INTERNATIONAL SCHOOL OF SPACE SCIENCE
L'AQUILA - ITALY

SERSES (Series of Events on Relations in the Sun-Earth System and Space Weather)
2008 Course on: Geomagnetism and Ionosphere

Ionospheric vertical radio soundings

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Introduction

•Amongst the big variety of techniques used to study the geophysical environment, methods using electromagnetic waves occupy a very prominent position.

•These techniques exploit radio waves modifications when they interact with the medium they pass through.

•The ionosphere is no exception: the most common way to study its behaviour is to emit radio wave pulses into the ionosphere and to study the backscattered echo.

•The echo signal contains information about the layers in which it may be refracted, reflected or absorbed.

•Also signals coming from satellites (NNSS, GPS) or from terrestrial emitting station (VLF emitters) can be used. They do not exploit the radar technique but their properties are affected by the medium they pass through.

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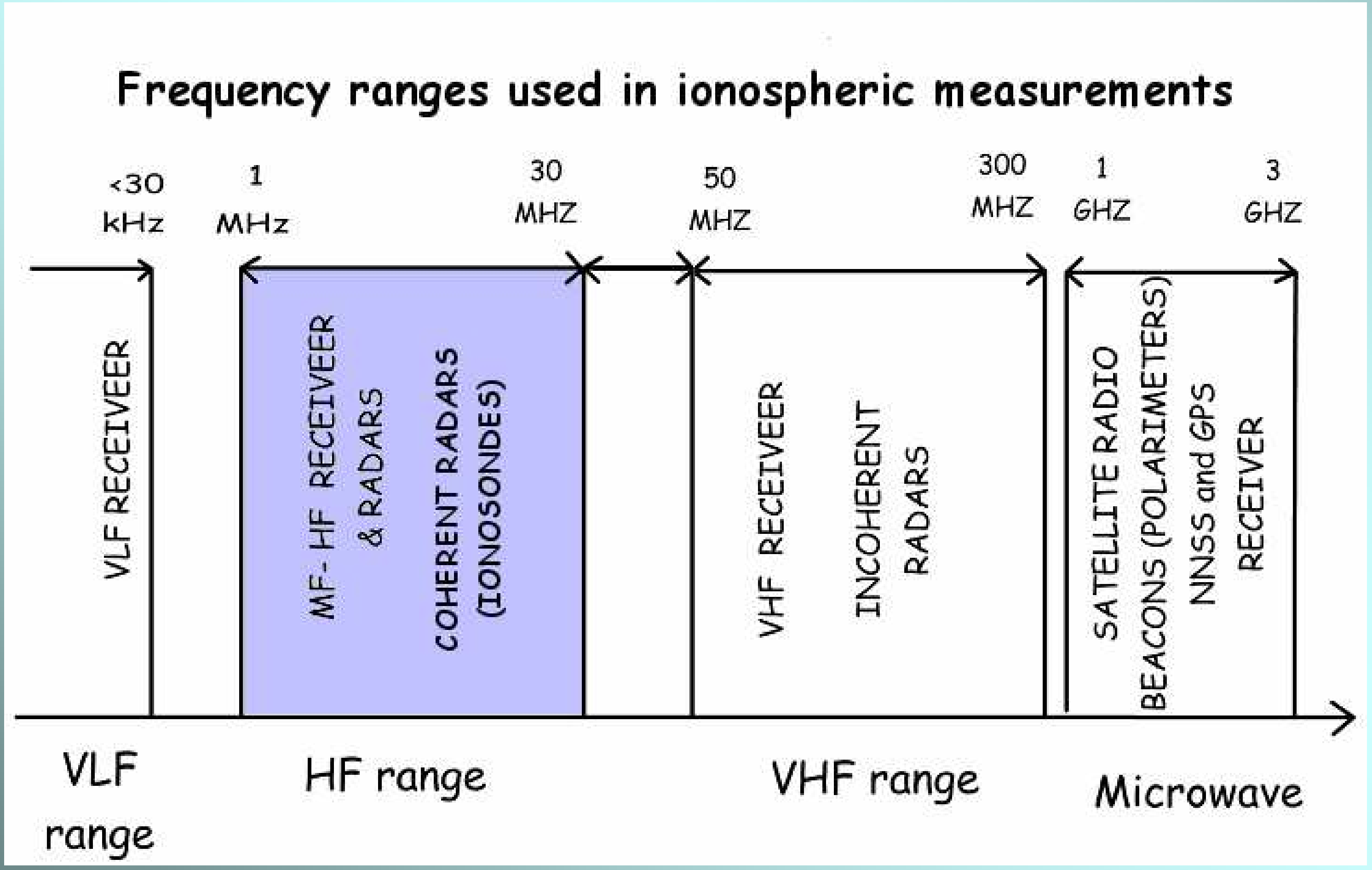
ELF	SLF	ULF	VLF	LF	MF	HF	VHF	UHF	SHF	EHF
3 Hz	30 Hz	300 Hz	3 kHz	30 kHz	300 kHz	3 MHz	30 MHz	300 MHz	3 GHz	30 GHz
30 Hz	300 Hz	3 kHz	30 kHz	300 kHz	3 MHz	30 MHz	300 MHz	3 GHz	30 GHz	300 GHz



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The vertical sounding technique

•The measure technique is based on sending pulses of energy at different frequencies towards the ionosphere and in measuring the backscattered echo delay to properly evaluate the position of ionospheric layers.

•In transmitting and receiving energy we assume the usage of antennas (TX and RX ones).

•The instrument able to perform such a measurement is called "ionosonde" and can be considered the radar’s “ancestor”.

•The first vertical sounding with pulse technique was performed in 1925 with a system developed by Breit e Tuve. However the existence of the ionosphere and the ionospheric reflection had been experienced some years before.

•The direct product of the vertical sounding is the ionogram: plot of echo's delay times (or heights) versus frequency.

•Next step is to work around the ionogram to retrieve the main ionospheric parameters and the density profile.

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RADAR Theory

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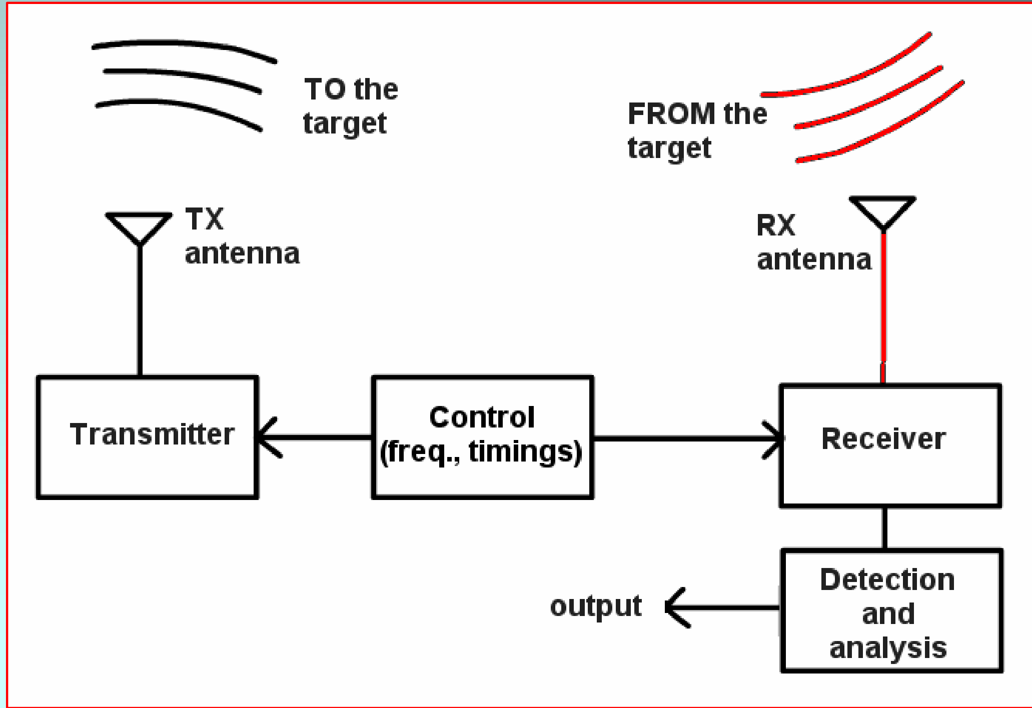
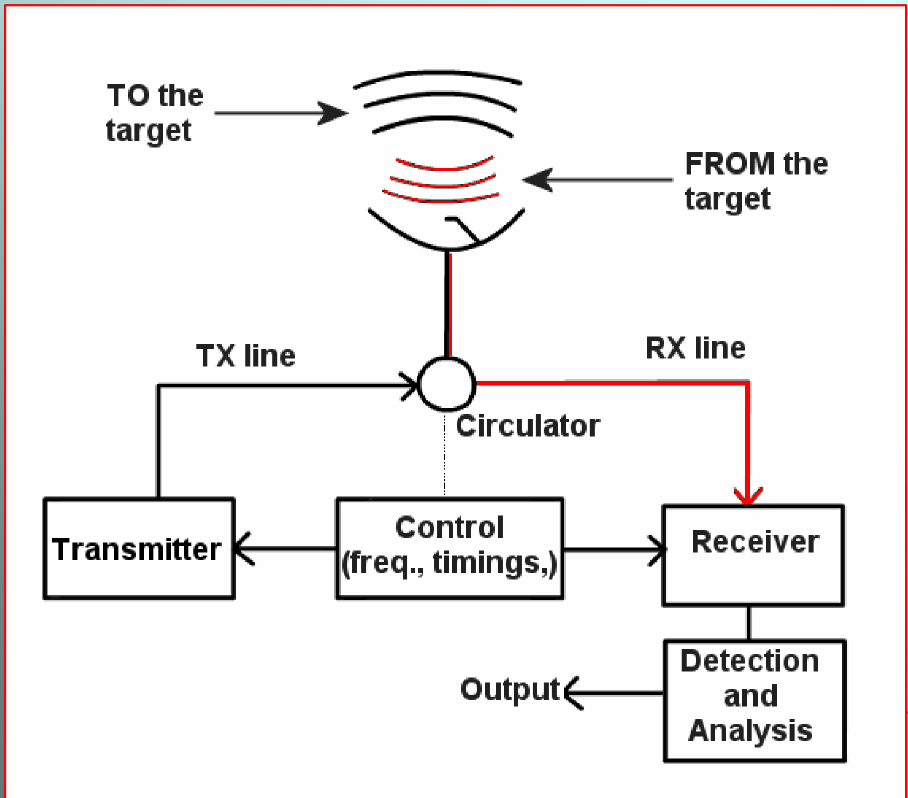
RAdio Detection And Ranging

Using e.m. pulses of proper frequency and amplitude it is able to find targets and to reveal the distance from the radar itself.



bistatic: two antennas



Independently of the type the control section communicates with both the TX and RX section so that the receiver can be tuned properly.

monostatic: one antenna (circulator to direct energy)

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$$P_r = \frac{(\lambda G_d)^2 \sigma P_{rad}}{(4\pi)^3 r^4}$$

Parameter	Definition	Unit
$\mathbf{P_r}$	Power at the receiver input	W
λ	Wavelength	m
$\mathbf{G_d}$	Antenna directive gain (density of power that is radiated in a direction)	
σ	Radar cross section (describes the target capability to reflect the energy)	m^2
$\mathbf{P_{rad}}$	Emitted power (power dissipated in the antenna characteristic impedance)	W
r	Distance between the radar and the target	m

Radar cross section is the area able to catch the incident wave and that is able to scatter the energy in the surrounding space isotropically:

$$\sigma = 4\pi r^2 \frac{P_s}{P_i}$$

where

r	distance;
P_i	incident density power on the target;
P_s	scattered density power at a distance *r* from the target.

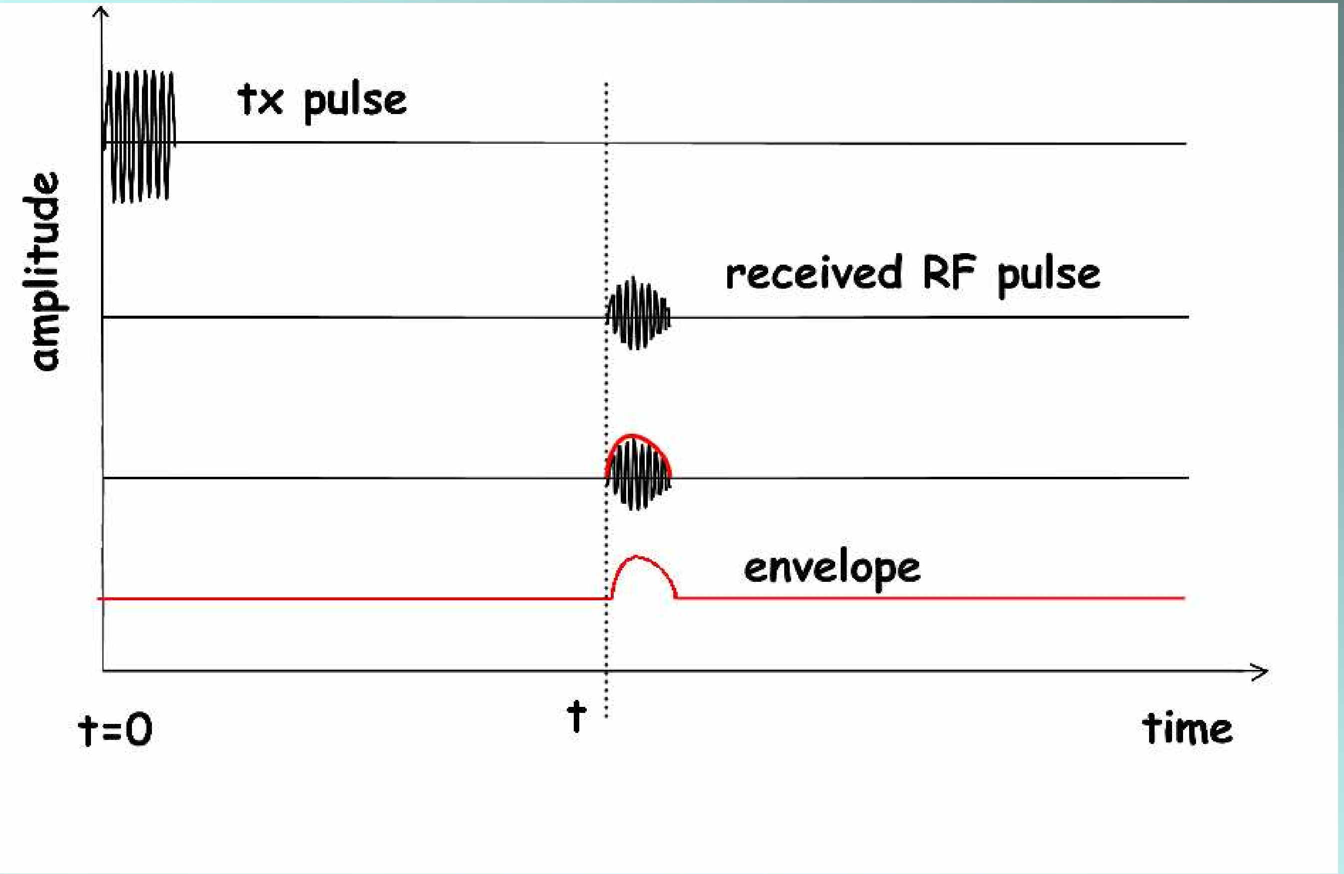
Pulse technique

Pulses of proper amplitude and duration are emitted by proper antenna in the target direction.

After a time "t" a possible echo reaches the receiver of the radar.

The evaluation of the distance is performed measuring the delay time between the emitted and the received pulse.

$$d = \frac{v \cdot t}{2}$$



The early model of radars were based on the envelope technique.

The receiver that is tuned on the emitted frequency is able to follow the relative maxima of the signal generating an electric signal that "envelopes" the received echo.

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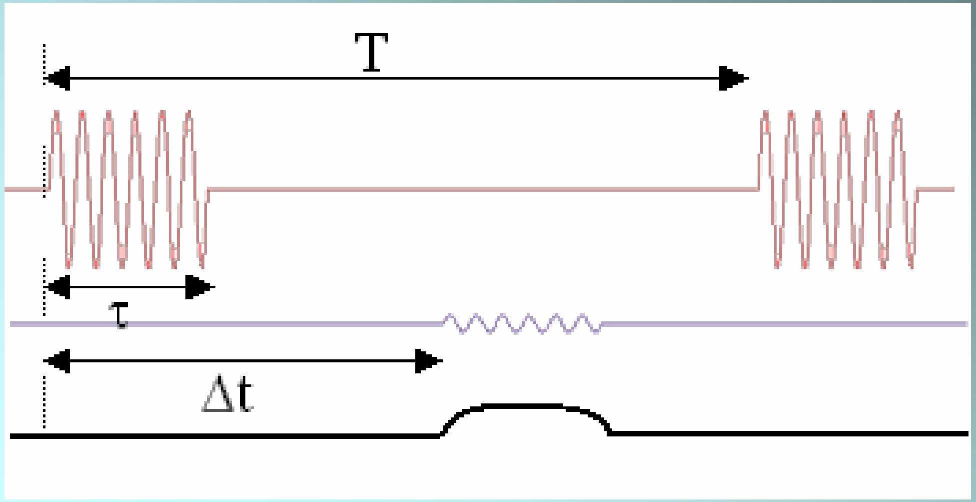
Envelope: basic principle

- Pulses of length equal to τ seconds repeated every T seconds are emitted trough a transmitting antenna.

- The power has to be adequate so that a detectable signal is obtained (design requirement).

- Reflected and attenuated energy from the target is received through RX antenna after an interval Δt.



- Using the envelope technique the receiving system generates a pulse whose length is approximately τ.

According to this simple model we can derive the main features of an envelope radar:

- Target's distance …………………………………………

$$d = \frac{c \cdot \Delta t}{2}$$

- Minimum distance ……………………………………….

$$d = \frac{c \cdot \tau}{2}$$

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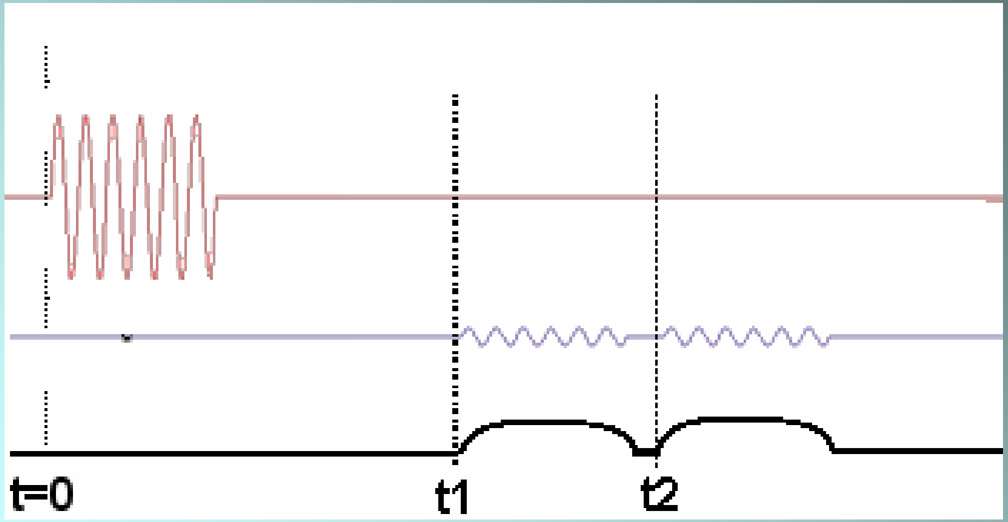
- To evaluate a radar's resolution we need to remember that 2 echoes can be distinguished if the arriving times are so that $t_2 - t_1 > \tau$



- Minimum distance between 2 targets (spatial resolution) …… $\delta d = \frac{c \cdot \tau}{2}$
- Maximum target distance………………………………………….. $d_{max} = \frac{c \cdot T}{2}$
- Energy from a P power amplifier……………………………… $E = P \cdot \tau$

Advantages

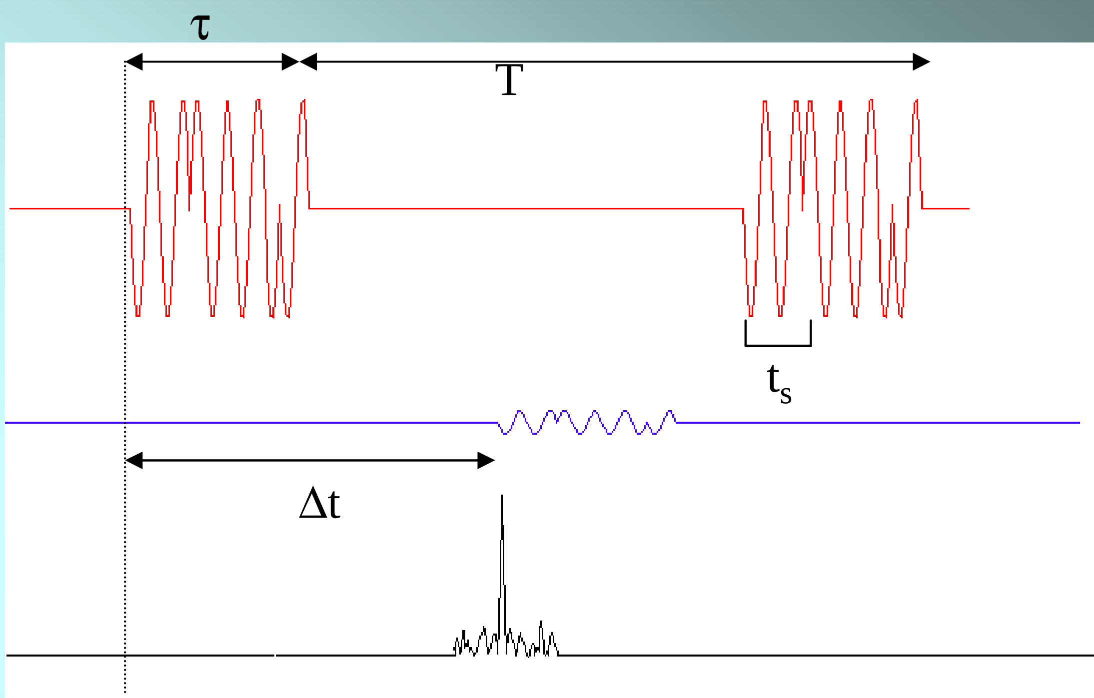
- Very simple TX and RX systems.
- There is the possibility of a complete analog receiver (no PC is needed).

Disadvantages

- Compromise for τ is needed.
- Sometimes we have a limited resolution.
- High power to get a good S/N.

Pulse compression: basic principles

- Varying repeatedly the phase inside the τ pulse we get the result that the resolution is the same corresponding to a narrower pulse called sub pulse t_s ("pulse compression").
- The definition of sub pulse is the minimum interval in which the phase is kept constant.
- The phase changes sequence is called CODE.



- The receiver is not completely analog; a mathematical process is necessary to look for the code in the received echo (correlation).
- The receiving process generates a very narrow peak corresponding to the delay (height) at which the code is found.
- It is a very robust process, with a very high noise immunity.

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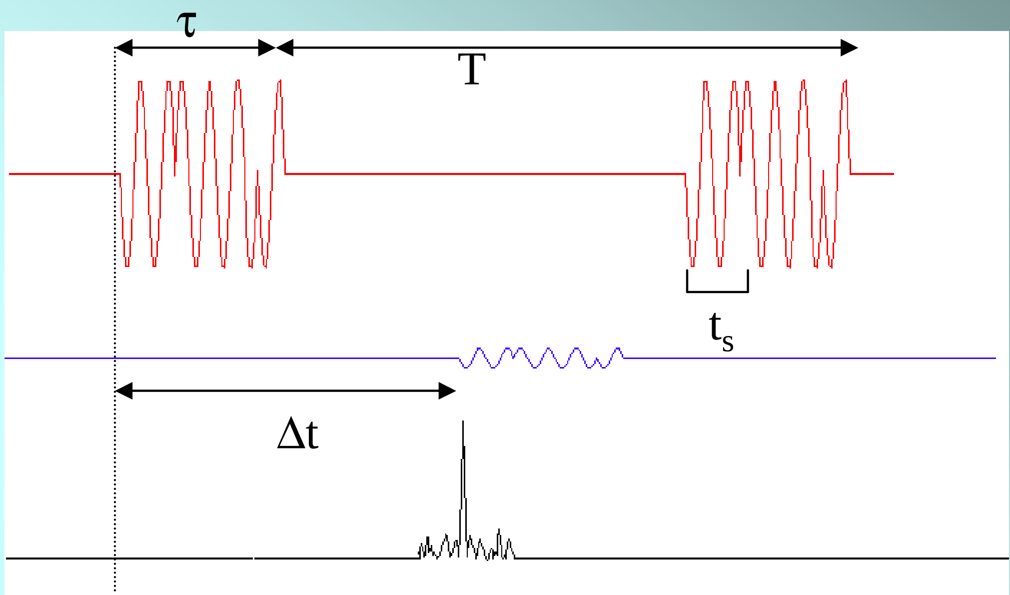

•Target's distance ……………………………………… $d = \dfrac{c \cdot \Delta t}{2}$

•Minimum distance between 2 targets (resolution) …… $\delta d = \dfrac{c \cdot t_s}{2}$

•Energy from a P power amplifier……………………….. $E = P \cdot \tau$

•Maximum target distance……………………………….. $d_{max} = \dfrac{c \cdot T}{2}$

Advantages

•Resolution depends on sub pulse length only.
•Greater values for τ.
•Less power to have the same energy.
•Higher S/N at receiver output
•Extra gain from correlation process

Disadvantages

•More complexity in TX pulse generation.
•More complex analysis to detect the target.
•A mathematical process is necessary.

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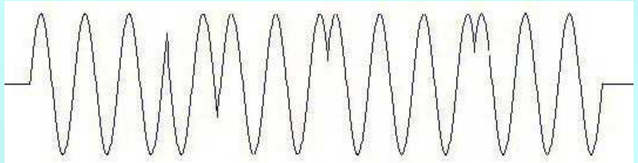
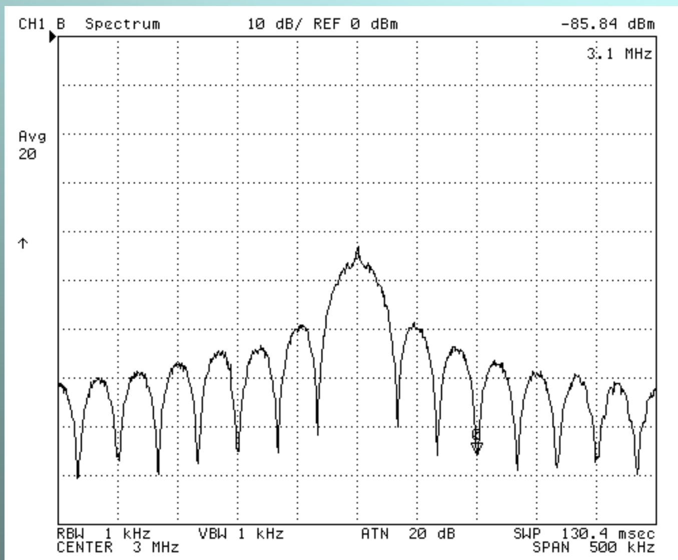
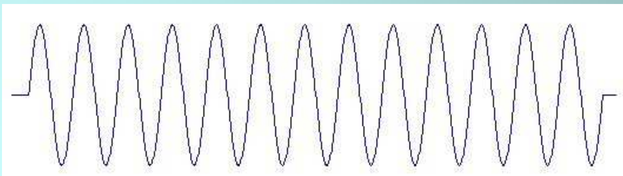
Why pulse compression works

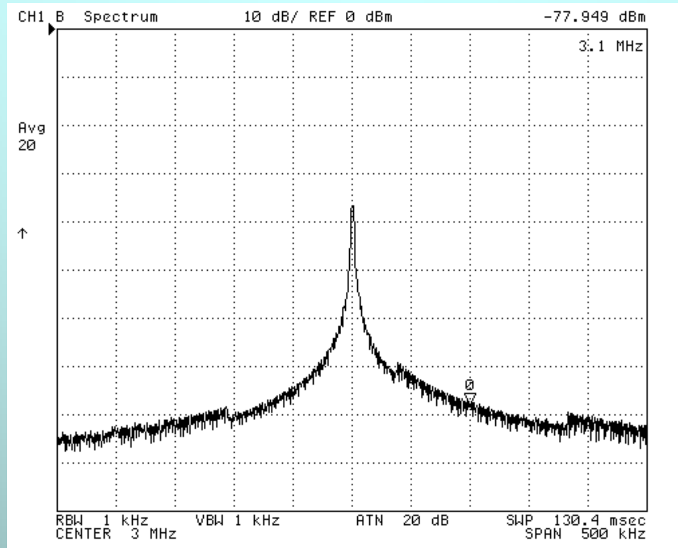


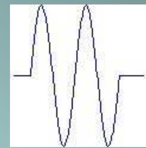
Pulse width 480µs
Repetition rate 60Hz
CODE
Band width ~66kHz



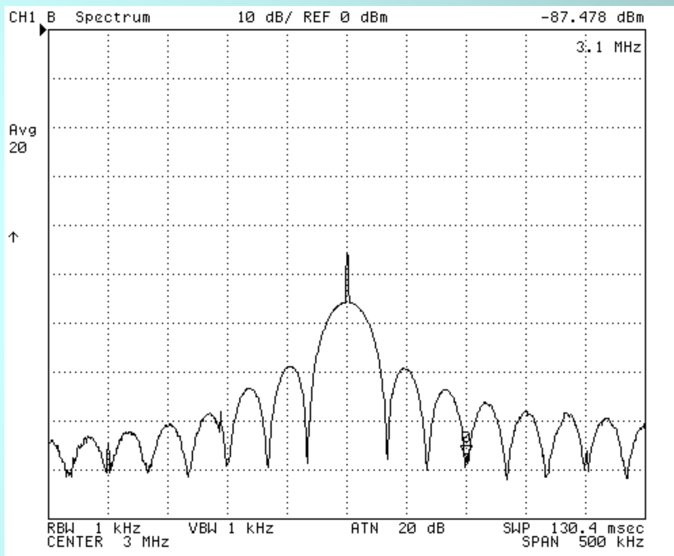


Pulse width 480µs
Repetition rate 60Hz
NO CODE
Band width ~4kHz





Pulse width 30µs
Repetition rate 60Hz
NO CODE
Band width ~66kHz



A particular radar: the ionosonde

- A radar is designed to fulfil some requirements depending on the target and the phenomena we want to highlight.

frequency range: (1 - 20) MHz with a step of 50 kHz or 100 kHz

resolution should be less than 20 km

minimum height is around 90 km

maximum height should be above 600 km

very high loss $\frac{\text{Rx power}}{\text{Tx power}} = 10^{-13} \quad \rightarrow \quad -130 dB$

the target is an infinite reflecting planes (ionized layers) more than single scattering points (radar cross section). This yields the equation radar to become

$$\cancel{P_r = \frac{(\lambda G_d)^2 \sigma P_{rad}}{(4\pi)^3 r^4}} \longrightarrow P_r = \frac{(\lambda G_d)^2 P_{rad}}{(4\pi r)^2 L}$$

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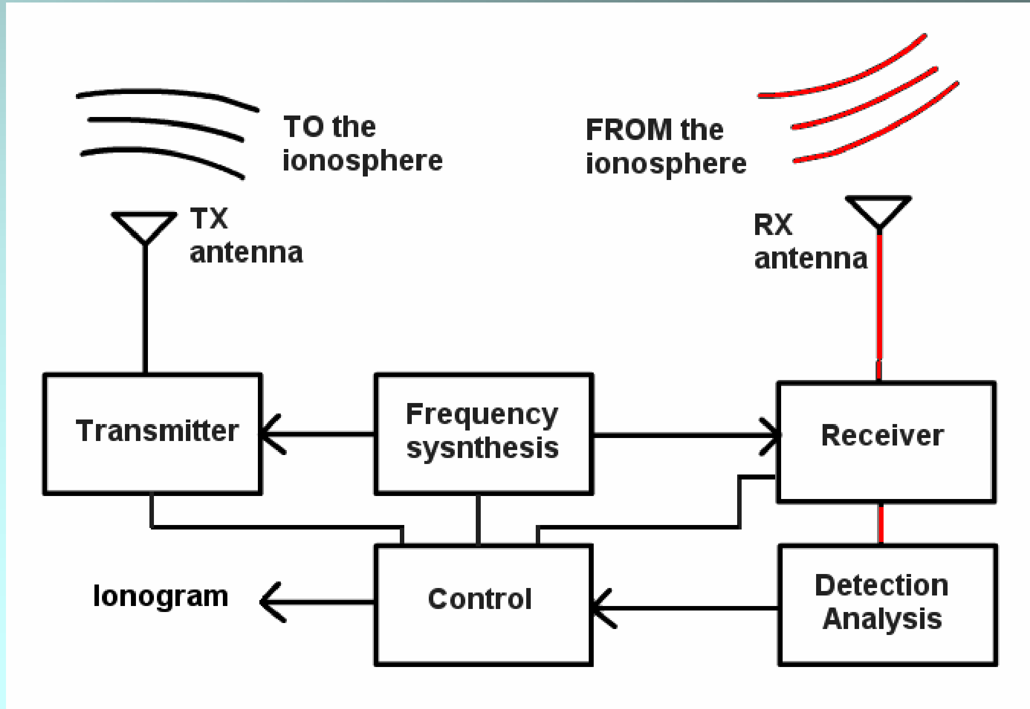
The ionosonde is, generally, a bistatic radar, with antennas in the same site (often on the same mast).

The blocks sketched aside are common to all ionosondes; the way in which we accomplish those functions differentiates the ionosondes.



Control system: enables the TX to emit energy and, after that, enables to receiver starting the so called "listening time".

Frequency synthesizer: generates the frequency to be transmitted tuning the receiver on that frequency.

Transmitter: amplifies small signals to a proper amplitude.

Receiver: converts information at different frequencies to a more comfortable value (etherodyne principle).

Detection and Analysis: recognizes good echoes amongst the noise evaluating the delay times of echoes.

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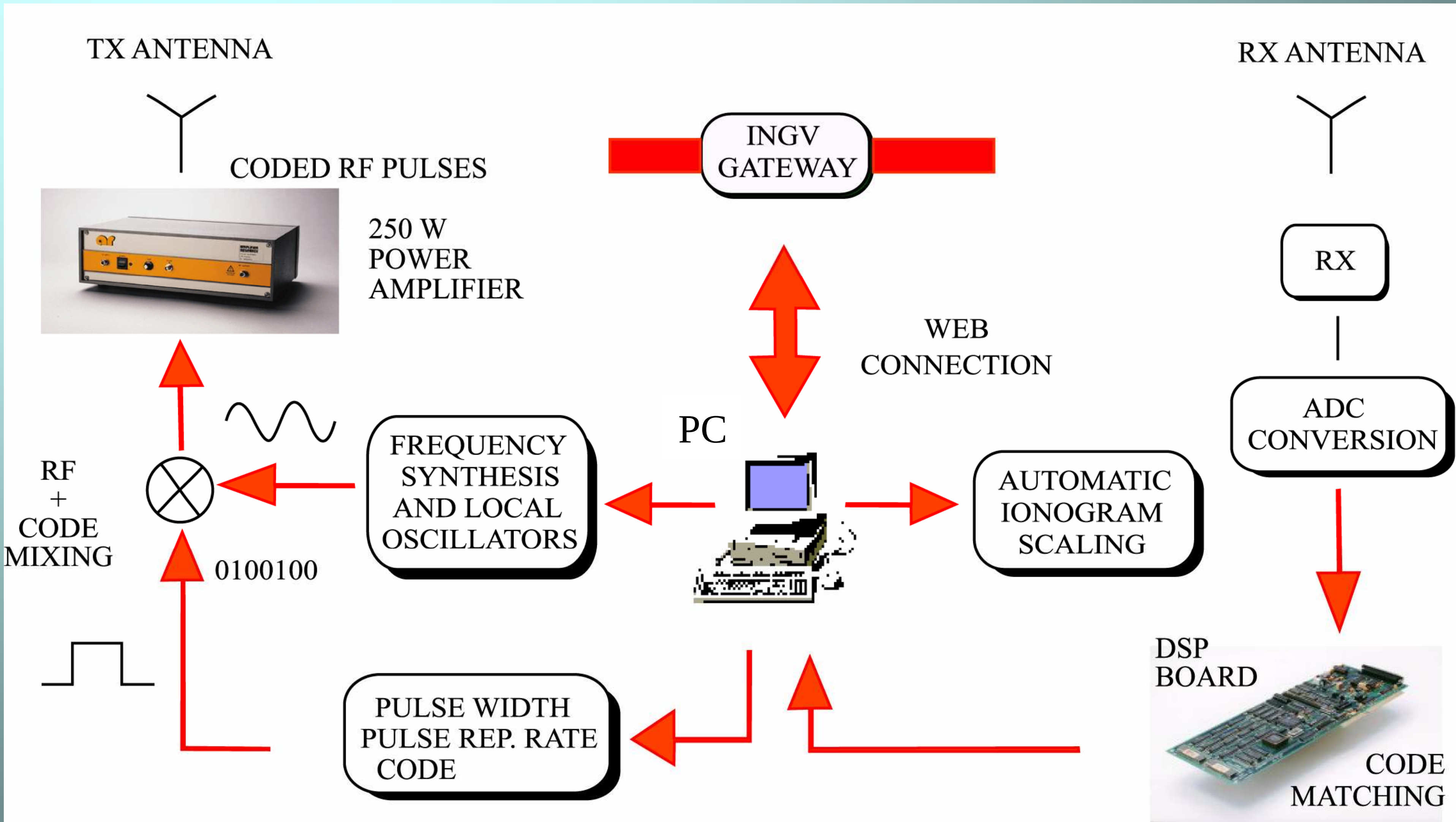
A concrete example: AIS-INGV ionosonde (Italian patent by INGV in 2004)



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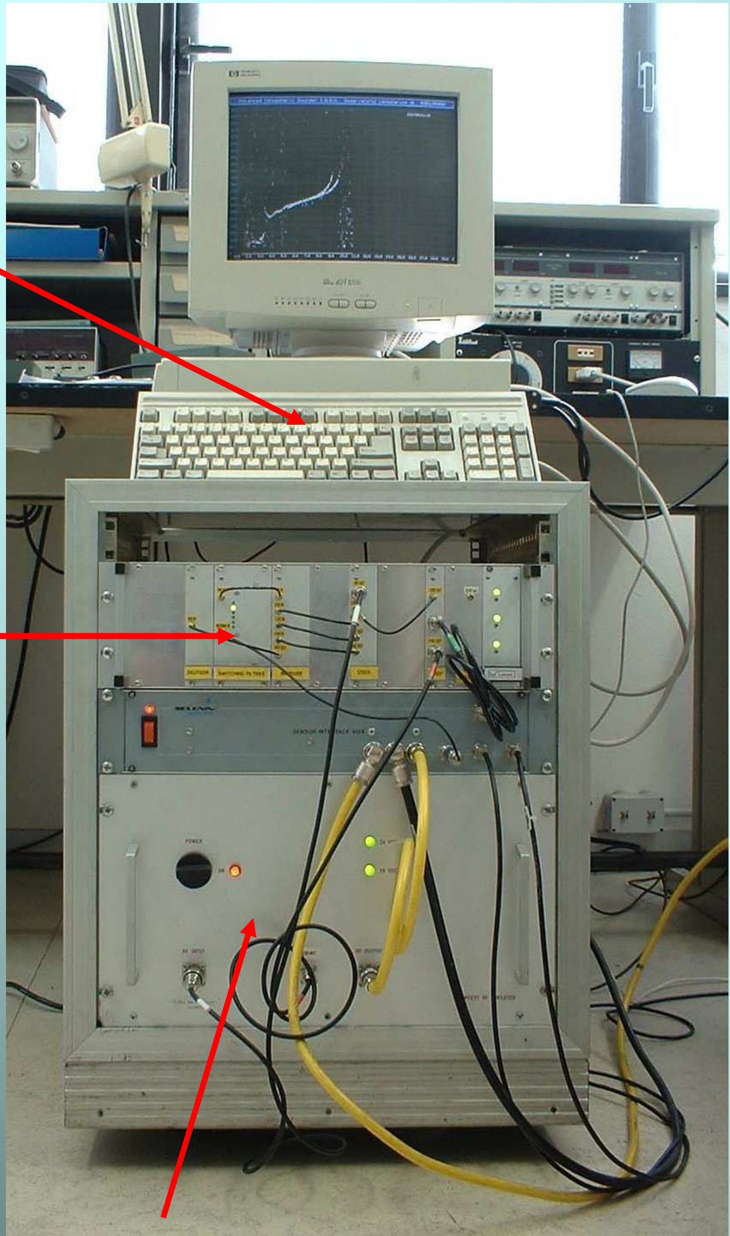
A concrete example: AIS-INGV ionosonde (Italian patent by INGV in 2004)

PC



Main unit

Power amplifier

Building main unit

Comparison between an envelope ionosonde and a modern pulse compression ionosonde

	Envelope	Pulse Compression
Frequency Range	1 – 20 MHz	1 – 20 MHz
Height Range	90 – 700 km	90 – 700 km
Pulse width (τ)	100μs	480μs (sub pulse 30μs)
TX power	> 5 kW	250 W
Vertical resolution	15 km	5 km
Pulse Repetition Frequency (1/T)	100 Hz	60 Hz
Receiver	Analog (envelope)	Digital (correlation)
Output	paper or film	file

Antennas for vertical ionospheric sounding

Antennas for the vertical ionospheric sounding are a crucial element in the general design.

The following things are valid for TX antenna as well as RX antenna:

- they have to be wide band due to the wide frequency range (a simple dipole is not allowed due to its resonance);
- the main radiation lobe needs to be directed upwards;
- they need to have a good gain because the ionospheric attenuation and the geometrical loss reduce greatly the signal amplitude.

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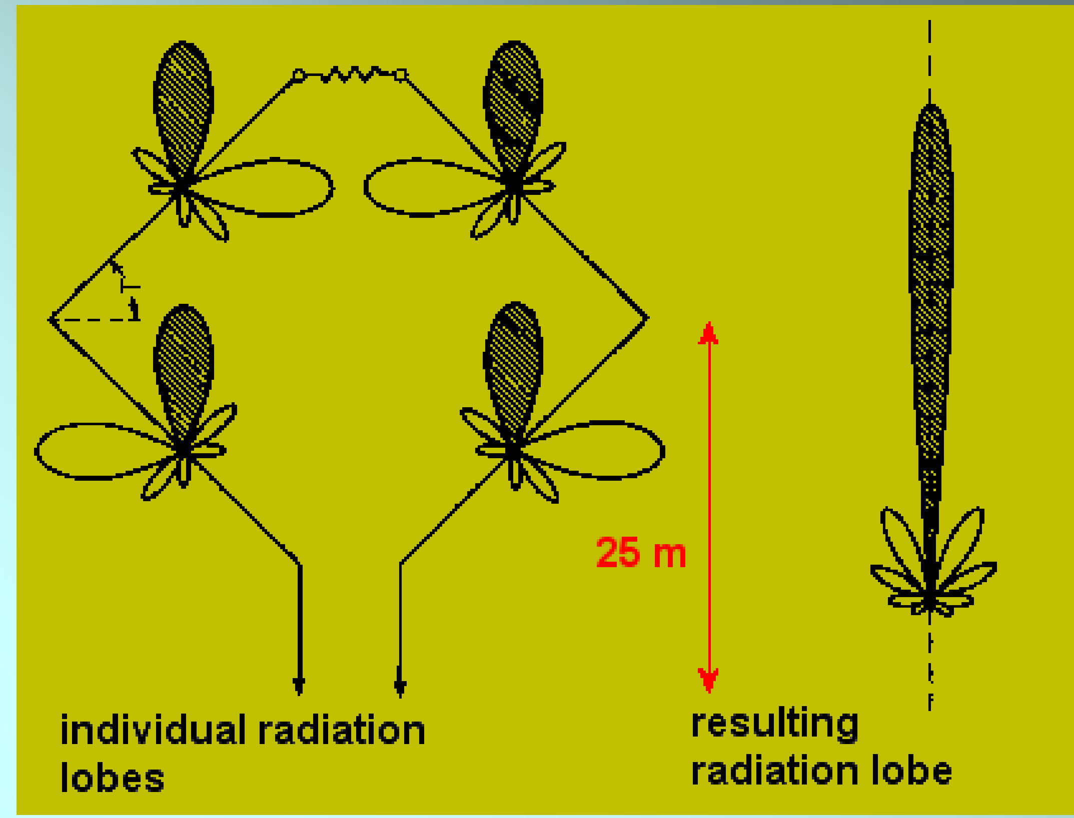
Rhombic antenna

A simple solution is the "rhombic antenna" as the picture suggests you.

Each side of antenna is approximately a wavelength long (10MHz correspond to 30m).

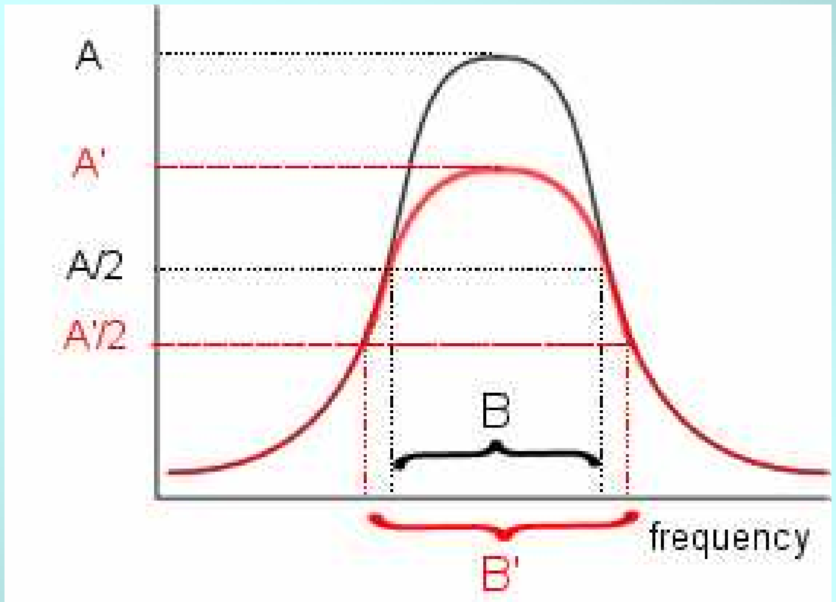
Each side contributes to the resulting radiation lobe in the sketched way; the shadowed lobes are added, while the others eliminate.



Each side of the antenna is a resonating element; the resistive load at the top is added to widen the band.

The band B is the full width at half maximum (FWHM).

The resistive load at the top of the antenna dissipates energy making the FWHM larger.



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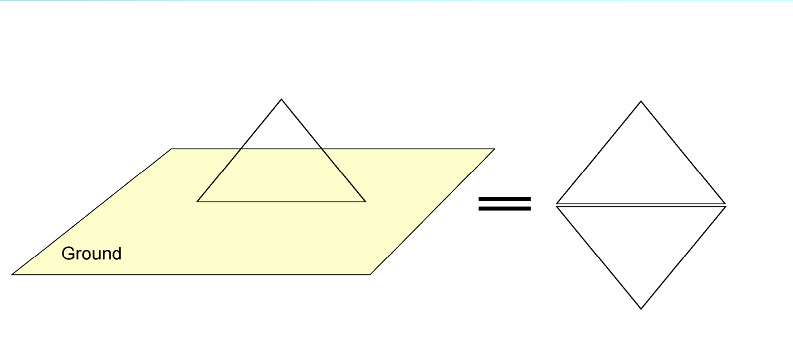
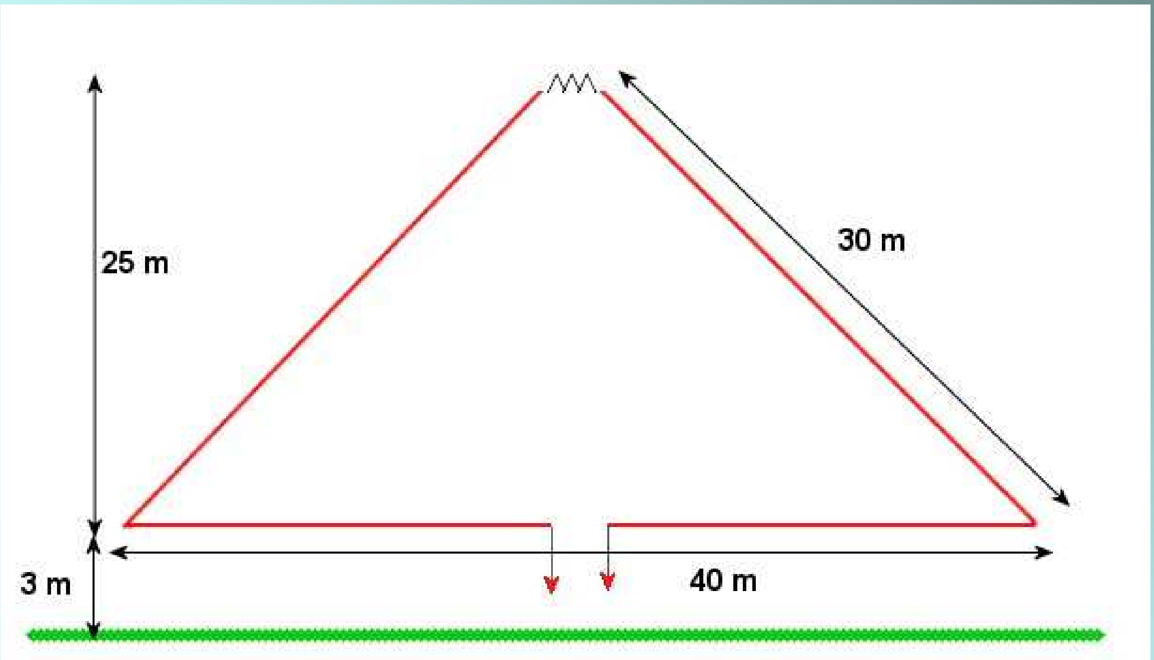
Delta antenna

A simplified version of rhombic antenna is the so called "delta" antenna.

•According to antenna theory, a delta antenna on a ground infinite plane (earth) is equivalent to a rhombic antenna.





•The final lobe composition and the widening effect of resistive load are similar to the rhombic.

•It is easier than rhombic antenna to build.

•The radiation lobe is around 60° (350 km diameter circle at 300 km height).

•Whatever comes from that area is practically indistinguishable.

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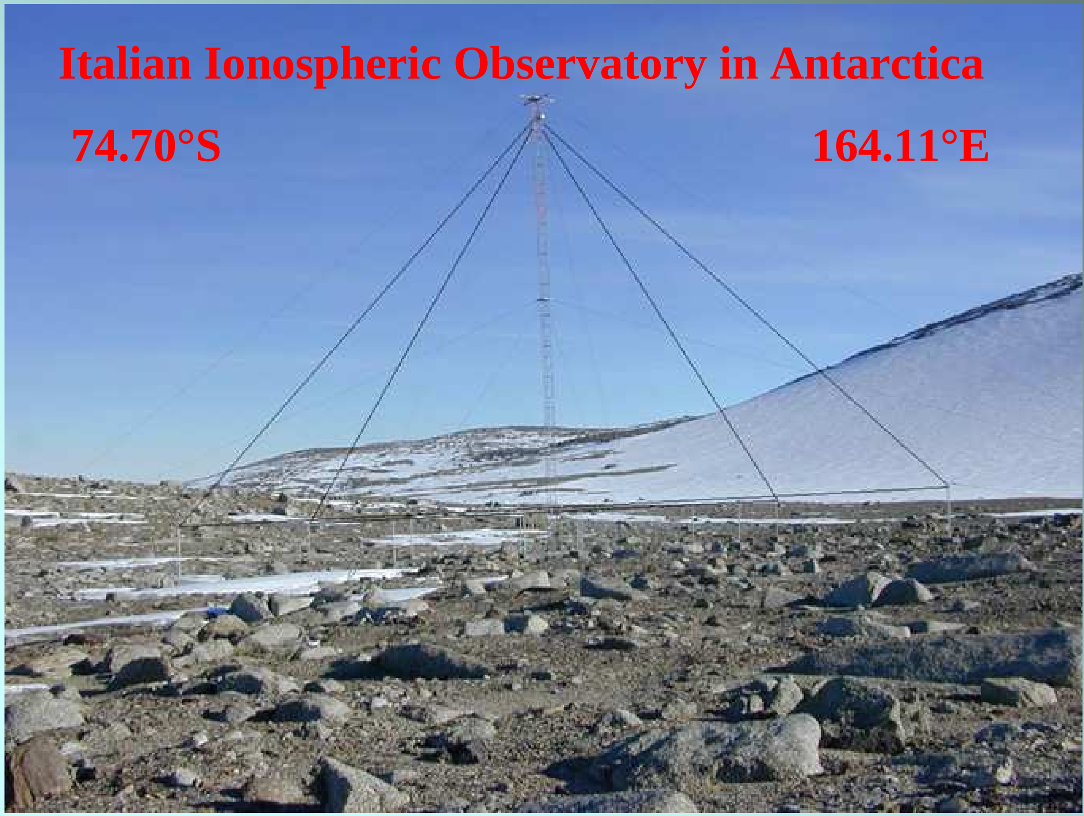
•As a triangular shape is simpler than a rhombic one we can arrange two antennas (TX and RX) on a single mast, 90 degrees shifted to limit cross talking.

•For both rhombic and delta a device is necessary to match the impedance of the amplifier to TX antenna and of the receiver to RX antenna (balun).



Advantages

•Impedance and gain vary slightly with the frequency (wide band concept).

•They are very efficient (gain).

•Building them is very simple though dimensions could limit their diffusion.

Disadvantages

•Dimensions (especially in rhombic antennas).

•Limited directivity.

•Part of the electrical power is wasted on the resistive load.

Measure principle

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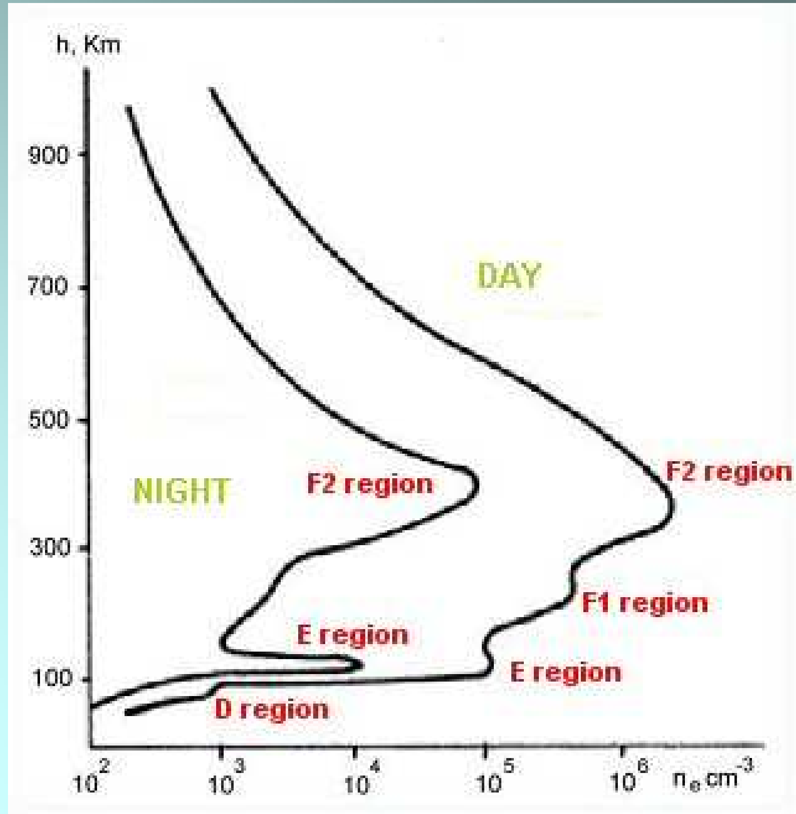
The vertical sounding principle



- Let's have a look to the principle which the measure is based on.
- Ionosphere is characterized by an electron density profile, that is the distribution of N along the height.
- We can consider the ionosphere as a plasma whose plasma frequency is:

$$f_p = \sqrt{\frac{Ne^2}{4\pi^2 \varepsilon_0 m}} \approx 9\sqrt{N}$$

$$n^2 = 1 - \left(\frac{f_p}{f}\right)^2$$

- For every used frequency, f, the reflection will happen when the refraction index n=0;
- Since the plasma frequency depends on N that varies with the height we have reflections from different altitudes.

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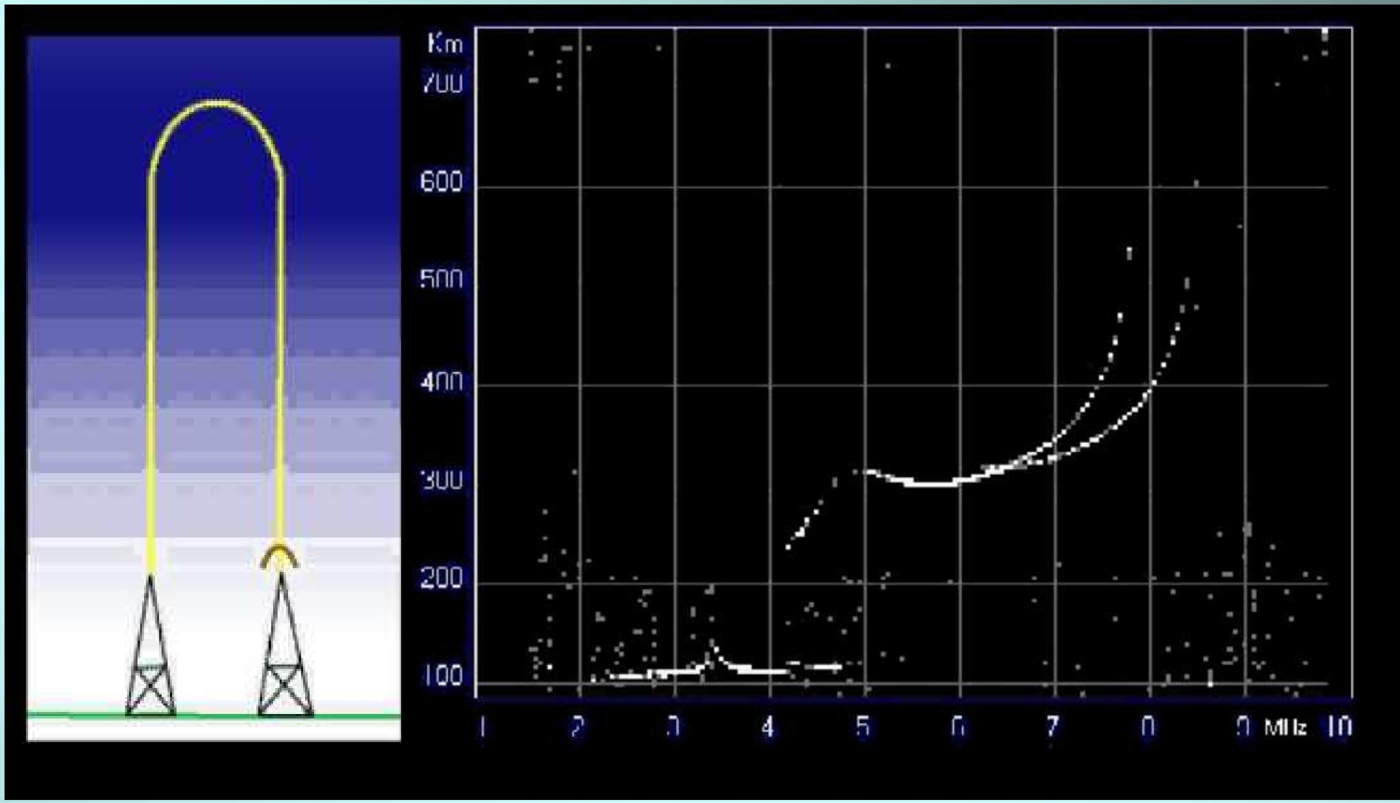
Making a sounding



Frequency limits: depend on the site, the season, the solar cycle.

Frequency step: (frequency resolution) from 50kHz to 100kHz (rarely 25kHz).

Sounding duration: can last from few seconds to several minutes .

Soundings scheduling: depends on application (every hour, …up to every 5 minutes).

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Ionogram

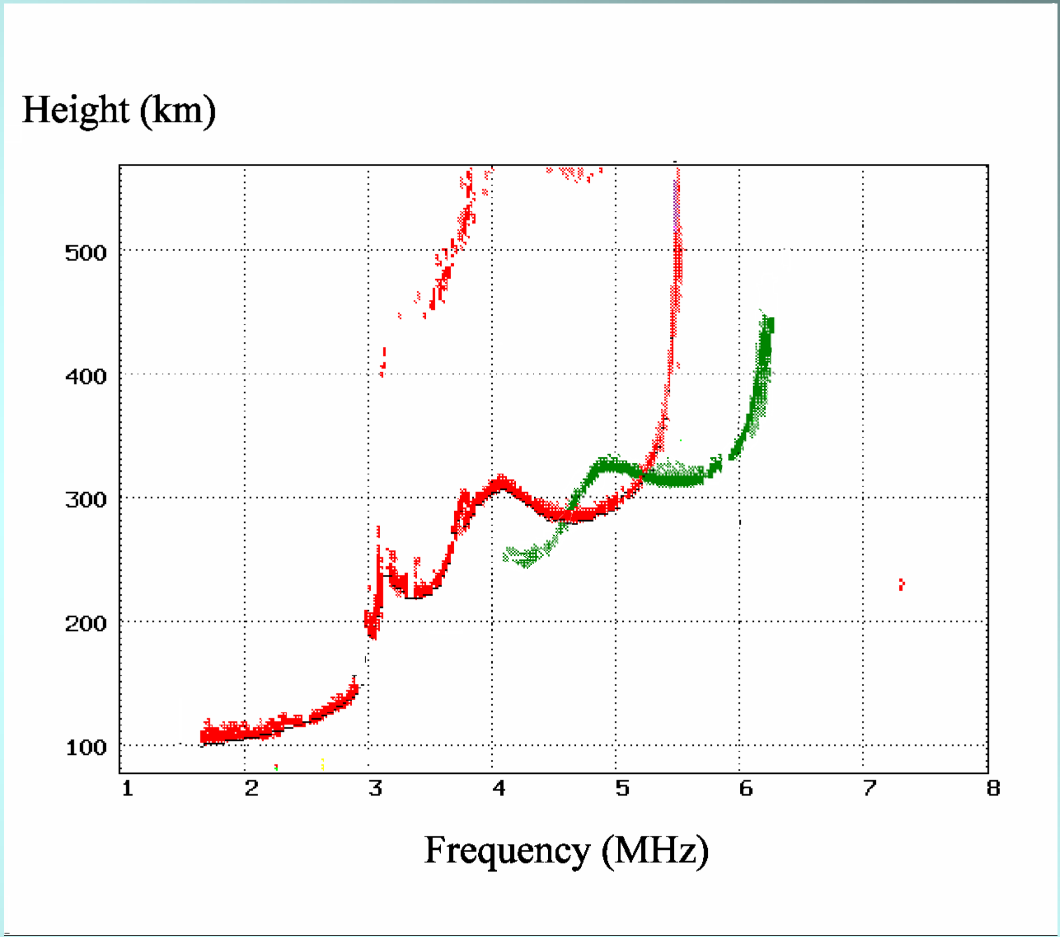
It is a plot in which the virtual heights of reflection on the ionospheric layers is sketched versus the frequency.

We use the term "virtual" because we are not measuring the real position of the layer.

The instrument converts the delay time into kilometres using the light speed in the vacuum and the relationship

$$h' = \frac{c \cdot \Delta t}{2}$$

While penetrating the plasma the speed decreases so that h < h'



The existence of earth magnetic field makes a second path possible being it the extraordinary trace.

From ionogram to the ionospheric parameters

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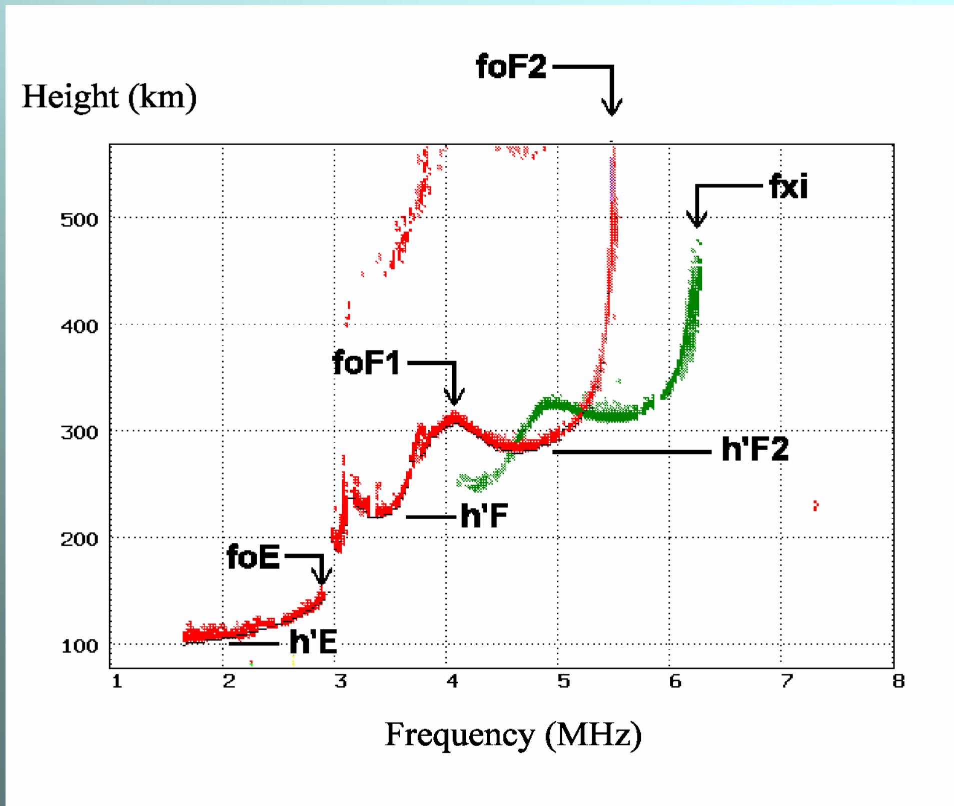
Once we get the ionogram the first step is to obtain the ionospheric characteristics (ionogram scaling).

Critical frequencies that correspond to cusps, maxima or asymptote

foE	critical freq. of E layer
foF1	critical freq. of F1 layer
foF2	critical freq. of F2 layer
fxI	critical freq. of extraordinary trace (it is also the maximum visible freq)



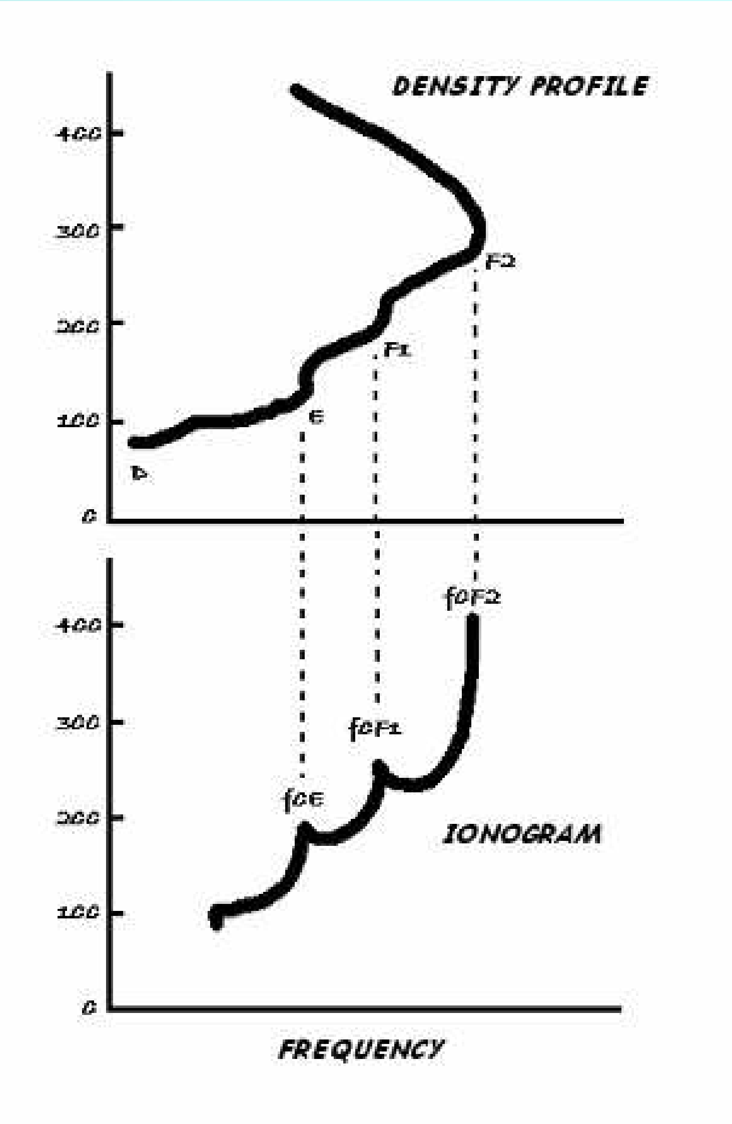
Virtual heights of the layer that correspond to relative minima on the ionogram

h'E	virtual height E layer
h'F	virtual height F layer
h'F2	virtual height F2 layer

These parameters are stored to create the history of a ionospheric observatory and are used in models to produce the ionospheric forecasts

From ionogram to the density profile

•To better describe the ionosphere we need to know the electron density profile.



•Knowing the ionogram point by point (virtual height-frequency couples) we can invert the ionogram to obtain the electron density profile.

•There are models partially empirical able to describe analytically the different ionospheric regions from elio-geophysical and ionospheric quantities.

•There are methods that derive the density profile automatically: they are particular interesting in real time mapping of ionosphere.

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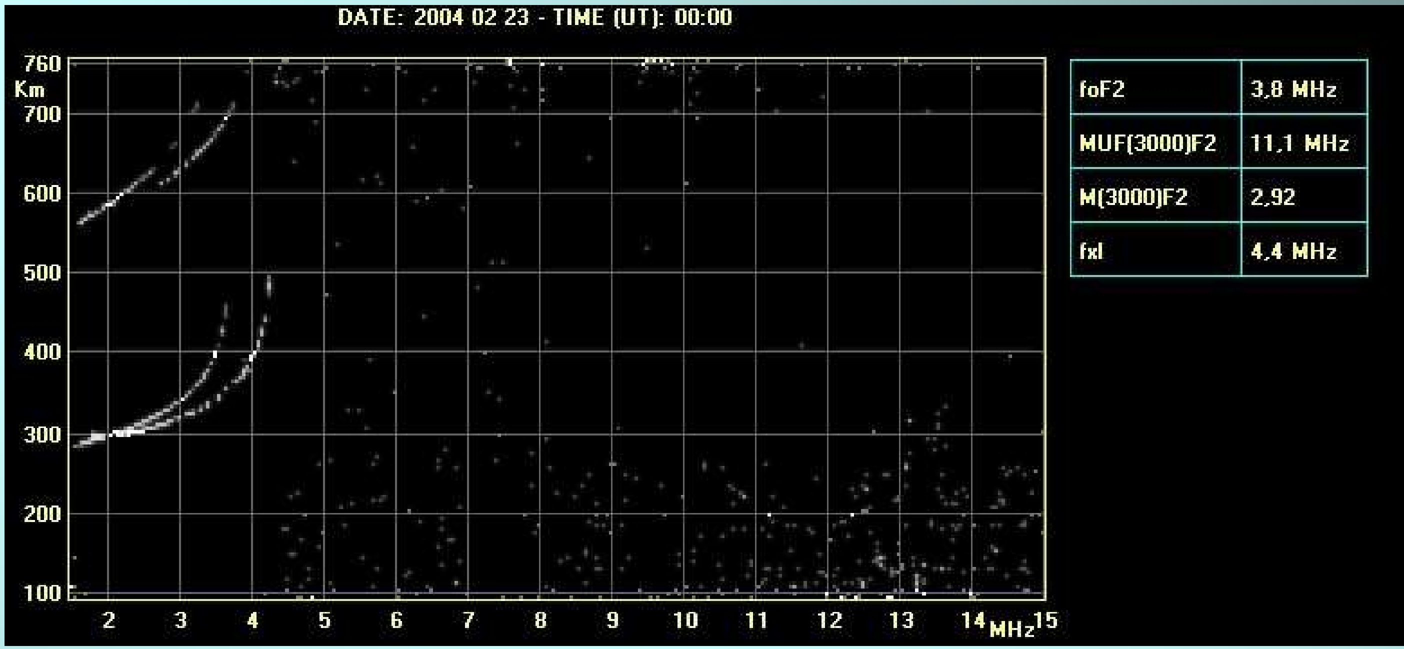

DATE: 2004 02 23 - TIME (UT): 00:00
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foF2
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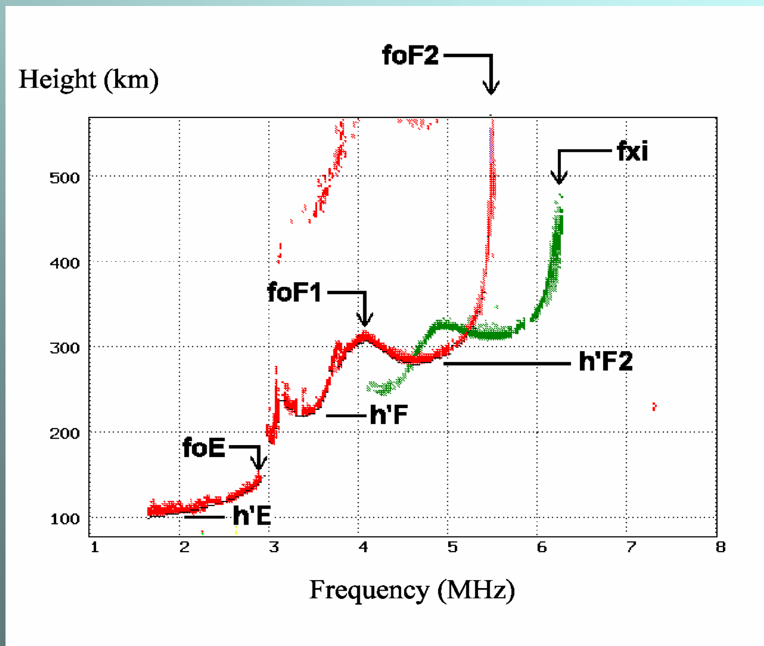
MUF(3000)F2
11,1 MHz
M(3000)F2
2,92
fxI
4,4 MHz



Height (km)
foF2
fxi
foF1
h'F2
h'F
foE
h'E
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300
200
100
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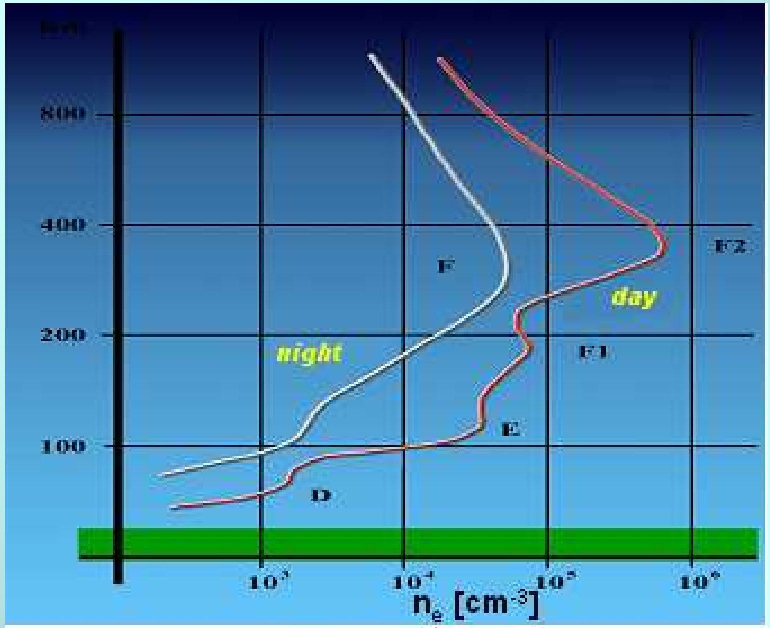
2
3
4
5
6
7
8
Frequency (MHz)



800
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10^4
10^5
10^6
n_e [cm^{-3}]

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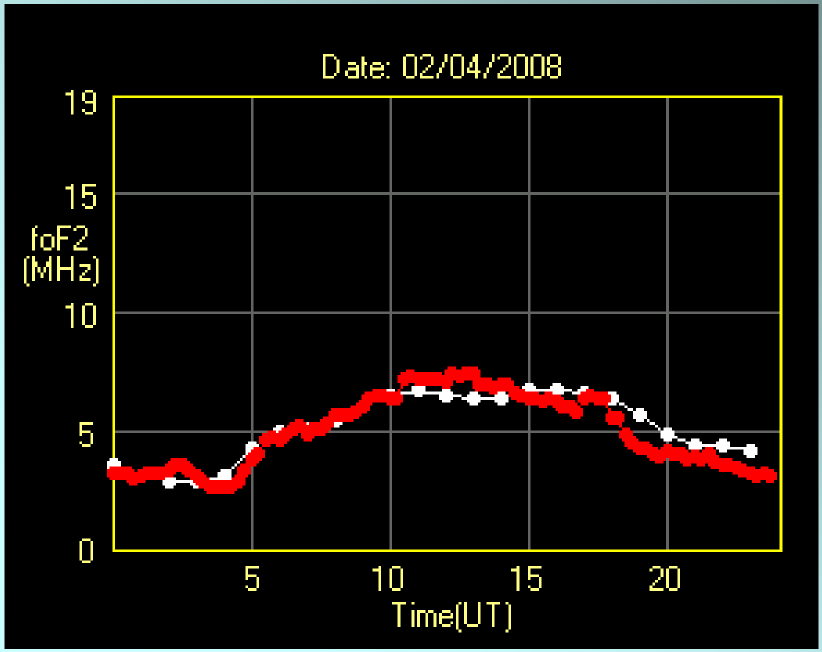
New role for a vertical sounding system

•The classic role of a ionosonde is to perform continuous sounding of the ionosphere to gather data for:

➢physics of ionosphere studies

➢forecasting



•Even though ionospheric models at medium latitudes are able to foresee the quiet conditions some weeks in advance, occasional variations due to variability of ionosphere are possible.

•Modern digital ionosondes allow to scale the ionogram within few minutes after sounding, making corrections of model possible so that values closer to the reality can be used in radio link.

•So the new role of the ionosonde is to be a monitoring system of ionospheric short term behaviour often in net configuration to allow a fast and complete map of the ionosphere in a region.

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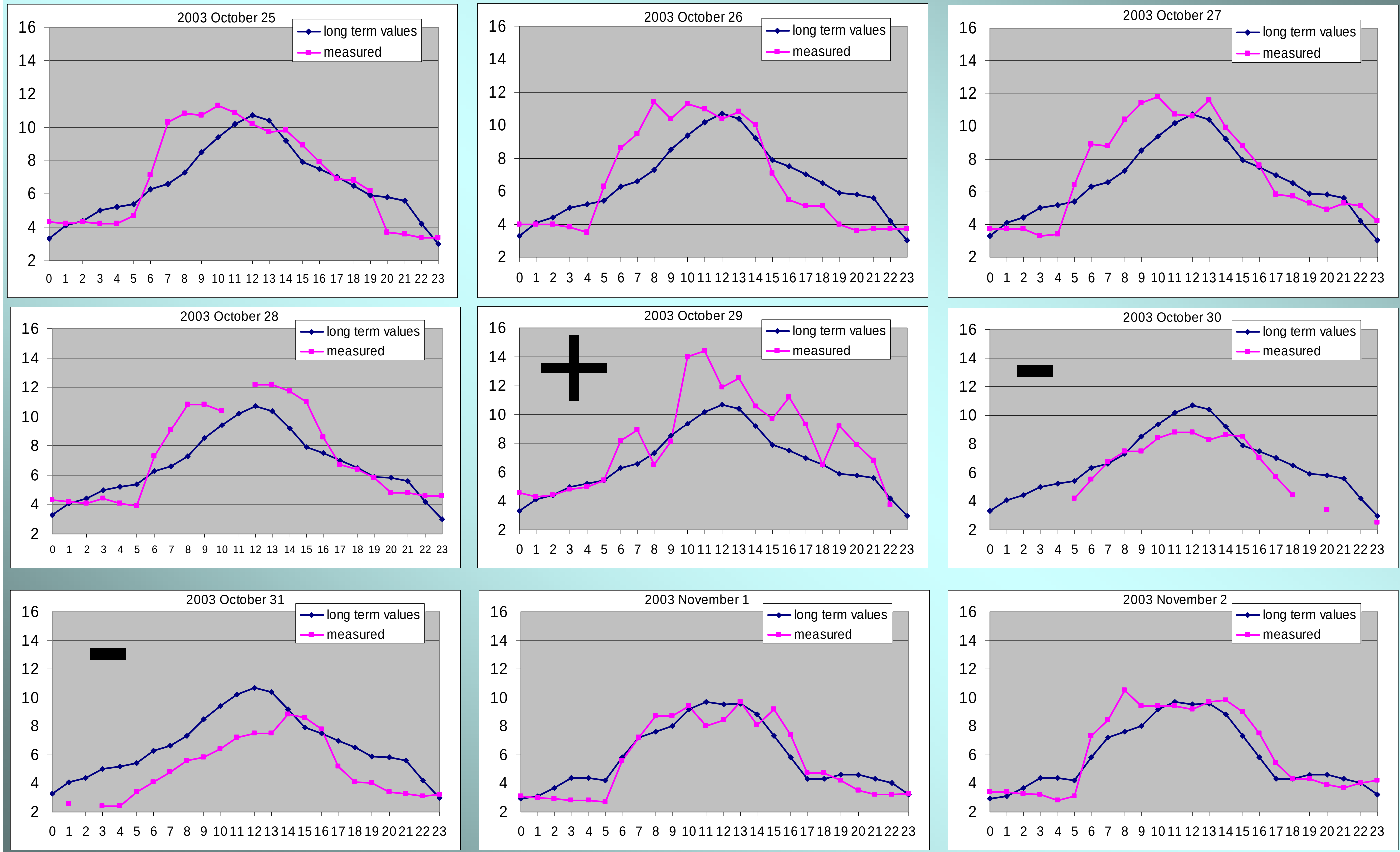
Halloween storm at Gibilmanna (Italy)
(37.9 N 014.0 E)



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