INVERSION METHODS IN ATMOSPHERIC REMOTE SOUNDING

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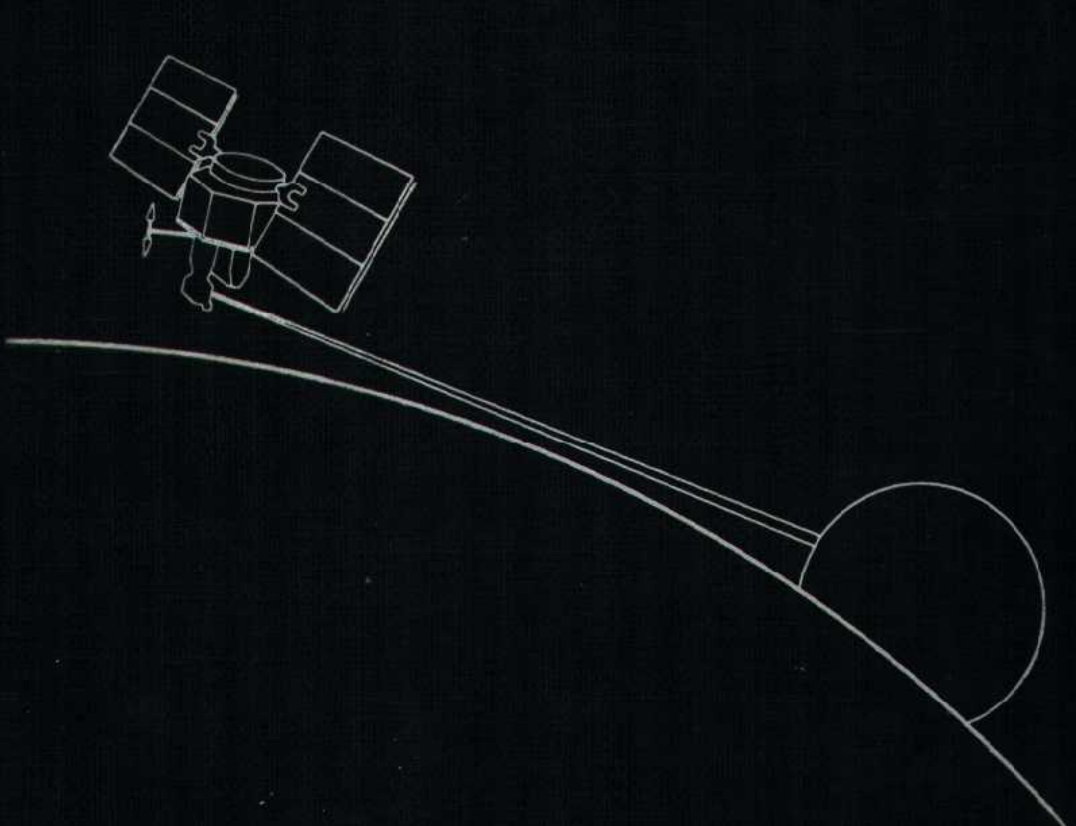

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PREFACE

This volume contains the technical proceedings of the First International Interactive Workshop on Inversion Methods in Atmospheric Remote Sounding, held in Williamsburg, Virginia, December 15-17, 1976. Seventy-three invited scientists from seven countries, representing universities, research laboratories, and U.S. Government agencies, participated in the workshop. The purpose of the workshop was to provide an interdisciplinary forum to review and assess the state of the art in inversion methods available for retrieving information about the atmosphere from remotely sensed data.

Twenty-one invited papers covered the mathematical theory of inversion methods as well as the application of these methods to the remote sounding of atmospheric temperature, relative humidity, and gaseous and aerosol constituents. The emphasis was on the assumptions, methodology, resolution, stability, accuracy, and future efforts needed in the various inversion methods. Also included are invited papers on the direct radiative transfer methods and results relevant to the inversion problem. The latter were presented in a special session on radiative transfer methods, held jointly with the Optical Society of America Topical Meeting on Atmospheric Aerosols, which preceded the workshop. One of the major workshop objectives was to enable researchers in different areas of atmospheric remote sounding to compare and optimize the utilization of these inversion procedures in their respective remote sounding techniques. Ample time was allowed for discussions following each paper and in two open discussion sessions. This fulfilled an important objective of the workshop. Discussions presented were recorded and the transcripts postedited. Each discussant edited his/her portion of the statements with the aim of improving its clarity without changing its substance.

Since NASA is involved in developing several remote sensing experiments designed to monitor the atmospheric constituents and properties from aboard space platforms, the editor suggested to M. P. McCormick, Langley Research Center, that organization of an interactive workshop dealing with the mathematical aspects of the inversion methods would greatly benefit all researchers concerned with inversion and radiative transfer methods. He, along with J. D. Lawrence, Jr., Langley Research Center, and M. Tepper, NASA Headquarters, concurred and supported the idea with the result that I undertook the assignment of organizing such a workshop with the goal of making the proceedings of the workshop readily available to the scientific community.

To ensure proper representation of major disciplines involved, a Workshop Program Committee, composed of A. Deepak (Chairman), Old Dominion University; M. P. McCormick (Associate Chairman), NASA Langley Research Center; B. M. Herman, University of Arizona; J. D. Lawrence, Jr., NASA Langley Research Center; and M. Tepper, NASA Headquarters, was set up. The committee was ably assisted in this endeavor by the following program consultants: M. T. Chahine, Jet Propulsion Laboratory; B. J. Conrath, NASA Goddard Space Flight Center; A. L. Fymat, Jet Propulsion Laboratory; J. Russell III, NASA Langley Research Center; and E. Westwater, NOAA/Environmental Research Laboratory.

Dr. Tepper opened the workshop, stressing the significance of inversion problems to NASA and its programs involved in the monitoring of atmospheric environments of the Earth and other planets. The challenges inherent in the inversion problem were perhaps best characterized by his analogy that the problem of the inversion method was like that of unscrambling an egg, wherein one investigates the scrambled egg to determine what it was like originally.

The editor wishes to acknowledge the enthusiastic support and cooperation of the participants, the members of the organizing committee, the program consultants, the session chairmen, and the speakers in making the workshop a very stimulating and valuable experience for everyone. Special thanks are due M. P. McCormick, whose wholehearted cooperation and active support as Associate Chairman assured the success of the workshop. Commendations are due the Science and Technical Information Program Division and especially the Technical Editing Branch, for their cooperation and high quality of workmanship in publishing this volume. Last but not least, it is a pleasure to thank and highly commend the superb job done by Mrs. M. Sue Crotts both in helping with the organization of the workshop and with the excellent quality of typing of the manuscripts.

Behind every successful remote sensing technique is at least one reliable inversion method. I hope this volume will be a lasting contribution to the field of inversion methods.

HYBRID METHODS ARE HELPFUL

H. C. van de Hulst
Leiden University

A basically simple problem like multiple scattering in a plane layer often permits the convenient use of different methods joined together. Sample numerical results to illustrate this point refer to X- and Y-functions, asymptotic fitting, the small-loss approximations, polarization in high orders, and photon path distribution.

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I. INTRODUCTION

Methods to solve problems in radiative transfer and in multiple scattering exist in such a wide variety that I shall not attempt another review. In any practical problem, the method must be chosen on the basis of expediency, and this, in turn, depends on many factors, such as: range of variables; desired accuracy of results; occasional or frequent computations needed; cost, available funds; and experience and taste. I emphasize in this paper the fact that in many situations a hybrid approach containing elements from different methods, though not "elegant", is the most practical. A normal rose or fruit tree consists of different varieties skillfully grown together because the desired properties of roots and fruits (or flowers) are not met in a single variety.

Before illustrating this point with a number of examples taken from Ref. 1, I wish to make a general remark. We all have learned to respect the power of mathematics. Solving a problem in mathematical physics often is like going somewhere by train. The mathematics is like the train: we enter at a station called equation and we get

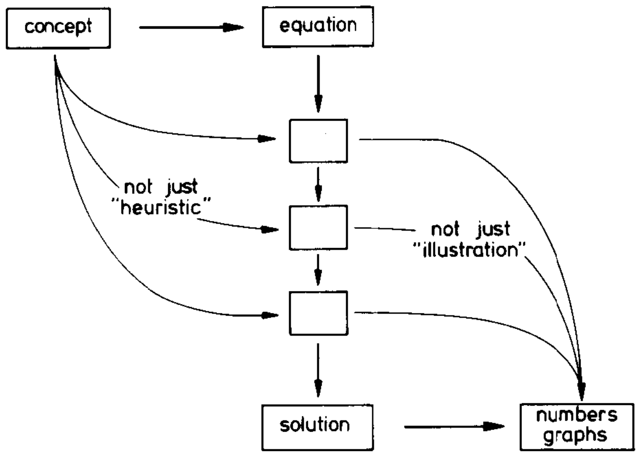

Fig. 1. A schematic diagram illustrating the advisability of accessing from physical concepts to intermediate results, whose interpretation may be as important as that of final numbers.

off at a station called solution (see Fig. 1). Once inside the train, we can relax and look out of the window, for nothing much can go wrong. In contrast, the roads from our home to the station and from the last station to our destination may be time-consuming, uncomfortable, or even hazardous. My point is that in many problems the train is suburban: it stops at certain intermediate stations. Boarding the train at one of those stops may be quite as safe, respectable, and economic as entering at the initial station which in our topic is called equation of transfer. At any rate, it is worth a try to find out which is simplest. Likewise, it often pays to evaluate and physically interpret certain intermediate results which is the same as getting off before the end station.

The philosophical message is that combining physics with mathematics makes a hybrid method anyhow. Therefore, we might as well experiment a little to find the most convenient connection.

II. THE X- AND Y-FUNCTIONS

Consider any given landscape (Fig. 2) with an isotropic light source placed at a point P and no other source of illumination. Looking at this landscape from a distance, say from the direction Q, we see a blob of light in which the source itself (dimmed or not) may still be discernible. We define the *gain* (from P to Q and conversely) as the intensity that reaches Q from source plus illuminated landscape divided by the intensity that would reach Q from the bare source placed at the same distance.

This definition is given in preparation of a discussion of the well-known X- and Y-functions for isotropic scattering. These functions were introduced by Ambartsumian in the early forties and extensively studied by Chandrasekhar about 1945, who defined them as solutions of certain simultaneous nonlinear integral equations.

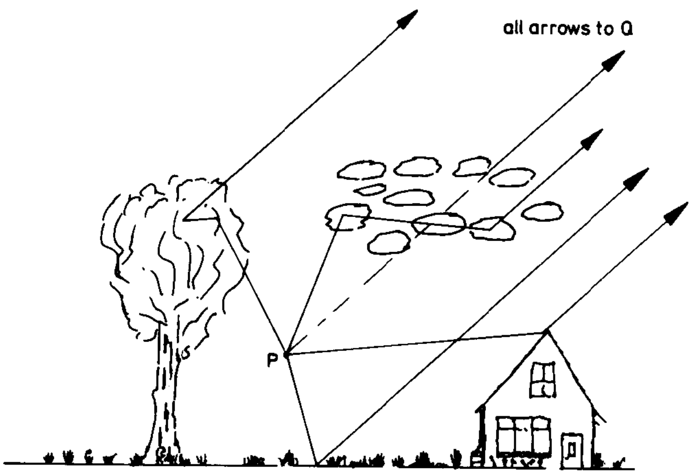

Fig. 2. A schematic sketch of a "landscape" with an isotropic source at P for illustrating the concept of gain between point P and a direction Q.

Far simpler, in the gain definition just given, we may take as the "landscape" a homogeneous slab of isotropically scattering particles with optical thickness b, the source P just outside the slab, and the direction Q subtending an angle θ with the normal. The X-function then is the gain with the source seen in front of the slab and the Y-function is the gain with the source (dimmed) seen through the slab. This is all there is to it: no problems of existence or uniqueness if we board the train at this station. Both functions depend on three variables: b, $\mu = \cos\theta$, and a = the albedo for single scattering.

I was quite pleased when in 1947 I rediscovered these definitions, from which Ambartsumian had started, and found that certain properties of these functions can be far more easily derived from these physical definitions. Since that time, I do not hesitate to use the two approaches mixed.

Figure 3 shows a selection of values of these functions. The Y-function usually is less than unity because the blob of scattered and multiply-scattered light does not fully compensate the dimming of the direct source. The X-function always is greater than unity because it includes a term unity arising from the unobstructed light from the source. The X-function for a semi-infinite atmosphere ($b = \infty$) usually is called the H-function. If $b = \infty$ and $a = 1$, all radiation incident on the atmosphere is returned as diffusely reflected light after many scattering events. If the landscape were a mirror reflecting all incident radiation, we would see the source double from any direction, which would mean $X(\mu) = 2$. The diffuse reflection leads to the same average value of 2 for $H(\mu)$, but the distribution with μ is different, ranging from $H(0) = 1.0$ to $H(1) = 2.908$.

As a counter example, in which the physical picture is of little use, I mention the extension of the H-function to arguments outside the domain $\mu = 0$ to 1. Such an extension is needed in a variety of problems. It is then convenient to plot the inverse

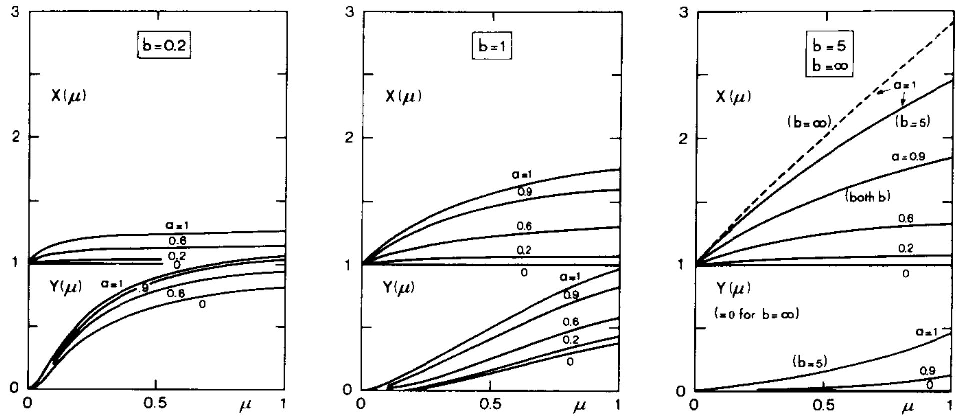

Fig. 3. Reminder of the dependence of the X- and Y-functions for isotropic scattering on the variables b, a, and μ. *The X-function for b = ∞ is called H-function.*

function $\{H(\mu)\}^{-1}$ against the inverse argument μ^{-1}. Figure 4 gives an example which happens to refer to anisotropic scattering but this makes no essential difference. We see that the graph continues to curve down for $\mu^{-1} < 1$ and reaches 0 at $\mu^{-1} = -k$, where k is the diffusion exponent, i.e., the value for which a self-consistent solution to the transfer equation in an unbounded medium exists in which the dependence on optical depth τ is given by the factor $\exp(\pm k\tau)$. The values and slopes at $\mu^{-1} = 0$ and $\mu^{-1} = -k$ occur in several standard problems.

We have taken these illustrations from isotropic scattering and one example from very simple anisotropic scattering. Phase functions of arbitrary form, or phase matrices with polarization, require a more elaborate set of formulas. Yet, the situation remains basically the same: carefully preparing the access at intermediate stations usually pays off in clarity or in speed of computation.

A final remark on the X- and Y-functions for single-scattering patterns of arbitrary form is that these same functions appear in

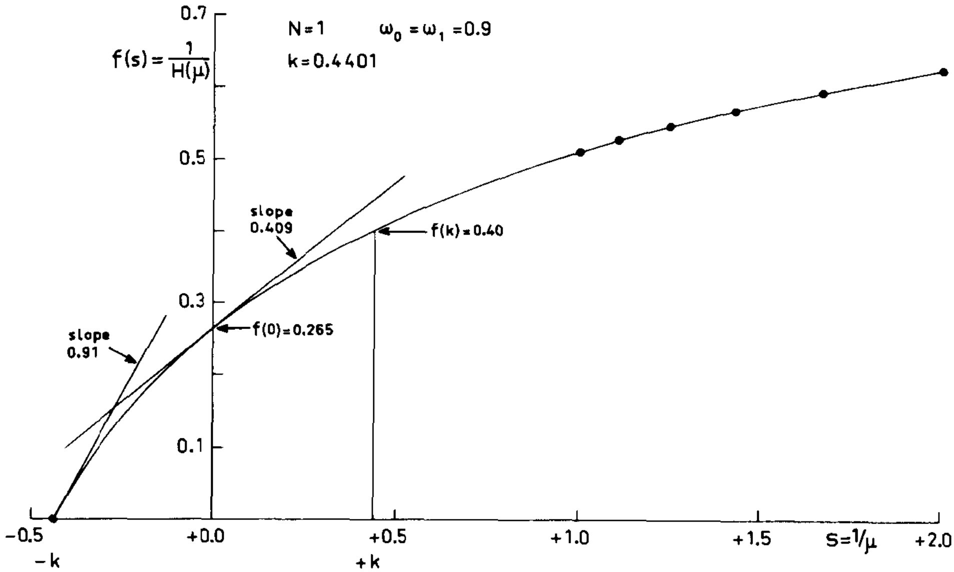

Fig. 4. A plot of $1/H(\mu)$ as a function of $1/\mu$ depicting the best way for visualizing the behavior of the H-function beyond the usual domain $0 \leq \mu \leq 1$ for linearly anisotropic scattering with $\omega_o = \omega_1 = 0.9$.

conceptually quite different methods. The sketch in Fig. 5, which we shall not explain in detail, shows four important methods of solving radiation transfer problems. In the second method, labeled "invariant embedding," the X- and Y-functions are introduced to describe the effect of a narrow layer added to one or the other side of a slab. The method of singular eigenfunction expansion works from an entirely different concept, in which the complete set of eigenfunctions for the unbounded medium is first established. The proper coefficients of each that match the boundary conditions are then found by applying orthogonality relations and it is in the course of establishing the half-range orthogonality relations that the X- and Y-functions have to be introduced.

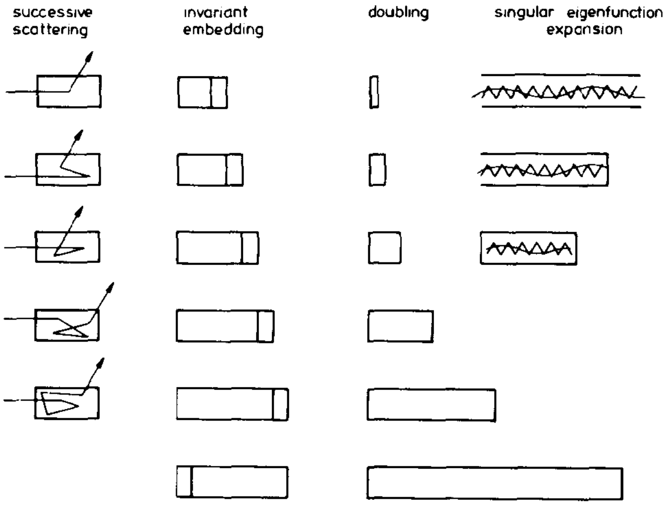

Fig. 5. Schematic representation of some commonly used methods to solve problems of multiple scattering or radiative transfer.

III. ASYMPTOTIC FITTING

Before describing this method, I wish to convey by means of Fig. 6 an impression of the range of variables in which the simplest approximations suffice. I refer to the legend for details. The diagram shows that, if the scattering is conservative, or nearly so, a wide range of four decades in the optical thickness b exists, in which we cannot in practice say: the layer is very thin, or it is infinitely thick. This is annoying because the convergence of almost any method is small for large b. This point is illustrated for the successive scattering method in Fig. 7.

The incidence is normal in this example and the scattering is isotropic, so that the source function for first-order scattering J_1 is 1/4 $e^{-\tau}$ in both examples. In the right-hand side example, the layer thickness is 1. At each successive scattering there are losses at both sides and the net effect is that after some five scattering events, the distribution has become symmetric and drops

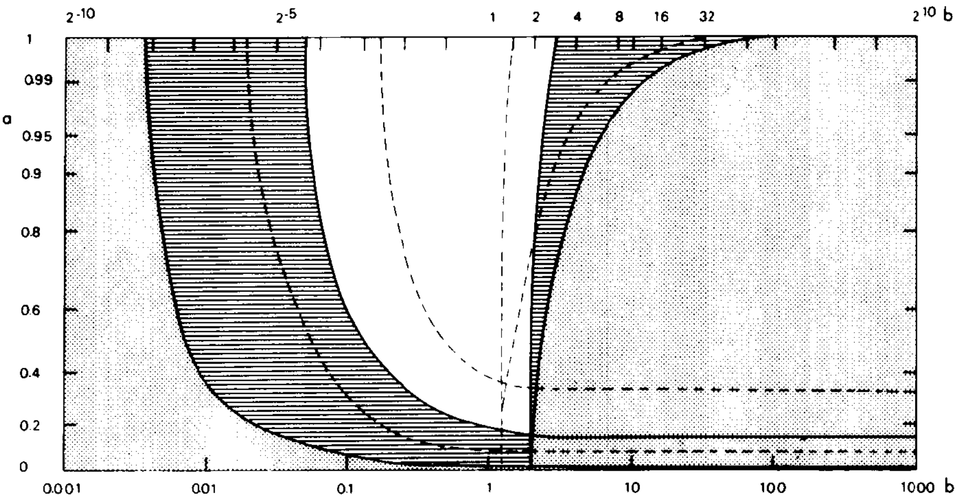

Fig. 6. Representation of the range of the variables b and a in which the simplest approximations suffice. The very simplest approximations are valid with an accuracy better than 1% in the shaded areas in this diagram: left single scattering, right the equations for a semi-infinite atmosphere. The next approximations, shown by hatched areas, are left single plus double scattering and right the thick-layer asymptotic formulae, again to a 1% accuracy. The corresponding 5% limits are shown by dotted curves. Scales are linear in log b and $\sqrt{1-a}$ *and the quantity treated is the plane albedo for normal incidence with isotropic scattering.*

with every further scattering by a constant factor 0.619. The convergence, then, is as a geometric series with this ratio. However, on the left-hand side example, the thickness is $b \gtrsim 10$. Here, the convergence seems rapid near $\tau = 0$, but is not at all visible yet at $\tau \gtrsim 3$. Eventually, the convergence will be as a geometric series with ratio 0.976 (for $b = 10$), or 0.993 (for $b = 20$), or as a series with terms proportional to $n^{-3/2}$ (for $b = \infty$). In any case, this convergence is too slow to make the method of successive scattering attractive.