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Sensitivity Analysis in Remote Sensing

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Dedicated to my parents,
Alexey and Euphalia Ustinov

Preface

Dear reader,

If you are reading these lines, then you are holding in your hands a book on a subject that I have been pondering about for a long time.

You see, there is a sizable amount of books on remote sensing, the science, which was born before the beginning of the Space Era, and which began blossoming after the Space Era had begun.

My concern about this literature, since a long time ago, was pretty simple. In the overwhelming majority of this literature, the methods of solution of the inverse problems of remote sensing were, and still are, a predominant subject. Nobody is arguing that effective methods of computation of jacobians—matrices containing the sensitivities, i.e., derivatives of the observed parameters with respect to parameters one wants to infer—are important. But with Moore's Law still at work, and who knows for how many more years, computers become even more and more powerful, and computation of sensitivities can still be tackled simply by brute force. All you need is to buy a more powerful computer, or to add a few more processors to your cluster already in use, and run your model again and again for small finite variations of its input parameters, one at a time.

This is not the case in the area of remote sensing, which deals with measurements from orbit of radiances emanating from the atmosphere. The most desirable parameters to be retrieved are vertical profiles of atmospheric parameters, which should be specified on a grid of the vertical coordinate running through many atmospheric scale heights, resulting in (many) tens of grid values of these input parameters. That is why the methods alternative to the above brute-force approach began to be developed in the middle of the last century, and their development in this particular area of remote sensing is still going on. I am referring to the methods based on the linearization and adjoint approaches. I have also made some contribution to the development and application of the adjoint approach in this area of remote sensing.

More than a decade ago I realized that these methods—those of sensitivity analysis of models—can be generalized to be applicable to essentially any area of remote sensing, where the models (as in radiative transfer) relevant to remote sensing based on radiances measured from orbit are based on corresponding differential equations with relevant initial and/or boundary conditions.

This is not to say that the adjoint approach, for example, is not used outside the realm of radiative transfer models. There is a blossoming area of research and applications called "variational assimilation of data." A common feature, a hallmark of this approach, is the single artificial observable, called the cost function (also known under other names), which is essentially a norm of residuals—differences between measured and simulated observables. The adjoint approach is used to compute the sensitivities of this artificial observable with respect to all model parameters of interest. Since these sensitivities turn out to be proportional to the residuals themselves, the convergence of the solution of the corresponding (very nonlinear) inverse problem is notoriously slow.

Instead, I have decided to see what can be done if one keeps the individual observables, and generalizes the idea of the adjoint approach used in the radiative transfer models toward a vector of such observables. This generalization turned out to be very straightforward, and after I applied this idea to a simple zero-dimensional model of atmospheric dynamics, I moved on to sensitivity analysis of a number of models in different areas of remote sensing.

A few years ago, I realized that the well-known technique of reducing the higher-order differential equation to a system of differential equations of first order can be used as a basis of a general approach to formulation of adjoint problems with higher-order equations. The general principles of the developed approach and the results of its application to a number of stationary and nonstationary equations are presented in this book, and this is the first time they are published.

This book is intended for a variety of readers. For students of remote sensing, this book will provide an introduction to the goals, objectives, and methods of sensitivity analysis. Researchers already active in the field will find many alternative viewpoints on many particular issues of sensitivity analysis. The author understands that some statements in this book may appear arguable to particular readers, but hopefully this book will not leave the readers indifferent to its general subject, sensitivity analysis. In the author's opinion, sensitivity analysis certainly deserves more attention among researchers and certainly represents a wide research field where much more still remains to be done.

Many individuals have supported this chain of research throughout my career. I owe a great deal of gratitude to them.

It began during my tenure as a Ph.D. student at the Space Research Institute (IKI) in Moscow, Russia. Prof. Vassili Moroz was my advisor, and he guided me all the way to defending my Ph.D. thesis in 1978. Later, he invited me to join the science team of Venera 15&16/PFS instrument successfully flown in orbit around Venus.

Another productive period of my work on this research theme is associated with my tenure at the Tartu Observatory in Tõravere, Estonia. It resulted in a second Ph.D. defended at the University of Tartu in 1992. I am much indebted to Charles Willmann, Kalju Eerme, Uno Veismann, Tõnu Viik, and to all the friendly staff of Tartu Observatory for their support of my work.

In the mid-1990s, I had an opportunity to apply the results of this research to the data of remote sensing of atmospheres of Jupiter, Saturn, Uranus, and Neptune obtained from the Voyager/IRIS instrument, first at NASA Goddard Spaceflight Center and later at Cornell University. I am grateful to Barney Conrath and Peter Gierasch for this opportunity.

I continued my research in sensitivity analysis at the Jet Propulsion Laboratory (JPL), where I was invited in 1998 to participate in development of the retrieval algorithms for the TES instrument, which was later launched onboard the EOS Aura spacecraft. I am grateful to Reinhard Beer for this invitation, which opened a way for me to participate in other exciting projects at JPL while continuing my research in sensitivity analysis.

All in all, I am much indebted to all of these individuals, who, directly or indirectly, guided me during all these years. Recently, I have summarized the results of this research in the form of a short course in sensitivity analysis, which was sponsored by the Science Division of JPL and delivered at JPL. I am grateful to Geoff James for making this happen.

This particular book would not see the light, but for a kind invitation from Springer to write it. I am grateful to Petra van Steenbergen for this invitation, and to Hermine Vloemans for her kind guidance during preparation of this manuscript. I am also grateful to my JPL colleagues, Van Snyder, Phil Moynihan, Suniti Sanghavi, and Bruce Bills for reviewing the draft of this manuscript, for their suggestions regarding improving the text, and for weeding out my typos and grammar errors, inevitable for this author, for whom English is not his native language. Of course, I take responsibility for any remaining typos and errors.

And, last but by no means least, I am immensely grateful to my wife, Lyudmila, for supporting me in my endeavors in general, and during the writing of this book in particular.

Altadena, CA, USA Eugene A. Ustinov

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