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Peter Waterman and *T*-matrix methods

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ABSTRACT

This paper summarizes the scientific legacy of Peter C. Waterman (1928–2012) who introduced concepts and theoretical techniques that have had a major impact on the fields of scattering by particles and particle groups, optical particle characterization, radiative transfer, and remote sensing. A biographical sketch is also included.

1. Introduction

At a wedding reception in 1998, Peter Waterman, feeling shy in an unfamiliar crowd, approached the only well recognizable figure in the room: an old, grand piano. Without meaning to, he became the entertainment of the night, playing original scores for the guests, filling the air with graceful energy. After the reception, the hotel manager followed Peter and his wife Karen into the elevator and asked if Peter would be interested in a job playing the piano at the hotel. Peter looked at Karen, smiled, and politely refused. Although music was an essential part of his life, his professional allegiance was to mathematical physics.

A quiet and unassuming man of habits, Peter Cary Waterman (Fig. 1) was well known to many but personally acquainted with a few. During his more than 50 years in science, he had (co)authored only 39 peer-reviewed publications; these are listed below in Section 8 and cited as [Wxx]. Yet his research has had a dramatic and long-lasting impact and to a large degree has guided the progress in the disciplines of electromagnetic, acoustic, and elastic wave scattering by obstacles.

2. Early years

Born in Albany, New York, on 14 June 1928 to Frederick Collins and Gertrude Melissa (Cary) Waterman, Peter Waterman graduated from Bethlehem High School, Delmar, New York, in 1946 (Fig. 2). He received a BS degree in physics from Syracuse University in 1951, and from 1952 to 1953, served as a physics instructor at Union College in Schenectady, New York. Waterman was subsequently appointed to an Alcoa Research Fellowship in the Division of Applied Mathematics at Brown University. There, his first few papers [W02, W03, W04, W06] and his MS thesis [W01] were studies of elastic wave propagation through anisotropic materials.

In 1954, Peter Waterman married Katherine Adella Dearstyne, with whom he had three sons: Diedrich, Jonathan, and Jeremy. Peter and Katherine divorced in 1975.

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Fig. 1. Peter Cary Waterman (1928–2012).

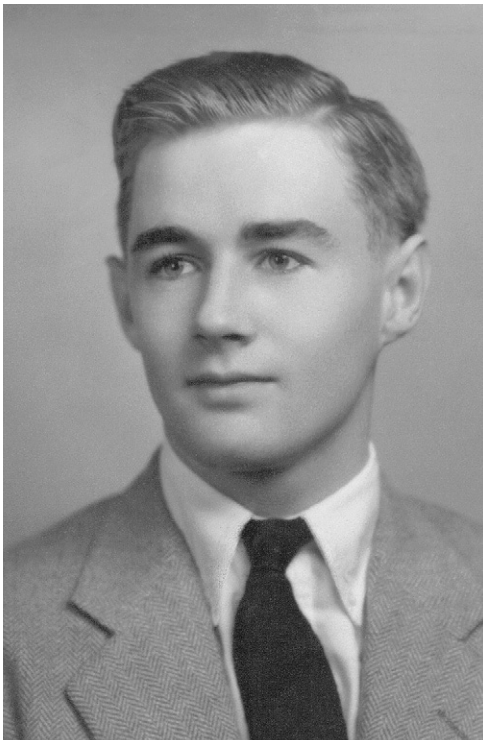

Fig. 2. Peter Waterman, a 1946 graduate of Bethlehem High School, Delmar, New York.

Waterman received his PhD degree in applied mathematics from Brown in 1958. His thesis on "Multiple scattering of waves" [W05] was supervised by Rohn Truell. This work will be discussed in Section 3.

After graduation, Waterman worked briefly for the Linde Company (1958), in Tonawanda, New York. There, he investigated the unmixing of gases in Laval nozzles, leading to two papers [W07, W08].

3. Multiple scattering

From 1959 to 1965, Waterman worked in the Research and Advanced Development Division of the Avco Corporation in Wilmington, Massachusetts. He extended his thesis work with Truell on three-dimensional acoustic scattering (governed by the Helmholtz equation, $(\nabla^2+k^2)u=0$, k being the wavenumber and u the acoustic field) by random arrangements of identical spherical obstacles, in the spirit of earlier work by Leslie Foldy and Melvin Lax. The main result is a formula for the effective wavenumber, K, assuming that the number of scatterers per unit volume, n, is small. Waterman and Truell [W09] obtained the formula

$$(K/k)^2=[1+2\pi nk^{-2}f(0)]^2-[2\pi nk^{-2}f(\pi)]^2, \tag{1}$$

where $f(\theta)$ is the far-field pattern for scattering of a plane wave by a single sphere. (The scattered field is asymptotically $r^{-1}e^{ikr}f(\theta)$ as $r\to\infty$, where r and θ are spherical polar coordinates.) Written out, Eq. (1) becomes

$$K^2=k^2+4n\pi f(0)+n^2\delta_2, \tag{2}$$

where

$$\delta_2=(2\pi/k)^2\{[f(0)]^2-[f(\pi)]^2\}. \tag{3}$$

The term proportional to n in Eq. (2) is well known. The second-order coefficient, δ_2, had been obtained by Urick and Ament [1] using a very different argument: the attraction of Waterman and Truell's derivation is that it is systematic, with testable assumptions, and that it has the potential for extension to other physical situations (such as electromagnetic scattering). In fact, it turned out later that the formula for δ_2, Eq. (3), is wrong: for a review and references, see Ref. [2]. Nevertheless, the paper [W09] has been very influential: it has been cited about 500 times and it was reprinted in 1996 in the SPIE Milestone volume on "Selected papers on linear optical composite materials," edited by Akhlesh Lakhtakia.

John Fikioris joined Avco in 1962. He graduated from Harvard University in 1963 with a PhD thesis on "The theory of radially stratified media," written under Ronold W. P. King's direction. Fikioris and Waterman [W12] improved and corrected the analysis in Ref. [W09]. They also wrote [W12, p. 1414]:

> The vector extension of the present work has been performed, in application to the electromagnetic case. The procedure and results of this extension will be described in a subsequent paper.

That paper did not appear until 2013 [W42]. For a description of how this came about, see Section 7.

4. The extended boundary condition

In 1965, Waterman published a paper [W13] on electromagnetic scattering by a perfectly conducting obstacle in which he introduced the "extended boundary condition". He was interested in developing a numerical method for three-dimensional obstacles of arbitrary shape, one that does not suffer from spurious irregular frequencies. He describes his formulation as follows: