A.A. 2021-2022

Corso di Laurea Magistrale in GEOSCIENZE

Metodi Elettromagnetici in Geofisica (6 CFU)
- MEMAG -

UD-1: Introduzione

Docente: Emanuele Forte

Tel. 040/5582271-2274

e-mail: eforte@units.it

What is Geophysics?

"*Geophysics is the application of physical principles and methods to problems in Earth Sciences*"

and/or

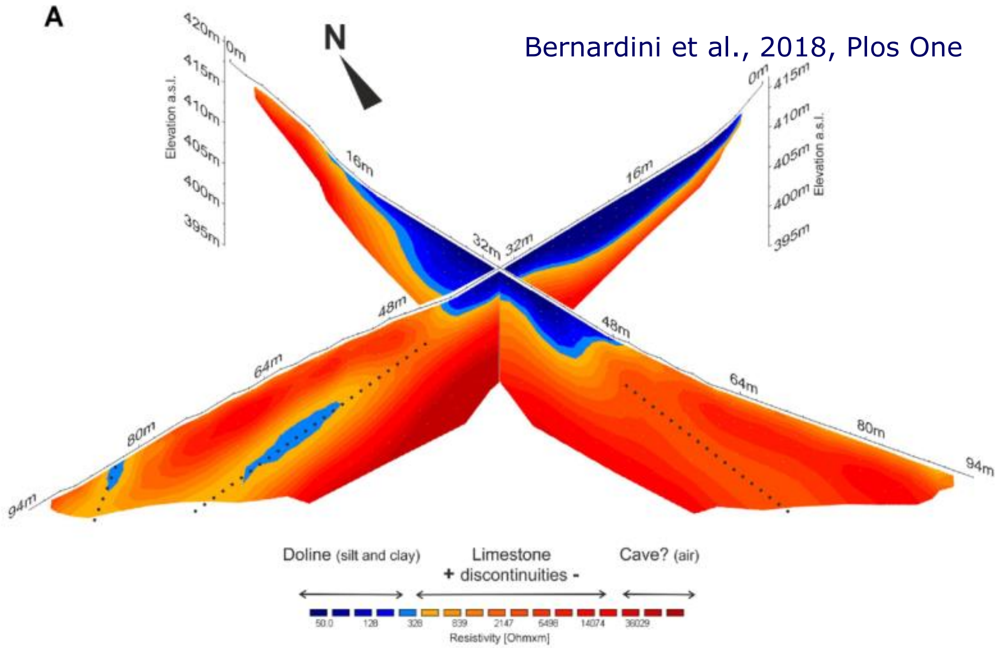
"*Geophysics is a branch of experimental physics dealing with the earth*" (SEG)

We describe "Methods" because Applied geophysics deals with **specific techniques and instruments** developed for different applications and based on peculiar **physical parameters (properties)** of the subsurface.

To select the **most appropriate geophysical method** to investigate a certain task/problem many integrated aspects need to be considered:

- What are the relevant ***physical parameters***? (density, EM velocity, electrical resistivity, …)
- What ***spatial scales*** are relevant?
- What about the achievable **resolution** (i.e. level of detail)
- What are the ***field conditions*** *and* ***noise*** *level*? (e.g. urban, offshore, …)
- Which ***acquisition geometries*** are optimal? (e.g. 1D vs 2D vs 3D)
- Is there useful ***a priori information***?
- Is there a ***cheaper*** alternative?
- …

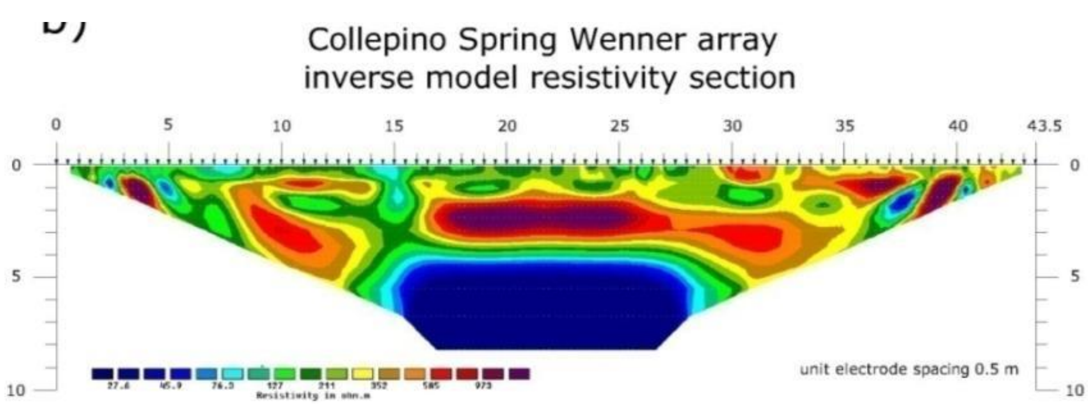
Unfortunately, the answer to these questions will depend strongly on the particular task/problem and it is strictly site-dependent!



Bernardini et al., 2018, Plos One

A detailed analysis is mandatory in order to asses the actual applicability of a method in a specific geological context.

Direct extrapolations can be very dangerous!



Ercoli et al., 2012, Journal of Applied Geophysics

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Why electromagnetic methods?

Rock & Mineral Resistivities

- Largest range of values for all physical properties.
- Native Silver = 1.6 x 10^{-8} Ohm-m (Least Resistive)
- Pure Sulphur = 10^{16} Ohm-m (Most Resistive)

Table 12.1 Resistivities of some rocks and minerals

Rocks, minerals, ores	Resistivity (ohm-m)
Sediments	
chalk	50–150*
clay	1–100
gravel	100–5000
limestone	50–10^7
marl	1–100
quartzite	10–10^8
shale	10–1000
sand	500–5000
sandstone	1–10^8
Igneous and metamorphic rocks	
basalt	10–10^7
gabbro	1000–10^6
granite	100–10^6
marble	100–10^8
schist	10–10^4
slate	100–10^7
Minerals and ores	
silver	1.6×10^{-8}
graphite, massive ore	10^{-4}–10^{-3}
galena (PbS)	10^{-3}–10^{2}
magnetite ore	1–10^5
sphalerite (ZnS)	10^3–10^6
pyrite	1×100
chalcopyrite	1×10^{-5}– 0.3
quartz	10^{10}–2×10^{14}
rock salt	10–10^{13}
Waters and effect of water and salt content	
pure water	1×10^6
natural waters	1–10^3
sea water	0.2
20% salt	5×10^{-2}
granite, 0% water	10^{10}
granite, 0.19% water	1×10^6
granite, 0.31% water	4×10^3

*Values or ranges, which have come from several sources, are only approximate.

Rock type	Resistivity (Ωm)
Clay and marl	1–67
Top soil	67–100
Clayey soil	100–133
Sandy soil	670–1,330
Limestone	67–1,000
Lignite	9–200
Sandstone	33–6,700
Sand and gravel	100–180
Schist	10–1,000
Granite	25–1,500
Basalt	10^3–10^6
Quartzite	10^2–2×10^8
Surface water (in igneous rock)	30–500
Sea water	0.20
Saline water 3 %	0.15
Saline water 20 %	0.05
Groundwater (in igneous rock)	30–150

Telford et al., 1976

From a large **resistivity contrast**

➔ a **wide applicability**

Table 1.1 Geophysical methods and their main applications

Geophysical method	Chapter number	Dependent physical property	Applications (see key below) 1	2	3	4	5	6	7	8	9	10
Gravity	2	Density	P	P	s	s	s	s	!	!	s	!
Magnetic	3	Susceptibility	P	P	P	s	!	m	!	P	P	!
Seismic refraction	4,5	Elastic moduli; density	P	P	m	P	s	s	!	!	!	!
Seismic reflection	4,6	Elastic moduli; density	P	P	m	s	s	m	!	!	!	!
Resistivity	7	Resistivity	m	m	P	P	P	P	P	s	P	m
Spontaneous potential	8	Potential differences	!	!	P	m	P	m	m	m	!	!
Induced polarization	9	Resistivity; capacitance	m	m	P	m	s	m	m	m	m	m
Electromagnetic (EM)	10	Conductance; inductance	s	P	P	P	P	P	P	P	P	m
EM–VLF	11	Conductance; inductance	m	m	P	m	s	s	s	m	m	!
EM – ground penetrating radar	12	Permitivity; conductivity	!	!	m	P	P	P	s	P	P	P
Magneto-telluric	11	Resistivity	s	P	P	m	m	!	!	!	!	!

P = primary method; s = secondary method; m = may be used but not necessarily the best approach, or has not been developed for this application; (!) = unsuitable

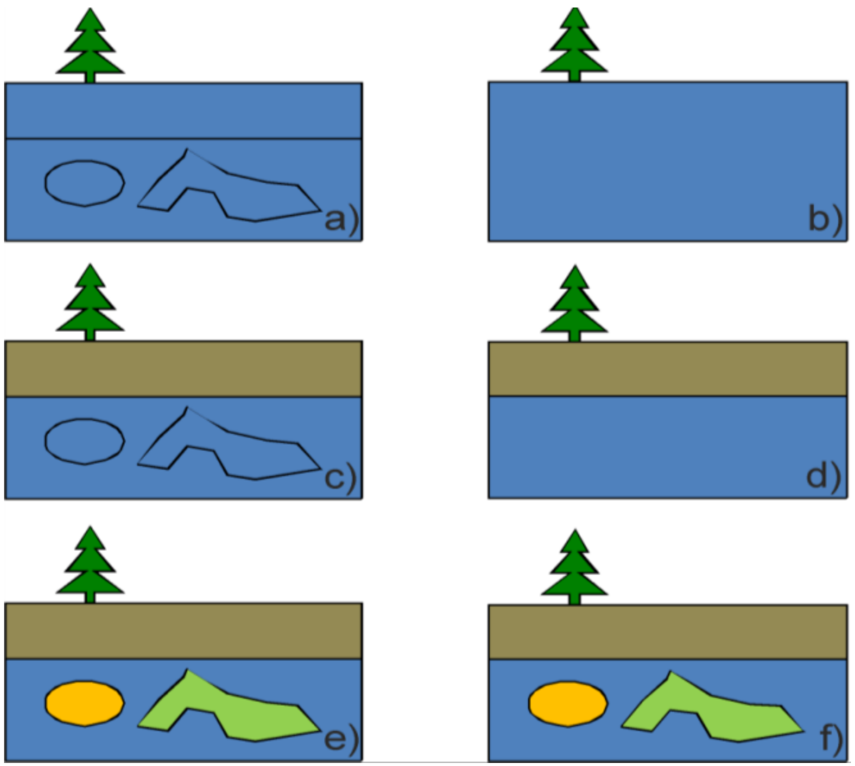
Applications
1 Hydrocarbon exploration (coal, gas, oil)
2 Regional geological studies (over areas of 100s of km^2)
3 Exploration/development of mineral deposits
4 Engineering site investigations
5 Hydrogeological investigations
6 Detection of sub-surface cavities
7 Mapping of leachate and contaminant plumes
8 Location and definition of buried metallic objects
9 Archaeogeophysics
10 Forensic geophysics

Telford et al., 2004

Is it a method suitable?

… It depends!

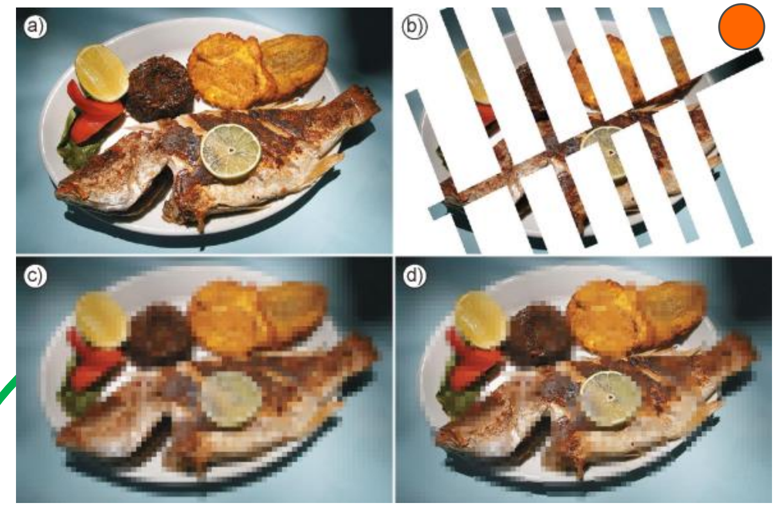
Physical Subsurface parameters | **Actual possible interpretation**



Forte, 2020

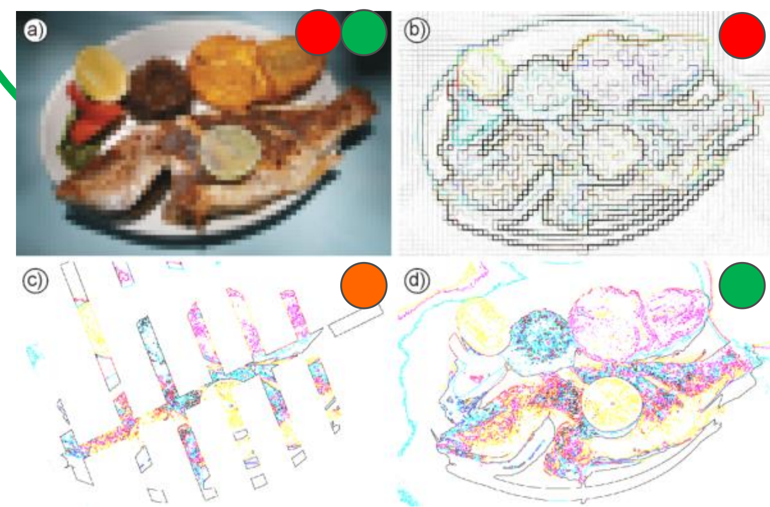
By the geophysical contrast (anomaly)

By data density, resolution, geometry



Modified from Vestrum and Gittins 2008

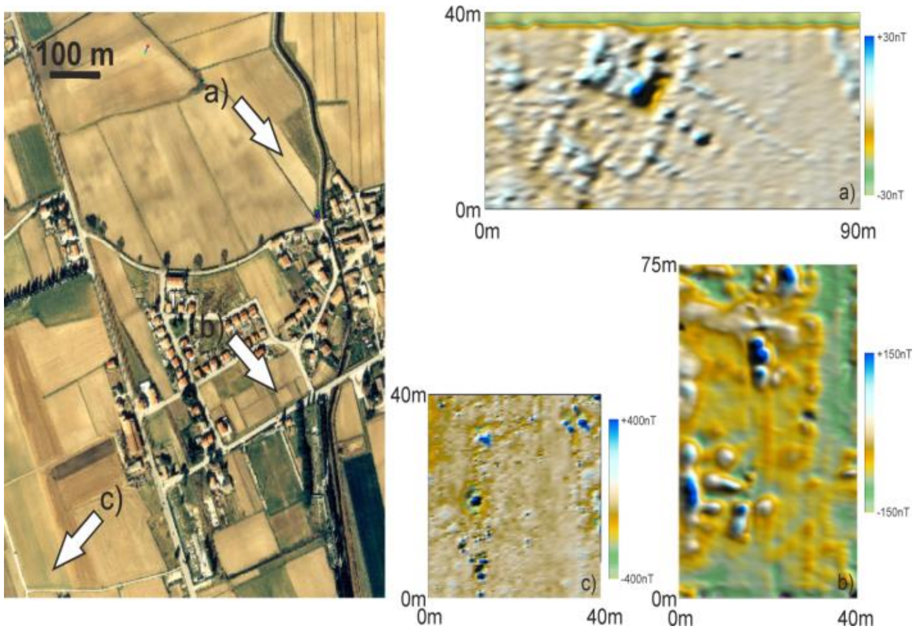
By the applied processing and its parameters



Modified from Vestrum and Gittins 2008
Forte, 2020

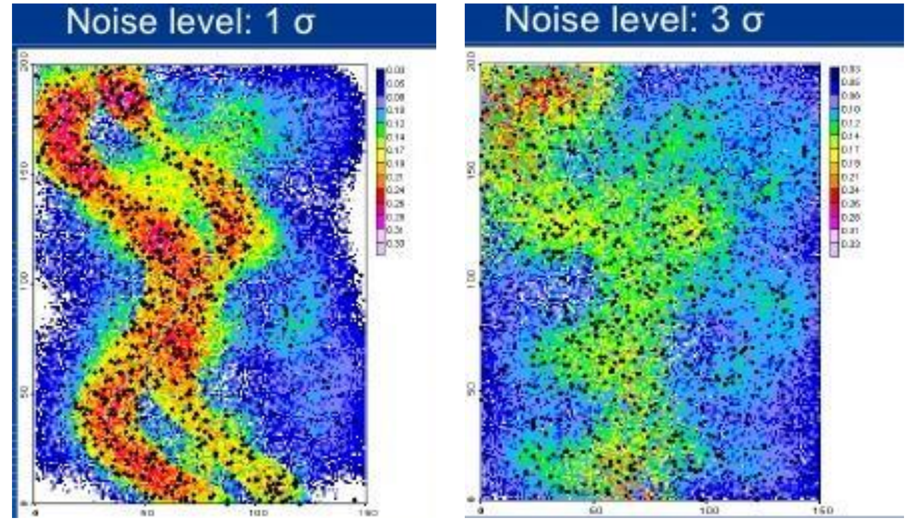
Is it a method suitable?

… It depends!

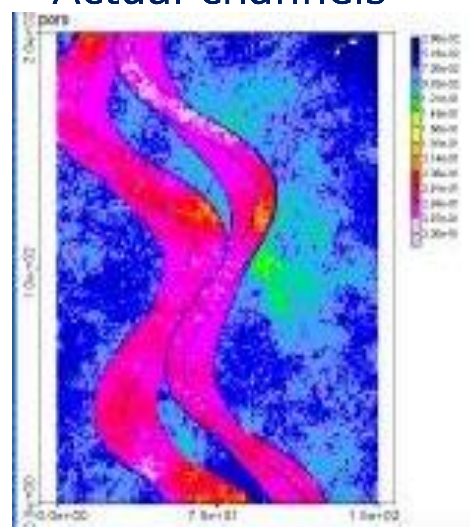


Forte, 2020

By the site characteristics/conditions



Actual channels

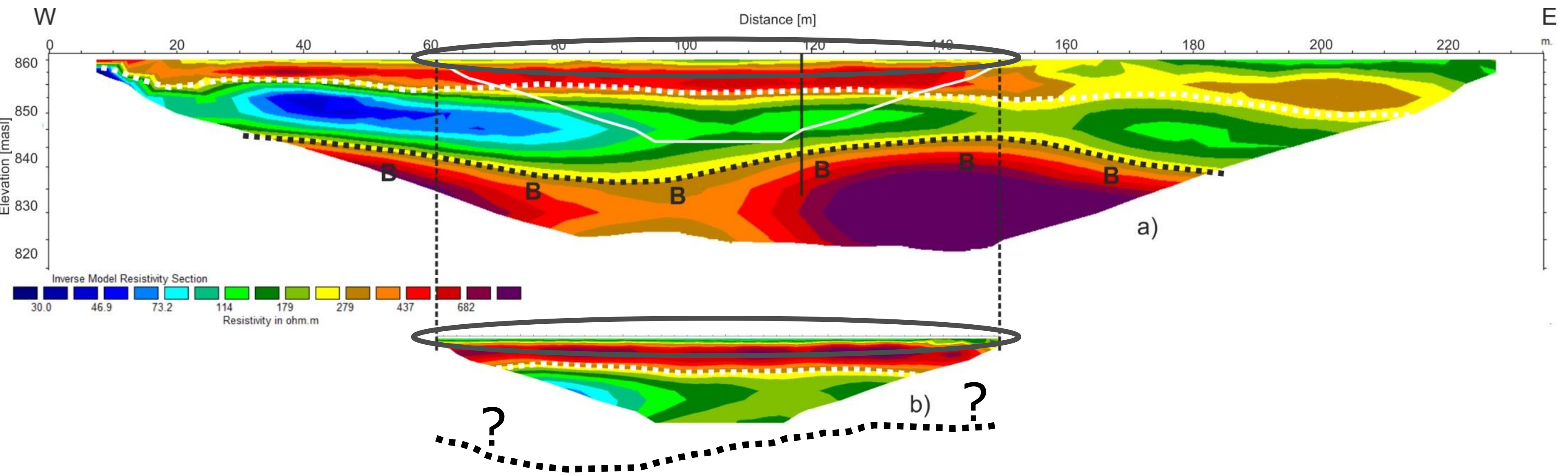


Signal to noise ratio (S/N)

Demyanov et al., 2018, Mathematical Geosciences

What about scales?

The same geophysical method can be adapted (up to a point) to different scales, but…

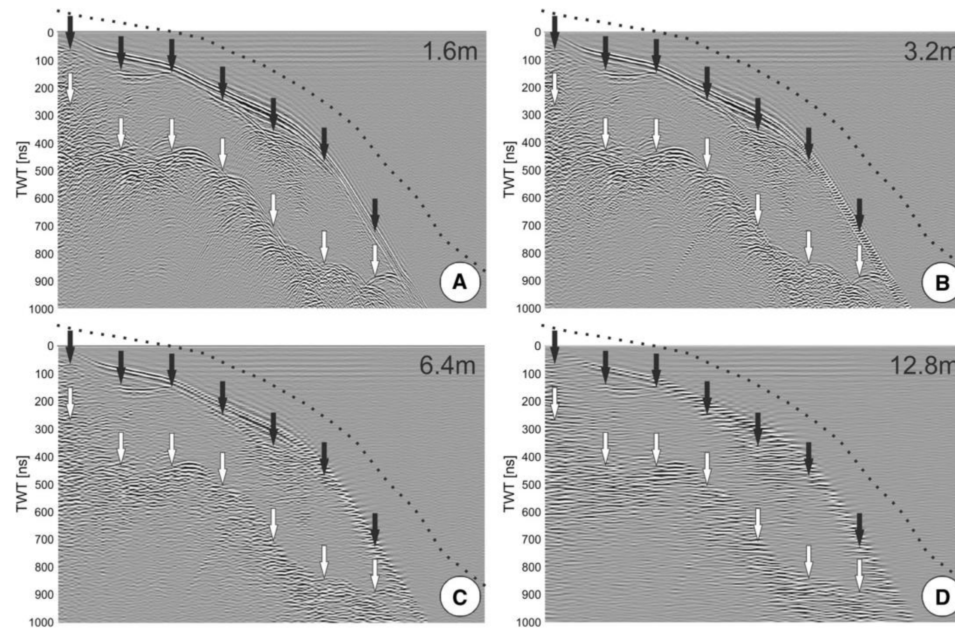


All the parameters of the experiments (i.e. of geophysical surveys) have to be tailored on the target:

For instance, just by increasing the number of measurements, we cannot assure an actual increasing of the resolution or imaging. Moreover, just by adopting a more sophisticated (… and longer, more expensive) algorithm, we cannot assure better results.

What about resolution?

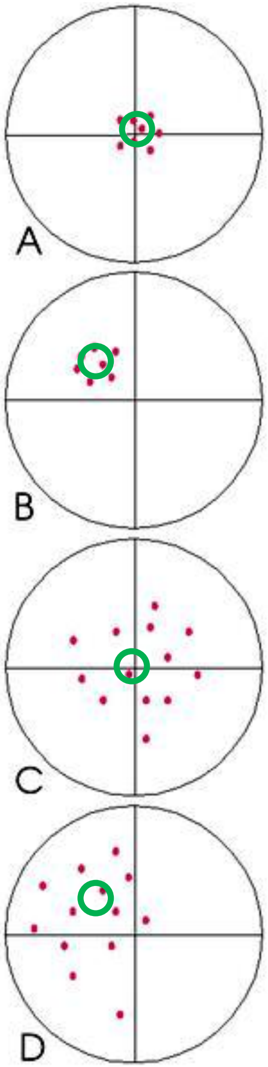
Keeping constant all the other parameters, **the resolution always decreases for increasing penetration depths (i.e. distance)!**



Forte et al., 2019

The same occurs when sampling (spatial and or temporal) and frequencies decrease

What about data **accuracy** and **precision**?



Precision: how close the measured values are to each other
➔ A,B more PRECISE than C,D.

Accuracy: how measurements are close to the true value
➔ A,C more PRECISE than B,D.

Precision and Accuracy depend by the instrument you are measuring with.
The precision is related to the repetiveness of a measure
The degree of accuracy is half a unit each side of the unit of measure

ATTENTION: When we measure something several times and all values are close, they may all be wrong if there is a Bias ➔ systematic coherent error/noise

MOREOVER: in geophysics often we don't know the true value ➔ How to estimate the data accuracy?

Errors and Noises

Lest men suspect your tale untrue,
keep probability in view, J. Gay

What is Noise?

*As geophysicists, the data at our disposal will always contain some features that we will not bother to explain. If we accepted our data as being absolutely precise and reproducible, then no model whose response disagreed with the observations even to the slightest degree could be correct. But **we don't believe that our data are exact and exactly reproducible**. And further, because we cannot calculate the exact response of our Earth models (because we cannot afford to put all the physics on the computer) and because we have only approximate models anyway (we cannot use an infinite number of parameters), there are likely to be deterministic aspects of the data that we cannot or do not want to explain.*

Scales and Snieder, 1998, Geophysics

Therefore, "NOISE" is the undesirable part of data that does not give any information. The information is instead often referred as "SIGNAL" or simply "DATA".
This concept is strictly related with the concept of measurement ERRORS, considering $\varepsilon = x - x_m$

Sometimes, in geophysics, some parts of the recorded SIGNAL are no longer used to obtain information of the subsurface and are thus considered as noise (e.g. spontaneous – self - electric potentials in active electrical methods or surface seismic waves – Ground roll – in reflection seismics).

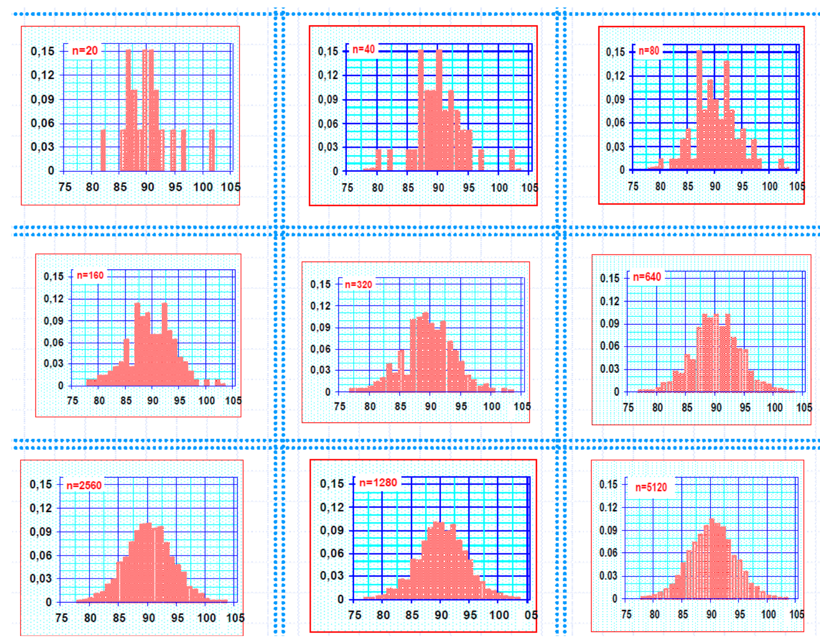
Errors and Noises

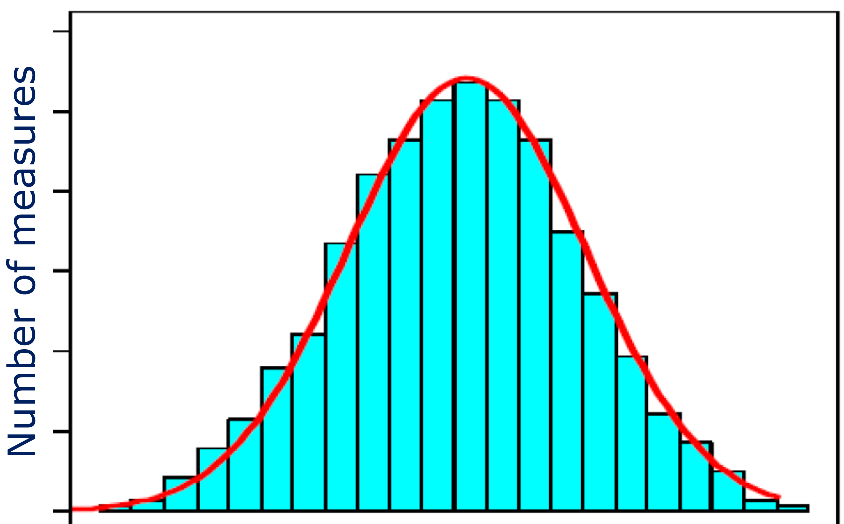
Random noises

Random (or incoherent) noises is due to not controllable and not unidirectional (i.e. with a null mean value) errors within a series of measurements. Such a noise is responsible of the variability of the measures around a mean value with constant experimental conditions.

Subg et al., 2015 - AEU

Sperimentally…





Often random noise has a "normal" (or Gaussian) distribution

Errors and Noises

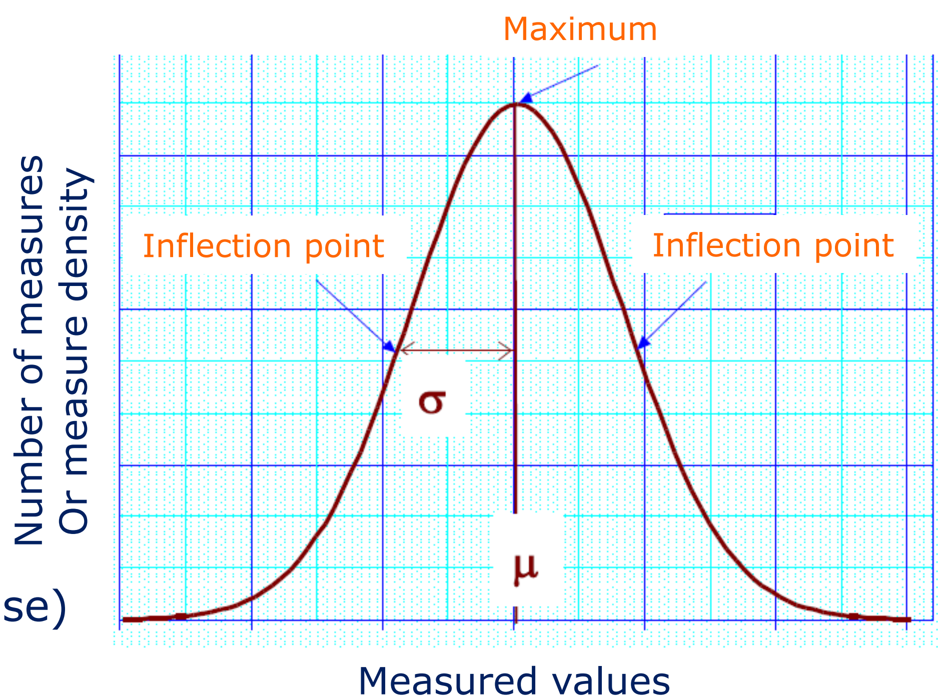
Random noises

Therefore if we consider a normal distribution of the errors we can made statistical calculations on it:

$$F(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$$

σ Is the **standard deviation**

μ Is the **mean** of all the measured values



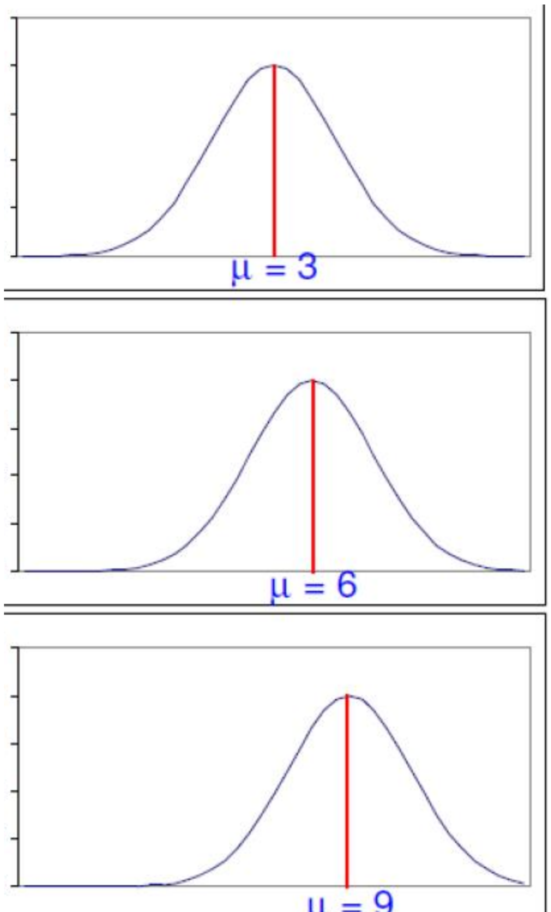
We remark that the random errors (or noise) $\epsilon = x - \mu$ have a behavior such that:

- Smaller errors are more frequent than large ones
- Positive and negative errors have (statistically) the same frequency.
- By increasing the total number of measurements the curve will be closer to the Gaussian function.

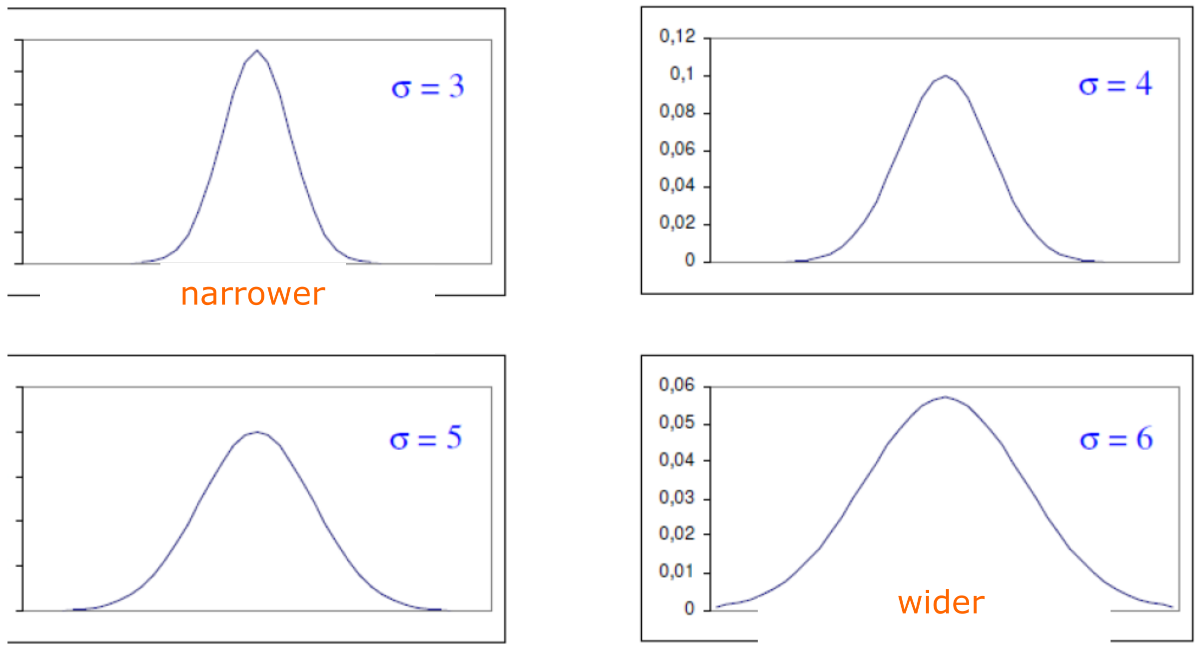
Errors and Noises

Random noises

Keeping σ constant



Keeping μ constant



Unfortunately, in geophysics, usually there are a few repeated measurements and this statistically approach is no longer applicable.
➔ So the **STACKING** strategy is often adopted.

Errors and Noises

Random noises

Simpler **stacking** is just the **arithmetic mean** of all the repeated measurements:

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i = \frac{x_{1+}x_{2+}\dots x_N}{N}$$

The deviation is the difference between the i-th measure and the mean:

$$d_i = \bar{x} - x_i$$

An estimate of the reliability (quality) of measurements is given by the **standard deviation**:

$$\sigma_x = \sqrt{\frac{1}{N}\sum_{i-1}^{N}(d_i)^2} = \sqrt{\frac{1}{N}\sum_{i-1}^{N}(x_i - \bar{x})^2}$$

Variance= $\sigma_x^2 = \frac{1}{N}\sum_{i-1}^{N}(d_i)^2$

By increasing the number of stacked values (N) it is possible to increase the Signal-to-Noise ratio (only if the noise is random!) by a factor:

$$S/N increment = \sqrt{N}$$

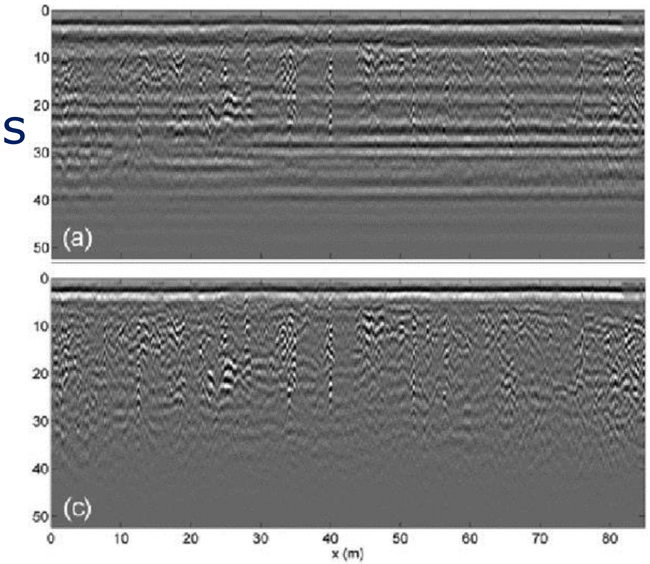
Weighted staking can give better results when Noise is somehow correlated. Weighting factor should be proportional to the signal amplitude divided by the noise variance σ^2

Errors and Noises

Coherent noise is any noise component which is somehow predictable and/or repetitive

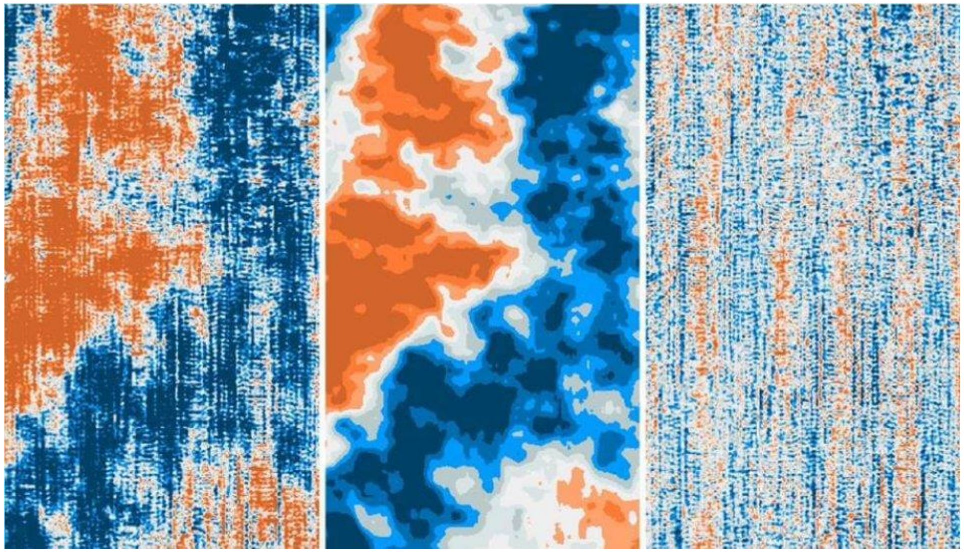
It can be coherent in terms of:

1) Time repetitiveness
2) Spatial and geometrical repetitiveness
3) Spectral repetitiveness
4) Magnitude and other attributes
5) Physical repetitiveness (e.g. due to a peculiar phenomenon)



Drahor et al., 2011

On the base of one or more of such criteria, coherent noises can be removed/attenuated

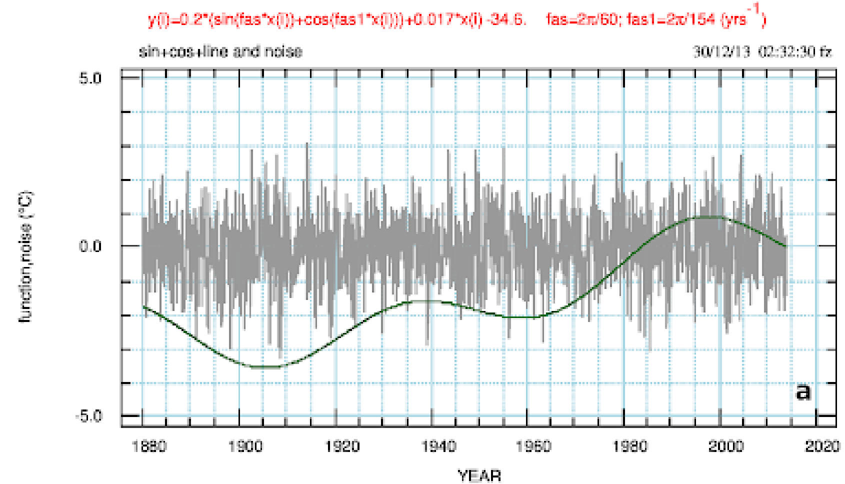


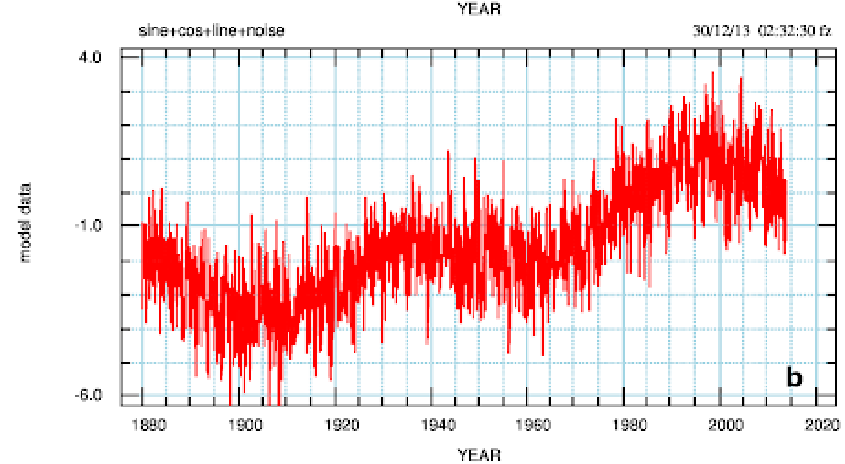
Original data Filtered data extracted C and R noise

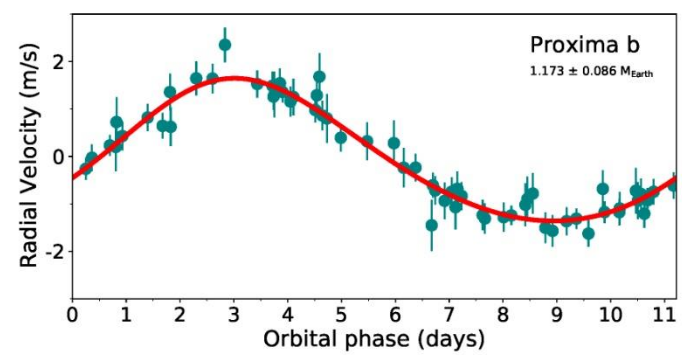
Errors and Noises

In geophysics very often more than the uncertainties of a measure the noise is crucial.

Stacking of data — the notion that averaging over repeated realizations of an experiment (stacking) reduces noise (compared to signal) presupposes that the noise in the different experiments is uncorrelated because only then do we get the desired noise-suppression. The criterion here is that: **the correlation in the noise is zero** for the different repeated measurements.



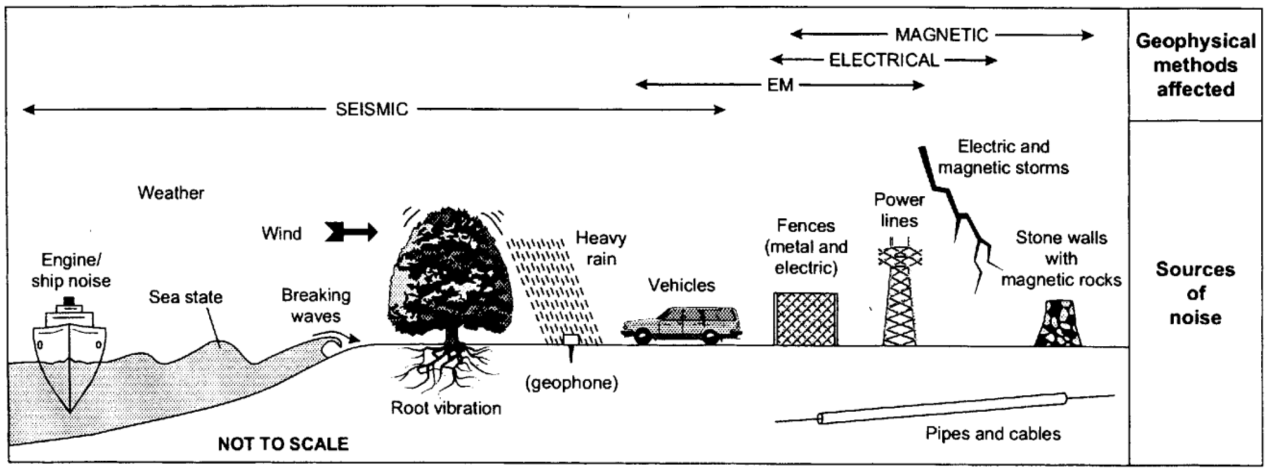




Unfortunately, not always noise is actually separable from the signal.
Moreover, often we cannot be sure which are actually the noise components within a “noisy” signal.

Errors and Noises

Noise types and characteristics depend by the geophysical method applied, i.e. by the physical parameters sampled.



Reynolds, 2011

Figure 1.10 Schematic illustrating some common sources of geophysical noise

Keep in mind that:

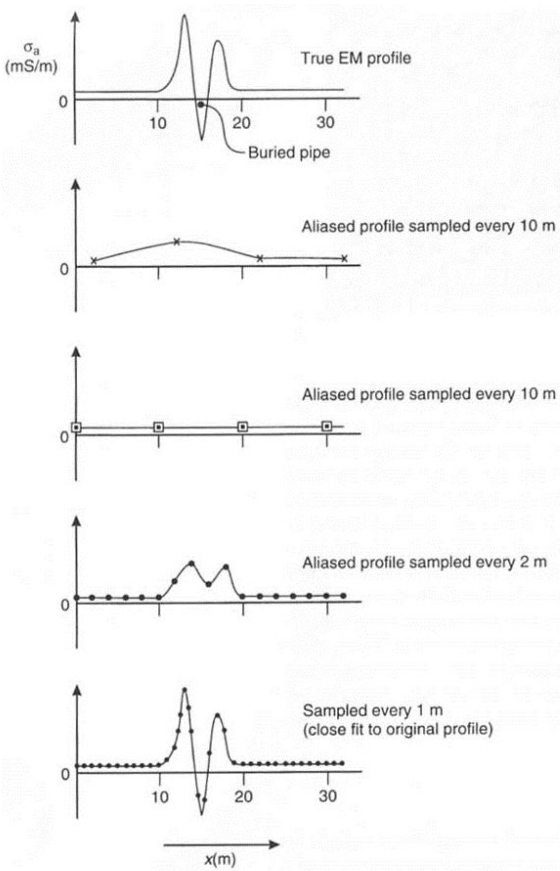
1) N(x,y,z,t,…)
2) There are "natural" noises and other due to human activities
3) Noises can be caused by the measure equipment
4) Noises can be inserted in the dataset during processing/inversion steps

Special types of "noises" are:

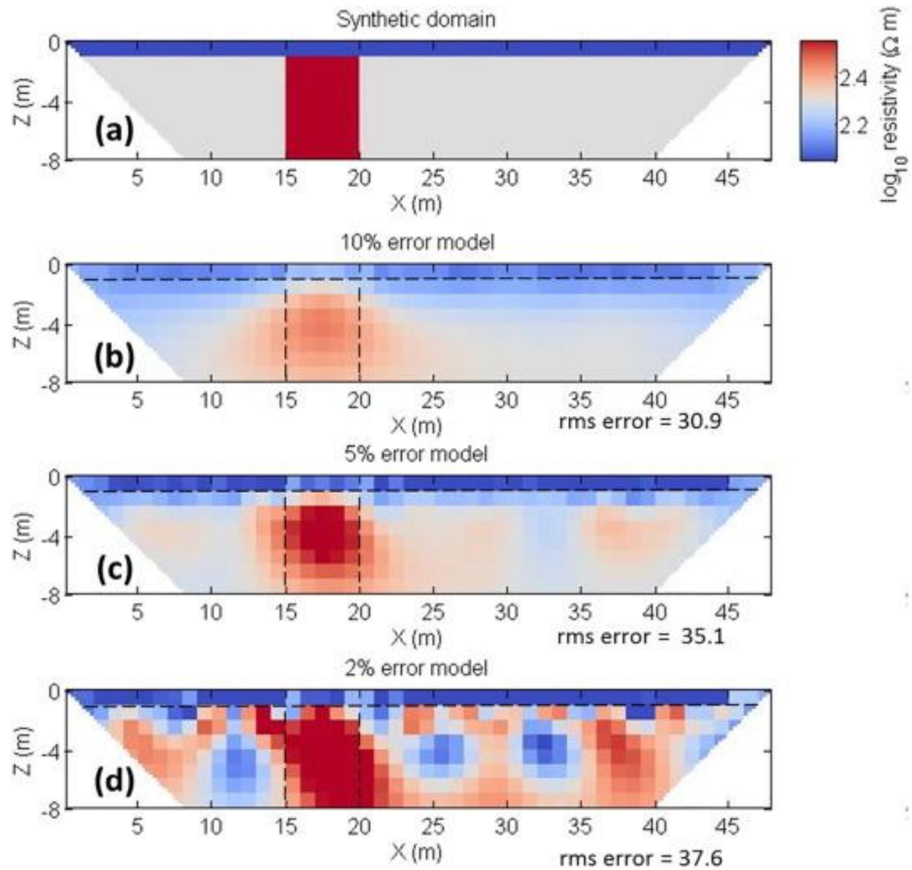
- *Interference (i.e. interaction between different signals or between signal with noise)*
- *Bias (related to direct current – DC – component shifting the signal)*
- *Clutter (related to unwanted echoes especially in GPR systems)*

Data sampling

How many samples? It depends by the objectives of the survey… and often is unpredictable!



Reynolds, 1997



Tso et al., 2017, J. of appl. geophysics

Data sampling

Geophysical data are always digitized, i.e. discretized during the acquisition process. Data exist only at fixed time and space discrete intervals $\Delta x, \Delta y, \Delta z, \Delta t$,… spaced by constant or variable values

Therefore, sampling is an irreversible process reducing analog signals, which contain an infinite number of values, into smaller and numerically manageable discrete series (Proakis and Manolakis 2006). However, such procedure causes an inevitable and unrecoverable loss of information between sampled values, which prevents the exact reconstruction of the input analog signal from the recorded discrete series and can cause significant signal distortions if the sampling is not properly set.

Sampling can be define as a function of time, space or other variables.

At the base there are the sampling theorems (Nyquist-Shannon):

Considering time sampling at constant Δt intervals and $T=n\Delta t$

The maximum frequency (a.k.a. Nyquist freq.) that can be correctly reproduced is equal to

$$f_{max} = f_N = \frac{1}{2\Delta t} = \frac{n}{2T}$$

The frequency resolution is equal to

$$\Delta f = \frac{1}{T} = \frac{1}{n\Delta t} = \frac{f_s}{n}$$

Where $f_s = \frac{1}{\Delta t}$

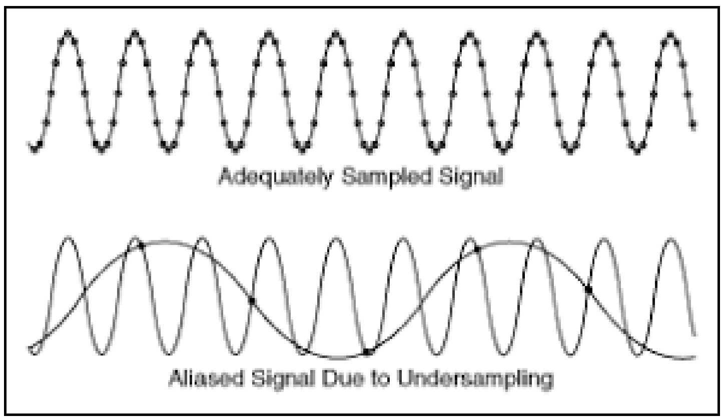
The minimum frequency that can be correctly reproduced is equal to

$$f_{min} = \frac{2}{n\Delta t} = \frac{2}{T}$$

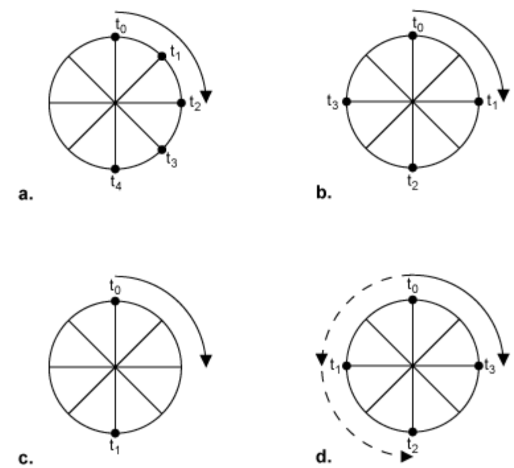
Data sampling

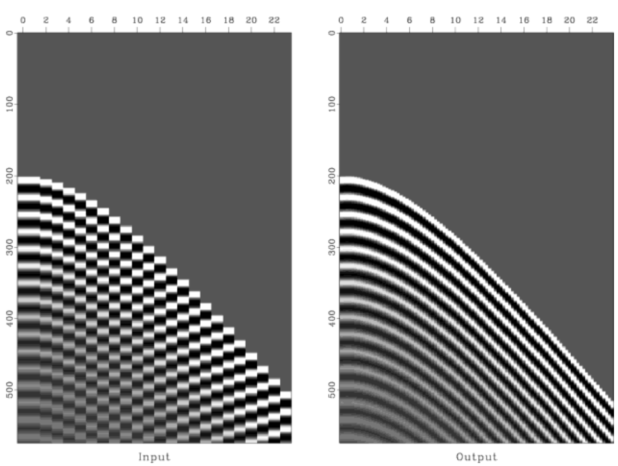
Outside from these limits spurious and erroneous information can arise ➔ **ALIASING**

Different types of aliasing can occur, related to frequency, space, kinematic or dynamic phenomena,…



1D aliasing





2D aliasing


Questions?