Chatelet Resources LLC
Science-based statistical modeling

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NanoVISA: probabilistic inference for commercial seismic monitoring and uncertainty quantification

Commercial seismic monitoring is used to study earthquakes generated by injecting fluids underground either to liberate oil, gas or hot water or to dispose of waste water and carbon dioxide. *Microseismic* events have a magnitude of less than zero on the Richter scale. They are used to map tiny cracks as they form and release amounts of energy that are smaller than the calories stored in a chocolate bar. Knowing the mechanics of small-scale fracturing allows engineers to better understand reservoirs so that they are able to optimize production by designing better hydro-fracturing treatments and mitigate environmental disaster by keeping hydrocarbons out of aquifers and avoiding well treatments and injections which might lead to *induced* seismic events, earthquakes that are large enough to be of public concern. Competitors in the large and growing market for commercial seismic monitoring can distinguish themselves by providing accurate, timely and complete information.

Three important factors contribute to the complete understanding of an earthquake: its *location*, *magnitude* and *moment*. Correct locations make it possible to construct accurate fracture maps, identifying hydro-fractures as well as natural cracks which might open up pathways for unwanted groundwater contamination. Magnitude gives a rough estimate of the amount of energy required to break the rock. Perhaps most importantly, moment tells an engineer the mechanisms by which rocks fail, making it possible to extrapolate the behavior of formations to other wells and reservoirs.

VISA stands for *Vertically Integrated Seismic Analysis*, a physically accurate statistical package for the automatic identification, location, magnitude and moment estimation of seismic events. NanoVISA is a proposed commercial adaptation of the existing NET-VISA system which has already changed the state-of-the-art in global seismic monitoring for illicit nuclear weapons testing. NET-VISA is currently installed at the International Data Centre (IDC) of the Comprehensive Test Ban Treaty Organization (CTBTO) [Arora et al, 2013; Russell, 2012, Shafer, 2011]. It was originally developed by Nimar Arora at

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the University of California, Berkeley in partnership with the CTBTO and is now being developed by Bayesian Logic Inc. and CTBTO. Compared to standard IDC data analysis, NET-VISA has been shown to reduce event location errors by half, find smaller events, reduce the false event rate by 40%, accurately estimate uncertainty, significantly reducing the human labor involved in producing an accurate seismic bulletin.

Through NanoVISA, the ideas behind NET-VISA have the potential to be adapted into breakthrough technology for commercial seismic data analysis. Using a unique representation of statistics and uncertainty combined with wave equation physics NanoVISA will, of course, improve event location and magnitude estimation. Its framework will make it possible to link rock physics directly into moment tensor estimation for a deep understanding of reservoir mechanics which has hitherto been elusive. The framework is essentially graphical which will make it easy to explain how results were obtained not only to geophysicists, but to executives, managers, financiers and, if ever it came to it, a jury. Furthermore, NanoVISA will produce more than a single answer – it will

- Improve event location
- Improve fracture monitoring during oil and gas well stimulations, allowing engineers to design better well treatments and optimize production
- Allow for finer understanding of fracture patterns, leading to better calibration of production models
- Produce event maps that are less noisy than current images, reducing the risk of fracture networks and well footprints overlapping
- Return defensible estimates of uncertainty regarding the causes of alleged induced seismic events
- Significantly reduce the cost of producing high quality data by reducing the need for human intervention during data analysis.

Expected Performance

NanoVISA has not yet been built. However, its performance is expected to be similar to that of NET-VISA, which has demonstrated dramatic improvement over current IDC processing. Figure 1 shows events produced by standard processing from a week of data compared to events from the same period that were listed in the Late Events Bulletin (LEB). Each event in the LEB is reviewed and corrected by a

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human analyst. The bottom figure shows events produced by NET-VISA also compared to LEB. The NET-VISA bulletin is more complete and clearly contains fewer spurious events than the IDC product.

In June of 2012, a test was performed in which IDC analysts evaluated 26 hours' worth of NET-VISA events using the same tools they use to evaluate standard events. Out of 135 events that were included in LEB for that day, the standard program found 101 and NET-VISA found 117, many of significantly smaller magnitude. Full results are given in [Arora et al, 2012].

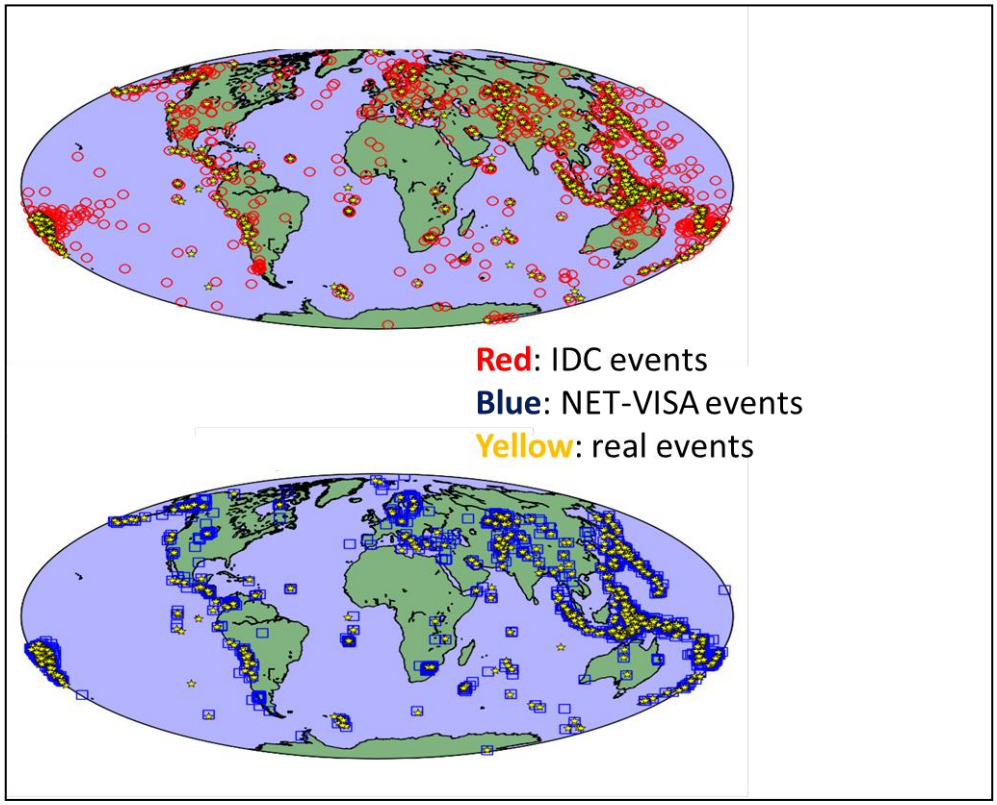

Figure 1: Performance of standard processing which generates many mislocated and spurious events (top) to NET-VISA (bottom).

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Brief Technical Description

VISA systems are composed of two parts: a probabilistic Knowledge Representation (KR) and an Inference Algorithm (IA). The KR is a rigorous mathematical framework which is used to compute the probability of any configuration of factors which affect the measurement of a seismic event across a given seismic array. These factors include location and magnitude of the event; seismic travel times as predicted by simple earth models; detection probabilities; and errors in azimuth, slowness, and phase labeling of arrivals. A pictorial representation of the KR for NET-VISA is given in Figure 2. The relationship between factors which do not have a known physical dependence that can be numerically modeled is learned from historical data and represented by conditional probability dependence.

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Given a set of measured data (which in the case of NET-VISA are arrivals that have been automatically identified at stations on the CTBTO seismic array), the IA proposes events and then uses the KR to compute the probability of these events and the arrivals associated with them, searching for the best set of events and associations. NET-VISA is the only program of its kind which not only maximizes the

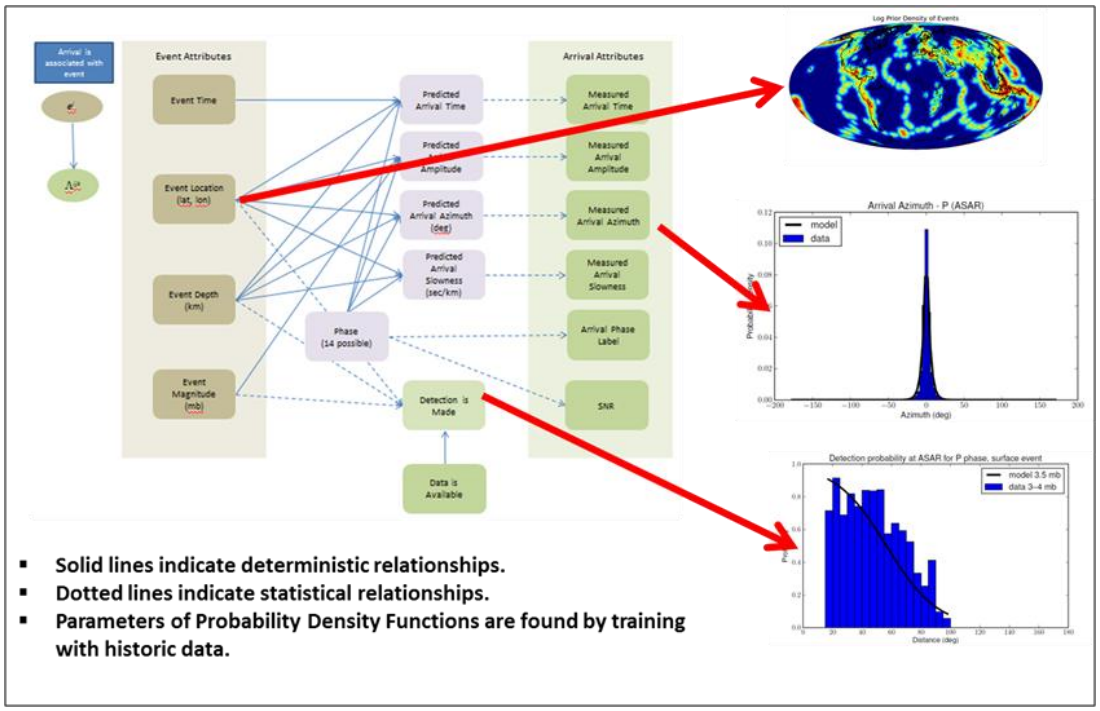

Figure 2: Pictorial representation of the KR for NET-VISA

probability of events and associations, but actually proposes them. Other Bayesian programs for locating seismic events such as PEDAL [Draelos et al, 2012] are capable only of evaluating events that have been pre-proposed, usually in a regular pattern, and so are constrained to finding events on a coarse grid. Others, like BAYESLOC [Meyers et al, 2007] are designed to relocate events that have already been listed in a previous seismic bulletin. From a practical point of view, this means that VISA systems find

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and locate events without needing to be "seeded" using existing bulletins. Therefore they are capable of finding small events which are missed by standard algorithms.

NanoVISA LLC Principal Team

Nimar Arora has a PhD in Computer Science with emphasis on Artificial Intelligence from the University of California, Berkeley. He was the original developer of NET-VISA and is currently upgrading the system under contracts with CTBTO. He is also a consultant to Oracle Corp. working in high performance computing, distributed systems, and database applications. He holds eighteen patents and has published many papers in computing, statistical modeling and sampling.

Heidi Kuzma has a PhD in Applied Geophysics from UC Berkeley. She has been deeply involved in and published widely on the application of computer learning to physical problems, including geophysical inversion, production analysis, seismic Amplitude Variation with Offset (AVO), and atmospheric modeling.

James W. Rector PhD is a professor of Applied Geophysics at UC Berkeley and principal of BGI Champion, a holding company for Oil and Gas projects. He has thirty years' experience as a successful entrepreneur in the oil industry, having started TomoSeis Inc. and Berkeley GeoImaging Inc. He holds numerous patents and has published seminal papers on all aspects of seismic analysis, particularly micro, passive and borehole seismic applications.

Janette Conradson is a business woman with over twenty years of experience as CEO and CFO of startup and midsized companies in various industries, including Emblem Geophysics, a provider of magneto telluric services for mineral exploration and BetaZi, LLC. BetaZi is a physics based probabilistic algorithm that accurately forecasts the production from oil, gas and water wells.

Mark Avery, Esq. is a corporate attorney who specializes in governance, finance and M & A, having represented mid to large size companies in a variety of industries including Oil and Gas, Computer Technology and Industrial Manufacturing.

Chatelet Resources LLC

Chatelet Resources LLC is a research studio specializing in combining state-of-the-art statistical knowledge representation with probabilistic inference to solve high-value problems which sit at the crux

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between physics, experiment and human intuition. We work on complex systems, building rigorous frameworks in which science, data and expertise mathematically interact. Each of our projects is spun into a separate company for which we find visionary partners who can demonstrate that they have the resources necessary to monetize our work.

Select References

Arora, N.S., S. Russell and E. Sudderth. 2013. NET-VISA:Network Processing Vertically Integrated Seismic Analysis. Bulletin of the Seismological Society of America, January 1. In Press.

Arora, N.S., J. Given, E. Tomauta, S. Russell, S. Spiliopoulos. 2012. Analyst Evaluation of Model-Based Bayesian Seismic Monitoring at the CTBTO. Monitoring Research Review.

Draelos, T. J., S. Ballard, C. Young, M. Gonzales and R. Brogan, 2012. A Seismic Event Detection and Signal Association Algorithm, EGU General Assembly 2012, proceedings: p. 6831.

Meyers, S.C., G. Johannesson, and W. Hanley (2007). A Bayesian hierarchical method for multiple-event seismic location, *Geophys. J. Int.* 171: 1049-1063.

Russell, S.. 2012. Physics, data and Bayes for global monitoring. American Geophysical Union Annual Mtg. Invited Presentation. Control ID 1502672.

Shafer, R.. 2011. Artificial Intelligence outsmarts the bomb. Forefront, University of California, Berkeley, Fall 2011: 8 – 11.