



**A.A. 2022-2023**

*Corso di Laurea Magistrale in GEOSCIENZE*

***Metodi Elettromagnetici in Geofisica (6 CFU)  
- MEMAG -***

**UD-1: Introduzione**

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# What is Geophysics?

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

and/or

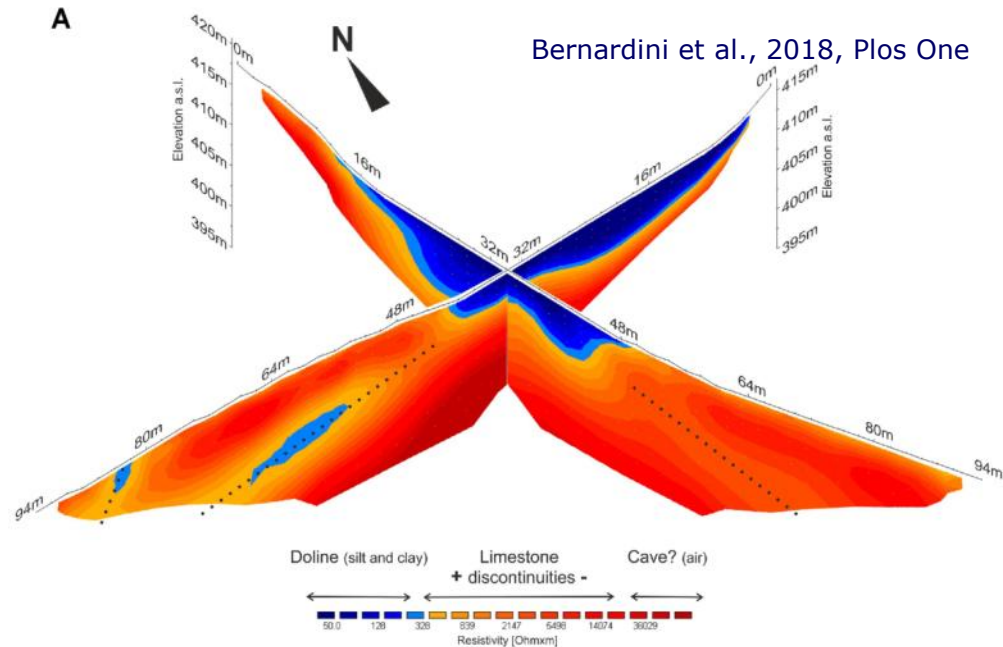
*"Geophysics is a branch of experimental physics dealing with the earth" (SEG)*

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:

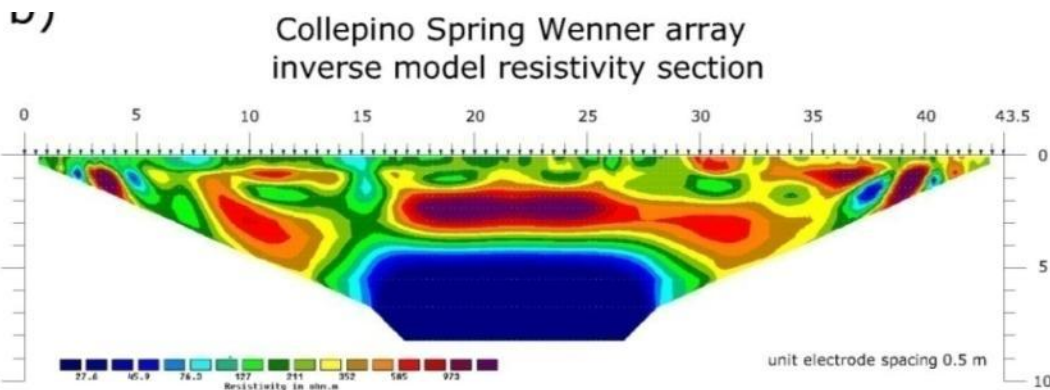
- What are the relevant **physical parameters**? (density, EM velocity, electrical resistivity, ...)
- What **spatial scales** are relevant?
- What about the achievable **resolution** (i.e. level of detail)
- What are the **field conditions and noise level**? (e.g. urban, offshore, ...)
- Which **acquisition 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!



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

Direct extrapolations can be very dangerous!



# Why electromagnetic methods?

## Rock & Mineral Resistivities

- Largest range of values for all physical properties.
- Native Silver =  $1.6 \times 10^{-8}$  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)
<i>Sediments</i>	
chalk	50-150*
clay	1-100
gravel	100-5000
limestone	50-10 <sup>7</sup>
marl	1-100
quartzite	10-10 <sup>8</sup>
shale	10-1000
sand	500-5000
sandstone	1-10 <sup>8</sup>
<i>Igneous and metamorphic rocks</i>	
basalt	10-10 <sup>7</sup>
gabbro	1000-10 <sup>6</sup>
granite	100-10 <sup>6</sup>
marble	100-10 <sup>8</sup>
schist	10-10 <sup>7</sup>
slate	100-10 <sup>7</sup>

*Minerals and ores*

silver	$1.6 \times 10^{-8}$
graphite, massive ore	$10^{-4}-10^{-3}$
galena (PbS)	$10^{-3}-10^2$
magnetite ore	1-10 <sup>5</sup>
sphalerite (ZnS)	$10^3-10^6$
pyrite	1 x 100
chalcocopyrite	$1 \times 10^{-5}-0.3$
quartz	$10^{10}-2 \times 10^{14}$
rock salt	$10-10^{13}$

*Waters and effect of water and salt content*

pure water	$1 \times 10^8$
natural waters	1-10 <sup>3</sup>
sea water	0.2
20% salt	$5 \times 10^{-2}$
granite, 0% water	$10^{10}$
granite, 0.19% water	$1 \times 10^6$
granite, 0.31% water	$4 \times 10^3$

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

Rock type	Resistivity ( $\Omega$ m)
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	$10^2-2 \times 10^8$
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
Gravimetry	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	Permittivity; 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<sup>2</sup>)
- 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

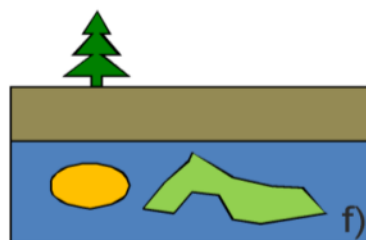
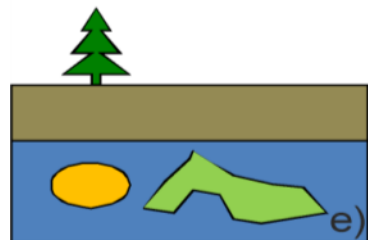
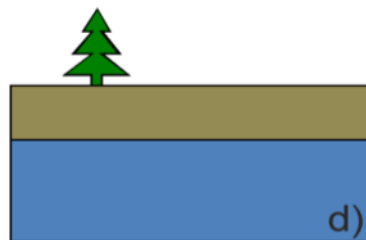
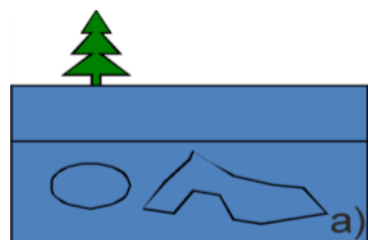
Telford et al., 2004

Is it a method suitable?

... It depends!

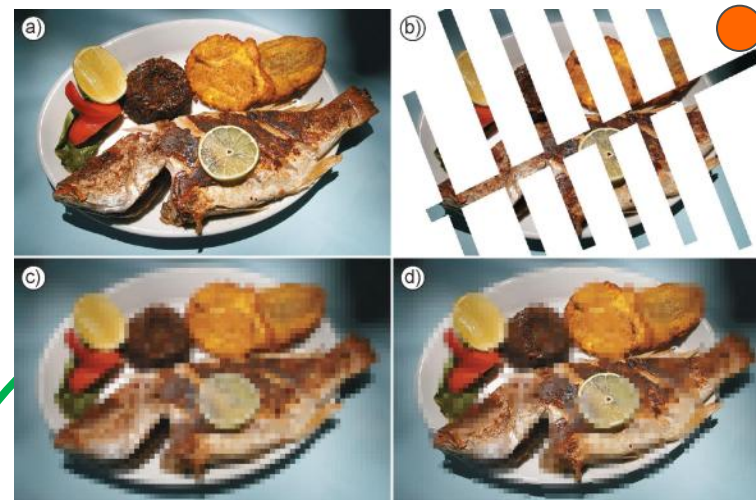
Physical  
Subsurface  
parameters

Actual possible  
interpretation



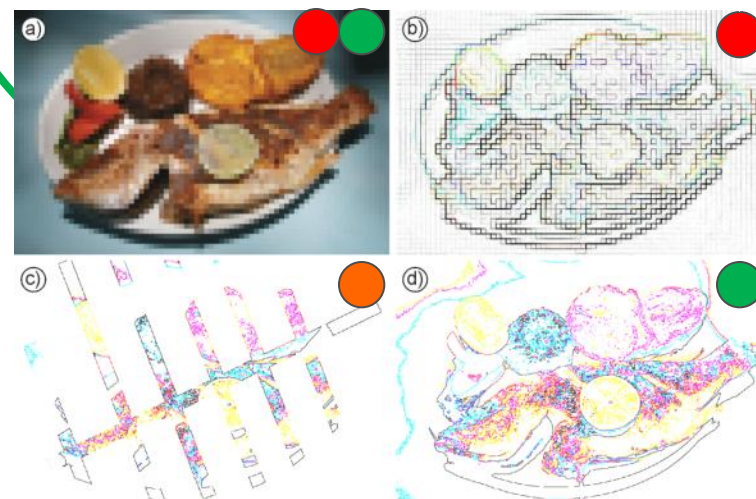
Forte, 2020

By data density, resolution, geometry



Modified from Vestrum and Gittins 2008

By the applied processing  
and its parameters



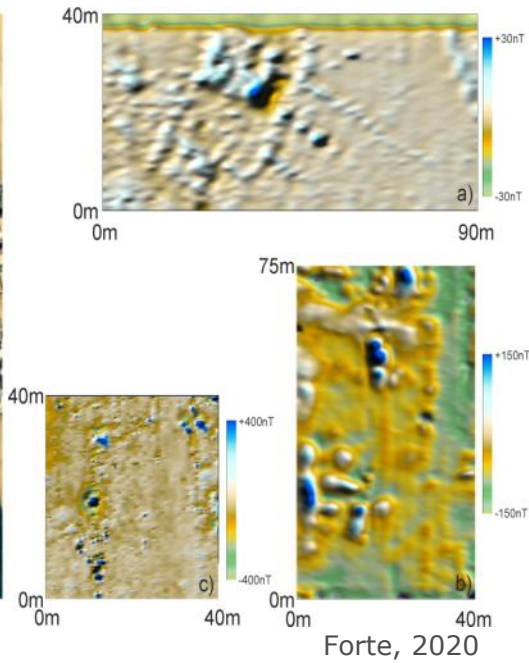
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Forte, 2020

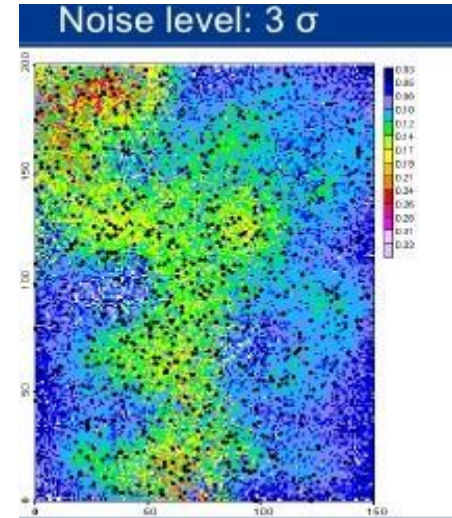
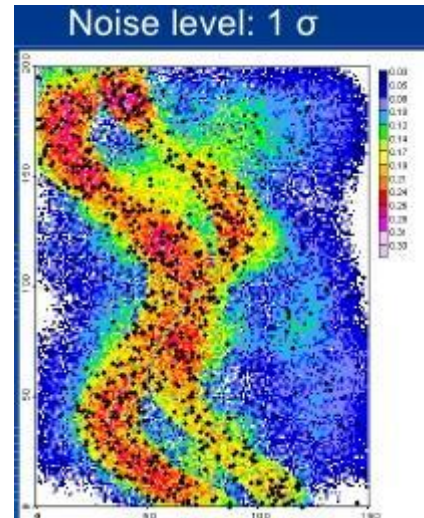
By the geophysical contrast (anomaly)



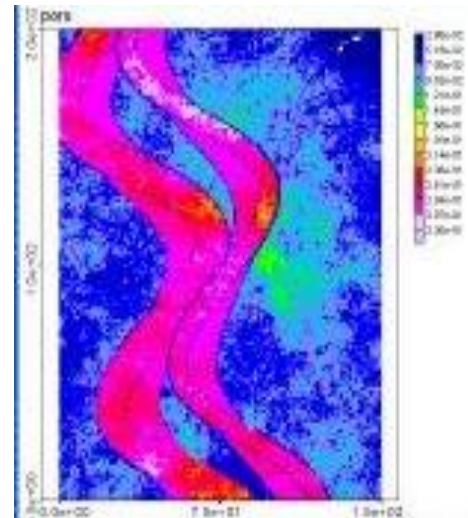
# Is it a method suitable? ... It depends!



Forte, 2020



## Actual channels



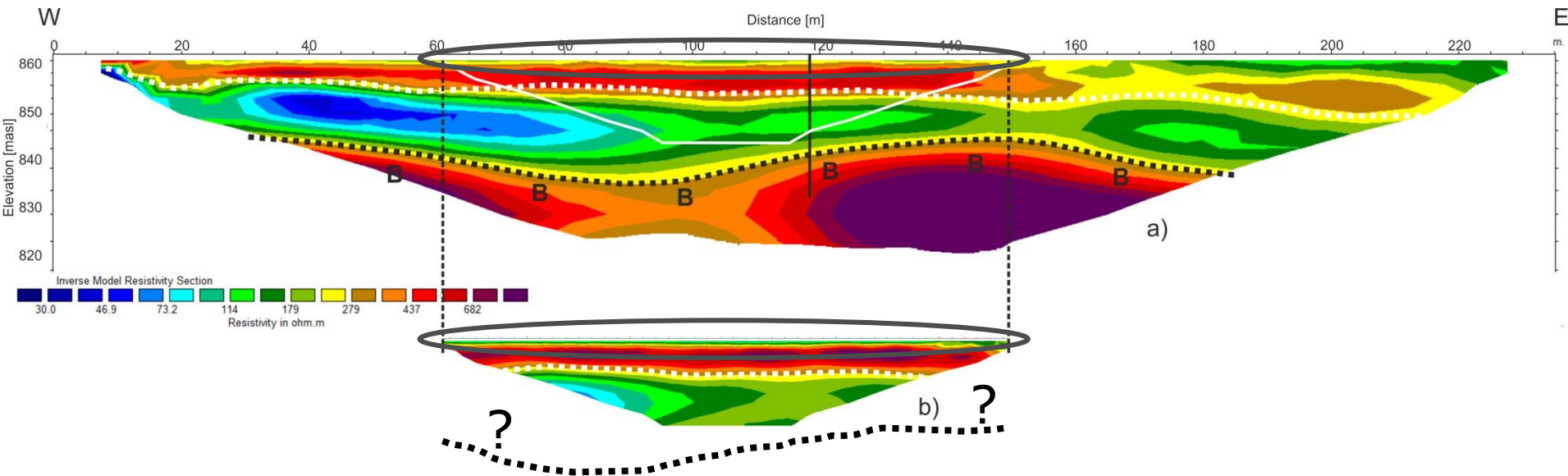
**Signal to noise ratio (S/N)**

**By the site characteristics/conditions**

Demyanov et al., 2018, Mathematical Geosciences

What about scales?

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



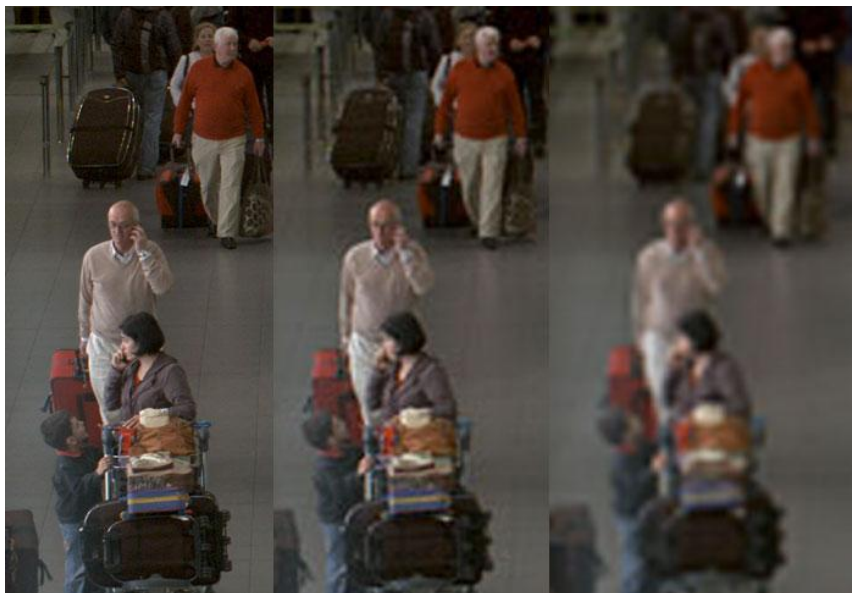
**All the parameters** of the experiments (i.e. of geophysical surveys) have to be tailored on the target:

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.

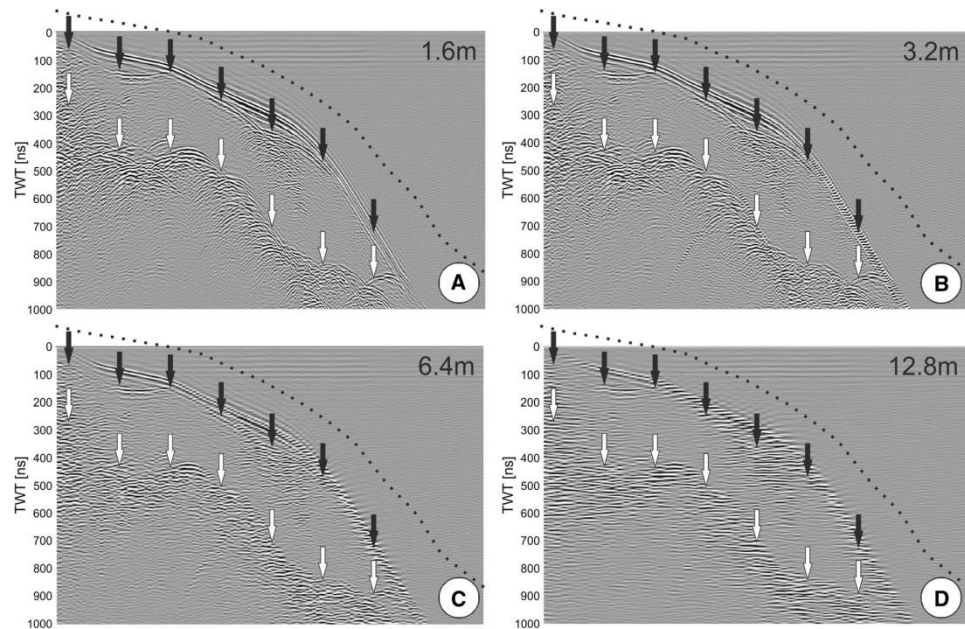


What about resolution?

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



DISTANCE

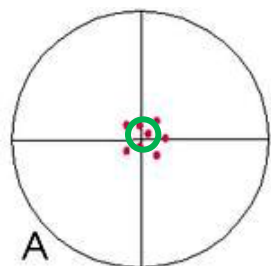


Forte et al., 2019

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

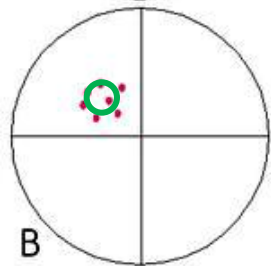


What about data **accuracy** and **precision**?



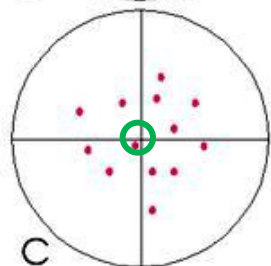
A

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



B

**Accuracy: how measurements are close to the true value**  
→ A,C more **ACCURATE** than B,D.

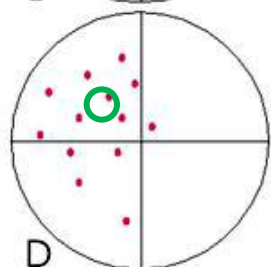


C

Precision and Accuracy depend by the instrument you are measuring with.

*The precision is related to the repetitiveness of a measure*

*The degree of accuracy is half a unit each side of the unit of measure*



D

**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).*

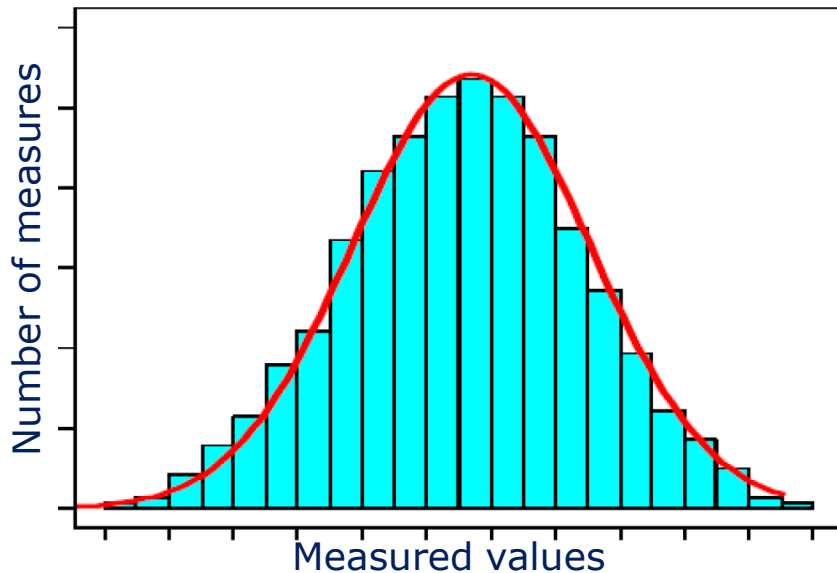
## Errors and Noises

### 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.

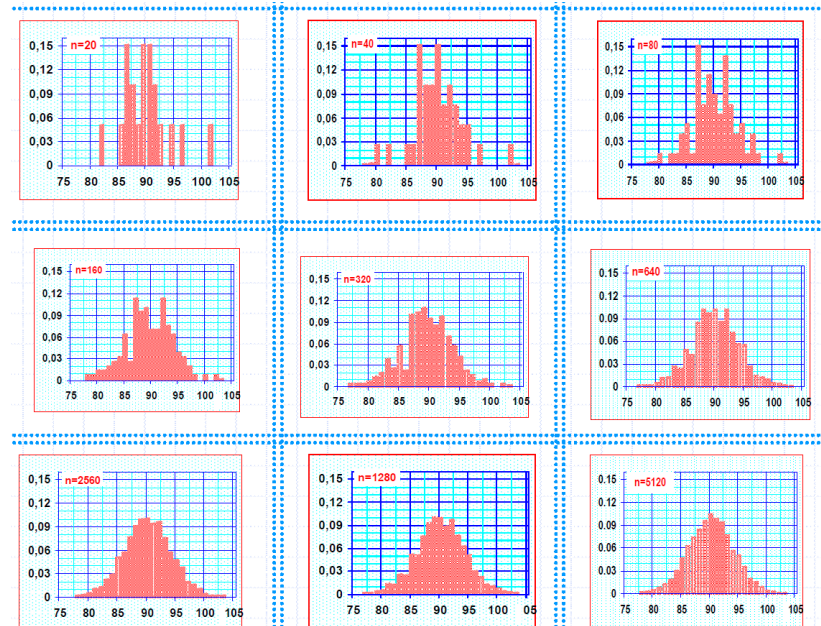


Subg et al., 2015 - AEU



Often random noise has a “normal” (or Gaussian) distribution

### Sperimentally...





## Errors and Noises

### Random noises

Therefore if we consider a normal distribution of the errors we can make statistical calculations on it e.g. the Gauss function:

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

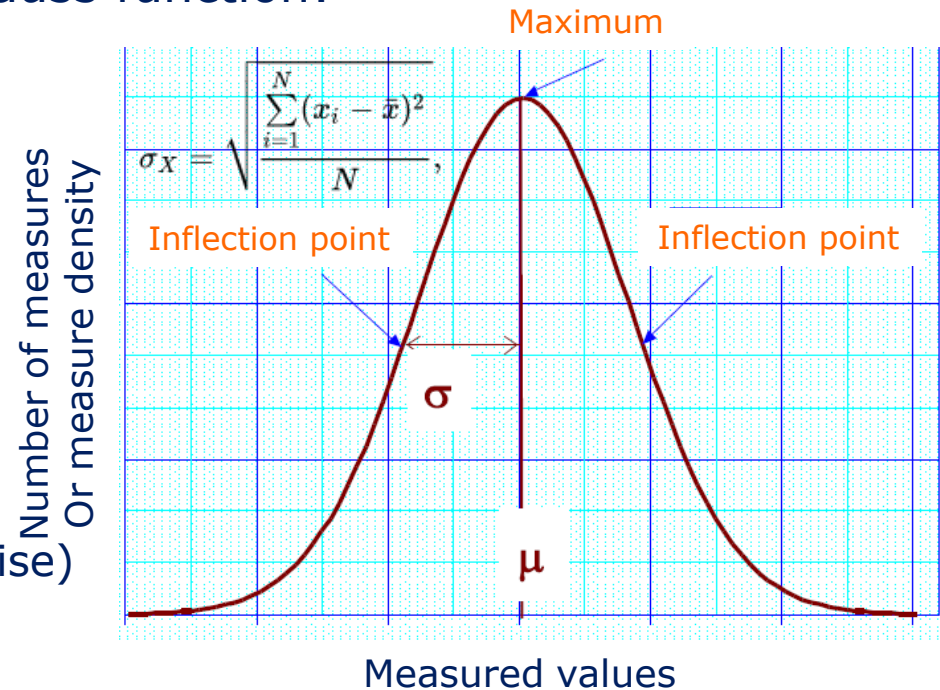
$\sigma$  Is the **standard deviation**

$\mu$  Is the **mean** of all the measured values

We remark that the random errors (or noise)

$\epsilon = x - \mu$  have a behavior such that:

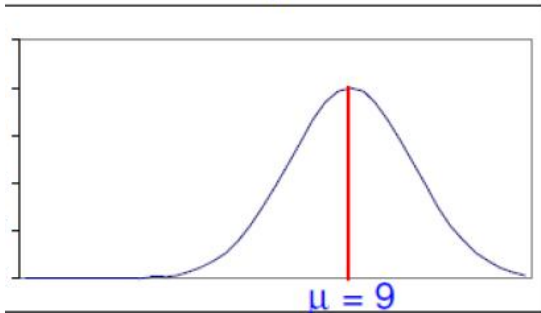
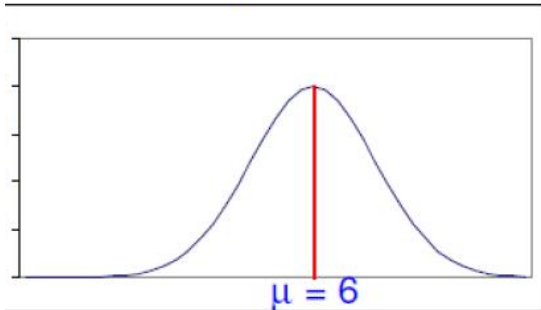
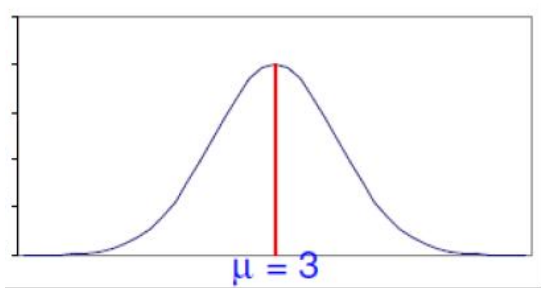
- Smaller errors are more frequent than large ones
- Positive and negative errors have (statistically) the same frequency.
- By increasing the total number of measurements the curve will be closer to the Gaussian function.



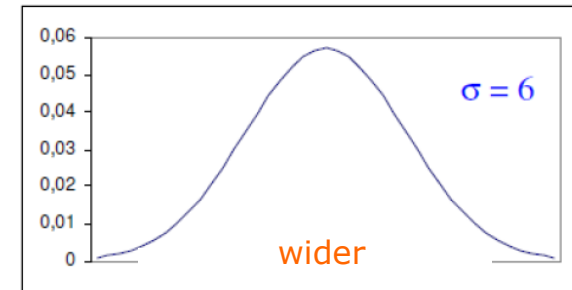
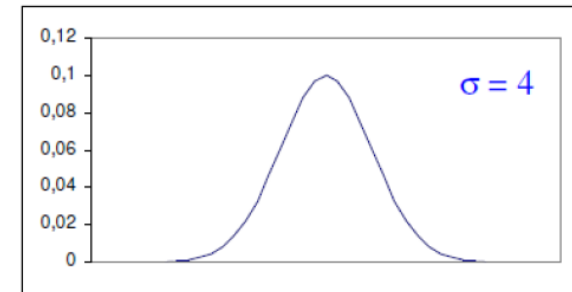
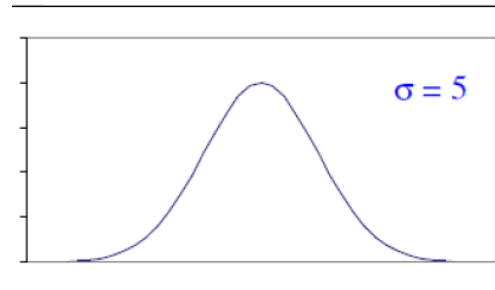
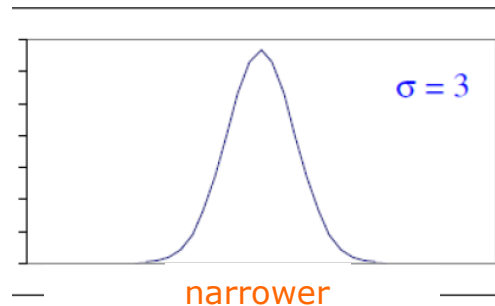
# Errors and Noises

## Random noises

Keeping  $\sigma$  constant



Keeping  $\mu$  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**:

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

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

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:

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

**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  $\sigma^2$



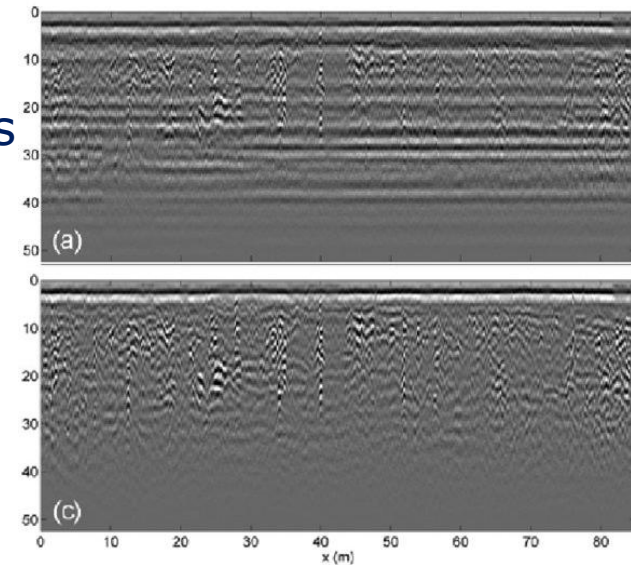
## Errors and Noises

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

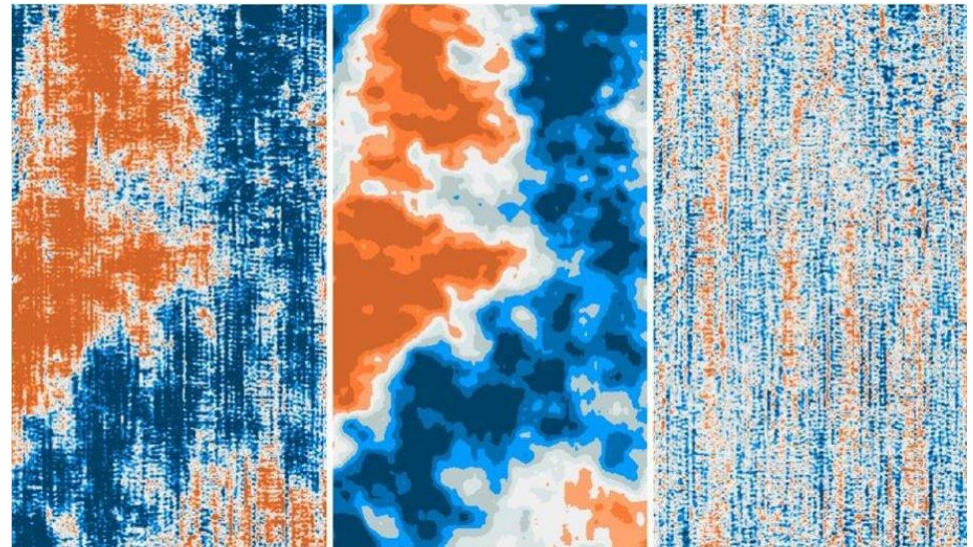
It can be coherent in terms of:

- 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)

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



Drahor et al., 2011



Original data

Filtered data extracted C and R noise

## Errors and Noises

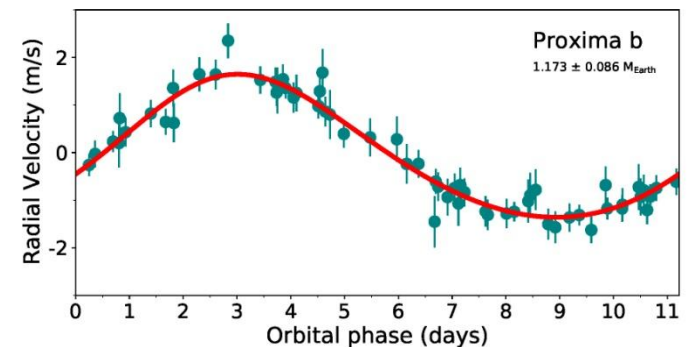
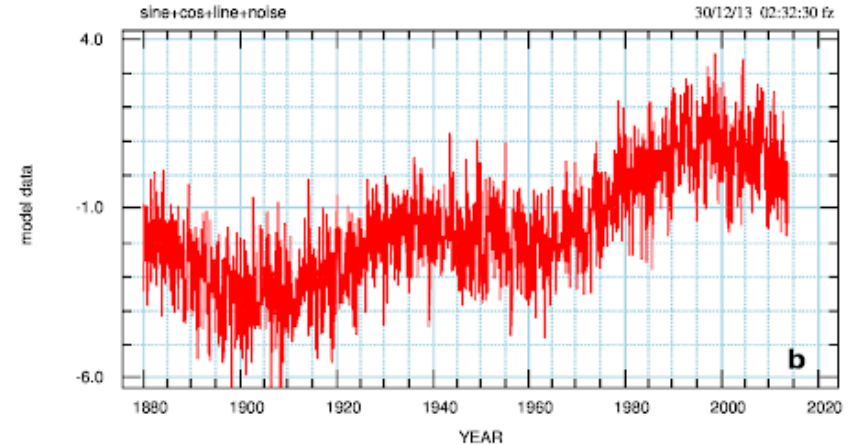
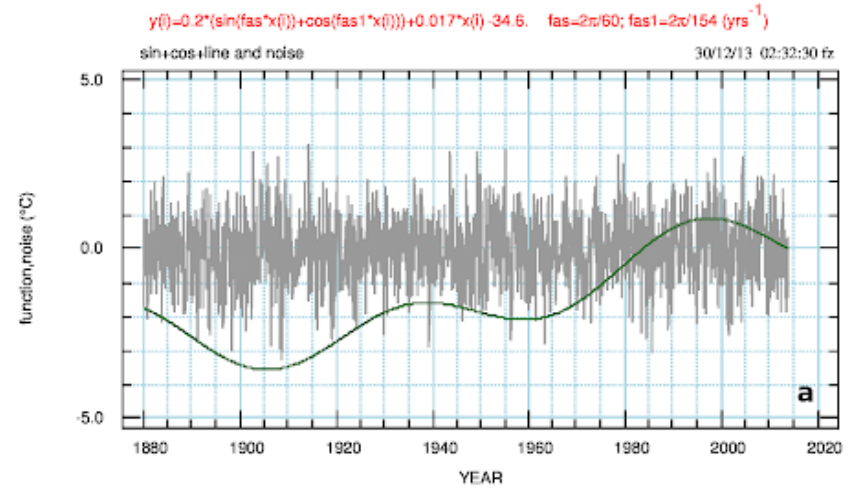
In geophysics very often more than the uncertainties of a measure the noise is crucial.

### 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.

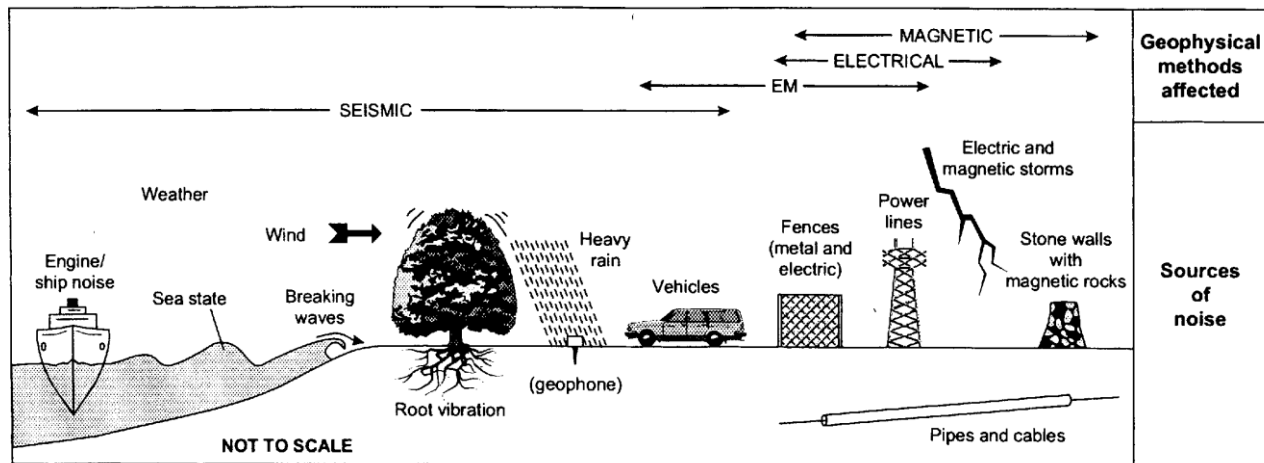
The criterion here is that:  
**the correlation in the noise is zero** for the different repeated measurements.

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.



Keep in mind that:

- 1)  $N(x, y, z, t, \dots)$
- 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)

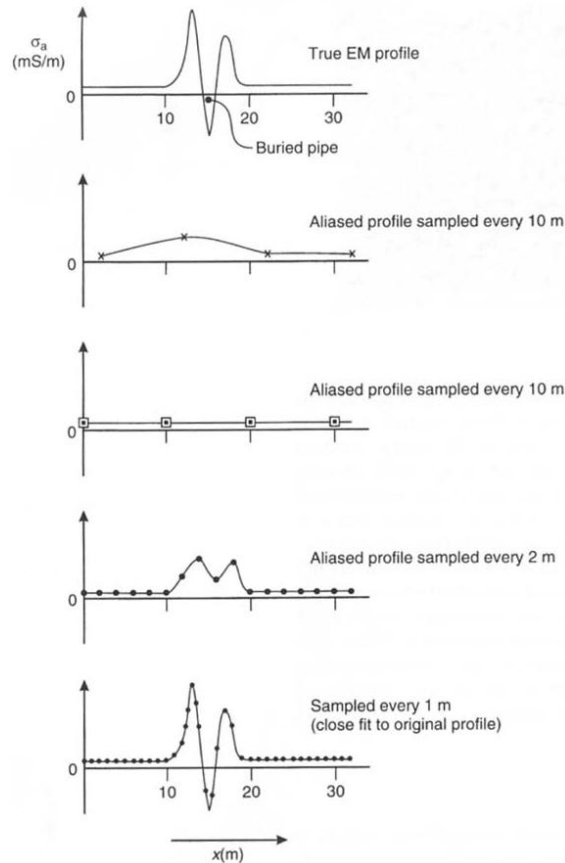
Reynolds, 2011

Figure 1.10 Schematic illustrating some common sources of geophysical noise

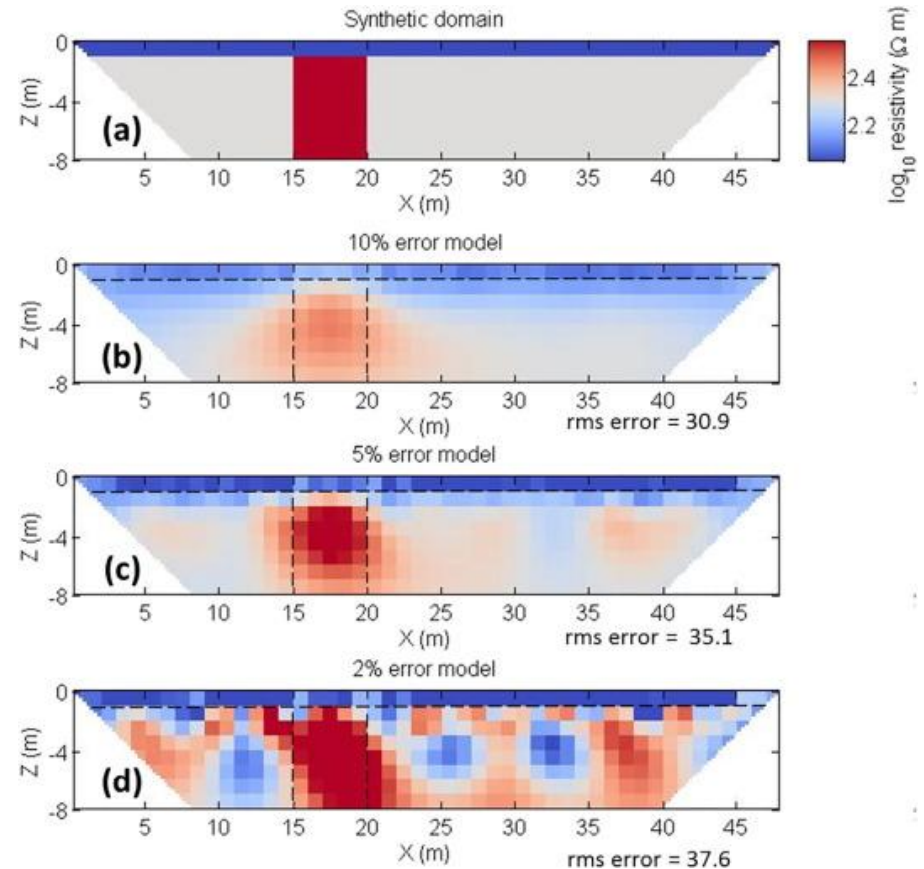


## Data sampling

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  $\Delta x, \Delta y, \Delta z, \Delta t, \dots$  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  $\Delta t$  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**  $f_s = \frac{1}{\Delta t}$

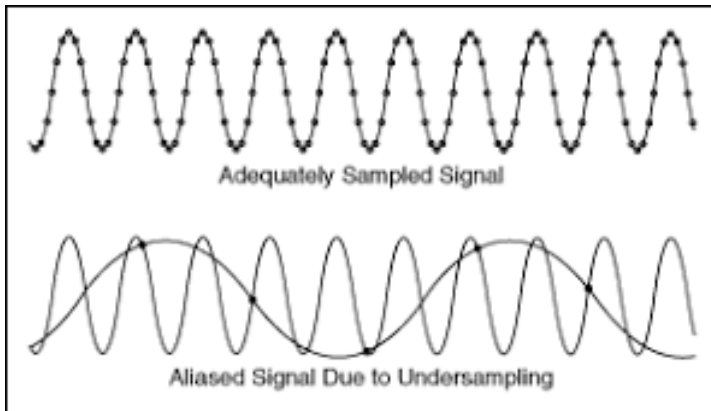
**The minimum frequency that can be correctly reproduced is equal to**

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

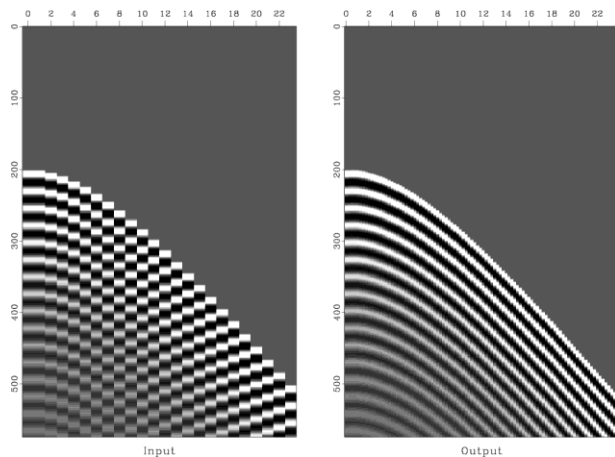
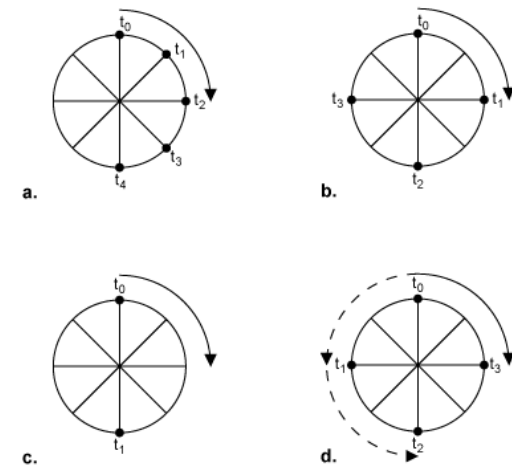
## Data sampling

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





