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Comprehensive *T*-matrix reference database: A 2012–2013 update

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ABSTRACT

The *T*-matrix method is one of the most versatile, efficient, and accurate theoretical techniques widely used for numerically exact computer calculations of electromagnetic scattering by single and composite particles, discrete random media, and particles imbedded in complex environments. This paper presents the fifth update to the comprehensive database of peer-reviewed *T*-matrix publications initiated by us in 2004 and includes relevant publications that have appeared since 2012. It also lists several earlier publications not incorporated in the original database, including Peter Waterman's reports from the 1960s illustrating the history of the *T*-matrix approach and demonstrating that John Fikioris and Peter Waterman were the true pioneers of the multi-sphere method otherwise known as the generalized Lorenz–Mie theory.

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1. Introduction

The comprehensive database of *T*-matrix publications was initiated in 2004 [1] and was followed by four updates [2–5]. It is quite symbolic that this fifth update appears in the special issue of *JQSRT* commemorating Peter C. Waterman and his scientific legacy. As such, it further demonstrates the vitality of the *T*-matrix method and its great usefulness in a wide range of applications. The total number of newly added references is 128 [6–133]. They mostly represent publications that appeared since 2012 in addition to several publications omitted inadvertently in Refs. [1–5].

As in Refs. [1–5], the current update has been compiled by adhering to the following general restrictions:

- The database contains only publications dealing with electromagnetic scattering.
- In general, publications on scattering by isolated infinite cylinders and systems of parallel infinite cylinders in unbounded space are excluded.
- Publications on the Lorenz–Mie theory and its various extensions to radially inhomogeneous, isotropic, spherically symmetric scatterers are not, generally, included.
- The database contains only references to books, peer-reviewed book chapters, and peer-reviewed journal papers.

Furthermore, we have continued to use the following operational definition of the *T*-matrix method:

> In the *T*-matrix method, the incident and scattered electric fields are expanded in series of suitable vector spherical wave functions, and the relation between the columns of the respective expansion coefficients is

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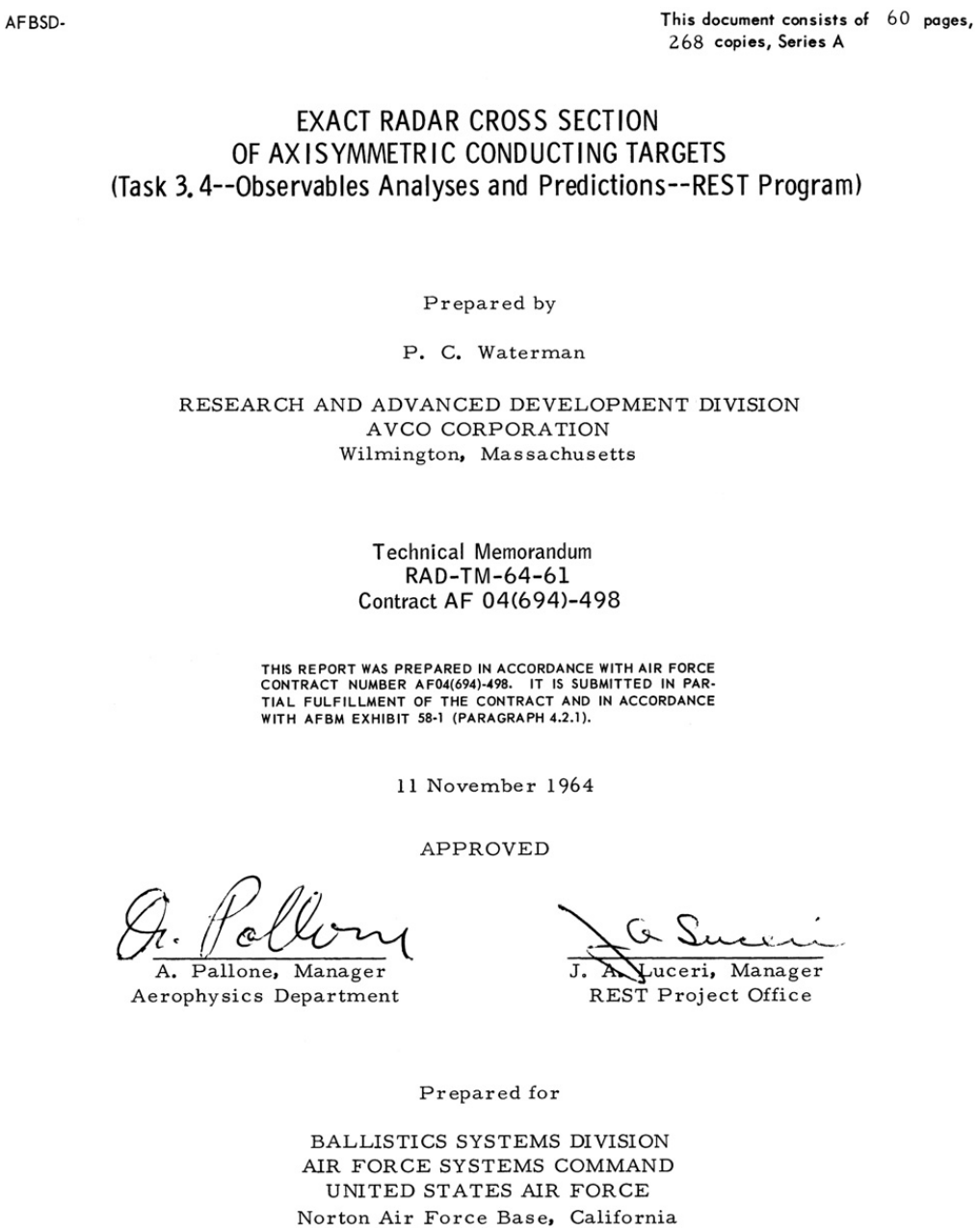
established by means of a transition matrix (or T matrix). This concept applies to the entire scatterer or to separate parts of a composite scatterer.

Obviously, this definition is more inclusive than the original notion of the extended boundary condition method [134]. As such, it encompasses what is otherwise called the multi-sphere method or the generalized Lorenz–Mie theory.

Following the previous practice, the various references are classified into a set of narrower subject categories. As before, the inclusion of a publication in the database does not constitute any formal endorsement or quality certification on our part. Also, we do not flag specifically those publications in which previously known results (such as the multi-sphere method, the superposition T-matrix method, or certain symmetry and transformation properties of the T matrix) are re-discovered.

We have used this opportunity to include several Peter Waterman's reports from the 1960s [35,120–123] helping to trace the origin and evolution of the T-matrix approach and representing significant historical interest (see Figs. 1–3). For example, the extended boundary condition method can be seen as rooted in Ref. [120], while Ref. [123] lists and documents the first T-matrix computer program and thereby reveals Peter Waterman as a pioneer of public-domain scientific software publishing. There is no doubt that the availability of that open-access computer program had played an important role in the early dissemination of the T-matrix method.



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EXACT RADAR CROSS SECTION
OF AXISYMMETRIC CONDUCTING TARGETS
(Task 3.4--Observables Analyses and Predictions--REST Program)

Prepared by

P. C. Waterman

RESEARCH AND ADVANCED DEVELOPMENT DIVISION
AVCO CORPORATION
Wilmington, Massachusetts

Technical Memorandum
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UNITED STATES AIR FORCE
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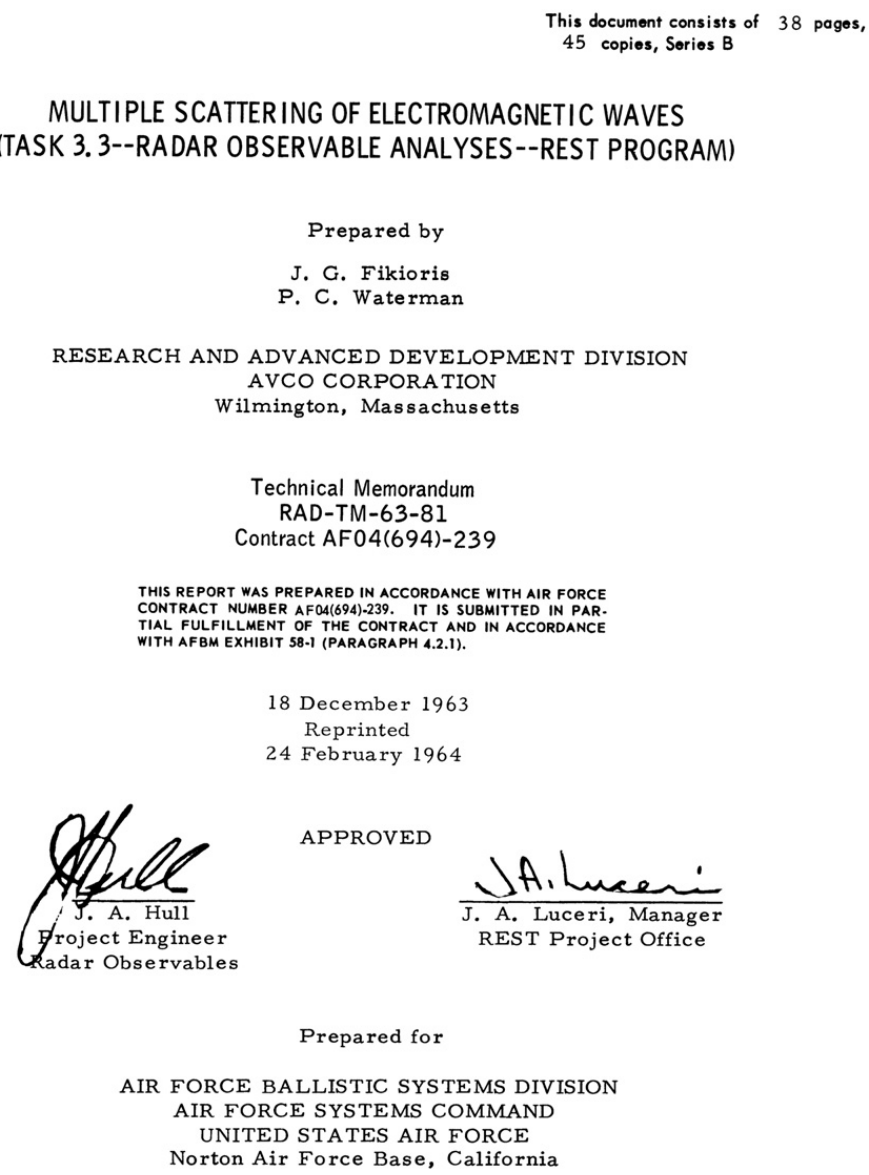
Fig. 1. Title page of Ref. [120].



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MULTIPLE SCATTERING OF ELECTROMAGNETIC WAVES
(TASK 3.3--RADAR OBSERVABLE ANALYSES--REST PROGRAM)

Prepared by

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P. C. Waterman

RESEARCH AND ADVANCED DEVELOPMENT DIVISION
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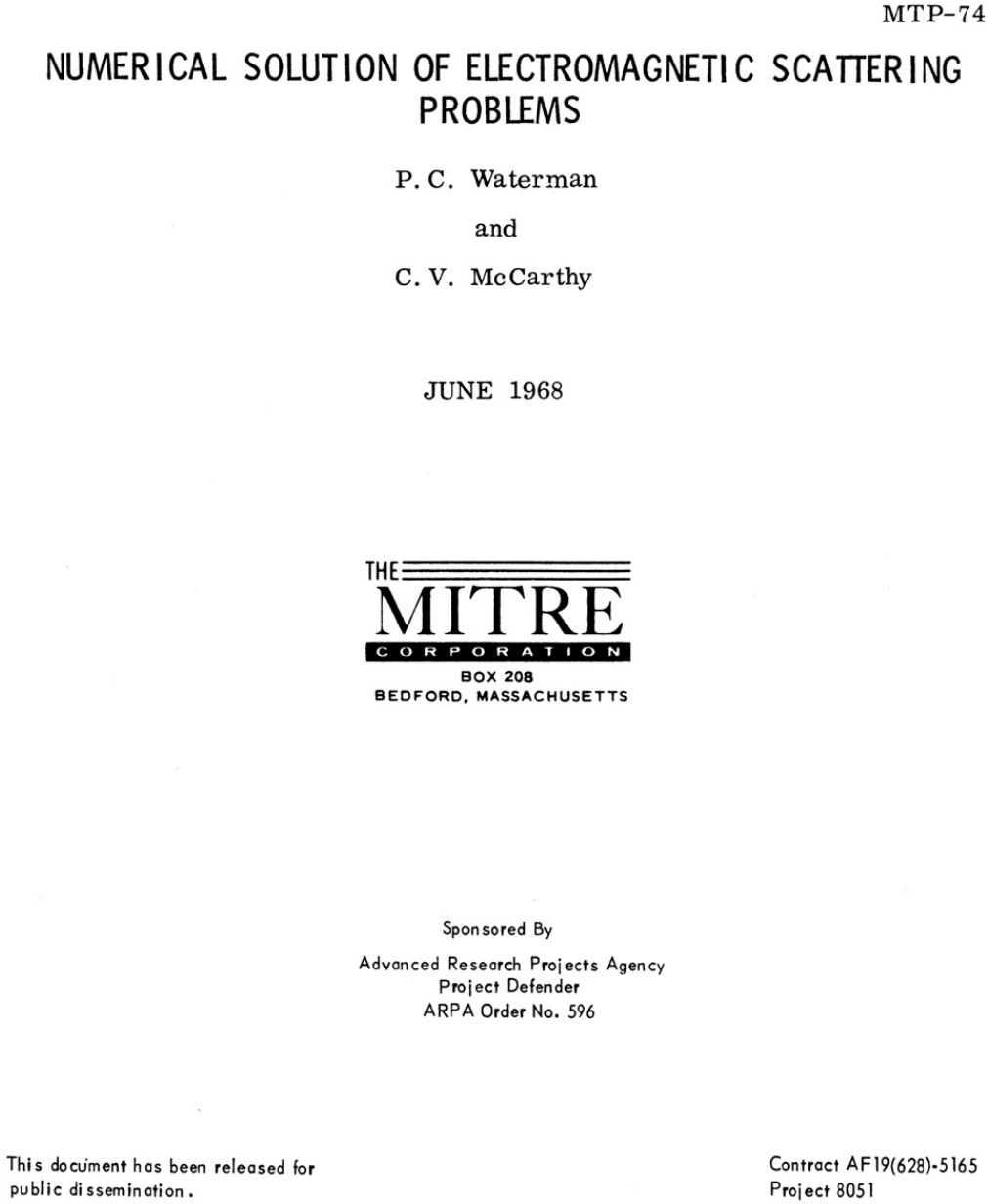
Fig. 2. Title page of Ref. [35].

The 1963 report [35] helps restore historical justice by revealing John Fikioris and Peter Waterman as the true pioneers of the multi-sphere method—the honor usually attributed to the well-known papers of 1971 by Bruning and Lo. Unlike other Waterman's research results, this report had not been published in the form of a peer-reviewed journal paper. The reasons for that remain uncertain, although a finalized manuscript of 1964 intended for submission to a professional research journal was discovered in Peter Waterman's archive in July of 2012 [82]. That manuscript is finally archived as part of this special issue [36].

Among the many advances documented in the publications referenced below, we note in particular the parallelized, optimized, and customized versions of *T*-matrix (or *T*-matrix-based) public-domain computer programs [45,49,55,102,111], efficient ways of improving the numerical stability of *T*-matrix computations [15,16,107,110,116], the generalization of the extended boundary condition method to the case of a scattering target in a parallel plate waveguide [61], and completely new application areas such as the simulation of the electron energy loss spectroscopy [81]. The full range of theoretical developments and practical applications of the *T*-matrix method is, of course, much broader.

2. Particles in infinite homogeneous space

1. *Reviews*: [58,76,100,125].
2. *History of the T-matrix method:* [35,36,82,120,121,122,123].
3. *Mathematics of the T-matrix method*: [9,78].
4. *Extended boundary condition method and its modifications, generalizations, and alternatives*: [15,16,34,47,52,61,78,95,120,122,123,131,132].
5. *T-matrix theory and computations for anisotropic, chiral, magnetic, and charged scatterers*: [73,80,102].
6. *Multi-sphere and superposition T-matrix methods and their modifications, including related mathematical tools*: [7,8,23,35,36,41,84,91,118,132].



MTP-74

NUMERICAL SOLUTION OF ELECTROMAGNETIC SCATTERING PROBLEMS

P. C. Waterman

and

C. V. McCarthy

JUNE 1968

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Fig. 3. Title page of Ref. [123].

7. *T-matrix theory and computations of electromagnetic scattering by periodic and aperiodic configurations of particles and photonic crystals*: [7,8,24,25,48,49,90,92,113,118].
8. *T-matrix theory and computations of electromagnetic scattering by discrete random media*: [6,26,36,77,86,115].
9. *T-matrix theory and computations for an obstacle in a parallel plate waveguide*: [61].
10. *Relation of the T-matrix method to other theoretical approaches*: [15,16,34,66,78,131].
11. *Symmetry properties of the T matrix, analytical ensemble-averaging approaches, and linearization*: [54,55,103,116].
12. *Software implementation, parallelization, GPU-acceleration, and customization of T-matrix computer programs*: [45,49,55,102,111,123].
13. *Convergence of various implementations of the T-matrix method*: [15,16,63,107,110,116].
14. *T-matrix calculations for homogeneous spheroids*: [10,12,15,16,17,27,31,32,33,38,42,43,46,49,50,52,67,68,70,71,72,74,75,81,87,89,93,97,98,101,103,104,105,106,110,112,114,119,121,124,127,133].
15. *T-matrix calculations for Chebyshev and generalized Chebyshev particles*: [10,33,98,103].
16. *T-matrix calculations for finite circular cylinders*: [15,16,18,20,21,33,57,60,74,79,88,103,104,107,113,116,117].
17. *T-matrix calculations for various rotationally symmetric particles*: [15,40,44,51,52,120,132].
18. *T-matrix calculations for ellipsoids, polyhedral scatterers, and other particles lacking axial symmetry*: [27,38,54,55,57,95,116,129].

19. *T-matrix calculations for layered and composite particles*: [34,62,63,80,131].
20. *T-matrix calculations for clusters of homogeneous spheres*: [6,19,21,26,28,29,30,48,56,59,69,65,77,81,83,85,86,91,94,96,100,103,115,126,128,130].
21. *T-matrix calculations for clusters of nonspherical monomers*: [15,24,25].
22. *T-matrix calculations for particles with one or several (eccentric) inclusions*: [15,99].
23. *T-matrix calculations of optical resonances in nonspherical particles*: [24,25,28].
24. *T-matrix calculations of optical and photophoretic forces and torques on small particles*: [20,21,71,100,109,111].
25. *T-matrix calculations of internal, surface, and local fields and near-field energy exchange*: [22,60,77,96].
26. *T-matrix computations for electron energy loss spectroscopy*: [81].
27. *Illumination by focused beams and non-plane waves*: [11,20,21,100,109,111].
28. *Use of T-matrix calculations for testing other theoretical techniques*: [48,56,74,75,77,86,91,93,112,115,129].
29. *Comparisons of T-matrix and controlled laboratory results*: [32,91].
30. *Use of T-matrix calculations for analyzing laboratory and in situ data*: [10,32].
31. *T-matrix modeling of scattering properties of mineral aerosols in the terrestrial atmosphere and soil particles*: [27,29,33,67,87,97,114,117,119,124].
32. *T-matrix modeling of scattering properties of carbonaceous and soot aerosols and soot-containing aerosol and cloud particles*: [56,69,83,126,130].
33. *T-matrix modeling of scattering properties of cirrus cloud particles*: [10,17,88,104,108,127].
34. *T-matrix modeling of scattering properties of hydrometeors and atmospheric radar targets*: [31,39,40,50,51,53,64,70,72,98,101,105,106].
35. *T-matrix modeling of scattering properties of noctilucent cloud particles*: [46].
36. *T-matrix modeling of scattering properties of aerosol and cloud particles in planetary atmospheres:* [79].
37. *T-matrix modeling of scattering properties of interstellar, interplanetary, cometary, and planetary-ring particles*: [37,59].
38. *T-matrix computations for industrial and military applications*: [68].
39. *T-matrix computations for biomedical applications*: [14,42,43,62,63,131].
40. *T-matrix computations of anisotropic and aggregation properties of colloids and other disperse media*: [19,44,94].

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