T-matrix theory of electromagnetic scattering by particles and its applications: a comprehensive reference database

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Abstract

The $T$-matrix method is one of the most powerful and widely used theoretical techniques for the computation of electromagnetic scattering by single and composite particles, discrete random media, and particles in the vicinity of an interface separating two half-spaces with different refractive indices. This paper presents a comprehensive database of $T$-matrix publications since the inception of the technique in 1965 through early 2004.

Keywords: Electromagnetic scattering; $T$-matrix method

1. Introduction

Since its formulation in 1965, the $T$-matrix method has become one of the most powerful, versatile, and popular theoretical techniques for treating electromagnetic, acoustic, and elastodynamic scattering by particles and surfaces. The most recent attempt to outline the vast realm of this technique and its practical applications by compiling a comprehensive publication database dates back to 1988 (Varadan et al., 1988); that list included 151 references. Although to attempt a similar compilation now would be very...
important, it is next to impossible. To make the task both useful and practicable, one has to be selective and to adhere firmly to well defined and meaningful guidelines. The three most important restrictions that we have adopted for this database are the following:

- With a few important exceptions, the database includes only publications dealing with electromagnetic scattering.
- As a rule, publications on scattering by isolated infinite cylinders and systems of parallel infinite cylinders in unbounded space are excluded.
- The database includes only references to books, peer-reviewed book chapters, and peer-reviewed journal papers.

Even with these restrictions, the database contains more than 700 references.

A critical issue that we faced at the outset of this project was to agree on a definition of the $T$-matrix method. The concept of a $T$ matrix has evolved quite dramatically since it was first introduced by P.C. Waterman in 1965. From being a minor bi-product of the extended boundary condition method, it has become the centerpiece of a vast domain of wave scattering science. We hope that we will not step on too many toes by suggesting the following definition:

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 established by means of a transition matrix (or $T$ matrix). This concept can be applied to the entire scatterer as well as to separate parts of a composite scatterer.

It is clear that in the framework of this definition, the classical Lorenz–Mie theory for homogeneous isotropic spheres and its generalizations for inhomogeneous spherically symmetric particles become a particular case of the $T$-matrix approach. Therefore, another inescapable restriction that we had to impose on this database was to exclude all references dealing with individual spherically symmetric scatterers. We hope that the reference list of the recent monograph by Babenko et al. (2003) will be at least a partial remedy for this deficiency.

In addition to compiling a unified masterlist of $T$-matrix publications on electromagnetic scattering by particles, we have tried to make the database more useful by classifying the various references into a set of narrower subject categories (Sections 2 and 3). Depending on the specific content of a publication, it may appear in one or several subject categories. The choice of the subject categories, especially categories such as Seminal publications, and assigning a publication to a category are somewhat subjective and are open to criticism. We feel, however, that the pros of this endeavor in terms of its utility to various categories of customers far outweigh its potential cons.

What we have not done in this paper is to assess the validity and importance of the results described in the specific publications included in the database. It is not inconceivable that some of the publications contain wrong results or duplicate results obtained in earlier publications. We believe that a critical assessment of the $T$-matrix publications should be the subject of a book or a review and is beyond the scope of this paper. Therefore, the reader should keep in mind that the inclusion of a publication in this database does not constitute any formal endorsement or quality certification on our part.

We realize that even with the restrictions adopted, it will be impossible to publish in a research journal another comprehensive database like this one even in a few years from now (see Fig. 1). However, we plan to maintain an updated version of this database on the web site http://www.giss.nasa.gov/~crmim
and ask the readers to help us in this endeavor by sending corrections and missing references to existing and future publications on the $T$-matrix method and its various applications.

2. Particles in infinite homogeneous space

2.1. Seminal publications

This subsection references the publications in which the $T$-matrix method was originally developed as well as those in which a major generalization or improvement of the $T$-matrix method was proposed.

Bruning and Lo (1971a)  
Khlebtsov (1992)  
Lakhtakia et al. (1983)  
Mackowski and Mishchenko (1996)  
Mishchenko (1991a)  
Peterson and Ström (1973)  
Peterson and Ström (1974)  
Rozenberg (1974)  
Schulz et al. (1999a)  
Tsang and Kong (1980)  
Varadan and Varadan (1980a)  
Varadan et al. (1979)  
Waterman (1965)  
Waterman (1969)  
Waterman (1971)
2.2. Books

<table>
<thead>
<tr>
<th>Authors</th>
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<tbody>
<tr>
<td>Barber and Hill</td>
<td>1990</td>
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<tr>
<td>Borghese et al.</td>
<td>2003</td>
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<tr>
<td>Chew</td>
<td>1995</td>
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<td>Doicu et al.</td>
<td>2000c</td>
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<tr>
<td>Mishchenko et al.</td>
<td>2002a</td>
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<td>Rozenberg</td>
<td>1974</td>
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<td>Tsang and Kong</td>
<td>2001</td>
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<td>Tsang et al.</td>
<td>1985</td>
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<td>Tsang et al.</td>
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<td>2001</td>
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<td>Varadan and Varadan</td>
<td>1980b</td>
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2.3. Reviews

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<tr>
<td>Barber</td>
<td>1980</td>
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<td>Fuller and Mackowski</td>
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<td>Mishchenko et al.</td>
<td>1996b</td>
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2.4. Extended boundary condition method and its modifications and generalizations

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<tr>
<td>Al-Badwaihy and Yen</td>
<td>1975</td>
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<td>Barber and Yeh</td>
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<td>Bates and Wall</td>
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<td>Boström</td>
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<td>Bringi and Seliga</td>
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<td>Doicu</td>
<td>1999</td>
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<td>Doicu</td>
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<td>Doicu and Wriedt</td>
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<td>Doicu and Wriedt</td>
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<td>Doicu and Wriedt</td>
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<td>Doicu et al.</td>
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<td>Eremina and Wriedt</td>
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<td>Iskander and Lakhtakia</td>
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<td>Wang et al.</td>
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<td>Zheng and Ström</td>
<td>1989</td>
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2.5. T-matrix theory and computations for anisotropic and chiral scatterers

<table>
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<tr>
<td>Doicu</td>
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<td>Eremina and Wriedt</td>
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<td>Hizal</td>
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<td>Lakhtakia et al.</td>
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<td>Liu et al.</td>
<td>2000b</td>
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<td>Sharma and Balakrishnan</td>
<td>1998</td>
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2.6. Superposition T-matrix method and its modifications, including related mathematical tools

Auger and Stout (2003)  
Auger et al. (2001)  
Borghese et al. (1979)  
Borghese et al. (1980)  
Borghese et al. (1994)  
Boström et al. (1991)  
Bruning and Lo (1971a)  
Bruning and Lo (1971b)  
Chew (1990)  
Chew et al. (1990)  
Cruzan (1962)  
Chew and Wang (1993)  
Danos and Maximon (1965)  
Fikioris and Uzunoglu (1979)  
Fuller (1994)  
Fuller and Kattawar (1988a)  
Fuller and Kattawar (1988b)  
Gérardy and Ausloos (1982)  
Hamid et al. (1990b)  
Mackowski (1991)  
Mackowski (1994)  
Mackowski (2001)  
Mackowski and Mishchenko (1996)  
Mishchenko and Mackowski (1994)  
Miyazaki and Jimba (2000)  
Ngo et al. (1996)  
Ngo et al. (1997)  
Peterson (1977)  
Peterson and Ström (1973)  
Rozenberg (1974)  
Saija et al. (2003b)  
Siqueira and Sarabandi (2000)  
Stein (1961)  
Stout et al. (2001)  
Stout et al. (2002a)  
Ström (1974)  
Tzeng and Fung (1994)  
Videen and Bickel (1991)  
Videen and Ngo (1998)  
Videen et al. (1995)  
Videen et al. (1996)  
Wang and Chew (1993)  
Wittmann (1988)  
Xu (1996a)  
Xu (1996b)  
Xu (1997b)  
Xu (1998b)  

2.7. T-matrix theory of electromagnetic scattering by infinite periodic arrays of particles

Modinos (1987)  
Peterson (1977)  
Varadan (1980)  
Waterman and Pedersen (1986)  

2.8. T-matrix theory and computations of electromagnetic scattering by discrete random media

Bringi et al. (1982a)  
Bringi et al. (1982b)  
Bringi et al. (1983)  
Chew (1989)  
Chen et al. (2003)  
Chew et al. (1990)  
Doicu and Wriedt (2001a)  
Guo et al. (2001)  
Lu et al. (1995)  
Ma et al. (1988)  
Neo et al. (1999)  
Siqueira and Sarabandi (2000)  
Stefanou and Modinos (1993)  
Tishkovets (2002)  
Tishkovets and Mishchenko (2004)  
Tishkovets and Mishchenko (2004)  
Tishkovets et al. (2002)  
Tishkovets et al. (2004a)  
Tsang (1984)  
Tsang and Kong (1982)  
Tsang and Kong (1983)
2.9. Relation of the T-matrix method to other theoretical approaches

Agarwal (1976)  
Bates (1969)  
Bates (1975)  
Bolomey and Wirgin (1974)  
Burrows (1969)  
Doicu (1999)  
Doicu and Wriedt (1999)  
Doicu et al. (1999b)  
Doicu et al. (2000b)  
Eremin (1995)  
Eremin (1998)  
Farafonov (2002)  
Farafonov et al. (2003)  
Hill et al. (1997)  
Kahnert et al. (2003)  
Kleinman et al. (1984)  
Lewin (1970)  
Lu and Chew (1995)  
Mackowski (2002)  
Millar (1969)  
Morgan et al. (1984)  
Rother (1998)  
Rother et al. (2002)  
Schmidt et al. (1998)  
Schulz et al. (1998a)  
Videen et al. (1998)  
Wriedt and Doicu (1997)  
Zurk et al. (1995)  
Zurk et al. (1996)

2.10. Symmetry properties of the T matrix and analytical orientation averaging approaches

Battaglia et al. (2001b)  
Borghese et al. (1984b)  
Borghese et al. (2001)  
Fucile et al. (1993)  
Fucile et al. (1995)  
Havemann and Baran (2001)  
Kahnert et al. (2001a)  
Khlebtsov (1991)  
Khlebtsov (1992)  
Mackowski (1994)  
Mackowski and Mishchenko (1996)  
Mishchenko (1989)  
Mishchenko (1990b)  
Mishchenko (1990c)  
Mishchenko (1990d)  
Mishchenko (1991a)  
Mishchenko (1991b)  
Mishchenko (1991c)  
Mishchenko (1991e)  
Mishchenko (1992a)  
Mishchenko and Mackowski (1994)  
Paramonov (1994c)  
Paramonov (1994e)  
Paramonov (1995a)  
Paramonov (1995b)  
Paramonov and Lopatin (1990)  
Schulz et al. (1999a)  
Sindoni et al. (1984)  
Skaropoulos (2003)  
Skaropoulos and Russchenberg (2002)  
Tsang et al. (1984)  
Varadan (1980)  
Varadan (1980a)  
Varadan et al. (1984)  
Varadan et al. (1985a)  
Varadan et al. (1985b)  
Varadan et al. (1987)  
Varadan et al. (1988)  
West et al. (1994)  
Wielaard et al. (1997)
2.11. Convergence of various implementations of the T-matrix method

Ding and Xu (1999)           Mishchenko et al. (1996a)
Doicu et al. (2000b)         Ramm (1982)
Kahnert et al. (2001b)       Ström and Zheng (1987)
Lakhtakia et al. (1984a)     Wiscombe and Mugnai (1986)
Lapalme and Pattitsas (1993a)

2.12. Benchmark T-matrix results

By benchmark numerical results we understand numbers with at least 3 correct first significant decimals. The accuracy of the numbers must be established by either comparisons with results generated by an independent method or by implementing a reliable internal convergence test.

Kuik et al. (1992)           Mishchenko et al. (1996a)
Mishchenko (1991a)           Voshchinnikov et al. (2000)
Mishchenko (2000)

2.13. T-matrix calculations for homogeneous spheroids

Abdulkin and Paramonov (2001) Barber (1977a)
Alpers et al. (2001)          Barber (1977b)
Astafieva and Babenko (1999)  Barber (1978)
Aydin and Zhao (1990)         Barber and Yeh (1975)
Aydin et al. (1989)           Barber et al. (1982)
Aydin et al. (1998)           Barber et al. (1983a)
Babenko and Petrov (2002)     Barber et al. (1983b)
Bantges et al. (1999)         Battaglia et al. (2001a)
Baran et al. (1998)           Battaglia et al. (2001b)
2.14. T-matrix calculations for Chebyshev and generalized Chebyshev particles

- Battaglia et al. (2001b)
- Chylek and Ramaswamy (1982)
- Chylek et al. (1981)
- Crosta et al. (2001)
- Crosta et al. (2003)
- Ding and Xu (1999)
- Flesia et al. (1994)
- Mannoni et al. (1996)
- Mishchenko (1989)
- Mishchenko (1990c)
- Mishchenko (1990d)
- Mishchenko (1991a)
- Mishchenko (1991d)
- Mishchenko (1994)
- Mishchenko (2000)
- Mishchenko and Sassen (1998)
- Mishchenko and Travis (1994b)
- Mugnai and Wiscombe (1980)
- Mugnai and Wiscombe (1986)
- Mugnai and Wiscombe (1989)
- Wiscombe and Mugnai (1986)
- Wiscombe and Mugnai (1988)

2.15. T-matrix calculations for finite circular cylinders

- Appleyard and Davies (2004)
- Baran (2003)
- Baran and Francis (2004)
- Baran et al. (2003)
2.16. T-matrix calculations for various rotationally symmetric particles

Aydin and Seliga (1984)  
Aydin et al. (1984)  
Barber and Massoudi (1982)  
Barber and Yeh (1975)  
Bates and Wong (1974)  
Bringi and Seliga (1977a)  
Bringi and Seliga (1980)  
Doicu and Wriedt (1997c)  
Hizal (1980)  
Lakhtakia and Iskander (1983a)  
Lakhtakia et al. (1983)  
Lapalme and Patitsas (1993a)  
Li et al. (2001)  
Mishchenko and Videen (1999)  
Mishchenko and Lacis (2003)  
Mishchenko and Macke (1998)  
Mishchenko and Macke (1999)  
Mishchenko and Sassen (1998)  
Mishchenko et al. (1997b)  
Ngo et al. (1997)  
Prodi et al. (1999)  
Schuh and Wriedt (2003)  
Ström and Zheng (1987)  
Sturniolo et al. (1995)  
Videen et al. (1996)  
Warner and Hizal (1976)  
Waterman (1965)  
Waterman (1971)  
Waterman (1973)  
Waterman (1979)  
Waterman (1980)  
Wriedt and Doicu (1997)  
Yeh et al. (1982a)  
Yeh et al. (1982b)  
Yang et al. (2003)  
Yilmaz et al. (2003)  
Zakharova and Mishchenko (2001)
2.17. T-matrix calculations for ellipsoids, polyhedral scatterers, and other particles lacking axial symmetry

Baran et al. (2001a)  Kahnert et al. (2002b)
Baran et al. (2001b)  Laitinen and Lumme (1998)
Havemann et al. (2003)  Schneider et al. (1991)
Kahnert et al. (2001b)  Wriedt and Doicu (1998b)

2.18. T-matrix calculations for layered and composite particles

Aydin and Zhao (1990)  Mazumder et al. (1992)
Aydin et al. (1983)  Quirantes (1999)
Bringi and Seliga (1977a)  Quirantes and Delgado (2001)
Doicu and Wriedt (2001b)  Wang and Barber (1979)
Doicu and Wriedt (2001c)  Wang et al. (1979)

2.19. T-matrix calculations for clusters of homogeneous spheres

Abel et al. (2003)  Chew et al. (1990)
Andersen et al. (2002)  Chew et al. (1994)
Arnold et al. (1994)  Cruz et al. (1989)
Auger and Stout (2003)  de Abajo (1999a)
Auger et al. (2000)  de Abajo (1999b)
Borghese et al. (1984a)  Flatau et al. (1993)
Borghese et al. (1984b)  Fonseca et al. (1993)
Borghese et al. (1984c)  Fonseca et al. (1994)
Borghese et al. (1987b)  Fucile et al. (1995)
Botet et al. (1997)  Fuller and Kattawar (1988a)
Bruning and Lo (1971b)  Fuller and Kattawar (1988b)
Chew (1989)  Fuller et al. (1986)
Gérardy and Ausloos (1982)
Gustafson et al. (2001)
Hamid (1996)
Hamid et al. (1990a)
Hamid et al. (1990b)
Hamid et al. (1991)
Holler et al. (2000)
Hovenier and Mackowski (1998)
Hovenier et al. (1996)
Ioannidou et al. (1995)
Jin and Huang (1996a)
Kattawar and Dean (1983)
Khlebtsov et al. (2000)
Khlebtsov et al. (2004b)
Kimura (2001)
Kimura et al. (2003)
Landgraf et al. (1999)
Litvinov et al. (2003)
Lu and Chew (1993)
Mackowski (1991)
Mackowski (1994)
Mackowski and Mishchenko (1996)
Manoharan et al. (2003)
Mishchenko (1996)
Mishchenko and Mackowski (1994)
Mishchenko and Mackowski (1996)
Mishchenko et al. (1995a)
Mishchenko et al. (2004)
Miyazaki and Jimba (2000)
Miyazaki et al. (2002)
Miyazaki et al. (2003)
Miyazaki et al. (2004)
Ovod (1999)
Ovod et al. (1998)
Pellegrino et al. (1997)
Petrova et al. (2000)
Petrova et al. (2001a)
Petrova et al. (2001b)
Pustovit et al. (2002)
Quinten (1999)
Quinten and Kreibig (1988)
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Quinten et al. (2002)
Quirantes and Delgado (2003)
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Ruppin (1999)
Saija et al. (1985)
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Saija et al. (2001b)
Saija et al. (2003a)
Saija et al. (2003b)
Schnaier et al. (2003)
Secker et al. (2000)
Siqueira and Sarabandi (2000)
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Stout et al. (2002b)
Tishkovets (1994)
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Tzeng and Fung (1994)
Usami (1999)
Vargas and Niklasson (2001)
Vargas and Niklasson (2002)
Videen et al. (1997a)
Videen et al. (1997b)
Videen et al. (1998)
Videen et al. (2000)
Wang and Chew (1993)
Wurm and Schnaiter (2002)
Xu (1995)
Xu (1997a)
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Xu (2003b)
Xu (2003c)
Xu (2004)
Xu and Gustafson (1997)
Xu and Gustafson (1999)
Xu and Gustafson (2001)
Xu and Wang (1998)
Xu et al. (1999)
Zhao et al. (2003)
Zhong et al. (2004)
2.20. $T$-matrix calculations for clusters of layered spheres

- Borghese et al. (1987a)
- Hamid et al. (1992)
- Hamid et al. (2003)
- Khlebtsov et al. (2004b)

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2.24. T-matrix calculations of optical forces and torques on small particles

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2.27. Use of T-matrix calculations for testing other theoretical techniques

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2.28. Comparisons of T-matrix and effective-medium-approximation results

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Fuller et al. (1999)  

### 2.29. Comparisons of T-matrix and controlled laboratory results

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### 2.31. T-matrix modeling of scattering properties of mineral aerosols in the terrestrial atmosphere and soil particles

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### 2.32. T-matrix modeling of scattering properties of carbonaceous and soot aerosols and soot-containing aerosol and cloud particles

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### 2.33. T-matrix modeling of scattering properties of cirrus cloud particles

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2.34. **T-matrix modeling of scattering properties of hydrometeors**

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2.35. **T-matrix modeling of scattering properties of terrestrial stratospheric aerosol and cloud particles**

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2.36. **T-matrix modeling of scattering properties of noctilucent cloud particles**

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2.37. T-matrix modeling of scattering properties of hydrosol particles

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2.38. T-matrix modeling of scattering properties of aerosol and cloud particles in planetary atmospheres

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2.39. T-matrix modeling of scattering properties of interstellar, interplanetary, and cometary particles

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2.40. T-matrix computations for industrial and military applications

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3.2. Spherically symmetric particles

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3.3. Non-spherically symmetric finite particles

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3.4. Finite particles on incident side of planar interface

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3.5. Finite particles on transmitted side of planar interface

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3.6. Two-dimensional particles near planar substrates

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