Geophysics for Natural Risks and Resources
ENVIRONMENTAL and ENGINEERING GEOPHYSICS

Introduction to GEOPHYSICAL PROSPECTING for ENGINEERING

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PRIVACY

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Outline

Geophysical methods for engineering

- Electrical methods (ERT Electrical resistivity methods, IP methods)

- Electro-magnetic methods (EM, RADAR)

- Seismic methods (Refraction Seismic, Reflection seismic, surface waves seismic)

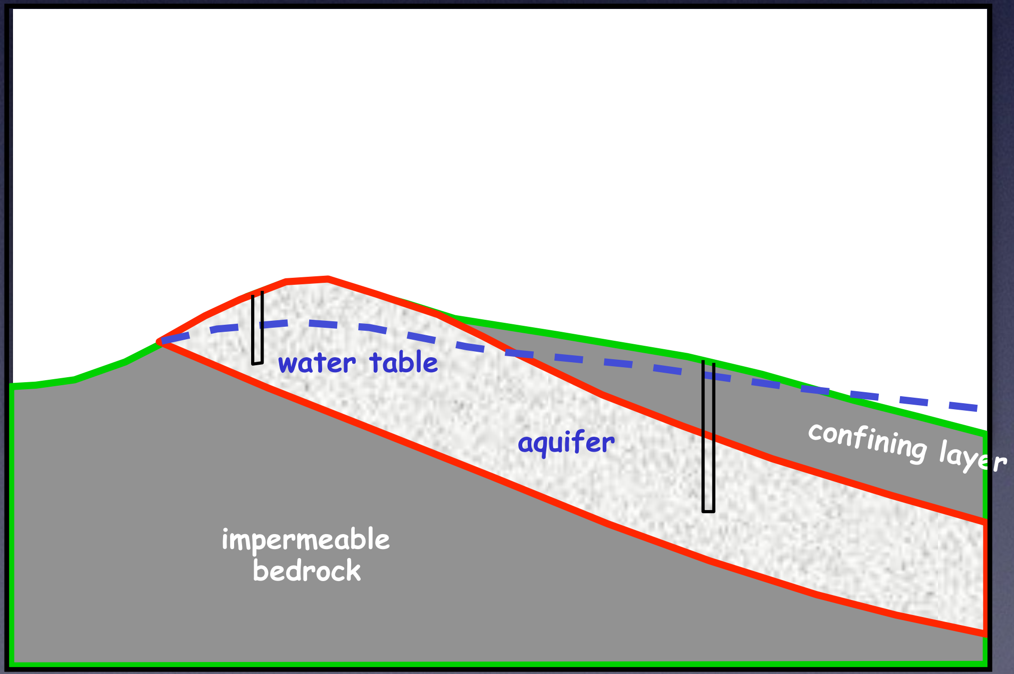
- definition of inversion problem
- resolution and depth penetration
- sketch of signal processing

Geophysical methods for the subsoil exploration

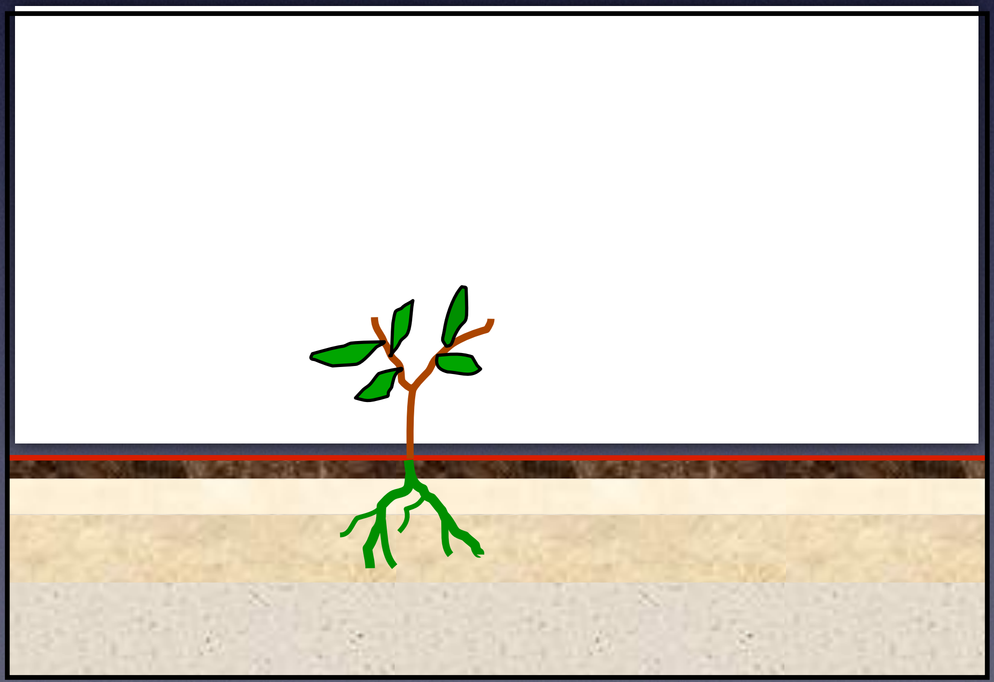
Method	Structure	Dynamic
Seismic	+ +	
Electro-Magnetic	+	++
DC resistivity methods	++	++
Ground Penetration Radar	++	+
Distributed Temp. Sensing		++
Magnetics	+	
Gravimetry	+	+
Spectral Induced Polarization	+	
Self Potential		+
Borehole logs	+ +	+

What geophysical methods can help define

- structure / texture (Seismic methods, EM methods, Electrical methods, Gravity methods, Radar etc)



large scale

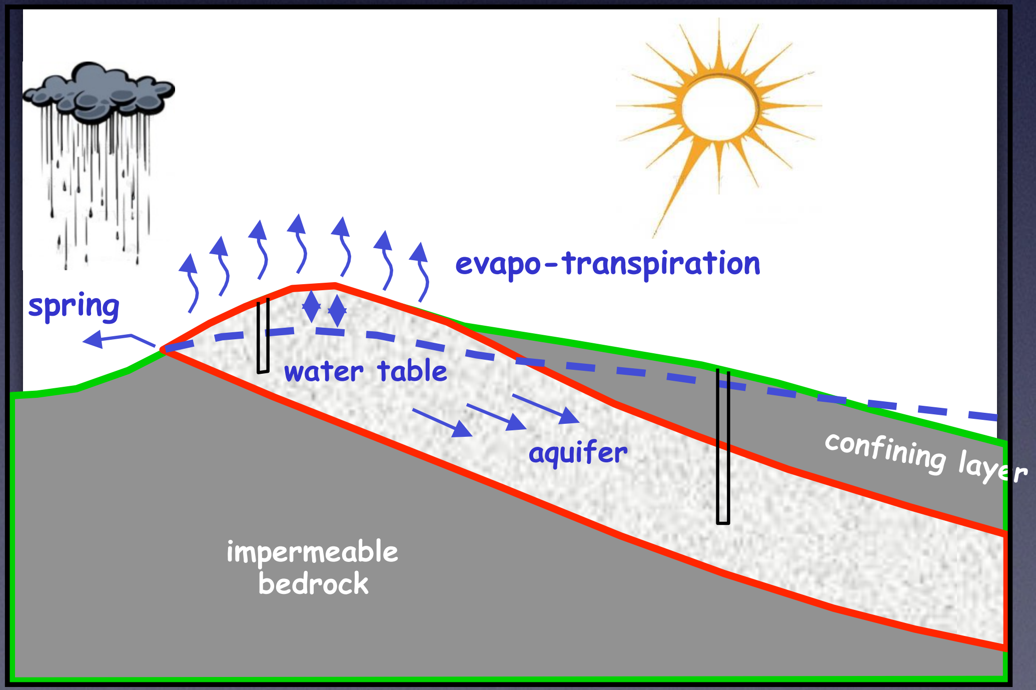


small scale

What geophysical methods can help define

- structure / texture (Seismic methods, EM methods, Electrical methods, Gravity methods, Radar etc)

- fluid-dynamics: e.g. time-lapse evolution of moisture content (DC resistivity methods, EM methods, GPR etc)



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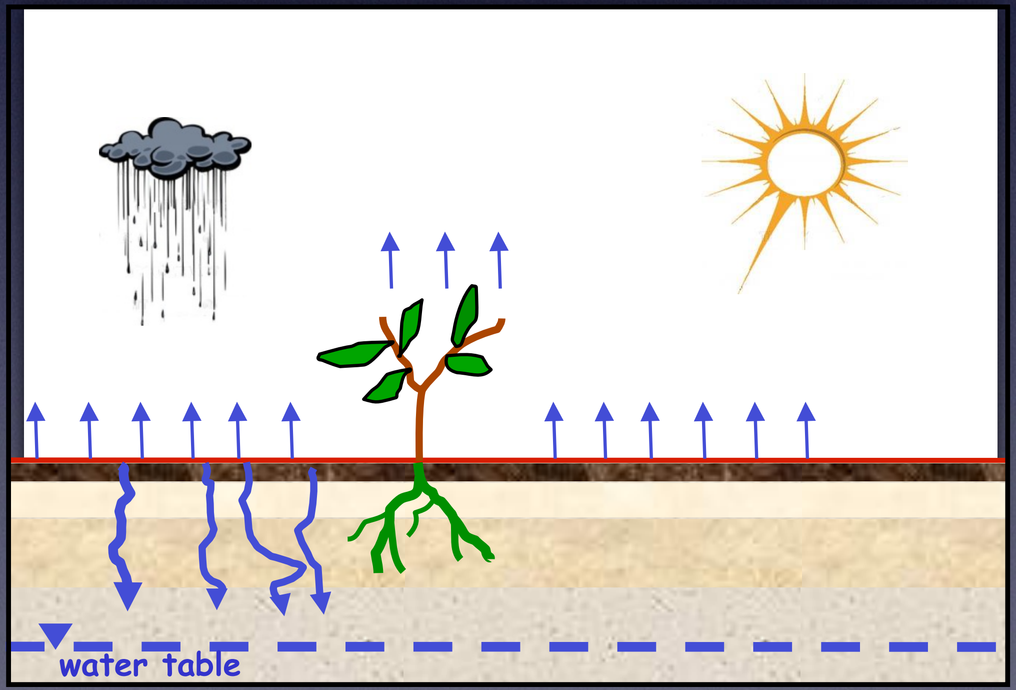
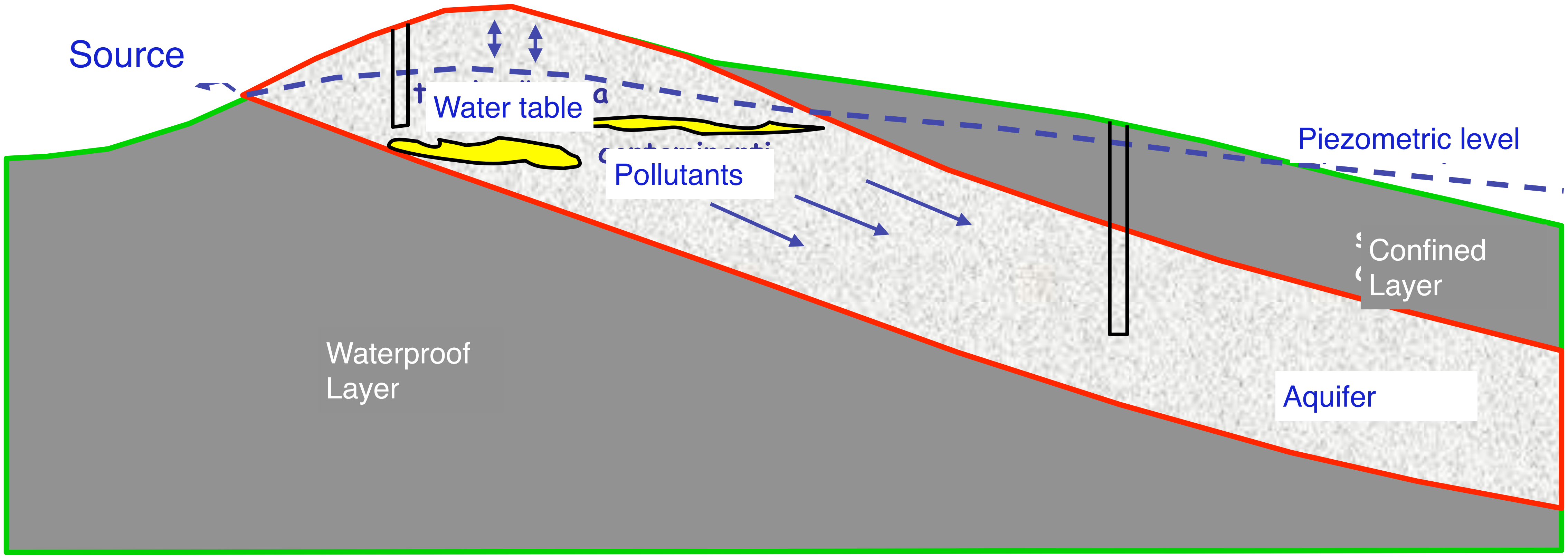


small scale

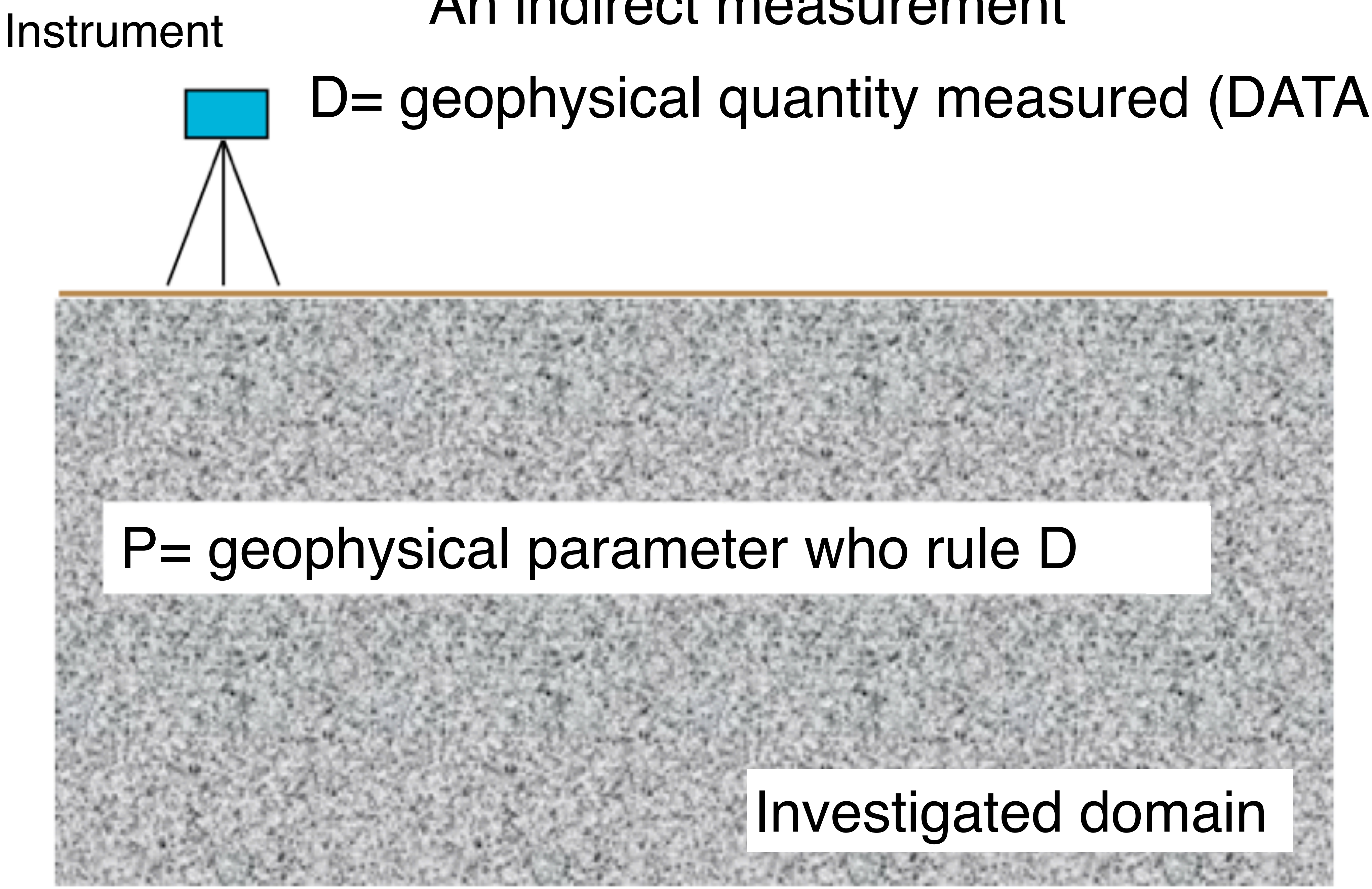
Aspects of environmental problem:

- ❑ Subsoil Structure
- ❑ Fluids dynamics.
- ❑ Presence of pollutants.



The geophysical measurement

An indirect measurement



Instrument

D= geophysical quantity measured (DATA)

P= geophysical parameter who rule D

Investigated domain

D= D (P, F= forcing conditions)

PHYSICAL PROPERTIES (P)

- ☐ **Seismic** : elastic moduli and density
- ☐ **Gravimetry** : density
- ☐ **Magnetic Methods** : magnetic susceptibility
- ☐ **GeoElectrics** : electric conductivity
- ☐ **Electro-Magnetic methods** : electric conductivity
- ☐ **Induced polarization** : electric complex conductivity
- ☐ **Spontaneous potential** : electric conductivity sources
- ☐ **Ground penetrating radar** : dielectric constant

PHYSICAL PROPERTIES (P)

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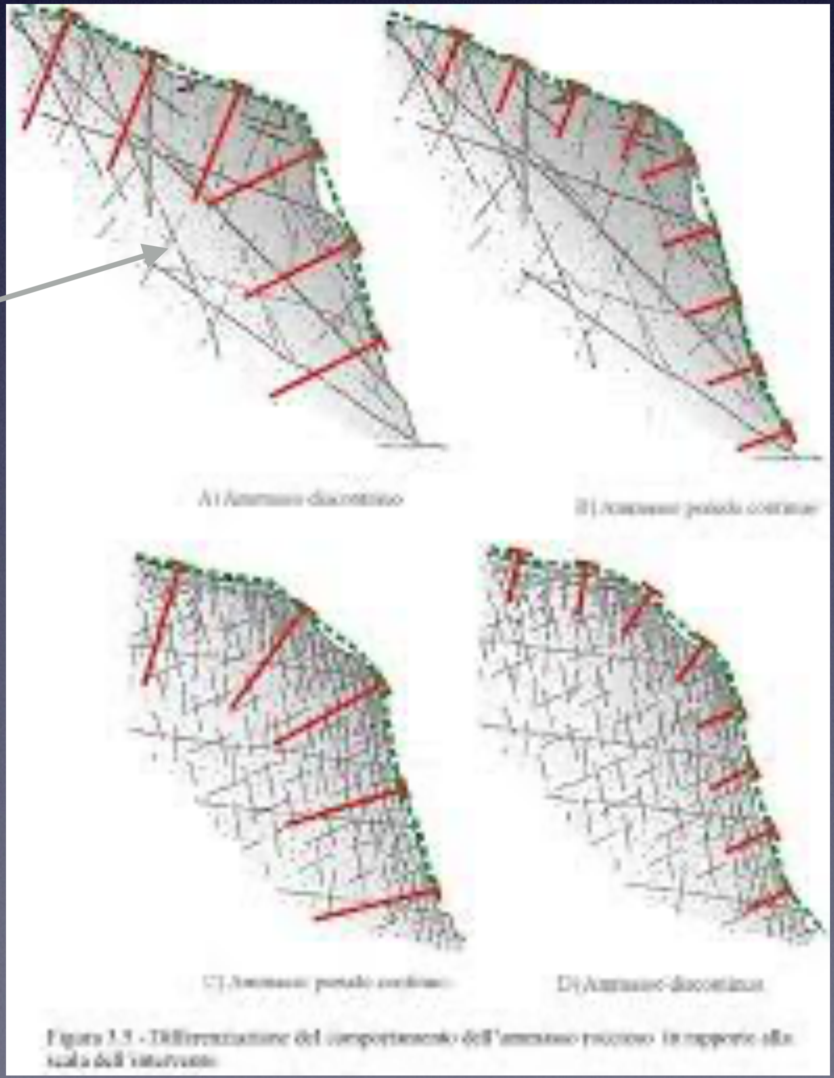
- **Ground penetrating radar** : dielectric constant

Do I need this course ?

Practical problem:
Design a classical net defence for rock falls

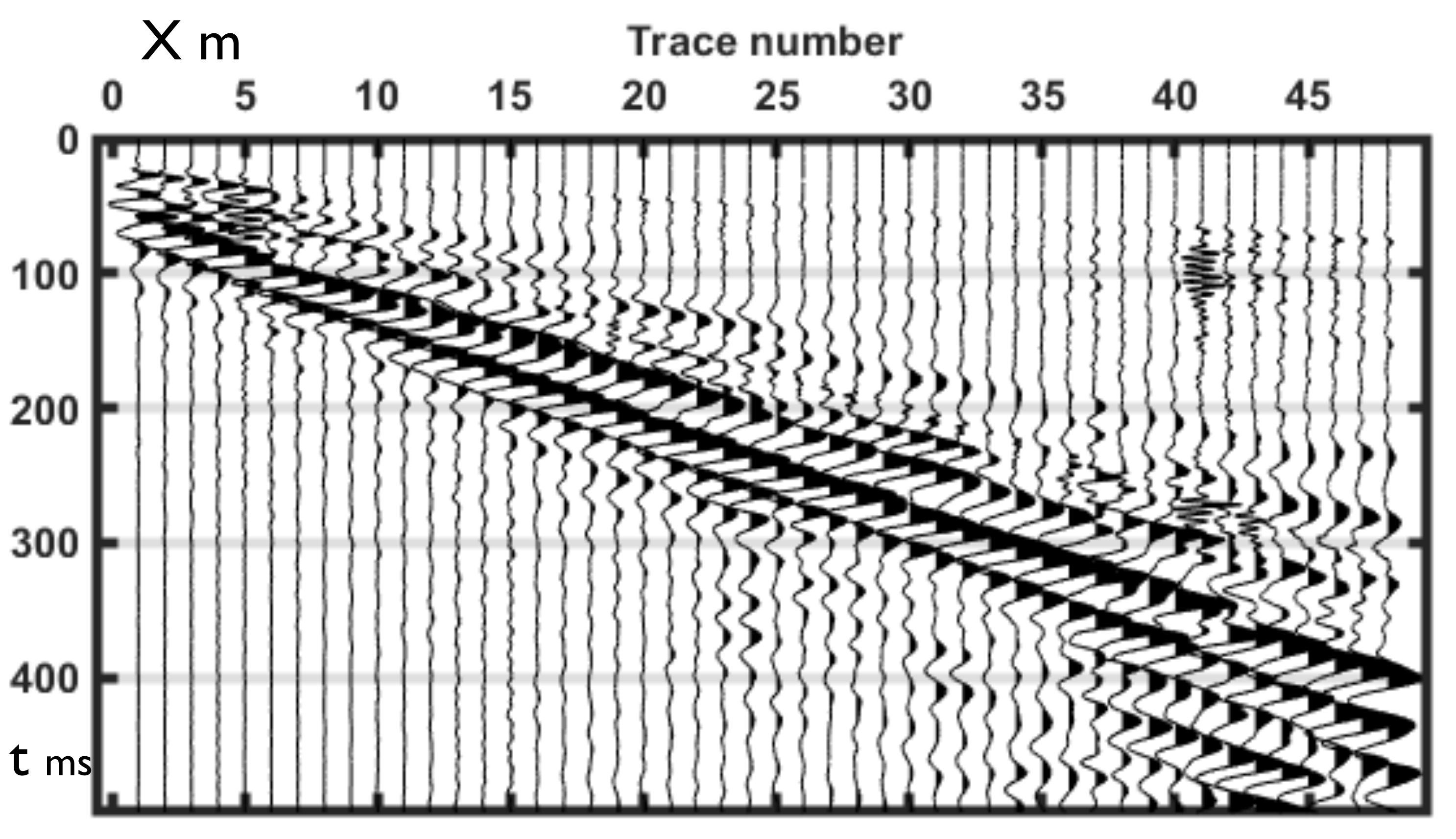


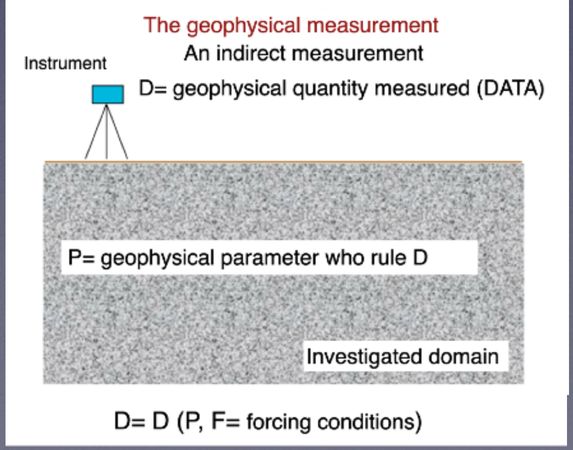
Nails must be anchored in the solid rock underneath debris…

How to do?

Seismic Methods

Study the wave elastic propagation in the subsoil and furnish the mechanical parameters





The geophysical measurement

An indirect measurement

Instrument

D= geophysical quantity measured (DATA)

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Investigated domain

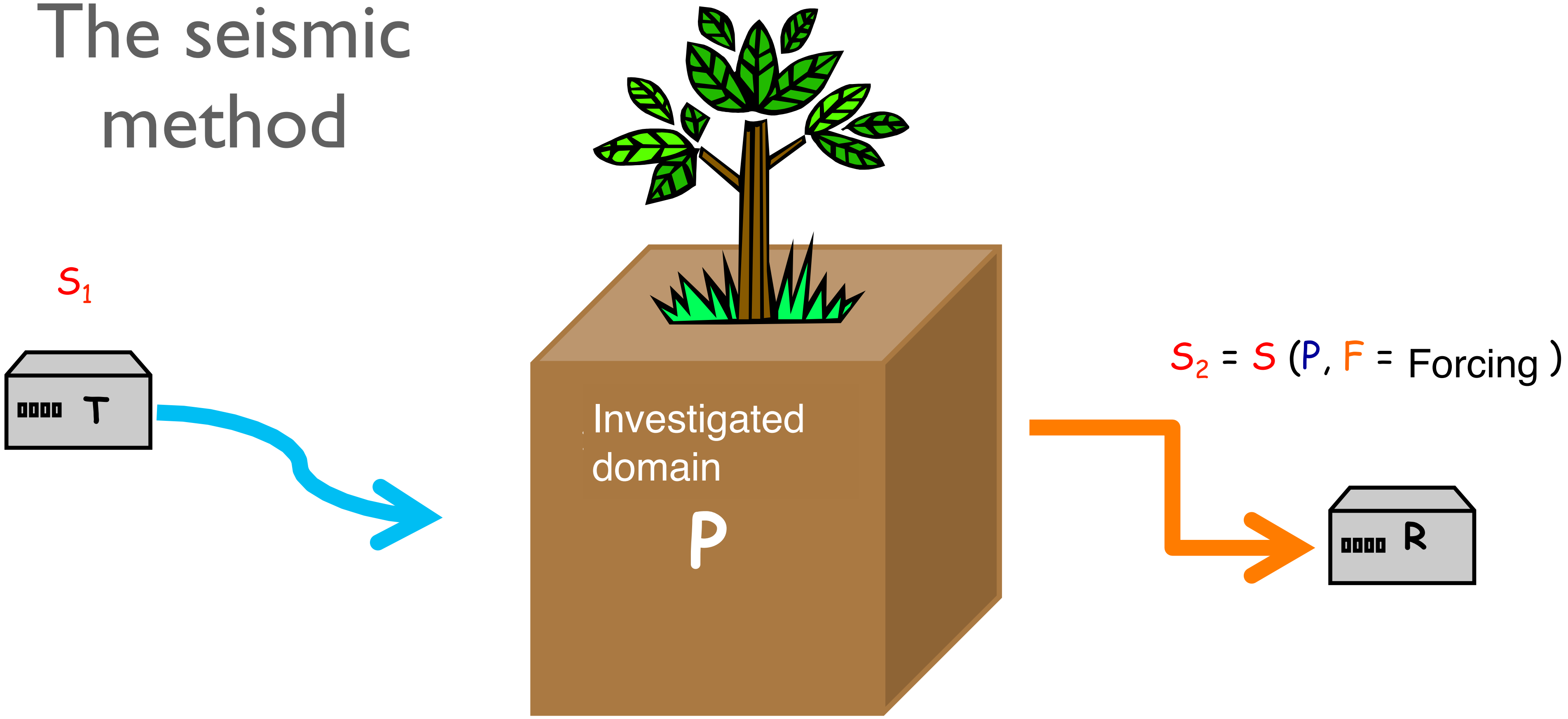
D= D (P, F= forcing conditions)

Physics parameter P

=

Elastic properties

The seismic method

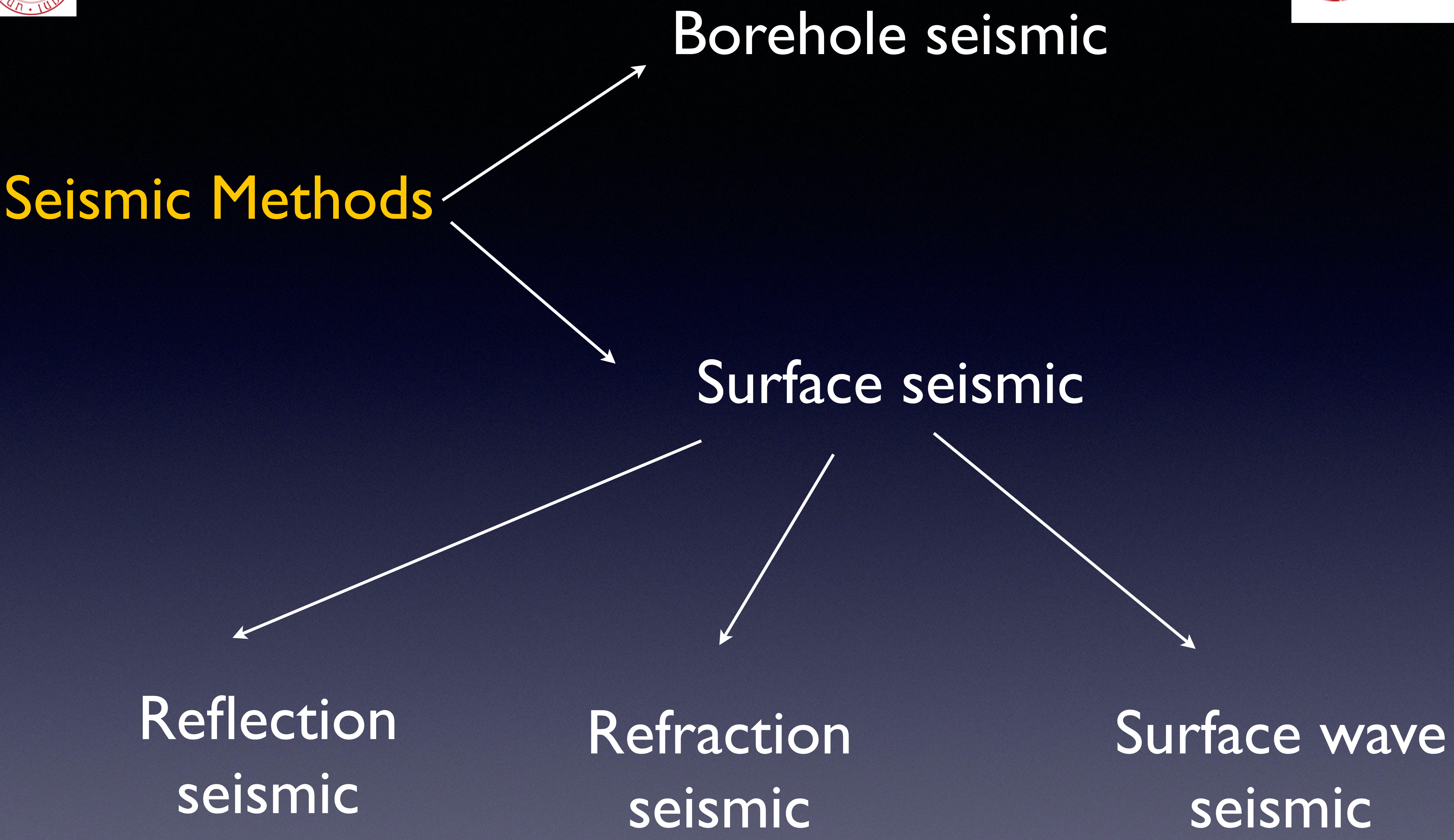


$S_2 = S(P, F = \text{Forcing})$

S_1 = Signal = Elastic wave source

S_2 = Signal = Induced vibration

P = Physical parameter Elastic moduli/ density



Seismic Methods

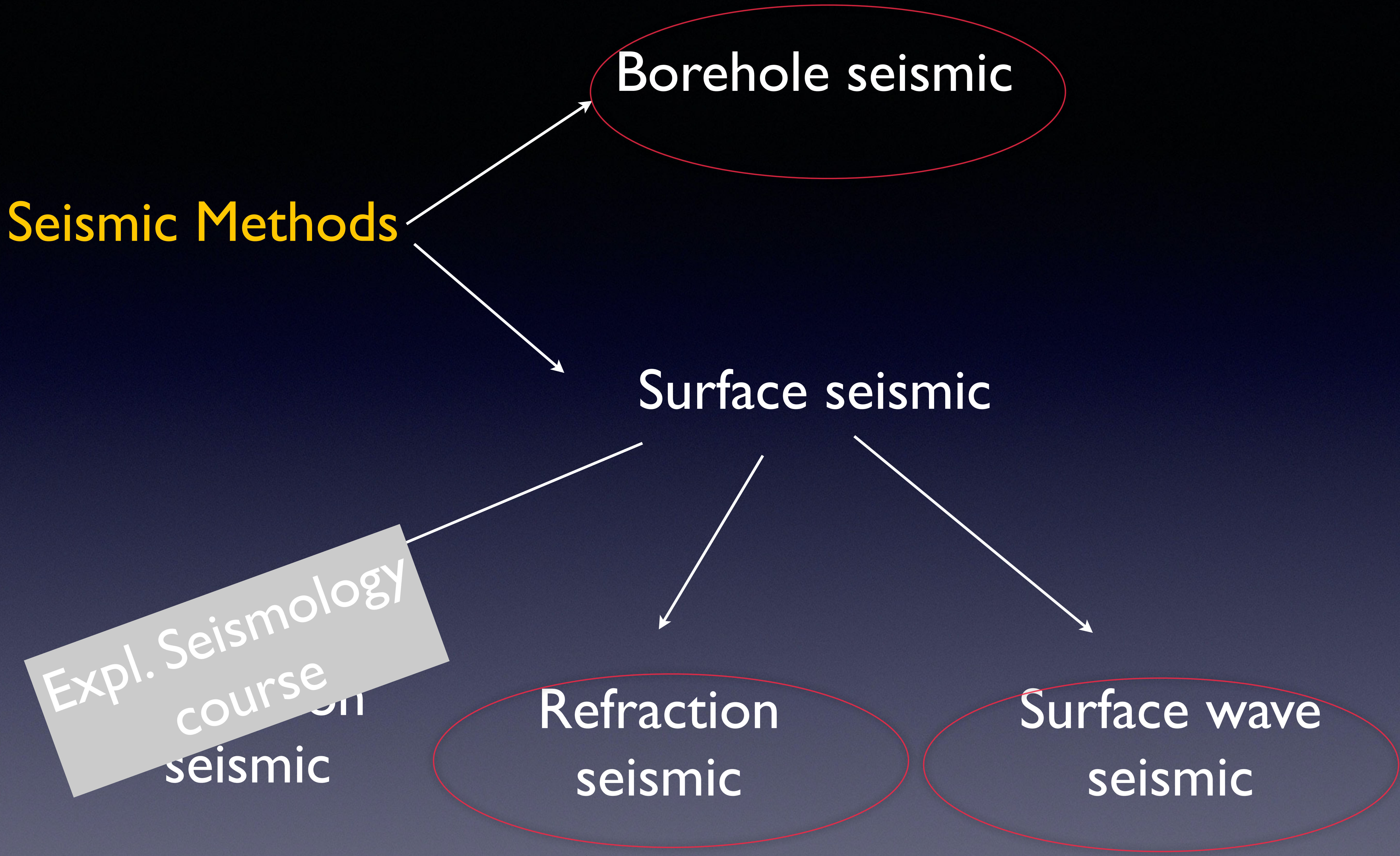
Borehole seismic

Surface seismic

Reflection seismic

Refraction seismic

Surface wave seismic



Seismic Methods

Borehole seismic

Surface seismic

Expl. Seismology course

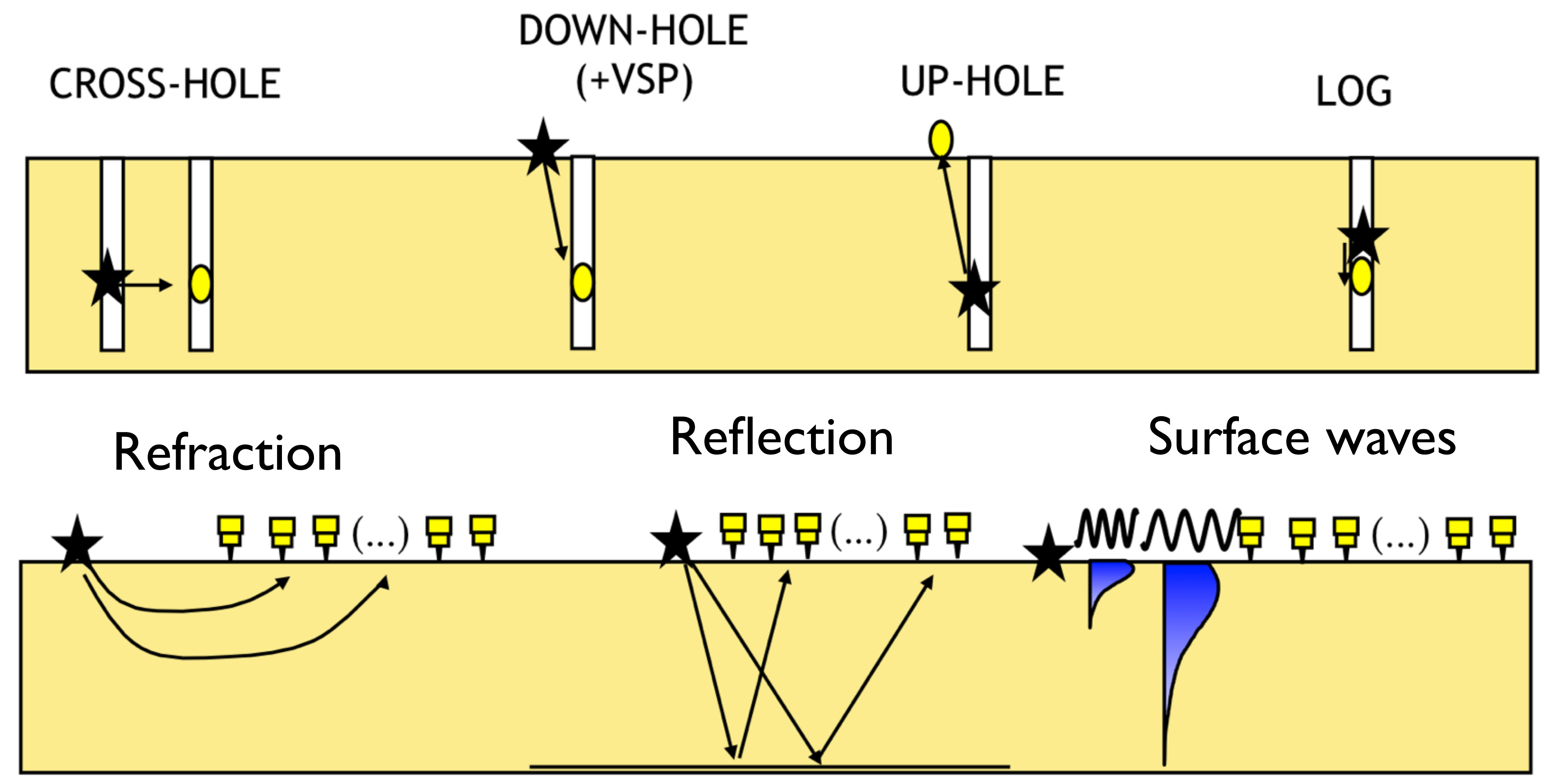
on
seismic

Refraction seismic

Surface wave seismic

Seismic Methods

Borehole Seismic



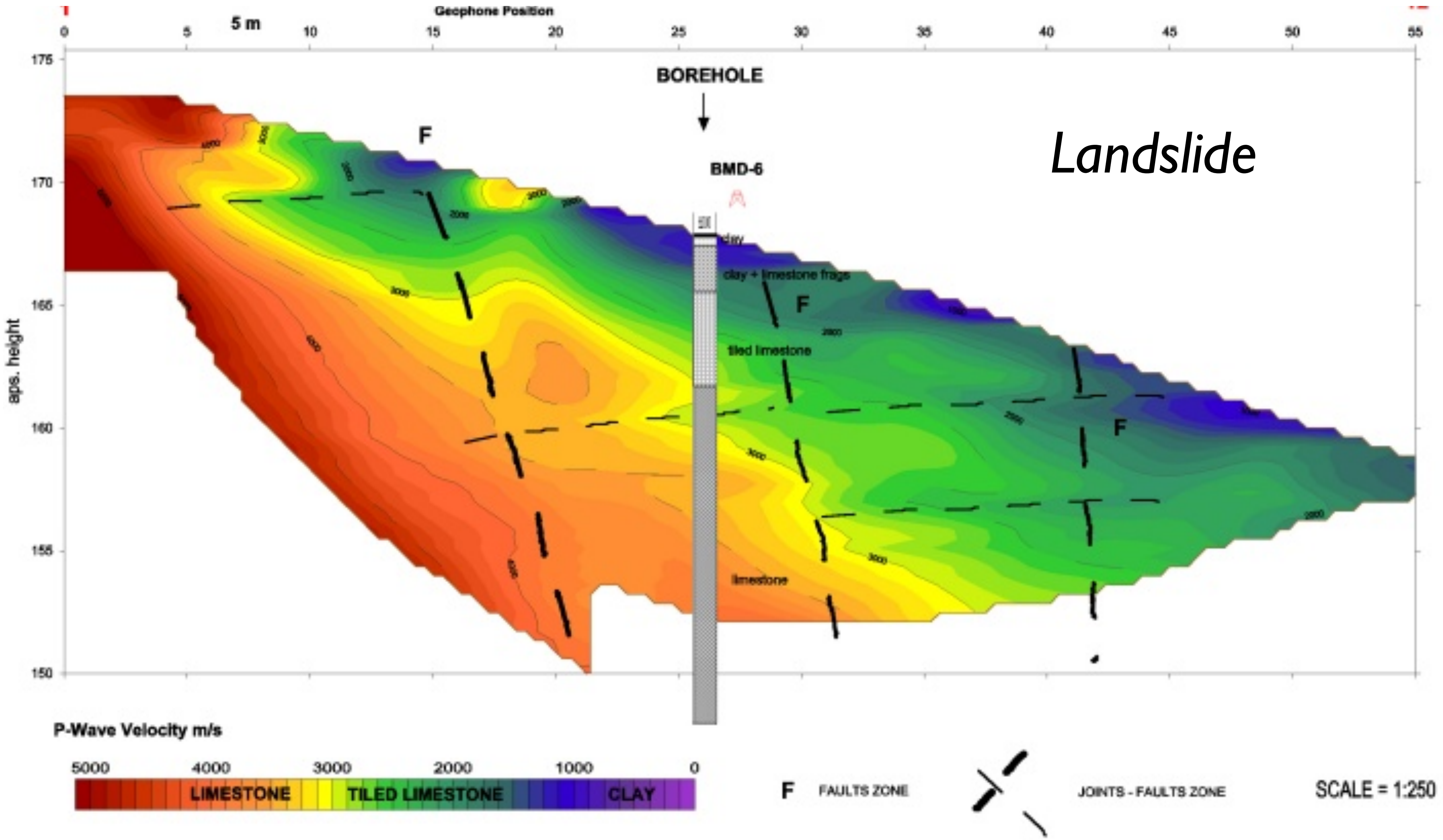
Surface seismic

Seismic Methods

Surface Seismic

Refraction seismic

2D Tomographic reconstruction of the seismic velocities



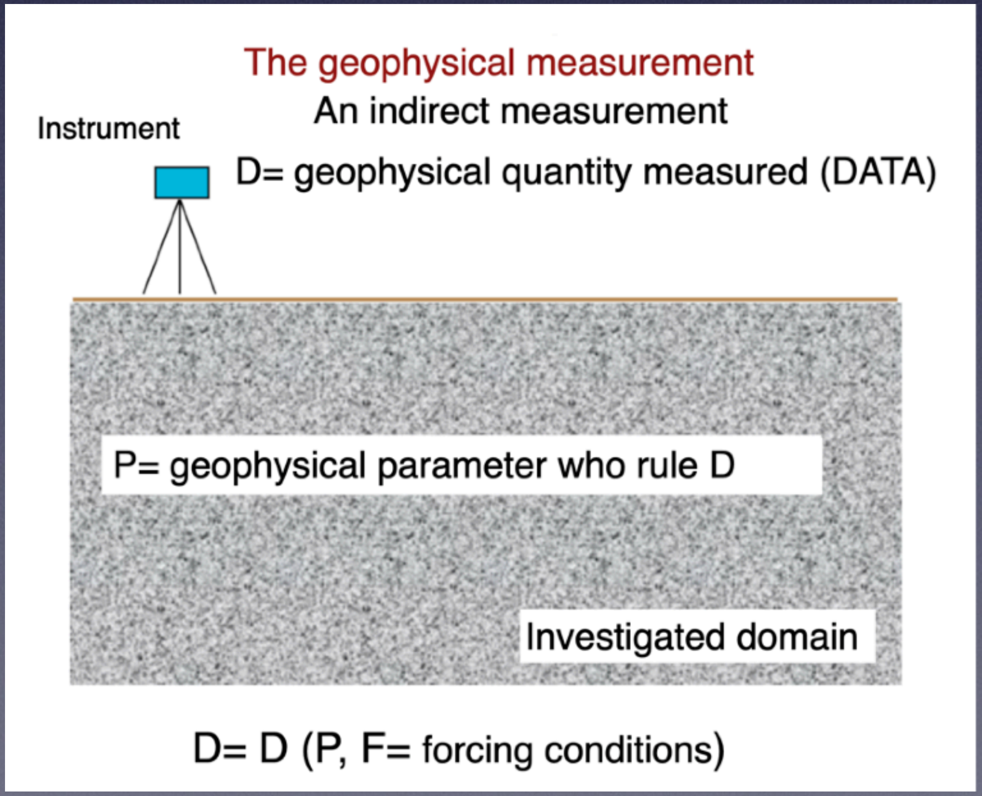
Landslide

Vp

II) Electric and ElectroMagnetic methods

Environmental and geological purposes

- e.g. HYDROgeophysics -



Physics parameter P

=

Electric properties

Electric Methods

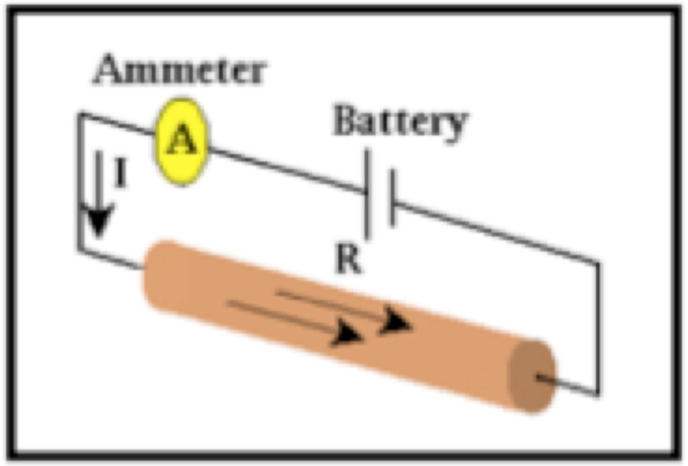
ELECTRIC RESISTIVITY TOMOGRAPHY

ERT

electrical-resistivity-tomography

OHM LAW

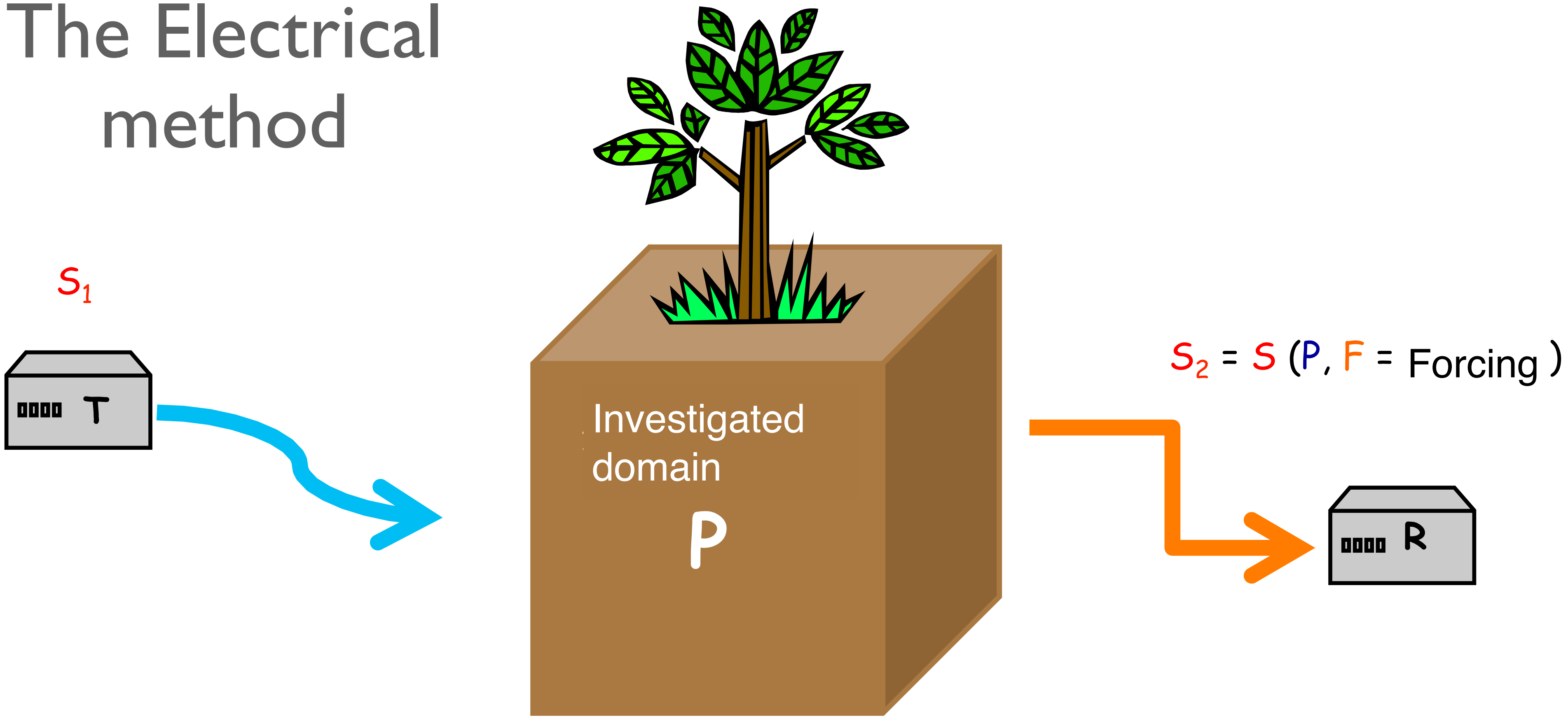
$$\boxed{\Delta V = I \cdot R}$$



Electric conductivity: $\sigma = \frac{1}{\rho}$

Electric Resistivity

The Electrical method



S_1

$S_2 = S$ (P, F = Forcing)

Investigated domain

P

S_1 = Signal = Injected current

S_2 = Signal = Potential voltage measured

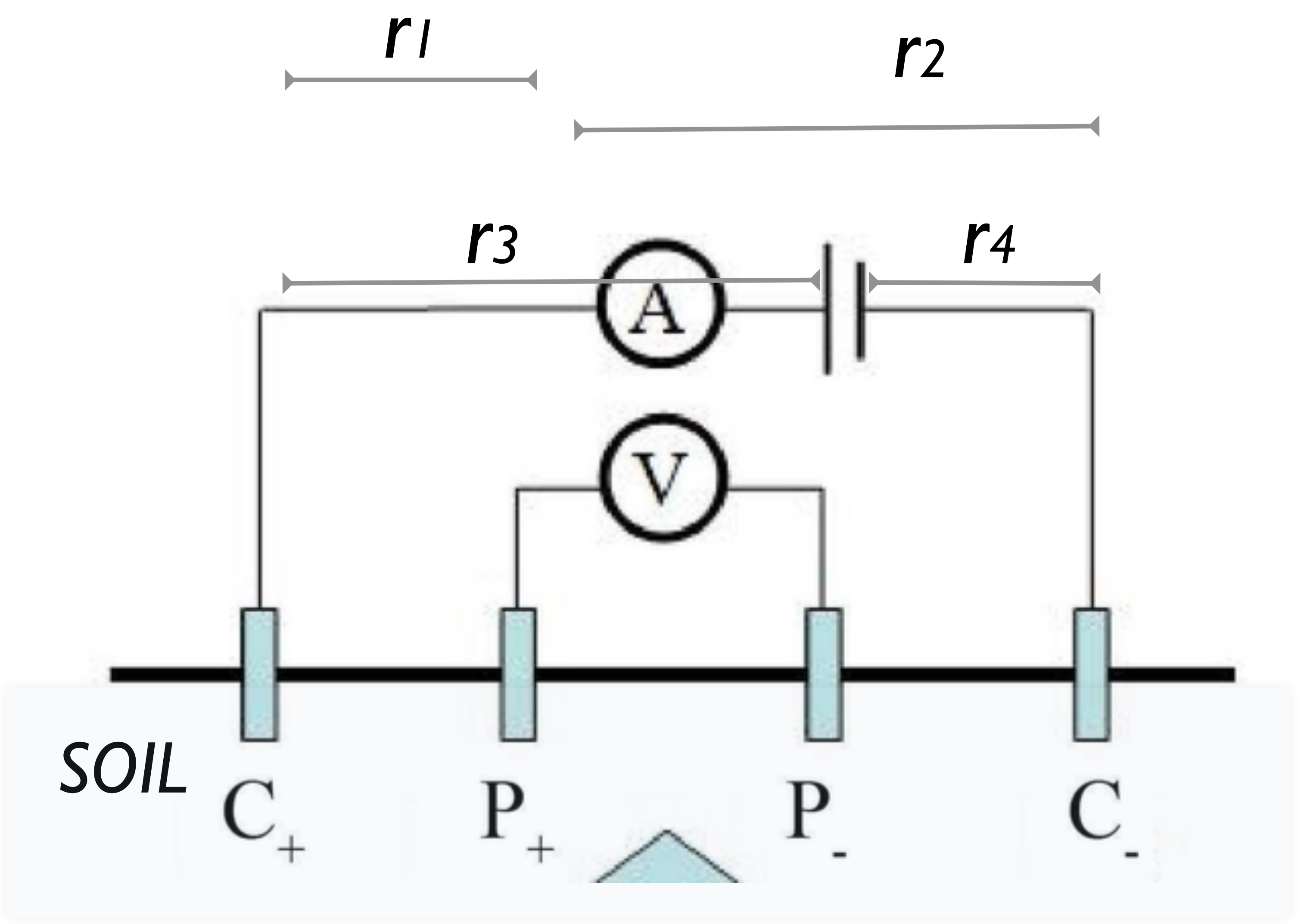
P = Physical parameter = Resistivity

ELECTRIC QUADRIPOLE

1) $$\Delta V = \frac{I\rho}{2\pi}\left[\left(\frac{1}{r_1} - \frac{1}{r_3}\right) - \left(\frac{1}{r_2} - \frac{1}{r_4}\right)\right]$$

K

Geometric Factor



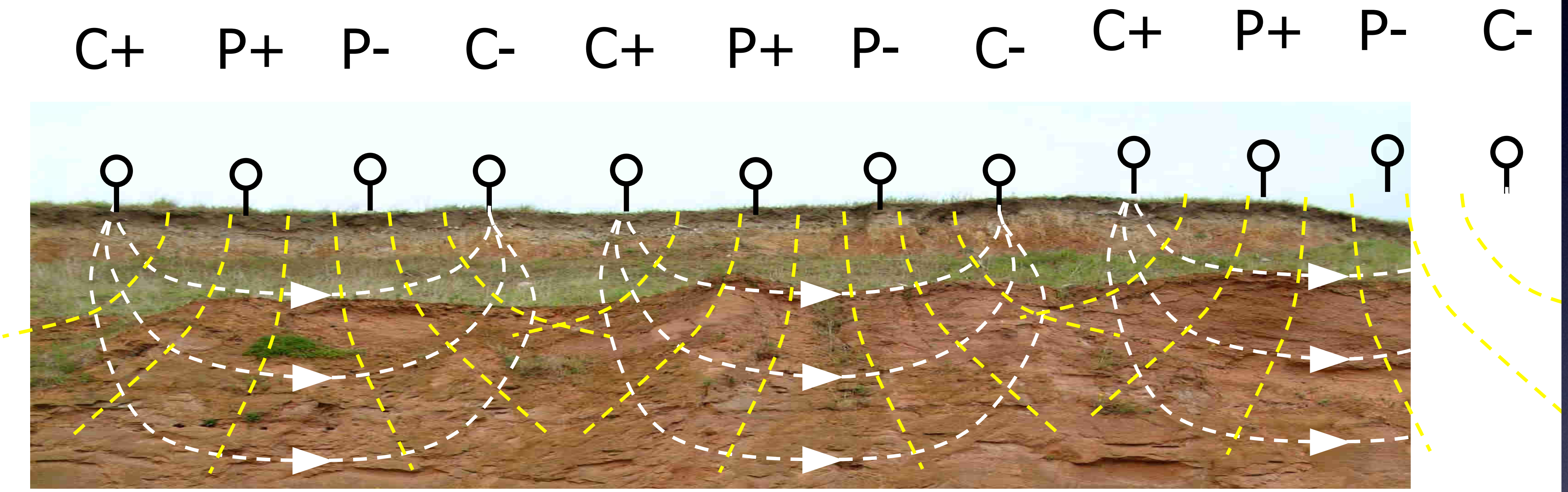
Apparent Resistivity

$$\rho_a = \frac{k\Delta V}{I}$$

ERT (Electrical Resisitivity tomography)

Resistivity profiling

We can profile the subsurface by moving our array



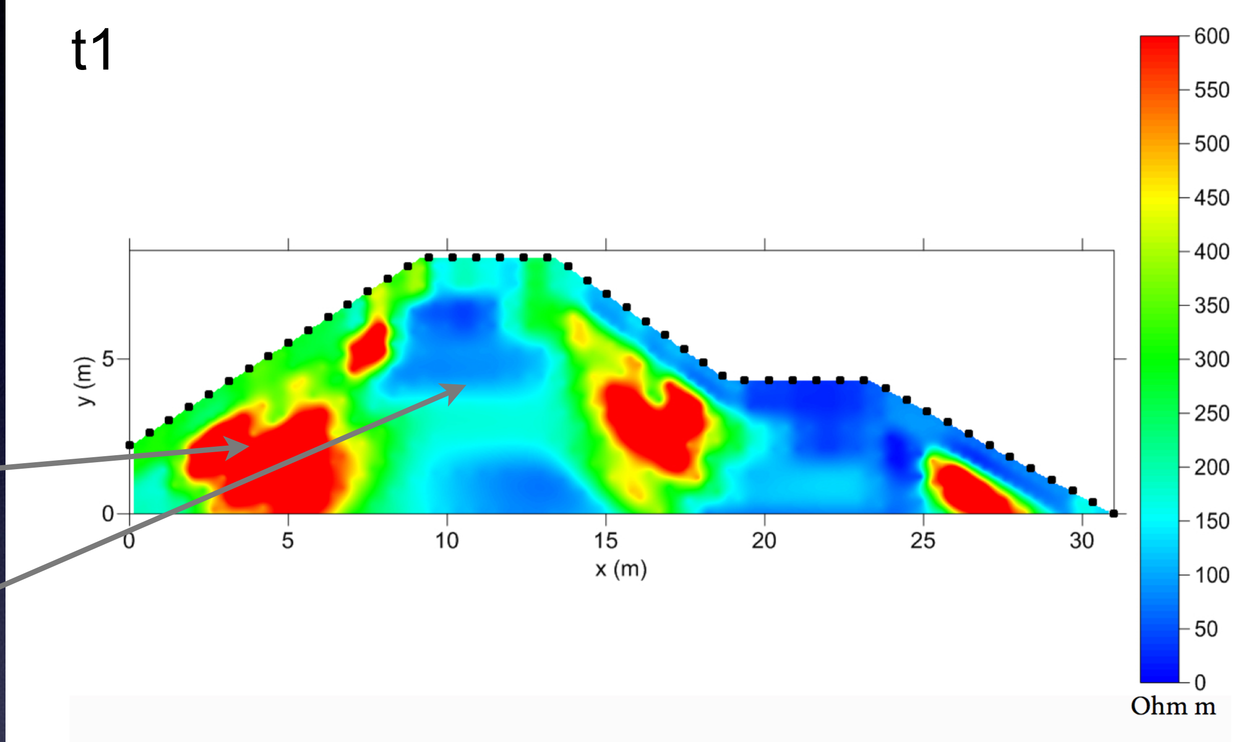
The depth we are sensitive to will depend on the array configuration and the subsurface properties. For the array above we may assume that the apparent resistivity is at about half the electrode spacing.

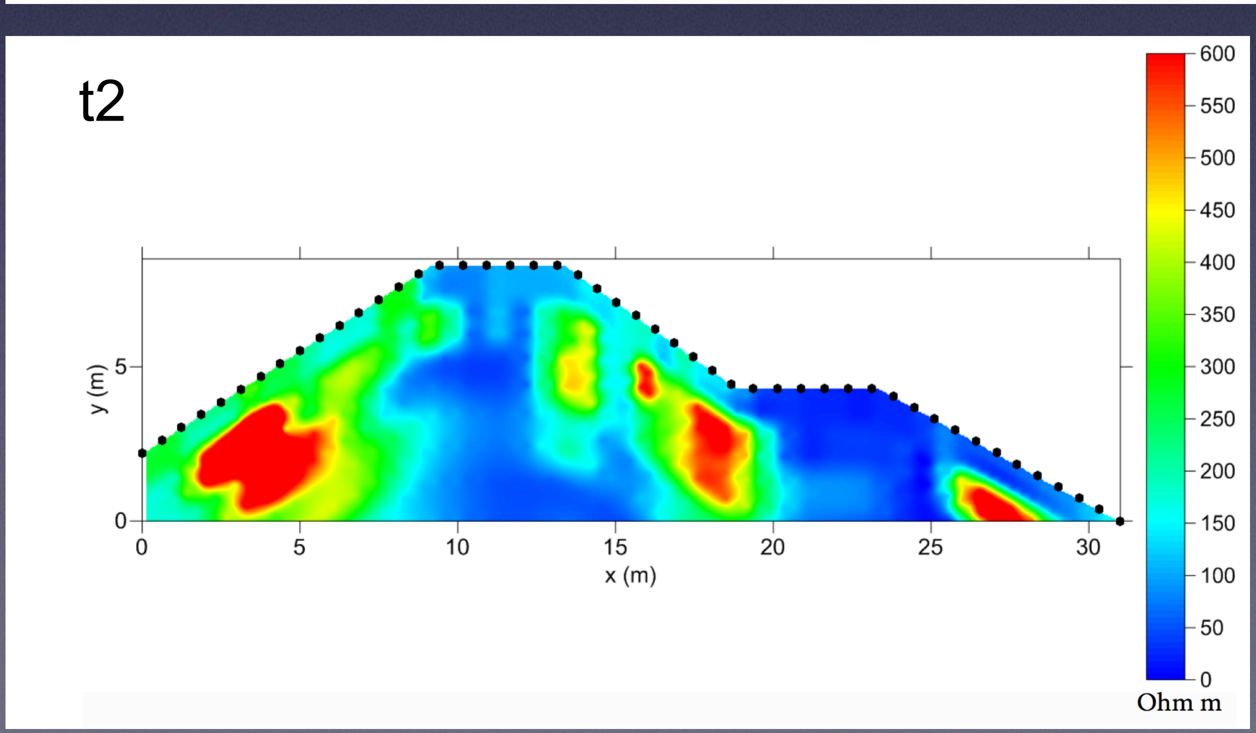
ERT Examples

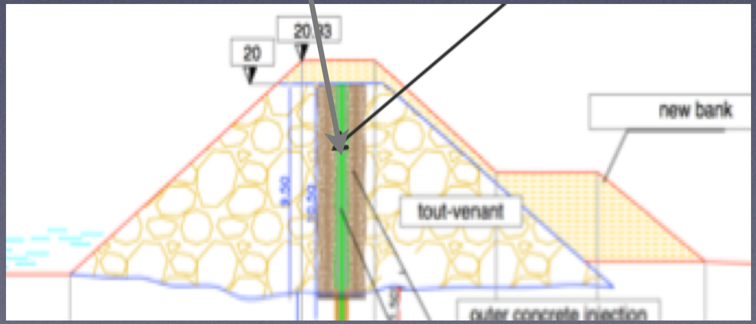
ERT on EMBANKMENT
- Top Resolution

Tout Venant

Jet Grouting Septum





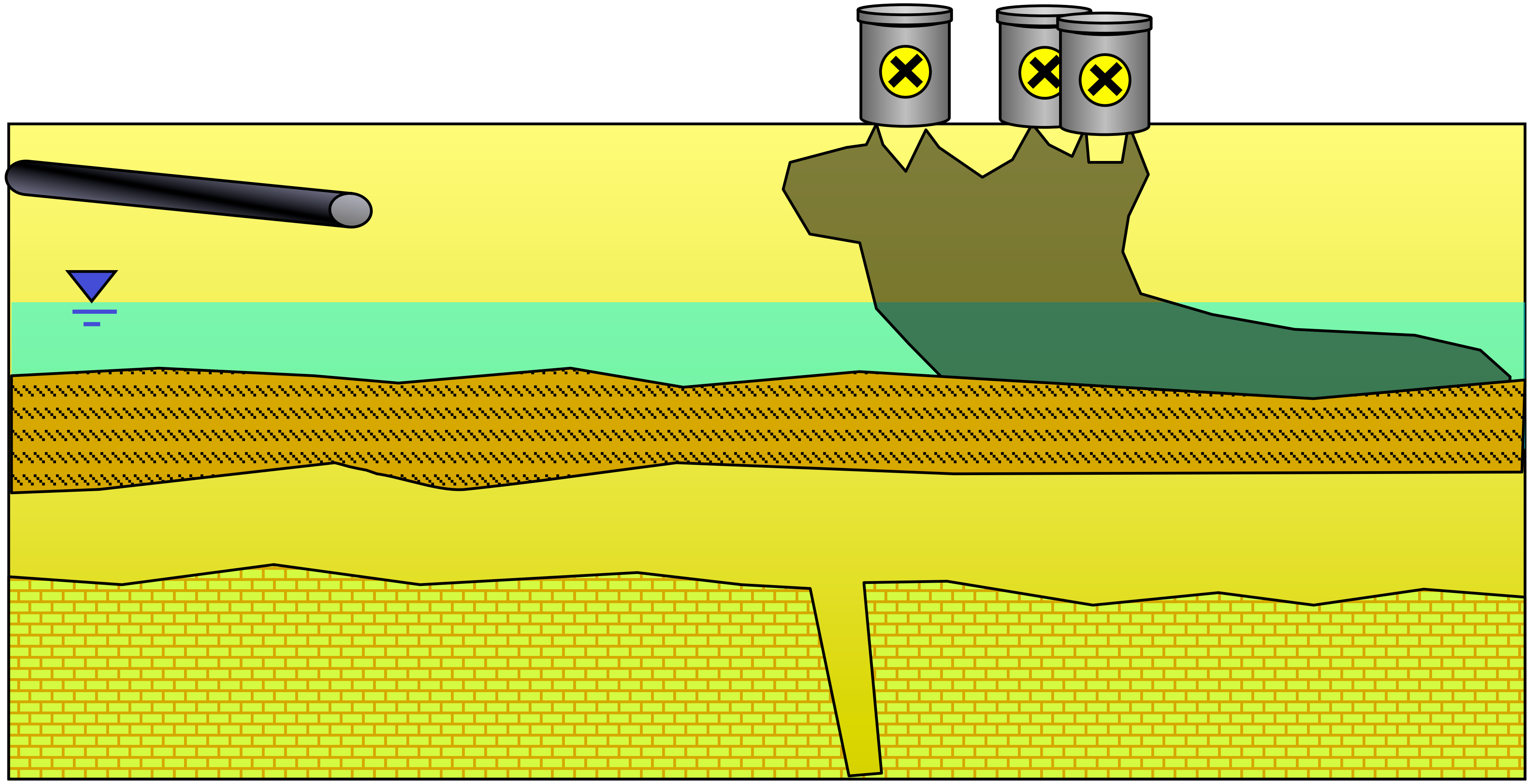


EM METHODS

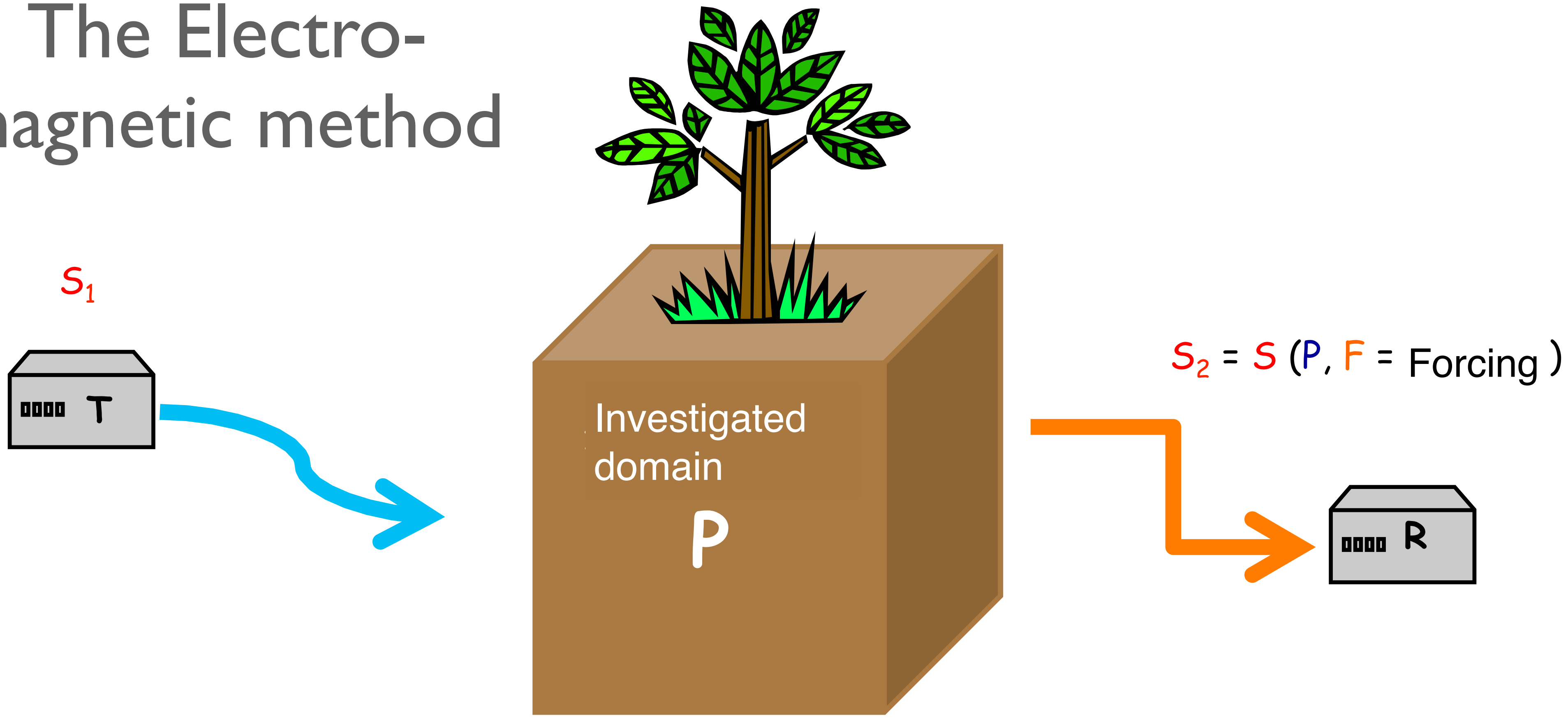
Electro-magnetic properties

APPLICATIONS:

- Mineral exploration
- Groundwater
- Mapping contaminants
- Landfill surveys
- Cavities
- Location of faults
- Geological mapping
- Archeological



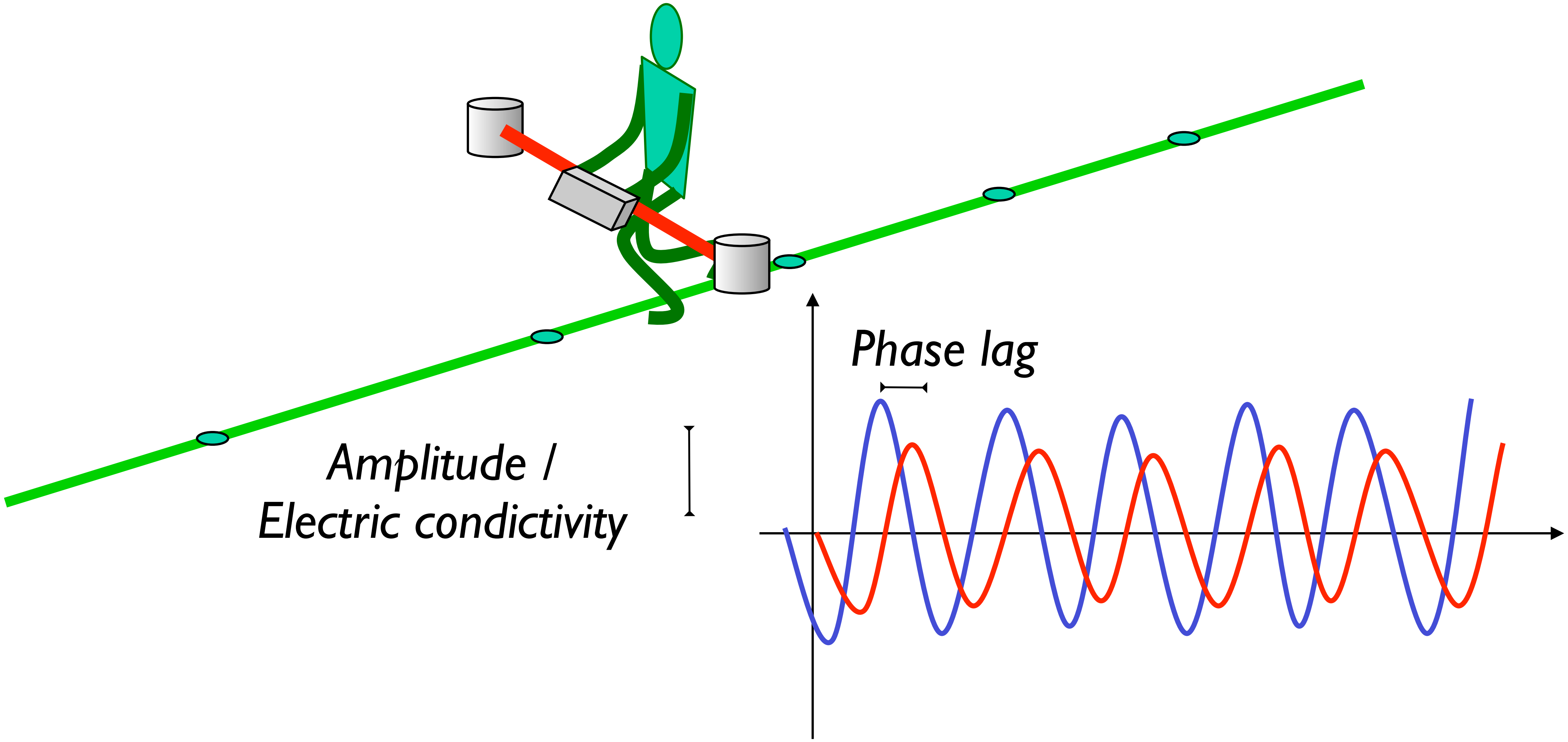
The Electro-magnetic method



S_1 = Signal = EM field

S_2 = Signal Induced EM field

P = Physical parameter Electrical conductibility

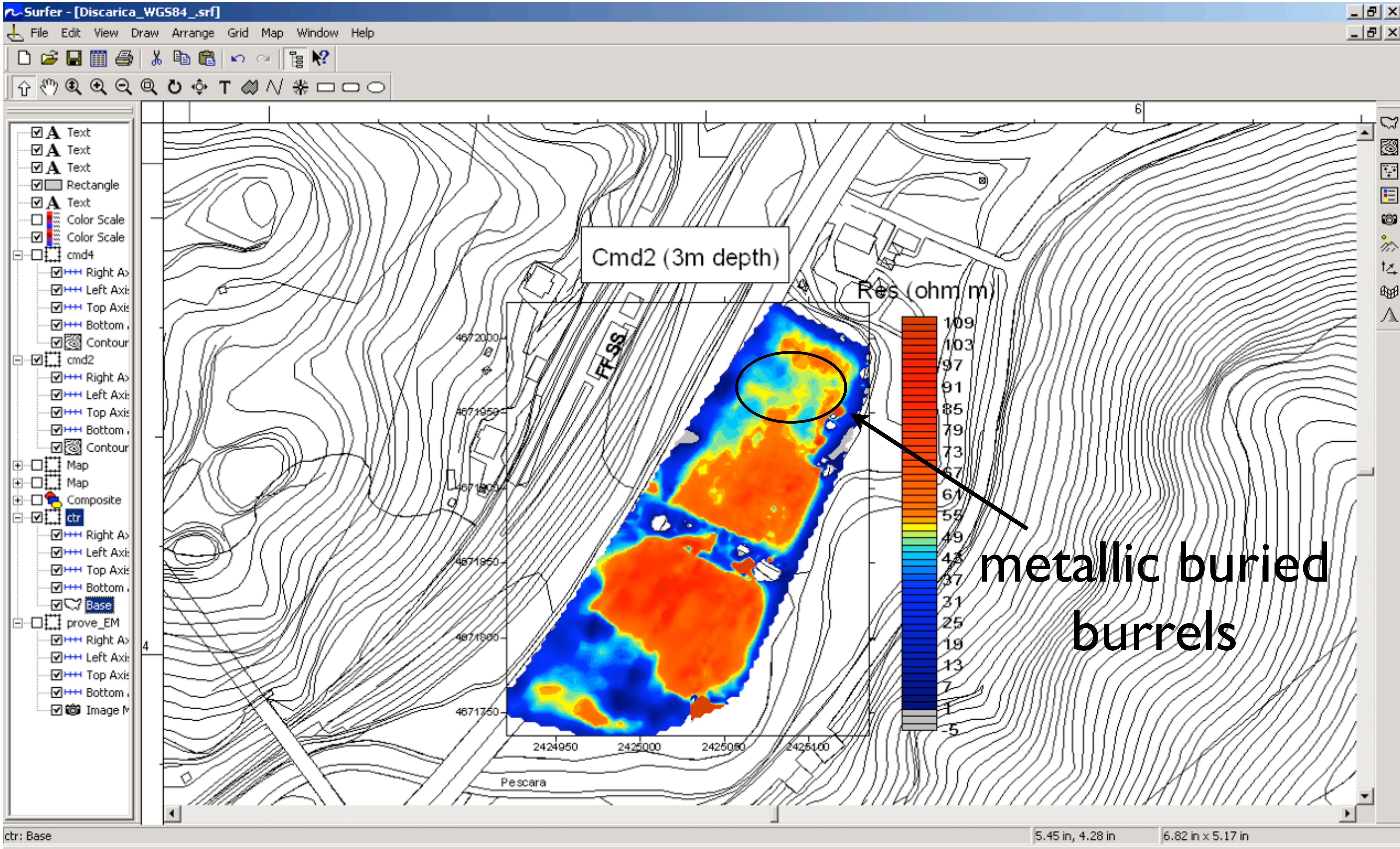


Relation between primary, secondary and resultant field: two values measured at each station

- Real (in-phase)
- Imaginary (quadrature, out-of-phase)

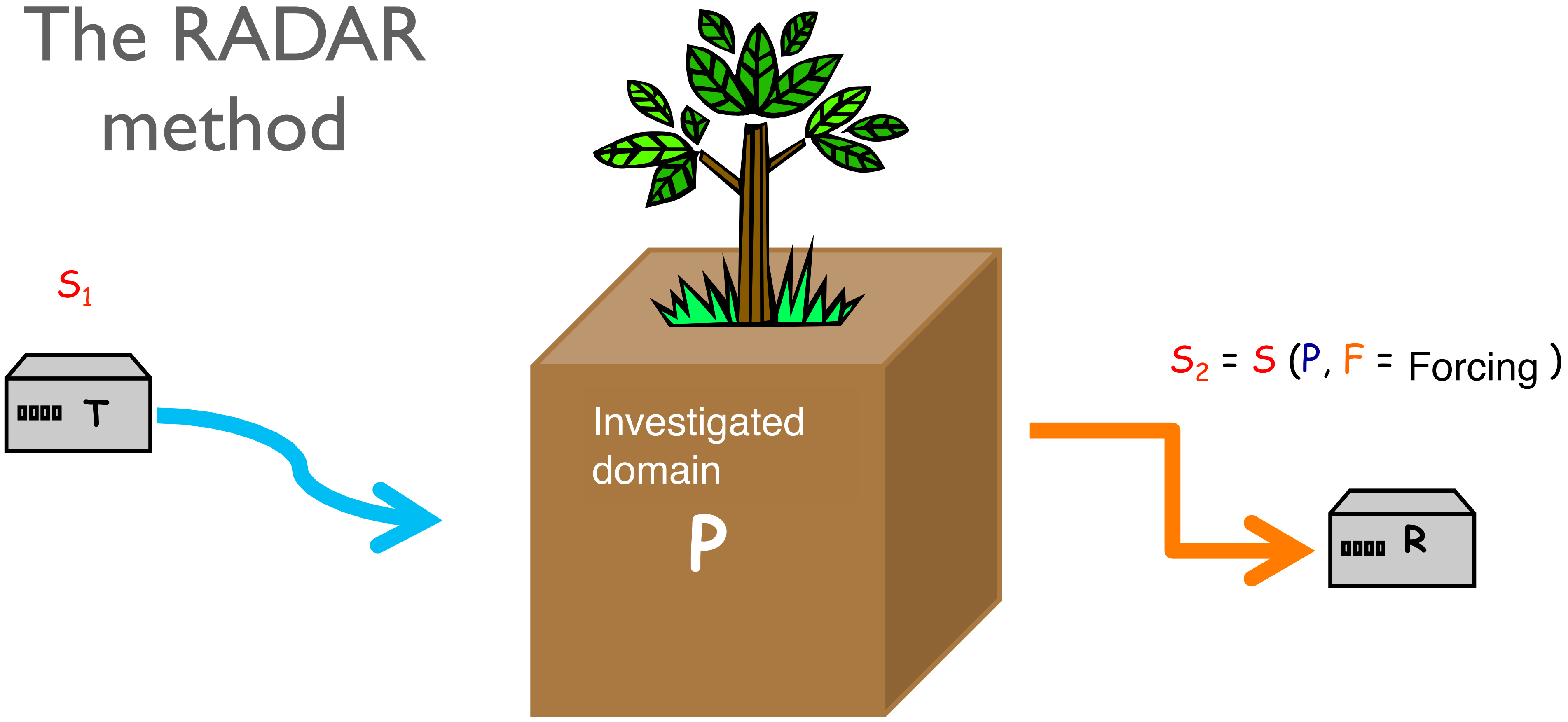
Amplitude
Phase lag

EM Example illegal landfill



metallic buried burrels

The RADAR method

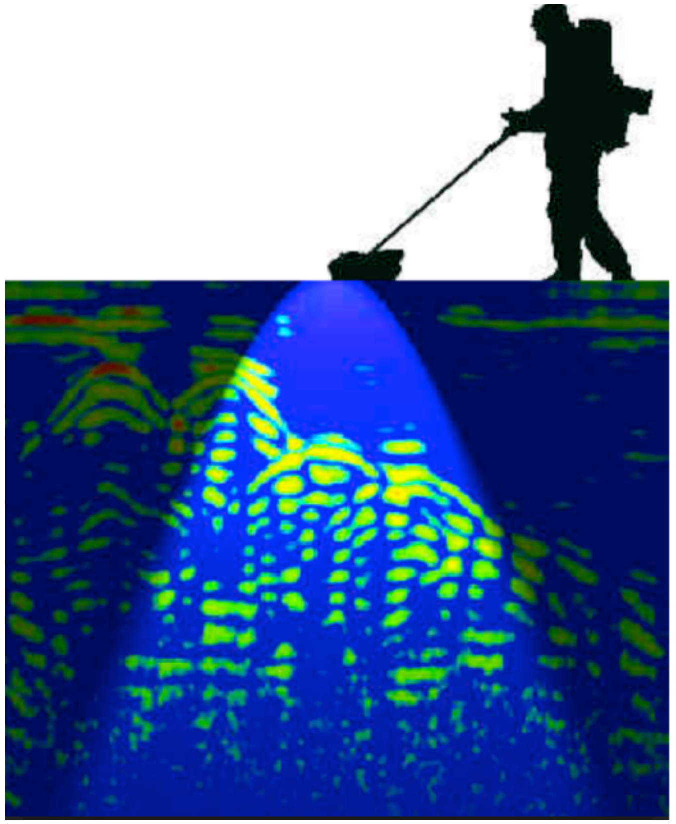


S_1 = Signal = High frequency electro-magnetic waves

S_2 = Signal = Reflected electro-magnetic waves

P = Physical parameter Dielectric contrast

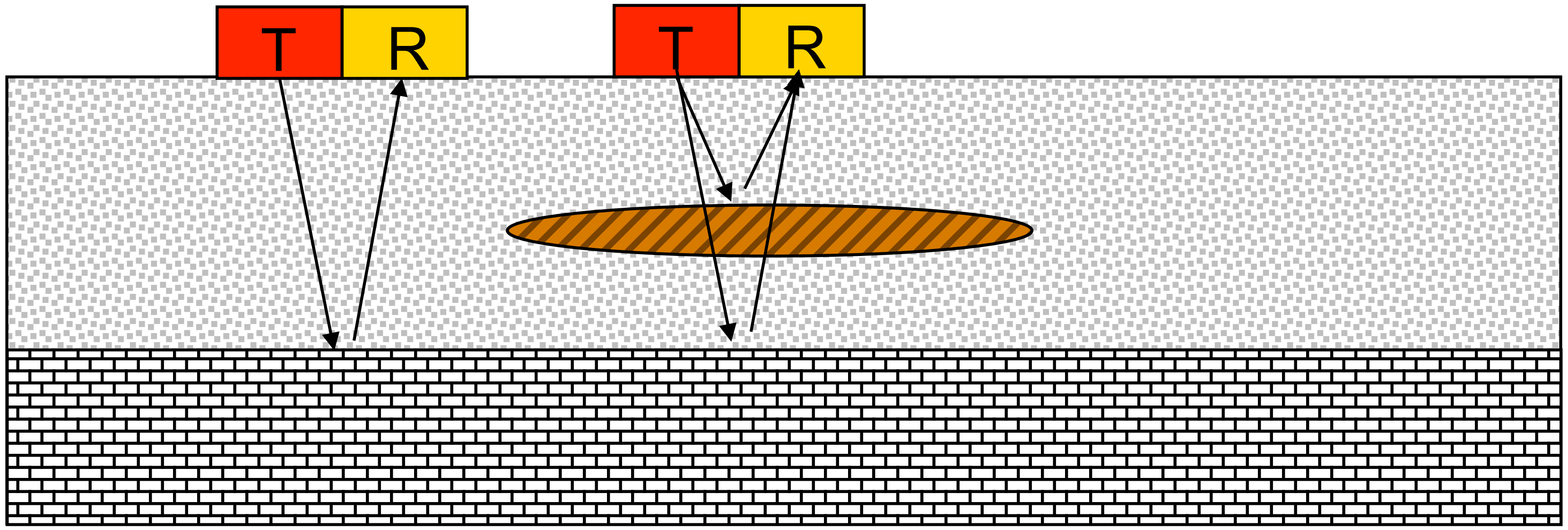
Georadar



G P R

Ground Probing Radar (or Ground Penetrating Radar) is a high frequency EM technique (in the band 10-2500 MHz) based on the response of the subsoil to a short EM pulse.

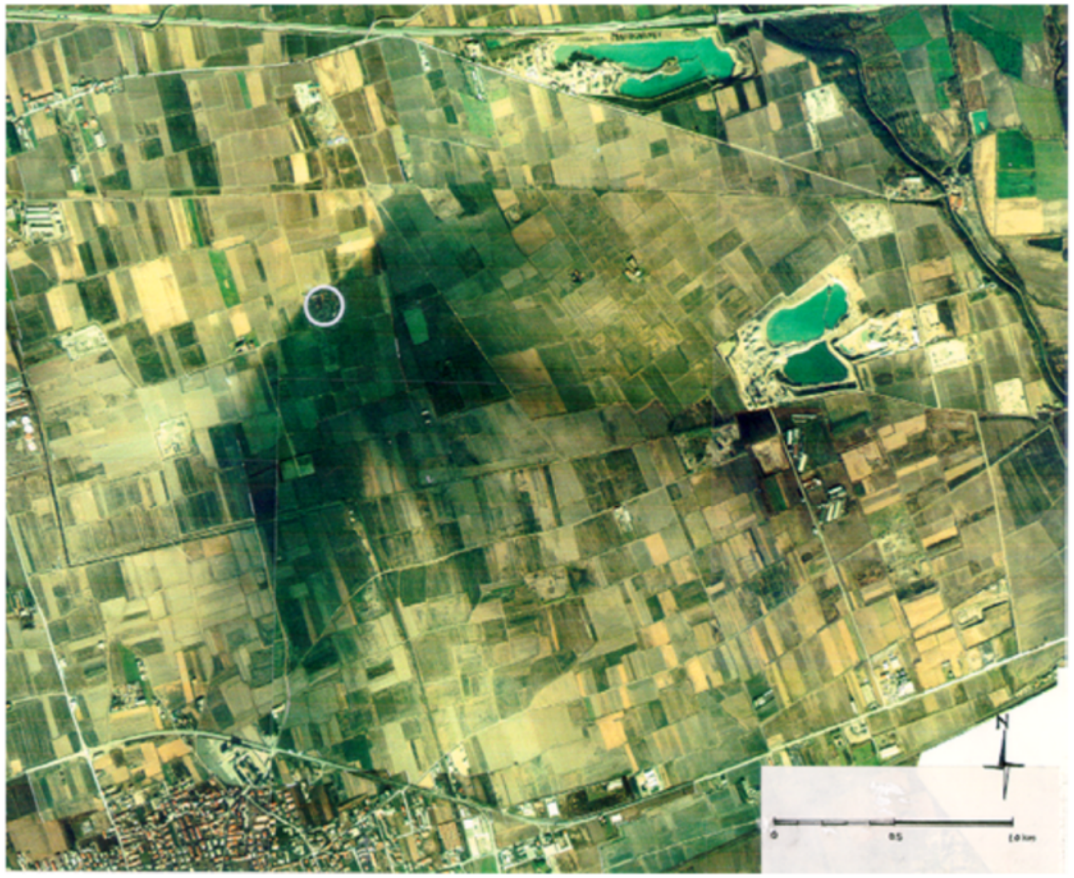
A signal of short wavelength is radiated into the ground, is reflected, refracted, diffracted and hence detects the anomalous variations in the dielectric properties.



Anomalies can be soil horizons, the groundwater surface, soil/rock interface, man made objects (pipes, foundations, cables…)

HIGH RESOLUTION, LOW PENETRATION DEPTH

Georadar



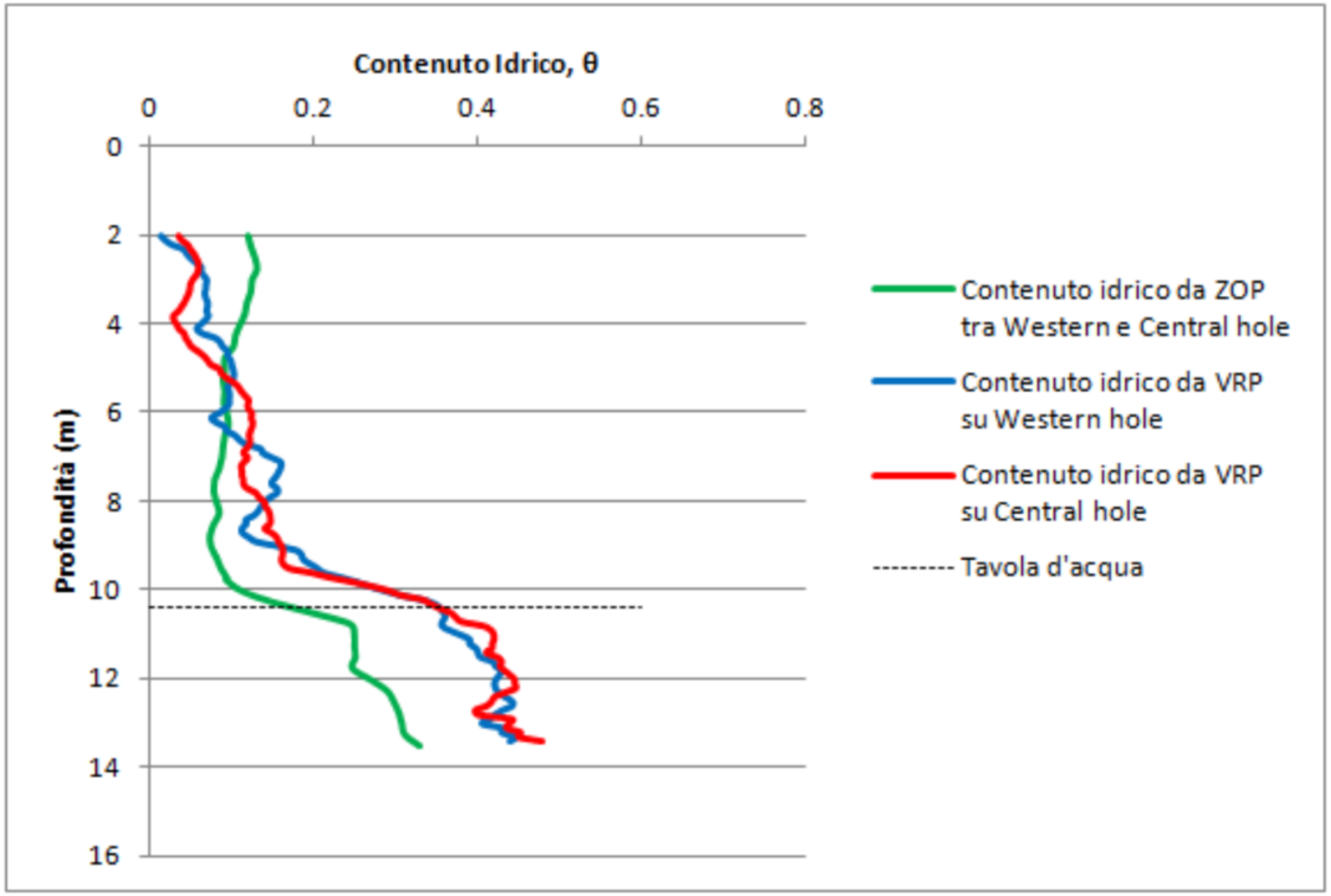
Vertical Radar Profile
VRP

△Velocity of EM waves = △ε

Topp Relation

$$\varepsilon_r = 3.03 + 9.3\theta + 146\theta^2 - 76.7\theta^3$$

Water cont.



Geophysical methods

Applications

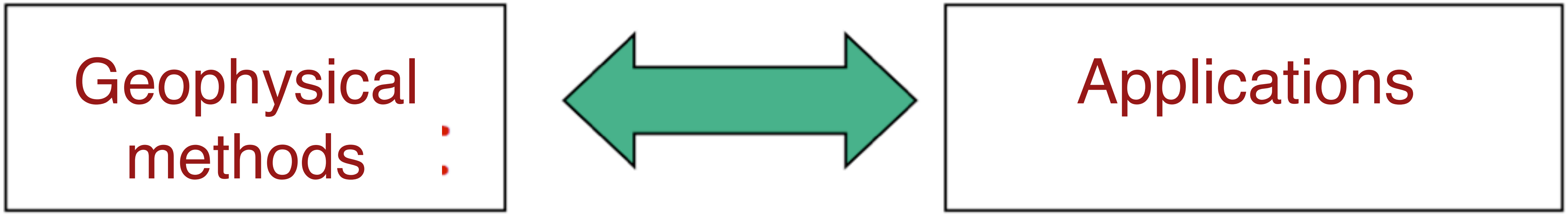
?

- ☐ Electric methods
- ☐ Seismic methods
- ☐ GeoRADAR
- ☐ EM methods
- ☐ Gravimetry
- ☐ Magnetism
- ☐ …

- ☐ Oil and Gas exploration
- ☐ Minerals exploration
- ☐ Engineering studies
- ☐ Hydrogeological studies
- ☐ Pollutants identification
- ☐ Geological characterisation
- ☐ Legal problems
- ☐ Archeology
- ☐ …

Take home messages

	S 1	P	S 2
Seismic methods	Elastic waves	Elastic moduli/ density	Induced vibrations
Electrical methods	Current injection	Resistivity	Voltage potential
Electro-magnetic methods	Electro-magnetic Field	Conductibility	EM secondary fields
Radar (EM)	Electro-magnetic waves	Dielectric contrast	Reflected EM waves



Geophysical methods

Applications

The choice of the methods must follow the criteria:

☐ The target must be suitable with the Physical Parameter measured

☐ The method must have enough spatial (or temporal) RESOLUTION and enough depth PENETRATION

☐ The cost

☐ Logistical issues

☐ Environmental impact

Not basing on the instrument I have…..

Geophysical methods ↔ **Applications**

The choice of the methods must follow the criteria:

- ☐ The target must be suitable with the Physical Parameter measured

INVERSION

- ☐ The method must have enough spatial (or temporal) RESOLUTION and enough depth PENETRATION

RESOLUTION

- ☐ The cost
- ☐ Logistical issues

Logistics !

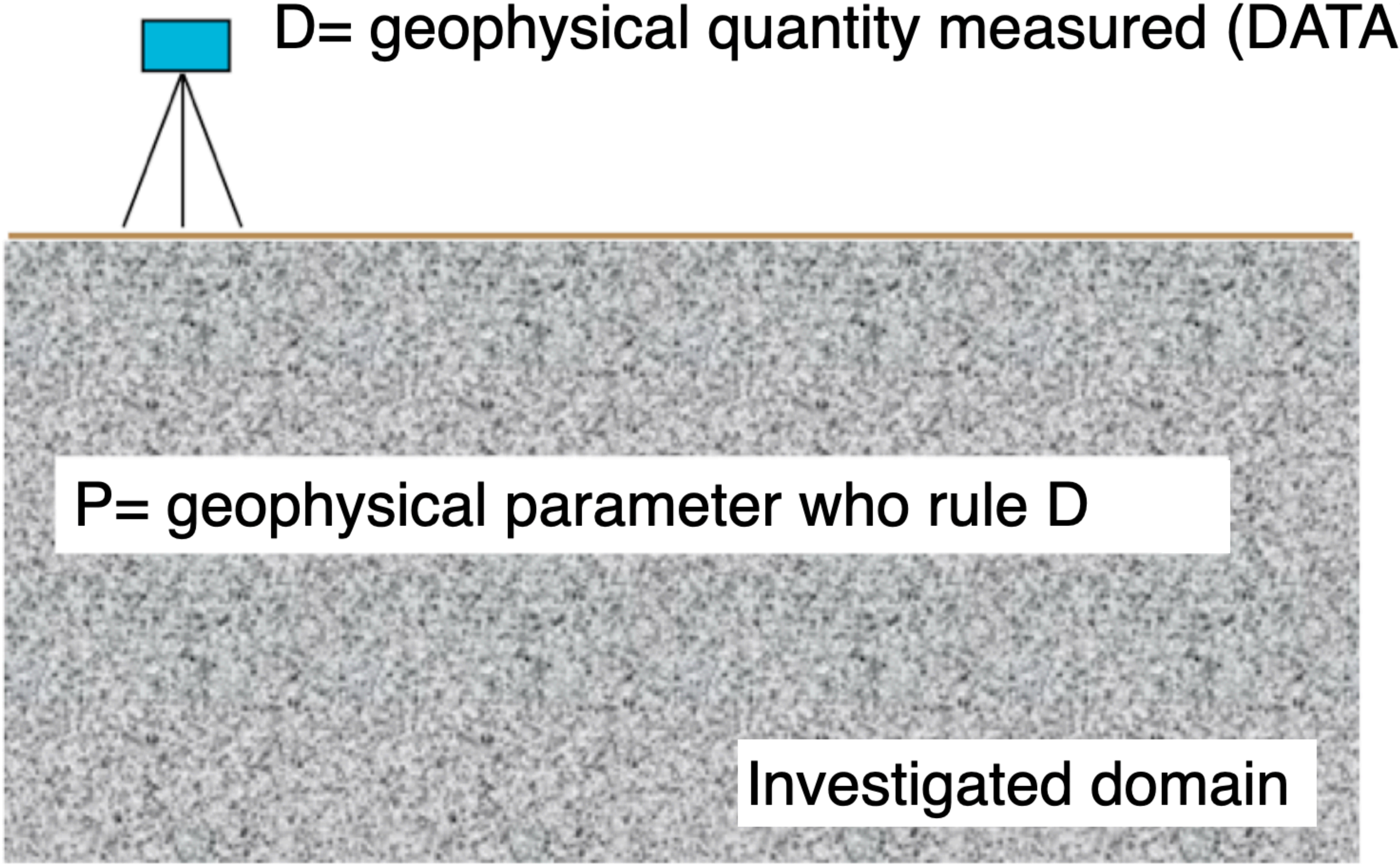
- ☐ Environmental impact

Concepts of Inversion
in
GEOPHYSICS

THE INVERSION

The geophysical measurement

An indirect measurement



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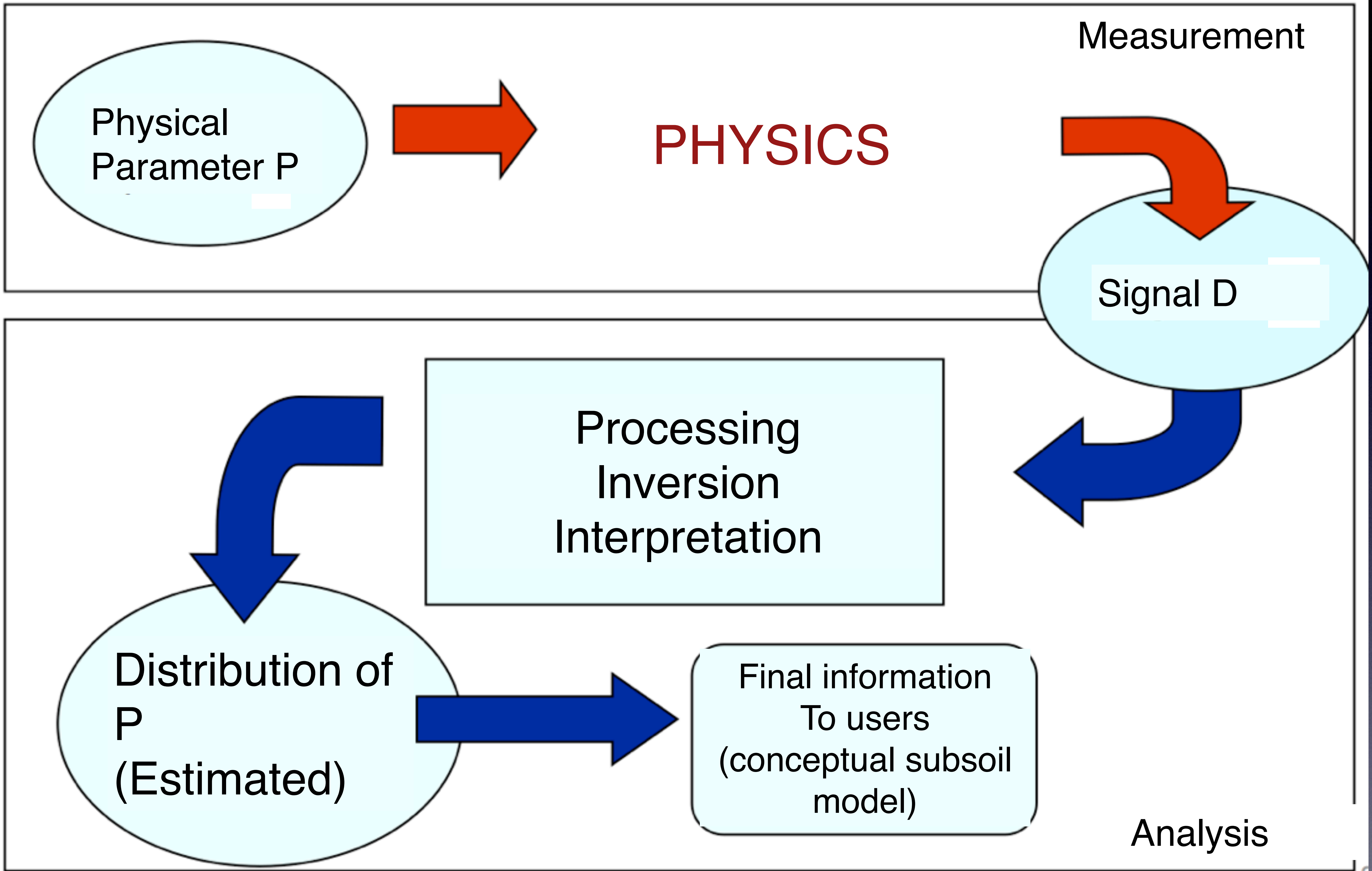
Investigated domain

D= D (P, F= forcing conditions)

Measurements and Analysis in Applied Geophysics



Measurement

Physical
Parameter P

PHYSICS

Signal D

Processing
Inversion
Interpretation

Distribution of
P
(Estimated)

Final information
To users
(conceptual subsoil
model)

Analysis

Forward and Inverse MODELS

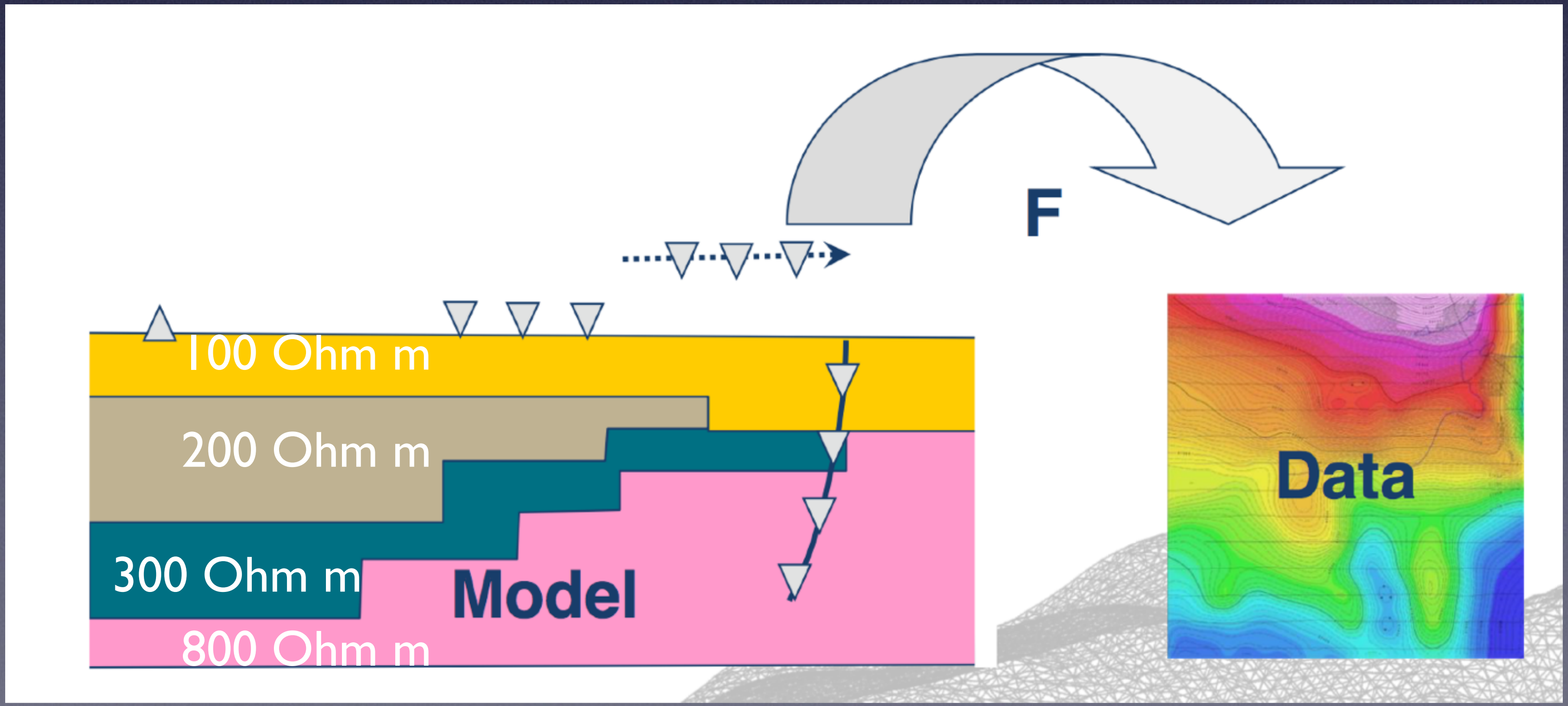
FORWARD MODEL

From a model M, I get a data distribution d

$$d = F\,(M)$$

output *input*

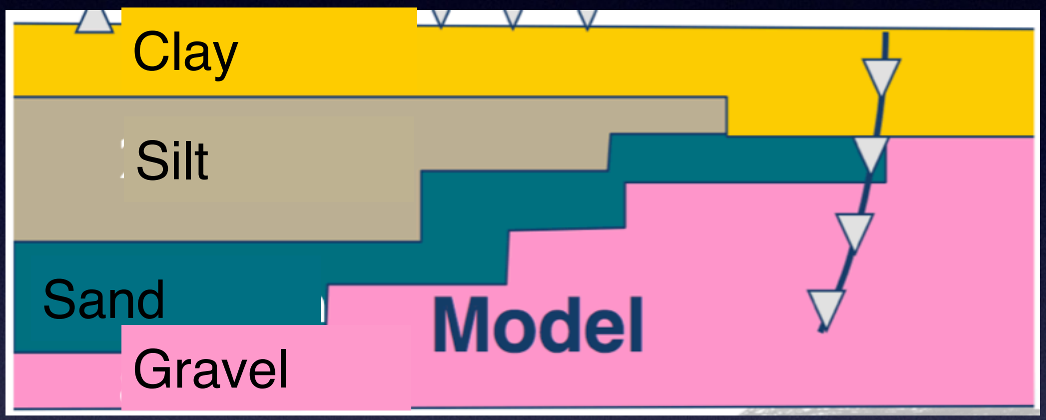
Where F is an operator which rules the relations between models and data



FORWARD MODEL

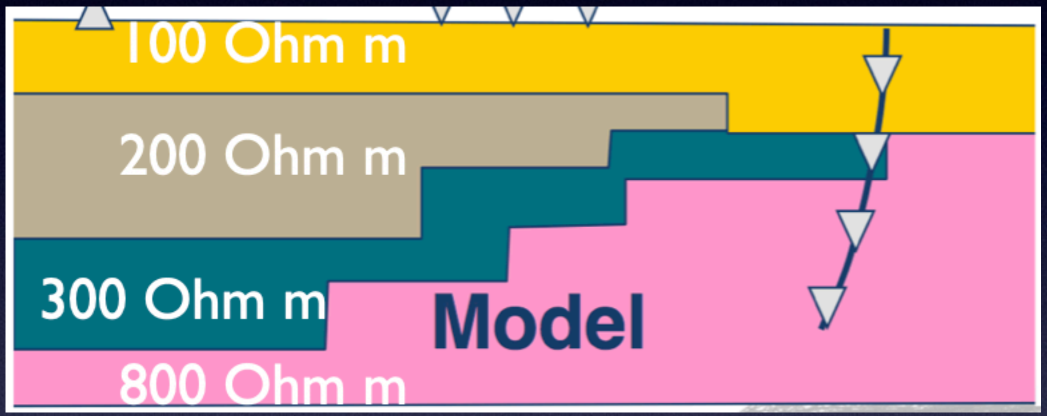
Example

1)

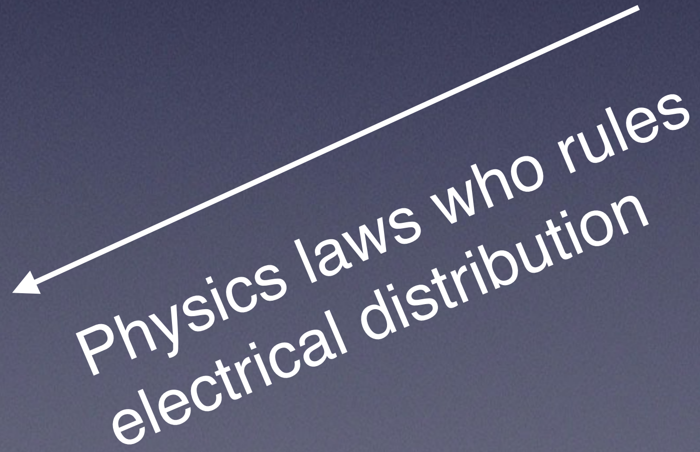


Model
of the subsoil

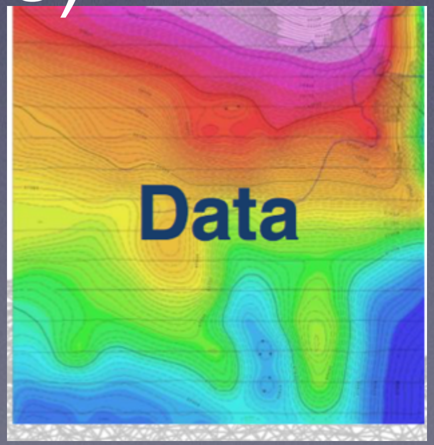
2)



Synthetical Electrical model
of the subsoil


Physics laws who rules
electrical distribution

3)

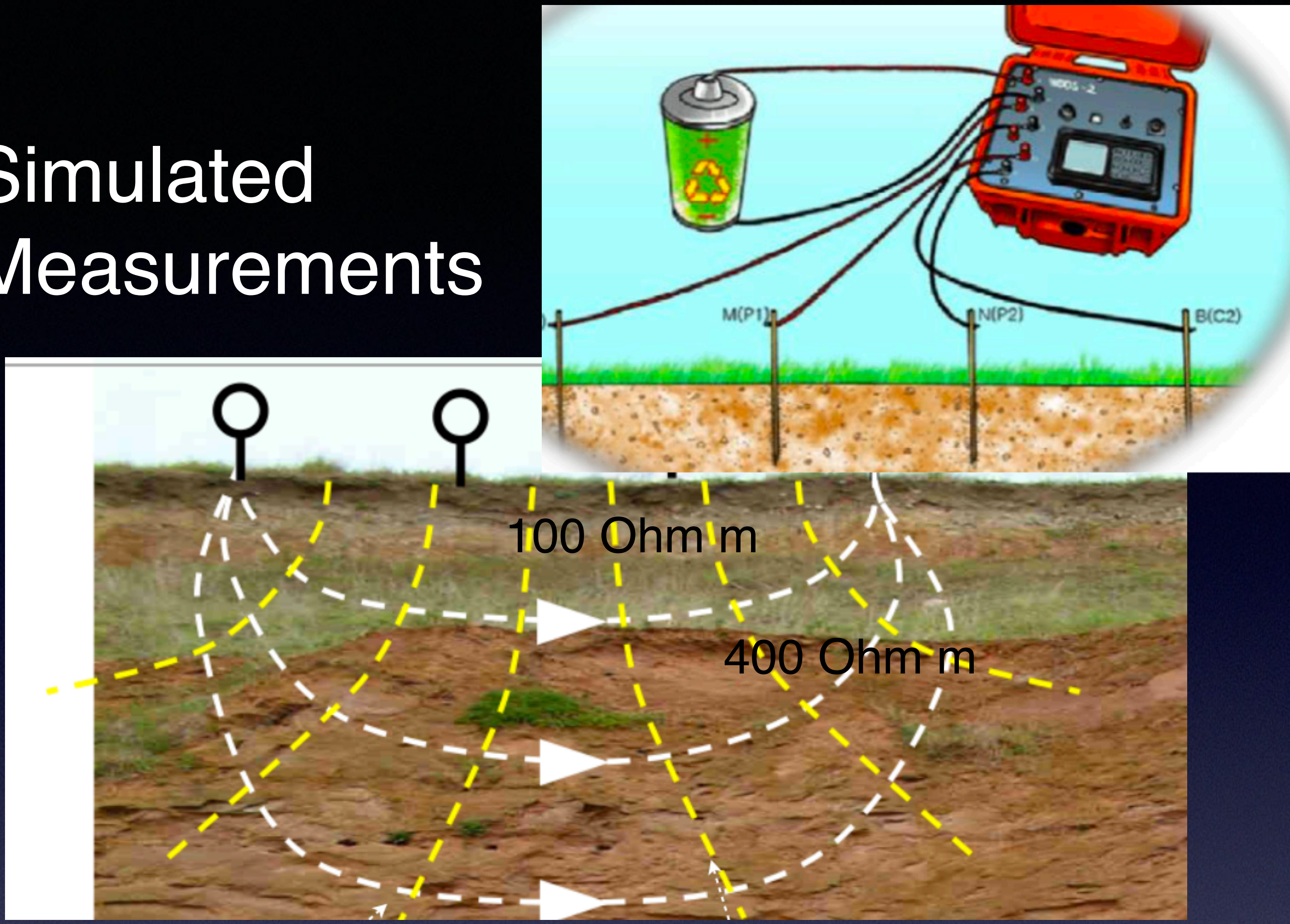


Knowing the physics,
I can simulate which DATA
I would collect in that subsoil

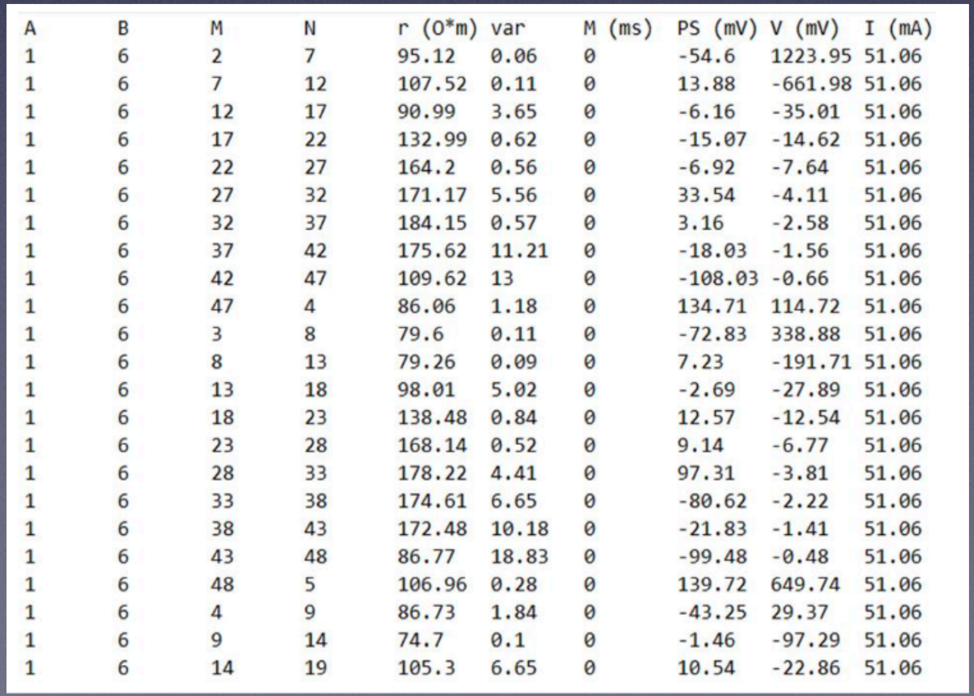
FORWARD MODEL

Model

Simulated Measurements



Instrument Data



A	B	M	N	r (O*m)	var	M (ms)	PS (mV)	V (mV)	I (mA)
1	6	2	7	95.12	0.06	0	-54.6	1223.95	51.06
1	6	7	12	107.52	0.11	0	13.88	-661.98	51.06
1	6	12	17	90.99	3.65	0	-6.16	-35.01	51.06
1	6	17	22	132.99	0.62	0	-15.07	-14.62	51.06
1	6	22	27	164.2	0.56	0	-6.92	-7.64	51.06
1	6	27	32	171.17	5.56	0	33.54	-4.11	51.06
1	6	32	37	184.15	0.57	0	3.16	-2.58	51.06
1	6	37	42	175.62	11.21	0	-18.03	-1.56	51.06
1	6	42	47	109.62	13	0	-108.03	-0.66	51.06
1	6	47	4	86.06	1.18	0	134.71	114.72	51.06
1	6	3	8	79.6	0.11	0	-72.83	338.88	51.06
1	6	8	13	79.26	0.09	0	7.23	-191.71	51.06
1	6	13	18	98.01	5.02	0	-2.69	-27.89	51.06
1	6	18	23	138.48	0.84	0	12.57	-12.54	51.06
1	6	23	28	168.14	0.52	0	9.14	-6.77	51.06
1	6	28	33	178.22	4.41	0	97.31	-3.81	51.06
1	6	33	38	174.61	6.65	0	-80.62	-2.22	51.06
1	6	38	43	172.48	10.18	0	-21.83	-1.41	51.06
1	6	43	48	86.77	18.83	0	-99.48	-0.48	51.06
1	6	48	5	106.96	0.28	0	139.72	649.74	51.06
1	6	4	9	86.73	1.84	0	-43.25	29.37	51.06
1	6	9	14	74.7	0.1	0	-1.46	-97.29	51.06
1	6	14	19	105.3	6.65	0	10.54	-22.86	51.06

Physics laws who rules electrical distribution

Knowing the physics,
I can simulate which DATA
I would collect in that subsoil

Forward and Inverse Models

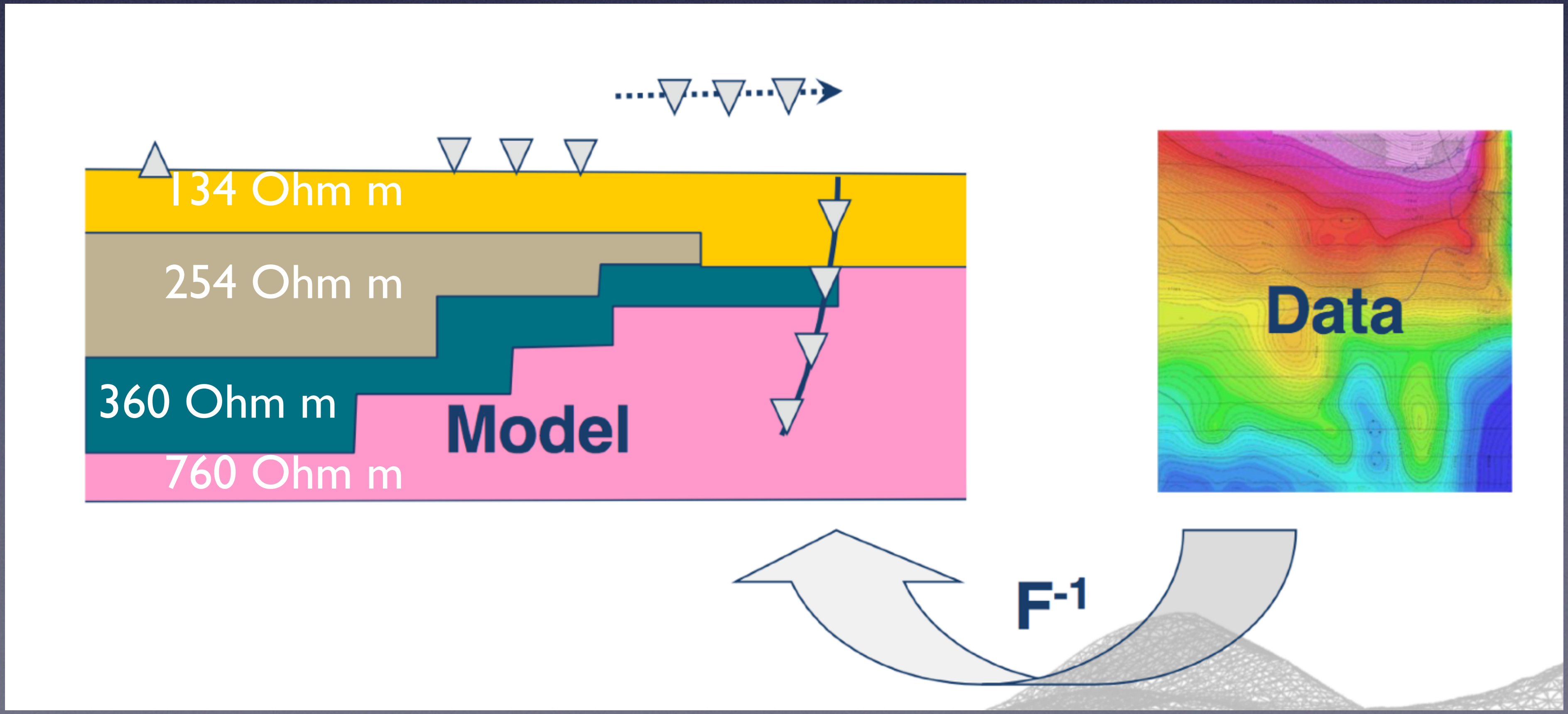
INVERSE MODEL

THE INVERSION in Geophysics are the mathematical and statistical techniques to determine the distribution of the Parameter P (*e.g. resistivity, density etc.*) starting from the observed DATA d

From the data collected d , I retrieve a subsoil model M

$$M = F^{-1}(d)$$

output *input*



Forward and Inverse Models

DIRECT

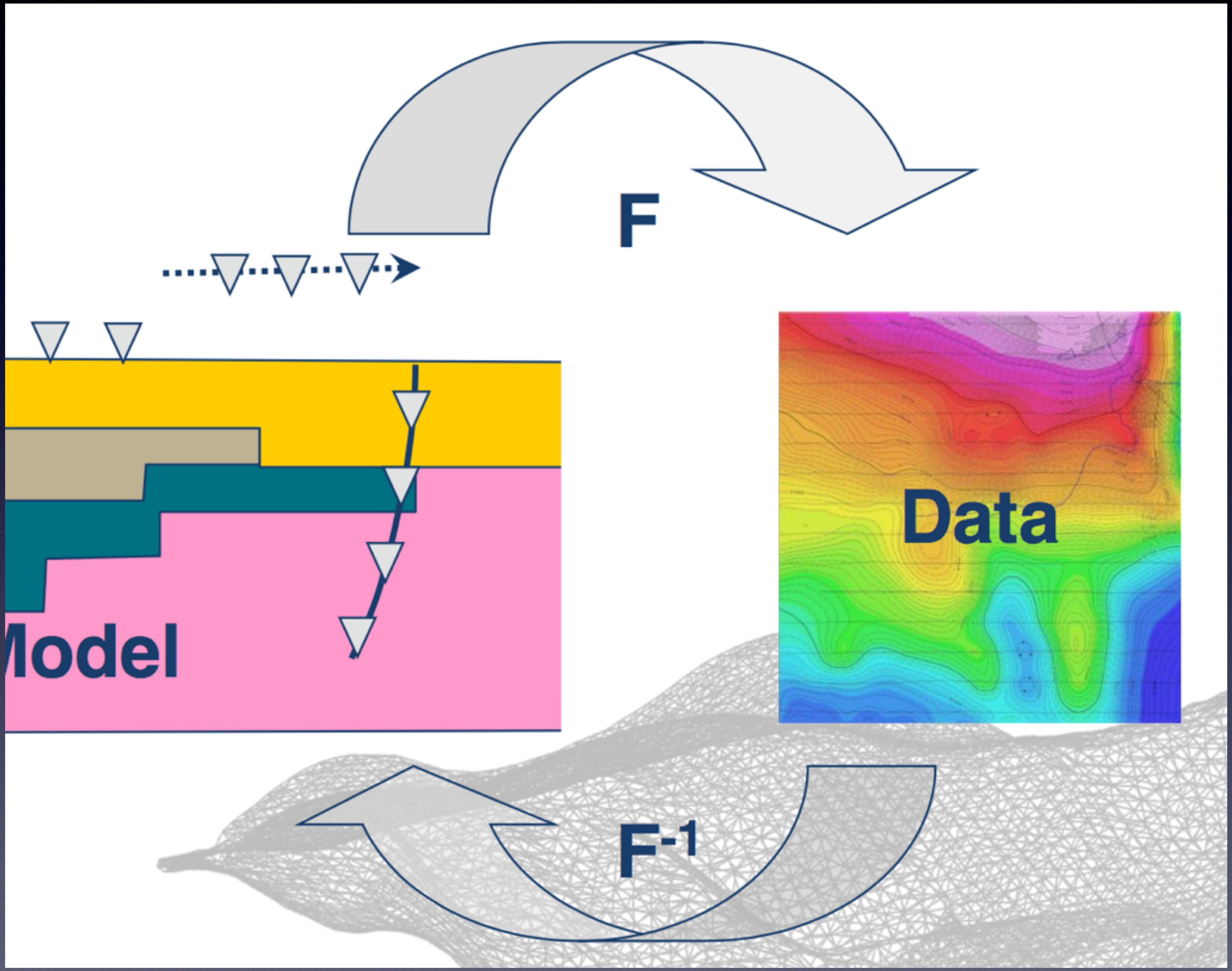
$d = F(M)$

output *input*

INVERSE

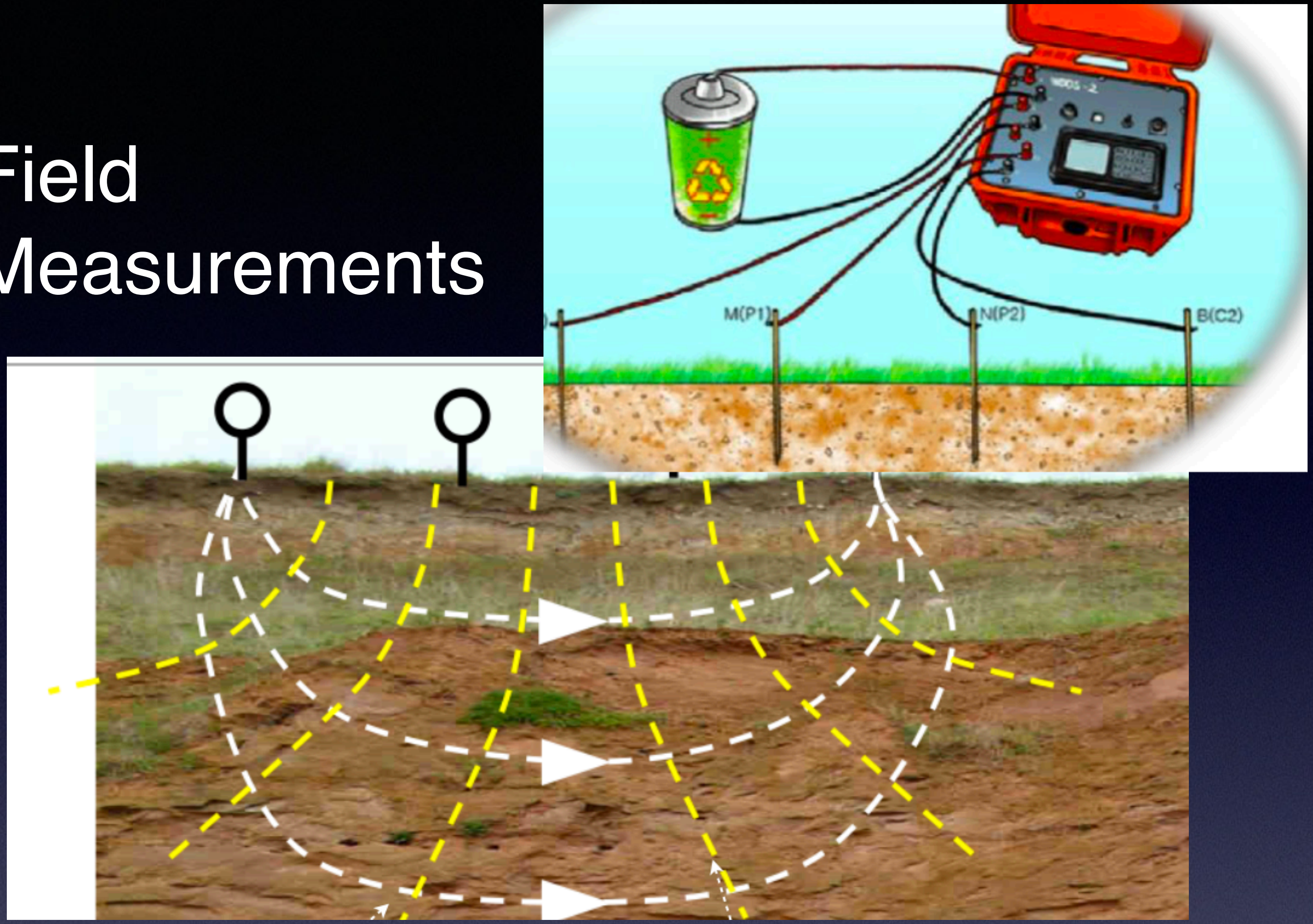
$M = F^{-1}(d)$

output *input*

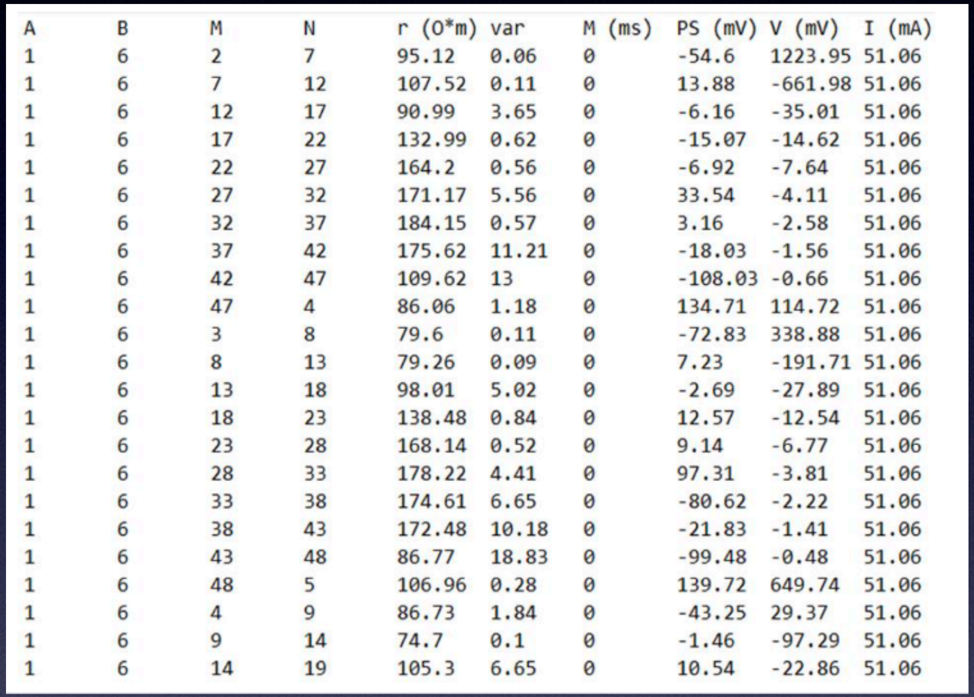


INVERSE MODEL

Field Measurements



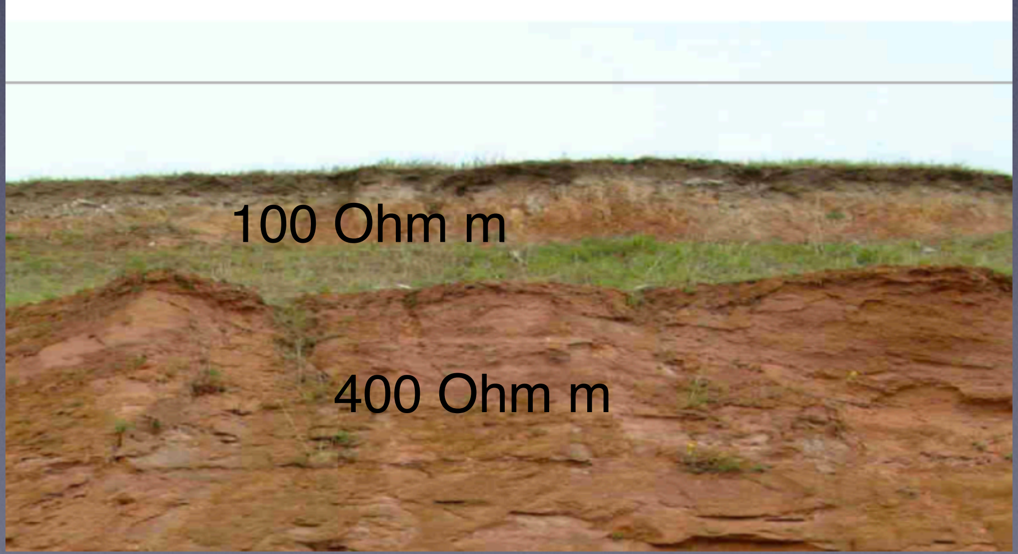
Collected Data



A	B	M	N	r (O*m)	var	M (ms)	PS (mV)	V (mV)	I (mA)
1	6	2	7	95.12	0.06	0	-54.6	1223.95	51.06
1	6	7	12	107.52	0.11	0	13.88	-661.98	51.06
1	6	12	17	90.99	3.65	0	-6.16	-35.01	51.06
1	6	17	22	132.99	0.62	0	-15.07	-14.62	51.06
1	6	22	27	164.2	0.56	0	-6.92	-7.64	51.06
1	6	27	32	171.17	5.56	0	33.54	-4.11	51.06
1	6	32	37	184.15	0.57	0	3.16	-2.58	51.06
1	6	37	42	175.62	11.21	0	-18.03	-1.56	51.06
1	6	42	47	109.62	13	0	-108.03	-0.66	51.06
1	6	47	4	86.06	1.18	0	134.71	114.72	51.06
1	6	3	8	79.6	0.11	0	-72.83	338.88	51.06
1	6	8	13	79.26	0.09	0	7.23	-191.71	51.06
1	6	13	18	98.01	5.02	0	-2.69	-27.89	51.06
1	6	18	23	138.48	0.84	0	12.57	-12.54	51.06
1	6	23	28	168.14	0.52	0	9.14	-6.77	51.06
1	6	28	33	178.22	4.41	0	97.31	-3.81	51.06
1	6	33	38	174.61	6.65	0	-80.62	-2.22	51.06
1	6	38	43	172.48	10.18	0	-21.83	-1.41	51.06
1	6	43	48	86.77	18.83	0	-99.48	-0.48	51.06
1	6	48	5	106.96	0.28	0	139.72	649.74	51.06
1	6	4	9	86.73	1.84	0	-43.25	29.37	51.06
1	6	9	14	74.7	0.1	0	-1.46	-97.29	51.06
1	6	14	19	105.3	6.65	0	10.54	-22.86	51.06

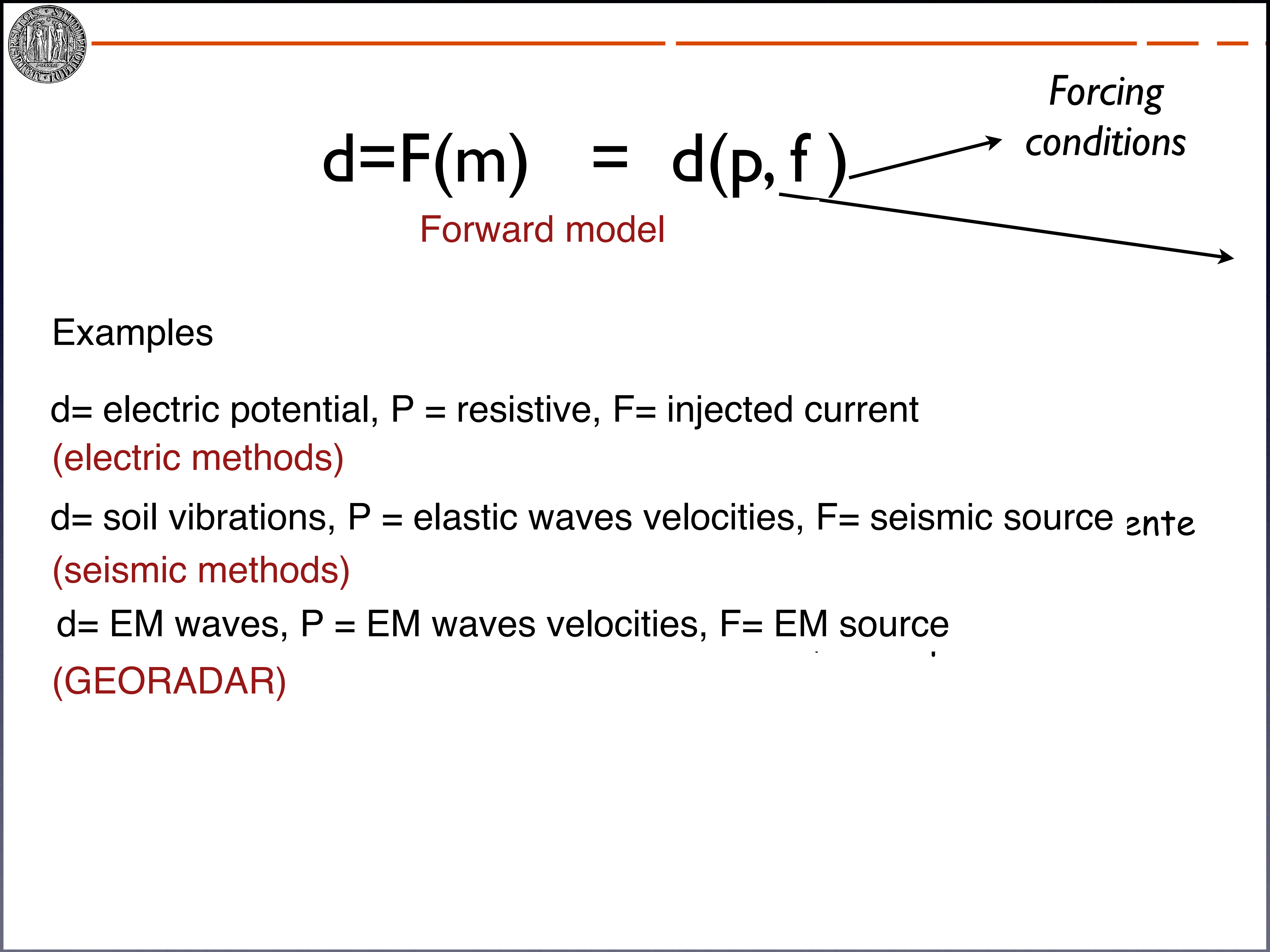
INVERSION

Model



From the collected DATA
I retrieve a model of the subsoil

Direct and Inverse models



$$d=F(m) \quad = \quad d(p, f)$$

Forcing conditions

Forward model

Examples

d= electric potential, P = resistive, F= injected current
(electric methods)

d= soil vibrations, P = elastic waves velocities, F= seismic source ente
(seismic methods)

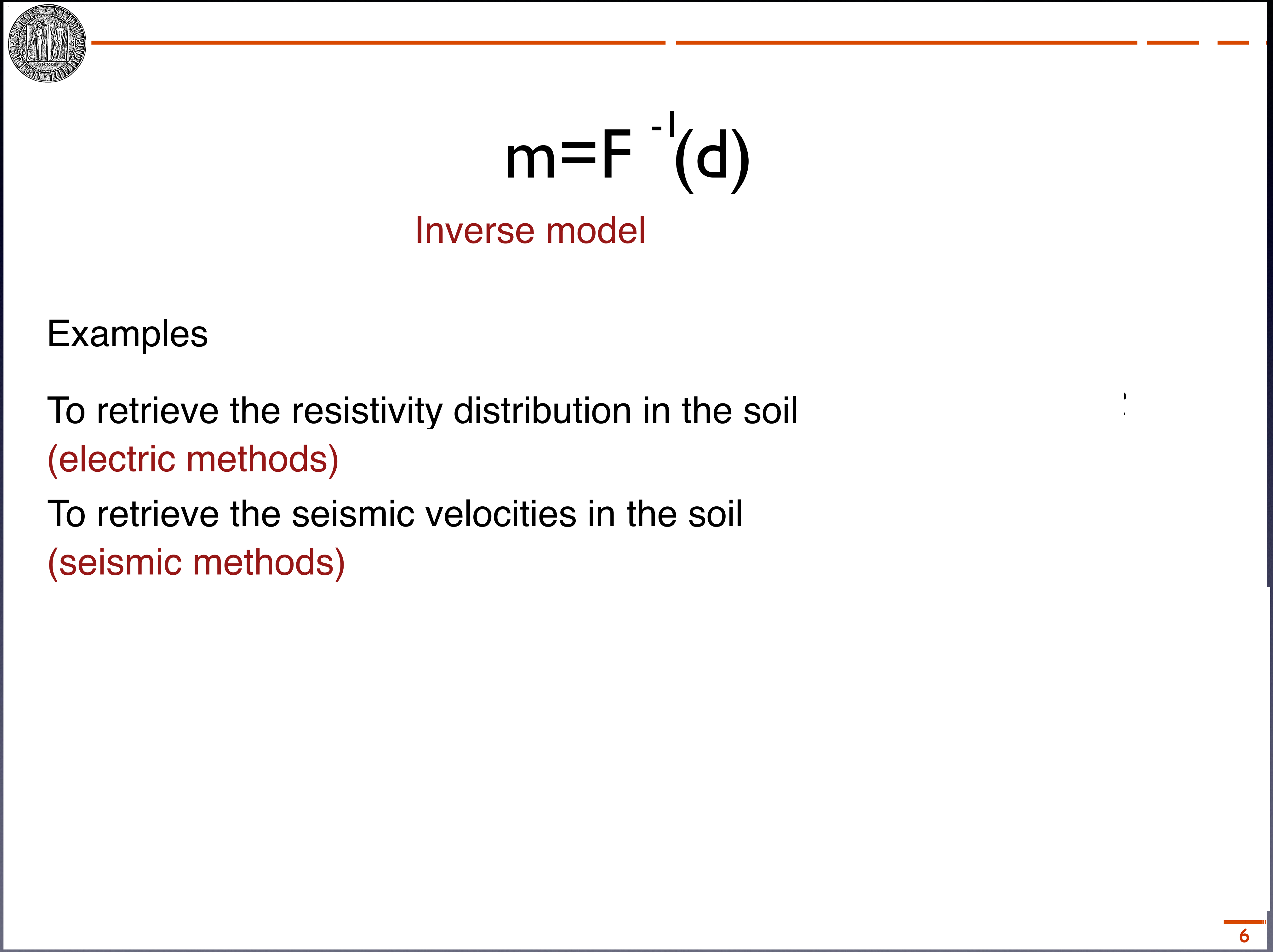
d= EM waves, P = EM waves velocities, F= EM source
(GEORADAR)

We do not want d
(Physical quantity measured)

but
P
(Physical earth Parameter)

We need the soil characteristics, retrieved by indirect not invasive methods

Direct and Inverse models



$$m=F^{-1}(d)$$

Inverse model

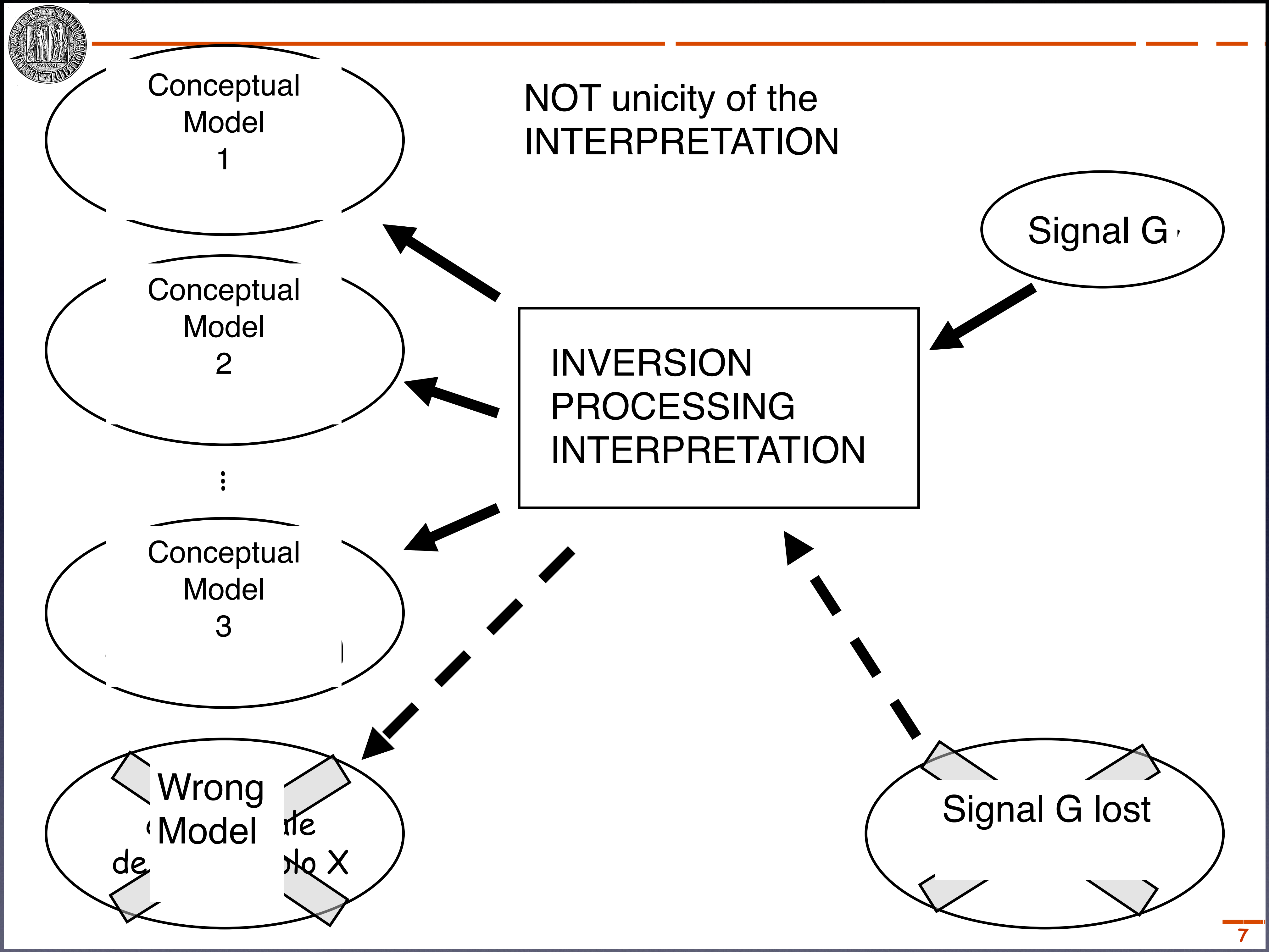
Examples

To retrieve the resistivity distribution in the soil
(electric methods)

To retrieve the seismic velocities in the soil
(seismic methods)

We need an Inversion Process

Direct and Inverse models



Conceptual Model 1

Conceptual Model 2

⋮

Conceptual Model 3

Wrong Model

de ile plo X

NOT unicity of the INTERPRETATION

Signal G

INVERSION PROCESSING INTERPRETATION

Signal G lost

The indirect methods are easy, fast, cheap…

The price of is the non unicity in the solution

The inverse model is mathematically **ill-posed** , it does not respect: unicity, linearity, existence of the solution…

- inversion: an ill posed problem

Hadamard 1923,

Math problem is well posed if:

1) for all the admissible data a solution exists (existence)

2) for all the admissible data the solution is unique (unicity)

3) solution depends in a continuous way from the data (stability)

Otherwise it is ILL POSED !

- inversion: an ill posed problem

Hadamard 1923,

Math problem is well posed if:

1) for all the admissible data a solution exists (existence)

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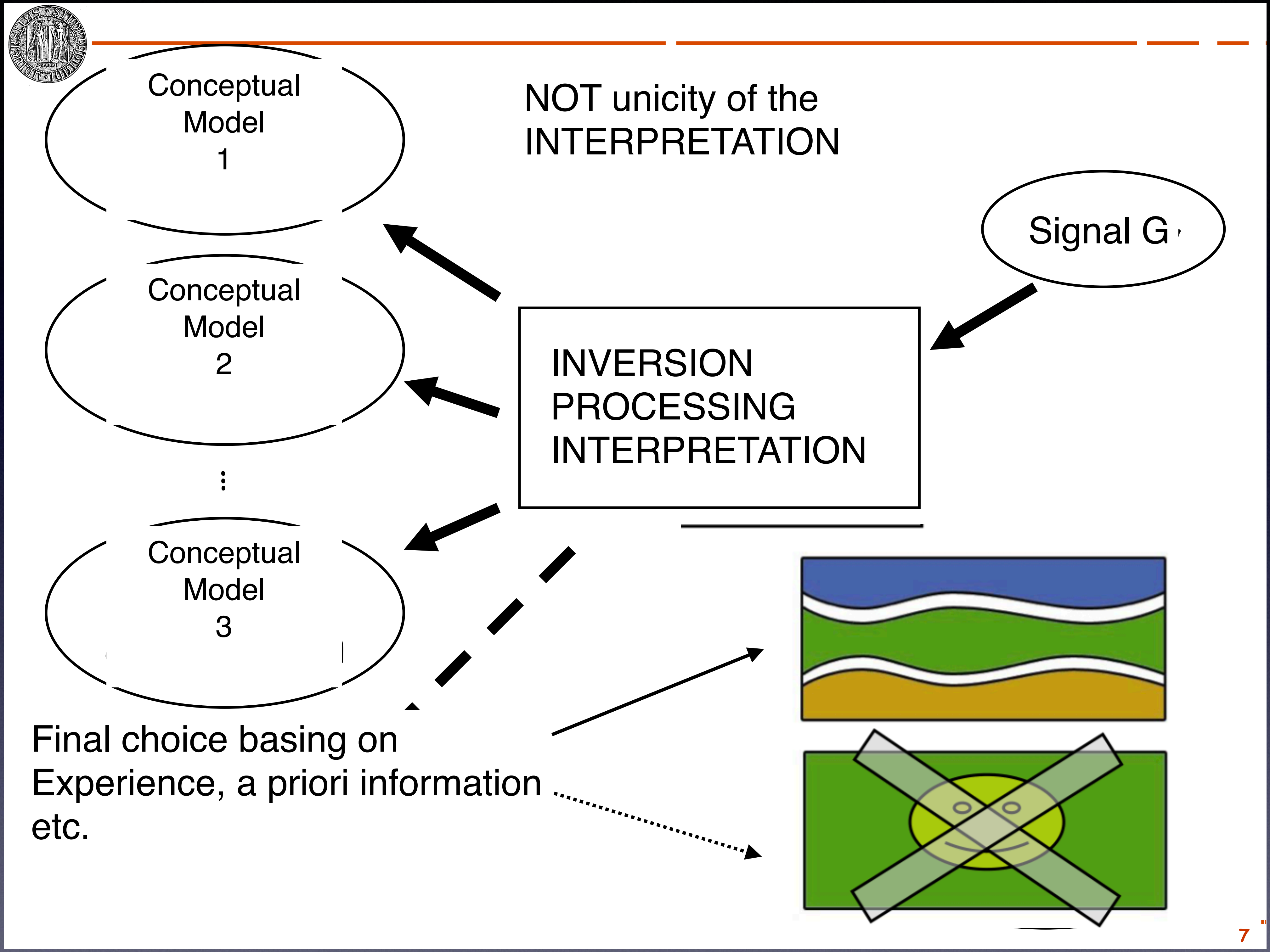
Inverse problem is ILL POSED !

Direct and Inverse models



NOT unicity of the
INTERPRETATION

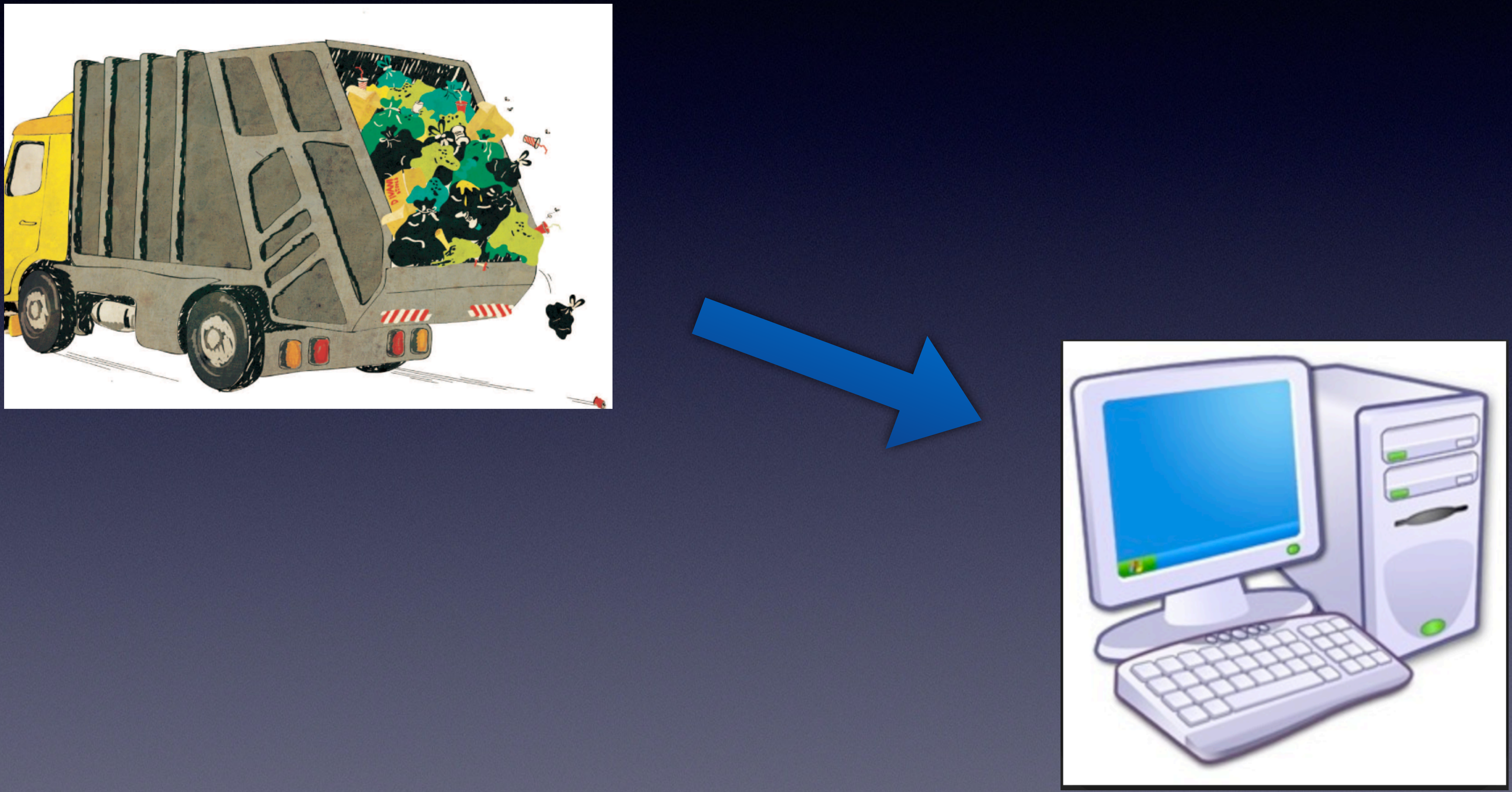
INVERSION
PROCESSING
INTERPRETATION

Final choice basing on
Experience, a priori information
etc.

Correct
Interpretation
Can be
Hard

- Bad cases

Bad data input to excellent inversion algorithm

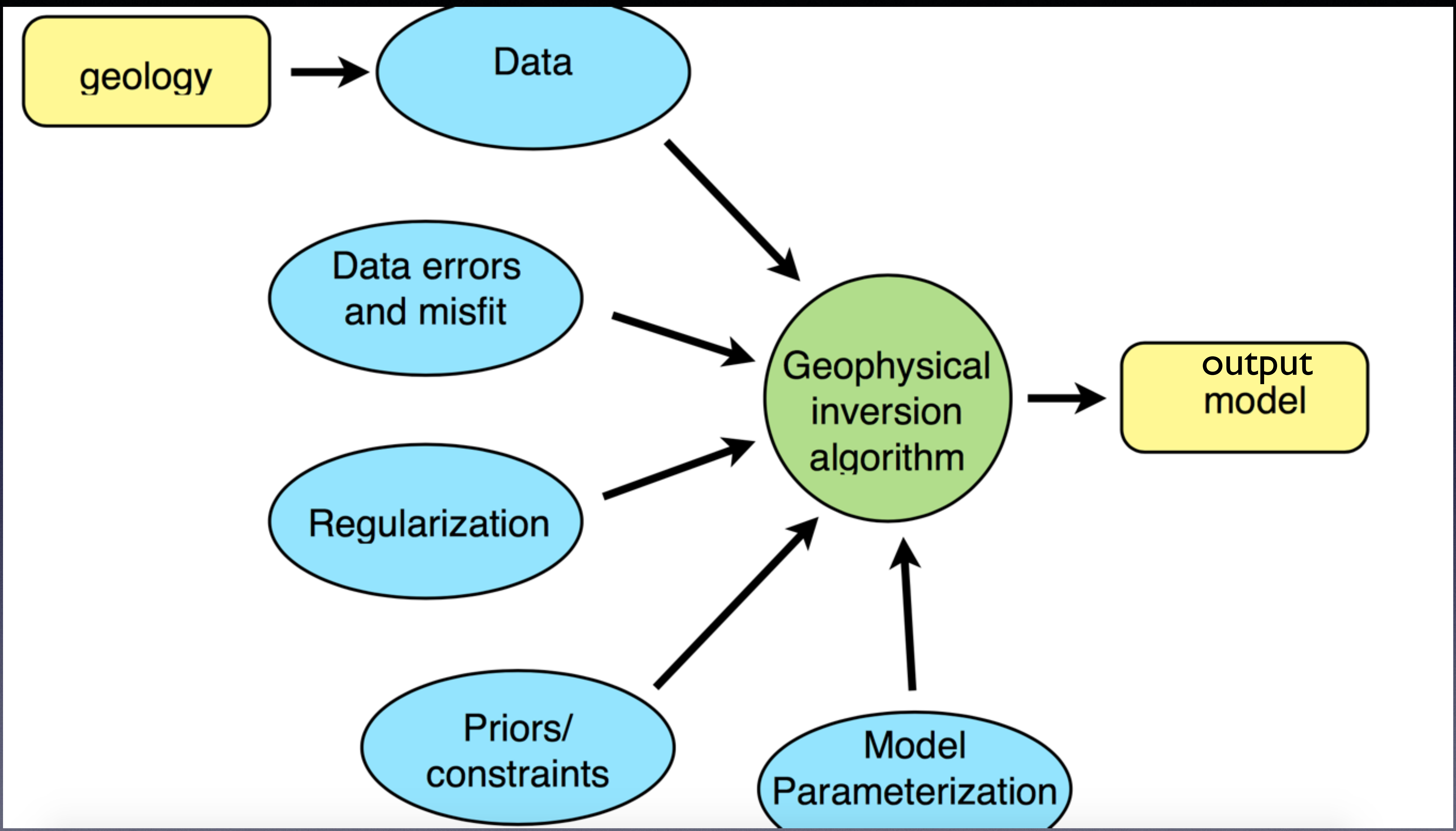


BAD OUTPUT

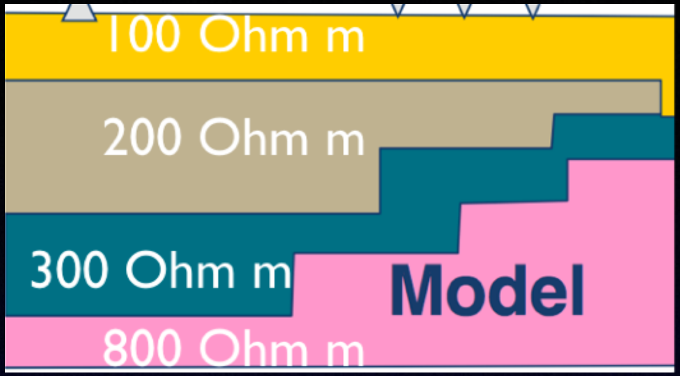
Garbage in, garbage out!

Inversion process

Find the model which minimise the data misfit

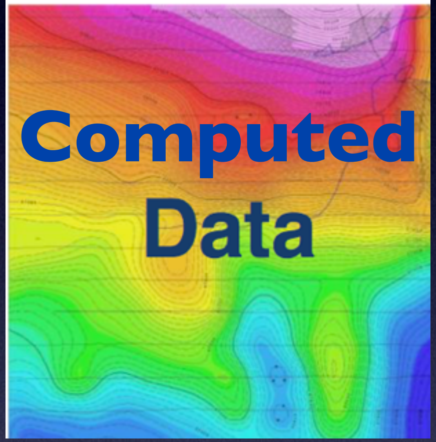


INVERSION PROCESS

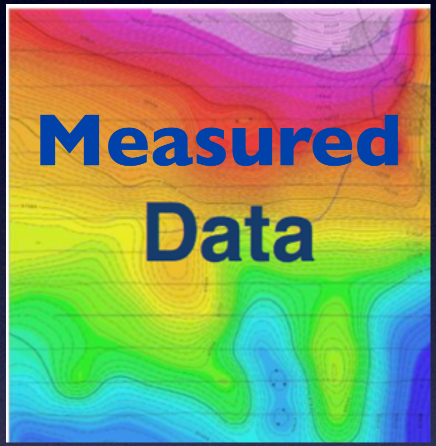


Forward model

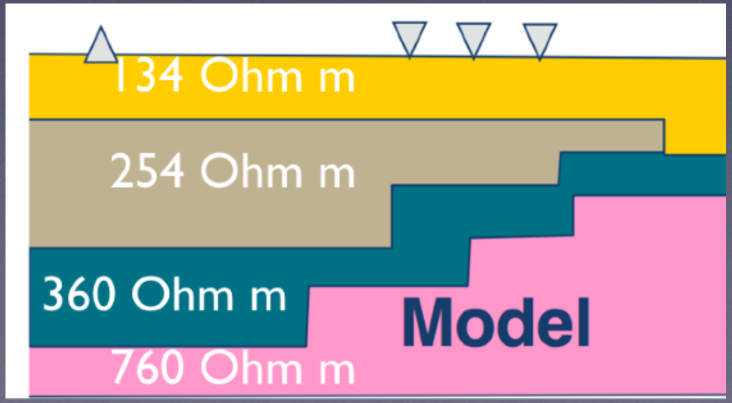
Input data



Comparing differences

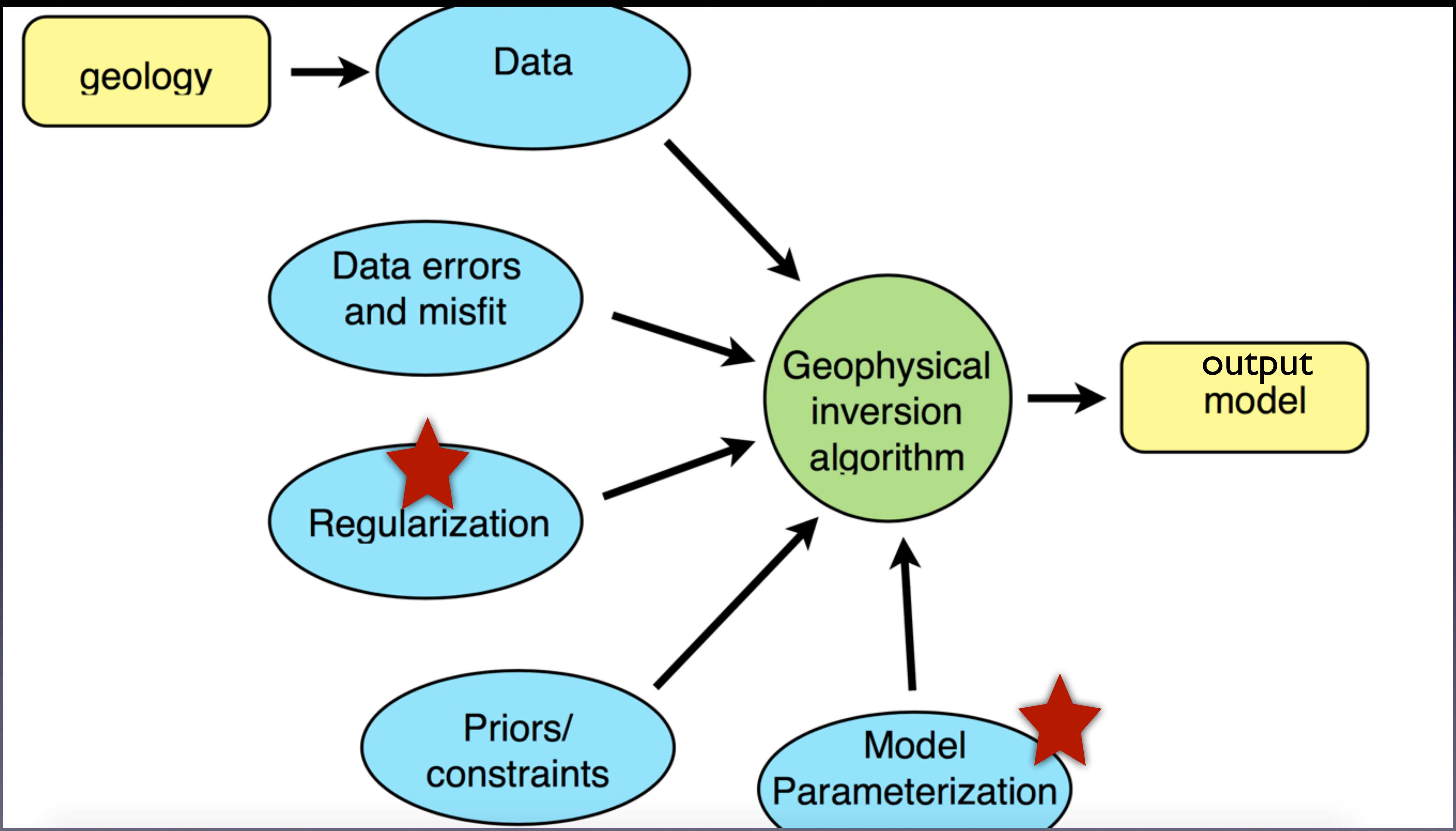


Find the model which minimize the differences



Output result

INVERSION PROCESS



geology

Data

Data errors and misfit

Regularization

Priors/ constraints

Model Parameterization

Geophysical inversion algorithm

output model

Inversion

Regularisation

Essential in ill posed problems

find the smoothest model that fits the data
(e.g. Tikhonov Regularization)

Ockham Razor (William of Ockham XIV sec)

"It is vain to do with more that which can be done with fewer"

«A parità di fattori la spiegazione più semplice è da preferire»

Find the best simplest model that fit the data

Inversion

Regularisation

Minimise the appropriate objective functions with several strategies, able to solve the given conditions

(linear or not linear)

↓

(Minimise the difference between observed dataset and calculated ones)

Inversion

Parametrisation

The problem of identify parameters need an parameters optimisation (Parametrisation).

1) Discretize the space
2) Choose the physical parameters for the starting model

$$d=F(m)$$

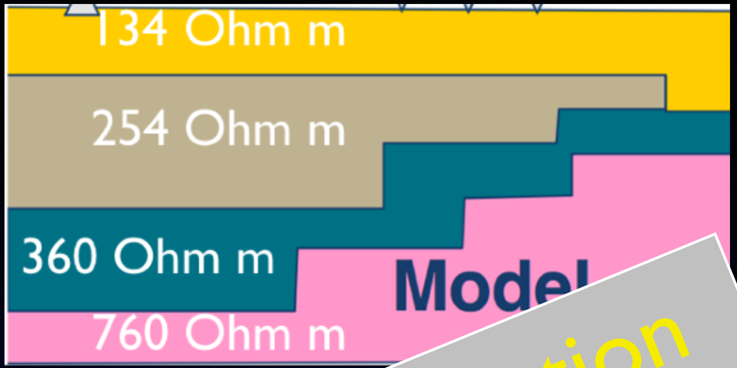
Direct model

$$m = (m_1, m_2, \ldots\ldots, m_N)$$

m_i models parameters (usually positive)

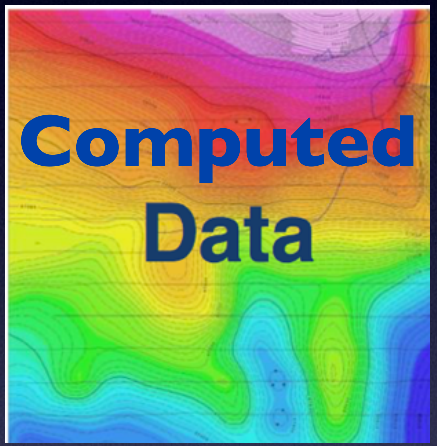
e.g.
We can parametrize in log(m) to avoid negative values

Inversion



Parametrisation

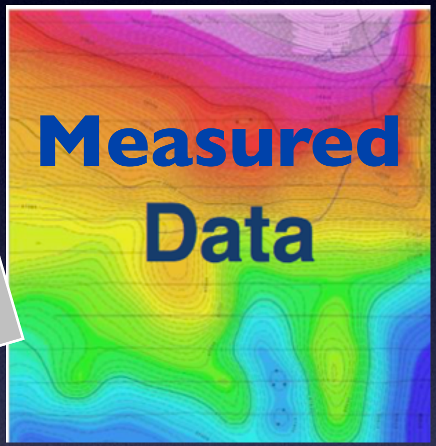
Forward model



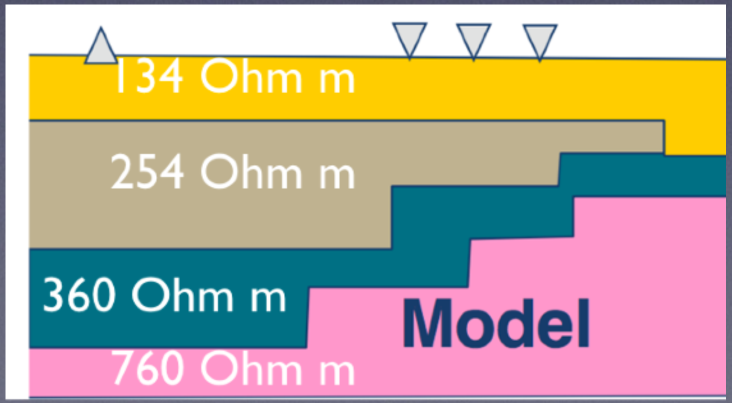
Comparing differen

Regularisation

Input data



Find the model which minimise the differences



Output result

EXTRA
MATERIAL

Inversion

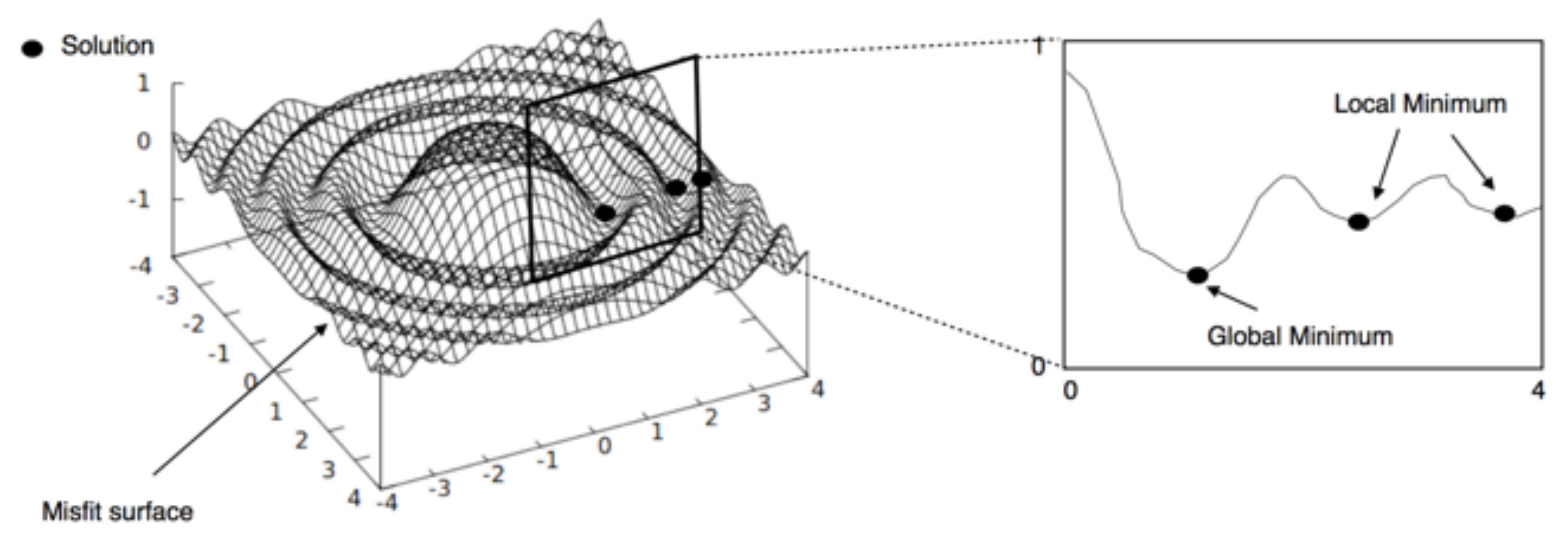
Find the model who minimise data misfit….

- Inversion
  - Linear
    - Least Squares Method
  - Not Linear
    - local Methods
    - Global Methods

Inversion

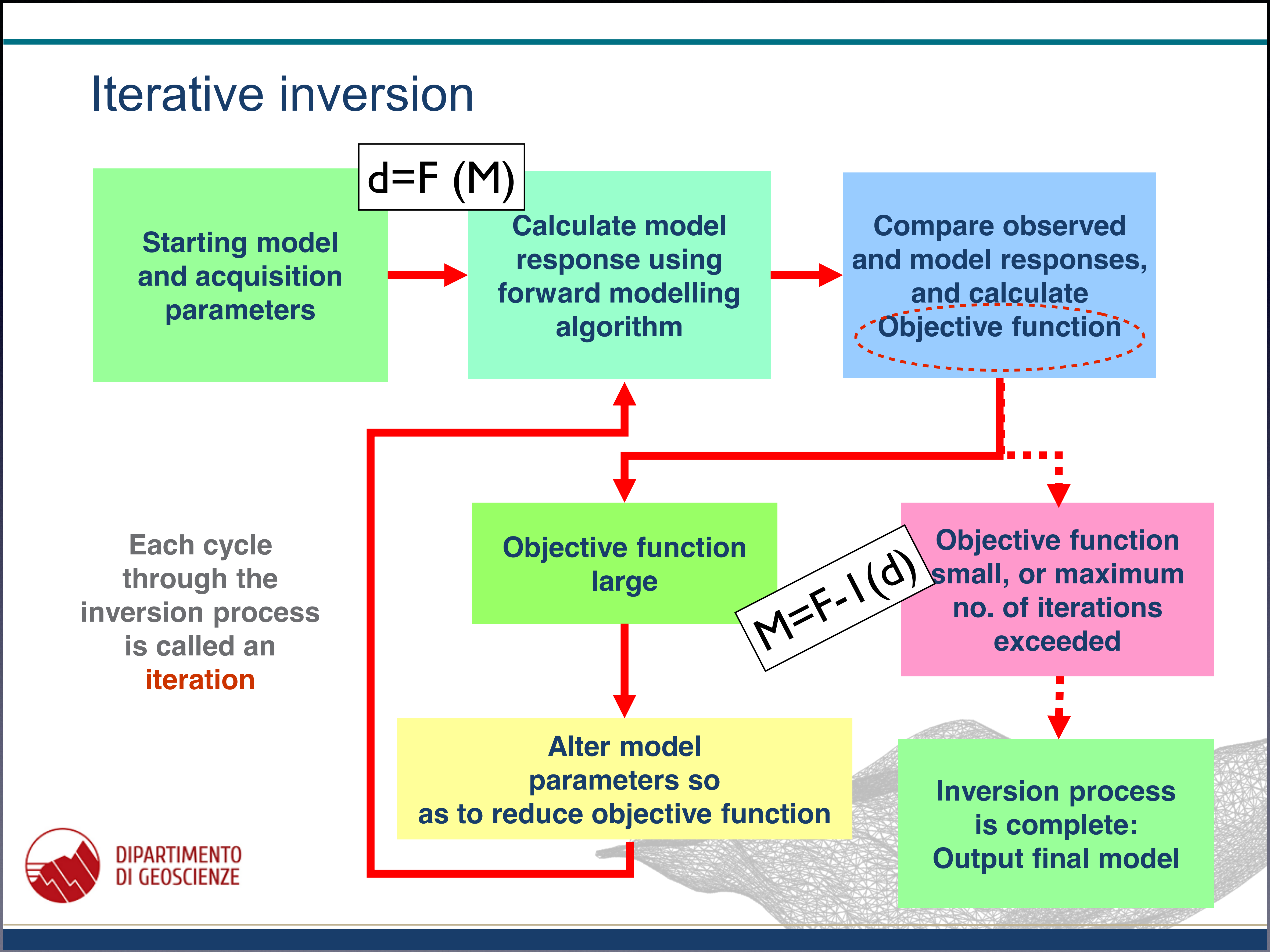
Inversion find the optimum value of the *misfit*, a functional of the difference between observed data and the synthetical one calculated from a starting model correctly parameterised.

The minima of the *misfit surface*, as a function of the parameters model, are the solutions.



Solutions can be local or global (e.g. Montecarlo methods)

Find the model who minimise the data misfit
Iterative Process



Iterative inversion

d=F (M)

Starting model and acquisition parameters

Calculate model response using forward modelling algorithm

Compare observed and model responses, and calculate Objective function

Objective function large

Objective function small, or maximum no. of iterations exceeded

M=F-1(d)

Alter model parameters so as to reduce objective function

Inversion process is complete: Output final model

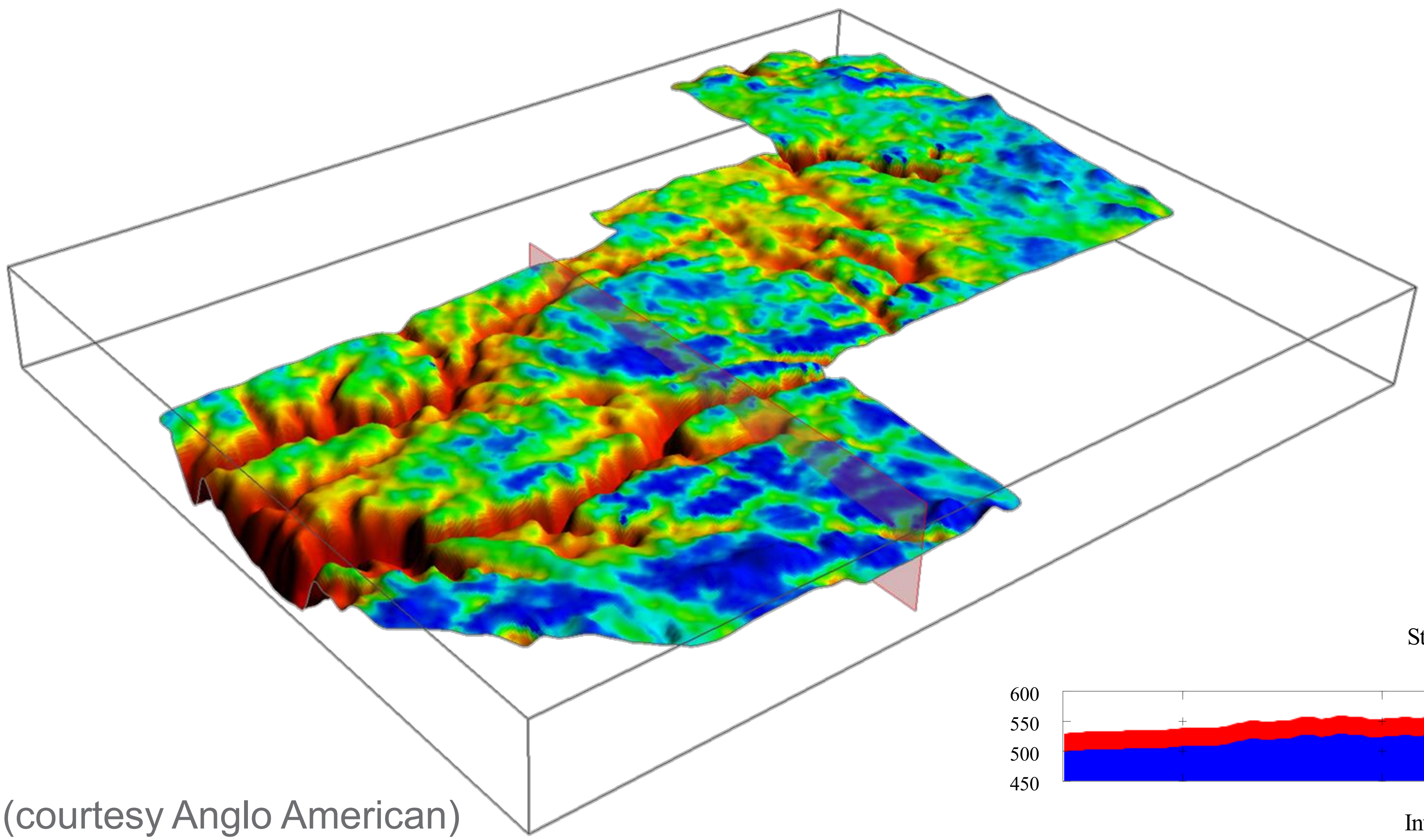
Each cycle through the inversion process is called an **iteration**

DIPARTIMENTO DI GEOSCIENZE

Inverse Modelling

Lithology Based Modelling

- Provide physical properties (single value or distribution) for each lithology and adjust the geometry to fit the data.

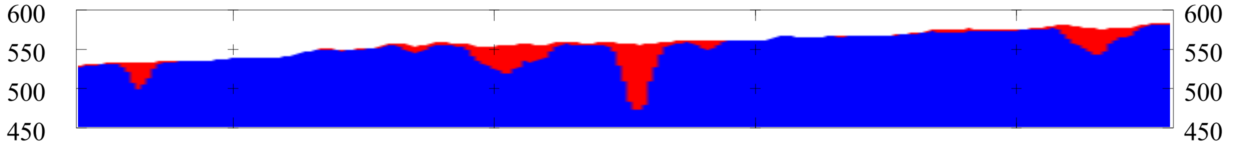


(courtesy Anglo American)

RESULT IS A GEOLOGICAL MODEL

Starting Model

Inverted Model



Mira Geoscience
...modelling the earth

Which Precision ??

The production manager asked a geologist, engineer, and geophysicist what 2 + 2 was.

The geologist thought for a bit and then said "*somewhere between 3 and 5*".

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The engineer fiddled with a calculator and said “*3.9999999*”.

Which Precision ??

The production manager asked a geologist, engineer, and geophysicist what 2 + 2 was.

The geologist thought for a bit and then said “*somewhere between 3 and 5*”.

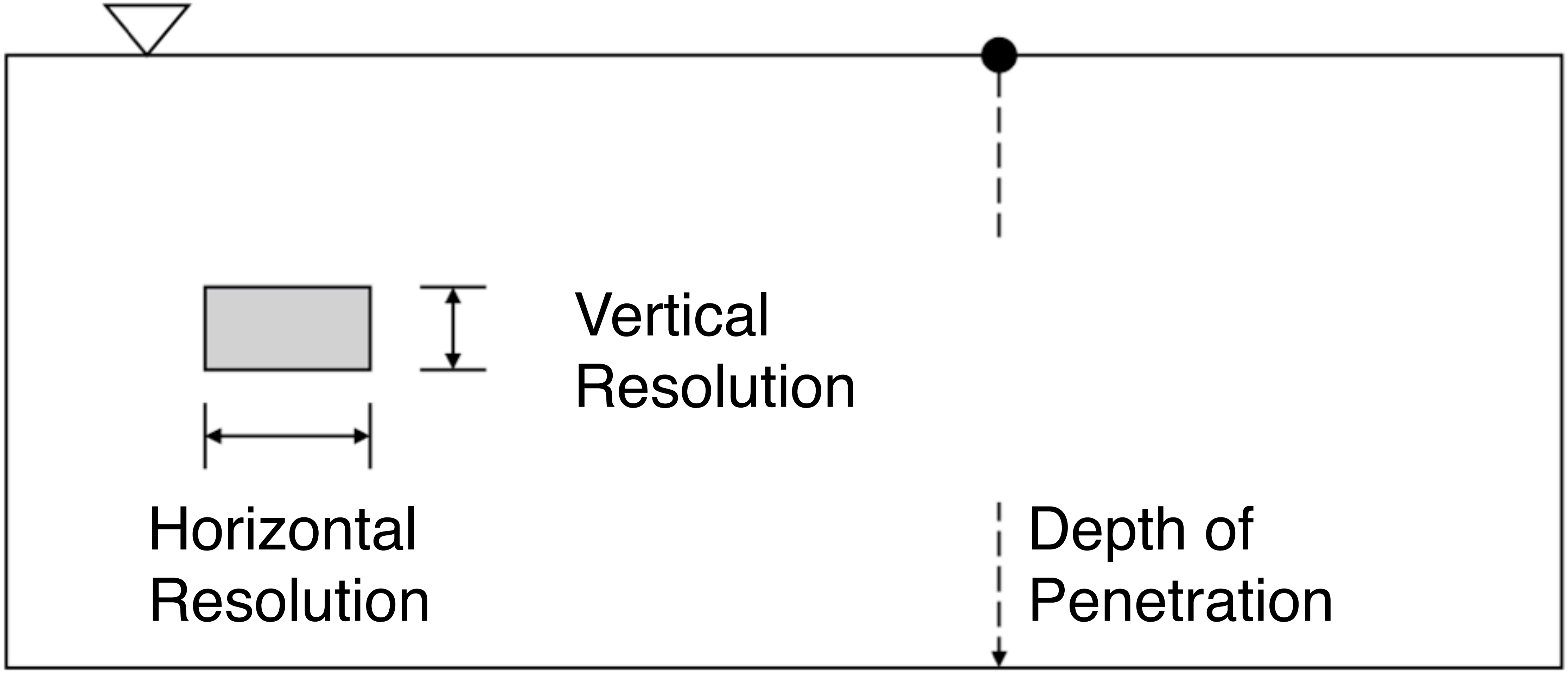
The engineer fiddled with a calculator and said “*3.9999999*”.

The geophysicist looked her in the eye and asked “*what answer do you want*” ??

Concept of Resolution

In the geophysical problem

The method should have enough RESOLUTION and PENETRATION



Vertical Resolution

Horizontal Resolution

Depth of Penetration

Resolution vs Penetration

Is always a compromise !

.

You can go deep with poor resolution,
or have details imaging but in the near surface

Elements of signal processing

Elements of signal processing

Every analog signal must be:

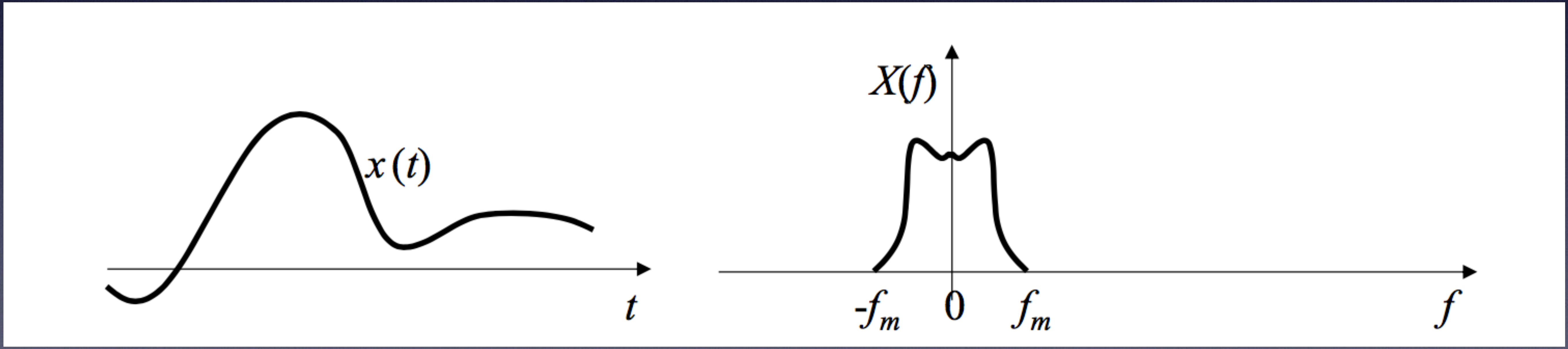
- recorded (then truncated)
- sampled

Elements of signal processing

The ALIASING problem

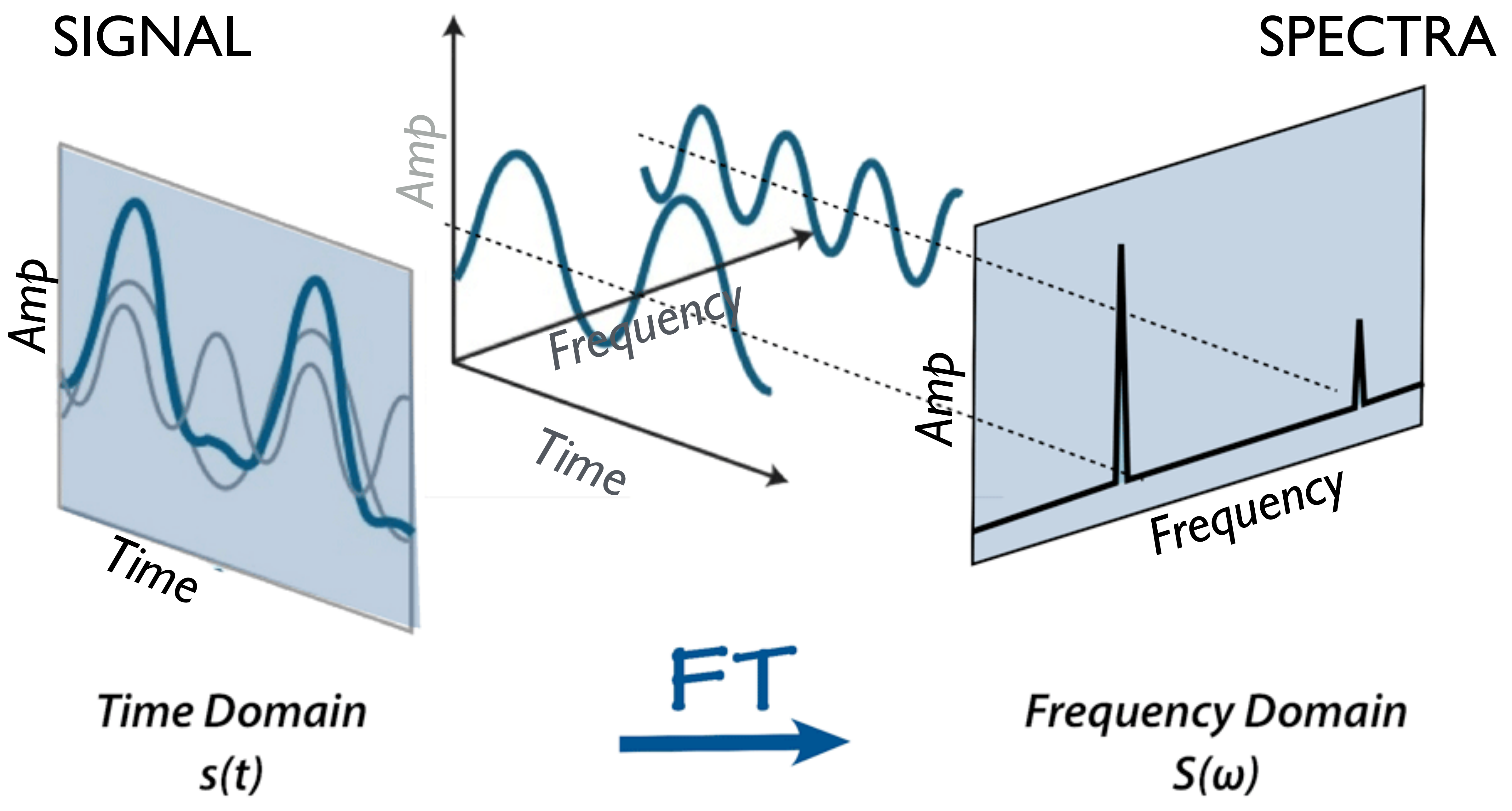
Time domain

Frequency domain



Fourier time-frequency transform

every signal can be decomposed in a sum of sinusoidal with different frequencies and amplitudes

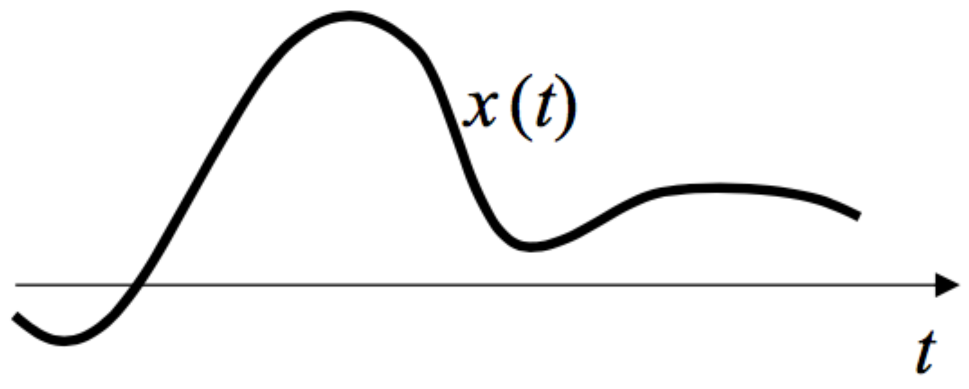


Ideal Sampling

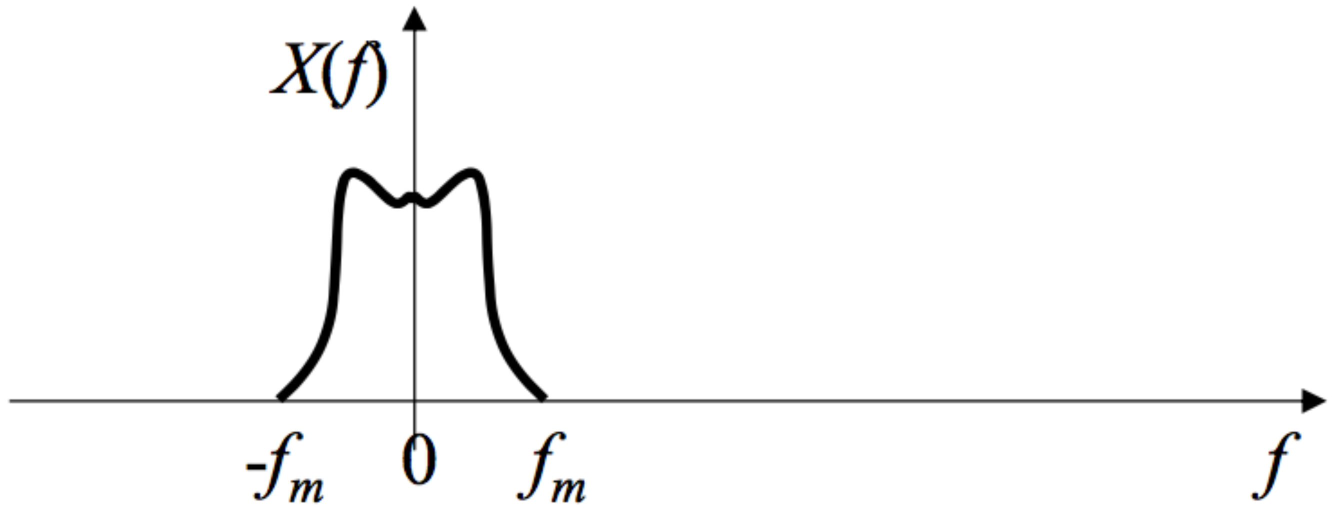
TIME DOMAIN.

FREQUENCY DOMAIN

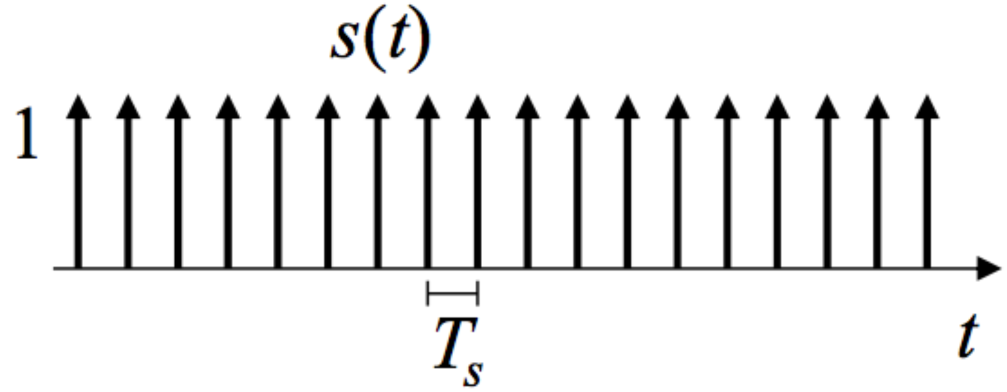
Function X(t)



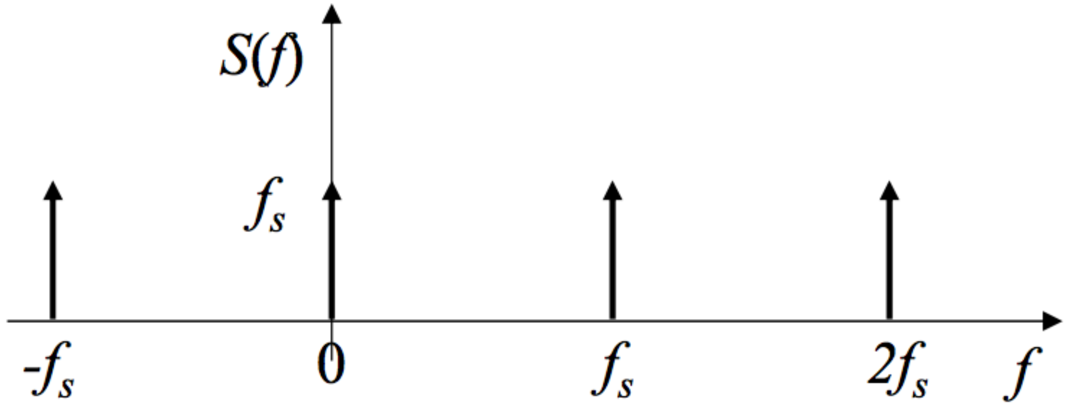
FFT transform



Impulse train s(t)



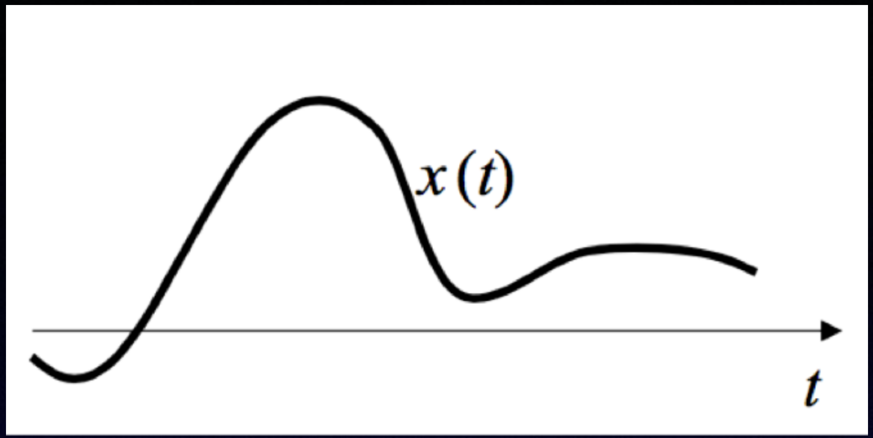
Impulse spectra s(f)



Ts = sampling interval

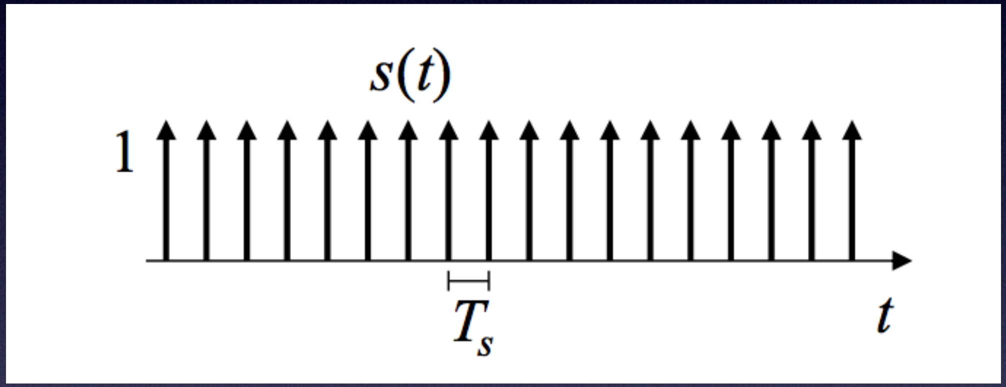
fs =1/Ts sampling frequency

SAMPLING ideal

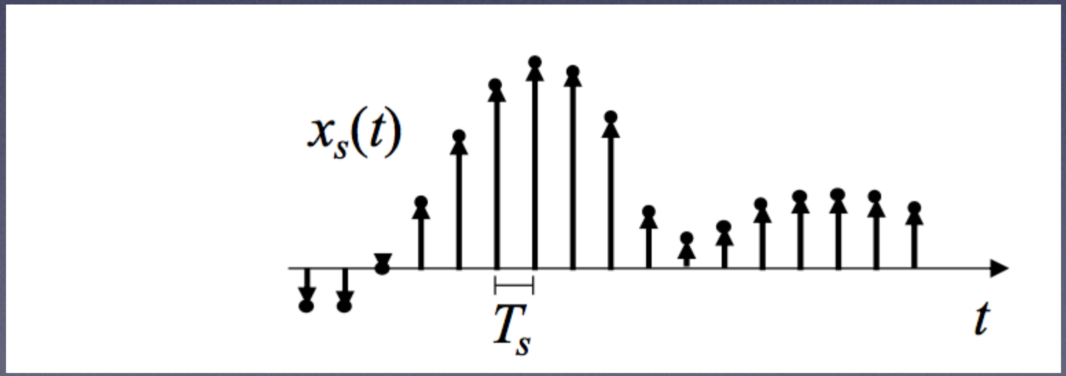


Signal x(t)

Multiplication



Impulse train s(t) with
Sampling Ts



Function xs(t) *SAMPLED*

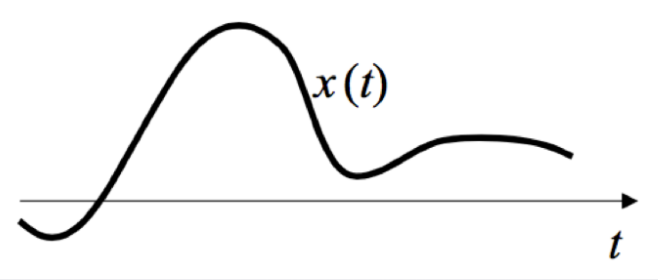
SAMPLING (ideal)

Convolution theorem

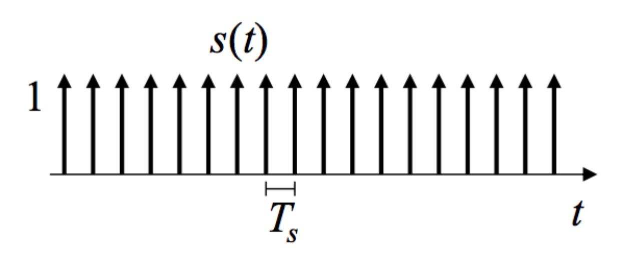
To algebraic multiplication in time domain corresponds to a convolution in frequency domain

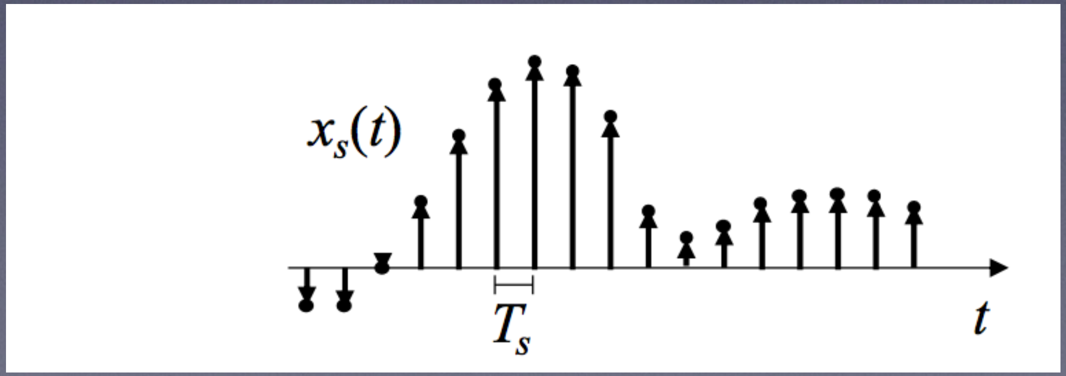
$$\boxed{x(t)\cdot s(t) \Leftrightarrow X(f) * S(f)}$$

Time domain



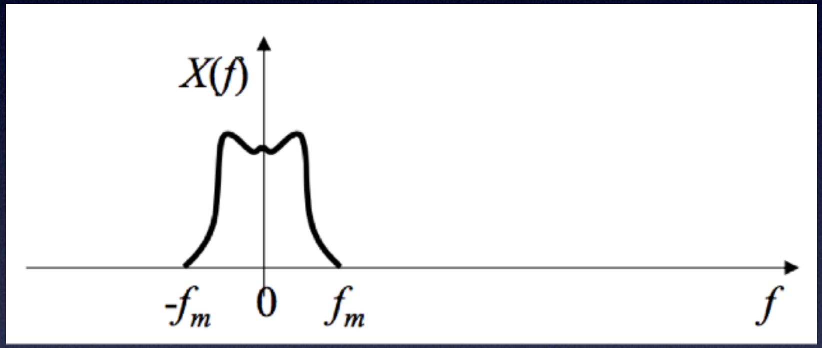
Multiplication X



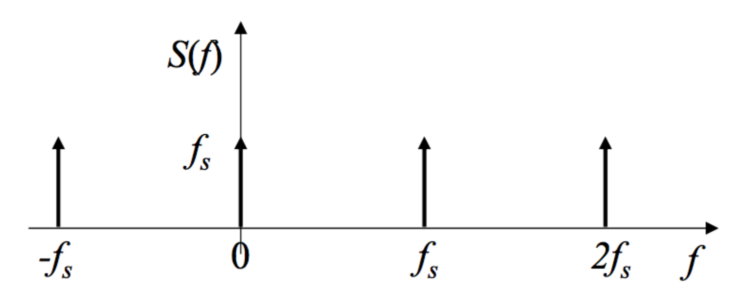


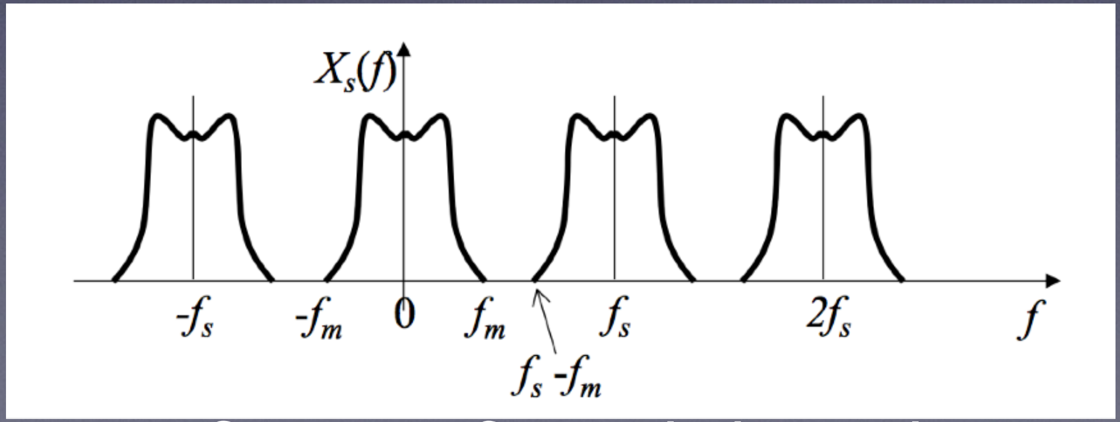
Sampled signal

Frequency domain



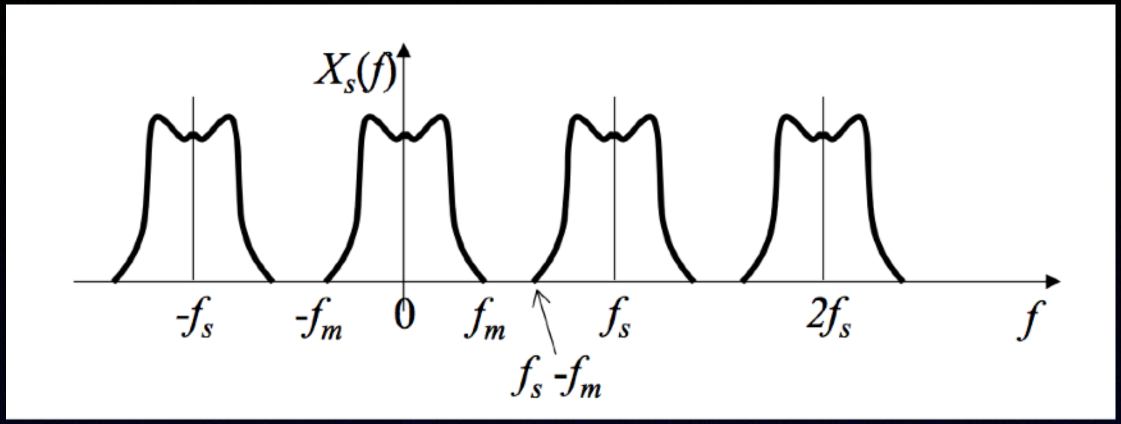
*Convolution **





Spectra of sampled signal

SAMPLING



f_s = Central frequency

f_m = Maximum frequency

To avoid overlap between functions, the sampling must be $\geq 2f_m$

Sampling THEOREM (or Nyquist theorem)

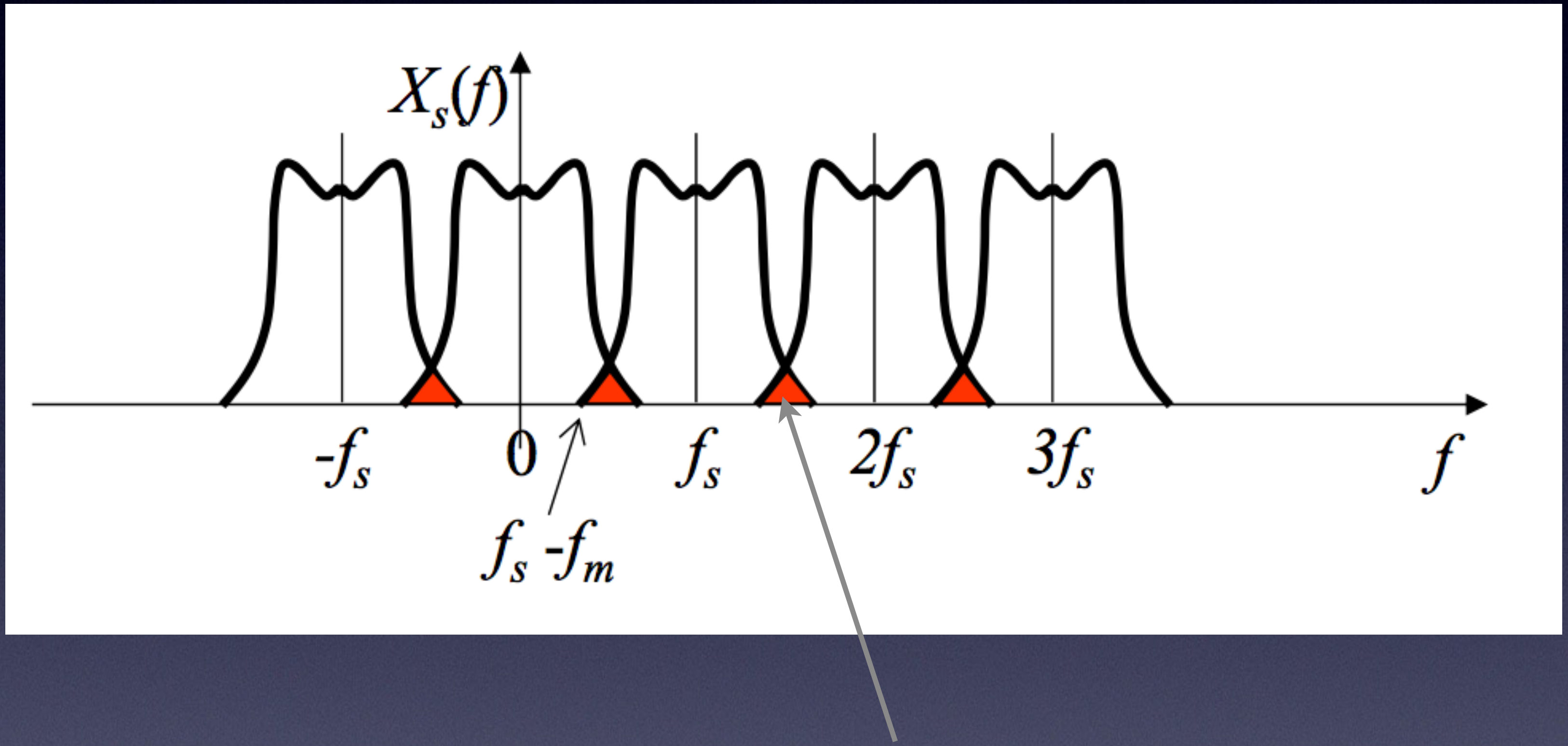
$$f_s = \frac{1}{T_s} \geq 2f_m$$

Given an analog signal s(t) , having maximum frequency Fm, the MINIMUM sampling frequency (f_s) must be > 2 Fm

SAMPLING

If Fs < 2Fm

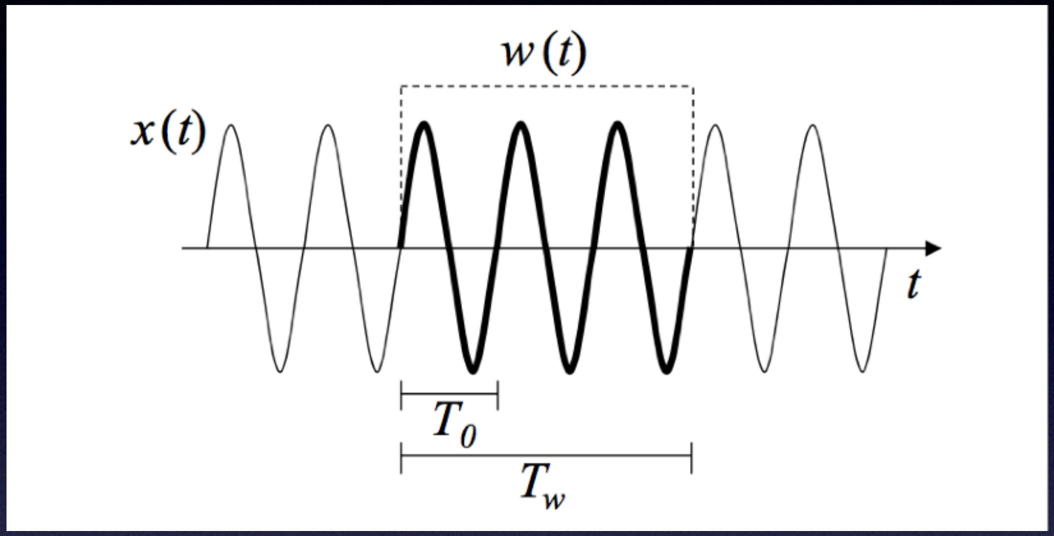
You cannot retrive correctly the starting signal s(t)



Because you have interferences due to overlapping

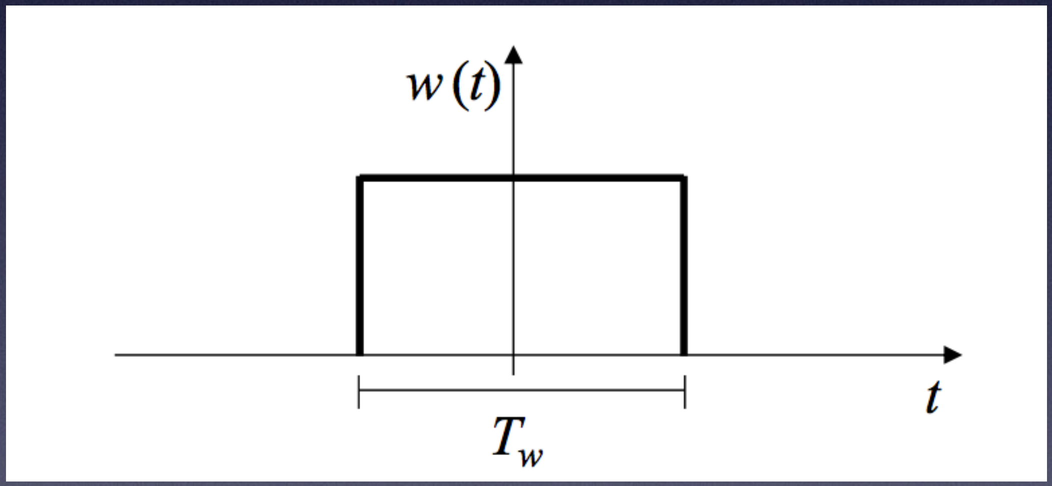
SAMPLING

CUTTING PROBLEM
finite recording



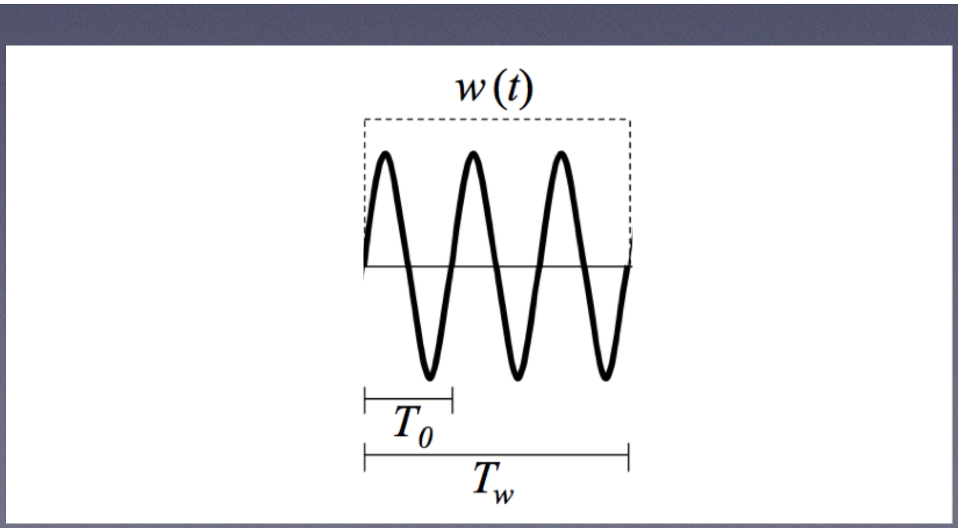
Signal continuous x(t)
(To = period)

Multiplication



Recording Window
With length 'Tw'

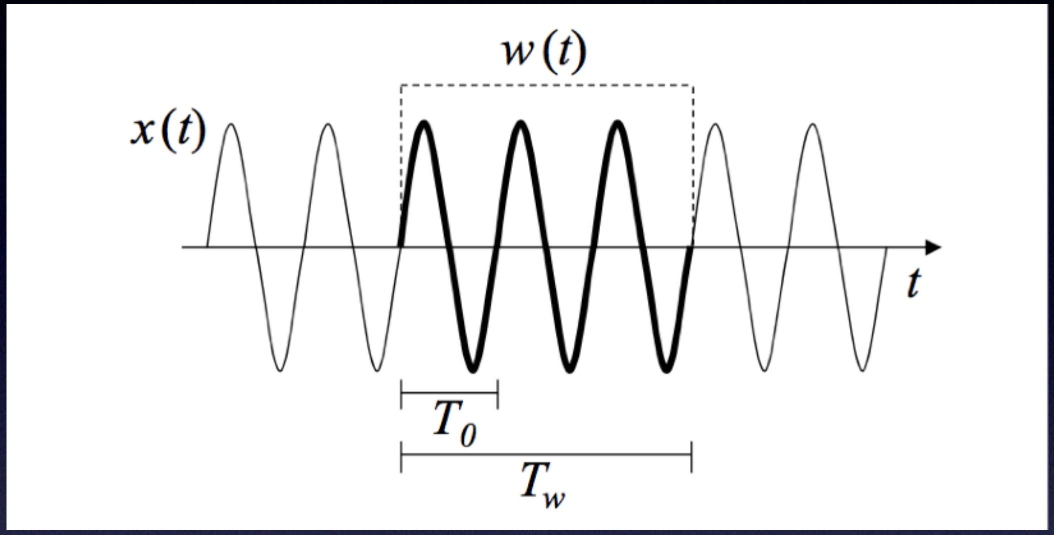
=



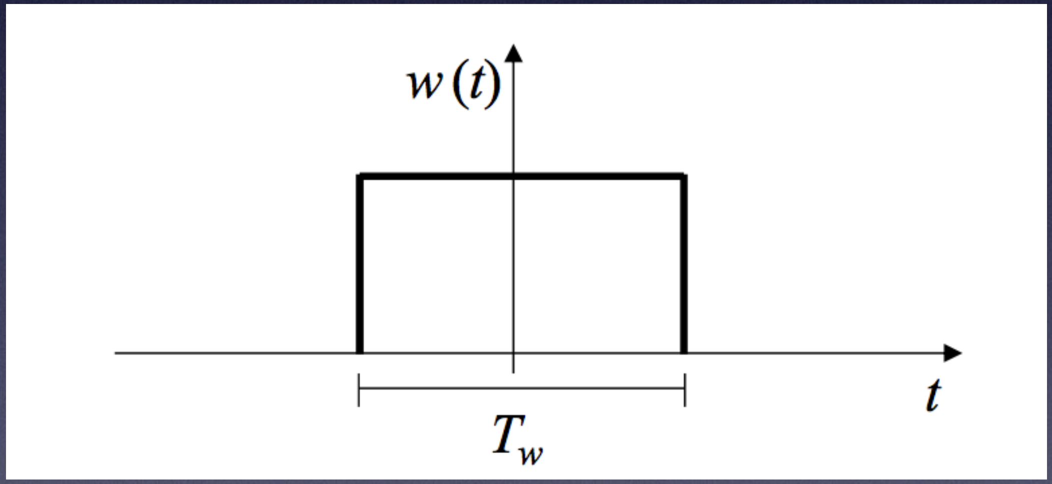
Signal x(t)
Cutter (recorded)

CUTTING PROBLEM
finite recording

Time Domain



Multiplication



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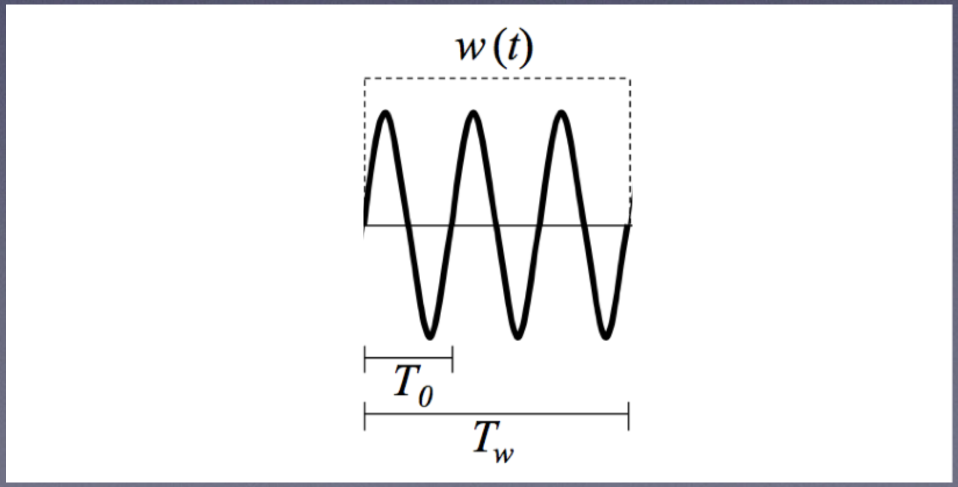
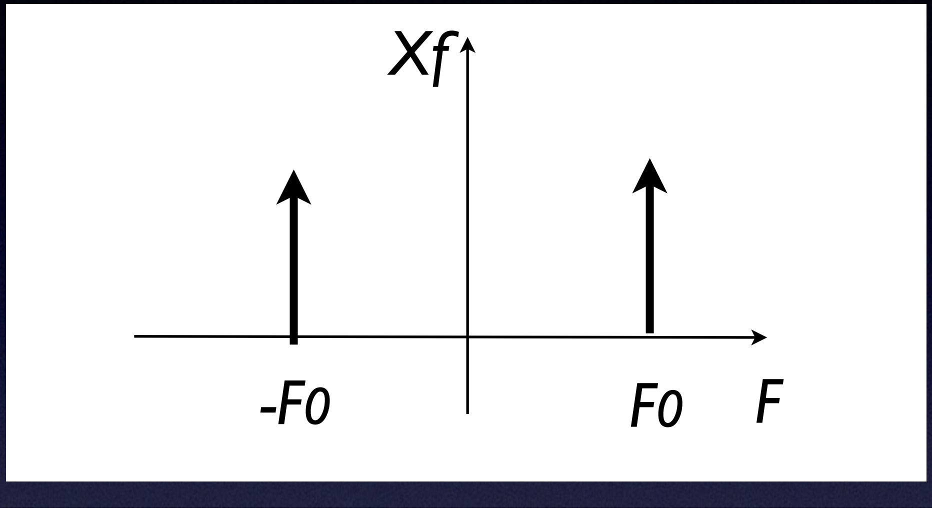
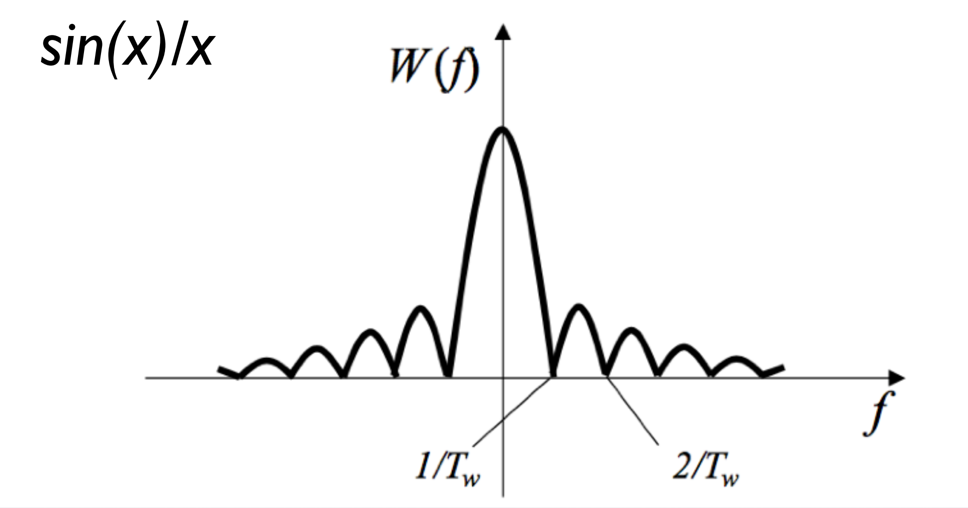


Frequency domain



Convolution



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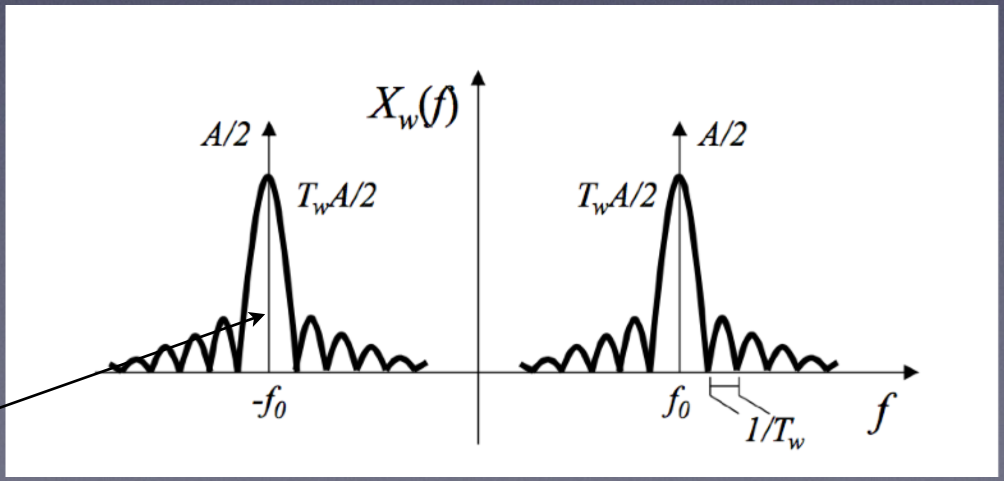


Frequency Dispersed

CUTTING PROBLEM

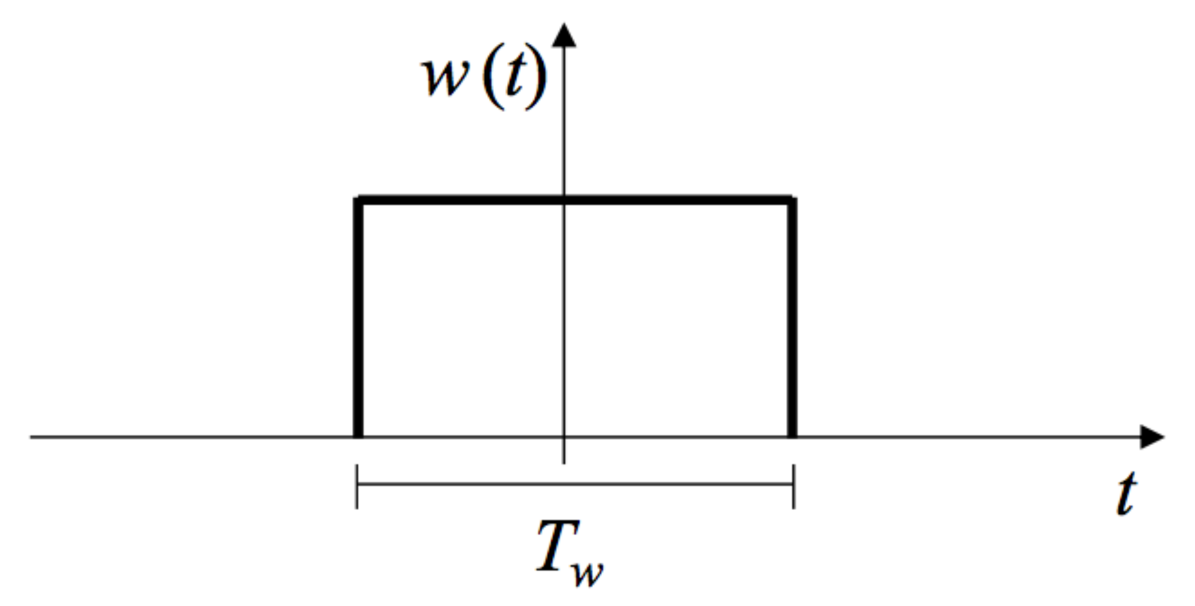
finite recording

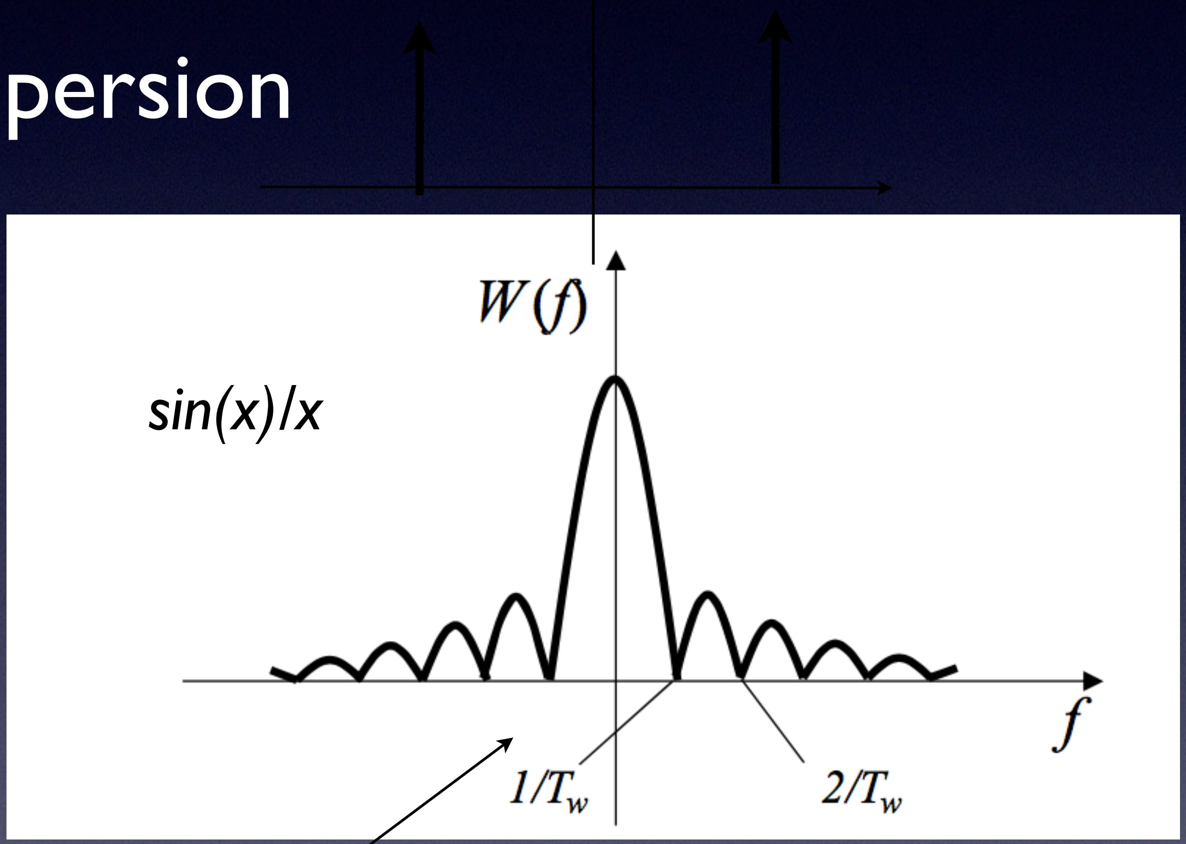
Time domain

Frequency domain

Principle of indetermination in time/frequency

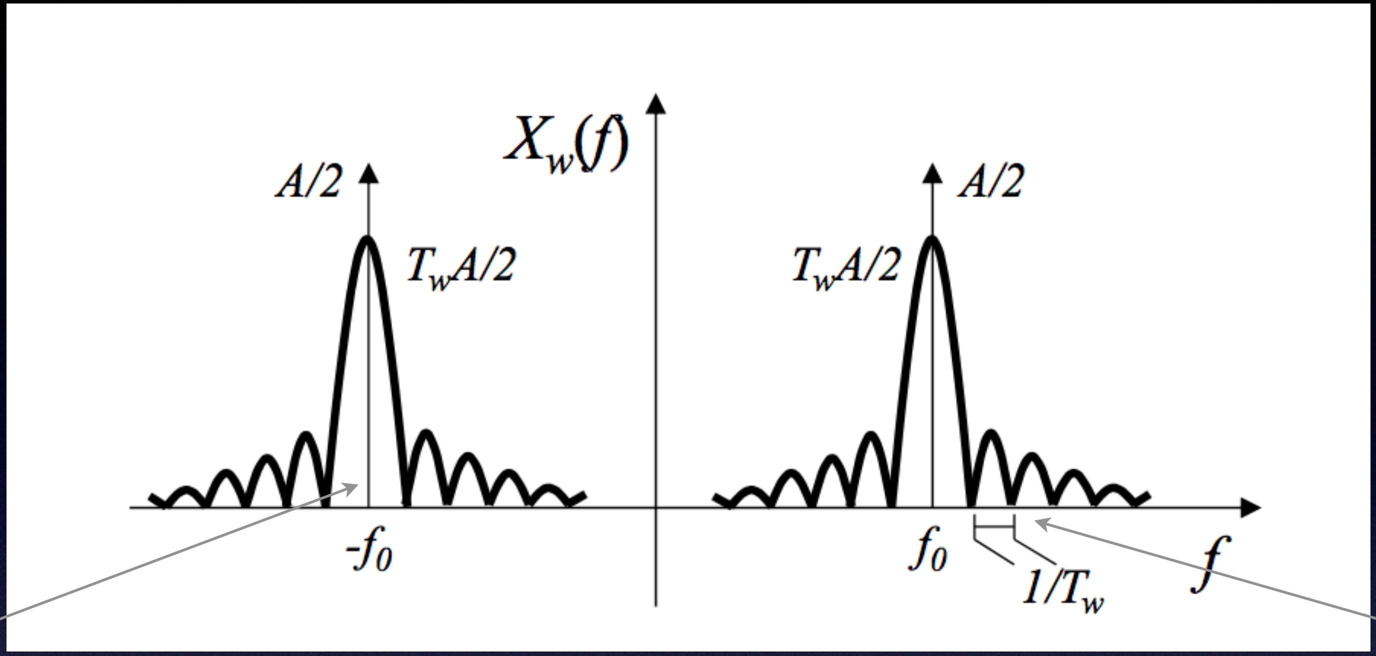
>>Tw << dispersion





Dispersione
in Frequenza

CUTTING PROBLEM
finite recording



Frequency Dispersion

Function of Tw (time of recording)

Frequency dispersion depends on the window recording Tw

>> Tw << dispersion

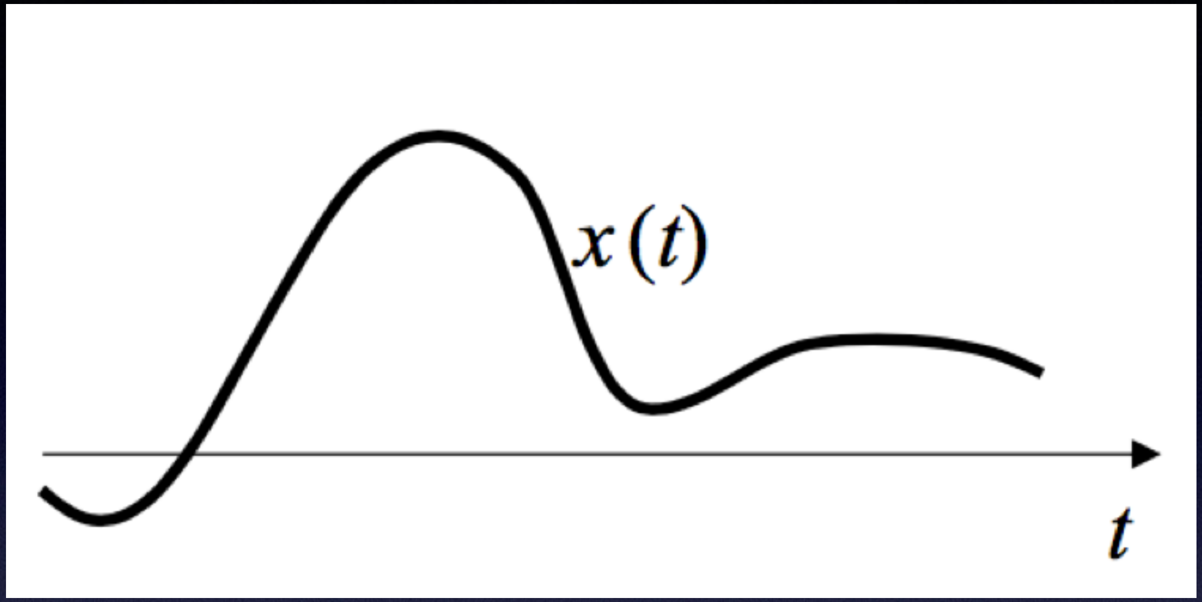
Rule of thumb

Tw > 8 T max

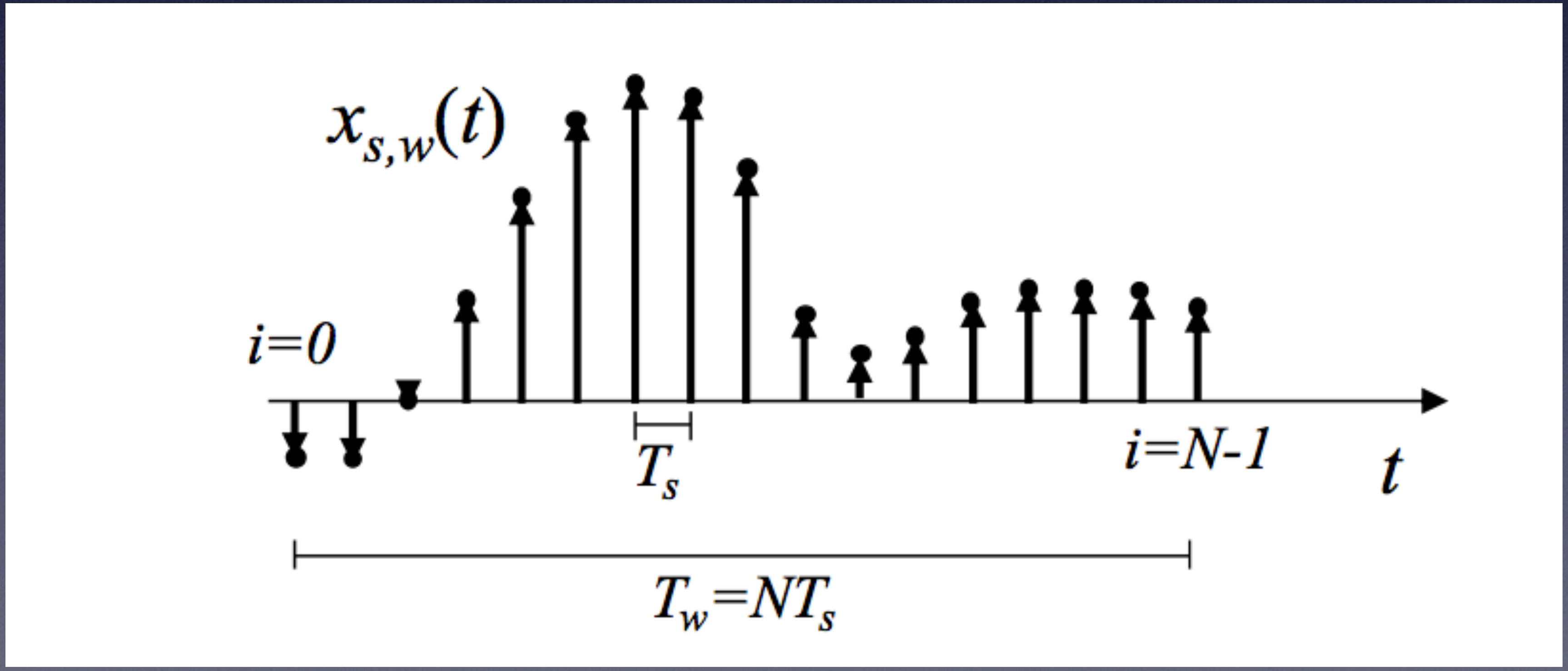
Recording time should be 8 times the Maximum Period of the signal

SAMPLING

Signal sampled and cutted



Continuous signal x(t)



Signal
Sampled with step Ts
And cute with
period Tw
Tw =N Ts

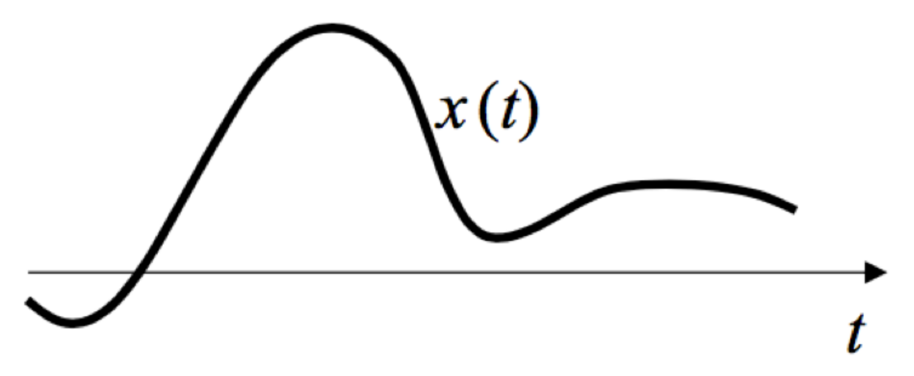
N>8

SAMPLING

EXAMPLES

T = PERIOD
f= FREQUENCY

TIME DOMAIN



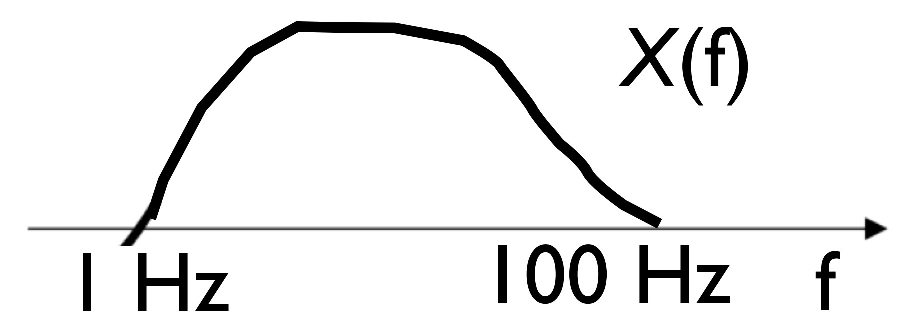
SAMPLING
(Aliasing)

$$f_s = \frac{1}{T_s} \geq 2 f_m$$

fs = 2 fmax= 200Hz

Ts = 1/200 = <u>0,005 s</u>

FREQUENCY DOMAIN



F min =1Hz

F max =100Hz

CUTTING

Tw > 8 T max

Tmax = 1/fmin= 1/1=1s

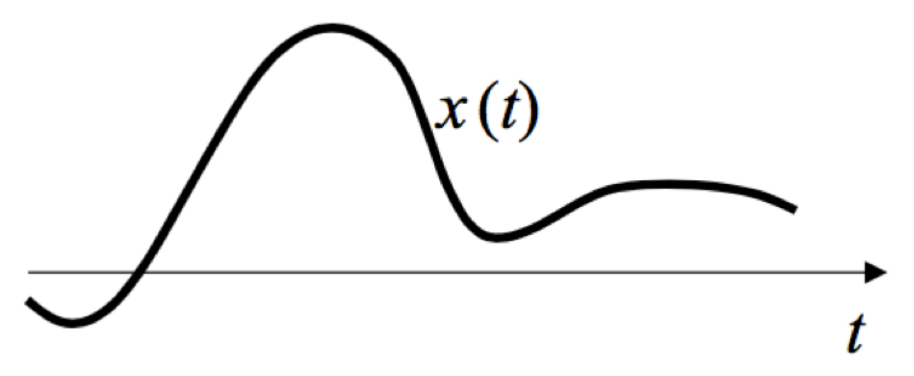
Tw = 8Tmax= <u>8s</u>

SAMPLING

EXAMPLES

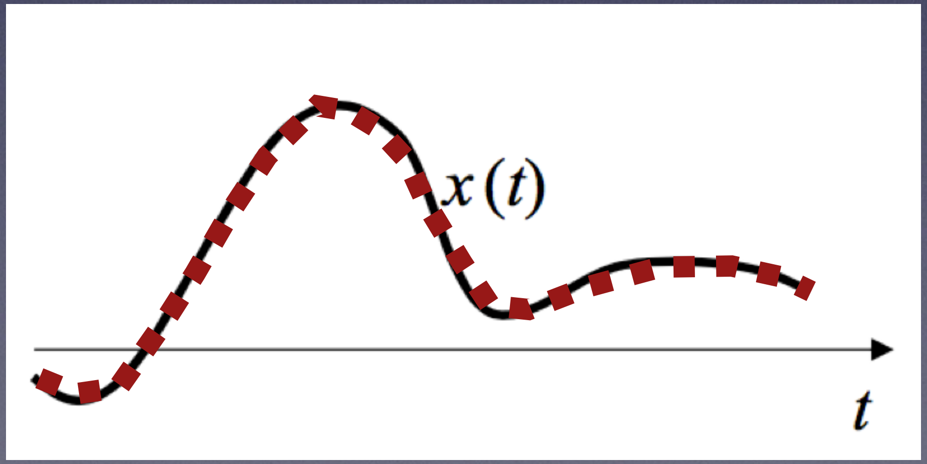
T = PERIOD
f= FREQUENCY

TIME DOMAIN signal



Signal having min frequency of 1 Hz (max period of 1s) and max frequency of 100 Hz (Min period of 0,01 s)

If sampled at 200 Hz for 8 seconds



It is well reconstructed !

SAMPLING

EXAMPLES

Even more easy…

When you are sending a WA vocal message

Voice is usually between 300Hz and 3400 Hz
(3•10e-3 seconds and 3•10e-4 seconds)

Your phone MUST have a sampler recorder that records your voice at **7800 Hz** (and at least for 10e-2 seconds)