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Imaging Three-Dimensional Bodies by Processing Multi-frequency Data through a Multiscale Swarm Intelligence Based Method

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This contribution is aimed at investigating the potentialities and current limitations of the multiscale particle swarm method when processing multi-frequency data scattered by three-dimensional structures. Such a global optimization approach demonstrated its effectiveness in solving complex two-dimensional imaging problems. Therefore, it has been suitably-modified for dealing with three-dimensional geometries and integrated into multi-frequency inversion schemes. Selected numerical results are shown in order to allow a preliminary evaluation of the reconstruction accuracy of the proposed implementations.

Introduction

Microwave imaging systems usually collect the electromagnetic radiation scattered by the unknown objects under test by using multi-view and multi-illumination acquisition setups. In order to improve the reconstruction accuracy of inversion algorithms, measurements at different frequencies are exploited as well. Toward this end, frequency-hopping strategies [1] or methods based on the simultaneous processing of multi-frequency data [2] - [4] have been proposed and investigated. Unfortunately, when dealing with multi-frequency field samples, some issues should be carefully addressed in order to obtain effective and reliable inversion schemes. As matter of fact, multi-frequency processing requires additional computational resources (in comparison with the monochromatic case) because of the increase of the unknowns as well as of the problem constraints. Furthermore, the constitutive parameters vary with the working frequency of the probing source, even though a suitable dispersion model might simplify the description of the relationship between dielectric parameters and operating frequency [2].

In this context, several works have been carried out in order to asses the capabilities of multi-frequency strategies, especially adopting single-step strategies [1] - [3]. Successively, other research works considered the processing of multi-frequency information through multi-scale strategies [4][5] in order to exploit the advantages of a multi-resolution expansion taking into account the enlarged set of information coming from the scattering experiments at different frequencies. In particular, the approach proposed in [5] has been focused on the reconstruction of two-dimensional profiles through a multi-scaling (IMSA) strategy integrated with a deterministic optimizer. In this paper, a preliminary assessment of the capabilities and the limitations of the customized extension of the 3D IMSA-PSO [6][7][8] when procecessing multi-frequency data is carried out.

Problem Formulation and Reconstruction Strategy

Let us refer to a three-dimensional scenario D characterized by the contrast function $\tau_p(\underline{r}) = \varepsilon_r(\underline{r}) - 1 - j\sigma(\underline{r})/2\pi f_p \varepsilon_0$ and illuminated by a set of $p = 1,\dots,P$ monochromatic (f_p being the p-th working frequency) incident electric fields impinging from V different directions ($\underline{E}_{v,p}^{inc}(\underline{r})$, $v = 1,\dots,V$, $p = 1,\dots,P$). For each illumination, the multi-frequency information available from the scattered field measures, $\underline{E}_{v,p}^{scatt}(\underline{r}_{m_{v,p}})$, is collected at $m_{v,p} = 1,\dots,M_{v,p}$ measurement points, $\underline{r}_{m_{v,p}} \in D_O$. The physical relationships between the contrast function and the scattering data are provided by the well known integral scattering equations [8]. Such equations are usually solved for a set of unknown parameters that in the multi-frequency case turns out to be $\underline{\gamma} = \left\{\tilde{\tau}(\underline{r}_n), E_{v,p,h}^{tot}(\underline{r}_n), p = 1,\dots,P, v = 1,\dots,V, n = 1,\dots,N, h = x,y,z\right\}$, $E_{v,p,h}^{tot}(\underline{r}_n)$ being the h-*th* component of the total field in the n-*th* discretization cell of D at the v-*th* illumination of the p-*th* frequency and $\tilde{\tau}(\underline{r}_n)$ is the contrast function at a reference frequency $\tilde{f}$. As a matter of fact, under some assumptions [2], the contrast at the p-*th* frequency can be expressed as function of that at $\tilde{f}$:

$$\tau_p(\underline{r}) = \mathrm{Re}\left\{\tilde{\tau}(\underline{r})\right\} + j\frac{\tilde{f}}{f_p}\mathrm{Im}\left\{\tilde{\tau}(\underline{r})\right\}. \quad (1)$$

Notwithstanding the enlarged information, the inverse scattering problem still remains ill-posed and ill-conditioned, therefore it is usually addressed by looking for $\underline{\gamma}_{opt}$ that minimizes the following cost function

$$\Psi(\underline{\gamma}) = \frac{\sum_{p=1}^{P}\sum_{v=1}^{V}\sum_{m_{v,p}=1}^{M_{v,p}}\sum_{h=x,y,z}\left|E_{v,p,h}^{scatt}(\underline{r}_{m_{v,p}}) - \Theta_{v,p}^{ext}\left[\underline{\gamma}\right]\right|^2}{\sum_{p=1}^{P}\sum_{v=1}^{V}\sum_{m_{v,p}=1}^{M_{v,p}}\sum_{h=x,y,z}\left|E_{v,p,h}^{scatt}(\underline{r}_{m_{v,p}})\right|^2} + \frac{\sum_{p=1}^{P}\sum_{v=1}^{V}\sum_{n=1}^{N}\sum_{h=x,y,z}\left|E_{v,p}^{inc}(\underline{r}_n) - \Theta_{v,p}^{\mathrm{int}}\left[\underline{\gamma}\right]\right|^2}{\sum_{p=1}^{P}\sum_{v=1}^{V}\sum_{n=1}^{N}\sum_{h=x,y,z}\left|E_{v,p,h}^{inc}(\underline{r}_n)\right|^2} \quad (2)$$

where $\Theta_{v,p}^{ext}$ and $\Theta_{v,p}^{\mathrm{int}}$ are the external and internal scattering operators [8]. The trial array $\underline{\gamma}$ is iteratively updated by expressing in an adaptive and multiresolution fashion the unknown distributions (i.e., fields and dielectric parameters) [8]. Towards this end and in order to effectively deal with multifrequency data, the 3D IMSA-PSO reconstruction strategy has been improved by taking into account the following key-points.

Firstly, the particle swarm algorithm has been suitably integrated in the multi-step and multi-frequency scheme in order to allow a more effective sampling of the solution space. Towards this end, besides the adaptive allocation of the unknowns that allows a step-by-step increase of the spatial resolution only in the regions of interest (RoIs) of D [8], the dimension of the discretization grid (N_p, $p = 1,...,P$) is chosen according to the information content of the data at each frequency [3]. In particular, the unknowns are expressed as

$$\tilde{\tau}(\underline{r}) = \sum_{l_s=1}^{L_s} \sum_{n(l_s)=1}^{\tilde{N}(l_s)} \tilde{\tau}(\underline{r}_{n(l_s)}) \Omega_{n(l_s)}(\underline{r}) \tag{3}$$

$$E_{v,p,h}^{tot}(\underline{r}) = \sum_{l_s=1}^{L_s} \sum_{n(l_s)=1}^{N_p(l_s)} E_{v,p,h}^{tot}(\underline{r}_{n(l_s)}) \Omega_{n(l_s)}(\underline{r}) \tag{4}$$

where l_s indicates the l-*th* resolution level at the s-*th* step of the multiresolution approach, and $\Omega_{n(l_s)}(\underline{r})$, $n(l_s) = 1,...,N_p$ is a suitable set of rectangular basis functions. In such a way, we obtain: (*i*) a reduction of the dimension of the solution space compared to both a bare approach where the investigation area is homogeneously discretized and a multi-frequency procedure with a discretization independent from the working frequency; (*ii*) an effective exploitation of the features of swarm intelligence in sampling complex and nonlinear solution spaces also when dealing three-dimensional scenarios.

Numerical Results

Let us consider a multilayer scatterer centered at $x_0 = y_0 = 0.0$ of volume $0.6 \times 0.6 \times 0.6\lambda^3$ (being λ the wavelength at 1GHz). The object function of the three dielectric layers are $\tau_1 = 0.5$, $\tau_2 = 1.0$, $\tau_3 = 1.5$, respectively. Moreover, the volume of each layer is equal to $0.2 \times 0.6 \times 0.6\lambda^3$. The investigation domain is a cube $L = 1.2\lambda$-sided, which has been illuminated by V=4 plane waves with the arrangement described in [8]. Concerning the scattering data, the scattered field has been collected at 21 points-like receivers located in G=3 rings ($\rho = 2.93\lambda$ in radius). These data (P=2, $f_1 = 1GHz$, $f_2 = 2GHz$) have been corrupted by adding a Gaussian noise characterized by SNR=30dB. The optimization problem has been handled by using at each step of the multi-step procedure a swarm of

$I = 20$ particles systematically moved in the solution space through the PSO-strategy with inertial weight and acceleration parameters calibrated in [7].

The results obtained by means of the PSO-based IMSA-MF are shown in Fig. 1, where the reference distribution is compared to the reconstructed one by considering a slice of the profile in the XY e YZ planes of the three-dimensional structure. The retrieved distribution allows one to distinguish the layered nature of the object under test, even though when the reference contrast increases the quantitative reconstruction of the profile becomes less accurate. As far as the computational cost of the proposed three-dimensional stochastic multi-scaling scheme is concerned, the multi-resolution strategy considerably contains the global optimization processing of multifrequency data, thanks to the optimal allocations of the problem unknowns provided by the IMSA.

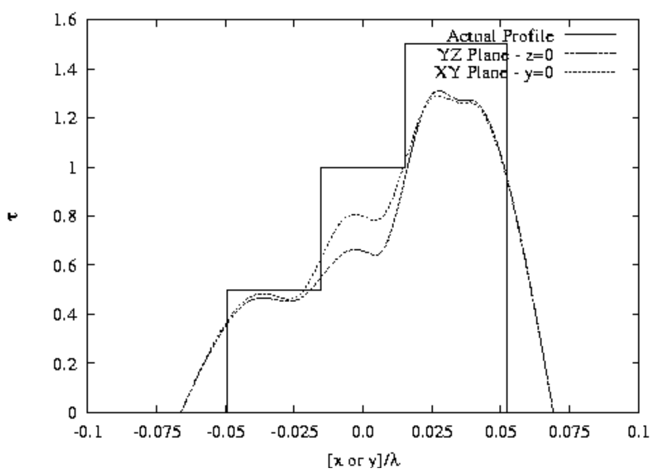

Figure 1. Multi-layer dielectric cube – Actual and reconstructed profile by means of the PSO-based multifrequency IMSA. Comparison between slices at z=0.0 in the YZ plane and x=0.0 in the XY plane.

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