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Commemoration of the centenary of the birth of S M Rytov
(Scientific session of the Physical Sciences Division of the Russian Academy of Sciences, 26 November 2008)

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A scientific session of the Physical Sciences Division of the Russian Academy of Sciences (RAS) was held in the Conference Hall of the P N Lebedev Physical Institute, RAS on November 26, 2008. The session was dedicated to the 100th anniversary of the birth of Sergei Mikhailovich Rytov.

The following reports were presented at the session:

(1) **Gulyaev Yu V** (V A Kotel'nikov Institute of Radioengineering and Electronics, RAS, Moscow) "Sergei Mikhailovich Rytov (Opening address)";

(2) **Barabanenkov Yu N** (V A Kotel'nikov Institute of Radioengineering and Electronics, RAS, Moscow) "Asymptotic limit of the radiative transfer theory in problems of multiple wave scattering in randomly inhomogeneous media";

(3) **Kaplan A E, Volkov S N** (Johns Hopkins University, Baltimore, USA) "Local fields in nanolattices of strongly interacting atoms: nanostrata, giant resonances, 'magic numbers,' and optical bistability";

(4) **Klyatskin V I** (A M Obukhov Institute of Atmospheric Physics, RAS, Moscow) "Modern methods for the statistical description of dynamical stochastic systems";

(5) **Dolin L S** (Institute of Applied Physics, RAS, Nizhny Novgorod) "Development of the radiative transfer theory as applied to instrumental imaging in turbid media".

An abridge version of the reports is given below.

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Sergei Mikhailovich Rytov
(Opening address)

Yu V Gulyaev

On July 3, 2008 we celebrated the 100th anniversary of the birth of Professor Sergei Mikhailovich Rytov — one of the outstanding Russian physicists in radiophysics and a Corresponding Member of the USSR Academy of Sciences.

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Sergei Mikhailovich Rytov
(03.07.1908 – 22.10.1996)

Sergei Mikhailovich obtained results of the paramount importance, which were recognized the world over in each field of physics where he worked — the theory of oscillations and acoustics, wave propagation, electrodynamics and optics, and, finally, statistical radiophysics. Some of these results became cornerstones of new fields in theoretical radiophysics. S M Rytov's work on parametric systems, the extension of the perturbation method, and its application to oscillator frequency stabilization belongs to the most prominent achievements of the Soviet school of the theory of nonlinear oscillations. Among other things he developed the method of smooth oscillations (known in the literature as Rytov's method and widely used to study wave propagation in randomly inhomogeneous media) which constitutes one of the most essential results in the series of research programs covering the diffraction of light by ultrasound waves. In statistical radiophysics, S M Rytov's work which he summarized in a monograph, paved the way for a new domain in the theory of thermal fluctuation noise and thermal fluctuation fields that allows a unified consideration of thermal electromagnetic fields in the entire range of frequencies — from quasistationary to optical.

It would be forgivable to end the story with this brief list: brevity is acceptable when speaking about a great person. I will nevertheless remind the reader of the main stages in the biography of Sergei Mikhailovich, mostly for the sake of the younger generations, who never had a chance of having worked alongside him.

Sergei Mikhailovich Rytov was born on July 3, 1908 in Khar'kov. In 1930, he graduated from the Physics and Mathematics Department of Moscow State University (MGU), and in 1933 entered a postgraduate course at MGU under the guidance of Academician Leonid Isaakovich Mandel'shtam. It must be mentioned that later he brilliantly continued in his profession of a physicist and a teacher the best traditions of the scientific school of L I Mandel'shtam, whom he always considered his mentor. Sergei Mikhailovich taught young scientists to follow these wonderful traditions, one of which was infinite devotion to science and another, to always demand the utmost of yourself.

In 1934, Sergei Mikhailovich began working as a researcher of the 1st rank at the optics laboratory of the Lebedev Physical Institute (FIAN in *Russ. abbr.*) and later, from 1950 to 1958, he headed the theoretical sector of this laboratory. In 1958, at the request of Academician Aleksandr L'vovich Mints, Sergei Mikhailovich was transferred to the theoretical division of the Institute of Radio Engineering of the USSR Academy of Sciences (RTI in *Russ. abbr.*) where he worked until his last days.

Sergei Mikhailovich devoted all his life to research. His talent and passion for work led him to spectacular results and he became a recognized authority in many areas of physics, first and foremost radiophysics.

His study of the diffraction of light on ultrasound became one of the foundations of acousto-optics, which later went through vigorous expansion and had various practical applications. The method of smooth oscillations he had developed (known as Rytov's method) proved to be a very powerful tool for studying wave propagation in randomly inhomogeneous media. Later Sergei Mikhailovich, his students, and his followers successfully used this tool. The results they obtained are partly summarized in widely known review papers published in *UFN* (*Phys. Usp.*) (1970 – 1975) and in the latest issues of his *Introduction to Statistical Radiophysics*; they have also influenced monographs and reviews written by other authors. Some of the fundamental results obtained by Sergei Mikhailovich were used at RTI to begin important research on the effects of the troposphere and ionosphere of the Earth on the accuracy of long-range radar systems being developed and on evaluating their potential in the conditions of the real atmosphere.

Sergei Mikhailovich's DSc thesis entitled "Modulated oscillations and waves" enormously affected progress in the theory of oscillations and brilliantly demonstrated the fruitfulness of the oscillation-based approach to various problems in physics. The thesis, published in the *Proceedings of the USSR FIAN* in 1940, became a desktop must for many researchers in oscillation theory. Sergei Mikhailovich continued working on the theory of oscillations and waves; he received important results on the theory of Thomson type self-induced oscillations, the theory of betatron and synchrotron oscillations, and the theory of parametric generators and amplifiers (1948 – 1963). He was the first to analyze the problem of resonance in parametric systems and he investigated the phenomenon of 'pulling' in the hard mode of the self-excitation of oscillations. His work on parametric systems, the extension of the perturbation method, and the application of this method to the problem of stabilization of generator frequency belong to the most important achievements of the Soviet school of the theory of nonlinear oscillations. His studies on the theory of oscillations were successfully extended by his numerous students and followers.

The theory of equilibrium thermal fluctuations of an electromagnetic field, developed by Sergei Mikhailovich and completed in collaboration with M L Levin, in which the classical reciprocity theorem 'unexpectedly' proved to be very efficient, led to a unified description of these fluctuations in the entire frequency range — from the quasistationary to the optical — and is widely used in a wide variety of fields of physics. The results of the theory were later generalized to the case of fields of any nature (1973).

Sergei Mikhailovich created the most general form of the phenomenological theory of the molecular scattering of light, which includes an analysis of Mandel'shtam–Brillouin spectra and depolarized radiation, as well as scattering spectra due to entropy fluctuations (1955 – 1970). This theory was confirmed by numerous experiments and earned general recognition.

It is also necessary to point out Sergei Mikhailovich's papers in which he for the first time gave a rigorous solution to the problem of reflection of electromagnetic waves from a layer with a negative dielectric constant, outlined the correct electrodynamic approach to the problem of wave propagation in tubes and generalized transmission lines with losses, considered a new type of phase diffraction structures, and achieved complete clarity on the question of the relation between the Poynting vector, the group velocity vector, and energy density when electromagnetic waves propagate through anisotropic media.

An inseparable part of Sergei Mikhailovich's creative activities was teaching; he loved doing it, teaching practically all his life and feeling the utmost responsibility to do so. The fact that he put this type of activity first on the list in his *Biographical data* is evidence of its significance in his life; he wrote that he started teaching already in 1928, while a 3rd-year student at MGU. Later he lectured in physics and mathematics at MGU and Gorky State University.

From 1947 on, practically to the end of his life, Sergei Mikhailovich Rytov held a part-time position at the Moscow Institute of Physics and Technology[1] as professor at the Chair of General Physics (until 1949) and then professor at the Chair of Radiophysics. He headed this Chair from 1953 till 1978 (i.e., for 25 years).

Everyone who heard Sergei Mikhailovich lecture at least once felt in awe of his art of lecturing, the honed form of

[1] MFTI in *Russ. abbr.*, until 1951 — The Physics and Engineering Department of MGU.

delivery, and his clarity, profoundness, and at the same time simplicity of presentation. Students loved their professor, and attending his lectures was a pleasure; after sitting for his exam they invariably left with a feeling of satisfaction regardless of the mark awarded: he was always correctness itself and impeccably fair.

I was one of those lucky students, attending his course 'Theory of Oscillations', and even got my 'excellent' mark from him personally. Like other students, I jotted down the synopsis of all the lectures of his course; in my later work in the field of oscillation theory and microwave acoustics I would hardly need any other source: Sergei Mikhailovich's course was that complete and that clear.

The pinnacle of Sergei Mikhailovich's pedagogical creativity was his course of lectures on statistical radiophysics, which he wrote and then brilliantly delivered for many years at MFTI. Here for the first time he came up with the most laconic and rich definition of radiophysics: "This is physics for radio plus radio for physics," which legitimized radiophysics in the company of related subjects. On the basis of these lectures, he wrote the first textbook in the world on statistical radiophysics for higher education — *An Introduction to Statistical Radiophysics* (1966), which gained high reputation both in this country and abroad.

Sergei Mikhailovich took active part in writing the physics textbooks whose editor-in-chief was N D Papaleksi (1939–1948), and the *Elementary Physics Textbook* whose editor-in-chief was G S Landsberg. Sergei Mikhailovich was editor-in-chief of 15 books, three of them being translations into Russian.

For a long time, from 1953, Sergei Mikhailovich had served as permanent head of the All-Moscow Radiophysics Seminar, which played an enormously important role in the progress of radiophysics in this country. Scientists from many scientific centers in the country took part regularly in the work of the seminar, so that in reality this was an All-Union seminar. The popularity and the high rating of the seminar stemmed most of all from the decisive scientific reputation enjoyed by Sergei Mikhailovich, from his ability to provide an expert evaluation of a contribution and to lucidly formulate its stronger and weaker points. The seminar was purely scientific, devoid of any official functions or formalities. The only 'official document' was the agenda with presentation titles and speakers' names, which was sent out to participants in advance by the secretary of the seminar. The meetings followed democratic rules ably controlled by Sergei Mikhailovich.

The seminar was the center of attraction not only for radiophysicists but also for specialists in the most varied fields of physics interested in methodology and the results of radiophysics research. It would be difficult to name any important new field in radiophysics that would not have been represented at the seminar. It was here that many research areas were given a nod of approval. The seminar was a real scientific school for its young participants. This was stimulated by a very special atmosphere of genuine devotion to science, an attitude of goodwill, and the inoffensive humour that Sergei Mikhailovich demonstrated during the sessions. It is not surprising therefore that not only Rytov's immediate students and staff members but also many others who benefited from contacts with Sergei Mikhailovich regarded themselves as members of his school.

Sergei Mikhailovich worked at RTI — the institute created for the purpose of solving defense-related problems of national importance — for more than 35 years, beginning from 1958. His work in the framework of RTI defense projects targeted principally important physics aspects that involved developing and designing ground-based high-aperture radioinformation complexes. People tried not to bother him with trifles. He initiated, and took active part in, a number of new areas of research important for RTI primary tasks.

We already mentioned that one of the areas in which S M Rytov worked was to find out how nonuniformity of the atmosphere affected the characteristics of long-range radars. We can also mention such fields as the development and design of low-noise parametric amplifiers, extension of acousto-optical methods for processing radar signals, the study of the ionosphere by means of rockets and artificial Earth satellites in the interest of long-haul radiolocation, etc.

In situations of dispute, S M Rytov occasionally acted as a highly respected arbiter. His opinion was invariably profoundly reasoned and scientifically sound, which made it possible to avoid mistaken or adventurist technical solutions, however attractive they may have seemed at first glance. He was often approached to obtain advice and consultation by directors' offices, by heads of departments, or by lower-rank staff members. No one was refused. His reports on important areas of research in science and technology at RTI seminars for large audiences of RTI staff are well remembered. The Laboratory of Theoretical Radiophysics that he headed was a center of attraction for talented creative young generations, first and foremost students and postgraduates of the base Chair of Radiophysics at MFTI; many of them later came to obtain CandSc and DSc degrees or became science managers and leading specialists in this country.

Sergei Mikhailovich was generous with his knowledge and his experience in the social activities of research institutions: he was a member of the Learned Councils of MFTI and RTI and of the editorial board of the journal *Radiotekhnika i Elektronika* [*Radioengineering and Electronics*]; sat on the Methodological Council on Physical and Mathematical Sciences of the All-Union Society 'Znanie' (Knowledge), the Interdepartmental Research and Development Council on Sun–Earth issues [2], and the Bureau of the Learned Council of the USSR Academy of Sciences for the complex problem the Propagation of Radiowaves; chaired a section of the Learned Council of the USSR Academy of Sciences on the issue of Statistical Radiophysics, etc.

For his outstanding contributions to science and industry S M Rytov was awarded the A S Popov Gold medal, the L I Mandel'shtam Prize, and the State Prize, and received many distinguished orders and medals.

Commemorating now the 100th anniversary of the birth of Sergei Mikhailovich Rytov, we remember with gratitude the enormous contribution he made to the inception and progress of radiophysics and related fields of science, to the formation of the school of radiophysics in this country, and to nurturing and training of new generations of scientists. He was uniquely devoted to science and had brilliant pedagogical skills and enviable human qualities. S M Rytov's name occupies a well-deserved place in the gallery of classic personalities of science in this country and abroad.

More detailed information on the life and scientific career of Sergei Mikhailovich Rytov can be found in the editorial of

[2] Renamed in 1978 the Learned Council of the USSR Academy of Sciences for the issue of Solar–Terrestrial Relations.

the special issue of the journal *Electromagnetic Waves and Electronic Systems* devoted to the 100th anniversary of the birth of this brilliant scientist.

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Asymptotic limit of the radiative transfer theory in problems of multiple wave scattering in randomly inhomogeneous media

Yu N Barabanenkov

1. Introduction

Wave propagation in disordered systems is considered one of the most difficult subjects of theoretical physics. The traditional approach involves the phenomenological radiative transfer theory [1, 2], which originated more than a century ago in the studies by Khvol'son (1890), Schuster (1905), and Schwarzschield (1906) devoted to light scattering in milk glasses and solar and foggy earth atmospheres; it is based on the notions of linear kinetic theory involving an elementary scattering act and radiation free path. In the 1950s, the development of the theory of partial coherence for wave fields prompted active studies of the applicability limits for the radiative transfer theory from the standpoint of the statistical theory of multiple wave scattering in randomly inhomogeneous media. Their results were regularly reported and critically discussed at the All-Moscow Radiophysics Seminar headed by S M Rytov from 1965 to 1985. Although this research was purely theoretical, it resulted in the prediction of weak light localization in randomly inhomogeneous media in 1973. Because this phenomenon lay at the applicability boundary of the radiative transfer theory, it could not be ignored.

As early as 1967, a derivation was proposed [3] (see also [4]) of the phenomenological radiative transfer equation in a discrete randomly inhomogeneous medium, with due regard for the correlation of scatterers in all orders and mutual irradiation of scatterers within the same effective inhomogeneity, i.e., a cluster of scatterers. A single scatterer was characterized by its shape, dielectric permeability, and conductivity; the method of Dyson and Bethe–Salpeter equations, the Feynman diagram technique, and the concept of the quantum mechanical scattering operator were used [5]. The transfer equation [3], with pair correlation of weak scatterers satisfying the applicability conditions of the Born approximation taken account, was used to investigate an increase in the free path length of microwaves in snow layers and conduction electrons in liquid metals [6], as well as the opposite effect of a decrease in the free path of light [7] and neutrons in a liquid [6] in the vicinity of a phase transition critical point. The contribution from higher correlations of weak scatterers to the light free path at critical opalescence was considered in Ref. [8], while Ref. [9] dealt with the influence of higher correlations due to large, optically dense scatterers on the transmittance of a layer composed of such particles.

Simultaneously with the derivation of the transfer equation [3], the applicability condition for the phenomenological transfer theory was formulated as the single-group approximation, i.e., the possibility to discard all repeated scattering of radiation on the same inhomogeneity. Additionally, it is required that inhomogeneities be in the far field of Fraunhofer diffraction with respect to each other. The first part of this condition, later called the approximation of independent scattering on effective inhomogeneities [10], disregards all loops in multiple wave scattering with a diameter of the order of or larger than the free path length of radiation.

The decisive role of the single-group approximation for the transfer theory was convincingly demonstrated with the model of multiple scattering of a nonstationary wave field in a randomly inhomogeneous and randomly variable medium, for which the concept of a finite 'lifetime' of an inhomogeneity can be introduced. From this model, thoroughly studied in Refs [6, 11], the transfer theory follows as an asymptotically exact Van Hove limit [12] under the condition that the ratio of the inhomogeneity lifetime to the radiation free path time tends to zero, but the ratio of the observation time to the free path time remains fixed. The second condition of the Van Hove limit prevents repeated scattering due to a selected inhomogeneity from occurring on a large time or space scale of radiation propagation. In repeated scattering, the effects of multi-group or dependent scattering, i.e., the loops, would have to be taken into account, and the phenomenological radiative transfer theory would need modifications.

The most thoroughly studied effect of multi-group or dependent scattering by effective inhomogeneities is manifested through the coherent enhancement of backscattering. It was first predicted as a wave correction to the solution of the transfer equation for scattering directed exactly 'backward' [13]. Reference [14] shows, based on the technique of cyclic (maximally crossed) Feynman diagrams, that the wave correction attains a relative value close to unity in a narrow backscattering cone whose angular width is of the order of the ratio of the wave length to the free path length of radiation.

The predicted cone of enhanced backscattering was experimentally observed by several groups [15–17]. It strongly stimulated research on the weak localization phenomenon in optics [18]. Coherent enhanced backscattering stems from coherent loops in which the field and its complex conjugate go around a given set of inhomogeneities in opposite ways. There also exist incoherent loops, in which case a set of inhomogeneities is passed by the field and its complex conjugate in the same order. The incoherent loops lead to the backscattering effect for nonstationary radiation in a modified transfer theory with time delay [19], where the delay time is of the order of the radiation free path time. Another variant of the transfer theory with time delay emerges on considering the effect of trapping [20] under multiple scattering of wave radiation, for example, a short femtosecond laser pulse [21], in a randomly inhomogeneous medium composed of resonant scatterers.

Taking account of loops in multiple wave scattering implies lifting the part of the applicability condition of the phenomenological transfer equation [3] that requires omitting repeated scattering of radiation by the same inhomogeneity. No principal obstacles are seen in using this equation to explore multiple light scattering by new artificial systems such as statistical ensembles of nanosclusters [22], in which each cluster represents a combination of a possibly large but finite number of atoms (or molecules) and requires describing light scattering with methods of quantum mechanics or