Scattering measurements in a parallel plate waveguide - First results

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Abstract

This paper describes a parallel plate waveguide designed for scattering and material measurements. The experimental setup can for certain scatterers be considered as a two dimensional radar cross section range. Measurements on metallic circular cylinders of finite length are performed, and the forward radar cross section and the extinction cross section are determined. Two different calibration methods are used, and it is found that the method employing a calibration object is the most accurate. It is concluded that the two dimensional radar cross section in the forward direction can be measured with ± 1 dB accuracy at the level of 10 cm and the accuracy at the level of 1 cm is estimated to ± 3 dB.

1 Introduction

A parallel plate waveguide setup designed for scattering and material measurements is described and the first results are presented in this paper. Two measurement types are envisioned for this setup. The waveguide can for certain scatterers be used as a two dimensional radar cross section (RCS) range where forward and monostatic scattering are measured. A two dimensional scattering experiment offers several advantages in material measurements compared to experiments in an ordinary three dimensional measurement chamber. The most important advantage is that there are closed form solutions to certain two dimensional scattering problems, *e.g.*, the Mie series for the circular cylinder [1, pp. 205–340]. This is in contrast to material measurements in, *e.g.*, rectangular waveguides or coaxial transmission lines where the samples are more complicated to manufacture with sufficiently good tolerances. The waveguide can also be used for transmission and reflection measurements with similar benefits as for scattering experiments. The latter kind of measurements will be described elsewhere. This paper describes the first measurements on this setup and focuses on methods to calibrate and an evaluation of the accuracy of the obtained data. Measurements on metallic circular cylinders are used for the purpose of determining the accuracy since the two dimensional RCS and extinction cross section can be calculated with arbitrary precision using the Mie series [1, pp. 205–219].

2 Theory

Consider the direct scattering problem of a time harmonic wave (time dependence $\mathrm{e}^{-\mathrm{i}\omega t}$) impinging on a cylindrical scatterer of arbitrary cross section in a parallel plate waveguide. The scatterer is assumed to have material parameters which are independent of the z-coordinate, where the $\hat{\boldsymbol{z}}$-direction is perpendicular to the waveguide plates. The scatterer is aligned so that its axis of symmetry is parallel to the z-axis, and the top and bottom surfaces of the scatterer are assumed to be in contact with the waveguide plates. By employing the fundamental TEM mode in the parallel plate waveguide, this becomes a two dimensional scattering problem with the far field amplitude F given by [2, p. 6]

$$F(\hat{\boldsymbol{\rho}}) = \lim_{k\rho\to\infty} \sqrt{\frac{\pi k\rho}{2}} \mathrm{e}^{\mathrm{i}\pi/4} \mathrm{e}^{-\mathrm{i}k\rho} u_{\mathrm{s}}(\boldsymbol{\rho}), \tag{2.1}$$

where $k = \omega/c_0$ is the free space wave number, $\rho = |\boldsymbol{\rho}|$ denotes the magnitude of the position vector $\boldsymbol{\rho} = \rho\hat{\boldsymbol{\rho}} = x\hat{\boldsymbol{x}} + y\hat{\boldsymbol{y}}$, and u_{s} is the z-component of the scattered electric field. Analogous with the RCS for the three dimensional case [3, p. 18], the bistatic RCS in two dimensions, per unit length along the z-axis, is defined as [2, p. 7]

$$\sigma(\hat{\boldsymbol{\rho}}) = \lim_{k\rho\to\infty} 2\pi\rho \frac{|u_{\mathrm{s}}(\boldsymbol{\rho})|^2}{|u_0|^2} = \frac{4}{k}\frac{|F(\hat{\boldsymbol{\rho}})|^2}{|u_0|^2}, \tag{2.2}$$

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where $u_0 \mathrm{e}^{\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{\rho}}$ is the incident electric field of the fundamental TEM mode. The extinction cross section per unit length along the z-axis is calculated from the far field amplitude using the two dimensional optical theorem [4, pp. 323–326]

$$\sigma_{\mathrm{ext}} = -\frac{4}{k}\frac{\operatorname{Re} F(\hat{\boldsymbol{k}})}{u_0}. \tag{2.3}$$

Note that only the far field amplitude in the forward direction contributes to (2.3).

3 Calibration

The measurement data is primarily recorded in a port, where it can be represented by a complex voltage V. To translate this signal to the far-field amplitude, from which the extinction cross section can be calculated, it is necessary to perform a calibration. In this section we present two different methods: one simple using just a measurement on the object under test and the empty setup, and one where also a calibration object similar to the one under test is used.

3.1 Calibration without a calibration object

Under the assumption that the transmitting antenna generates a cylindrical wave, the signal at the receiving antenna for an empty setup can be written

$$V_0 = v_{\mathrm{cal}}\sqrt{\frac{2}{\pi k d}}\mathrm{e}^{-\mathrm{i}\pi/4}F_0\mathrm{e}^{\mathrm{i}kd} = v_{\mathrm{cal}}\frac{\alpha F_0 \mathrm{e}^{\mathrm{i}kd}}{\sqrt{d}} \tag{3.1}$$

where F_0 is the far field of the transmitting antenna, d is the distance between the antenna phase centers, and v_{cal} is the calibration vector, representing the effects of the empty setup, and $\alpha = \sqrt{2/(\pi k)}\mathrm{e}^{-\mathrm{i}\pi/4}$. The incident field at the object position d_1 is $u_0 = \alpha F_0 \mathrm{e}^{\mathrm{i}kd_1}/\sqrt{d_1}$, and the far field amplitude of the scattered field is $F = S u_0$, where S is the scattering coefficient. The received signal with object present is

$$V_1 = V_0 + v_{\mathrm{cal}}\frac{\alpha S u_0 \mathrm{e}^{\mathrm{i}k(d-d_1)}}{\sqrt{d-d_1}} = V_0 + v_{\mathrm{cal}}\frac{\alpha^2 S F_0 \mathrm{e}^{\mathrm{i}kd}}{\sqrt{(d-d_1)d_1}} \tag{3.2}$$

where we assume a low coupling between the antennas and the object so that the calibration vector is the same as for the empty setup. We can then solve for the scattering coefficient as

$$S = \frac{V_1 - V_0}{V_0}\frac{1}{\alpha}\sqrt{\frac{(d-d_1)d_1}{d}} = \frac{V_1 - V_0}{V_0}\sqrt{\frac{\pi k d}{8}}\mathrm{e}^{\mathrm{i}\pi/4} \tag{3.3}$$

where we assumed a symmetrically placed object, $d_1 = d/2$, in the last step. This expression is equal to the normalized complex valued far field amplitude for the object, $S = F/u_0$, and can be used to calculate the RCS by (2.2) and the extinction cross section by (2.3).

3.2 Calibration using a calibration object

The calibration procedure above assumes low coupling between the antennas and the object under test, so that the scattering characteristics of the setup can be captured by the same calibration vector v_{cal} as for the empty case. By introducing a scattering object with known scattering properties, we can improve the accuracy as follows.

A common technique in coherent radar measurements is to subtract a background signal from the signal for the object [5, pp. 626–628]. It is assumed that the difference between these signals is proportional to the far field amplitude as

$$F = a_{\mathrm{cal}}(V_1 - V_0) \tag{3.4}$$

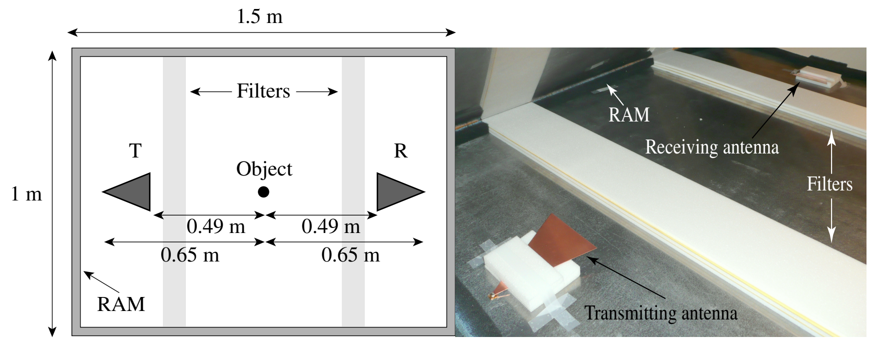

Figure 1: A schematic drawing of the parallel plate waveguide with the transmitting (T) and receiving (R) antennas. The left part of the figure shows the setup with the top plate removed.

where a_{cal} is a calibration vector. To eliminate a_{cal}, an additional signal V_{cal} for a calibration object is recorded, typically a metal cylinder where the corresponding far field amplitude F_{cal} can be calculated accurately by Mie scattering theory [1, pp. 205–219]. The calibration vector is then

$$a_{\mathrm{cal}} = \frac{F_{\mathrm{cal}}}{V_{\mathrm{cal}} - V_0} \quad \Rightarrow \quad \frac{F}{u_0} = \frac{F_{\mathrm{cal}}}{u_0}\frac{V_1 - V_0}{V_{\mathrm{cal}} - V_0} \tag{3.5}$$

and the RCS and extinction cross section can again be computed from (2.2) and (2.3). The accuracy of this calibration procedure improves if the calibration object is similar to the object under study, since it takes into account the possible higher order scattering effects that may be introduced by the presence of a strongly scattering object. The downside is that it requires a theoretical calculation of the calibration object's far field amplitude, which can usually only be performed for simple geometries like cylinders.

4 Experimental setup

A pair of wideband TEM horn antennas are positioned facing each other at a distance of 0.98 m with the sample placed at the midpoint of the parallel plate waveguide, see Figure 1. The distance between the two plates is 20 mm. The TEM mode is supported. To suppress the higher order modes with the electric field parallel to the plates (first cutoff frequency at 7.5 GHz), a filter consisting of two parallel metallic strips with a Rohacell® foam spacing is designed. The filter does not suppress higher order modes with the electric field perpendicular to the plates. The measurement uses an HP 8720 network analyzer transmitting a continuous wave without online hard or software gating in the frequency interval [1,20] GHz. The interval is swept using 1601 frequency points. The source power from the network analyzer is set to 10 mW for the measurements described here. The power output from the antenna is lower mainly due to cable losses.

Calibration measurements are performed using a metallic cylinder with 10 mm radius and 20 mm height as the object. The cylinder is in electrical contact with both the bottom and top plates of the waveguide. This is followed by measurements of the direct path signal that is coherently subtracted from the calibration object measurement. This subtraction is necessary to suppress the direct antenna to antenna coupling signal and the background reflections in the chamber. The sample is measured and the direct path data is subtracted from the sample data in the same way as for the calibration measurement. The processed sample data is then calibrated with the calibration vectors obtained using the two calibration methods described above. Time gating is not performed in this experiment.

5 Results and discussion

Measurements on a metallic cylinder with 8 mm radius are performed in order to estimate the accuracy of the measurement setup and to compare the two calibration methods. The measured raw data is therefore calibrated with

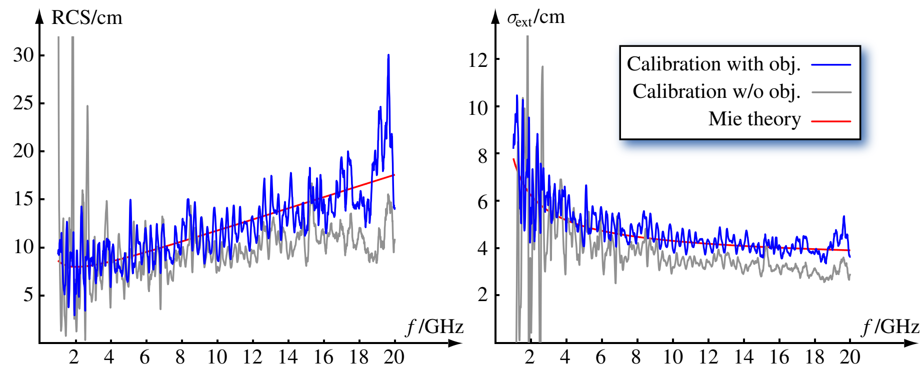

Figure 2: Forward RCS and extinction cross section measured for a metallic cylinder with 8 mm radius compared with theory. The distance between the antenna phase centers, d, is assumed to be 1.14 m.

the two calibration methods described in Section 3, and the calibrated data is shown in Figure 2.

The figure shows that the accuracy of the simple measurement, using only data for the object and the empty setup, can be improved by using the data from an additional calibration object. The measured RCS data, calibrated with an object, shows noise that corresponds to ± 1 dB accuracy at an RCS level of 10 cm for the frequency range [3,18] GHz. The accuracy at an RCS of 1 cm is therefore estimated to ± 3 dB using the calibration method with a calibration object. For the lowest and highest frequencies the accuracy is lower. These results are expected to improve as the design of the setup is refined, paying more attention to reduce additional scattering from the walls. The calibration with the method using only the empty setup to obtain a calibration vector results in a forward RCS that has a systematic deviation from the theoretical result based on the Mie series. The distance between the antenna phase centers, d, that is unknown is here assumed to be 1.14 m, corresponding to phase centers at the middle of the antennas. Choosing other values for d will affect the size of this deviation. Equation (2.3) is used to determine the extinction cross section from the forward RCS amplitude. The figure shows that the determination of extinction cross section is more accurate using the calibration method with a calibration object.

6 Conclusions

It is concluded that the forward RCS can be measured with ± 1 dB accuracy at a level of 10 cm and the accuracy at an RCS of 1 cm is estimated to ± 3 dB using the calibration method with a calibration object. This calibration method also gives the best results when determining the extinction cross section. It is not clear in detail what causes the discrepancies for the other calibration method. Further studies are needed to clarify this.

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