DIAMOND DRILL HOLES, BLAST HOLES & COKRIGING
(June 2016 version)

Serge Antoine Séguret, MINES ParisTech, Fontainebleau, France
Sebastian de La Fuente, Codelco, Radomiro Tomic, Chile

Presenting author: Serge Antoine Séguret

CODELCO
Produciendo Futuro
Codelco Chili

Mine-Planning 2015
4th International Seminar on Mine Planning
July 8-10, 2015
Antofagasta, Chile

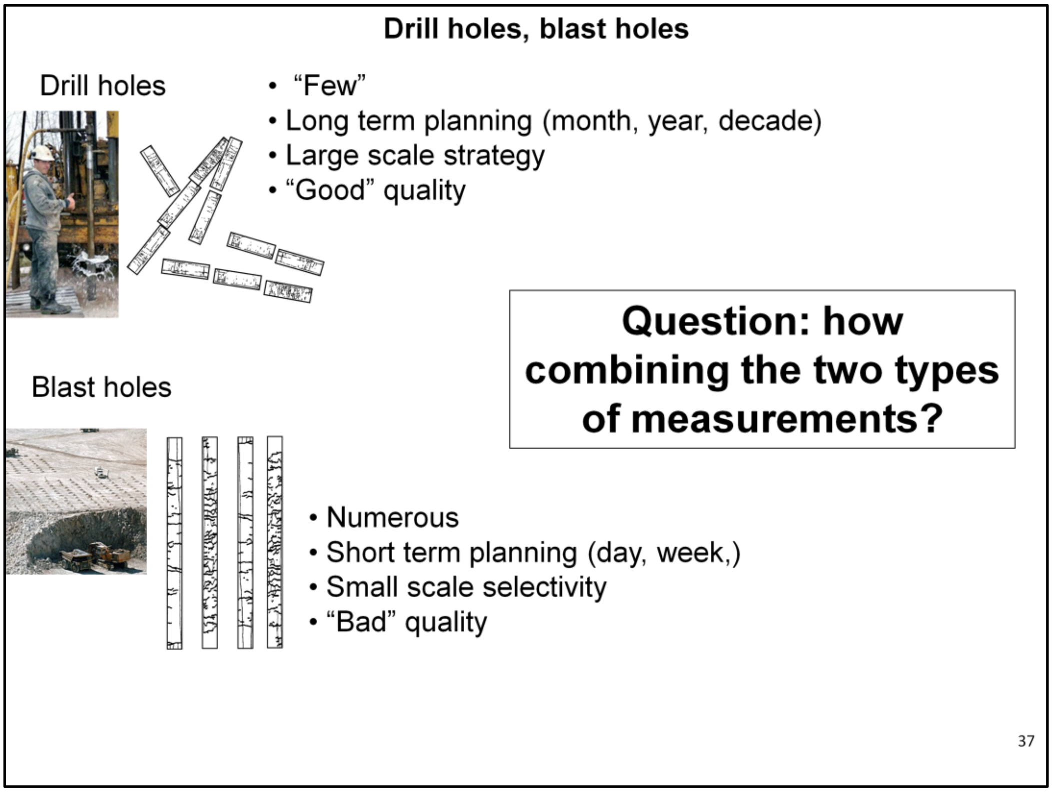
MINES ParisTech

Good morning everyone

It is my pleasure to present the work entitled

“Diamond Drill-Holes, Blast-Holes and Cokriging”

… a work supported by Codelco and the Paris School of Mines



Typically in open pit mines, geologists, mining engineers, metallurgists, have at their disposal two types of measurements for the grades:

A first type, from drill holes – "diamond drill holes" in our case.

A second type, from the blast holes.

Because they are much more expensive, the diamond drill holes are less numerous than the blast holes, and it is usual to encounter sampling rates ranging from one over three to one over ten or worse.

Not only the sampling density is involved but also how samples are distributed in space too, as shown on the slide:

- The circles, representing the drill holes, are widely spaced, see the left horizontal cross-section
- In the same figure, the green crosses, representing the blast holes, are more densely spaced
- Vertically, on the right-hand figure, it is the reverse, with almost continuous drill hole information while the blasts are more widely spaced

These differences make it even more difficult to compare the statistical properties of the two types of measurements, including when calculating directional variograms because statistical inference conditions are not the same

Another difference concerns the way the measurements are used.

The long road that leads to the opening of the mine is marked by drilling campaigns, to achieve the block model that will condition the exploitation at large scale as well as for medium- and long-term planning. Typically, kriging and Geostatistics are used to build the model at this stage.

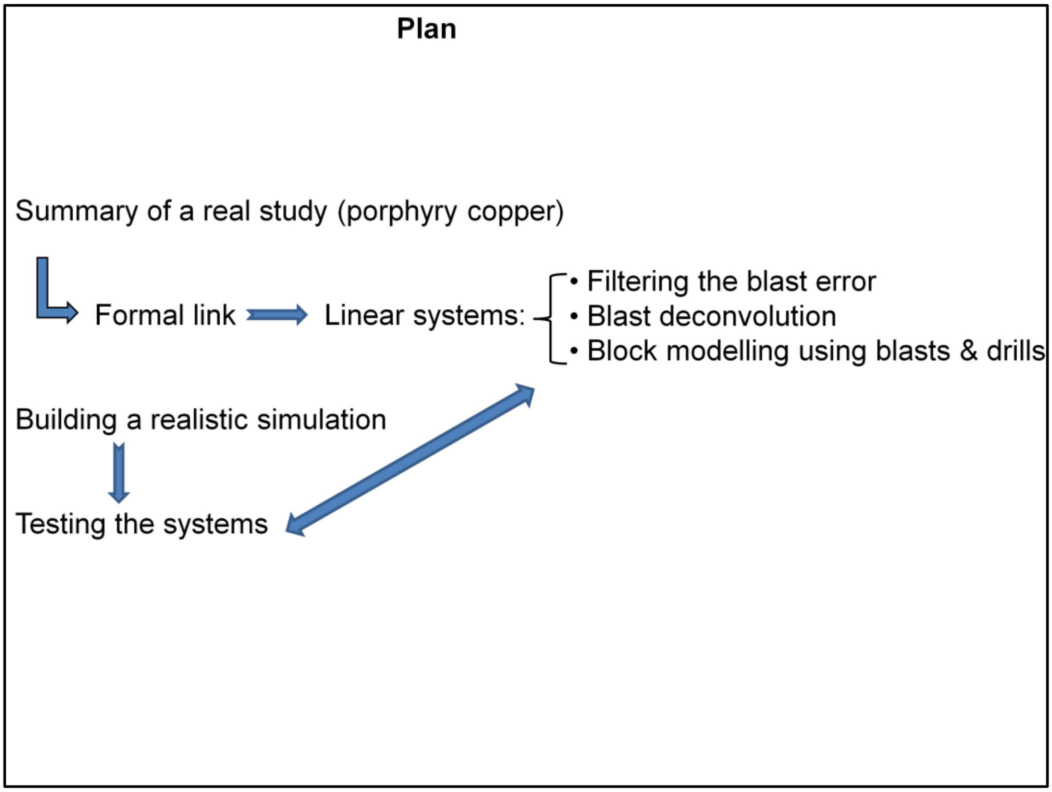
In addition, the blast holes are used for short term planning with no need of Geostatistics, a simple moving average is often used to estimate the block quantity of metal

These separate uses of two types of measurements that are supposed to represent the same thing raise questions about their relationship. In particular, would it not be possible to enrich the short-term estimate, now based only on blast holes, by adding the drill hole measurements?

Finally, we often hear, without real justification, that the diamond drill holes are much better than the blast ones.

We ask the questions:

- Better how?
- Better for what?
- Is it true?



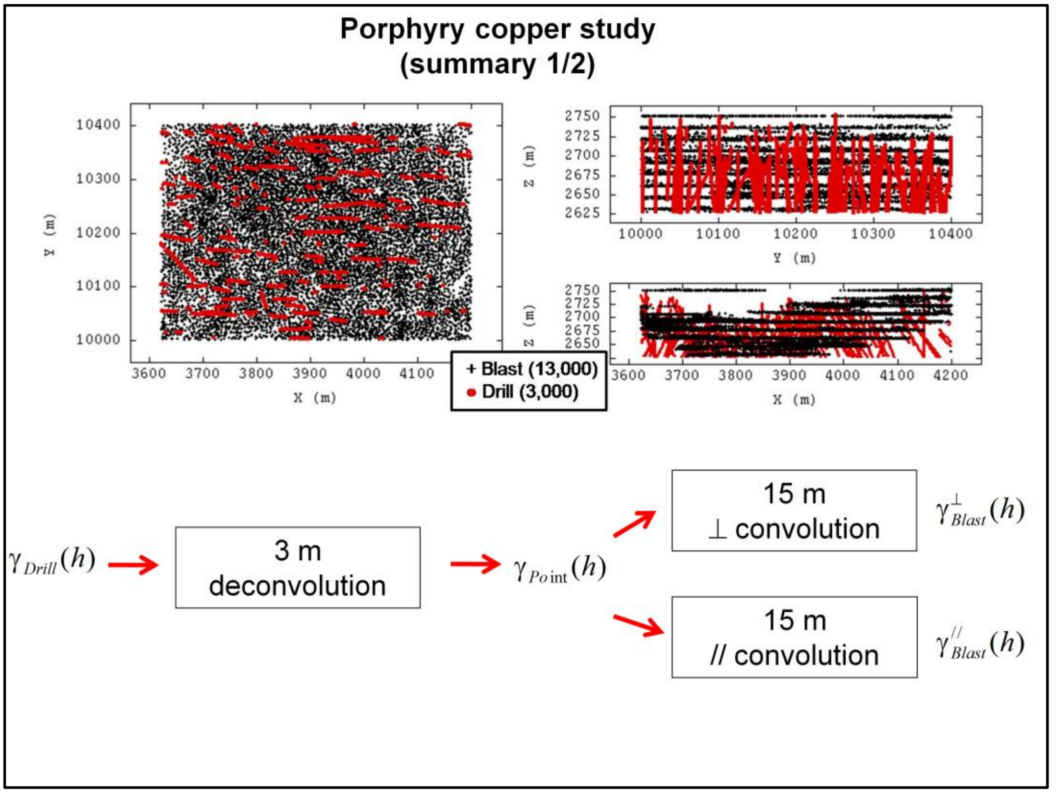
To answer these questions, we propose the following steps:

➢ We begin by summarizing a formal study of blast and drill-holes which was presented some months ago at a sampling congress in Bordeaux, France

➢This study makes possible some linear systems likes:

- Removing the blast error by kriging
- Estimating point-support values using blast measurements
- Bock modelling using blast and drill measurements together

We test the different systems on a simulation



➢The data are from an open-pit copper mine in Northern Chile where a sub domain was chosen for analysis because it is almost homogeneously covered by around 3,000 drill-hole samples (3m long) and 13,000 blast-hole samples (15m long)

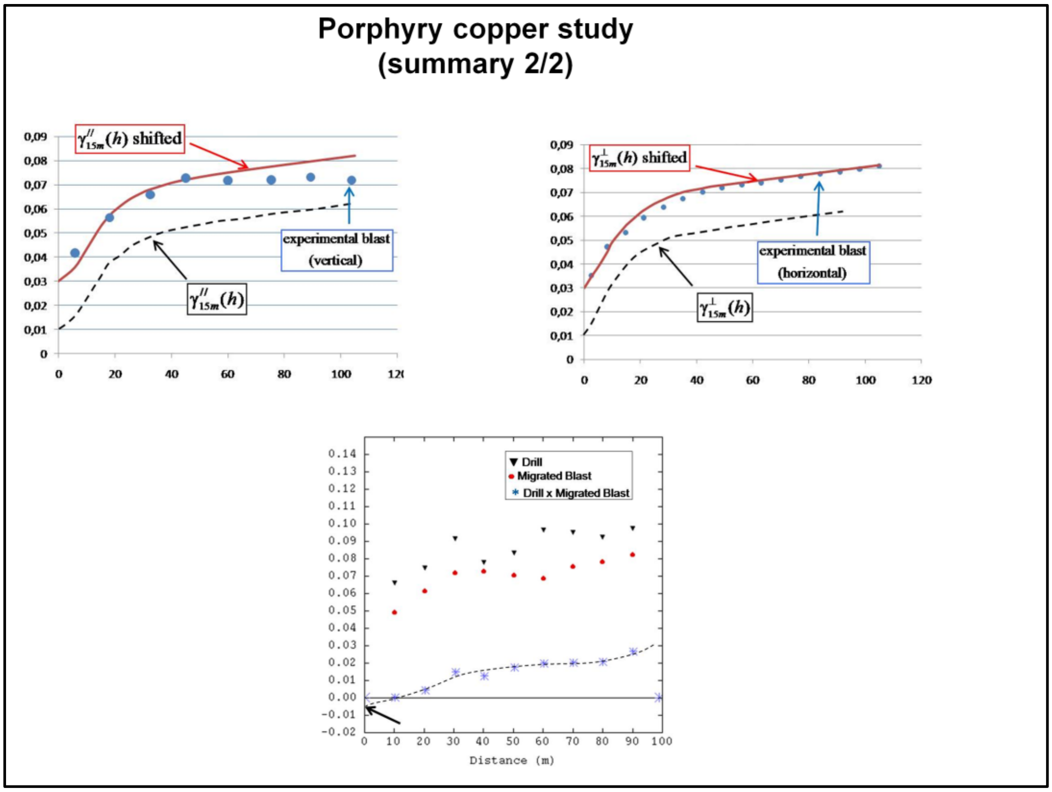
➢The geostatistical comparison between the two measurement types is divided into two steps:

- Starting from the drill variogram, identifying the basic structures that model its behavior and deducing the underlying point-support variogram

- Making the theoretical convolution of the point variogram on 15-meter long supports and comparing it to the blast variogram

➢ It is important to distinguish two situations: variogram calculation parallel or perpendicular to the regularization direction because the formulae are not the same

➢ Comparisons are completed by cross analyses based on migrated data.



➢3 structures were identified on the drill variograms, nugget effect, exponential and linear with a weak slope

➢ The upper left-hand figure shows the vertical comparison. The dotted blue line represents the experimental vertical blast variogram, the dotted black line represents the present model and the red line the model we would obtain with a more realistic nugget effect. One can see that apart from the problem of the nugget effect, the variation range is acceptable, even if the linear part of the theoretical structure does not appear in the vertical experimental blast variogram

➢ The upper right-hand figure shows the horizontal comparison. Again, apart from the nugget effect, the fitting is good.

➢If we omit the problem of the nugget effect, we see that both blast and drill holes can be considered a regularization of the same phenomenon in accordance with their respective supports.

➢In order to obtain a significant number of measurements at the same location, around 1,000 blast samples were migrated to drill locations when the migration distance did not exceed 10 meters (see bottom left-hand figure).

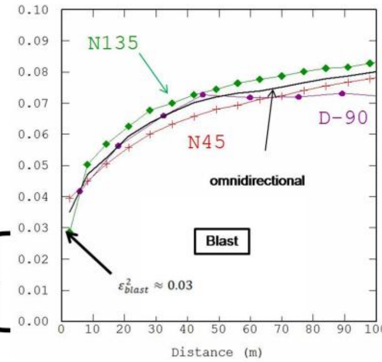
➢The bottom right-hand figure presents the variograms. Red points indicate the migrated blast variogram, black triangles show the drill variogram and the stars represent their cross variogram which does not show a significant nugget effect, possibly a small negative one without anything like the effects encountered on the individual variograms.

Model

$$Y_{blast}(x,y,z) = Y(x,y,z) * p_{15m}(z) + R_{blast}(x,y,z)$$

$$\gamma_{blast}(h) = \gamma_{15m}(h) + \gamma_{R_{blast}}(h)$$

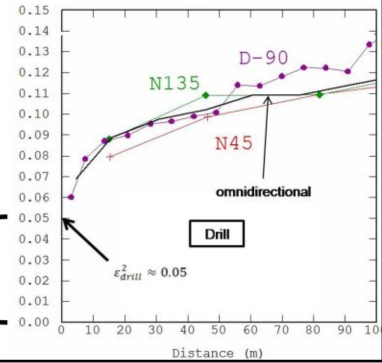
Blast sampling error



$$Y_{drill}(x,y,z) = Y(x,y,z) * p_{3m}(z) + R_{drill}(x,y,z)$$

$$\gamma_{drill}(h) = \gamma_{3m}(h) + \gamma_{R_{drill}}(h)$$

Drill sampling error



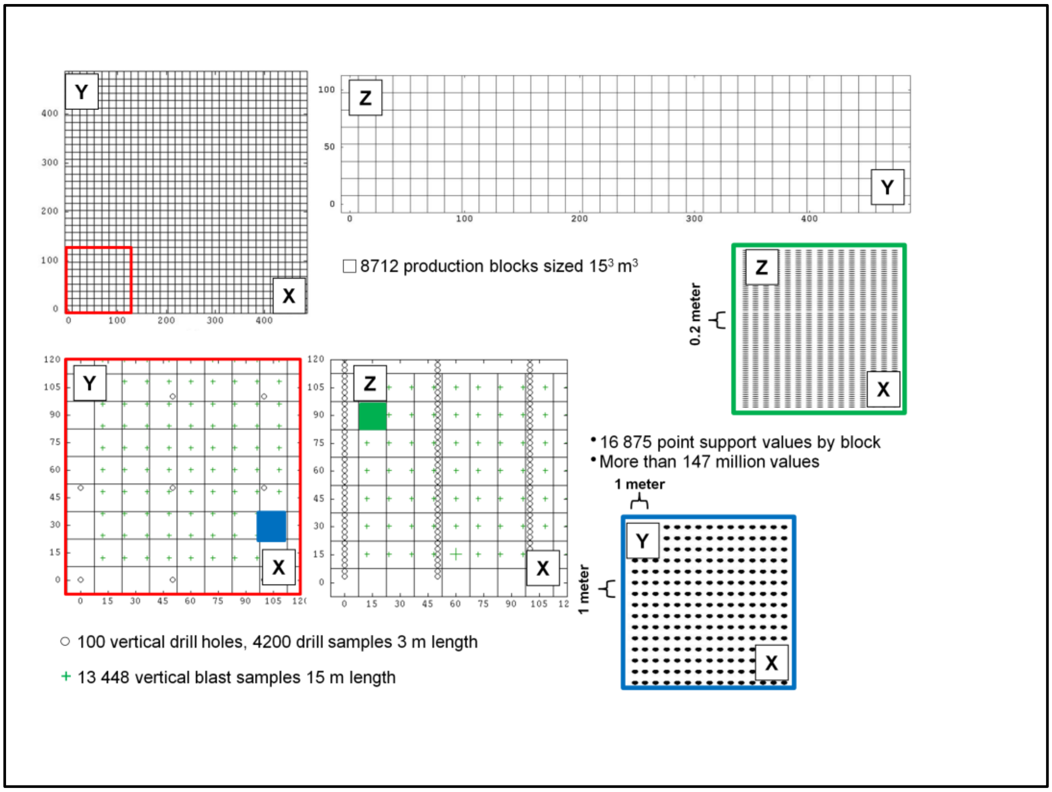
➢The conclusion is that the drill-holes have their own errors, independent of the blast ones, and the two measurements share only the structured parts of the variogram: the exponential and linear structures

➢ In this deposit – and more generally, in this company - diamond drill hole grades and blast hole grades are consistent in the sense that, apart from the nugget effect, the structured part of their respective variograms follows the theoretical laws of regularization. This result may surprise but one must admit that it is impossible to say that grade measurements from drill holes are better than those from blast one:

- Yes, there is a reduction of variance for the blast, but this is due to the support which is larger
- In both cases, the ratio of nugget effect to the variance is around 40 percent

➢ This result justifies the present practices where selectivity is based only on blasts

➢ This formal link establishes that the blasts (respectively the drills) are considered as a regularization over 15 meters (respectively 3 meters) of the point-support copper grade "Y of x, y, z" plus a residual "R" proper to each type of measurement and independent of each other.



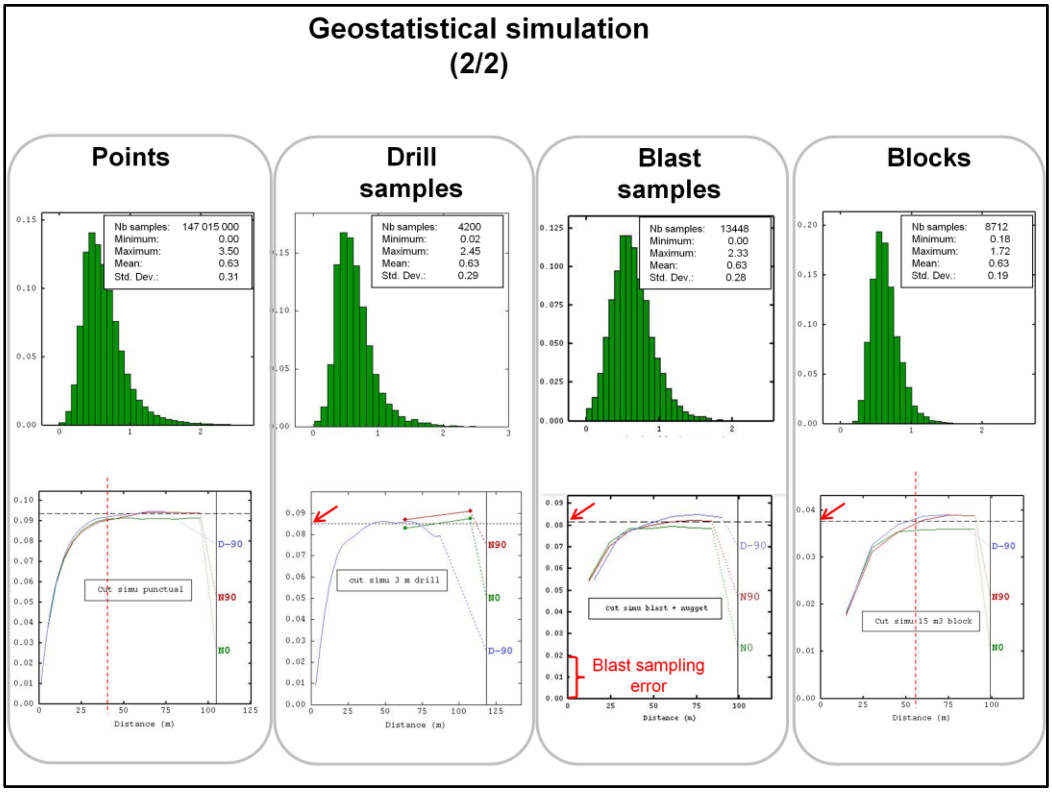
- A refined simulation of point-support grades was done every meter horizontally and every 20 centimeters vertically

- Then, 100 vertical drill holes were created by averaging, every 50 meters horizontally, all the values along 3 meters vertically. In this way we obtain more than 4000 drill samples

- In the same way, more than 8000 15 meter-long vertical blast holes were produced with a horizontal spacing of 12 meters

- The true 15 meter cubic block value is found by averaging the more than 150 million point-support values contained in the block

- The sampling ratio is approximately one drill to three blasts and the domain covered by the simulation is 400 by 400 meters squarred horizontally and 100 meters vertically



➢ The grades have an exponential variogram with a practical range of around 30 meters

➢ For simplification, the drills have no errors

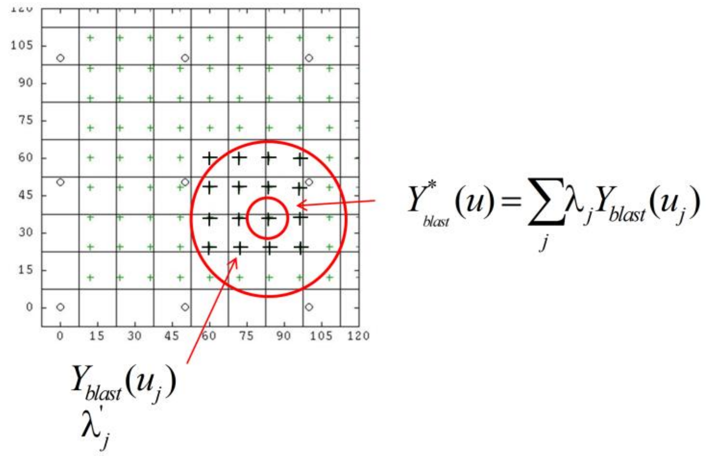
➢ We add to the blasts a random noise with a nugget effect of 0.2, representing the blast sampling error

➢ The grades are realistic with 0 as minimum, 3.5 as maximum, an average equal to 0.63 as in the real deposit and the distribution has a correct right queued

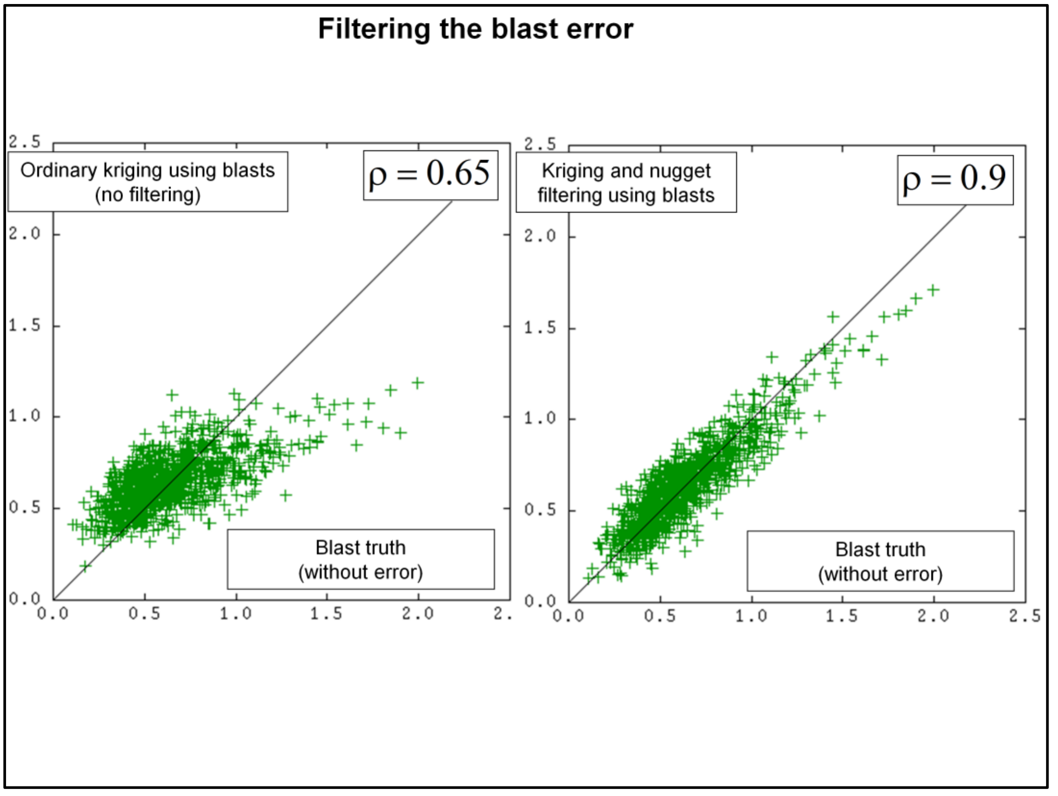
➢ We verify that the sills of drill, blast and block variograms obey the laws of regularization

1 Filtering the blast error

$$\begin{pmatrix} C*\mathcal{P}_{15m} + C_R\delta(0) & 1 \\ 1 & 0 \end{pmatrix}\begin{pmatrix}\lambda \\ \mu\end{pmatrix} = \begin{pmatrix} C*\mathcal{P}_{15m} \\ 1 \end{pmatrix}$$



- As we are in a stationary case, matrices are presented using covariance C, it is simplier
- The first test that we propose is to remove the blast error. This filter can be applied to each blast measurement, using a local neighborhood of surrounding blast samples.
- The system is presented symbolically with a matrix formalism. In the system, “gamma R” disappears from the second member of the linear system. In this way we remove from the estimation, the part associated with the measurement error.
- Generally speaking, this does not mean that in the remaining part “gamma star P”, there is no nugget effect, it means that only the “natural” part remains i.e. the part due only to the sampling error. In our case, we recall that there is no natural nugget effect
- The neighborhood must contain the sample from which the noise has been removed; otherwise, the filtering is not efficient.
- For comparison, the estimation is made by kriging with no filtering, using the same neighborhood (but without the target sample this time, otherwise kriging will give back the value of the data point).
- We select, among all the simulated blasts, a subset of around 1000 samples on which estimations will be conducted, using the additional samples (in case of ordinary kriging) and all the samples in case of nugget filtering.
- The reference is the “truth” i.e. the blast without errors which we know because we work on a simulation where everything is known



- Here are the results

- On these scatter diagrams, the horizontal axis represents the true blast without any sampling error

- On the left scatter diagram, the vertical axis is a usual kriging. The correlation with the truth is 0.65

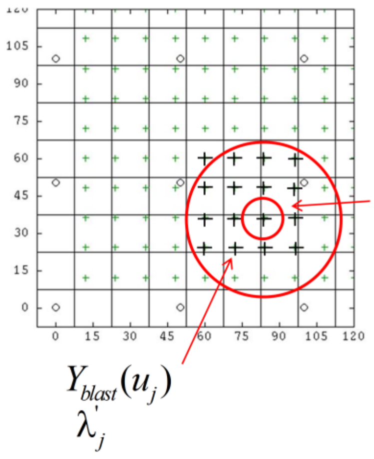
- On the right, when the filtering is activated, the correlation increases to 0.9. Why?

- Because with filtering, the kriging neighborhood can incorporate the target point where the filter is applied. This point takes a high kriging weight (more than 65%). Although noisy, this point is closer to the truth than any average based on surrounding points which explains why the filter estimate is closer to the truth

- So finally, the advantage of this linear system is to enable the kriging neighborhood to incorporate the target point information

2 Blast deconvolution

$$\begin{pmatrix} C * \mathcal{P}_{15m} + C_R\,\delta(0) & 1 \\ 1 & 0 \end{pmatrix}\begin{pmatrix} \lambda \\ \mu \end{pmatrix} = \begin{pmatrix} C * p_{15m} \\ 1 \end{pmatrix} \quad \mathcal{P}_{15m}$$



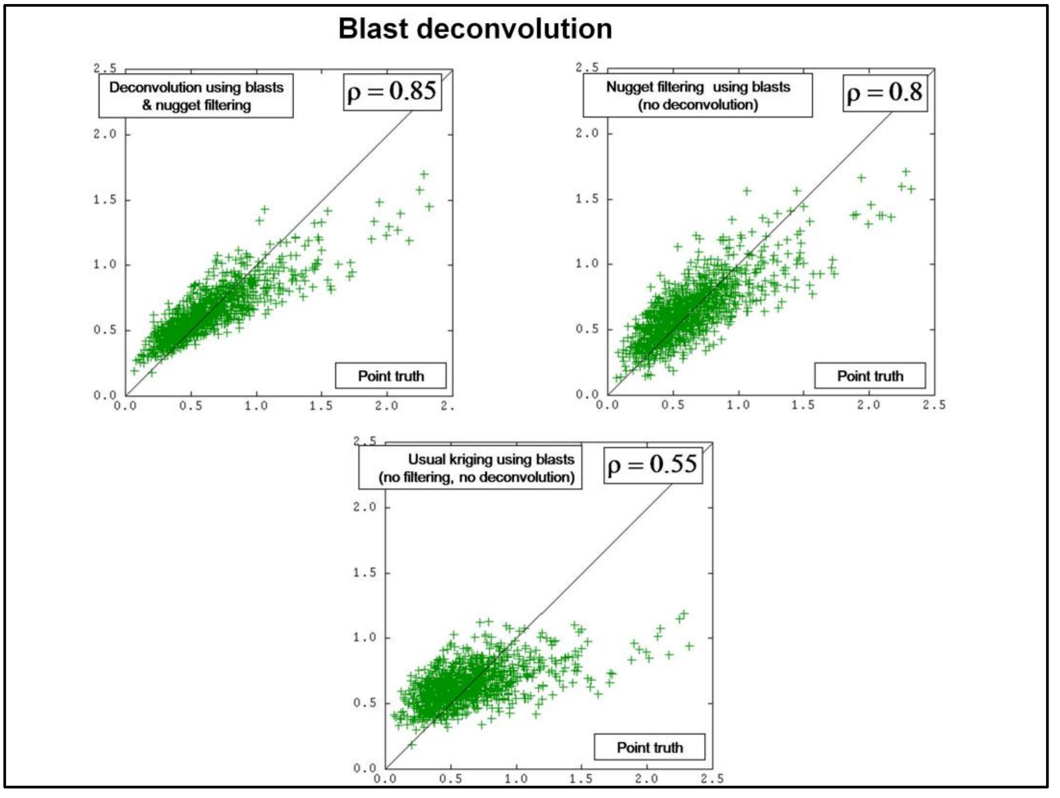
$$Y^*_{point}(u) = \sum_j \lambda_j Y_{blast}(u_j)$$

- Now we propose a second test

- It can be interesting to remove the effect of regularization on the blast with a kriging system that estimates, for each blast measurement, a “point” value, while simultaneously removing the part of the nugget effect associated with blast errors.

- The difference with the previous system is that in the second member of the system, the capital letter for “P” - a two-time convolution - is replaced by a small “p” – a one-time convolution

- A comparison is made with the true point value, and with previous estimates (estimating a blast with or without nugget effect).



➢ In the three scatter diagrams, the horizontal axis represents the true point-support value

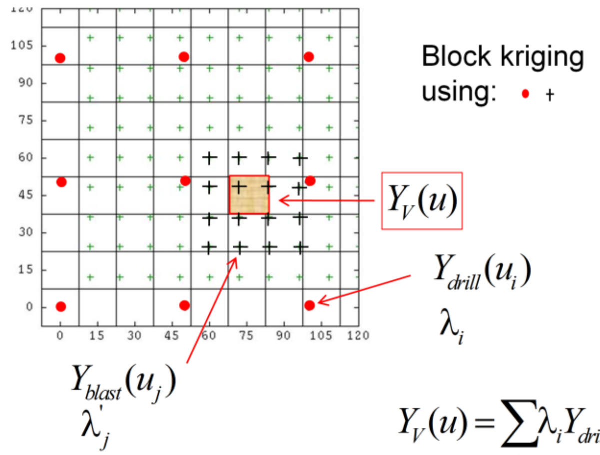
➢ The upper left scatter figure presents the result when a deconvolution is made, together with error filtering. The correlation with the true value is good, it equals 0.85

➢ The upper right-hand figure presents the result of the error removal with no deconvolution. It corresponds to the previously presented system but this time as compared with the point support value, the reason why the correlation equals 0.8 and not 0.9 when compared to the blast values. In comparison with the left-hand figure, the deconvolution increases significantly the accuracy of the estimation

➢ The bottom figure shows the results when no filtering and no deconvolution isdone. The correlation is very low, it equals 0.55. The reason is the same as in the previous case. Filtering and/or deconvolution can use the target points where the filter is applied

3 Cokriging using blasts and drills

$$\begin{pmatrix} C * \mathcal{P}_{3m} & C * p_{3m} * p_{15m} & 1 \\ C * p_{15m} * p_{3m} & C * \mathcal{P}_{15m} + C_R \delta(0) & 1 \\ 1 & 1 & 0 \end{pmatrix} \begin{pmatrix} \lambda \\ \lambda' \\ \mu \end{pmatrix} = \begin{pmatrix} C * p_{3m} * p_V \\ C * p_{15m} * p_V \\ 1 \end{pmatrix}$$



$$Y_V(u) = \sum_i \lambda_i Y_{drill}(u_i) + \sum_j \lambda'_j Y_{blast}(u_j)$$

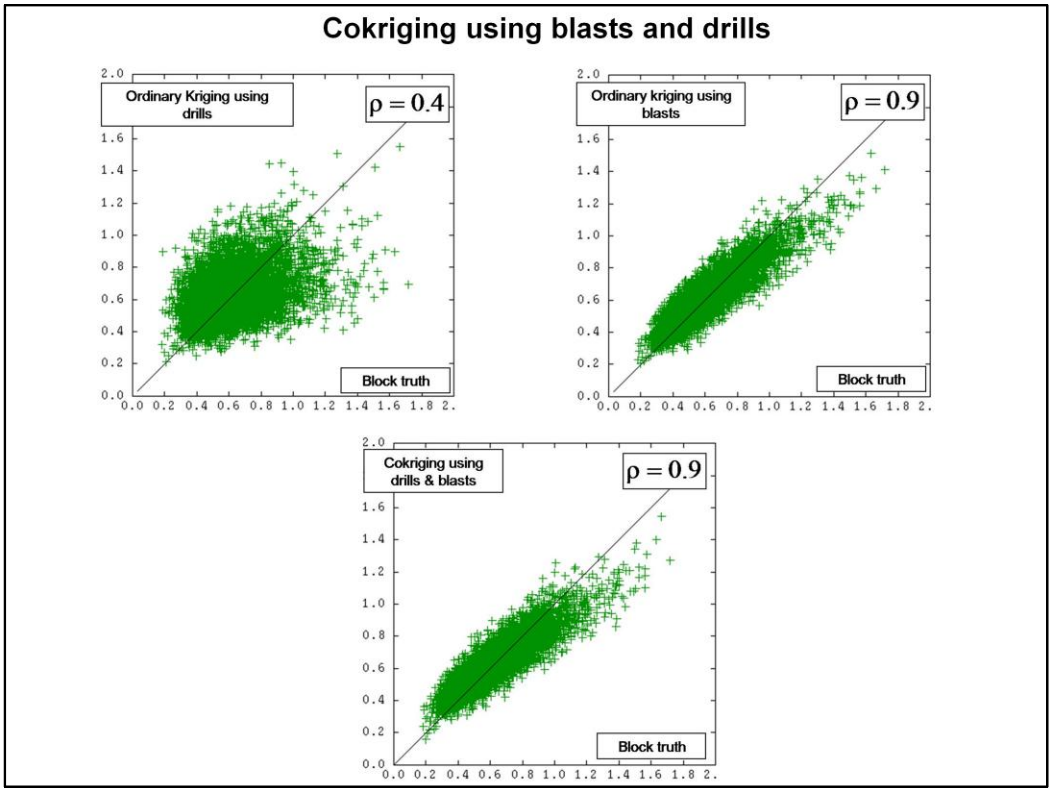
- The third test is made to locally renew the mine planning block model by using blasts and drills together

- In the figure, red points represent the drill samples, green crosses the blast samples. The final estimation is a combination of the two measurements.

- This is a cokriging system with linked mean because drills and blasts have the same average, which is mandatory for carrying out all these calculations

- The objective is estimating the average grade at the block scale V

- We compare with the other systems:
  - •Block grade estimate by kriging using only drill holes
  - •Block grade estimate by kriging using only blast holes

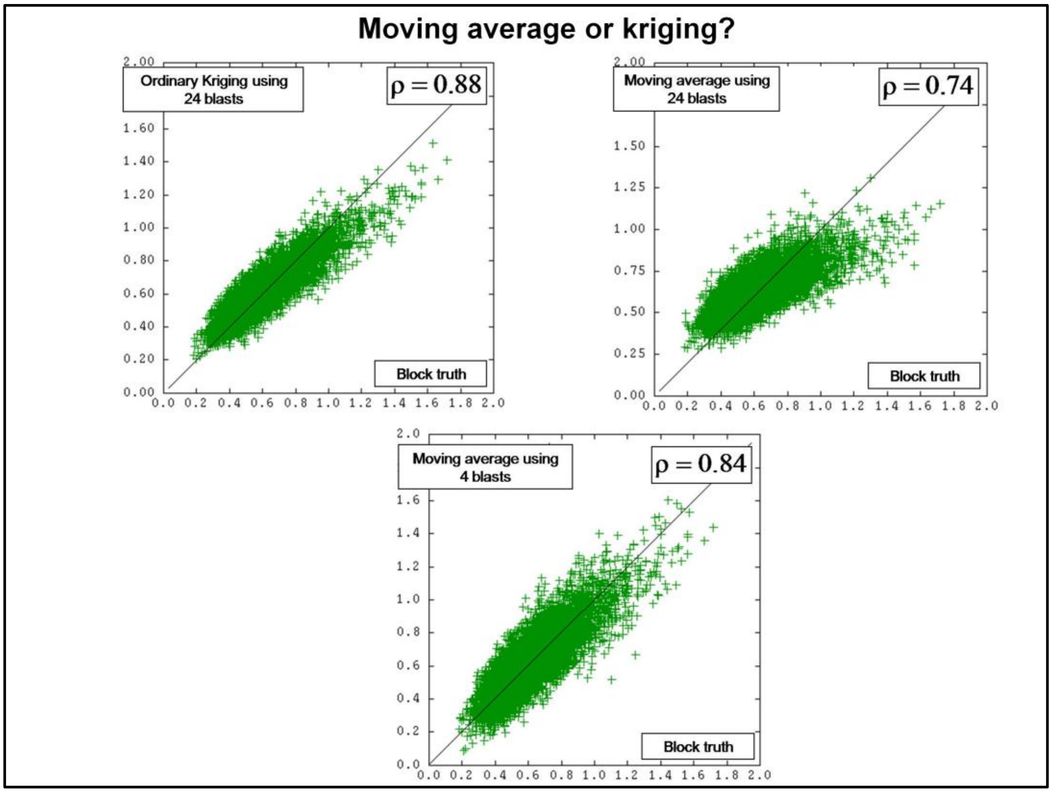


- ➢ Here are the results. For the three scatter diagrams, the horizontal axis is the true block grade

- ➢ The upper left diagram is the result obtained by ordinary kriging using drills; upper right diagram the result when using blasts. The jump by the correlation coefficient from 0.4 (OK using drills) to 0.9 (OK using blasts) is impressive . Even if the blasts are regularized over 15m, the fact that they are more numerous and respect the variogram (up to a nugget effect) justifies their use when possible, instead of the drills, and the use of the blasts in selection for mining operations

- ➢The bottom diagram concerns cokriging using blast and drill together. The performance is similar to Ordinary Kriging using only blasts. In our case cokriging is not useful because the blasts are so numerous and of such good quality that adding a drill contribution does not improve the results

- ➢Notice that the nugget effect of the blasts has no impact on the results because with a block estimate, the average of the variograms is obtained by a random sampling of the block which neutralizes the nugget effect.

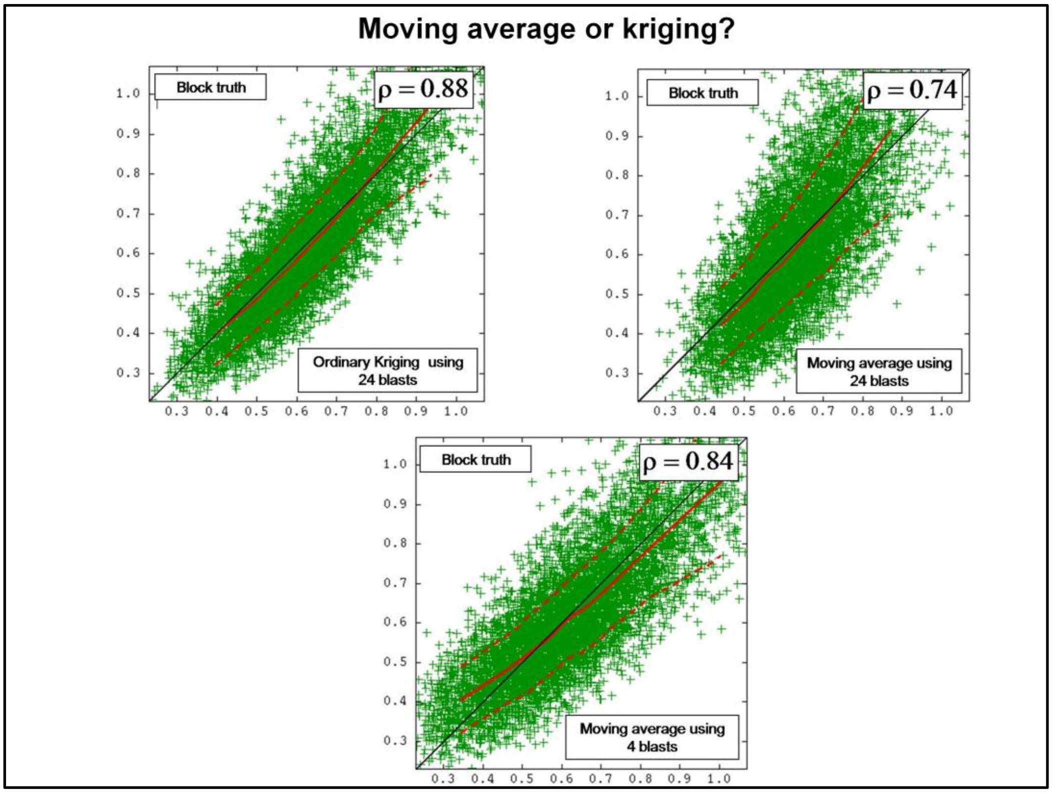


Actually, the short term planning is based on average using the blast included in the block, so question is asked to see if kriging can give some improvement. We are comparing three experiments:

- Ordinary Kriging using 24 surrounding blasts measures (previous work);
- Moving average using the same 24 surrounding blast measures;
- Moving average using 4 blast measures of the same level.

Using the same data points, replacing Ordinary kriging by an average reduces the correlation with the truth from 0.884 to 0.741. This is a very important reduction which should indicate the practitioners to use kriging.

Now, if practitioners want to keep their habits, one can see that when using only four points, the result is better that when using 24 points because the smoothing is less important: the correlation with the truth goes from 0.741 to 0.839, a performance still under the performance when using kriging.



But using so few points is risky for conditional bias reasons. To illustrate this concept, let us consider again the previous scatter diagram, but this time with the truth for the vertical axis and the curve of the mathematical expectation of the truth given different estimates. We focus on the most representative [0.3, 1] range of grades.

The red curves represent the discrete calculation of the conditional expectation of the truth, given the different estimates.

When doing kriging using 24 points , the conditional expectation curve is close to the first diagonal and when we select the block according to their estimates, we get in average what we expect, with perhaps a tiny tendency to underestimate the high grades.

When we replace kriging by a moving average using 24 points, we are still close to the diagonal, with a tiny tendency to overestimate the low grades and underestimate the high grades.

When we still do a moving average, but with only 4 points this time , the conditional bias appears clearly: in the range of the low grade, we systematically underestimate the average grade of the blocks and can decide to classify as waste blocks which are in practice richer than expected. Reversely, in the range of the high grades, this moving average with only 4 points systematically overestimates the average grade of the block so that we classify as rich blocks which must be considered as waste.

This is for all these reasons that one must use enough points in the kriging neighborhood (let us say at least 20), and reason why kriging and Geostatistics have been created, more than 50 years ago. It is perhaps useful to recall it here.

Conclusion

- Blasts, not so bad
- Drills, not so good
- Coherency between both
- Many linear methods (Error filtering, deconvolution…)
- Blasts sampling density → Cokriging not useful

The study of a porphyry copper deposit showed a formal link between blast and drill holes, leading to numerous linear systems able at least to:

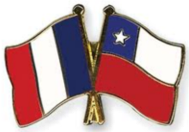
- Filter the blast error
- Blast deconvolution
- Block modelling using blasts & drills

Tested on a simulation, these systems has proven their interest, as well as the danger to replace kriging by a moving average, especially when using few points.

Acknowledgment

CODELCO
Produciendo Futuro
Codelco Chili

- Codelco



- Chile
- France

MINES ParisTech

- Paris School of Mines