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Multi-shot Calibration Technique for Microwave Imaging Systems

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Abstract—This paper proposes a novel “multi-shot” calibration technique that reduces imaging microwave reconstructions artifacts, compensating for uncontrolled variations during the measuring process and later propagated in the inversion. The calibration combines different consecutive sets of measured data with simulated ones in a post-processing stage, providing benefits without the need for additional experimental reference calibrations. The proposed scheme is tested experimentally in a non-trivial scenario. A microwave scanner images an early-stage hemorrhagic stroke in the left parietal lobe, applying a differential imaging algorithm based on the truncated singular value decomposition. Though, the proposed mechanisms can be used for other microwave imaging devices. The results reveal that the calibration procedure improves the quality of the retrieved images compared to the non-calibrated approach, cleaning the images and making the interpretation of imaged contrast variation easier.

Index Terms—Measurements calibration, microwave imaging, numerical simulation, microwave antenna arrays, microwave propagation.

I. INTRODUCTION

Microwave imaging (MWI) is a technology that relies on the contrast of the electrical properties (permittivity and conductivity) at microwave frequencies between a target and its background to retrieve quantitative or qualitative images of a domain of interest (DOI). Therefore, quantitative algorithms as the distorted Born iterative method (DBIM) or the contrast source inversion (CSI) algorithm aim to recover the actual dielectric values [1], [2]. In contrast, qualitative ones focus on identifying the location and shape of the contrast, e.g., the truncated singular value decomposition (TSVD) applied to weak scatters [3]. MWI approaches thus a nonlinear and ill-posed inverse scattering problem moving from a limited number of measurements, usually out of DOI, to a description of dielectric map in DOI [4]. Hence, a non-well-conditioned problem and corrupted input data might cause unwanted artifacts on the retrieved images.

MWI is a technology with a high potential of applicability on day-to-day problems due to its characteristics of penetrability and non-ionizing nature that have allowed it to spread over several fields. For instance, it is being researched in medical applications where pathological conditions present traceable variations in time as breast cancer [5], brain stroke [6], [7],

cervical diseases [8], knee injuries [9]. Moreover, MWI has been used in the industrial domain for food quality assessment [10]–[12]. As a solution, MWI is projected as a complement to other imaging alternatives most of the time, e.g., ultrasound or magnetic resonant imaging (MRI). MWI is a technology in development and thus faces multiple challenges, especially in the applied field.

In all real scenarios, the MWI systems deal with weak signals, highly affected by the noise, suffering the introduction of different types of errors and variations compared to the ideal nominal contexts. Thus, calibration techniques are required to mitigate these unavoidable issues. For example, it is common practice in our days to use preliminary know-scenarios or targets to tune or characterize the MWI device [5]–[7], [13], [14]. Also, it can be applied novel techniques like the one proposed by the authors in [15], where instead of rendering the measurement close to the EM operator, it is calibrated using the measured and simulated data. Another novel approach, yet application depending, is presented in [11], where the authors propose a phaseless parametric inversion for system calibration. In general, the calibration aims to reduce the undesired perturbation’s effects on the final dielectric mapping applying diverse strategies.

Here, we propose a novel “multi-shot” calibration technique that reduces imaging microwave reconstructions artifacts, compensating for uncontrolled variations during the measuring process as shown later in Sect. IV. The calibration combines different consecutive sets of measured data with simulated ones in post-processing, extrapolating the information of interest. Thus, the technique provides a good trade-off between the data required and benefits on the imaging reconstruction. It just needs an additional set of measurements, which is a reasonable condition for many systems. Moreover, the proposal is a complementary alternative to other calibration solutions, easily implementable since no additional hardware or complex setups are required.

The paper is organized as follows. Section II comments on the MWI prototype, the imaging algorithm, as well as describes the “multi-shot” calibration procedures. Section III details the experimental validation including the setup and results. Finally, Sect. V presents the conclusions and future work.

Considering the left branch, as the other is equivalent, the first step is to apply the dubbed ‘‘HwSw-Cal’’, which uses hardware and software calibration [6]. The hardware part (HW) bases on the transmission coefficients measured in the auxiliary reference channel described in Sect. II-A, and aims to reduce the effects of multiplicative inaccuracies on scattering transfer parameters between all the antenna pairs. For instance, HW calibration faces drift errors in the VNA and/or in the switching matrix and uncertainties due to environmental conditions. The HW calibration used the S-parameters of the channel at t_0 and t_1 , which is not affected by the intentional variation in DOI, to compensate the response at t_1 as shown in Eq. 4. A more detailed explanation of the Hw calibration can be seen in [6].

$$\overline{\Delta S}_{p,q}(t_0, t_1) = S_{p,q}(t_0) - \frac{S_{\text{REF}}^{\text{REF}}(t_0)}{S_{\text{REF}}^{\text{REF}}(t_1)} S_{p,q}(t_1) \quad (4)$$

In addition to the described Hw calibration, a second calibration, ‘‘software calibration’’ (Sw), is also applied. This technique uses a known scenario in both the numerical modeling and the real system [13]. Then to adjust the measurements, we apply the HW calibrated data to the SW calibration as write in Eq. 5, which has shown reach better results than just applied one of them [6].

$$\widetilde{\overline{\Delta S}}_{p,q}(t_0, t_1) = \frac{\tilde{S}_{p,q}^{\text{H}}}{S_{p,q}^{\text{H}}} \overline{\Delta S}_{p,q}(t_0, t_1), \quad (5)$$

where $\tilde{S}_{p,q}^{\text{H}}$ and $S_{p,q}^{\text{H}}$ are the simulated and measured scattering parameters for the generic p, q antenna pair in the known case, respectively. Here, we use healthy state as known scenario.

Once the scattering parameters are calibrated, the retrieved dielectric maps are obtained projecting the calibrated differential scattering data into the linearized operator (see Sect. II-B). Then, the contrasts are normalized and interpolated in a 1 mm^3 voxel grid, tetrahedral one initially, to later apply a voxel filtering. The voxel filter acts as a low-pass filter on the data, removing the spikes (atypical points) on the reconstructions and smoothing the image. It performs a 3-D average as illustrated in Fig. 3, where the voxel in blue is averaged with its neighbors. Thus, depending on the voxel’s position in DOI, it enters in one of the depicted cases. Though, most of the voxels consider its 29 closest surrounding neighbors. Figure 4 presents a comparison between a filtered and non-filtered case.

Finally, after getting the two pre-processed contrast maps, a point to point averaging between them is applied. Here, it is worth noticing that the averaging might be further extended using the cases $S(t_3) - S(t_0)$ and $S(t_2) - S(t_1)$.

III. EXPERIMENTAL VALIDATION

For the experimental validation, we set a simplified monitoring scenario of an early-stage stroke using a 3-D printed single cavity anthropomorphic head phantom [24], and plastic pod for mimic the stroke as shown in Fig. 5. These are filled with mixtures mimicking the electrical properties of the average brain tissues and blood, around $\epsilon_r = 45, \sigma = 0.7$

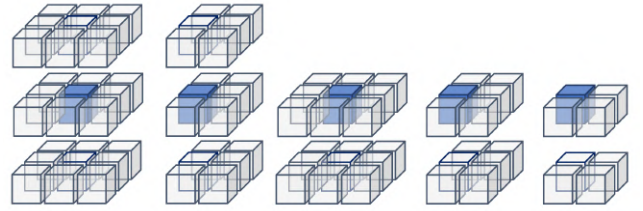


Fig. 3. Voxel filtering considering the different vicinity configurations. The blue voxel indicates the filtered one.

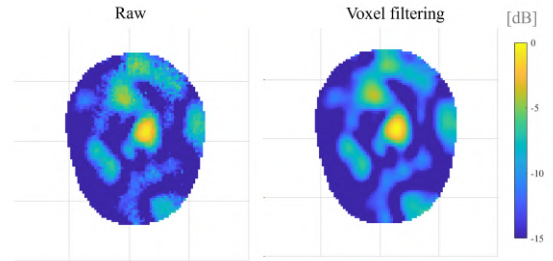


Fig. 4. Reconstruction applying and without applied voxel filtering.

and $\epsilon_r = 65, \sigma = 1.55$ at 1 GHz, respectively [6]. Moreover, the stroke dimension and its location were based on a left parietal lobe lesion, pathology that might cause speech impairments [25]. This modeled situation is specially challenging considering the dimensions and non-even shape of the stroke target as shown in Fig. 5.

The validation then considers two sets of consecutive measures (shot) of the healthy (without the stroke) and unhealthy situations, i.e., two initial measures of the healthy scenario and then two unhealthy ones. Though, this configuration might also represent the variation between to different states of a stroke. The VNA is set measures around 1 GHz, with input power of -6 dBm and the intermediate filter (IF) to 50 Hz, reaching a the noise floor above -110 dB . The measuring time of the whole 24×24 S-matrix is in the order of the 6 minutes per set, however, there is an additional time slot between the healthy an unhealthy measurements, that was used to introduce the stroke inside the head. Besides, for the unhealthy cases, the stroke is fixed in its position using a wooden stick and an external support.

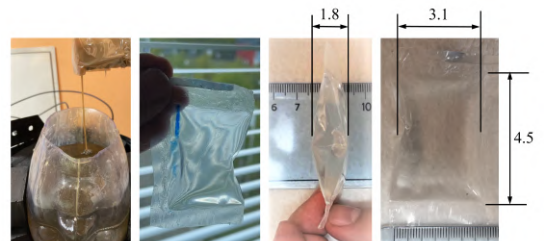


Fig. 5. Phantoms used during the experiment. (Left-to-right): Anthropomorphic head phantom with target hold inside; pod-shaped stroke; lateral view; frontal view. All dimensions in [cm].

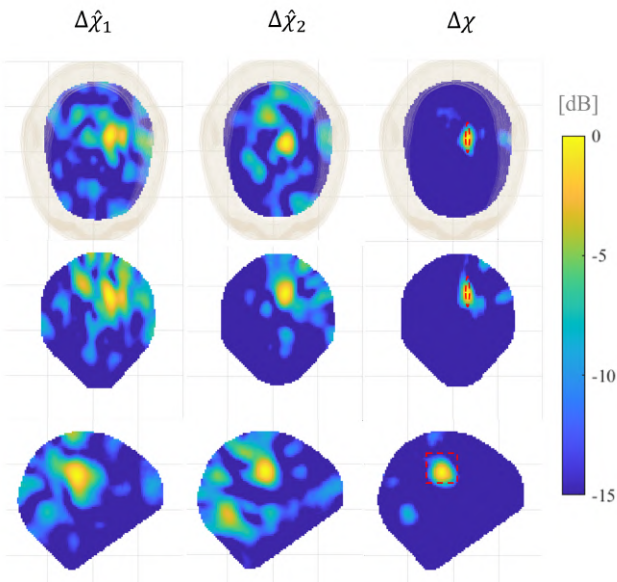


Fig. 6. Amplitude normalized of the reconstructed dielectric contrast. (Top-to-bottom Rows): Transverse plane; Frontal plane; Sagittal plane. The red squares in the right column indicates the position and shape of the stroke.

IV. RESULTS

The results are summarized in Fig. 6. The columns refer to the normalized reconstructed dielectric contrast using the different sets of differential S-parameters, healthy and unhealthy scenarios, and the one applying the “multi-shot” calibration. The rows consider the transverse, frontal, and sagittal planes center at the maximum of each reconstruction. Here, it is worth mentioning that the resulting contrast is a 3-D image, although just the main views are presented.

From the results, it can be noticed first that the imaging algorithm can identify the location of the stroke correctly and with a reasonable estimation of the shape in all cases. Also, it is noticeable from the non-multi-shot calibrated results the repetitively of the experiment, yet the artifacts generated by the remained non-HwSw-calibrated disturbances.

On the other hand, The calibrated results improve the quality of the retrieved images, removing a large number of artifacts. The final results show a precise detection of the stroke, isolated from the background, and a good shape retrieval even in the shortest dimension of the target (less than 2 cm).

V. CONCLUSIONS

This work presented an off-line complementary calibration tool that allows improving the quality of the reconstruction from a microwave imaging system using a “multi-shot” approach. The proposed technique counterbalances the undesired perturbation propagated in the imaging using a double set of measurements and reconstructions. Here, the technique was applied to imaging a brain stroke, experimentally emulated, showing significant improvements on the resulting images. Though, the technique could be used as complementary calibration for other MWI systems. We aim to extend the

validation of the “multi-shot” calibration testing in complex scenarios and other MWI systems for future work.

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