Lecture Notes in Statistics
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Space, Structure and Randomness

Contributions in Honor of Georges Matheron in the Field of Geostatistics, Random Sets and Mathematical Morphology

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Lecture Notes in Statistics
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I am glad that I had the chance to meet Georges Matheron personally once in my life, in October 1996. Like many other statisticians, I had learned a lot in the years before from his books, papers, and research reports produced in Fontainebleau. From the very beginning, I had felt a particular solidarity with him because he worked at the Ecole des Mines de Paris, together with Bergakademie Freiberg one of the oldest European mining schools.

The first contact to his work occurred in talks with Hans Bandemer, who in the late 1960s had some correspondence with Georges Matheron. Proudly he showed me letters and reprints from Georges Matheron. He also had a copy of Georges Matheron’s thesis of 1965, 300 pages narrowly printed. Its first part used Schwartz’ theory of distributions (Laurent Schwartz was the supervisor) in the theory of regionalized variables, while the second part described the theory of kriging. Hans Bandemer was able to read the French text, translated it into German language and tried, without success, to find a German publisher. Unfortunately, the political conditions in East Germany prevented a meeting between Hans Bandemer and Georges Matheron.

A bit later, in 1969, I saw George Matheron’s book “Traité de Géostatistique Appliquée”. It is typical of the situation in East Germany at the time that this was a Russian translation published in 1968, based on the French edition of 1967. (We could not buy Western books and most of us could not read French. At the time the Soviet Union ignored the copyright laws.) I was very impressed by the cover illustration showing a gold-digger washing gold.

Georges Matheron’s Traité is a fascinating book, and for me and many others it was the key reference in geostatistics at the time. The progress achieved in this work is perhaps best expressed by the following quote from the postscript (written by A.M. Margolin) of the Russian translation:

“We find in the monograph the fundamental ideas and notions of a mathematical theory of exploration, called by Matheron ‘geostatistics’. Geostatistics is characterized by a concept which corresponds to the
mathematical problems of exploration, by fundamental basic notions
and by a large class of solvable problems.

In comparison to classical methods of variation statistics [the simple
methods using mean and variance and Gaussian distribution],
which were until the 1950s nearly the only way of application of math-
ematics in geological exploration, geostatistics is directed to the true
mathematical nature of the objects and tools of exploration...

According to geostatistics, the uncertainty which is characteristic
for results of exploration is a consequence of incompleteness of ex-
ploration of the object but not of its randomness. In this probably the
increasing possibilities of the geostatistical theory consist and the prin-
cipal difference to variation statistics, which is based on the analysis
of geological variables irrespectively to the locations of observation...

Not at the time, but later on when I had learnt more about public relations
in science, I admired Matheron’s cleverness in coining terms: It was very
smart to call statistics for random fields ‘geostatistics’ (to use a very general
word, which suggests ‘statistics for the geosciences’, for a more limited class of
problems) and least squares linear interpolation ‘kriging’ (originally ‘krigeage’;
in Freiberg it was for a long time not clear whether it should be pronounced
‘kri-ving’ or ‘kraig-ing’ – as suggested by the Russian translation – or ‘kreeidge-
ing’.)

Georges Matheron’s “Random Sets and Integral Geometry” of 1975 was a
landmark in my own scientific development. The mid 1970s were a great time
for stochastic geometry and spatial statistics, which then became more than
just geostatistics. In that time mathematical morphology was also shaped,
and Jean Serra’s work in image analysis became known outside Fontainebleau,
both in theory and in applications. The first image analyser, the famous Leitz
TAS, was produced, based on ideas of Georges Matheron and Jean Serra.
We, the scientists in East Germany, were unable to order the book in a
book store, but I got a copy from Dieter König in exchange for a book on
queueing theory. Up to this day, for me (and many others, I believe) Georges
Matheron’s book is the key reference in random set theory; the cover of my
copy is now in pieces, and many pages are marked with notes. Unfortunately,
the book has not been reprinted since.

This book gives an excellent exposition of the topics named in the title, it is
very clearly written, and of just the right theoretical level. Georges Matheron’s
work also led me to Hadwiger’s, whose monograph on set geometry is now
one of my most beloved mathematical books in German language. So Georges
Matheron had an excellent base for the integral-geometric part of his work. It
is a great combination of many mathematical fields, such as integral geometry,
set geometry, Choquet’s theory of capacities (in fact Matheron developed
it independently), and ideas of Poisson process based stochastic geometry
(created in particular by Roger Miles) to obtain a new, rich and fruitful theory.
Georges Matheron’s book contains many gems. I name here only the theory
of the Boolean model (he writes ‘boolean model’, with small ‘b’), the Poisson polyhedron, and the granulometries.

It was Georges Matheron who made notions of measurability properties rigorous in the context of random sets. This can be explained in terms of Robbins’ formula for the mean volume of a compact random set:

\[ E\nu(X) = \int_{\mathbb{R}^n} p(x)dx \]

where \( p(x) = P(x \in X) \). Its proof is based on Fubini’s theorem and was already given – in part – in Kolmogorov’s famous book of 1933. It was Georges Matheron who showed that the mapping \( \text{set} \rightarrow \text{volume} \) is measurable. The \( \sigma \)-algebra with respect to which measurability is considered (based on Fell’s topology) is today called Matheron’s \( \sigma \)-algebra. Some of his results for models related to Poisson processes were the starting point for further scientific work, when it became clear that methods from the theory of marked point processes can be used to generalize them. Through his book, Georges Matheron has been a teacher and inspirer for a large number of mathematicians in the last three decades.

In 1989 Georges Matheron published the book “Estimating and Choosing”. Grown older, I was offered the honour to serve as one of its reviewers. This is a philosophical book, discussing the fundamental question of spatial statistics: “Why does it make sense to perform statistical inference for spatial data, when only a sample of size \( n = 1 \) is given?” Indeed, very often a statistician has only data from one mineral deposit, or from one forest stand; a second sample taken close to it can typically not be considered as a sample from the same population, because of different geological or ecological conditions. He developed the idea of ‘local ergodicity’, which is plausible and justifies the statistical approach. Each spatial statistician should read the book. I also enjoyed its sarcastic humor.

In June 1983 Dominique Jeulin came to Freiberg as an invited speaker at a conference. For me and colleagues like Joachim Ohser and Karl-Heinz Hanisch this was the first chance to meet a scientist from Georges Matheron’s school. Dominique Jeulin spoke about multi-phase materials, rough surfaces, and image transformations. He is likely the first French person I ever met, and I learned that French English differs greatly from German English. Dominique had to repeat three times his ‘Stojáng’ until I understood that he asked for me. The contact to him, which is still lively, finally led to the meeting with Georges Matheron.

After the big changes of 1989/90 we had many West German PhD students at Freiberg. One of them, one of the best, was Martin Schlather. Martin had studied one year at Fontainebleau, had written a diploma thesis there, and had been given oral exams by Georges Matheron personally. Thus, he could tell me first hand about Georges Matheron’s personality and about the situation at Fontainebleau. Like anybody who ever had personal contact
with Georges Matheron Martin admired him, both as a mathematician and as a person. Martin told me that Georges Matheron's work is much more comprehensive than his books and journal publications suggest. So we are all extremely grateful to Jean Serra for publishing a CD with the reports and papers by Georges Matheron. I agree with Martin and Jean that one will find wonderful ideas and solutions to hard problems as one goes through this material.

It was Martin Schlather who encouraged me to travel to the Fontainebleau conference in 1996. This conference was organized by Dominique Jeulin in honour of Georges Matheron, and the lectures are published in the volume Jeulin (1997). There we met Georges Matheron, who did not give a lecture, but was sitting in the front row in the lecture room, obviously listening with attention. One afternoon there was a reception in the municipal hall of Fontainebleau. The maire decorated Georges Matheron (and others) with a medal, for reasons that I did not completely understand, either scientific or political. Georges Matheron was polite enough to bear the ceremony, but quite obviously he did not take it very seriously. He told me anecdotes, and his body language was clear enough. I had no difficulty in communicating with him, he accepted my poor English, and I understood him very well.

In the evening I was honoured by an invitation to the family of Jean Serra, where I also met Mesdames Matheron and Serra. It was an enjoyable, not very long evening, with friendly non-mathematical talk, and a bit of French wine.

In the end, I never orally discussed mathematical problems with Georges Matheron, but I appreciated the contact over many years, through studying his work, and through a few comments that he made on my work. I believe that there is only a small number of international mathematical conferences which Georges Matheron attended. His example shows that a mathematician who does not visit conferences can be nevertheless be influential and widely known. Perhaps, Georges Matheron could have had even more influence. However, did he really want this?

Back to Freiberg, I had the idea of honouring him there. At the time I was the president of the little Technische Universität Bergakademie Freiberg and saw the chance of honouring him with a Dr.h.c. degree. I asked Dominique Jeulin. He liked the idea but warned me that Georges Matheron would probably never come to Freiberg, and if he did, I could not expect his collaboration in a public relations event to the benefit of my university, as I was hoping for. To my regret, I did not pursue the idea any further.

In October 2000, the sad news of Georges Matheron’s death spread. I regretted that I had not seen him again after 1996. As a keepsake to Georges Matheron, I asked Jean Serra for Georges Matheron’s personal copy of Hadwiger’s book – expecting a book with many pencil notes. To my surprise I learned that Georges Matheron had used a library copy.

I am very happy that this volume is now ready, which will honour Georges Matheron, one of the great mathematicians of the 20th century.
A few words about Georges Matheron (1930-2000)

Jean Serra

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That day, Paris was steaming hot, as it may happen in July when there is not the slightest breeze of wind to cool the air. Despite the vigour of his nineteen years, Georges Matheron, while waiting for his turn, was suffocating and finally lost his composure before the board of examiners of the Ecole Normale Supérieure. Fortunately, he came second at the Ecole Polytechnique, which he entered a few weeks later. That was in 1949. He probably had missed the opportunity to work in the best possible environment for him, and at the time he did not know that the path he was heading for would involve him in earth sciences for the rest of his professional life.

Those who have practised geostatistics all know how fascinating it is to discover the mineral world underground, to figure the structures from drillhole variograms, like a blind person fingering an object to guess its shape. However G. Matheron was the first one to know that excitement, all the more as he was creating the mathematical tool while using it to comprehend the earth substratum. Moreover he designed it so that the description of the mineral space and the estimation of mining resources be indissolubly linked, like the two sides of the same coin.

After two years spent at the Ecole Polytechnique, two more years at the Ecole des Mines and another one in the military service, it was in Algeria that the Corps des Mines sent him for his first appointment. He had married one year before, and landed in Algeria with wife and child. He quickly took over the scientific management (1956), then the general management (1958) of the Algerian Mining Survey.

It takes imagination to realize how important it was for a young French engineer. The huge Algerian territory stretches as far as the Saharan South and abounds in orebodies of all kinds. It is one of the reasons why the International Geological Congress has been held in Algiers in 1952, just two years before he arrived. It was also in the early 50's that papers written by three South-African authors, Krige, Sichel and de Wijs, laid the statistical foundations from which G. Matheron would base his theory of geostatistics, that was revolutionary at the time.
What does not kill you makes you stronger. In the early 60’s, French Algeria collapsed, France recalled its executives to the home country and reorganized its mining research by creating the BRGM (Geological and Mining Survey) in Paris. G. Matheron was assigned a “Geostatistical department”, practically reduced to himself. The BRGM did not believe in geostatistics, and the only mining partners came from the CEA (∼ Atomic Energy Commission), namely A. Carlier and Ph. Formery. This solitude was in fact a blessing which enabled him to devote himself to the final development of what will be called later linear geostatistics.

The genesis of the following works is instructive, and tells a lot about the personality of G. Matheron. In Algeria, he invented the random functions with stationary increments, while being sceptical about the probabilistic framework. Every deposit is a unique phenomenon, that occurred once only in geological times; besides, when one estimates its reserves, one does not compare its drillings with those of more or less similar deposits. This unique phenomenon, studied in itself, does not offer any more hold to probabilities, than if one wanted to know the proportion of hearts in a deck of cards by drawing only one card once.

It was within that “semi-random” framework that G. Matheron wrote the first volume of his “Traité de Géostatistique Appliquée” (treatise of applied geostatistics) in 1962, which was based upon the Algerian experience, then the second volume (1963) on kriging, which solved the problems of local estimation raised by the uranium deposits of the CEA. Even today, the reader is amazed at such a skilful mastery of first the mathematics, then of the physics of the topic, with the right simplifying approximations. The rule of one-to-one correspondence for instance, in volume I, is still a masterpiece, where each term of the limited expansion of the theoretical variogram (whose estimation is empirically accessible) corresponds, with a known invariable weight, to a term of the limited expansion of the deposit estimation variance (which is sought for).

However this rule could be formulated in a deterministic framework as well as in probabilistic terms. Hence a third book, entitled “La théorie des variables régionalisées et leur estimation”, which became his PhD thesis in 1963. The deterministic and random parts were developed successively, with much rigour, and all theoretical conclusions drawn. But G. Matheron waited twenty years before expressing himself, in “estimating and chosing”, upon the choice of either approach according to the context – the mathematician was ahead of the physicist.

As the BRGM continued to ignore the practical interest of his sextuple integrals, G. Matheron looked elsewhere to collect followers, through teaching. A “geostatistical option” was created at the Ecole des Mines de Nancy, which provided him with his first PhD student. The latter, Jean Serra, rapidly branched off and oriented methods and applications towards the new field of mathematical morphology (random event or deterministic fate?). The quality of the iron ore of Lorraine was defined as much by its grade as by its suit-
ability to grinding, which could only be quantified from the mosaic of the petrographic phases, as they appear under the microscope. Hence the idea of measuring petrographic variograms, and extending the concept of variogram to that of the hit-or-miss transformation, then to that of opening, etc. For more than one year, the master and the disciple, though separated by three hundred kilometers, met each month, sharing their enthusiasm, their notes, and the advancement state of the “texture analyser”, which the student was developing with Jean-Claude Klein. Many years later, in 1998, when describing this intense period at the research committee of the Ecole des Mines de Paris, G. Matheron would say: “these were the most beautiful years of my life”.

In April 1968, the Ecole des Mines de Paris gave G. Matheron the opportunity to create the “Centre de Morphologie Mathématique” in Fontainebleau, with J. Serra as the other permanent researcher. The events of May 1968 were favourable to them, thanks to all the public founds they released, so that in two years the team grew from two to twelve persons. It spread on both fronts of geostatistics and mathematical morphology. From that time, the first gained international recognition, and proposals for mining estimations coming from the five continents arrived at the Centre. Moreover, from the early 70’s, the CMM had been asked to map the sea bed, atmospheric pressures, etc. The application fields broadened and with them the variety of the problems to be solved; for example, that of submarine hydrography led G. Matheron to invent the universal kriging (1969), then the random functions with generalized covariances (FAI-k, 1973), which both released the constraint of the stationarity hypothesis. Another example: the integration of local mining estimations into operating management programs led G. Matheron to conditional simulations, less accurate than kriging, but which did not smooth the data. Finally, during the 70’s, G. Matheron formalised and proposed a definitive answer to the major issue of mining estimation, namely the change of support. In this case, the problem is no longer to estimate the variance of panels with respect to their size, as in linear statistics, but to be able to predict their whole distribution function, in order to fit mining exploitations to the economic conditions (1976).

In parallel with these developments, the mathematical morphology group became independent and evolved to an autonomous centre in the early 80’s. Indeed, from the beginning, its applications covered the whole field of optical microscopy, and while metallography and porous media still pertained to earth sciences, medical histology and cytology addressed quite another audience.

G. Matheron did not show more than a polite interest in such applications of mathematical morphology. He did not penetrate them like he had done with mining technology. Morphological applications were too varied, and what excited him was to extract from them some general approaches, which could be conceptualised. This is why were produced the theories of granulometries, of increasing operators, of Poisson hyperplanes and of Boolean sets, which he gathered into the book *Random sets and Integral Geometry*, in 1975. The
topic of porous media was the sole exception. This application already had a whole specific physical framework, varying according to the considered scale (Navier-Stokes equation at the microscopic level, Darcy equation at larger scales). How can such changes be linked? To what extent can random sets provide tractable models? Throughout his career at the CMM, G. Matheron kept involved with these questions and indicated fruitful directions.

At the beginning of the 80’s, his professional life took a more “morphological” turn. On the theoretical level, the geostatistical vein seemed to be exhausted, whereas morphologists had just designed new operators, products of openings and closings, which had the property of being both increasing and idempotent (here the word “morphologists” refers to the members of the CMM team as well as to the American S.R. Sternberg, the German D. Stoyan or the Australian G.S. Watson, among others). As these operators used to apply to both frameworks of sets and numerical functions, G. Matheron situated his approach at the broader level of the complete lattices and constructed a general theory of the increasing and idempotent operators that he called *morphological filtering* (1982-1988). In spite of appearances, these new levels can easily be integrated into the structure of his overall work. Morphological filtering gave a simplified and denoised vision of the numerical functions, as did kriging for mapping. Increasingness and idempotence had replaced linearity and the master observed the consequences of that genetic change.

Since the 90’s, multimedia have been the dominant theme in Mathematical Morphology, bringing into focus the three topics of motion, segmentation and colour. Today, these topics still concentrate most of the CMM activities. However, G. Matheron did not take interest in them. Since he inserted mathematical morphology into the lattice framework, he pursued the idea to extend also his random set theory. In order to do so, complete lattices must be first equipped with adequate topologies. G. Matheron’s efforts were devoted to this task until his retirement, which was punctuated by an unpublished and last book on compact lattices (1996).

Jean Serra

*September 2004*
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