UWB SHORT RANGE IMAGING

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Abstract – One of the main concerns when imaging extended real objects is the capacity of the system to correctly reconstruct the object cross section electric properties. In this paper, the imaging capabilities of an UWB short range system are analyzed, based on the Multifrequency Bi-Focusing Imaging (MFBF) and Time Difference of Arrival (TDOA) techniques, and its capability to reconstruct high contrast objects are studied.

Based on an analytical formulation for a dielectric cylinder the different spatial and frequencinal sampling criteria have been verified and its behaviour for highly contrasted objects has been obtained. An experimental validation has been finally performed using two collinear arrays of antennas working in transmission and reception respectively.

Keywords: imaging, UWB, TDOA, MFBF

1. INTRODUCTION

Since the United States Federal Communication Commission (FCC) opened the spectrum from 3.1 GHz to 10.6 GHz for unlicensed uses, numerous applications in communications and sensor areas have been projected. Different UWB systems can be developed for applications such as wireless communications, radar, sensing, location and imaging. Investigation on this field will soon provide low cost and low power prototypes with integrated services that will coexist with today’s narrowband systems and services.

In that direction, in a previous publication [1], the location capabilities of a short range UWB system were studied using two different techniques, one based on a multifrequency approach and the second based on a time delay measurement. The aim of the current paper is now to state their imaging capabilities. The first method consists of a multifrequency bi-focusing (MFBF) [1] imaging technique that synthetically focuses an incident transmitted field and the corresponding scattered received field on every “pixel” of the reconstructed scenario. The second method obtains an estimation of the scatter image position using the time difference of arrival (TDOA) [1] technique, a problem well studied in multi-static radar literature [2]. The technique is based on multi-path time measurements rather than amplitude or phase information of the received signal.

First, in paragraph 2, the Nyquist criteria that must be accomplished by the interrogation geometry and the frequency sampling to obtain a correct image of a given area is extensively studied. Then in the last two paragraphs, a dielectric cylinder’s reconstruction from its scattered field (paragraph 3) and experimental results (paragraph 4) are presented and discussed for canonical interrogation geometries.
2. SPATIAL AND FREQUENCIAL NYQUIST CRITERIA FOR IMAGING CAPABILITIES

In this paragraph, the Nyquist criteria that the interrogation geometry and frequency sampling must accomplish in order to obtain a correct image of a given area are stated and discussed. The problem can be stated as follows. The information obtained from the time-frequency and geometry scanning protocols can be translated into the two-dimensional spectral domain of the object. Under low contrast Born objects frequency and geometrical scanings are partially equivalent and optimized combinations can be found to fulfill the spectral domain. Under non-Born conditions however those properties are not applicable and new criteria need to be found.

From modal expansion of scattered fields it is well known that in order to obtain an image with a resolution of $\lambda/2$ at the highest frequency (refer to [1] for a detailed explanation) in all directions, a good encircling interrogation geometry with a minimum number of antennas, $N \geq 2ka$, that will refer as “Spatial Nyquist criterion”, are needed. $a$ is the maximum radius of the interrogation area and $k = \frac{2\pi}{\lambda}$ at the highest frequency. As a result a certain maximum angular step is allowed depending on the electrical size of the object.

Fig. 1 shows the reconstruction results for a dielectric cylinder of 25cm diameter using an encircling circular geometry with a) 128 transceivers (sequentially acting as emitters and receivers) and b) 16 transceivers. Only when Nyquist is satisfied ($N > 2ka$), the reconstructed image is uniform over the cylinder and the contours are perfectly determined.

![Figure 1: Reconstructed image of a 0.25cm diameter cylinder with a) 128 emitters and receivers; b) 16 emitters and receivers.](image)

For not encircling geometries, such as the linear reflection geometry shown in Fig. 2, resolution decreases in the transversal axis, because Nyquist criteria is not satisfied in that direction. In this case, the distortion is proportional to:

$$R \frac{\lambda_{/\text{max}}}{L_{\text{Array}}}$$

(1)

where $L_{\text{Array}}$ is the length of the antenna array and $R$ the distance from the scatter to the sensor antennas.
In addition to the previously mentioned Nyquist criteria, to ensure a good imaging free of distortion and of false replicas, the MFBF method has to verify the following equation regarding the separation between frequency samples:

$$\Delta f \leq \frac{1}{T_f} = \frac{c}{2R},$$

(2)

Therefore, the number of frequency samples $N_f$ to obtain a correct image of the scatters without replicas inside the area of interest must be:

$$N_f \geq \frac{(10.6 - 3.1) \cdot 10^9}{\Delta f}$$

(3)

By accomplishing what we will refer to as the “Frequency Nyquist criterion”, it is ensured that replicas of the scattered object appear out of the desired area, as shown in the following figures. Figure 3a) has been obtained with less samples ($N_f = 5$) than the given by eq.2 with $R=1$ m. Distorted replicas appear every 10 cm. The second simulation satisfies the Nyquist criteria, so replicas are out of range.

Once the partial Nyquist criteria (spatial and frequency) are been stated, the objective now is to find how both criteria have to be combined depending into the contrast of the object.
3. DIELECTRIC CYLINDER IMAGING

In this section, the field scattered by a dielectric cylinder due to an incident wave has been simulated and results processed using both MFBF and TDOA based methods in order to reconstruct its image. The effect of the geometry and the object contrast will be studied.

If we consider an infinite line of constant current placed in the vicinity of a circular dielectric cylinder with parameters $\varepsilon_d$, $\mu_d$ we can express the scattered field by equation [3]:

$$E_z = \frac{\beta^2 I}{4\omega \varepsilon} \sum_{n=-\infty}^{\infty} H_n^{(2)}(\beta \rho') J_n(\beta a) H_n^{(2)}(\beta \rho) e^{j(\phi-\phi')} \text{ for } a \leq \rho \leq \rho'$$

By post-processing the simulated scattered field in each receiving antenna and applying the MFBF and TDOA methods, the images of the cylinder obtained for different antenna set-ups are shown in figure 5.

For reflection geometry, only the contours of the cylinder can be well defined in the direction orthogonal to the array, thus increasing the number of views of the cylinder, the whole contour would be determined. Results show (difficulty on seeing the internal values of the object) to be coherent with what could be expected from not accomplishing the Spatial Nyquist criterion. This is as well the reason of the distortion appearing in the transmission geometry.

When using a circular geometry where all antennas are transmitters and receivers simultaneously, a perfect image of the inside of the cylinder is obtained. Differences between the three antenna geometries reconstructed images are related to the Fourier Diffraction Theorem [4] as the recovered spectral space differs.

In order to size the real benefits of using wide band systems compared to single frequency ones, different simulations have been conducted with cylinders of diverse permittivities using the whole UWB range and at 10.6 GHz alone. Fig. 6 shows the results. Meanwhile at low permittivities, results do not significantly differ, as permittivity increases, UWB images show to be of high quality and single frequency ones fail.
It is interesting to briefly comment all these results with a temporal perspective. Indeed, it is well known that from each medium change, for example, when entering the dielectric cylinder, a reflected wave is generated. Its shape is quite similar to the transmitted pulse and that is why a matched filter is used in the TDOA method in order to distinguish real reflections from noise or interference. Taking this into account, it can be easily shown that from each sensor pair at least two reflections can be detected. The separation between them is directly related with the permittivity of the cylinder. Therefore, the number of samples required is not as evident as initially may seem.

4. **EXPERIMENTAL RESULTS**

In order to validate the previous results, an experimental UWB measurement (3.1-10.6 GHz) was done. One cylinder of 25cm diameter filled with water was placed between two scanning Ridged Horn antennas operating as transmitter and receiver respectively, connected to the network analyser. The interrogation geometry, shown in Fig. 7, consists on two parallel linear synthetic arrays of 32 elements, separated 32mm. The reconstructing region is the rectangular area between the two parallel synthetic arrays separated 1.14m. The measurements were taken inside an anechoic chamber in order to avoid an excessive reflection of the environment.
Fig. 7. a) Geometry of the experimental set-up b) Experimental reconstruction of a cylinder of water and 0.3m diameter

Results of the reconstruction show a correct placement of the cylinder, a quite uniform reconstruction of the inside, a good contour accuracy on the y-axis and a poorer one in the x-axis due to the fact of not using an enough encircling geometry. The result corresponds quite well with the theoretical one of Fig 5 b).

5. CONCLUSIONS

UWB short range imaging is possible for Born and non-Born objects under a certain Nyquist criteria for frequency and geometrical scannings.

For low contrast Born objects, optimisations on the established criteria can be applied, as frequency and geometrical data are partially equivalent.

Further research must be conducted to determine how partial Nyquist criteria can be combined depending on the contrast of the object.

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