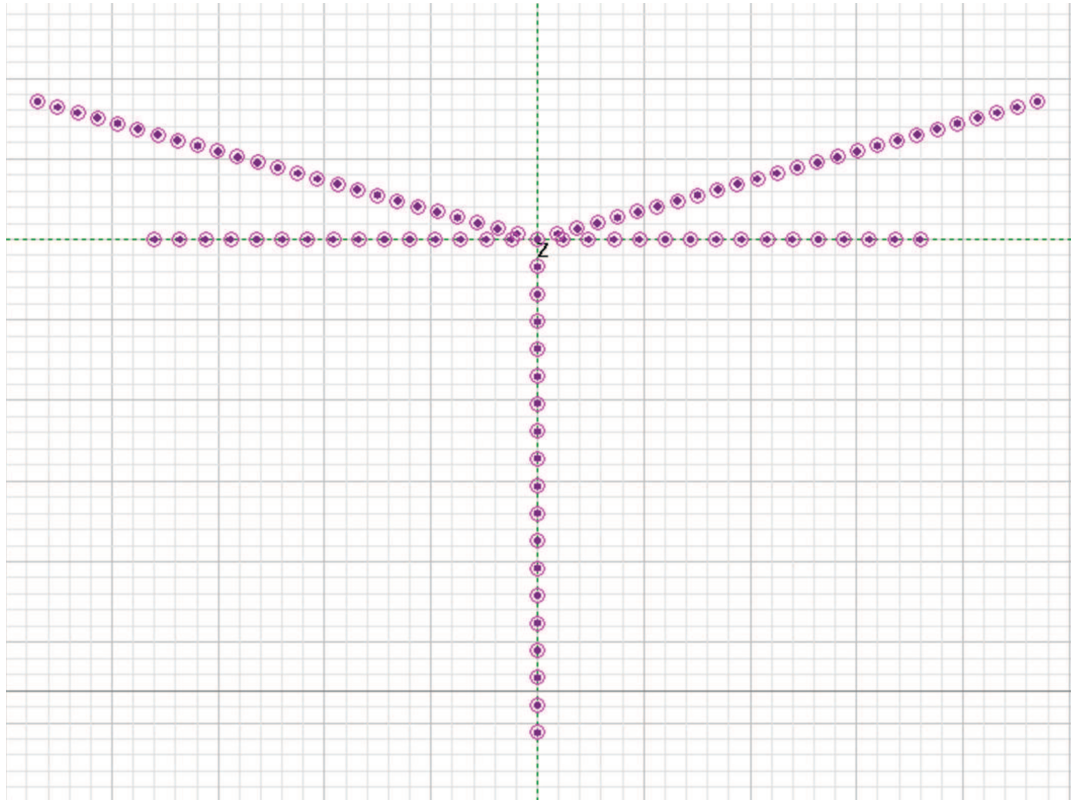
Figure B.2. *Concentric Circles Tx Array.* Clockwise from the left: top view of the 50 elements Rx array (the double rectangle has the surface of a soccer field: 110 by 90 meters); 3d view of a single radiating element; 3d view of a portion of the Tx antenna.

configuration of the transmitting array with the following characteristics:

- the Tx array is made up of 50 elements within a circular perimeter with a radius of 130 meters, displaced along 4 concentric circles;

- the single radiating element is a mono-conic structure with a diameter of about 6 meters.

A virtual representation of the described antenna is proposed in figure B.4.

B.3   Single Radiating Element of the Array

The chosen geometry for the single radiating element is the "Reversed-cone" schematized in figure B.5.
The abrupt discontinuity associated with the truncation of the cone, which may emphasize the frequency dependence of the radiation diagram, is reduced through
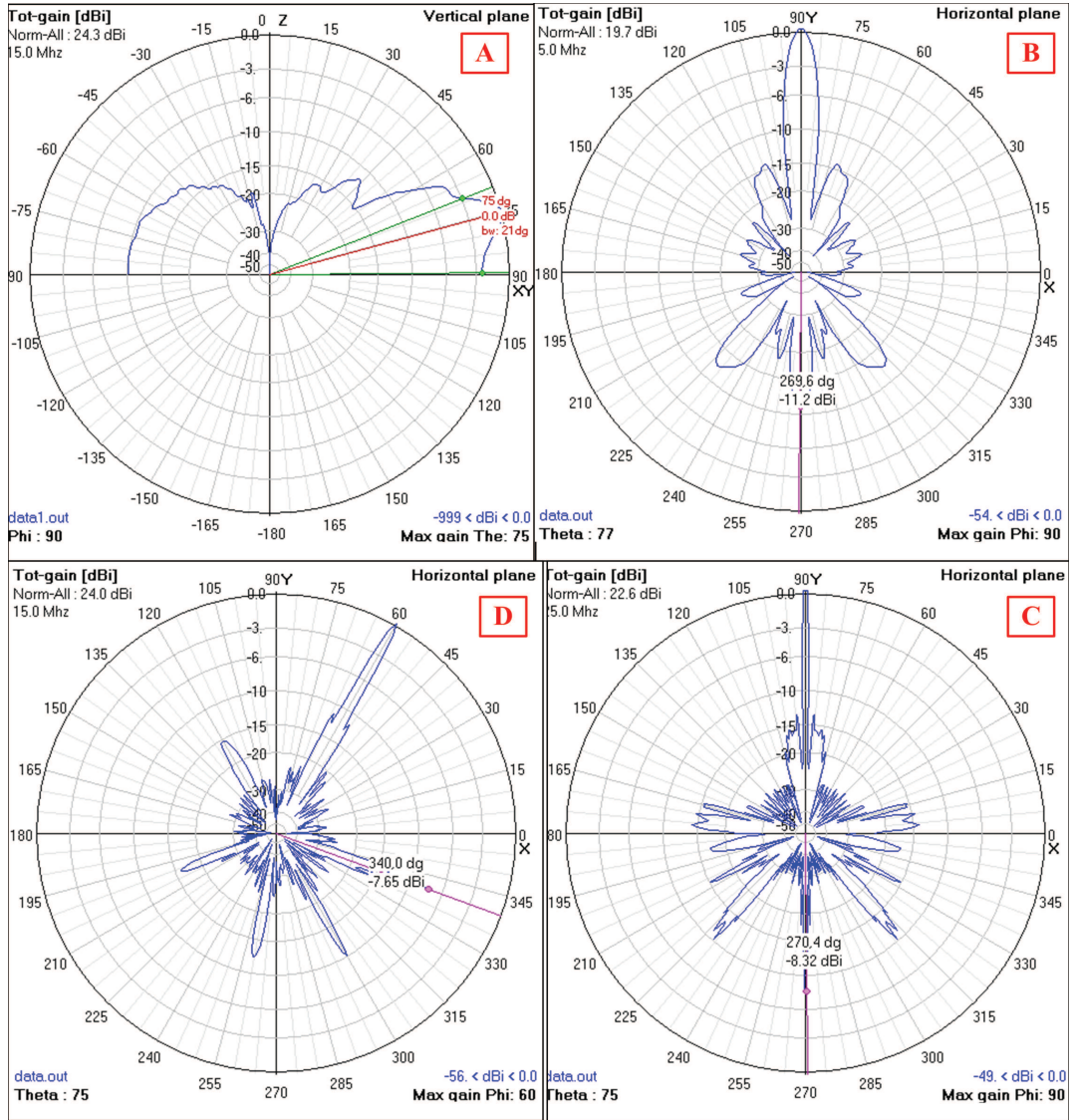
Figure B.3. Radiation Diagram for the *"dragonfly"* configuration illustrated by the previous picture.

the introduction of a " cap". This *cap* is dimensioned in such a way that the complete antenna results inscribed in a hemisphere. The excitation is applied in correspondence of the row segment that connects the lower vertex of the cone to the ground plane; this segment is 0.25 meters long.

As is known, the input impedance of a cone antenna depends on the angle of opening α, which represents one of the design parameters together with the vertical segment of length CH. The number of radial conductors employed to approximate the conical surface of the antenna also influences the frequency dependence
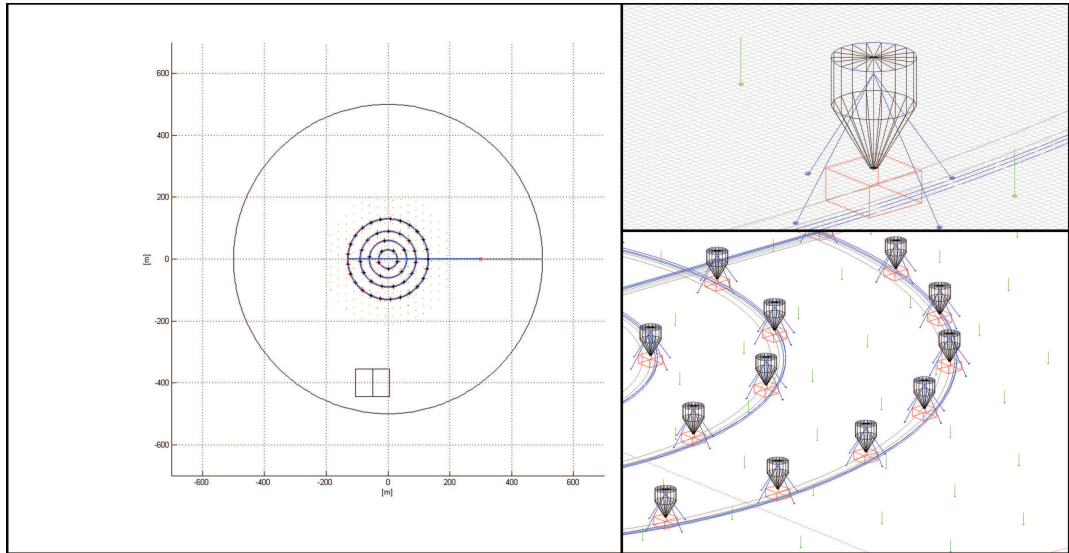
Figure B.4. *Concentric Circles Tx Array.* Clockwise from the left: top view of the 50 elements Rx array (the double rectangle has the surface of a soccer field: 110 by 90 meters); 3d view of a single radiating element; 3d view of a portion of the Tx antenna.

$$TH = CS = CH + CCH = CH / \cos(\alpha),$$
$$CCH = TH - CH,$$
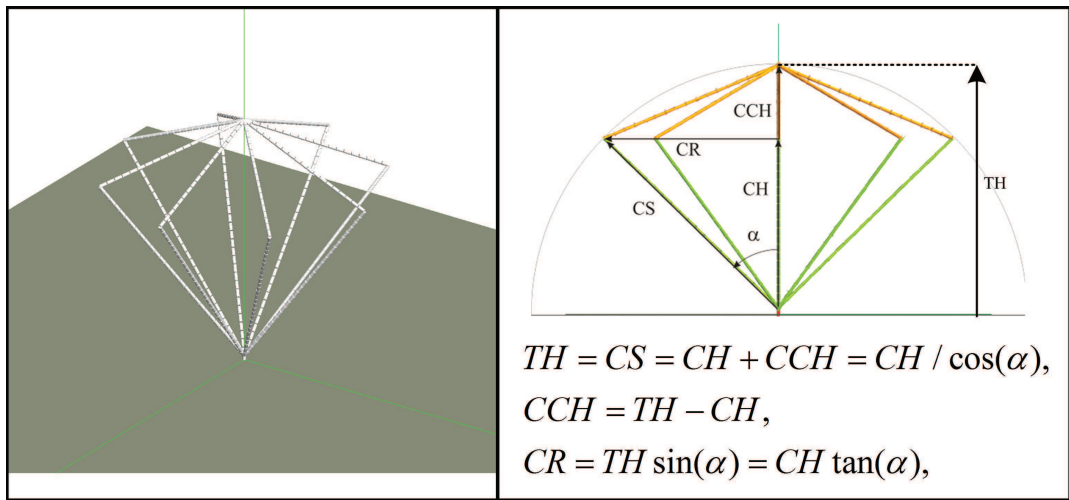$$CR = TH \sin(\alpha) = CH \tan(\alpha),$$

Figure B.5. *Reversed-cone antenna*: 3d view and side view with geometric parameters.

of the input impedance. Finally, the thickness and the length of the wires that form the antenna are factors to be taken into account during the project. In this regard, we note that the use of high thickness cables is particularly advantageous to reduce the overall size of the antenna: the greater the thickness of the cables will be, and the more compact the antenna will result, considering the same per-

formance in terms of both input impedance and radiation pattern. Based on the above considerations, the electromagnetic behaviour of the mono-cone antenna was investigated as a function of various design parameters in order to define the suitable configurations and to highlight any eventual mutual dependencies. For an infinite bi-cone antenna, the input impedance can be deduced analytically as:

$$Z_{in} = 120 ln \left(cot \left(\alpha/2 \right) \right)$$

considering that for a mono-cone element on a PEC plane the input impedance correspond to the half of that of a bi-cone element, we can evaluate the mono-cone opening angle as a function of the input impedance through the equation:

$$\alpha = 2 cot^{-1} \left(e^{Z_{in}/60} \right)$$

This formula allows to evaluate the theoretical value of $\alpha = 47°$ corresponding to an input impedance of 50 Ohm, without accounting for the limited dimensions of the element. However the EM analysis has shown that the optimum opening angle corresponding to an input impedance of 50 Ohm for a "finite" mono-cone element on the entire operating band (considering [5÷ 25] MHz) is close to the theoretical value for an infinite structure and approximately 45°. Furthermore, it was noted that this optimal value of the opening angle of the cone tends to be independent from the variation of the other design parameters. Therefore, the simulation results shown in the following are all relative to a single-cone antenna with an opening angle $\alpha = 45°$, the height of the cone, the number N of wires employed to approximate the surface of the cone and their thickness, can assume instead different values.

B.4   Evaluation of the EM radiation

In order to evaluate the EM field radiated by the LOTHAR's antenna system and consequently to establish some important perimeters we define the following three *Zones of Influence*:

- *Population Zone* (ZP): region where the measured rms value of the EM field is lower than the level set for the population exposition.

- *Workers Zone* (ZW): region where the measured rms value of the EM field is higher than the limit for the population exposition and lower than the limit established for the radar operators.

- *Action Zone* (ZA): region where the measured rms value of the EM field is higher than the action limit for the radar operators.

In table B.1 are presented two possible configuration of the radar parameters in transmission employed for the evaluation of the radiated field. In both cases the a Perfect Electrical Conductor is supposed to be present below the antenna array. Note that the value of the Duty-Cycle expressed in table is evaluated considering pulses of 4 ms and a PRF of 40 Hz.

Case	Frequency [MHz]	Take-off [deg]	Duty-Cycle [%]	Total Peak Power [MW]
1	17.5	11.5	16	1
2	21.5	14.5	16	1

Table B.1. Two configurations of the Tx parameters for the evaluation of the antenna's irradiated field.

For an operative frequency higher than 10 MHz the rms values of the radiated EM field for the respective zones of influence are evaluated as:

– $E_{ZP} < 28$ [V/m];

– $28 < E_{ZW} < 61$ [V/m];

– $E_{ZA} > 61$ [V/m].

If we consider a radiating Tx array system consisting of 50 elements distributed along four concentric circles with radius of 30, 60, 90 and 130 meters and configured with the same parameter's value listed in table B.1, then the radiated EM field presents an effective safety zone that starts at 500 meters from the center the array. This value is taken as a reference for the design of the area in transmission.
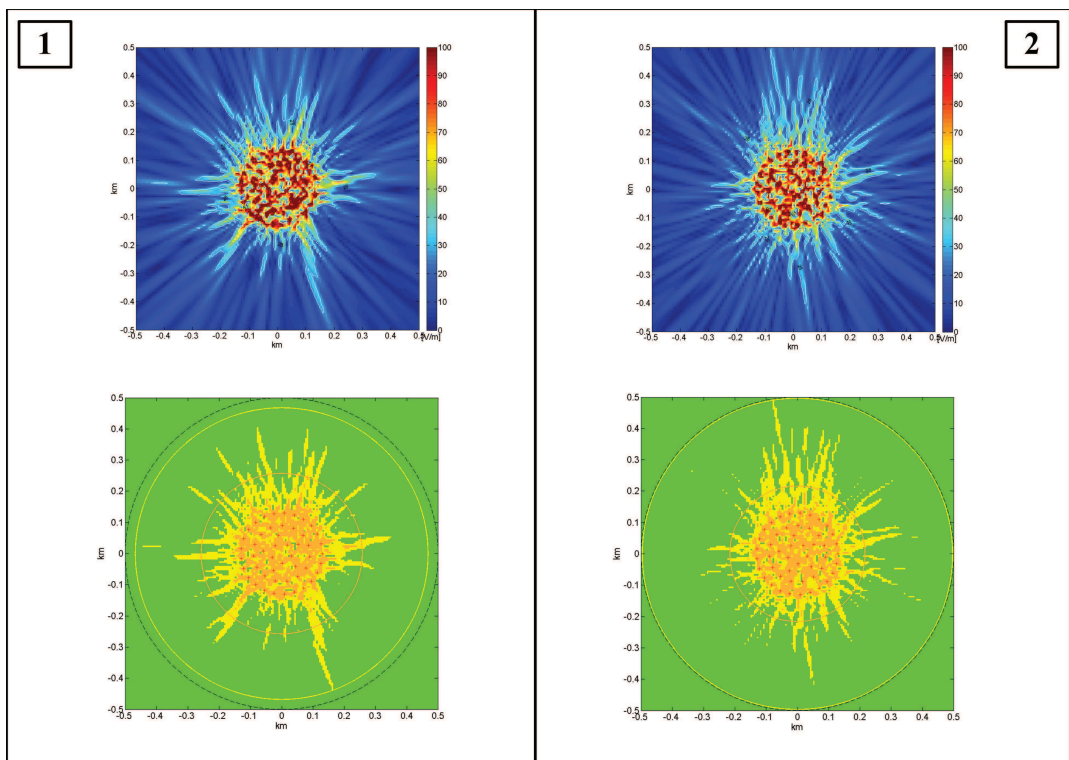
Figure B.6. Effective Radiated Field (top) and relative regions of influence for the two study cases presented in table B.1.