MARIE – a MATLAB-based open source software for the fast electromagnetic analysis of MRI systems

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Target audience: RF engineers and MR physicists. **Purpose:** MARIE (MAgnetic Resonance Integral Equation suite) is a MATLAB-based open source prototype software for frequency domain fast electromagnetic (EM) analysis of MRI systems. This analysis includes the full-wave EM simulation of the coil design in the presence of the human body. The goal is to compute the port parameters at the operational frequency, and the detailed EM field distribution in the inhomogeneous body, in order to obtain relevant figures of merit such as B1+, B1- and local SAR maps.

Method: The underlying engine of MARIE is based on integral equation methods applied to the different domains that exist in traditional MRI problems (for example, except in interventional cases, the coil and body occupy separate spaces). The natural domain decomposition of the problem allows us to apply and exploit the best modeling engine to each domain. The inhomogeneous human body model is discretized into voxels, and modeled by volume integral equation (VIE) methods [1]. The homogeneous conductors that form the coil design and shield are tessellated into surface triangles (that allow to model complex and conformal geometries), and modeled by surface integral equation (SIE) methods [2]. Both models are coupled by applying standard dyadic Green functions [3]. Due to the nature of integral equation methods, there is no need to model or discretize the surrounding air or non-electromagnetic materials, although the solution fields can be computed anywhere outside the discretized domain by applying the same free-space Green functions. Also, no boundary condition needs to be defined (integral equations satisfy the radiation condition by construction), which simplifies the setting of the problem for the user: the inputs are the voxelized definition of the inhomogeneous body model, the tessellated geometry of the coil design (which the external ports defined), and the frequency of operation.

Once the models are generated, fast numerical methods are applied to solve the complete system. A set of nested iterative methods with the appropriate preconditioning is used to solve the effect of each port [4]. Fast Fourier Transform (FFT) techniques exploit the regularity of the voxelized grid and accelerate the matrix vector products [1]. Depending on the different analysis scenarios, some numerical models or tasks can be pre-computed to accelerate the solution, and a wide variety of strategies are used to reduce either computational time or memory consumption.

Intended as a development platform, the open-source software includes a simple and intuitive GUI for the standard MRI analysis: scattering analysis for the body, frequency sweep to characterize coil designs, and coupled solver to analyze the complete system including the coils and body. But it also includes a set of well-documented scripts to allow experienced users to create their own analysis, by using or modifying the existing code. The input of the body is voxel-based, and can be read from simple files that define position and tissue properties. The input of the coil design is based on a geometric description, and the software is coupled with gmsh [5], an automatic open-source mesh generator. The underlying numerical routines can be used to address other relevant problems, such as the generation of ultimate intrinsic SNR and SAR on realistic body models, fast coil design and optimization, and generation of patient specific protocols, among others.

Fig. 1.A – Snapshot of MARIE's graphic user interface with body and coil models loaded.

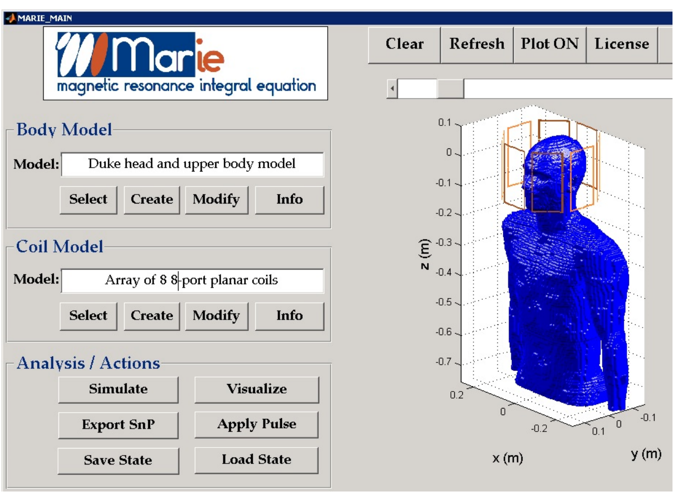
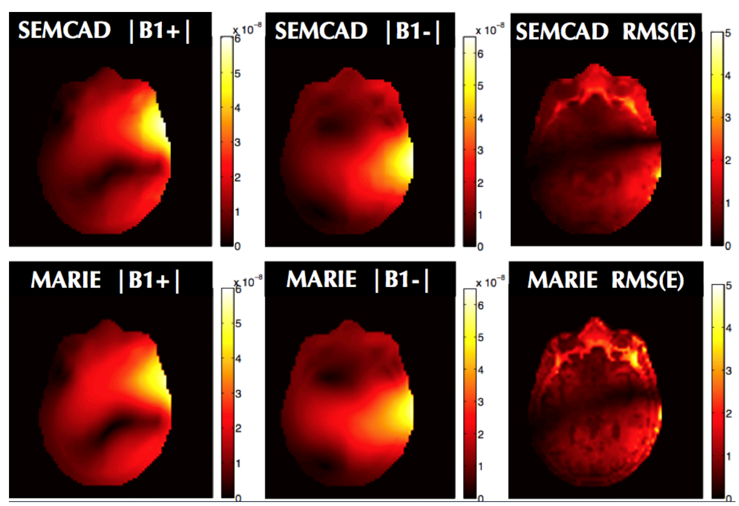


Fig. 1.B – Comparison of the (left) B1+, (center) B1-, and (right) RMS(E) maps for DUKE. Top maps are with SEMCAD [6], bottom with MARIE.



Results and Discussion: Figure 1.A shows a snapshot of the GUI. Figure 1.B shows representative field maps inside an inhomogeneous body model (3mm resolution DUKE [7]), for a tuned and matched 8-gap planar coil, and compared against SEMCAD (SPEAG, Switzerland) results for the same example. Notice that despite the differences in modeling strategies and discretization, the maps show a good qualitative agreement. An extensive validation of the code has been performed, benchmarking it against a wide variety of commercial and open-source solvers, e.g. SEMCAD, FEKO (EMSS, South Africa), SCUFF-RF [8].

The software, running on MATLAB and on a single standard GPU-accelerated windows desktop, is able to solve a complex scattering problem in ~2-3 min. It can perform a frequency sweep of a complex coil in ~3-5 min. per frequency point. Furthermore it can solve the complete inhomogeneous body and coil system in ~5-10 min. per port, depending on the resolution and error tolerance required.

References: [1] Polimeridis et al, JCP 2014. [2] Rao et al, TAP 1982. [3] Tai, IEEE 1994. [4] Villena et al, arxiv 2014. [5] Geuzaine et al, IJNME 2009 [6] SEMCAD, SPEAG Ch. [7] Christ et al, PBM 2010 [8] Reid et al, PRL 2009.

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