Marc Hallin — Summary of Research Activities

Marc Hallin's research activities are covering an exceptionally broad spectrum of fundamental and applied statistical topics. They are essentially concentrated on four main subjects (Time series; Asymptotic inference; Semiparametric and rank-based inference; High-dimensional panel data), and three secondary ones (Nonparametric inference for random fields; Stochastic inequalities and exact inference; Multivariate analysis). Of course, these seven topics also have a number of intersections.

1 Time series models with time-dependent coefficients.

Marc Hallin's interest in stochastics and mathematical statistics started rather late, after a PhD dissertation (Université libre de Bruxelles, 1976) in game theory (Structures de coalition et problèmes de négociation. Echanges d'information dans les jeux à information incomplète, in French) under the supervision of Simone Huyberechts. Time series models with time-dependent coefficients were his first subject in stochastics. The main results he obtained in that direction were published between 1983 and 1987 in [26], [27], [36], [37], [47], [71], and [95].

In [27] and [36], he proposes a complete and original solution to the so-called spectral factorization problem for multivariate, q-dependent processes. This problem consists in characterizing the set of all moving average models (with time-dependent matrix coefficients) yielding a given (time-dependent) q-dependent autocovariance structure, along with their invertibility properties.

More precisely (letting $q = 1$ for simplicity; L, as usual, stands for the lag operator), consider the first-order m-dimensional linear difference operator of order one $\mathbf{A}_t(L) := \mathbf{A}_{t0} + \mathbf{A}_{t1}L$, and the corresponding first-order moving average process

$$\mathbf{X}_t := \mathbf{A}_t(L)\boldsymbol{\varepsilon}_t = \mathbf{A}_{t0}\boldsymbol{\varepsilon}_t + \mathbf{A}_{t1}\boldsymbol{\varepsilon}_{t-1}, \quad t \in \mathbb{Z}, \tag{1.1}$$

where $\{\boldsymbol{\varepsilon}_t \ ; \ t \in \mathbb{Z}\}$ is orthogonal second-order white noise (note that two operators $\mathbf{A}^1_t(L) := \mathbf{A}^1_{t0} + \mathbf{A}^1_{t1}L$ and $\mathbf{A}^2_t(L) := \mathbf{A}^2_{t0} + \mathbf{A}^2_{t1}L$ such that $\mathbf{A}^1_{t0} = \mathbf{A}^2_{t0}\mathbf{O}_t$ and $\mathbf{A}^1_{t1} = \mathbf{A}^2_{t1}\mathbf{O}_{t-1}$ for some sequence of orthogonal matrices $\mathbf{O}_t$ define the same MA(1) model). Denoting by $t \mapsto (\boldsymbol{\Sigma}_t \ , \ \boldsymbol{\Gamma}_t)$, with $\boldsymbol{\Sigma}_t := \mathrm{E}[\mathbf{X}_t\mathbf{X}'_{t-1}]$ and $\boldsymbol{\Gamma}_t := \mathrm{E}[\mathbf{X}_t\mathbf{X}'_t]$ its covariance and autocovariance matrices (at time t), define the autocovariance linear difference operator (of order two) as

$$\boldsymbol{\Gamma}_t(L) := \boldsymbol{\Gamma}'_{t+1} + \boldsymbol{\Sigma}_t L + \boldsymbol{\Gamma}_t L^2, \quad t \in \mathbb{Z}.$$

The link between the MA(1) model (1.1) and the corresponding autocovariance function can then be summarized as the symbolic factorization of difference operators

$$\boldsymbol{\Gamma}_t(L) = \mathbf{A}_t(L) \circ \mathbf{A}^*_t(L), \quad t \in \mathbb{Z}, \tag{1.2}$$

where the operator $\mathbf{A}_t^*(L)$ is the adjoint of $\mathbf{A}_t(L)$. The spectral factorization problem consists, for a given $\mathbf{\Gamma}_t(L)$, in characterizing the class of MA(1) operators $\mathbf{A}_t(L)$ for which the symbolic factorization (1.2) holds.

In order to solve this problem, Marc Hallin introduced in [27] an ingenuous concept of *positive definite matrix continued fraction*, for which he establishes necessary and sufficient convergence conditions. In [27], he showed that $t \mapsto (\mathbf{\Sigma}_t\ ,\ \mathbf{\Gamma}_t)$ is a valid 1-dependent, m-dimensional autocovariance function iff the matrix continued fractions

$$\mathbf{\Phi}_t^+ := \mathbf{\Sigma}_t - \mathbf{\Gamma}_{t+1}' \left(\mathbf{\Sigma}_{t+1} - \mathbf{\Gamma}_{t+2}' \left(\mathbf{\Sigma}_{t+2} - \mathbf{\Gamma}_{t+3}' \left(\dots \right)^{-1} \mathbf{\Gamma}_{t+3} \right)^{-1} \mathbf{\Gamma}_{t+2} \right)^{-1} \mathbf{\Gamma}_{t+1}, \quad t \in \mathbb{Z} \tag{1.3}$$

and

$$\mathbf{\Phi}_t^- := \mathbf{\Gamma}_t \left(\mathbf{\Sigma}_{t-1} - \mathbf{\Gamma}_{t-1} \left(\mathbf{\Sigma}_{t-2} - \mathbf{\Gamma}_{t-2} \left(\dots \right)^{-1} \mathbf{\Gamma}_{t-2}' \right)^{-1} \mathbf{\Gamma}_{t-1}' \right)^{-1} \mathbf{\Gamma}_t', \quad t \in \mathbb{Z} \tag{1.4}$$

both converge; if they do, they moreover satisfy

$$\mathbf{\Sigma}_t \geq \mathbf{\Phi}_t^+ \geq \mathbf{\Phi}_t^- > \mathbf{0}, \quad t \in \mathbb{Z}.$$

The following one-to-one correspondence then exists between the family of all possible MA(1) models (1.1) satisfying the factorization condition (1.2) and the family of all real symmetric matrices $\mathbf{\Phi}_0$ such that $\mathbf{\Phi}_0^- \leq \mathbf{\Phi}_0 \leq \mathbf{\Phi}_0^+$. For each such matrix, denote by $\mathbf{\Phi}_t$ the solution of the linear recursion

$$\mathbf{\Phi}_t = \mathbf{\Gamma}_t (\mathbf{\Sigma}_{t-1} - \mathbf{\Phi}_{t-1})^{-1} \mathbf{\Gamma}_t' \quad t \in \mathbb{Z} \tag{1.5}$$

with "initial" value $\mathbf{\Phi}_0$: then,

$$\mathbf{\Sigma}_t \geq \mathbf{\Phi}_t^+ \geq \mathbf{\Phi}_t \geq \mathbf{\Phi}_t^- > \mathbf{0}, \quad t \in \mathbb{Z}, \tag{1.6}$$

and the MA(1) model defined by

$$\mathbf{A}_{t1} \mathbf{A}_{t1}' = \mathbf{\Phi}_t \quad \text{and} \quad \mathbf{A}_{t0} = \mathbf{\Gamma}_{t+1}' \mathbf{A}_{t+1,1}' \quad t \in \mathbb{Z}, \tag{1.7}$$

satisfies (1.2). Conversely, if $\mathbf{A}_t(L)$ satisfies (1.2), then $\mathbf{\Phi}_t := \mathbf{A}_{t1} \mathbf{A}_{t1}'$ is a solution of (1.5) satisfying (1.6).

Moreover, the model associated with $\mathbf{\Phi}_0 = \mathbf{\Phi}_0^-$ is the (unique) Wold-Cramér representation of the second-order process characterized by the autocovariance structure $(\mathbf{\Sigma}_t\ ,\ \mathbf{\Gamma}_t)$, whereas the (infinitely many) Granger-Andersen-invertible representations of the same process are characterized by the values of $\mathbf{\Phi}_0$ such that $\mathbf{\Phi}_0^- \leq \mathbf{\Phi}_0 < \mathbf{\Phi}_0^+$; recall that only the Wold-Cramér representation produces efficient forecasts.

In [71] and [95], these results are applied to the particular case of periodic moving average processes, leading to an elegant characterization of their invertibility properties, for which only overly restrictive sufficient conditions were known. Models with periodic coefficients have been proposed in econometrics as an alternative to traditional seasonal modelling.

Autoregressive processes with time-dependent coefficients are considered in [26], where a time-dependent version of the Yule-Walker equations is obtained.

All the above papers are dealing with the probabilistic properties of models with time-varying coefficients, not with problems of statistical inference. Hypothesis testing problems are considered in [82], and [132], where a Le Cam approach is adopted in the detection of a periodic behavior in AR and VAR processes, and locally asymptotically maximin tests are derived for testing the null hypothesis of a stationary behavior, against periodic alternatives.

2 Semiparametric and rank-based inference.

The most important part of Marc Hallin's research activity has been devoted to a decision-theoretical approach of rank-based inference, and extensions thereof: see [33], [38], [45], [48], [50], [54], [55], [57], [60], [65], [67], [68], [70], [73], [75], [79], [80], [89], [93], [97], [101], [104], [105], [107], [108], [109], [110], [112], [118], [119], [122], [123], [124], [125], [133], [134], [136], [139], [140], [141], [142], [145], [149], [150], [151], and [152].

In the late seventies, after the seminal contribution of Hájek, later on summarized and systematized in such monographs as Puri and Sen (1985), *Nonparametric Methods in General Linear Models*. John Wiley, New York), rank-based inference was considered as an essentially complete theory.

The potential applications of the classical theory of rank-based inference is somewhat narrow; indeed, traditional rank-based methods

- are essentially limited to the context of general linear models with independent observations (location, scale, regression, ANOVA, etc.)
- only can handle univariate observations (except for methods based on componentwise rankings, which in most respects are quite unsatisfactory)
- make little use of the power of the Le Cam theory (in general, only the so-called Le Cam third Lemma is used, mainly in order to compute local powers—a practice that goes back to Hájek and Šidák 1967).

All over his career, Marc Hallin has been working on removing those restrictions, into a variety of directions:

- to a time series models first, and, more recently, to the very broad class of semiparametric models described below
- to more general concepts of ranks (related to appropriate group invariance arguments), such as signs and ranks for median- or quantile-restricted models ([140] and [152]), ranks and some adequate indicators (in the context of Ornstein-Uhlenbeck processes, see [110]; for unrestrictedly heteroskedastic series, see [97]), and to multivariate settings (pseudo-Mahalanobis ranks and signs, hyperplane-based ranks and signs: see [122], [123], [133], [134], etc.)

by fully exploiting the power of Le Cam's theory of locally asymptotically normal experiments, and the related modern theory of semiparametric inference (in the spirit of Bickel, Klaassen, Ritov, and Wellner).

Semiparametric models, where the underlying density or innovation density plays the role of a nuisance parameter) indeed are the context where rank-based methods naturally come into the picture. A far-reaching result is obtained in [125], where it is shown that conditioning central sequences with respect to the maximal invariants (ranks, for instance) of appropriate generating groups yields the same results as the more traditional tangent space projections, hence lead to semiparametrically efficient inference. This result provides a fundamental and very strong justification for considering rank-based inference, by showing that ranks (or more general invariants) actually retain all the information related with the parameter under study, while everything else (typically, an order statistic) only carries information about the nuisance.

Ranks are thus, in a sense, performing the tangent space projections, without requiring explicit computation of the tangents, and without any unpleasant ad hoc procedures such as sample splitting. As a corollary, ranks can reach parametric efficiency in a given model if and only if this model is adaptive in the semiparametric sense. And, of course, they also bring along the many advantages related to distribution-freeness: exact distributions, unbiasedness, increased robustness, ...

This general result applies to a variety of models: location, scale, regression, ANOVA, of course, but also ARMA, bilinear models (in the vicinity of the linear ones), random coefficient autoregressive models (in the vicinity of the nonrandom ones), ARCH and GARCH models, ... as well, in the multivariate context, as to their elliptical counterparts. In all these models, this result allows for semiparametrically efficient (at some prespecified density f) distribution-free tests, or for uniformly (over classes of possible densities f) semiparametrically efficient permutation tests (see [125] for details and examples).

In most of these contexts, generalizations of the classical Chernoff-Savage Theorem hold: see [73] for univariate time-series problems, [122] and [123] for nonserial and serial elliptical models. This celebrated theorem, stating that rank tests based on Gaussian scores perform uniformly better than Student tests, thus holds in much more general cases. In time series, for instance, the asymptotic relative efficiencies, with respect to the corresponding daily practice correlogram methods, of the normal-score rank-based procedures developed in [70], are uniformly larger than one. This should be a strong incentive for bringing ranks into practice in this context.

Marc Hallin also obtained generalizations (to the univariate serial setup, in [107], as well as to some multivariate setups, in [122] and [123]) of the no less famous Hodges and Lehmann ".864" Theorem. In its original version, this theorem shows that the lower bound for the asymptotic relative efficiencies, still with respect to Student tests, of Wilcoxon-type methods for location, is .864. It is interesting to note that, in higher dimensions (k-dimensional observations, the Gaussian reference being Hotelling rather than Student), this Hodges-Lehmann bound in not a monotonic function of k, with a maximum value of .916 at dimension $k = 2$; see [122] and [123].

Another classical topic in rank-based inference is R-estimation. Unlike rank tests, however, R-estimation, despite a long history, never really made its way to applications, and a widespread idea is that "ranks are fine for testing but not for estimation". The reasons for this are twofold. A first complex of reasons is of practical nature. In contrast with rank-based test statistics, R-estimators in general are not expressed under explicit closed forms, but as solutions of unpleasant optimization procedures involving discrete-valued objective functions (one exception is the traditional Hodges-Lehmann R-estimator of location). But there are also more fundamental reasons: asymptotic variances of R-estimators typically depend on the unknown underlying density; they cannot be computed exactly, and involve the estimation of cross-information quantities (denote by $\mathcal{I}(f, g)$ such a quantity when the scores are those which are optimal under density f and the actual density is g) that cannot be estimated easily. For instance, in the Wilcoxon case, for one-sample location, one has to estimate $\int g^2(z)dz$, where g is the unspecified density of the observations.

Statistical decision theory nevertheless suggests that the advantages of rank-based methods depend on the model under study, not on the specific inference problem under consideration. From the point of view of the asymptotic theory of statistical experiments, once a type of scores (Wilcoxon, van der Waerden, Laplace, ...) has been chosen, the rank transformation indeed simply consists of mapping the original sequence of statistical experiments $\mathcal{E}^{(n)}$, say, onto another sequence $\underset{\sim}{\mathcal{E}}_f^{(n)}$, the properties of which (namely, distribution-free central sequences, invariance, local powers, ...) are considered attractive from the point of view of hypothesis

testing. These attractive properties actually belong to the corresponding local Gaussian shift experiments; if they are considered attractive from the point of view of hypothesis testing (this includes semiparametric efficiency as well as the Chernoff-Savage and Hodges-Lehmann results), they should be considered equally attractive from the point of view of point estimation.

Now, local powers of locally asymptotically efficient rank tests typically depend on noncentrality parameters based on a *cross-information matrix* of the form $\mathcal{I}(f,g)\mathbf{\Gamma}_f$. The asymptotic theory of experiments indicates that optimal estimators can be constructed to make their asymptotic variances coincide with the inverses of these cross-information matrices. The same theory provides a one-step form *(à la Le Cam)* for these estimators, involving the same rank-based central sequence as the optimal rank tests just described. The problem with this one-step R-estimator is that it explicitly depends on the same unknown cross-information quantity $\mathcal{I}(f,g)$ as their asymptotic variances. In [142], we show how an ingenious local likelihood maximization argument, exploiting the LAN structure of the experiment under study, avoids a direct estimation of this quantity. Under this one-step form, R-estimators are easily computed (for the broad range of models considered in [125] as well as for the elliptical models in [122], [133], and [141]. This fact, and the semiparametric efficiency result in [125] should revive our interest in R-estimation methods.

Yet another topic related with rank-based inference is that of (auto)regression rank score methods. This concept of regression rank scores was introduced by Gutenbrunner and Jurečková from a duality argument applied to Koenker and Bassett's celebrated regression quantiles. Regression rank scores indeed are defined as the solutions of the parametrized linear program dual to the one that defines regression quantiles. The "miracle" with regression rank scores is that, contrary to the more classical "aligned rank statistics" computed from estimated residuals, regression rank score statistics are insensitive to the presence of unspecified parameter values, and asymptotically reconstruct the actual corresponding rank-based statistics, even though exact residuals (hence exact ranks) cannot be computed from the observation. The concept has been extended to the time-series context by Koul and Saleh (1995). In [105], locally asymptotically optimal tests based on such autoregression rank scores are derived for linear constraints on the coefficients of an autoregressive model. The related estimation procedures are provided in [119]. In [93] and [101], the technique is applied to the problem of autoregressive order identification, and to the problem of testing independence between two autoregressive series with unspecified coefficients. Kolmogorov-Smirnov tests based on autoregression rank scores are constructed in [118], and a very efficient method for estimating the innovation sparsity function (the inverse of the density of the unobservable innovation process at some given quantile) is proposed in [121]. Finally, [145] proposes a class of serial statistics which, contrary to Koul and Saleh's, is entirely based on (auto)regression rank scores (thus involving multiple integrals over the quantile ranges of several lagged residuals), and thus enjoy strict asymptotic distribution-freeness—something the corresponding aligned rank statistics cannot achieve.

His main collaborations in this area of rank-based methods have been Jean-François Ingenbleek, Madan Puri, Bas Werker, Catherine Vermandele, Jana Jurečková, Hira Koul, Hannu Oja, and Davy Paindaveine.

3 Asymptotic inference.

Another important part of Marc Hallin's research deals with asymptotic inference problems that are not directly related to ranks. This mainly includes locally optimal asymptotic inference in

linear and nonlinear time series models:

- multivariate ARMA models with a regression trend ([76] provides the first general LAN result for this important multivariate model),
- bilinear models ([81] and [96]),
- periodic time series models ([82] and [132]),
- numerical performance of Edgeworth expansions ([90] and [91]),
- long memory ([103] and [106], where fractional models are shown to be LAN, and an adaptive locally asymptotically maximin estimator is provided for the memory index d),
- detection of random coefficients in autoregression ([126], with an atypical LAN result),
- testing independence between multivariate time series ([135] and [148]; quite surprisingly, this crucial problem had never been attacked from the point of view of optimality, and all existing procedures so far were quite heuristic), and
- the study of the asymptotic behavior of some traditional M- and L-estimators under non-standard conditions ([92], [102], [113], and [114]).

4 High-dimensional time series.

Marc Hallin's interest in high-dimensional time series (a dimension that in applications can be as high as several hundreds or one thousand) was aroused through his collaboration with macroeconometricians (M. Forni, M. Lippi, and L. Reichlin). Data sets in macroeconometrics indeed often come under the form of very large panels of interrelated time series. Together, they constructed a dynamic factor model method, inspired by Brillinger's concept of dynamic principal components. Under their approach, and provided that a finite number q of eigenvalues of spectral density matrices explode as the dimension of the panel increases (an assumption that seems to be satisfied, in most real data sets, with fairly small values of q), the observed series decompose into two unobserved components, a *common component*, and an *idiosyncratic* one. Common components have dynamic dimension q, and can be handled by multivariate time-series methods, whereas the idiosyncratic ones, being only mildly intercorrelated, can be treated one by one via univariate time series methods. The originality of the approach is that, contrary to the static models considered elsewhere in the literature, it does not impose any restriction on the data generating process.

The challenging problem consists of course in separating these two unobserved components by means of numerically tractable, yet consistent methods. In [111], they propose such a method, and establish its consistency as both the series lengths and the dimension of the panel go to infinity. Rates are obtained for this consistency in [129], and the corresponding forecasting problem is treated in [137]. The problem of determining the number of independent shocks governing the data is treated in [147], based on information criterion techniques. Finally, macroeconomic and financial applications are considered in [116] and [128].

Whether static or dynamic, factor models with large cross-section dimension are attracting increasing attention in finance and macroeconometric applications. In finance, they are at the heart of the extensions proposed by Chamberlain, Rothschild, and Ingersol of the classical arbitrage pricing theory[1]. In macroeconomics, they are used to identify economy-wide and

[1] Chamberlain and Rothschild, *Econometrica* 1983; Ingersol, *Journal of Finance* 1984.

global shocks, to construct coincident indexes, and to forecast individual macroeconomic series by taking advantage of the information scattered in a huge number of related series.

The Forni-Hallin-Lippi-Reichlin dynamic factor methods have attracted the interest of a number of economic and financial institutions, including several central banks and national statistical offices, who are using it in their current analysis of the business cycle, or intend to do so (among them, the European Central Bank, the Federal Reserve, the National Bank of Switzerland, the Banca d'Italia, ...). A real time coincident indicator of the EURO area business cycle (EuroCOIN), based the same method, is published every month by the London-based Center for Economic Policy Research and the Banca d'Italia: see http://www.cepr.org/data/EuroCOIN/ Also based on that method, a similar monthly index is established for the US economy by the Federal Reserve of Chicago.

5 Nonparametric inference for random fields.

Marc Hallin's interest in non parametric estimation for random fields was triggered by his meeting with L.T. Tran. Together, they have written a series of four papers ([83], [117], [130], and [131]) on this subject which is seldom treated in the nonparametric literature, and, in view of its applications, certainly deserves further attention. A fifth paper, with Z. Lu and K. Yu [156], is developing local spatial regression quantile techniques. The contribution of these papers mainly deals with spatial kernel and locally linear methods, both for density estimation and (quantile) regression, with isotropic as well as non-isotropic asymptotics, under unspecified spatial dependence structure. The difficulty with random fields, as opposed to time series, is that space, unlike time, is neither one-dimensional nor well ordered. Moreover, spatial interactions can be extremely complex, and parametric models of spatial dependence accordingly are rather unreliable.

6 Stochastic inequalities and exact inference.

Exact inference has always been one of Marc Hallin's main concerns, which does not contradict his interest in asymptotics. Ranks actually also belong to that stream of his activity. Permutational distributions and stochastic inequalities are another way of ensuring exact sizes, under unspecified densities, of tests and confidence regions. This approach has been adopted in [64] for permutation tests against serial dependence, where a problem of permutational extreme values turns out to take the form of a travelling salesman problem. In general, such problems cannot be solved exactly, but, quite surprisingly, due to the specific structure of the weights implied by the statistical nature of the problem, an explicit solution is obtained here, that was apparently not known in the Operations Research community.

His interest in such questions also has motivated a series of papers joint with J.-M. Dufour ([58], [62], [63], [69], and [139]) on exact bounds on null-distributions of test statistics. Among them, [69] shows how a bound B_E, proposed by Eaton in 1974, can be implemented (Eaton did not provide any explicit form, and the statistical applications of that bound had never been investigated). The implementable version they are proposing allows for evaluating tail probabilities for linear combinations of independent, possibly nonidentically distributed, bounded random variables, and its importance was substantiated by a result of Pinelis (1991) showing that the minimum of B_E and a traditional Chebyshev bound is optimal in a fairly general sense. That paper brings B_E to a numerically tractable form, and shows how it can be further improved

in a statistical context (B_E actually was derived in a general setting, and does not assume, for instance, that n, which in statistical applications turns out to be the sample size, is known). Applications include the computation of critical values for a broad class of permutation tests.

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