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Directional radiometry and radiative transfer: The convoluted path from centuries-old phenomenology to physical optics

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ABSTRACT

This Essay traces the centuries-long history of the phenomenological disciplines of directional radiometry and radiative transfer in turbid media, discusses their fundamental weaknesses, and outlines the convoluted process of their conversion into legitimate branches of physical optics.

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1. Introduction

It is a great honor to have become the second recipient of the Hendrik C. Van de Hulst Award presented by Elsevier in the general category of Electromagnetic Scattering. It is also a special pleasure for me to receive this award following Prof. Joop W. Hovenier (Fig. 1) who has always exerted strong influence on my research and had unknowingly served as an implicit adviser during my PhD studies and early years in science. Part of the award ceremony was a Van de Hulst Lecture presented at the 14th Conference on Electromagnetic and Light Scattering (ELS) on 20 June 2013. Another official part of this award is the honor and obligation to publish in the *Journal of Quantitative Spectroscopy and Radiative Transfer* (*JQSRT*) a scientific Essay intended to summarize the recipient's personal view of the state-of-the-art of one or more disciplines related to electromagnetic scattering by particles and particulate media. Needless to say, these disciplines are expected to have been foci of the recipient's own research leading to the Van de Hulst Award.

The formats and styles of the Van de Hulst Lecture and the Van de Hulst Essay are still in a state of flux since only two such lectures have been presented and only one such Essay has been published [1]. On one hand, this lack of established traditions appears to represent a challenge. Yet on the other hand I feel that it sets me free to adopt an ad hoc format for this Essay and essentially speak my mind with the hope that the result will be instructive to the *JQSRT* readership. Therefore, I have decided to focus on the current state of the disciplines of directional radiometry and radiative transfer as I understand them following

Abbreviations: CCD, charge-coupled device; DTO, dyadic transition operator; ELS, Electromagnetic and Light Scattering; FEs, Foldy equations; GISS, Goddard Institute for Space Studies; *JQSRT*, *Journal of Quantitative Spectroscopy and Radiative Transfer*; MMEs, macroscopic Maxwell equations; NASA, National Aeronautics and Space Administration of the USA; PST, Poytning–Stokes tensor; QED, quantum electrodynamics; RTE, radiative transfer equation; RTT, radiative transfer theory; VIE, volume integral equation; WCR, well-collimated radiometer

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Fig. 1. Joop Hovenier (left) and Michael Mishchenko at ELS-XIV in Lille on 17 June 2013.

almost 30 years of research. More specifically, this Essay will largely be devoted to the centuries-long history of the phenomenological stage of these disciplines which, intriguingly, is not over yet, followed by the history of the uneasy process that has ultimately led both disciplines to become full-fledged branches of physical optics.

Although Van de Hulst's classical treatises on light scattering [2] and radiative transfer [3] have been essential sources of my knowledge of both disciplines, I have had the privilege of meeting him in person only twice. The first meeting occurred in Leningrad (now St. Petersburg) in October of 1990 during a Symposium dedicated to the 100th anniversary of the radiative transfer equation (RTE). That Symposium was organized by Academician Viktor Sobolev and Professor Vsevolod Ivanov and served to assemble many members of the renowned Soviet school of radiative transfer (Fig. 2). Professor Van de Hulst (Fig. 3) was a special invitee and a de facto ambassador of the western school. The majority of presentations were given in Russian, and so during two sessions I was asked by Vsevolod Ivanov to translate the talks into English personally for Professor Van de Hulst. That task of speaking so much English for the first time in my life turned out to be a challenge, and by the middle of the second session my tongue and lips started to fail. Professor Van de Hulst did notice that and with a soft smile told me not to worry since most formulas required no translation. I was also asked to accompany Professor Van de Hulst on his commutes between Pulkovo (the location of the famous Pulkovo Astronomical Observatory) and Petrodvorets (the location of the Astronomy Department of the Leningrad University). One of these trips coincided with a beautiful sunset which we could observe through the train window; looking at splendid colors of that sunset naturally triggered an instructive discussion of various atmospheric optical phenomena.

Our second meeting occurred during the inaugural Conference on Light Scattering by Non-Spherical particles in May of 1995. That event was organized by Joop Hovenier at the Free University of Amsterdam [4] and served to initiate the prominent series of ELS conferences.

The 1998 ELS conference was convened at the NASA Goddard Institute for Space Studies (GISS) in New York, and Professor Van de Hulst had kindly agreed to open it with a keynote lecture. He was very enthusiastic about the occasion to visit the place where he spent a six-month sabbatical in 1962, the result of which was his famous NASA report on the adding/doubling method [5]. Unfortunately, just two days before the opening of the conference Professor Van de Hulst faxed me with an apology for being unable to come to New York because of certain health issues. However, he was still able to contribute the instructive Foreword [6] to the monograph on light scattering by nonspherical particles [7] which has proved to be an important collective outcome of the New York conference.

Since Joop Hovenier did his PhD work under the supervision of Professor Van de Hulst and since my early research had benefitted so much from Joop's publications (especially the 1983 review [8] co-authored by Cornelis van der Mee), I consider myself one of Van de Hulst's "indirect" disciples. My direct scientific genealogy can be traced to Academician Viktor Ambartsumian, one of the founders of theoretical astrophysics. Indeed, I did my PhD work under the supervision of Dr. Edgard Yanovitskij whose PhD thesis was in turn supervised by Academician Sobolev (Fig. 4), the prominent Soviet astrophysicist and the best known PhD student of Academician Ambartsumian (Fig. 5). My early research was also influenced by two other members of the Ambartsumian–Sobolev school of radiative transfer, Vsevolod Ivanov and Helmut Domke (Fig. 6). Furthermore, Vsevolod Ivanov served as an Official Opponent on my PhD and Habilitation thesis defenses.

As already mentioned, I owe my initial basic knowledge of the theory of radiative transfer to Van de Hulst's monograph [3], as well as to the so-called "blue Sobolev" [9].[1] That nickname refers to the navy blue color of the cover in the original Russian edition of this well-known monograph and was used by Soviet scientists to distinguish it casually from the "black Sobolev" [11]. As a novice in the field of radiative transfer, I took for granted the apparent simplicity and obviousness of the main phenomenological concepts of this discipline and for some time had not realized that the "traditional" radiative transfer theory (RTT) is, figuratively speaking, a "colossus with feet of clay". My awakening started in 1986 when I read the Russian edition of the 1978 book by Ishimaru [12]. It was quite surprising to learn that

[1] Another essential source was the famous review by my future colleagues at GISS James Hansen and Larry Travis [10]. This paper was immensely popular among my Soviet colleagues despite the fact that only a few preprints and even fewer reprints were in circulation. I still vividly remember how upset Edgard Yanovitskij became when he found that his copy of the preprint had been stolen from his desk. While being unethical, this was obviously an act of desperation on someone's part as well as an implicit compliment to a great publication. In 1985, the first year of my PhD studies, it took a bit of courage to send a postcard to Larry Travis asking for a reprint. I thought that I had no chance since 11 years after the publication of the paper all reprints were likely to be gone; furthermore, I did not know the street address (it was not included as part of the authors' affiliation) and sent the postcard to NASA GISS, New York, NY 10025, USA. To everyone's (and my own) surprise, two months later I became a proud owner of an original reprint. Needless to say, I never left it on my desk unattended.