Geostatistics with Applications in Earth Sciences

Second Edition

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By

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In memory of

My Parents

Preface to the Second Edition

Geostatistics is expanding very fast: concept- and technique-wise. Keeping in view the importance of the subject, it was thought appropriate to bring out the second edition of this book. In this process, Chapter 1 has been expanded incorporating more details on sampling and sampling designs. In Chapter 2, a section on simulation has been introduced with emphasis on Monte-Carlo simulation with worked out examples. In Chapter 5, a procedure to compute variogram in the case of irregular grid has been outlined. Minor modifications have been made in all other chapters. A new chapter on Introduction to Advanced Geostatistics has been introduced with discussions on universal kriging, disjunctive kriging, conditional simulation and median polish kriging. Review Questions are given at the end of each chapter to facilitate a better understanding of the subject by the student/practitioner. The software codes are put in a CD for convenience of the students/practitoner of geostatistics. A few additions have been made in the bibliography making it more exhaustive. This contains references to the concepts and methods presented, in-depth treatment of related topics and possible extensions. My grateful thanks are due to Dr. H.S. Saini, Principal, Guru Nanak Engg. College, Hyderabad for very helpful support. I hope that this edition will be a welcome one.

August 2008 **D.D. Sarma**

Preface to the First Edition

This book has been designed to serve as a text book for post graduate students and research workers in earth sciences who require a background of and a feel for Statistics and the Theory of Regionalised Variables. The book is titled 'Geostatistics with Applications in Earth Sciences'. Although the word geostatistics is used throughout Europe signalling the Theory of Regionalised Variables as propounded by Prof. George Matheron and his colleagues at the Centre de Geostatistique, Fontainebleau, France, still it was considered necessary to include in this book some important classical statistical methods which are essential for modelling the processes concerning earth resource systems for optimum appraisal. Thus, Chapters 1 to 4 deal with the classical statistical methods including a discussion on Box-Jenkins models of Time Series Analysis and Chapters 5 to 8 deal with a discussion on the Theory of Regionalised Variables and restricted upto Kriging (Stationarity Case). Chapter 9 deals exclusively with the software developed for some of the problems. Practical application of these methods in earth sciences is explained at every stage.

In all, it is hoped that this book would serve as a practical guide to geostatistics. The units of measurement used in the examples cited in the text are the real ones. No attempt has been made to convert non-metric units into metric units.

I wish to express my grateful thanks to Dr. Harsh K. Gupta, Secretary, Dept. of Ocean Development, Govt. of India and former Director, National Geophysical Research Institute for the facilities provided to me in the completion of this project and for the Foreword; to Dr. Hari Narain, Former Director, National Geophysical Research Institute, Hyderabad, Former Vice-Chancellor, Banaras Hindu University, Varanasi, Former Surveyor-General, Survey of India and Member, Advisory Council, Directorate General of Hydrocarbons, GOI for the Preface. The Chairman and Managing Director of Bharat Gold Mines Ltd., Kolar gold fields, Karnataka, the Chairman and Managing Director of Chitradurga Copper Corporation, Chitradurga, Karnataka, the Chairman and Managing Director of Hutti Gold Mines Ltd., Hutti, Karnataka, the Chairman and Managing Director of Hindustan Zinc

Ltd., Udaipur, Rajasthan, and the Director-General of the Geological Survey of India have provided with the necessary assay data for stochastic and geostatistical modelling studies carried out by me at the National Geophysical Research Institute. I express my grateful thanks to all these authorities. Acknowledgements are due to my colleagues, Mr. N.H. Prasada Rao and Mr. J.B. Selvaraj for their help in the finalisation of the software programs listed in this volume. Mr. G.R.K. Rao and Mr. C. Shyam Sunder have done an extremely good job in text processing. Mr. M. Jayarama Rao, Mr. O. Prasada Rao of the Maps & Drawings section of NGRI have given their support in tracing the figures listed in the text. Any shortcomings are due to me.

November 2001 **D.D. Sarma**

Contents

Some Important Symbols Used in the Text

$\gamma(h)$	semi-variogram between two points separated by distance h
$\gamma_L(h)$	semi-variogram between two cores each of length L separated by distance h
$\gamma^*(h)$	experimental semi-variogram based on point samples
$\gamma^*_L(h)$	experimental semi-variogram based on core samples
a	range of influence of a semi-variogram
C	sill of a semi-variogram
C_o	nugget effect
m	slope of the linear semi-variogram
$\bar{x}$	sample mean
μ	population mean
s_x, s	standard deviation of x
σ	population std. deviation
$\bar{g}$	mean value of the observations/grades
y	logarithm of the variable
$\bar{y}$	mean value of the logarithms of observations
s_y	standard deviation of the logarithms of observations
Z_N	standard normal deviate in the context of confidence limits for the mean $\bar{z}$
H_L	standard normal deviate in the context of confidence limits for the mean ($\bar{x}$) of logarithms of data.
$\bar{g}_E$	average grade above cutoff-E
S.E	standard error

σ_k^2	kriging variance
Re.V	Regionalised Variable
R.V	Random Variable
RF	Random Function
$E\{Z(x)\}$	expectation of $Z(x)$
$C(h), \sigma(h)$	stationary covariance function
λ_t	weights assigned to various samples in the context of Kriging
$V(x)$	domain V centered at x
$v(x)$	smaller domain v centered at x
$\sigma_{E:}^2 (v/V)$	dispersion variance
μ	Lagrangian parameter
$P\{Z = z_i\}$	probability of Z taking value z_i
μ_k	kth moment about the mean
$r(x, y)$	correlation coefficient between x and y
$M_z(t)$	moment generating function
$\Lambda(z)$	denotes lognormal frequency function
M	in the context of lognormal theory, denotes population mean
θ_1	in the context of moving average process, denotes the parameter
ρ_k	autocorrelation coefficient at lag k
$\phi_1, \phi_2, \ldots \phi_k$	auto-regressive coefficients
ϕ_{kk}	partial autocorrelation coefficient at lag k
$S_F(f)$	spectral density estimates by FFT method
$U_E(f)$	spectral density by maximum entropy method
U_M	updated variance
Z	in the proper context, denotes Regionalised/Random Variable
$Z(x_i), Z_i, x_i$	the value of the regionalised variable at each data point x_i
C_L	sill value of the variogram with core samples of length L as samples
$\sigma^2(o/L)$	within variation in core of length L
s_p	standard deviation of point samples
s_v	standard deviation of samples with volume v

$s^2(0/V)$	sample variance of point samples in volume V
$\bar{\gamma}(x_i,V)$	average variogram between x_i and the volume V
$\bar{\gamma}(v,v)$	average value of the variogram between any two points x and x' sweeping independently throughout the volume v
$\bar{\gamma}(V,V)$	average value of the variogram between any two points y and y' sweeping independently throughout the volume V
$\sigma^2(v/V)$	variance of v in V
$\sigma_E^2(v,V)$	Extension Variance. Error committed when the grade of a sample of volume v is extended to the grade of volume V
σ_{ij}	covariance between neighbourhood samples i and j.
$\forall j$	for all j