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High-resolution microwave diagnostics of architectural components by particle swarm optimization

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We present a very simple monostatic setup for coherent multifrequency microwave measurements, and an optimization procedure to reconstruct high-resolution permittivity profiles of layered objects from complex reflection coefficients. This system is capable of precisely locating internal inhomogeneities in dielectric bodies, and can be applied to on-site diagnosis of architectural components. While limiting the imaging possibilities to 1D permittivity profiles, the monostatic geometry has an important advantage over multistatic tomographic systems, since these are normally confined to laboratories, and on-site applications are difficult to devise. The sensor is a transmitting-receiving microwave antenna, and the complex reflection coefficients are measured at a number of discrete frequencies over the system passband by using a general-purpose vector network analyzer. A dedicated instrument could also be designed, thus realizing an unexpensive, easy-to-handle system. The profile reconstruction algorithm is based on the optimization of an objective functional that includes a data-fit term and a regularization term. The first consists in the norm of the complex vector difference between the measured data and the data computed by a forward solver from the current estimate of the profile function. The regularization term enforces a piecewise smooth model for the solution, based on two 1D interacting Markov random fields: the intensity field, which models the continuous permittivity values, and the binary line field, which accounts for the possible presence of discontinuities in the profile. The data-fit and the regularization terms are balanced through a tunable regularization coefficient. By virtue of this prior model, the final result is robust against noise, and overcomes the usual limitations in spatial resolution induced by the wavelengths of the probing radiations. Indeed, the accuracy in the location of the discontinuities is only limited by the system noise and the discretization grid used by the forward solver. The algorithm we chose to optimize the objective is based on the particle swarm paradigm. Each feasible solution is coded as a location in a multidimensional space, explored by a number of "particles" each moving with a certain velocity, which is partly random and partly induced by the experience of both the particle itself and the "swarm" of all the other particles. In our case, the search is complicated by the mixed continuous-binary nature of our unknowns, but the swarm intelligence approach maintains the advantage of its intrinsic parallelism. The experimental results we obtained from both simulated and real measurements show that, for typical permittivity values and radiation wavelengths, the spatial resolution is highly improved by the line process. From real measurements in the range 1.7-2.6 GHz, we accurately reconstructed the permittivity values of our test phantom and located the discontinuities within the limits imposed by our discretization grid (with 1.5 mm cell thickness). At present, the applicability of our reconstruction method is still limited by the forward solver, which is based on a cascaded transmission-line model that assumes normal and plane-wave incidence. We are developing a new solver based on a closed-form Green's function in multilayered media, which should enable us to model appropriately both the microwave sensor and the illumination geometry, thus improving the accuracy of the computed reflection coefficients in the objective functional.