Antenna Phase Center and Angular Dispersion Estimation Using Planar Acquisition Setup Applied to Microwave Breast Imaging

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***Abstract*— We propose a "near-field phase center" estimation technique based on planar acquisition setup. It requires a single antenna and an electrically small object to serve as target. The technique allows to estimate the phase center spatial coordinates, as well as its angular dispersion. This data is useful in microwave imaging applications where the antenna operate in near-field regime, such as medical applications (e.g. breast and head imaging). We demonstrate that for a commonly used Vivaldi antenna operating in the 2-5 GHz band, the angular dispersion of the pseudo phase center can be as high as 50 mm. Moreover, we show that incorporating this data in the signal processing algorithms improves the imaging results, by applying it to microwave breast imaging. We believe this type of antenna-characterization techniques will leverage the use of more informative imaging algorithms (e.g. truncated singular value decomposition), since they increase the accuracy of the distance calculations, thus improving the signal to noise ratio.**

***Index Terms*— angular dispersion, antenna measurement, balanced antipodal Vivaldi antenna (BAVA), microwave imaging (MWI), near-field measurement, phase center.**

I. Introduction

Microwave imaging (MWI) has long been studied for remote sensing applications, such as synthetic aperture radar. In the last two decades, there has been a big research investment on MWI for medical applications, in particular breast and head imaging [1]-[4].

In such systems, the probing antennas are distributed around the body and pick up the weak signals originated from the tissues inside. Moreover, they are intentionally placed very close to the body, in order to minimize the amplitude loss due to the radial spread of the travelling wave, which would further decrease the level of the incoming signal. As a consequence, the antennas operate in the near-field regime.

Here, we investigate a technique for estimation of the "pseudo near-field phase center" (PNPC) of the probing antenna, as well as its angular dispersion. Contrarily to techniques found in literature [5],[6], which require at least two antennas, the proposed measurement technique only requires the antenna under test (AUT) and a single target that linearly sweeps the space. This way, the setup gets much simplified and we eliminate any distortion caused by the probe.

We discuss the impact of calibrating the PNPC by applying it to the microwave breast imaging setup developed within our group [7]. The "phase center" data is accounted in the imaging algorithm, thus producing more accurate images of the breast. Although the discussion is based on a particular application, the technique may be applied to other MWI applications that operate in close proximity to the body.

The paper is organized as follows: section II formulates the problem, whereas section III describes the acquisition setup. The phase center estimation results and the discussion of the impact on the imaging results are addressed in section IV. Lastly, the conclusions are drawn in section V.

II. Problem formulation

In this section, we formulate the problem under study in this paper. For simplicity, the formulation will be applied to breast imaging, but it can be easily extended to other applications.

Figure 1 sketches the problem at hands, where the breast is the imaging domain. Therein, we identify the antenna illuminating the body, located at coordinates $(r_a, \theta_a, \varphi_a)$, the tumor at coordinates $(r_t, \theta_t, \varphi_t)$ and a generic synthetic focal point under test with coordinates $(r_p, \theta_p, \varphi_p)$. Lastly, we designate the coordinates of the synthetical focal point referred to the phase center of the antenna as $(r'_p, \theta'_p, \varphi'_p)$.

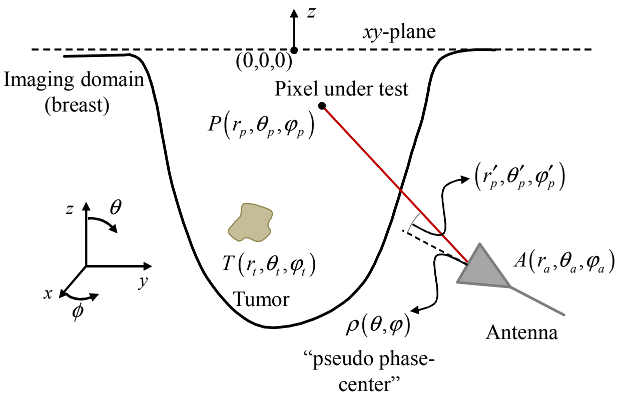

Figure 1: Representation of the problem being analyzed.

Given the proximity of the antenna to the body, the antenna observation angles (θ'_p, φ'_p) may take values as high as 60 degrees. As a result, it is not possible to designate a static spatial point from which we assume the energy is being radiated, which would be the conventional definition of phase center. Instead, we define the phase center as a two term factor: $\rho(\theta,\varphi) = \rho_0 + \Delta\rho(\theta,\varphi)$, where ρ_0 is a fixed reference point, and $\Delta\rho(\theta,\varphi)$ accounts for the spatial fluctuation of the phase center depending on the observation angles. For an adequate calibration of the PNPC, both terms need to be characterized *a priori*.

If the information about the phase center is known, we can account for it in the imaging algorithm, thus obtaining more accurate images of the body. In that case, the reflectivity of the synthetical focal points of the imaging domain can be calculated as [7]

$$refl(r,\theta,\varphi) = \frac{1}{N_a N_f} \sum_{N_a} \sum_{N_f} \mathbf{S}_a \exp\{2jk_0 D_i\}, \qquad (1)$$

where k_0 is the free-space wave-number, N_a is the number of probing antennas, N_f is the total number of useful frequencies, $\mathbf{S}_a$ designates the measured reflections from the breast (after skin reflection is removed), and the term $D_i(\theta,\varphi)$ comprises the distance travelled by the propagating wave between $\rho(\theta,\varphi)$ and (r_p,θ_p,φ_p). The final image is then calculated as

$$I(r,\theta,\varphi) \propto |refl(r,\theta,\varphi)|^2 \qquad (2)$$

For convenience, the final images will be presented in dB scale and using Cartesian referential, $10\log_{10}[I(x,y,z)]$.

This imaging algorithm corresponds to a matched filter technique, which is quite robust to errors in the distance calculations. At this stage, we intentionally opted for this type of techniques, in order to obtain reliable images of the body, as a tradeoff with spatial resolution.

III. PLANAR ACQUISITION SETUP

In this section, we describe the measurement setup used to characterize $\rho(\theta,\varphi)$. It only requires the probing AUT and an electrically small "omnidirectional" target. By using a spherical metal target instead of a probe antenna for PNPC estimation, we eliminate the influence of the probe, which may also have a moving phase center. The target sweeps the space over an area in front of the antenna, as represented in Figure 2.

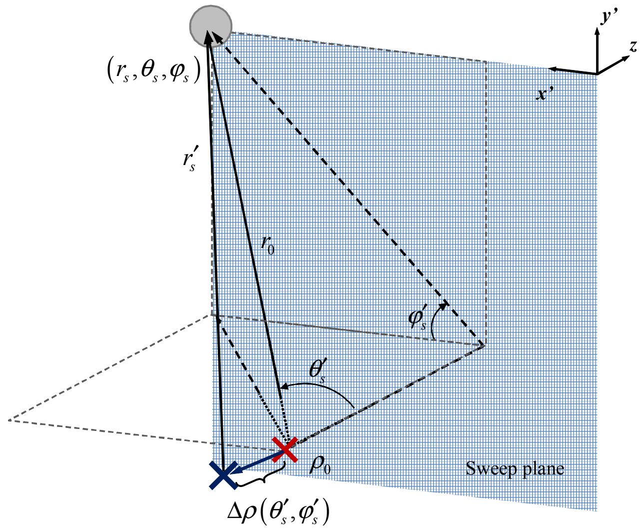

Figure 2: Representation of the planar acquisition setup for "pseudo near-field phase center" estimation, where the spherical target sweeps a plane and the antenna acquires its echo.

For each position of the target, (r_s,θ_s,φ_s), the antenna records the input reflection coefficient containing the echo of the target along frequency, $\mathbf{S}_s$.Based on the latter, we can infer the distance at which the target is detected, r'_s, by analyzing the signals in time domain. To this end, one may assume the reference point (0,0,0) to be located on the aperture of the antenna.

Once distances r'_s are calculated, we may compute ρ_0 coordinates as the average coordinates of the pseudo phase center in both vertical $(\theta'_s, \varphi'_s = 90^\circ)$ and horizontal $(\theta'_s, \varphi'_s = 0^\circ)$ planes:

$$\rho_0 = \frac{1}{2}\left[\rho(\theta'_s, \varphi'_s = 90^\circ) + \rho(\theta'_s, \varphi'_s = 0^\circ)\right]. \qquad (3)$$

In turn, $\rho(\theta'_s, \varphi'_s = 90^\circ)$ and $\rho(\theta'_s, \varphi'_s = 0^\circ)$ are computed as the spatial coordinates that minimize the following least-square problems:

$$\rho(\theta'_s, \varphi'_s = 90^\circ) = \min_{\theta'_s \le \theta'_{max}} \left\{ \sqrt{\sum_{\theta_s} \left[r'_s(\theta'_s, \varphi'_s = 90^\circ) - r_s^{avg}(\theta'_s, \varphi'_s = 90^\circ) \right]^2} \right\} \qquad (4)$$

$$\rho(\theta_s',\varphi_s'=0^\circ)=$$

$$\min_{\theta_s'\le\theta_{\max}'}\left\{\sqrt{\sum_{\theta_s}\left[r_s'(\theta_s',\varphi_s'=0^\circ)-r_s^{avg}(\theta_s',\varphi_s'=0^\circ)\right]^2}\right\} \quad (5)$$

In these expressions, r_s' designates the distance between the ρ_0 under test and the spherical target, and $r_s^{avg}(\theta_s',\varphi_s'=90^\circ)$ and $r_s^{avg}(\theta_s',\varphi_s'=0^\circ)$ designate the average values of the measured r_s' in the two main planes. Note that the least square problems have to be limited to an angular interval of interest, $\theta_{\max}'$. If not done so, the solution may converge to a point that is physically not relevant. We note that this is not mandatory, since the term $\Delta\rho(\theta,\varphi)$ can accommodate any variations of ρ_0. Once ρ_0 is estimated, $\Delta\rho(\theta,\varphi)$ is computed as the distance difference between r_0 and r_s' (recall Figure 2).

Lastly, we highlight that this formulation does not take into account any frequency dispersion behavior of the antenna phase center, but only its angular dependency.

IV. Experimental Results

A. Phase center estimation results

The technique described in the previous section was applied to the balanced antipodal Vivaldi antenna (BAVA) presented in [7]. It operates in the [2, 5] GHz band and the radiation pattern is mostly focused towards the breast within the band of interest. Vivaldi antennas provide a very broad frequency bandwidth, but the phase center is known to vary along frequency. To the best of the authors' knowledge, this was the first time that the angular dispersion of Vivaldi antennas was studied in the context of MWI.

To this end, we performed the measurements using a 14 mm metallic sphere. The sweep plane was 100 mm distance from the antenna along the *z* direction, whereas the *x* and *y* sweep extended from -175 mm up to 175 mm with a measurement step of 5 mm. The sweep was performed using a Bosch Rexroth XZ linear positioner. Moreover, in the $\rho(\theta_s',\varphi_s'=90^\circ)$ and $\rho(\theta_s',\varphi_s'=0^\circ)$ calculations, we considered $\theta_{\max}'=30^\circ$. This value was empirically chosen.

It is evident that for $\theta \le 30^\circ$, $\Delta\rho(\theta,\varphi)$ is very close to zero (which justifies why we have set $\theta_{\max}'=30^\circ$). As the incoming angles become greater, the PNPC gets farther away from ρ_0. Moreover, the range of values of $\Delta\rho(\theta,\varphi)$ extends from -10 mm up to 50 mm in the worst case scenario. As a result, the benefit of calibrating the PNPC should be more evident for larger angles.

B. Impact on imaging results

To demonstrate the influence of calibrating the near-field "phase center" we will apply the proposed technique in the context of microwave breast imaging. To this end, we will use our group's imaging setup which is fully described in [7]. Some of the most relevant features of the system are:

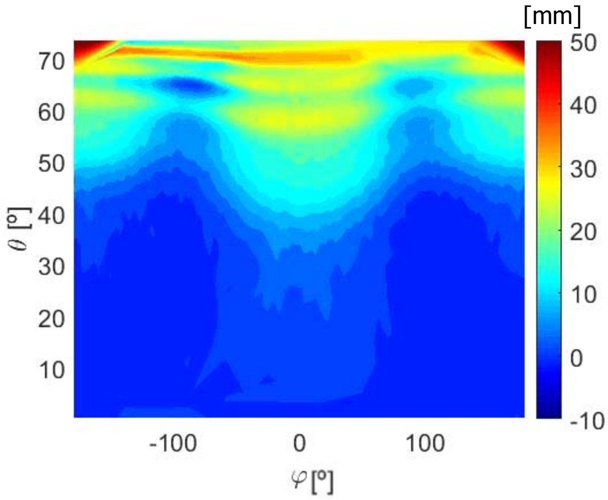

Figure 3: Phase center variability term, Δρ(θ, φ), showing a variability of up to aprox. 50 mm.

- It does not require an immersion liquid. We have done so for practical and hygiene reasons;
- The breast phantom represents a realistic non-uniformly shaped breast. Also, the containers are filled with the corresponding tissue-mimicking liquids;
- The artifact removal and imaging algorithms incorporate the shape of the breast in the calculations, in order to improve the results.

The results presented next imply the subtraction of the free-space input reflection coefficient, as well as the calibration of the equivalent electric length of the antennas, as discussed in [8].

Figure 4 (a) and (b) show the reflectivity map of the breast using the PNPC information, whereas Figure 4 (c) and (d) illustrate the same results without using the PNPC data. The tumor is positioned at (x,y,z) = (15,-20,-30) mm and N_a = 72 antennas.

The detection is quite good and the tumor is at approximately the right coordinates. There is a slight improvement in the results. In fact, the magnitude increases about 0.3 dB when using the PNPC information. Moreover, the magnitude of clutter next to the highest intensity pixel decreases, thus improving the tumor-to-clutter ratio. It should be mentioned that the system has limited resolution along *z* due to the consideration of only three antenna heights.

Although the image quality for this particular example is rather low, we believe this technique may leverage the use of better imaging techniques. In fact, one of our goals is to apply signal processing techniques that produce better spatial resolution (e.g. truncated singular value decomposition, TSVD), rather than the standard matched filter. However, these techniques require high signal to noise ratio, i.e. better knowledge of the physical model, which in our case corresponds to more accurate distance calculations to input in (1).

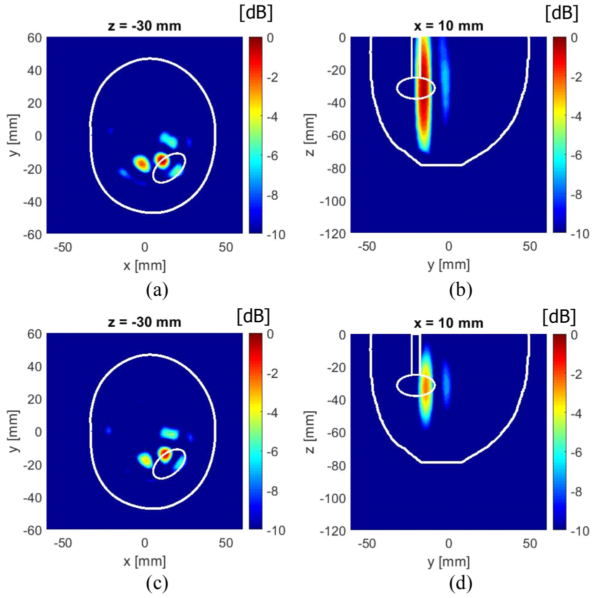

Figure 4: Reflectivity map of the reconstructed breast in dB: (a) and (b) represent the breast imaging results with the PNPC calibration technique; (c) and (d) represent the breast imaging results without using the PNPC calibration technique.

V. CONCLUSION

Microwave imaging is a popular research subject. In particular, it is showing lots of potential for medical applications, such as breast cancer screening and head hemorrhage detection. The accuracy and quality of the images obtained with this technology depend significantly on the calculation of distances between the antenna and the synthetical focal points. One of the system components that introduce larger errors is the antenna.

Here, we investigated whether the calibration of the "near-field" phase center of the antenna influences the imaging results. To this end, we firstly characterized the spatial variation of the "phase center" using a single-antenna measurement setup. We found that for a Vivaldi antenna, which is commonly used in medical MWI, the angular dispersion of the phase center can be as large as 50 mm.

This information was inputted into the signal processing algorithms and we processed the data acquired with our microwave breast imaging system. The results show slight improvement in the accuracy of the image, which we believe may leverage more informative imaging algorithms that require better signal to noise ratios.

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