Invitation to join a Research Consortium on:

CONTINUOUS INTERPRETATION

OF WELL TEST DATA

BY DECONVOLUTION

(Phase II)

from

Professor A. C. Gringarten
Centre for Petroleum Studies

Department of Earth Science and Engineering

Imperial College London
Prince Consort Road, London SW7 2AZ
Tel: 0171 594 7440, Fax: 0171 594 7444
E-mail: a.gringarten@imperial.ac.uk

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Prof. A. C. Gringarten

Centre for Petroleum Studies, Imperial College, London SW7 2AZ, UK.

EXECUTIVE SUMMARY

With current trends towards intelligent wells and fields, continuous bottomhole well pressure monitoring is becoming the norm in new field developments. Theoretically, this should allow operators to better control well performance and address problems before they become irreversible. In practice, the need to interpret the raw information provided by permanent gauges, and the lack of manpower or expertise for doing so prevents real time intervention. Therefore, some sort of automatic interpretation and alarm system is required to benefit from the full potential of downhole permanent gauges.

A new **deconvolution** algorithm developed at Imperial College by von Schroeter *et al.*[1] makes the development of such tools possible. Contrary to deconvolution algorithms previously published in the literature, the Imperial College algorithm provides stable results. Different implementations of the algorithm have been reported in the literature and as a result, deconvolution is rapidly becoming a significant step in well test analysis. Benefits are numerous: it provides information over a radius of investigation that corresponds to the total duration of the production period, which can be orders of magnitude greater than that available from individual flow periods used for conventional well test analysis; it can reduce considerably the required duration of an extended well test, by revealing boundaries before they become visible in individual flow periods; it allows differentiating between alternative interpretation models; and it may be the only way to interpret well test data, for instance in the case of multilateral horizontal wells in low permeability reservoirs.

The current deconvolution algorithm is only valid for a single well. In order to exploit fully the potential of deconvolution, the algorithm must be able to handle multiwell systems, where pressure interference occurs, and provide a deconvolved derivative for every interfering well. This has been the subject of a 2005-2007 research project at Imperial College sponsored by a consortium of 14 companies[°]. It was found that, contrary to early expectations, a direct extension of the single well deconvolution algorithm was impractical, because of the number of control parameters required, and that a more promising approach was to reformulate the deconvolution problem within the framework of Bayesian statistics. The 2005-2007 research work concentrated on analytic Bayesian solutions which unfortunately require simplifying assumptions which are difficult to check. A better approach is now proposed, which is to use Markov chain Monte Carlo (MCMC) methods.

The primary objective of this proposal is to complete the deconvolution work started in the 2005-2007 Imperial research project, using Bayesian statistics in order to obtain a robust multiwell deconvolution algorithm that can be used by practicing engineers in a wide variety of field conditions to control and optimise well performance.

A second objective is to investigate the use of Bayesian statistics for well test interpretation model identification, in order to obtain estimates of reservoir properties and future flow/pressure behaviours with stated levels of accuracy.

° Saudi Aramco, BG, BHP, BP, Chevron , ConocoPhillips, ENI, Gaz de France, Occidental Petroleum, Petro SA, Schlumberger, Shell, Total, Weatherford

BENEFITS

- Access to a stable deconvolution algorithm which allows to continuously interpret well test data in the presence of interference effects, with stated levels of accuracy.
- A methodology which provides probability ranking of possible interpretation models on the basis of their deconvolved pressure signals
- Thorough interpretation of company's own data, as part of the evaluation of the algorithm.
- Annual forum at Imperial College to review progress and provide input into research directions.

RESEARCH AREA

Permanent downhole pressure gauges are increasingly being installed in new developments around the world. Their reliability has greatly improved and they now can operate for several years. They provide a pressure record of everything that is happening to the well and, in the long term, they are likely to replace production tests for well and reservoir monitoring.

In theory, information from permanent gauges should permit operators to react to problems as soon as they appear. In practice, the need to interpret the raw information provided by permanent gauges and the lack of manpower and expertise for doing so prevents real time intervention. Instead, permanent gauge records are archived and only examined after the existence of a problem has been recognised, to identify its cause and evaluate possible solutions. Unfortunately, the corresponding delay often makes the damage irreversible.

Interpretation of permanent pressure gauge data is especially challenging because of the size of the data sets, which can consist of thousands of un-planned flow periods at different rates and millions of pressure points stretched over years of recording time. Such data sets contain information about the reservoir at distances from the well which can be several orders of magnitude larger than the radius of investigation of a single flow period, but the full potential information content cannot be obtained with conventional analysis methods. Conventional well test analysis is based on pressure derivatives, calculated over individual flow periods which are likely to be of short durations compared to the duration of the entire test and therefore may not show features, such as boundaries, that have actually been reached during the test. In addition, pressure derivatives are affected by all sorts of errors, notably in rates, and may be distorted by the differentiation algorithm, thus providing at best an ambiguous picture of the well behaviour.

The full information potential can only be achieved with **deconvolution**. Deconvolution transforms variable rate pressure data into a single constant rate initial drawdown with duration equal to the total duration of the test and yields the corresponding pressure derivative normalised to a unit rate.

The only published algorithm that provides stable results is one which has recently been developed at Imperial based on the Total Least Square method[1]. This algorithm estimates the initial pressure, rate errors and normalised derivative by minimising an error measure which is a weighted combination of pressure match, rate match, and a penalty term based on the overall curvature of the graphed derivative and whose purpose is to enforce smoothness of the result. As the weight of the pressure match is normalized to one, the estimate actually depends on two weights only, one for the rate match, the other for the roughness penalty. The user must choose a level of regularisation that imposes just enough smoothness to eliminate small-scale oscillations while preserving genuine reservoir features.

Different implementations of the algorithm have been reported in the literature and as a result, deconvolution is rapidly becoming part of the standard interpretation tool kit, along with conventional analysis methods. It is clear that deconvolution provides insight into well behaviour to a level never reached before, and represents as major a breakthrough in well test analysis as the derivative method when it was introduced twenty years ago. Specifically, deconvolution provides information over a radius of investigation that corresponds to the total duration of the production period, which can be orders of magnitude greater than that available from individual flow periods used for conventional well test analysis; it also can reduce considerably the required duration of an extended well test, by revealing boundaries before they become visible in individual flow periods. And it allows differentiating between alternative interpretation models.

Deconvolution can only be applied to systems governed by linear equations, which implies single-phase liquid flow in the reservoir. As with conventional analysis, it still works with gas or gas and liquid if pseudo-pressures are used. On the other hand, it does not work in its present form if there is interference from other active wells in the same reservoir, which is a common occurrence in high permeability reservoirs. It also does not work if the initial pressure is non-uniform, or, in commingled reservoirs, if layers are at different initial average pressure.

In order to exploit fully the potential of deconvolution, the algorithm must be able to at least handle multiwell systems, where pressure interference occurs. This has been the subject of a 2005-2007 research project at Imperial College sponsored by a consortium of 14 companies. The objectives of the 2005-2007 project were as follows:

1. To extend the existing formulation[1] for the deconvolution of well test data from a single well to perform simultaneous deconvolution of multiple, possibly overlapping segments of the pressure signal, yet allowing only a single, consistent update of the production rate signal (segmented deconvolution in time);

2. To establish a sound mathematical framework for the analysis of well test data from multiple, possibly interfering wells by deconvolution (deconvolution in space);

3. To attempt a generalization of the formulations obtained under Objectives 1 and 2 to the case with multiple interfering wells where the pressure signals recorded for each well are to be segmented and analyzed simultaneously, yet separately, allowing only a single, consistent update of each production signal (segmented deconvolution in time and space);

4. To develop efficient algorithms for the numerical solution of these problems, and to improve the efficiency of the existing algorithm[1];

5. To test these algorithms with simulated data sets; and

6. To apply the algorithms to field data sets provided by the sponsors.

Objective 2 was fully achieved, and the results were published in an SPE paper[2]. Meanwhile, an algorithm for this problem had already been published by Levitan[3]. As this algorithm is based on a formulation very similar to the one envisaged at the outset of the current project, algorithm studies originally planned for this objective were abandoned. Research was also carried out on Objectives 1, 3, and 4. Considerable progress was made; however, difficulties which were not properly understood when the original proposal was conceived necessitated a shift in emphasis towards a novel direction. As a consequence, there are at present no finished algorithms, and Objectives 5 and 6 could not be attempted. The main origin of the difficulties was a growing realization that a straightforward extension of the single well algorithm to multiple wells and/or multiple data segments would not be practically useful for the following reasons:

- Estimates from current deconvolution algorithms[1-4] depend on a number of weight parameters which govern the relative importance of the various contributions to the objective function (viz. rate and pressure matches and curvature penalty). As Levitan[4] first recognized, some of these weight parameters have a statistical interpretation in terms of uncertainty levels in the data. This suggests that their choice ought to be based on sound statistical criteria rather than ad-hoc recipes of the type currently in use.

- The necessity to constrain the choice of weight parameters becomes even more urgent in the joint analysis of data from multiple data segments and/or multiple wells: Here the number of weight parameters increases linearly with the number of data segments and quadratically with the number of wells, and would thus quickly exceed the degree of freedom desirable in a method which purports to be objective and practical.

It was concluded that the most promising strategy to deal with these difficulties would be to reformulate the deconvolution problem within the framework of Bayesian statistics. According to this framework, inference from the data is embodied in the joint posterior probability density function (pdf) of the hypothesis parameters, and their best estimate is obtained by maximizing this pdf. The main benefits of following this approach are as follows:

- A priori unknown process parameters such as uncertainty levels in the data can be made part of the testable information. This means that they can be estimated if desired; alternatively they can be treated as “nuisance parameters”, which amounts to considering the marginal pdf of the remaining parameters. In both cases, the effect of all hypothesis parameters is properly accounted for.

- The statistical approach leads to a unified description of the best estimate and its uncertainties as a function of the uncertainties in the data (by contrast, estimate and sensitivity analysis given in Ref. 1 were more limited in scope since they depended on a priori choices of the process parameters).

In the framework of Bayesian statistics, data analysis is understood as maximizing the posterior probability $prob(H|D;I)$ of the explanatory hypothesis H under the constraints given by data D and prior information I. Bayes' rule: $prob(H|D;I) = \frac{prob(D|H;I) \times prob(H|I)}{prob(D|I)}$

relates this probability density function (pdf for short) to three others, namely:

$prob(D|H;I)$: the probability of the data given hypothesis and prior information, also known as likelihood of the data;
$prob(H|I)$: the probability of the hypothesis based on prior information alone, or prior; and

prob(D|I): the probability of the data based on prior information alone, or evidence.

Here the evidence does not depend on the hypothesis and is therefore irrelevant for the optimization problem. Suppose that the hypothesis parameters are split into two groups, say “parameters of interest” (which are to be estimated) and “nuisance parameters” (which need not be estimated, but whose influence must nevertheless be accounted for). Then a plausible strategy consists of the following steps:

1. Bayes' rule relates the posterior pdf of the hypothesis parameters to statistical assumptions about their prior pdf's and about uncertainties in the data. By substituting appropriate assumptions, one obtains the joint posterior pdf for the entire set of hypothesis parameters.
2. By integration over the nuisance parameters, the joint posterior pdf is reduced as far as possible to the marginal posterior pdf of the parameters of interest.
3. Maximization of this marginal posterior pdf provides estimates and reliabilities for the parameters of interest.
4. If desired, a conditional estimate of the nuisance parameters can be obtained by maximizing the joint posterior pdf, where estimates from step 3 are substituted for the parameters of interest.

In the deconvolution problem of well test analysis, the main parameters of interest are the response signals for each well/gauge pair while a conditional estimate suffices for the initial pressures at each gauge, the error levels of the input signals, and the differences between measured and estimated rates at each well. For this choice, and for the case of a single gauge/well pair, the above programme has been carried out up to and including step 2. Before algorithm studies for step 3 could begin, some hard analytical obstacles had to be overcome:

1. The marginal posterior pdf is a highly nonlinear function of the 20 to 40 response parameters per well/gauge pair. Even for a single well/gauge pair, this will require gradient based algorithms; results from experiments with Mathematica's implementation of the simplex algorithm due to Nelder and Mead were discouraging. However, the objective function depends on the estimate through nonlinear functions and matrix operations such as determinants and generalized inverses; an efficient evaluation of its gradient remains to be developed.

2. Alternatively, the rate updates could be considered parameters of interest in step 2, which would leave a marginal pdf depending on the initial pressure, response signals, and rate updates. Depending on the size of the data set, this strategy leads to an optimization problem which depends on a larger set of parameters (typically at a few hundred per active well), but in an analytically more tractable way.

Steps 3 and 4 contain yet a number of other challenges which touch upon the aims and ambitions of well test analysis at its most fundamental level:

3. A meaningful estimate must include information about its own reliability. This can take the form of confidence intervals if the pdf to be maximized is unimodal and approximately Gaussian about the maximum. Even in this most simple case, further analytic work is required to study the propagation of uncertainties from input data and response estimates to the reliabilities of the conditional estimates.

4. There are situations in which the resulting pdf is unlikely to be unimodal; such situations include:
   - ambiguous data sets which admit more than one explanatory hypothesis, and
   - data sets which are incompatible with the superposition principle as a whole, but where parts are compatible with different explanatory hypotheses (such as in Synthetic Example 2 in Ref. 4).

   Here the objective of analysis can only be a probability-ranked list of alternative estimates together with their individual reliabilities. The algorithmic challenge lies in a complete exploration of the relevant pdf over its entire parameter space without trapping by local extrema. Algorithms for this problem have been suggested (with buzz words such as Simulated Annealing, Genetic Algorithms, and Nested Sampling), but this area itself still appears to be the subject of intense mathematical research and controversy.

In summary, the focus of the research has been on finding an analytic Bayesian solution for the posterior pdf of the ratio of the noise variables by assigning ignorance prior distributions to the variance parameters and then integrating out to form marginal posterior distributions for them. This turned out to be extremely hard to do satisfactorily as reasonable credibility intervals for ratios of variances cannot be obtained using ignorance priors: there is too much prior probability in the tails for the denominator variable, and as such the credible intervals are so wide as to be useless.

At this stage, it was decided to seek assistance from the statistics group at Durham University, which is a leader in Bayesian statistics and has extensive experience in general problems allied to modelling of oil reservoirs (history matching, parsimonious representations of reservoirs, leak detection in oil and gas pipelines, and statistical methods to handle computer models such as reservoir simulators). It appears that the problem could be solved using Markov chain Monte Carlo (MCMC) methods, which provide all marginal and joint posterior pdfs, provided that the problem is structured appropriately. These methods also have sets of assumptions to obey, and one has to pay attention to convergence of the estimates.

OBJECTIVES

The present proposal involves a close cooperation between the Centre of Petroleum Studies at Imperial College (Prof. Alain C. Gringarten) and the statistics group at Durham University (Prof. Michael Goldstein, Dr. David Wooff and Dr. Peter Craig. Michael).

The primary objective of this proposal is to complete the deconvolution work using Bayesian statistics started in the 2005-2007 Imperial research project in order to obtain a robust multiwall deconvolution algorithm that can be used by practicing engineers in a wide variety of field conditions to control and optimise well performance.

A second objective is to investigate the use of Bayesian statistics for well test interpretation model identification, in order to obtain credible estimates of reservoir properties and future flow/pressure bahaviour with stated levels of accuracy.

SCOPE OF WORK

The work in this proposal will be primarily conducted by two post-doc staff supervised by both Prof. Gringarten and Dr. Wooff and located in the statistics group at the University of Durham

1. The first task of a post-doctoral appointment will be:

- To reframe the error problem in order to solve it using MCMC methods;
- To consider what prior information is exploitable (it may be that there is less than total ignorance);
- To apply MCMC;
- To carry out a sensitivity analysis in order to judge the effects of varying the inputs (prior settings) on the outputs;
- To calibrate the outputs to known situations, where possible.

2. The above problem is univariate. Addressing the error sources for the multivariate pressure/flow signals is, in principle, also achievable through Bayesian statistics. The main effort here would be in structuring the problem properly in order to introduce appropriate correlations between the variables of interest. Hence, the second task of a post-doctoral appointment will be:

- to extend the Bayesian approach to multidimensional pressure/flow problems;
- to consider what correlation structures are appropriate, and to determine whether there is exploitable prior information which could help us in doing so, and specifying such prior distributions;
- to apply MCMC, sensitivity analyses and calibration studies as for univariate.

3. One major aim is to provide a methodology which gives credible predictions of reservoir properties and future flow/pressure with stated levels of accuracy. Part of the general problem involves classification of reservoirs on the basis of their deconvolved pressure signals. It is worthwhile to revisit the entire problem from a wholly Bayesian perspective to determine whether there is scope for enhancements. In particular, there may be nice ways to re-interpret the classification problem, and possibly nice ways to give a Bayesian handling of the deconvolution problem. Hence, the third task of a post-doctoral appointment will be:

- to consider the major aims of the approach (prediction) from a wholly Bayesian perspective of the overall problem, in order to identify areas which might benefit from further structuring/analysis.

- This is more open-ended than the first two tasks, but a holistic treatment would be probably highly rewarding in terms of delivering good and accurate results to the industry, and in providing research outputs.

The work will be performed by staff and MSc students from the Centre for Petroleum Studies at Imperial College, and by staff from the Department of Department of Mathematical Sciences, University of Durham, with input and guidance from industry partners.

BRIEF RESUME OF PRINCIPAL RESEARCHERS

Prof. Alain C. Gringarten - Professor of Petroleum Engineering, Imperial College

Prof. Gringarten will be the principal investigator for this project. He holds the Chair of Petroleum Engineering at Imperial College in London and is also director of the Centre for Petroleum Studies, Department of Earth Science and Engineering, which covers all petroleum activities at Imperial. Before joining Imperial College in March 1997, Dr. Gringarten spent 25 years with service companies, first with Schlumberger where he was Director of Engineering and created their well test interpretation service; then with Scientific Software-Intercomp, where he held several senior technical, marketing and management positions including Executive Vice President for E&P Consulting and Products. Prof. Gringarten is a recognised expert in well test analysis and has published numerous articles on that subject. He received the Society of Petroleum Engineers (SPE) Formation Evaluation award for 2001, the 2003 SPE John Franklin Carll award, the 2004 SPE Cedric Ferguson certificate and was a SPE Distinguished Lecturer for 2003-2004. Prof. Gringarten holds an engineer degree from Ecole Centrale, Paris, France; and obtained an MSc and a Ph.D. in Petroleum Engineering from Stanford University.

Prof. Michael Goldstein - Professor of Statistics, University of Durham

Michael Goldstein is Professor of Statistics and presently Head of the Department of Mathematical Sciences, University of Durham. He has worked for the last thirty five years on the foundations, methodology and applications of Bayesian statistics. In particular, with a series of EPSRC grants, he has developed a general approach termed Bayes linear analysis, which is similar in spirit to the usual Bayesian approach, which is concerned with making probabilistic inferences which combine expert knowledge with empirical data, but concerns the appropriate treatment of problems which are too complicated for full probabilistic specification, either for reasons of computational tractability or because of the complexity of making a full and meaningful prior belief specification. Over the last fifteen years, he has been involved in applying this approach to the analysis of all of the sources of uncertainty arising when studying large scale physical systems via complex mathematical models. This work has been supported by two EPSRC grants concerning model calibration and forecasting for oil reservoirs, based around a close relationship with our industrial collaborators, Energy SciTech Ltd, and with a NERC grant in the RAPID thematic initiative, where these methods were applied to large climate simulators. The fundamental methodology, currently supported by a group of four postdocs funded by EPSRC and industry, is currently being generalised to address basic problems arising in areas such as systems biology, energy science and cosmology.

Dr. David Wooff - Senior Lecturer in Statistics, University of Durham

David Wooff is Senior Lecturer in Statistics, University of Durham, and Director of the University's Statistics and Mathematics Consultancy Unit since its establishment in 1996. His main interests are applied statistics and the application of Bayesian statistical approaches to industrial problems. These currently include Bayes linear methods for commodity trading; the next generation of methods for software testing via Bayesian graphical models; parsimonious representations of oil reservoirs; and a Bayesian approach to detecting leaks in pipelines. He has co-authored (with Michael Goldstein) a research monograph on Bayes linear methods and has published over 30 peer-reviewed articles since 2000. He sits on the scientific committee of the Knowledge Transfer Network for Industrial Mathematics, and is an editorial board member for the Open Software Engineering Journal. Recent and current research students have worked in the areas of child growth statistics; clinical data analysis and dimension reduction; Bayesian commodity trading; training evaluation; and Bayesian approaches to exploiting e-commerce traffic.

Dr. Peter Craig - Lecturer in Statistics, University of Durham

Peter Craig is Lecturer in Statistics, University of Durham. He has a particular interest in environmental applications of Bayesian methodology and statistical computation. From 1994 to 2000, he was an active member of the Durham research group working on statistical methodology for computer experiments with particular reference to hydrocarbon reservoirs, work which was partly funded by research grants from SERC and EPSRC, culminating in an article in the Journal of the American Statistical Association. Subsequently he worked on an EPSRC funded study of adsorption of pollutants on contaminated and since 2004 he has been part of the collaboration between the Durham statistics group and the risk assessment team at DEFRA's Central Science Laboratory. Growing out of that he has worked since 2004 as an ad hoc expert with the Plant Protection Products and their Residues (PPPR) panel of the European Food Safety Authority on scientific opinions related to risk assessment for pesticides: two related to the IESTI formulae for acute risks to humans from dietary exposure and the third in aquatic ecotoxicology. An article on calculation of multivariate normal tail probabilities has recently appeared in Journal of the Royal Statistical Society, Series B. Recently completed PhD students have worked on robust exploratory analysis of variance and Bayesian methods in spatial-temporal epidemiology. Current students are working on design for spatial sampling in pesticide trials, computation for exact tests, risk assessment topics and unification of uncertainty for competing climate models. He was an Associate Editor for The Statistician and JRSS A from 2002 to 2006 and is now Associate Editor for the Australian and New Zealand Journal of Statistics.

Centre for Petroleum Studies (CPS) at Imperial College

The Centre for Petroleum Studies is a focus for research, postgraduate teaching and professional development within the framework of petroleum sciences and engineering at Imperial College. Its main objectives are to facilitate multi-disciplinary research between geologists, geophysicists, petroleum engineers and members of other key disciplines in order to advance the state of the art in exploration, appraisal/development and reservoir management, and to plan and implement related postgraduate teaching programmes which reflect current best practice within the petroleum industry. The Centre has one of the largest concentrations of petroleum scientists and engineers in a UK academic institution, with almost 50 members of staff providing research expertise across the complete Exploration-Production spectrum.

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