DESIGNING FOR ELECTROMAGNETIC RADIATION HAZARDS COMPLIANCE

Humans are exposed to electromagnetic fields (EMF) almost everywhere. With the development of new technologies, new field sources are constantly being added to the environment. Recent examples of such field sources include:

- 5G base station transmitters
- Transmitters for vehicle-to-vehicle (V2V) or vehicle-to-everything (V2X) communication
- Transmitters in Internet-of-Things (IoT) devices
- High-voltage systems in electric vehicles (EV)

At sufficiently high-power levels, EMFs can adversely affect people's health. This has led to the establishment of standards and regulations for EMF transmissions by electrical and electronic devices. Altair® Feko® assists in verifying the compliance of their electronic devices with the EMF exposure safety regulations applicable within the geographic regions where in which their devices operate.

Radiation Hazard Standards and Categories of Exposure

Typically, local safety regulations reference safety standards established by a competent technical authority. In the domain of EMF exposure, the most prominent and most frequently referenced standard is the "Guidelines for Limiting Exposure to Electromagnetic Fields (100 kHz to 300 GHz)," published by the International Commission on Non-Ionizing Radiation Protection (ICNIRP). Similar standards include those published by the International Electrotechnical Commission (IEC), the Institute of Electrical and Electronics Engineers (IEEE), various local standardization or regulatory authorities, and military standardization authorities (MIL-STD-464C, for example).

Using numerical simulation, EMF exposure can be evaluated and limited early in the design process to avoid expensive corrections within later stages of development.

While the standards for the evaluation of radiation hazards are numerous and vary in scope, the basic concepts they use to evaluate physical quantities are often similar. Most distinguish between "general public exposure" and "occupational exposure," and between "basic restrictions" and "reference levels."

Occupationally exposed individuals are adults who are exposed to EMF radiation under controlled conditions associated with their occupational duties. These individuals are trained to be aware of potential EMF risks and employ appropriate mitigation measures to protect themselves from harm.

The **general public** includes people of all ages and of varying health circumstances, including groups or individuals who are at high risk from EMF exposure. Members of the general public may have no knowledge of or control over their exposure to electromagnetic fields.

Basic restrictions refer to dosimetry values inside the human body and are measured in terms of either specific absorption rate (SAR) or absorbed power density (APD). Basic restrictions can be difficult to measure but can be simulated using human body models.

Reference levels are easier to evaluate. These are derived from basic restrictions to provide a simpler approach to demonstrating compliance with a standard's guidelines. Reference levels refer to incident electromagnetic fields or incident power density without explicitly considering the human body in the evaluation process.

Other important parameters include **frequency range** and **averaging time interval**, over which the other quantities must be averaged.

Physical Effects on the Human Body at Different Frequencies

Different EMF frequency ranges have different effects on the human body, as illustrated in Figure 1.

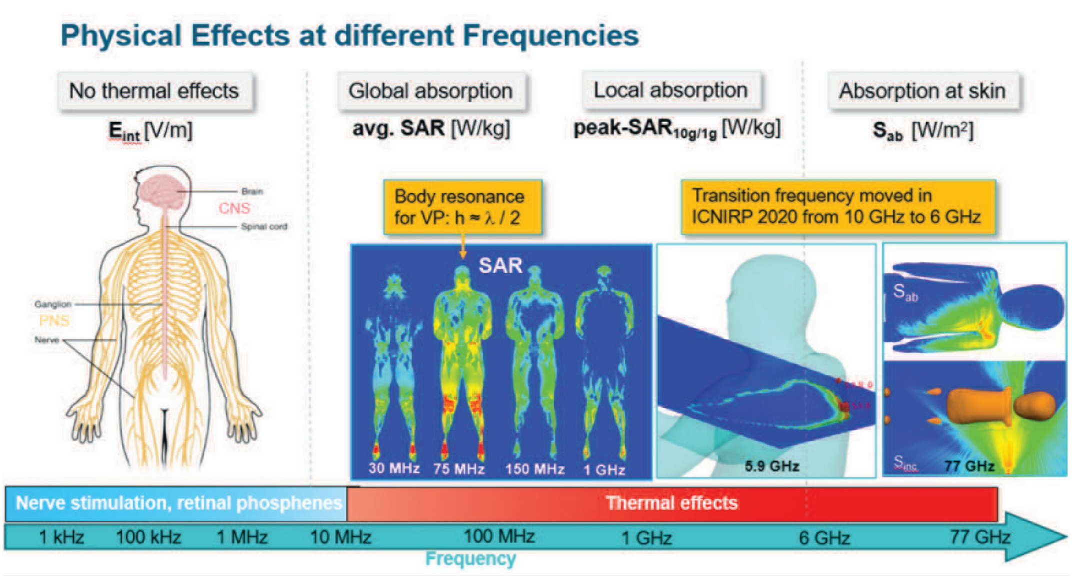


Figure 1: Physical effects on the human body of EMF radiation at different frequencies

Low-frequency EM fields of up to 10 MHz can induce EM fields within the human body, which can stimulate nerves and induce retinal phosphenes (the bursts of light or color you may sometimes see when your eyes are closed or in low-light situations).

As EM frequency increases, heating effects predominate, and the likelihood of nerve stimulation decreases. At frequencies between 30 MHz and 1 GHz, if a body's size is in the range of half of the wavelength of the field, body resonance effects can be observed. In this frequency range, average specific absorption rate (SAR) is the most important evaluation quantity. SAR is a measure of the amount of power deposited by a radiofrequency field in a certain mass of tissue and is therefore quantified in watts per kilogram (W/kg).

Beyond 1 GHz, heating of the body becomes more superficial. Above 6 GHz, this heating occurs predominantly in the skin. For frequencies between 1GHz and 6 GHz, local absorption should be evaluated with the peak SAR averaged over a 10 g mass (peak-$SAR_{10g/1g}$).

For frequencies above 6 GHz, absorbed power density (S_{ab} in W/m²) provides a good measure of the power absorbed in tissue and closely approximates the temperature rise at the surface of the skin.

It should be noted that in the 2020 revision of the ICNIRP guidelines, the transition frequency between specific absorption rate (SAR) and absorbed power density (S_{ab}) was moved from 10 GHz to 6 GHz.

Radiation hazard analysis objectives and scenarios tend to vary by industry and use case. We'll look at several cases in a variety of industries.

Telecommunications: Trade-Off Between Coverage and Exposure

In the telecommunication systems design process, engineers generally seek to optimize the trade-off between the best connectivity performance and the lowest electromagnetic exposure.

Take, for example, a coverage analysis for a telecom base station in an urban setting, as shown in Figure 2. One could enlarge the coverage area simply by increasing the transmitter power. However, increasing transmitter power also increases the size of the radiation hazard (RADHAZ) zones around the transmitter.

Normally, for this type of base station RADHAZ zone analysis, reference levels are sufficient.

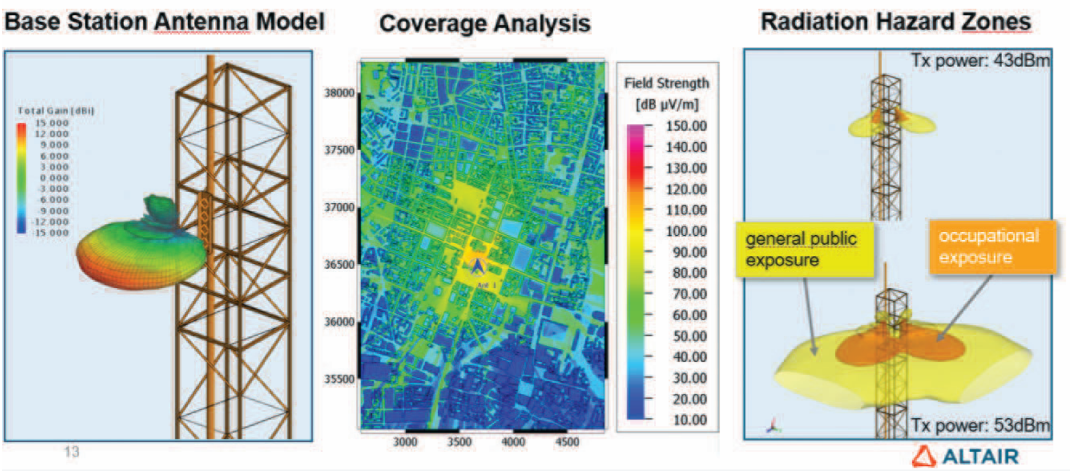


Figure 2: Analyzing the trade-off between best coverage and lowest exposure for a telecommunications base station

Healthcare: Minimizing Power Absorption and Heating

In healthcare applications, the principal exposure-limitation objective is to minimize power absorption and heating by the human body. Normally, a human body model must be included in the evaluation (using the basic restrictions defined earlier) to look at the local distribution of the thermal effects of the radiated power within the human body.

Typical medical device applications include analyses of the EMF fields radiated by MRI machines and pacemaker antennas (Figure 3).

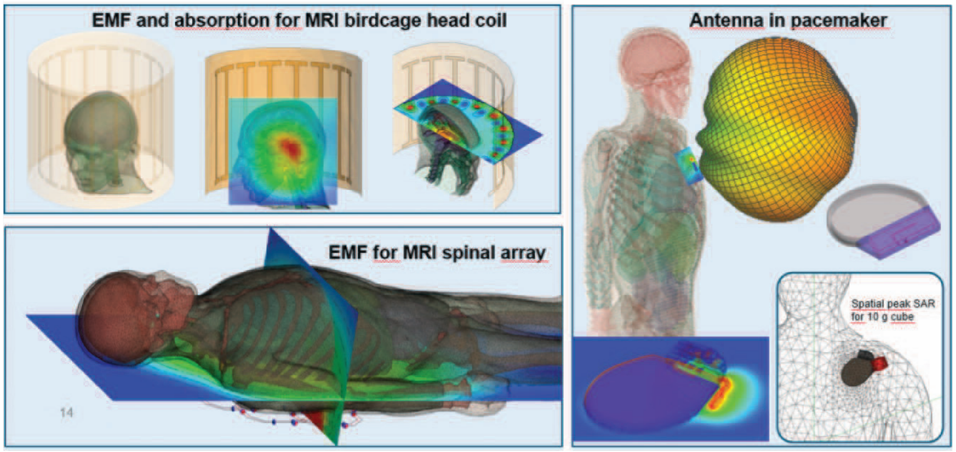


Figure 3: Analyzing the local distribution in the human body of EM power radiated by medical devices

Radiation Hazard Analysis in Defense Applications

Defense systems like military ships, land vehicles, and aircraft often employ antennas with very high transmission power. Because these systems normally operate in areas removed from the general public, however, analysis of the occupational exposure case is normally sufficient.

Standards used in the defense industry for limiting EM radiation hazards include:

- ICNIRP Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz)
- ANSI/IEEE C95.1: Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz
- MIL-HDBK-240A: Hazards OF Electromagnetic Radiation to Ordnance Test Guide, Department of Defense, USA
- MIL-STD-464C: Electromagnetic Environmental Effects Requirements for Systems, Department of Defense, USA.
- ARPANSA: Maximum Exposure Levels to Radiofrequency Fields — 3 kHz to 300 GHz, Australian Radiation Protection and Nuclear Safety Agency (ARPANSA)
- NAVSEA OP 3565/NAVAIR 16-1-529: Electromagnetic Radiation Hazards (Hazards to Ordinance), Naval Sea Systems Command

When conducting radiation hazard analyses in the defense sector, distinctions are made between three types of scenarios, each of which has different limits and reference levels.
These three scenarios are:

- Hazards of Electromagnetic Radiation to Personnel (HERP)
- Hazards of Electromagnetic Radiation to Ordnance (HERO)
- Hazards of Electromagnetic Radiation to Fuel (HERF)

Process for Simulation of RADHAZ Zones in Altair Feko

Before looking at an example of radiation hazard simulation and analysis for a defense application, let's examine the process for simulating EMF transmission RADHAZ zones in Altair Feko.
Here are the steps (as illustrated in Figure 4):

1. Create an antenna model to be analyzed (a shipboard HF radio antenna, for example)
2. Add relevant scattering objects (the ship's structure, the helicopter shown in Fig. 4, etc.)
3. Compute EM nearfields and power density (E, H, S) around the antenna using a solver in Feko
4. Compute RADHAZ zone visualization isosurfaces defined with implicit equations
    - E(x,y,z) = Eref, H(x,y,z) = Href, S(x,y,z) = Sref
    - With reference levels—Eref , Href, or Sref—from the relevant standard (e.g. ICNIRP 2020)

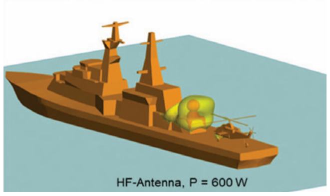


Figure 4: RADHAZ zone simulation in Feko

The size and shape of the radiation hazard zones will depend upon:

- Transmission power (Figure 5)
- Transmission frequency (Figure 6)
- Antenna nearfield pattern
- Any nearby secondary radiators that are excited by the antenna

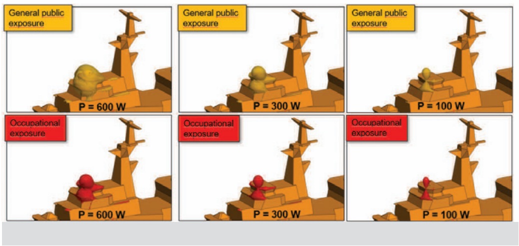


Figure 5: RADHAZ zones of an HF radio antenna for different power levels

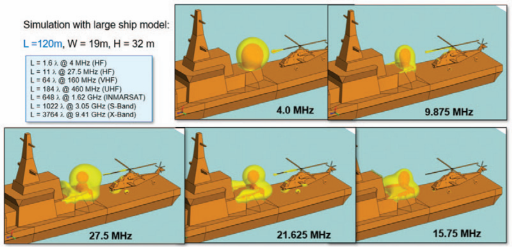


Figure 6: RADHAZ zones of an HF radio antenna for different transmission frequencies

Different Solvers for Different Frequencies

Solver choices for radiation hazard simulation in Feko are also frequency dependent.

For **low-frequency applications, like HF** radio antennas, the **Method of Moments (MoM)** works well.

At higher frequencies, including the **UHF and VHF** bands, the **Multi-level Fast Multipole Method (MLFMM)** is both efficient and accurate.

For **radar applications**, asymptotic methods like the **Uniform Theory of Diffraction (UTD)** and **Ray Launching Geometrical Optics (RL-GO)** are good choices.

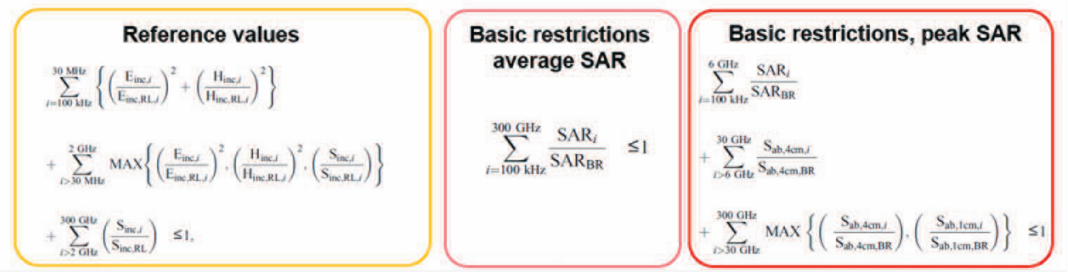
All these methods are available and hybridized in Feko.

Simultaneous Exposure to Multiple Frequency Fields

An important aspect of RADHAZ evaluation—especially in defense applications like naval vessels, military land vehicles and aircraft, where several transmitters may be near crew members—is simultaneous exposure to electric fields from different sources at different frequencies.

Exposures to fields of different frequencies are additive in their effects. Additivity should be examined with summation formulas applied to relevant frequencies under practical exposure situations.

ICNIRP 2020 lists separate **summation formulas** for reference levels and basic restrictions (Figure 7). Postprocessing scripts for summation formulas are available in the Altair Knowledge Base at community.altair.com.



Reference values

$$\sum_{i=100\text{ kHz}}^{30\text{ MHz}} \left\{ \left(\frac{E_{\text{inc},i}}{E_{\text{inc,RL},i}} \right)^2 + \left(\frac{H_{\text{inc},i}}{H_{\text{inc,RL},i}} \right)^2 \right\}$$

$$+ \sum_{i>30\text{ MHz}}^{2\text{ GHz}} \text{MAX} \left\{ \left(\frac{E_{\text{inc},i}}{E_{\text{inc,RL},i}} \right)^2, \left(\frac{H_{\text{inc},i}}{H_{\text{inc,RL},i}} \right)^2, \left(\frac{S_{\text{inc},i}}{S_{\text{inc,RL},i}} \right) \right\}$$

$$+ \sum_{i>2\text{ GHz}}^{300\text{ GHz}} \left(\frac{S_{\text{inc},i}}{S_{\text{inc,RL}}} \right) \leq 1,$$

Basic restrictions average SAR

$$\sum_{i=100\text{ kHz}}^{300\text{ GHz}} \frac{\text{SAR}_i}{\text{SAR}_{\text{BR}}} \leq 1$$

Basic restrictions, peak SAR

$$\sum_{i=100\text{ kHz}}^{6\text{ GHz}} \frac{\text{SAR}_i}{\text{SAR}_{\text{BR}}}$$

$$+ \sum_{i>6\text{ GHz}}^{30\text{ GHz}} \frac{S_{\text{ab,4cm},i}}{S_{\text{ab,4cm,BR}}}$$

$$+ \sum_{i>30\text{ GHz}}^{300\text{ GHz}} \text{MAX} \left\{ \left(\frac{S_{\text{ab,4cm},i}}{S_{\text{ab,4cm,BR}}} \right), \left(\frac{S_{\text{ab,1cm},i}}{S_{\text{ab,1cm,BR}}} \right) \right\} \leq 1$$

Figure 7: Summation formulas for evaluation of RADHAZ exposure to multiple frequencies

Figure 8 illustrates an example of multiple frequency exposure evaluation for a naval warship. Multiple antennas are located around the ship's bridge, each transmitting at a different frequency.

To begin the evaluation, RADHAZ zones are computed for each antenna. Feko calculates both occupational exposure and general public exposure zones. The summation formulas are then used to compute the combined RADHAZ zones for all the antennas together. We'll look at how these formulas are applied while examining the evaluation process for low-frequency magnetic fields later in this document.

In this case, the HF radio has the greatest impact on the shape of the RADHAZ zone because of its very high transmission power.

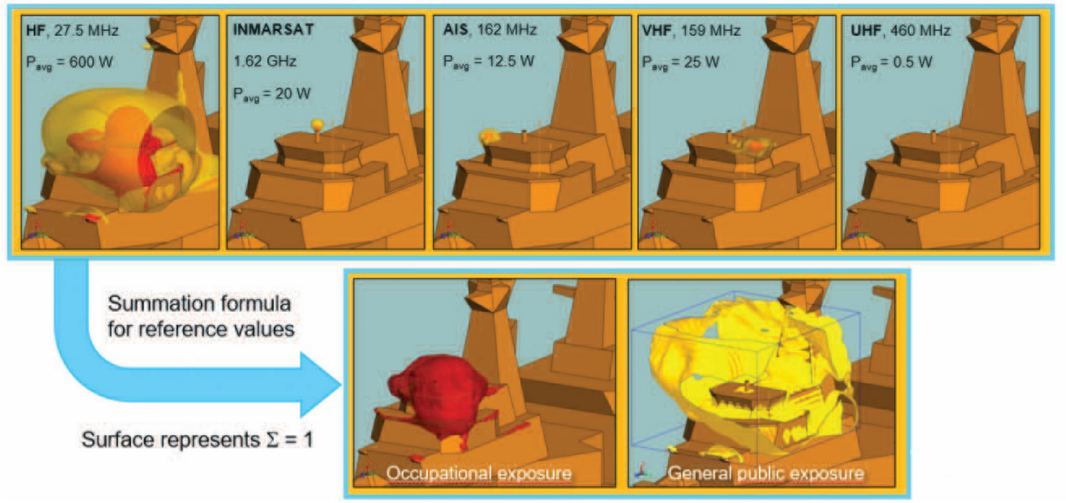


Figure 8: Evaluating simultaneous exposure to multiple frequency fields

Antenna Modeling Process

For modeling antennas and incorporating them into larger models, the Feko component library contains a range of parametrized antenna models—as well as typical scattering objects like ships, aircraft and vehicles—for a variety of applications.

Using these model components, the modeling process is as follows:

1. Choose a generic model of the type you're designing
2. Choose the solver type (appropriate to your chosen antenna's frequency)
3. Choose any additional frequency conditions for which you wish to solve (single frequency, frequency range, both, none)
4. Add to the model your specific antenna parameters:
    - Coordinate transformations (axis/angle of rotation)
    - Port
    - Voltage source
    - Radiated power
    - Near field request
5. Mesh the model
6. Start the simulation

Feko will then compute the RADHAZ zones for occupational exposure and general public exposure.

RADHAZ Zones for Radar Antennas

For radar antennas on ships, the pulse characteristic and rotation of the scanning beam must be considered.

Take the case of a rotating S-Band antenna (f = 3.05 GHz) on a ship, as shown in Figure 9. For the transmitting radar pulse, one computes the average transmitted power (P_{avg}) from peak power (P_t), pulse length (τ) and pulse repetition frequency (f_{PR}).

- Averaged transmitted power: $P_{avg} = Pt \cdot \tau \cdot f_{PR}$

Because the beam is scanning (rotating), the hazard is further reduced. An additional factor of 2x half power beam width / 360° may be applied in the average power calculation.

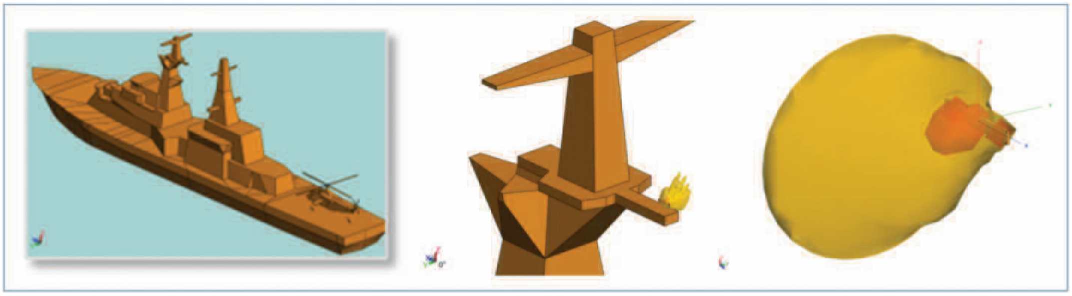


Figure 9: RADHAZ zone simulation for a scanning radar mounted on a ship

Depending on the antenna's mounting position and the positions of scattering objects, the shape of the RADHAZ zone of the mounted antenna will almost certainly differ, due to reflections, from the zone calculated for the component in isolation.

For this simulation, the hybrid MoM/LEPO method was used. Running the simulation required 968 Mb of memory and a runtime of 300 seconds, plus 9.34 ms per field point for each orientation.

Radiation Hazard Analysis in Automotive Applications

Recent trends in the automotive industry—including drivetrain electrification, advanced driver assistance systems (ADAS), autonomous driving (AD), shared mobility and vehicle connectivity—have introduced numerous sources of EMF radiation within and surrounding the latest offerings from the sector. All these sources must be considered in these vehicles' radiation hazard analyses.

Low-Frequency EMF in Vehicles

With the rise of EVs, many new low-frequency field sources must now be analyzed for their potential effects on passengers and the public at large. Examples of these low-frequency sources include:

- High-voltage cables routing power from the battery to the drivetrain and other components
- Inductive charging systems for wireless power transfer
- Seat-heating systems

In the case of high-voltage cables, OEMs must design their systems to secure compliance with EM radiation hazard regulations. ICNIRP has published special guidance on determining compliance with its guidelines in the cases of pulsed and complex non-sinusoidal waveforms below 100 kHz, which is relevant to such cases.

Inductive charging systems should be designed for high transfer efficiency with low scheduling of magnetic fields in the vicinity of the power transfer interface. Even simple seat-heating systems can become relevant sources of EMF emissions that must be analyzed and accounted for.

In all low-frequency cases, the goal of the analysis is to prevent nerve stimulation, as thermal effects will not occur in this frequency range.

Evaluation Process for Low-Frequency Magnetic Fields

To generate a simulation for this analysis, the input data includes the cable path within the vehicle along with the amplitude and waveform of the current.

The time-domain signal of the current of the cables has a significant impact on the result. Therefore, it's convenient to factorize the 3D field simulation into the emission simulation of the unit source (B-Field, internal E-Field transfer function) and the spectrum analysis of the time-domain signal using Discrete Fourier Transformation, as shown in Figure 10. With multiplication, you get the frequency response of the magnetic flux density (B-field) or the internal electric field (E-field) inside the body.

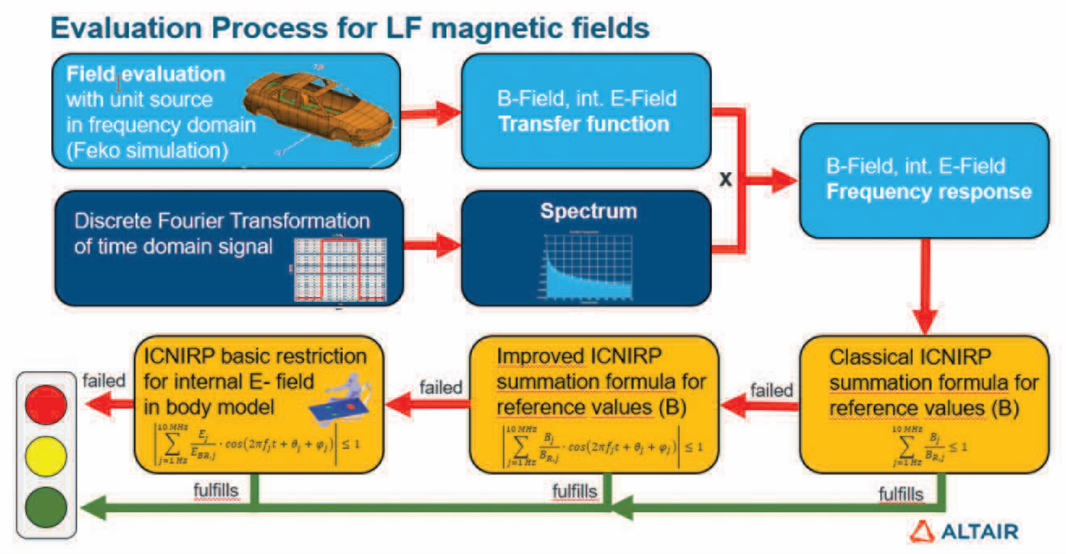


Figure 10: Evaluation process for low-frequency magnetic fields

Next, one applies the classic ICNIRP summation formula (shown previously in Fig. 7) to reference levels over relevant evaluation points. If the sum is less than or equal to one ($\sum \leq 1$), compliance is proved. However, the classic summation formula is quite conservative. It doesn't account for the phase of the magnetic flux density. As a result, ICNIRP has proposed an improved summation formula that takes phasing into account.

Therefore, if the result from the classic formula doesn't meet the requirements, one can apply the improved ICNIRP reference level summation formula. Again, if the sum is less than or equal to one ($\sum \leq 1$), compliance is proved.

If the result achieved with the improved formula also fails, one can then apply the ICNIRP basic restrictions summation formula using the model of the internal E-field inside the human body.

High-Frequency Automotive Applications: Antennas for Mobile Communication

Vehicle antennas for mobile communication—4G, 5G, WLAN, V2V, etc.—operate at higher frequencies (30 MHz to 6 GHz) where thermal effects predominate. If incorrectly designed or positioned, they could cause heating in the bodies of passengers or bystanders.

Modern mobile standards use the multiple-input and multiple-output (MIMO) method for multiplying link capacity. Multiple transmission and receiving antennas are therefore required at different positions on the vehicle. All this makes antenna evaluation far more complex than it was in the past.

Take the case of an antenna positioned on a vehicle's rear bumper or trunk lid as shown in Figure 11 (a reference configuration from IEC/IEEE 62704-2). While external positioning is likely to provide enough distance between the antenna and passengers, radiation hazards to bystanders could become relevant.

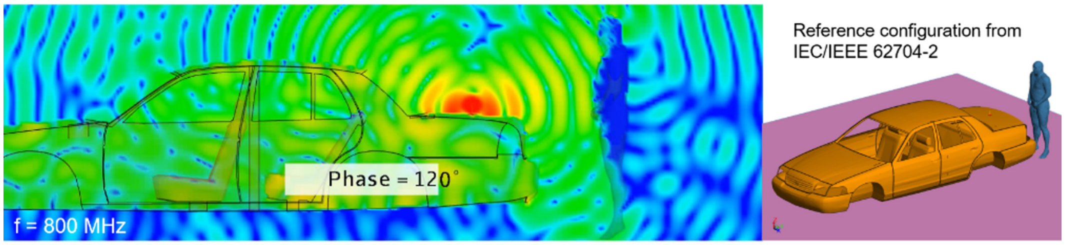


Figure 11: Simulation of high-frequency radiation from an aft-mounted mobile antenna on a vehicle

In the case of an antenna placed inside the vehicle's passenger compartment, it's important to evaluate radiation hazards at the passenger positions. In a worst-case scenario, a thin metallic IR coating (e.g. d = 6nm, s = 61.73 MS/m) on the car windows could have a significant effect (Figure 12).

These coatings are used frequently to reduce the heating of the passenger compartment by IR radiation (sunlight). They also attenuate electromagnetic fields, however, causing most of the radiated power of the antenna to be distributed within the vehicle as standing waves. Such scenarios must be avoided.

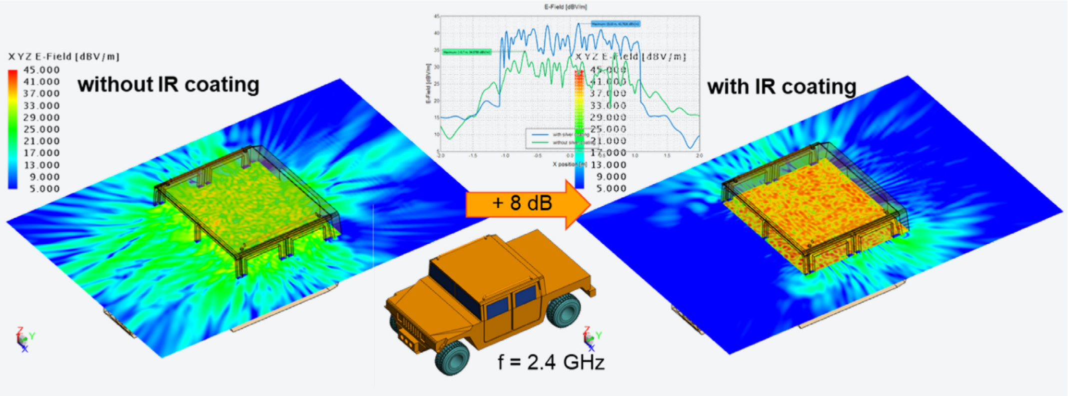


Figure 12: Passenger compartment radiation hazard from an internal WLAN antenna due to reflection by metallic window coating

Methods for Computing Absorption in Dielectric Bodies

Several options are available in Feko for modeling the absorption of radiation in dielectric bodies, as seen in Figure 13. Users can choose an appropriate combination of hybridized methods, depending on their model's size, frequency, and complexity.

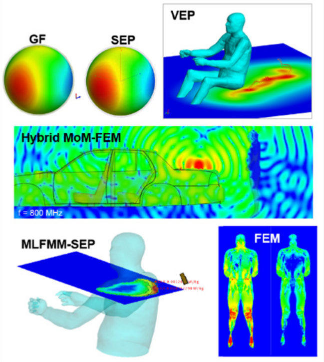


Figure 13: Several options are available to model dielectric bodies in Feko.

Green's Function (GF), for example, is good for evaluating planar or spherical multi-layer structures. Solutions generated with this method are derived from analytical expressions without approximation errors from mesh discretization. Thus, they can be used as reference simulations for validating other approaches.

The **Volume Equivalence Principle (VEP)** uses a tetrahedron mesh and is recommended for very low frequencies.

The **Finite Element Method (FEM)** is very practical for inhomogeneous human body models, as material parameters can be better assigned to tetrahedron meshes.

The **Surface Equivalence Principle (SEP)** is recommended for homogeneous models at frequencies up to 3 GHz, while the **Surface Impedance Method (SI)** is very efficient for very high frequencies above 10 GHz, when radiation absorption occurs predominantly in human skin.

For frequencies between 3 GHz and 10 GHz, the **Dielectric Surface Impedance Approximation (DSIA)** is a new method that was added to Feko in 2021. It combines the advantages of SEP and SI, combining very good convergence behavior (like SI) with a peak average SAR evaluation over the entire body (as in SEP).

Finally, the **Finite Difference Time Domain (FDTD)** method is best suited to problems that include highly inhomogeneous materials. This method is a popular choice in biomedical applications for modeling the human body. It's also a highly efficient solution for wideband problems and is well suited to the analysis of broadband antennas. A single FDTD simulation with a pulsed excitation can be used to characterize a wideband frequency antenna response.

Conclusions

For electronic devices, compliance with the legal regulations regarding radiation hazards must be verified.

With Feko, engineers can evaluate RADHAZ scenarios early in a project's design phase, when corrections are least costly to make. The hybridized solvers in Feko allow the selection of the most appropriate simulation method for the frequency, scale, and complexity of the application at hand.

More Information

For additional examples and demonstrations of how Feko can be used to accomplish radiation hazard analysis in a wide variety of complex scenarios, be sure to view our on-demand webinar on this topic, "Designing for Electromagnetic Radiation Hazard Compliance."

If you'd like to learn more about Feko, visit the Feko product page.

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ii. IEC 62311:2019, Assessment of electronic and electrical equipment related to human exposure restrictions for electromagnetic fields (0 Hz to 300 GHz), IEC, April 2019.

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