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Drift correction for scattering measurements

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The authors propose a method to correct for drift errors which occur when performing three-dimensional scattering field measurements. This method has the advantages of being fast, without loss of information and with no need of *a priori* information on the scatterer. It is based on the properties of limited spatial bandwidth of the scattered field. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2404978]

Thanks to the success of the two-dimensional scattering field databases that we have measured in the anechoic chamber of the Institut Fresnel and proposed to the inverse problem community,[1–3] we are now extending these studies to three-dimensional (3D) spherical bistatic configurations.[4] This introduces challenges due to the low level of signal as well as its sensitiveness to small disturbances. A careful characterization of the experimental errors is therefore necessary, and as they are mainly responsible for the scattered field variations, we will focus therein on drift errors. The objective is double: improve scattered field measurement accuracy and reduce acquisition time as it can take several hours for one incident illumination for 3D inverse scattering applications. To compensate for this drift error, we propose a fast correction based on a limited spectral bandwidth criterion, with the benefit of no loss of information and no need of *a priori* knowledge on the scatterer. After introducing the measurement setup and describing this correction protocol, we will highlight its influence on the acquisition process.

The configuration of the faradized anechoic chamber of the Institut Fresnel[2] is presented in Fig. 1. Its consists of a vector network analyzer (VNA, Agilent-HP 8510) used in a multisource setup with two synthesizers, two deported mixers, and two wide-band ridged horn antennas (ARA DRG118). The receiving antenna (vertically polarized here) is positioned on an arm rotating around the vertical z axis in the same azimuthal plane $(x0y)$ as the target. Due to restrictions coming from the physical existence of the arch, the receiving angular position ϕ_r is varying between $-130°$ and $130°$. The transmitting antenna (vertically polarized here) is fixed on the arch in the same azimuthal plane. The object, which can rotate on 360° (z axis) with angular position ϕ_o, is supported by a positioner supposedly transparent in the frequency band (from 2 to 18 GHz with a step of 1 GHz here).

The target scattered field is not directly measured but determined by complex subtraction of two field measurements: the total field E_t^{meas} with the presence of the target and the incident field E_i^{meas} without the object. Calibration is then performed using a metallic sphere as reference target.[5]

The pattern of this scattered field is very different from the measured fields. It has a very low level of magnitude, with up to 20 dB of difference for the dielectric sphere case presented afterwards. It also presents very slow variations along the receiver positions whereas the incident field can vary of 2π in less than 1° at 18 GHz. Thus, measurement accuracy, in particular, on the phase, is primordial and even more drastic for 3D configurations.

The characterization of experimental errors is a mandatory step to improve the measurement accuracy.[5,6] A careful analysis of the different errors has thus been made and it seems that the drift error is predominant in our case. Indeed, the incident and total field measurements are not performed at the same time and require several hours. During this time, the field phase and/or magnitude can be drifted (cable drift and network analyzer drift) due to some factors related to time (as temperature, for example). To show the influence of the drift errors, the scattering of a small dielectric sphere (diam=50.75±0.05 mm, $\epsilon_r=2.50\pm0.13$) has been studied. The dielectric constant has been measured with the commercial kit EPSIMU.[7]

In Fig. 2, the scattered field E_d^{simu} computed analytically using Mie series,[8] and the measured one E_d^{meas} are plotted at 18 GHz. The discrepancy between these two fields is numerically evaluated by an error criterion defined at each frequency f by

$$\mathcal{F}(f) = \frac{\sum_{\phi_r} |E_d^{\text{simu}} - E_d^{\text{meas}}|^2}{\sum_{\phi_r} |E_d^{\text{simu}}|^2}, \tag{1}$$

which has a value of 0.484 for the case of Fig. 2 at 18 GHz. A minimum tolerance variation of 0.1% in magnitude and 0.017 rad in phase is necessary to maintain an error criterion below 0.001. Unfortunately, we have experimentally noticed

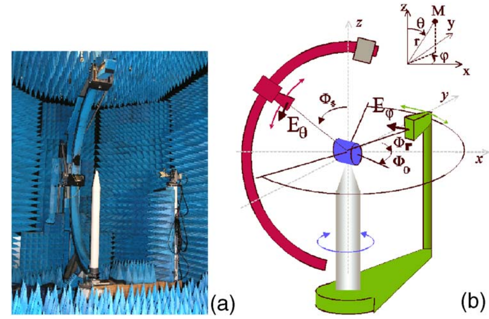

FIG. 1. (Color online) (a) Picture and (b) schematic of the experimental setup.

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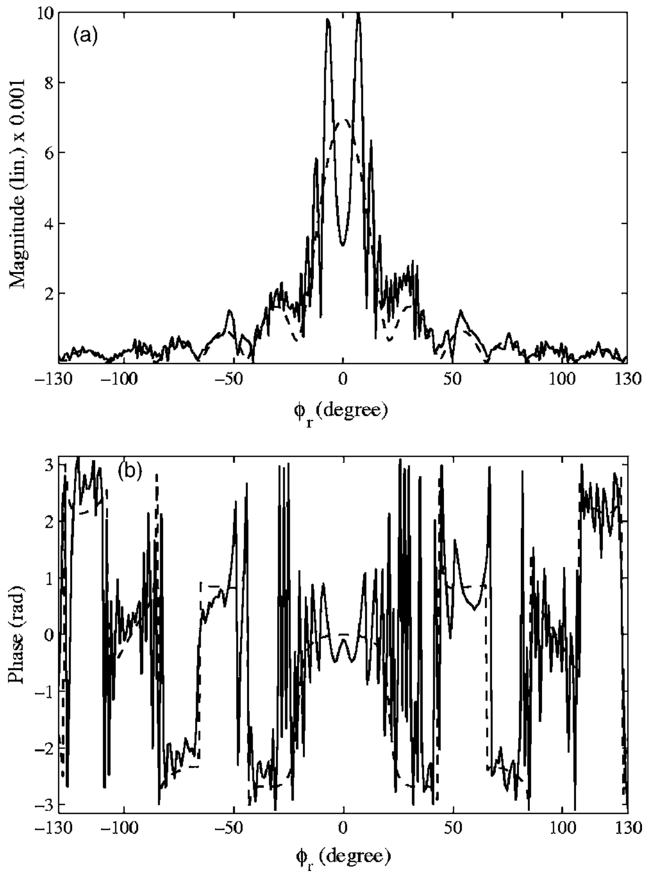

FIG. 2. (a) Scattered field amplitude and (b) phase obtained at 18 GHz [(—) measured and (--) simulated].

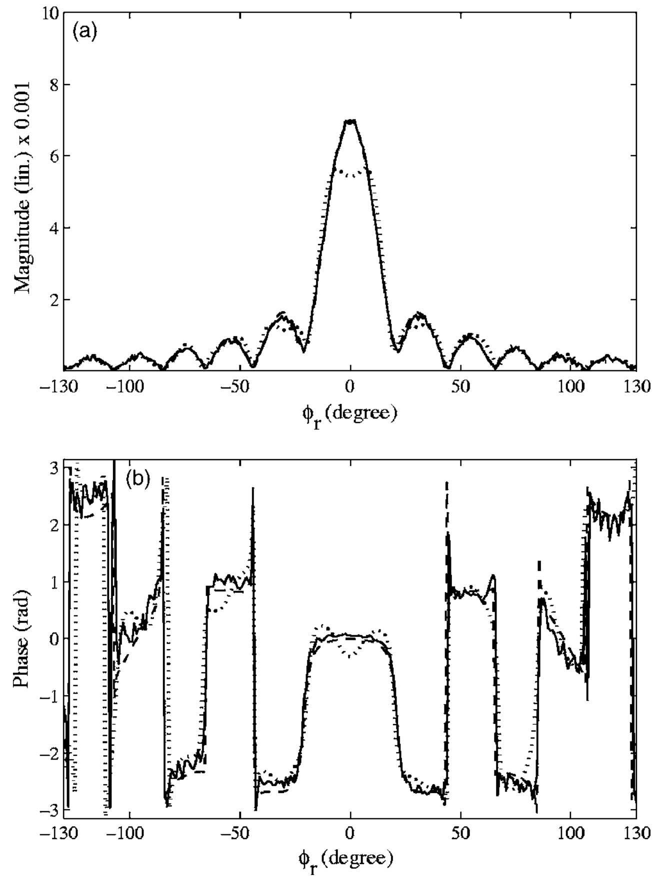

FIG. 4. (a) Scattered field amplitude and (b) phase obtained at 18 GHz [(—) measured and drift corrected, (⋯) measured and low-pass filtered, and (--) simulated)].

variations around 1% in magnitude and 0.01 rad in phase for 10 h of measurement time. The VNA and the temperature cable drifts[9] are themselves responsible for variations of 0.9% in magnitude and 0.09 rad in phase. Therefore, drift errors have significant effects on the scattered fields.

The goal is to quantify the drift error term for a given source illumination. One solution is to measure several times the same point during total and incident field measurements and deduce the drift coefficients.[10] This method provides good results but is very slow (30% additional measurement time in our configuration). We propose a different approach which is based on the properties of limited spatial bandwidth of the scattered field.

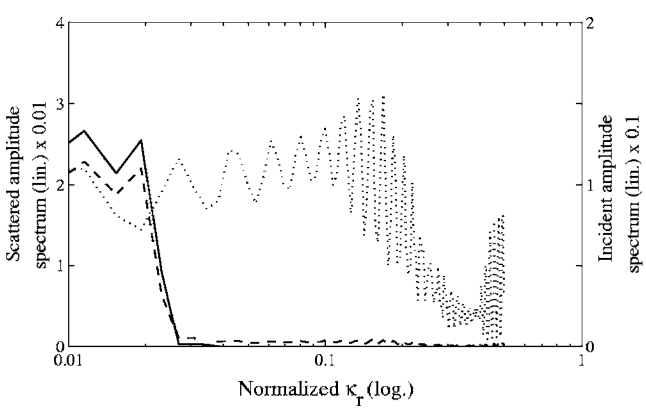

FIG. 3. Spectrum of the (⋯) incident field, (--) scattered field before correction, and (—) scattered field after correction.

It has been shown[11] that the electromagnetic fields scattered by bounded sources present specific properties when measured on an observation curve Γ described by a proper parametrization $r=r(\xi)$. In particular, the *generalized reduced field*,[12] $F(\xi)=E_d(r(\xi))\ \exp(j\psi(\xi))$, obtained from the measured field by extracting a suitable phase function $\psi(\xi)$ can be approximated by spatially band-limited functions with an error which becomes negligible as the bandwidth governing the sampling representation exceeds a critical value W. In our case, the observation curve Γ is a circle which totally encircles the induced sources, and the phase function $\psi(\xi)$ is nothing but a constant.[12]

All these properties stand for the scattered field but not for the total and incident fields. Therefore, by performing a Fourier transform of the different fields along the receiver positions, as shown in Fig. 3, we can notice that the incident field presents a large spectrum with high frequency components whereas the scattered field has a more compact spectral support. In fact, the spectrum of E_d^{meas} is much broader than expected with high frequency components that are responsible for the large oscillations observed in Fig. 2.

One simple idea would be to low-pass filter the scattered field. This implies to know in advance the cutoff frequency to limit information loss. As the bandwidth W depends only on the scatterer size and shape,[12] this requires *a priori* information on the scatterer.

Here, another approach is proposed. We assume that the drift error between the total and incident fields can be described by a complex coefficient. As the associated acquisi-

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tion time on all receiver positions is around 40 min for a given source position and a given target orientation, we neglect the drift and take the complex coefficient as a constant along the receivers for a given incidence. This complex coefficient $ae^{j\gamma}$ is introduced to compute a corrected scattered field E_d^c such that

$$E_d^c = E_t^{\text{meas}}(ae^{j\gamma} - 1) + E_d^{\text{meas}}. \tag{2}$$

The best drift coefficients a^* and γ^* are adjusted by minimizing the bandwidth $B_{E_d^c}$ of the corrected field E_c^d,

$$B_{E_d^c}(a^*, \gamma^*) = \min_{a,\gamma} \frac{\int \kappa_r^2 |\hat{E_d^c}(\kappa_r)|^2 d\kappa_r}{\int |\hat{E_d^c}(\kappa_r)|^2 d\kappa_r}, \tag{3}$$

where $\hat{E_d^c}$ denotes the Fourier transform along ϕ_r and κ_r is the associated Fourier coordinate.

Comparison between the spectral bandwidth minimization effect and a standard low-pass filter is visible in Fig. 4. In one case, the spectrum was corrected with best values $a^*=0.999$ and $\gamma^*=-0.093$ rad (see Fig. 3). In the second case, a rectangular window was used with a cutoff frequency of 0.05. Both approaches remove the high frequency part. But the drift correction term also acts on the low frequency part and maintains the information content. With the proposed drift correction, the scattered fields from Fig. 2 are now considerably improved, as shown in Fig. 4. This is also visible in the error criterion $\mathcal{F}$ which has been divided by 60, from 0.484 to 0.008 (and from 0.600 to 0.009 if averaged on all frequencies), compared to 0.067 obtained with the filtering process.

The drift correction provides interesting features for the measurement time. Indeed, for 3D inverse problem application, both the incident field and the total field are necessary and take a long time to obtain. Without the correction, when using a total field and an incident field measured one month apart, the scattered field was inexploitable. Nowadays, after correction, the scattered field is extracted and thus we can spare one field measurement.

Another way to reduce the acquisition time is to minimize the number of receiver positions.[12] After correction, we can extract the maximum spatial frequency and deduce the corresponding sampling step. For example, by performing this postprocessing protocol, with a sampling step of 5° (10° when possible) instead of 1°, we can gain 40% (50%) of measurement time.

The drift correction presented here has been tested on various objects and measurement configurations with the same very satisfactory results. This method, which takes into account the underlying physics of the electromagnetic fields, is a very useful tool for increasing the measurement accuracy of the 3D database that will soon be available for the scientific community working on the theoretical aspects of scattering.

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