The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

310/1749-47

ICTP-COST-USNSWP-CAWSES-INAF-INFN
International Advanced School
on
Space Weather
2-19 May 2006

---

# *Techniques*

*Cesidio BIANCHI*
*Istituto Nazionale di Geofisica e Vulcanologia*
*Dipartimento di Aeronomia*
*Via di Vigna Murata 605*
*00143 Rome*
*ITALY*



Strada Costiera 11, 34014 Trieste, Italy - Tel. +39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it, www.ictp.it

# Vertical ionospheric sounding: a technique to measure the electronic density in the ionosphere.

Ionospheric Measurements techniques (receiver, radar, advanced ionospheric sounder, and related techniques)

Cesidio Bianchi INGV - Roma Italy

# Ionospheric properties related to radio waves

The most useful way to perform systematic measurements in the ionosphere is to use radio waves. This can be done exploiting the properties of the ionosphere when it interacts in various way with the electromagnetic waves.

For this reason the radio techniques for probing the ionosphere are spread in nearly each fields of radio frequency.

We explore the structure of the ionosphere transmitting vertically radio waves of different frequencies that are reflected by the ionospheric layers. By using special receivers we detect how the reflected signal has changed with respect to the transmitted one.

## Techniques of vertical soundings

-Envelope radar

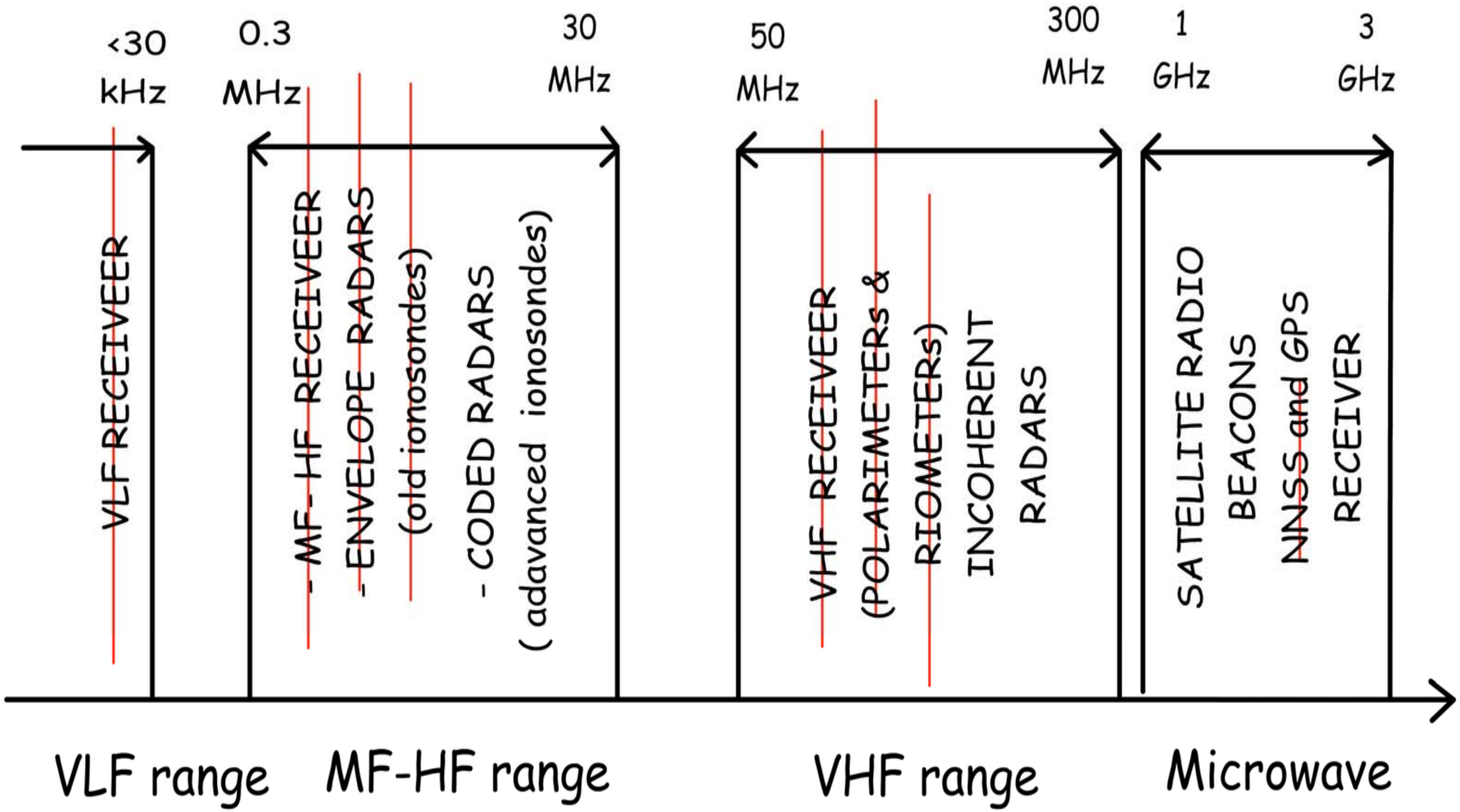
- Chirp radar

-Phase coded radar

-Doppler shift measurement

- incoherent scatter radar

# Range of frequency and recent employed techniques



# Radio & Radar principles

- The radio is a device that either generates, or responds to radio waves.

- The radar (radio detector and ranging) is a device able to transmit a pulsed radio wave and receive its echo evaluating also the range and the modification of the transmitted radio wave.

# Basic requirements for receivers:

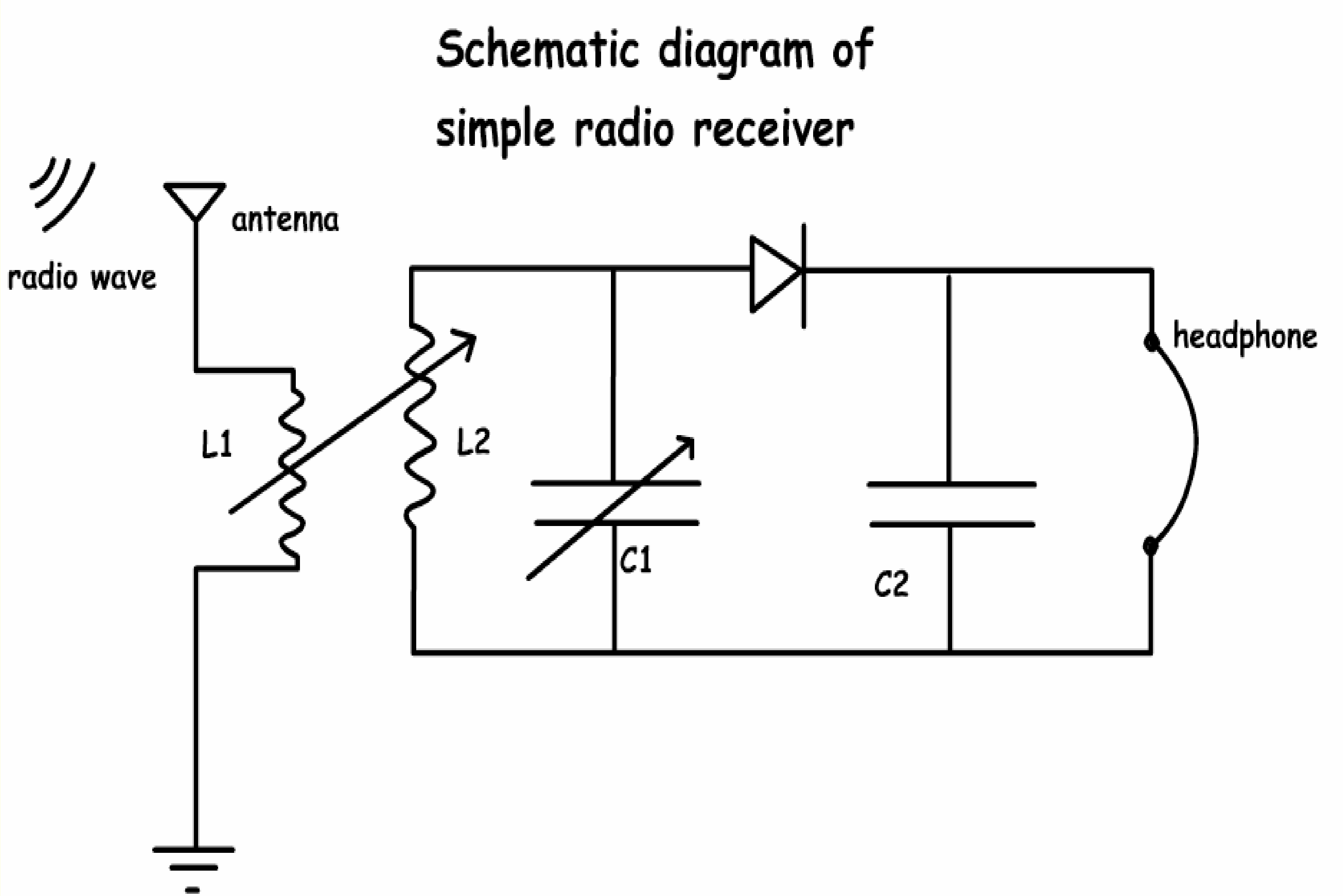
- Receiving, and demodulating AM, FM, phase coded waves

.

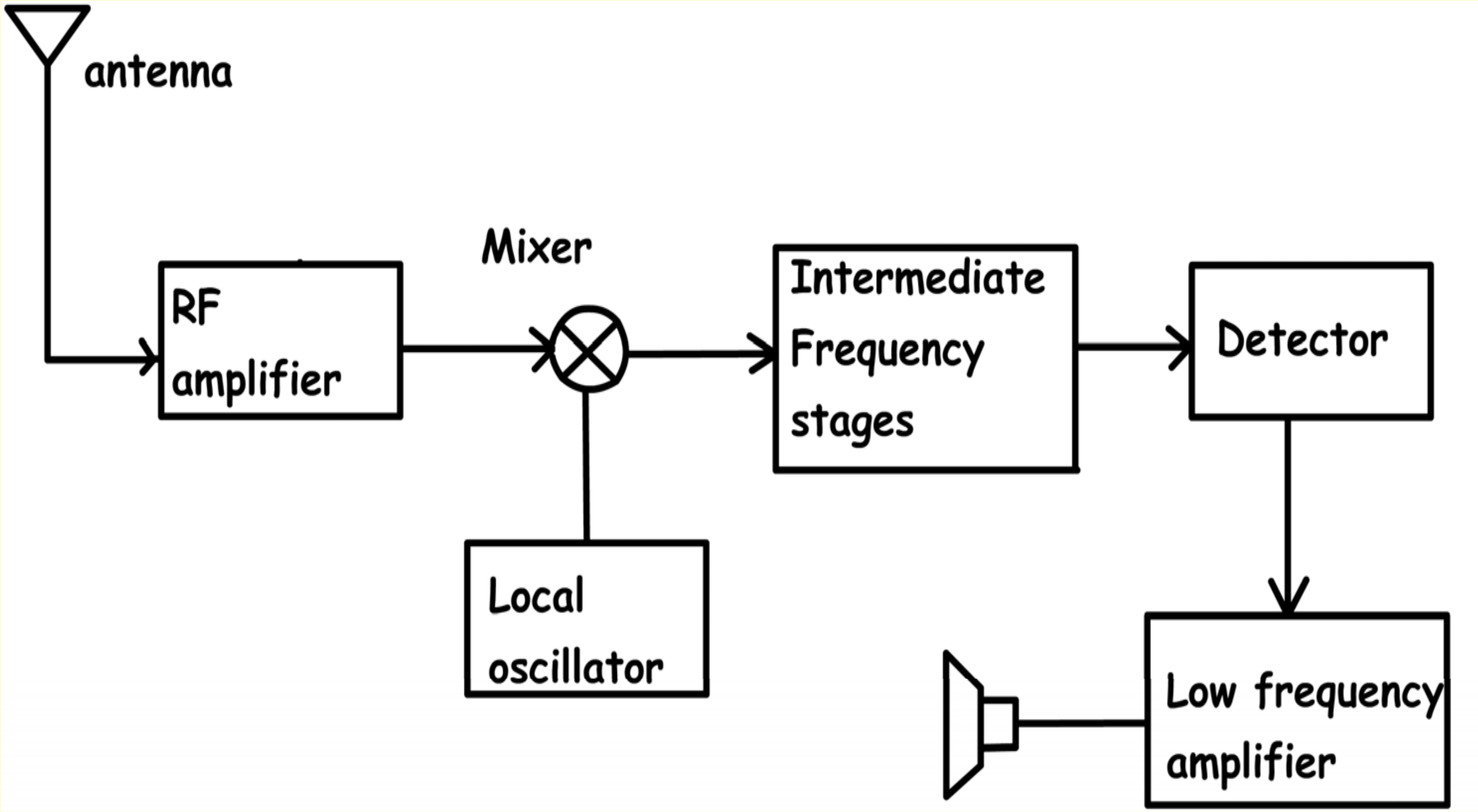
- tune to a specific signal

- amplify the signal that is picked up

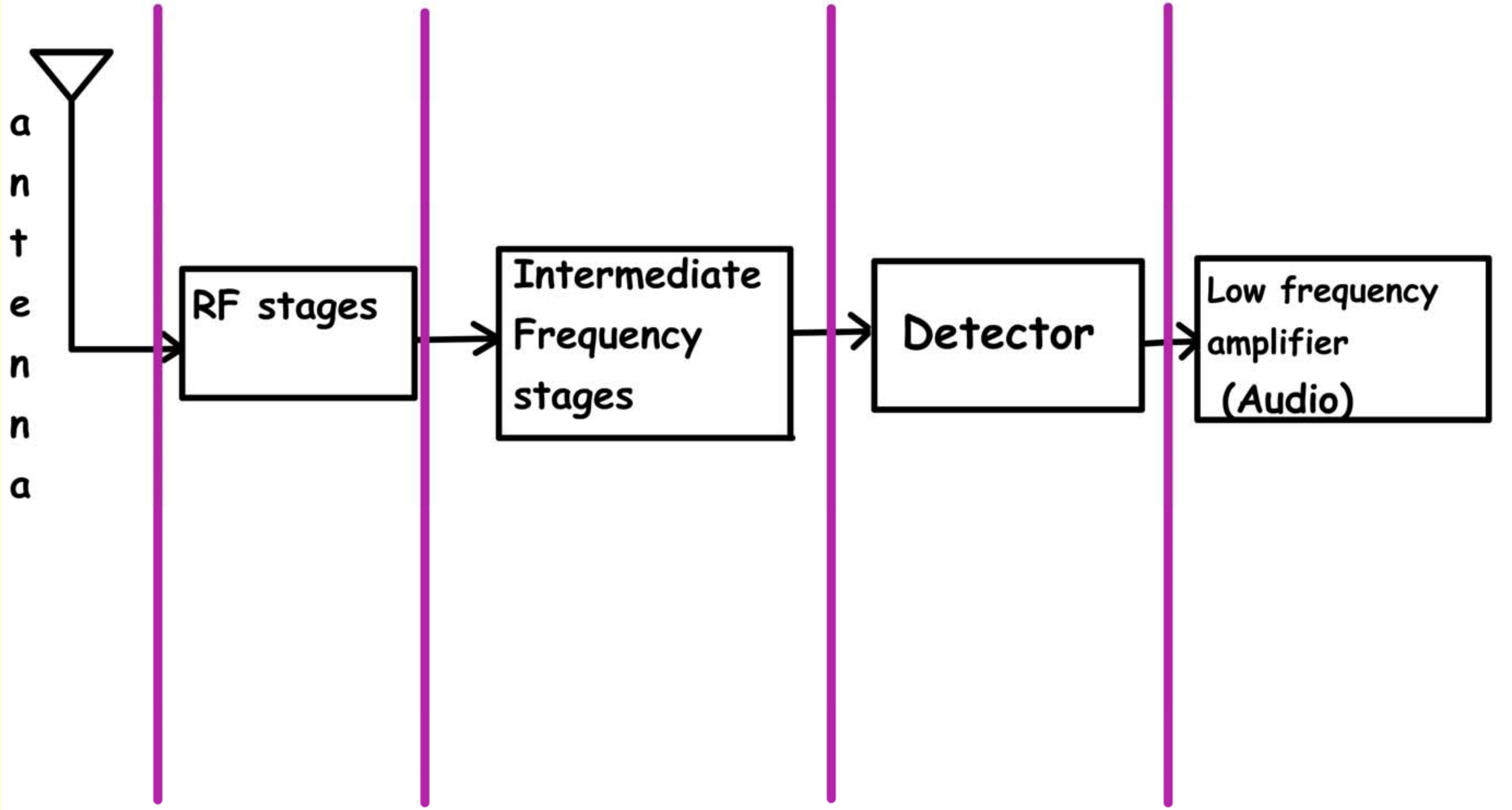
# Radio Receiver



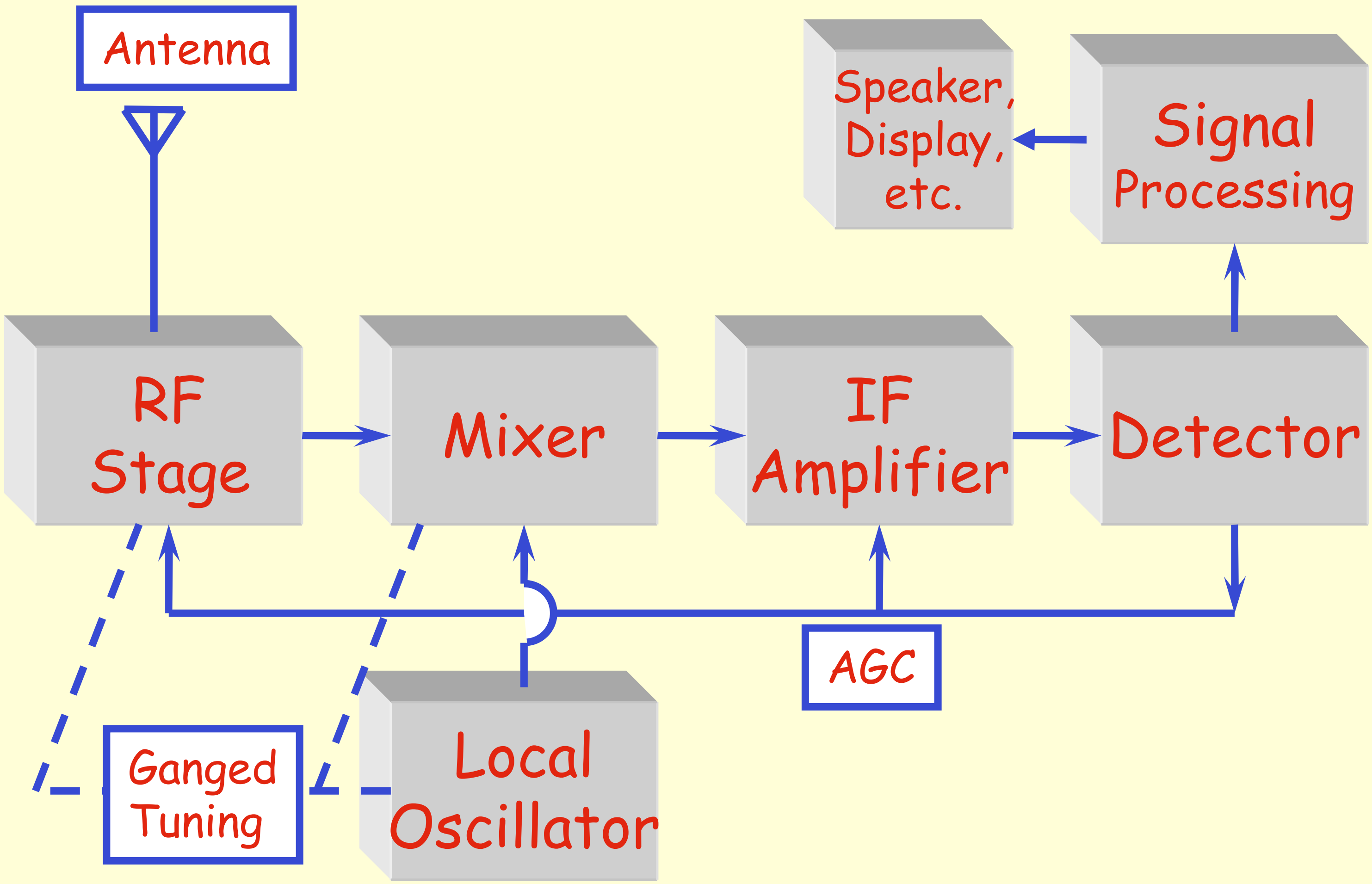
# Superherodyne receiver



# sections


antenna
RF stages
Intermediate Frequency stages
Detector
Low frequency amplifier (Audio)

# Radio receiver block diagram

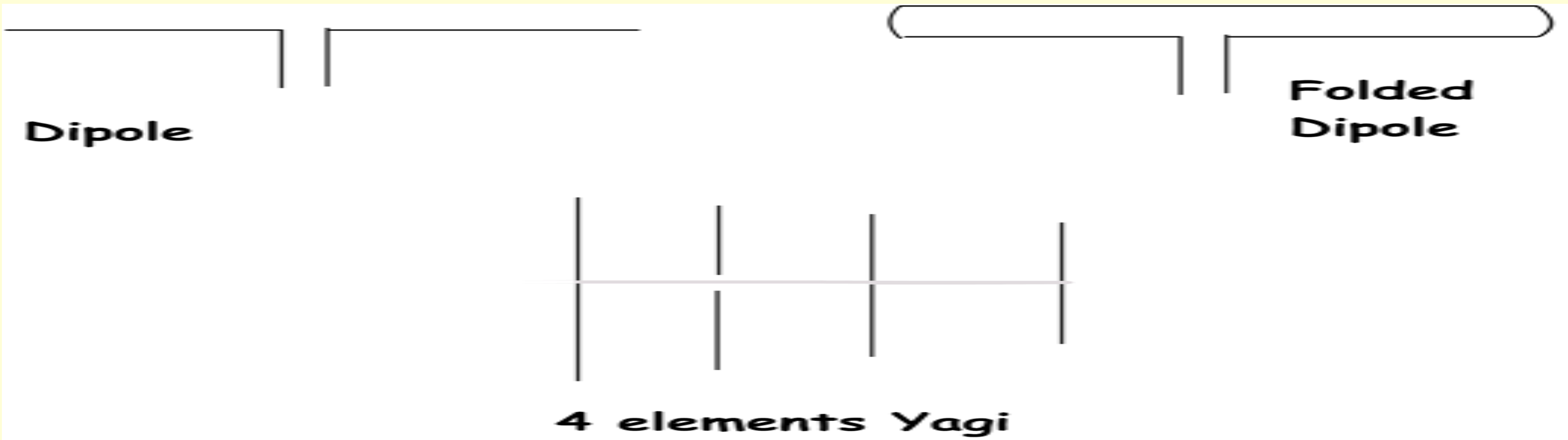


# functions & requirements

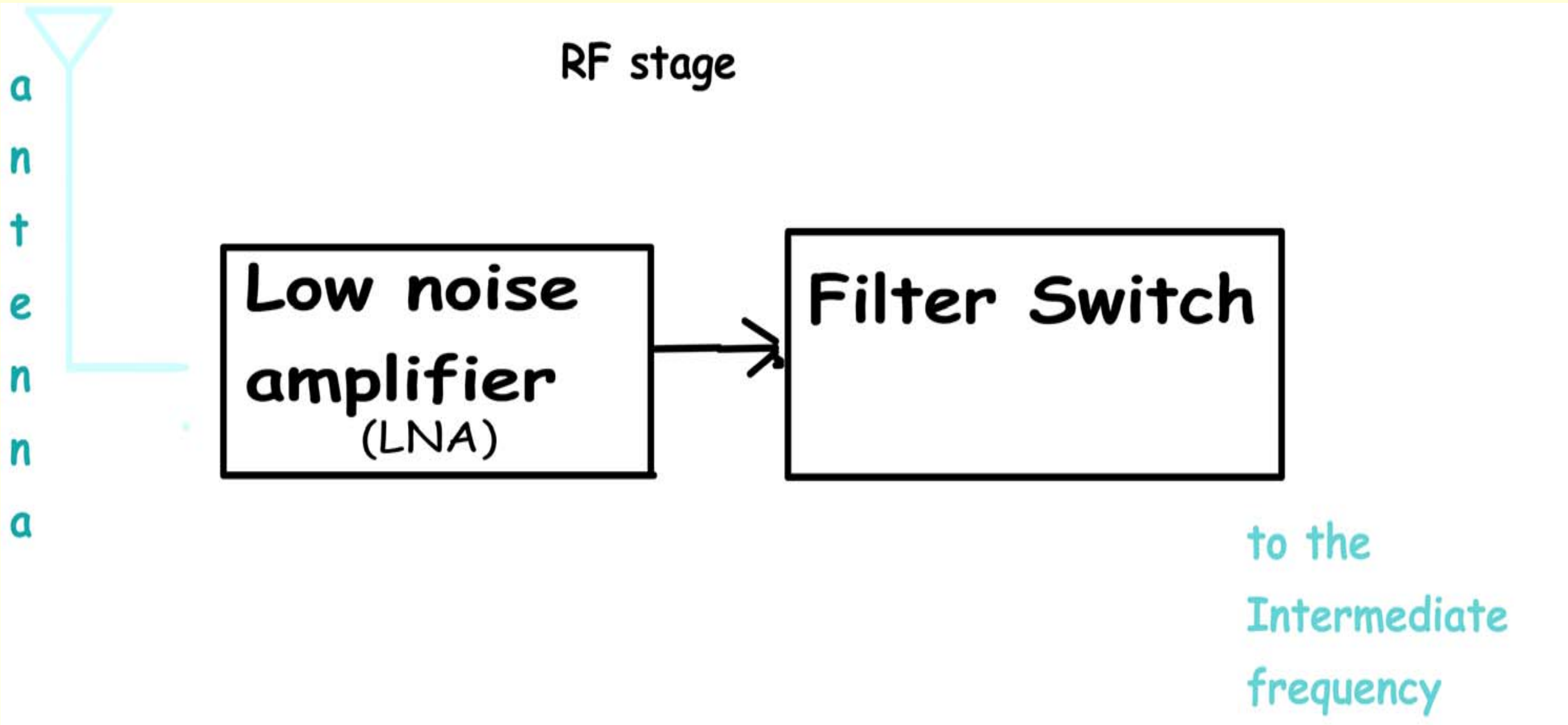
- modulation (amplitude, frequency, phase etc..) (information)
- filter (selectivity)
- amplifier (dynamic, sensitivity and linearity)
- detection (dynamic and linearity)
- control (dynamic and linearity, AGC, selectivity)

# antenna

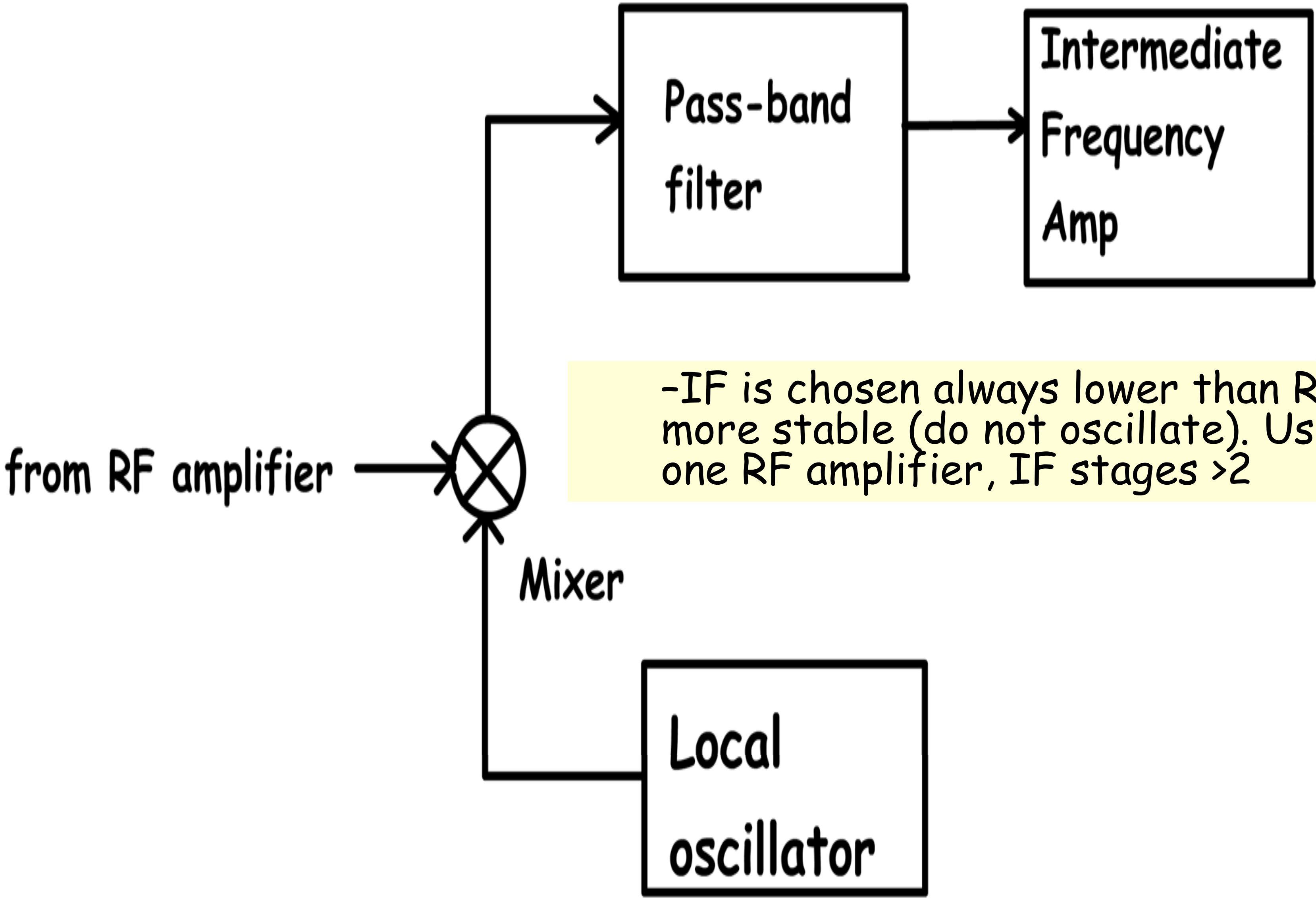
A radio antenna may be defined as a structure associated with the region of transition between a guided wave and free space or vice versa (Kraus)



# RF front-end


RF stage
a
n
t
e
n
n
a
Low noise amplifier
(LNA)
Filter Switch
to the
Intermediate
frequency

# Intermediate frequency

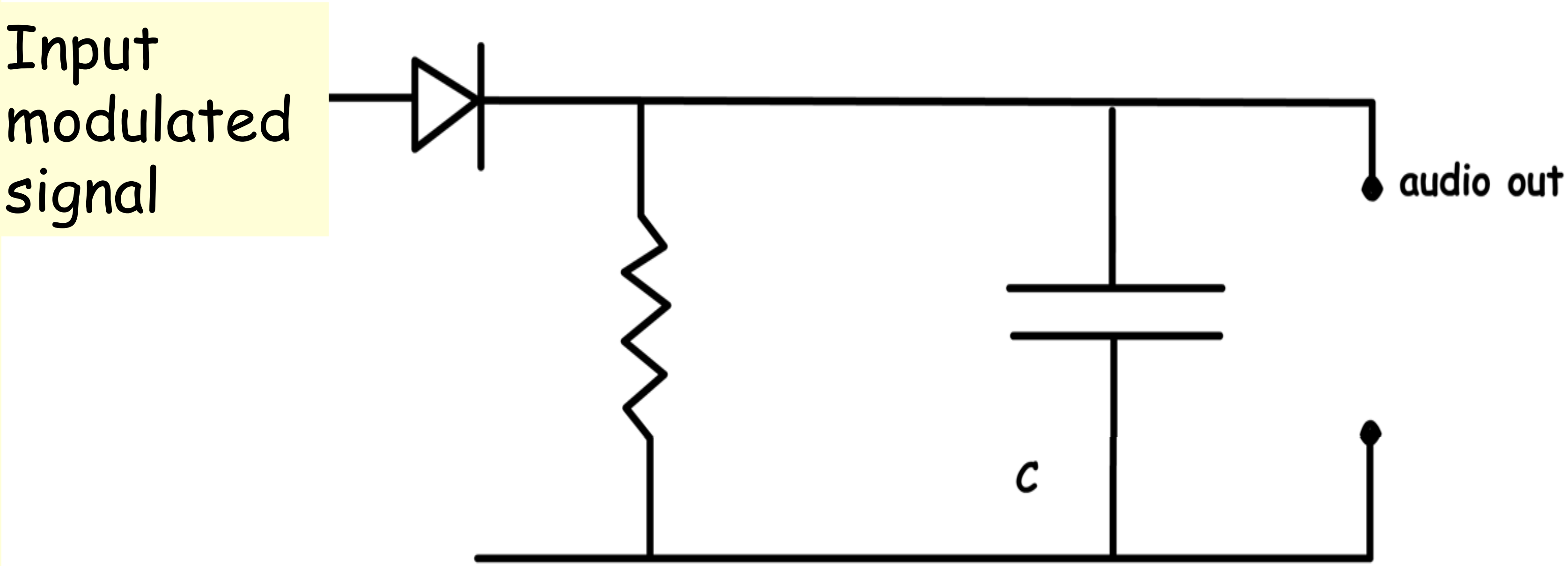



–IF is chosen always lower than RF: more stable (do not oscillate). Usually one RF amplifier, IF stages >2

Mixer- By a local oscillator LO, the RF is converted to IF (RF to IF translation). Shape of the envelope remain the same. BW is unchanged

# Detection process

Envelope detector




Digital receiver or radar

A/D converter

# Detection

Two types

- Coherent (synchronous): frequencies used for demodulation are exact copy of Tx carrier
- Non-coherent (asynchronous): envelope detection

# Internal noise

The white noise is due to the random motion of the electrons. The voltage across the two resistor terminal at the absolute temperature T is:

$$V_{rms}=2(KTRB)^{0.5}$$

where K is the Boltzmann constant (J/Hz)and

B is the band of frequency considered.

Under well matched condition the power is P=KTB (W)

By definition the noise factor F is:

Signal-to-noise ratio(input) / Signal-to-noise ratio (output)

# Internal noise 2

In the receiver it is useful to define the noise factor F in quantitative way as:

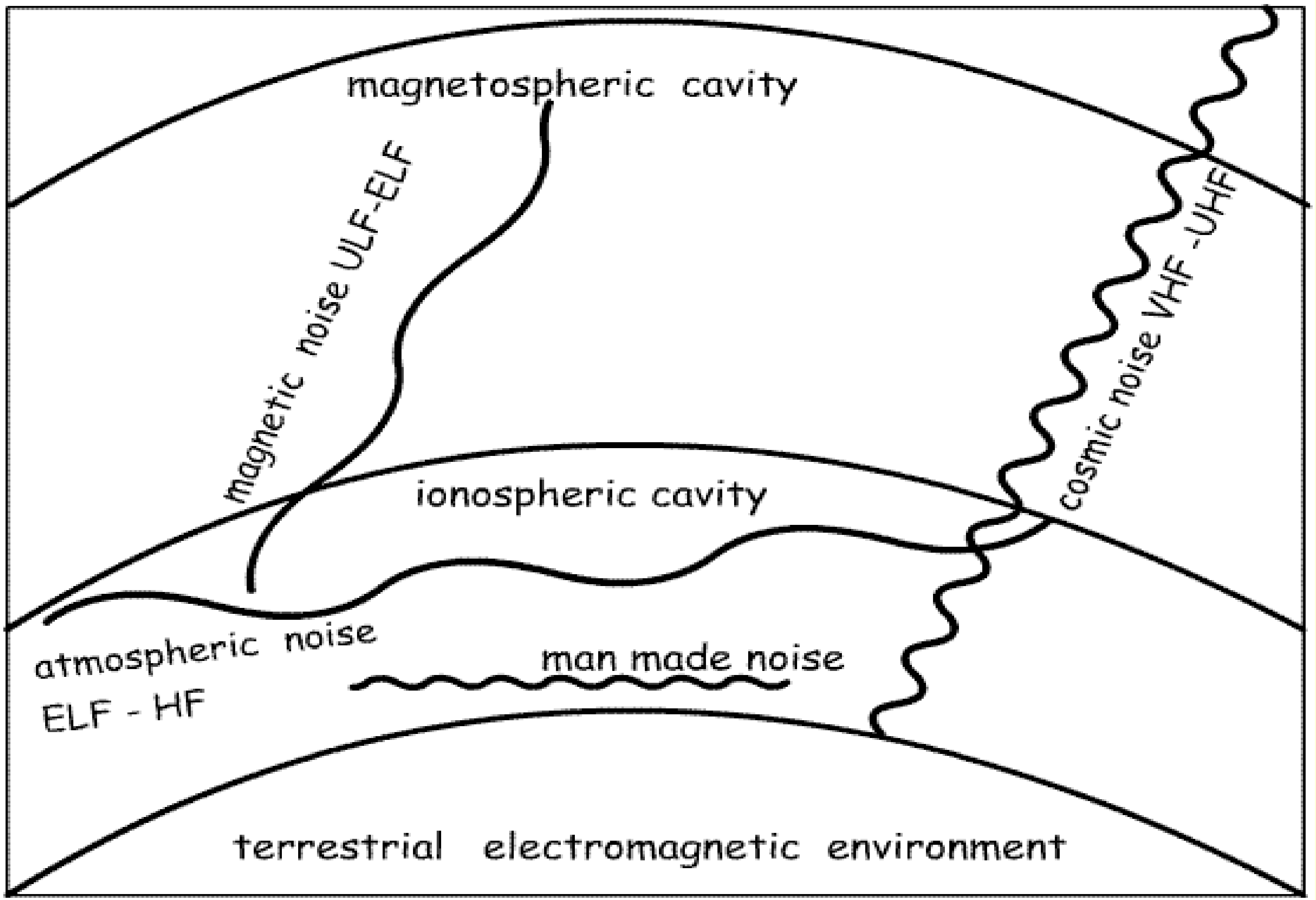
$$F = \frac{Pi / KToB}{GPi/(GKToB + P_A)}$$

where $P_i$ and $P_A$ are the input noise and additional noise measured at amplifier the output

The noise figure is

$$f_{noise} = 10 \log_{10} F$$

# environment



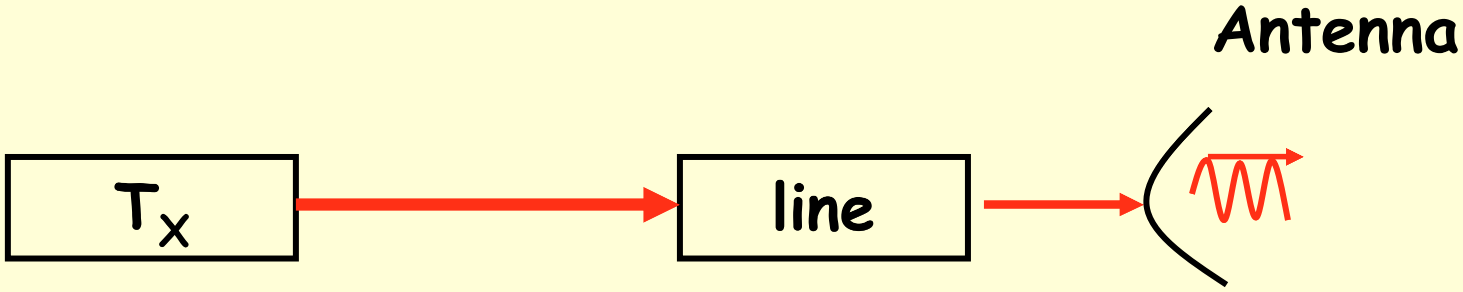
## noise & interferences

- What is important at the antenna level is the signal-to-noise ratio (S/N)
- The noise level does not allow to increase the sensitivity as we desire.

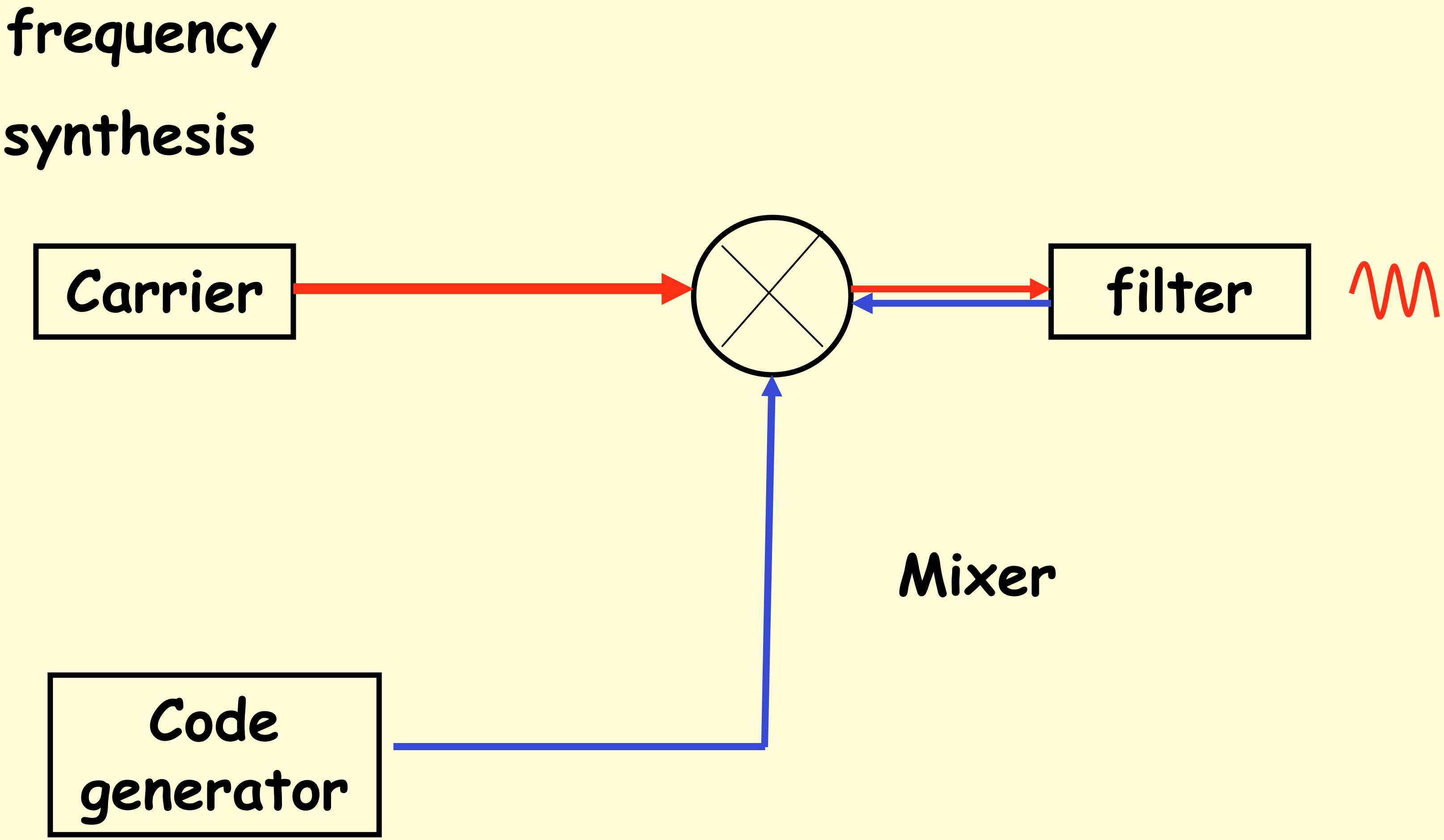
- Terrestrial environment is continuously exposed to electromagnetic radiations, which set up a “background” of electromagnetic noise. The electromagnetic background refers to the environment in which there are both natural and manmade electromagnetic noise.

- Broadcasting stations can cause strong interferences which affect the reception of the signal

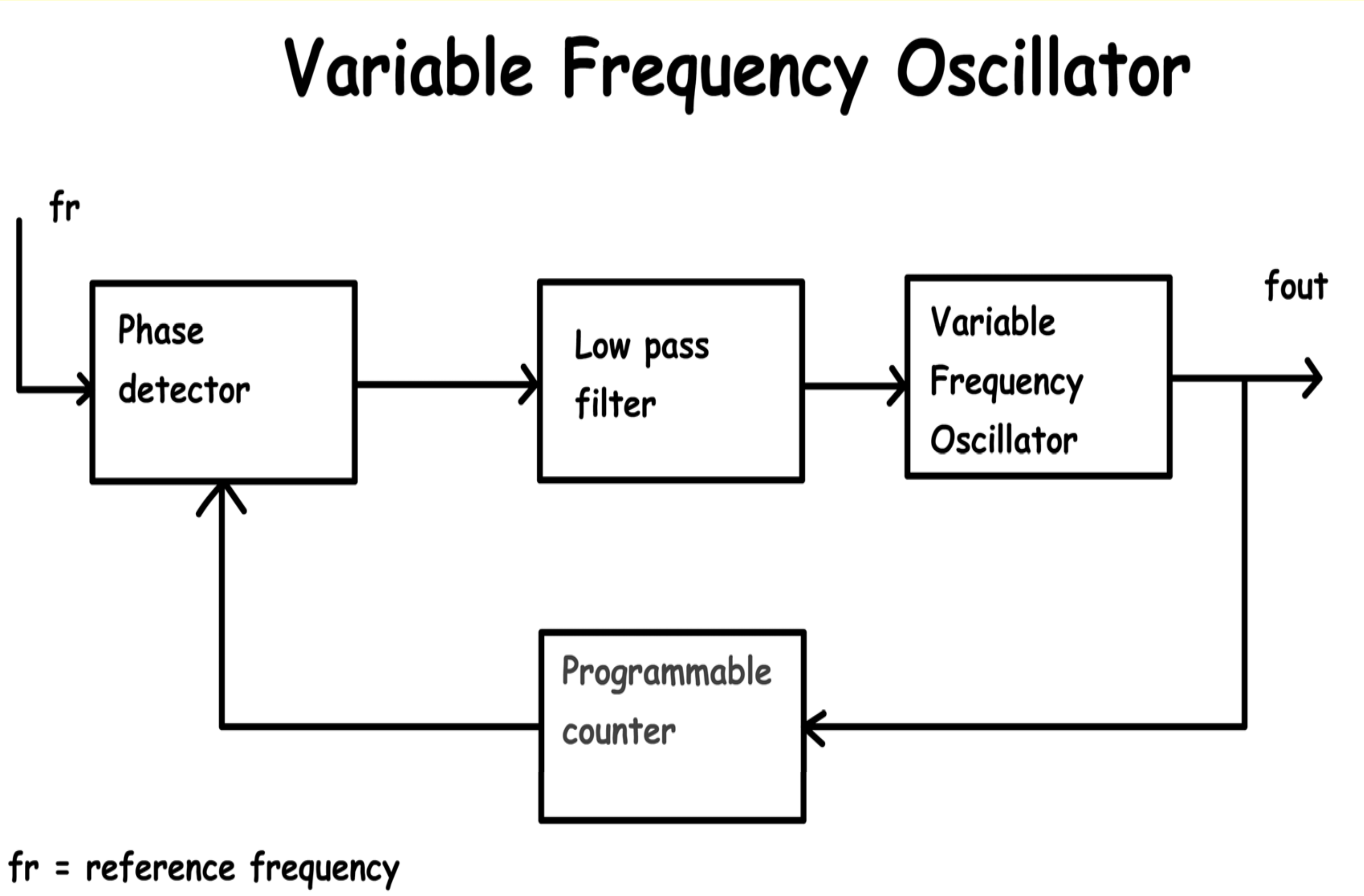
# Transmitter



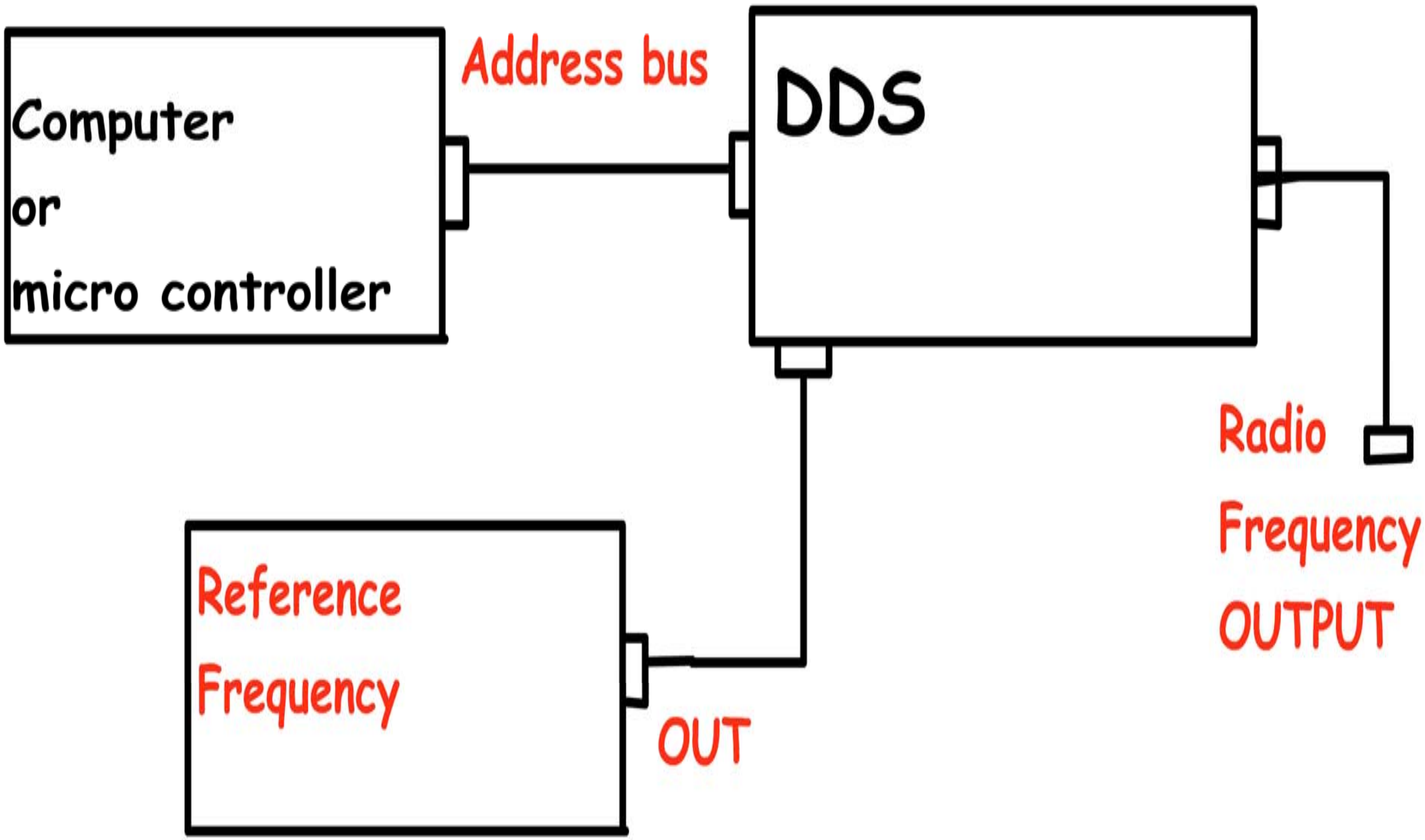
# Transmitter
## (modulation process)



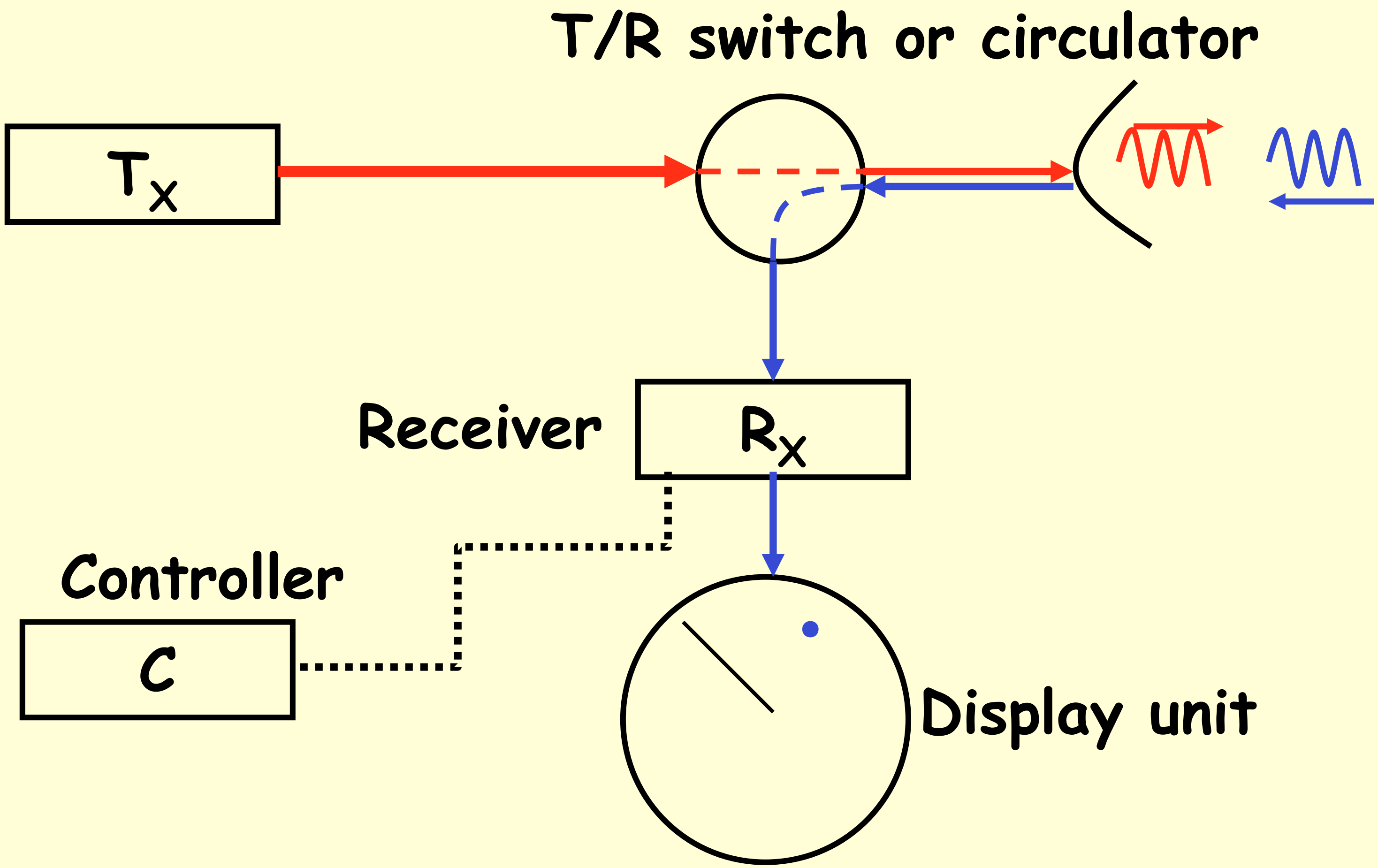
Frequency synthesizer



# Direct Digital Synthesis

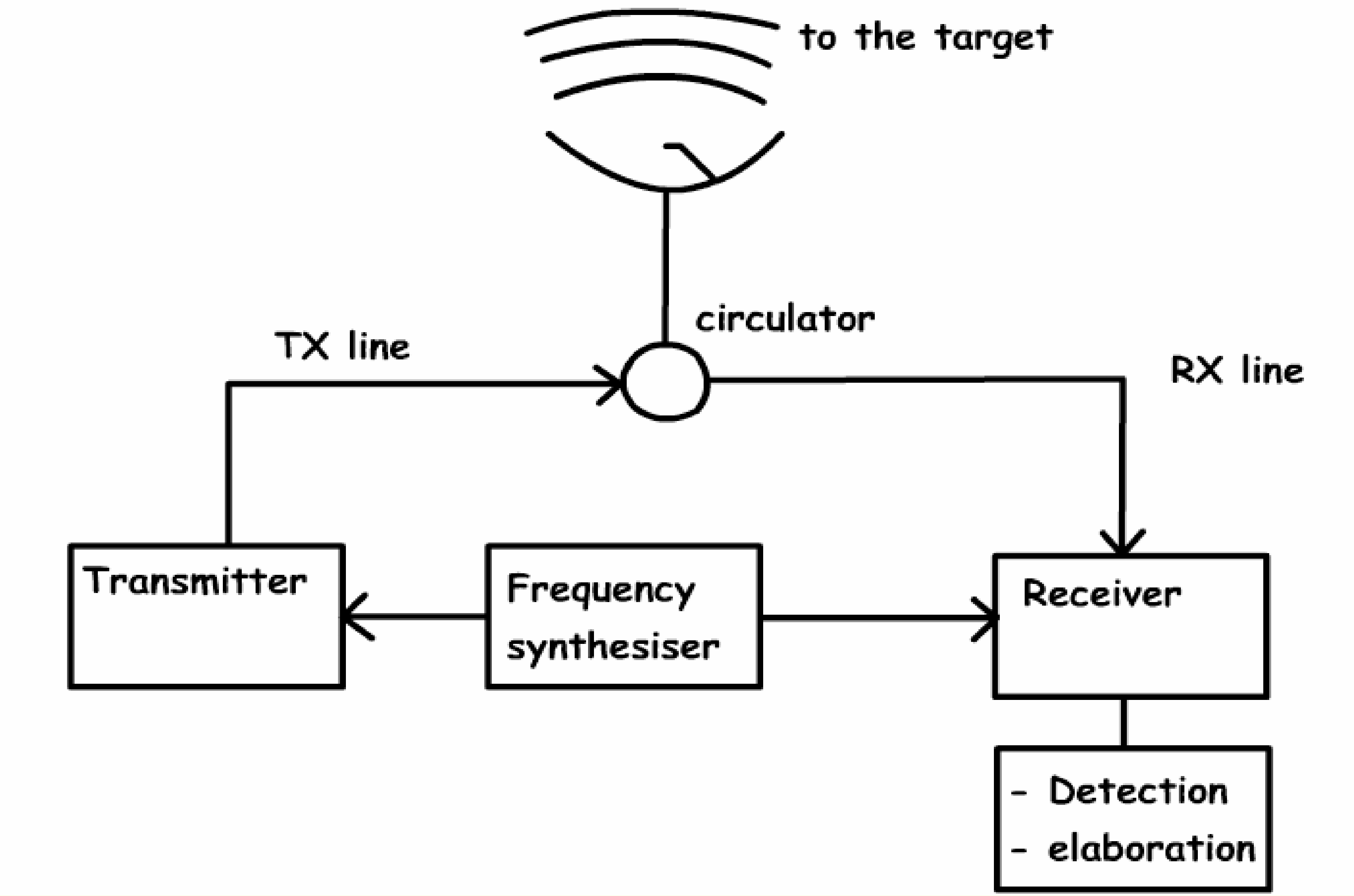


# Radar

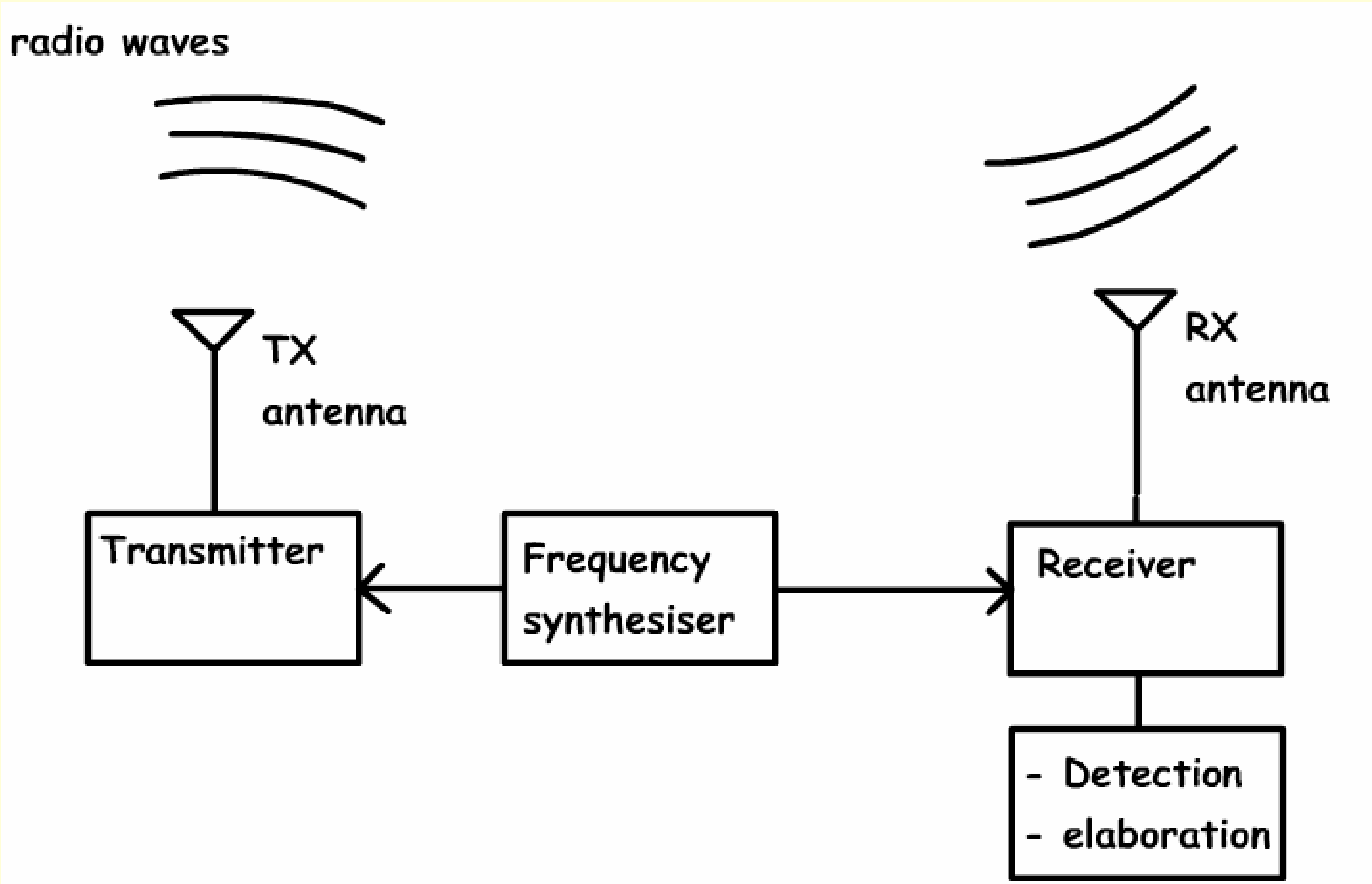


T/R switch or circulator
$T_X$
Receiver
$R_X$
Controller
C
Display unit

# Mono static radar



# Bi-static radar



# Radar equation

The radar equation represents the physical dependences of between the received power $P_r$ and transmitted power $P_t$.

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

- $\sigma$ is radar cross section (characterizes the target's ability to scatter or reflect energy) [$m^2$]

- $G_d$ is the directive gain of antenna (measure of the concentration of the radiated power in a particular direction) [unitless].

- $r$ is the distance measured from the radar to the target
- $\lambda$ is the wavelength of signal received by radar antenna

# Radar cross section

- Radar cross section is defined as:

$$\sigma = 4\pi r^2 \left( \frac{|E_s|}{|E_i|} \right)^2$$

where $E_s$ and $E_i$ are defined as the scattered and incident electric fields, respectively. $E_s$ is measured at the receiving antenna, whereas $E_i$ is measured at the target level . Since the scattered electric field is inversely proportional to distance, *r*, the radar cross section reduces to the following:

$$\sigma \equiv 4\pi r^2 \left( \frac{\left|\frac{E_s}{r}\right|}{|E_i|} \right)^2 = 4\pi \left( \frac{|E_s|}{|E_i|} \right)^2$$

# Radar equation for coherent reflectors

For very large targets (coherent reflectors) the radar equation will be the following:

$$P_r = \frac{(\lambda G_d)^2 P_t}{4\pi \; r^2}$$

Note that the dependence on the distance now is $1/r^2$ and the radar cross section does not appear in the equation. In the ionospheric vertical sounding the above equation is used while in the incoherent scatter radar the dependence on the distance is $1/r^4$ and the radar cross section depend of the plasma density.

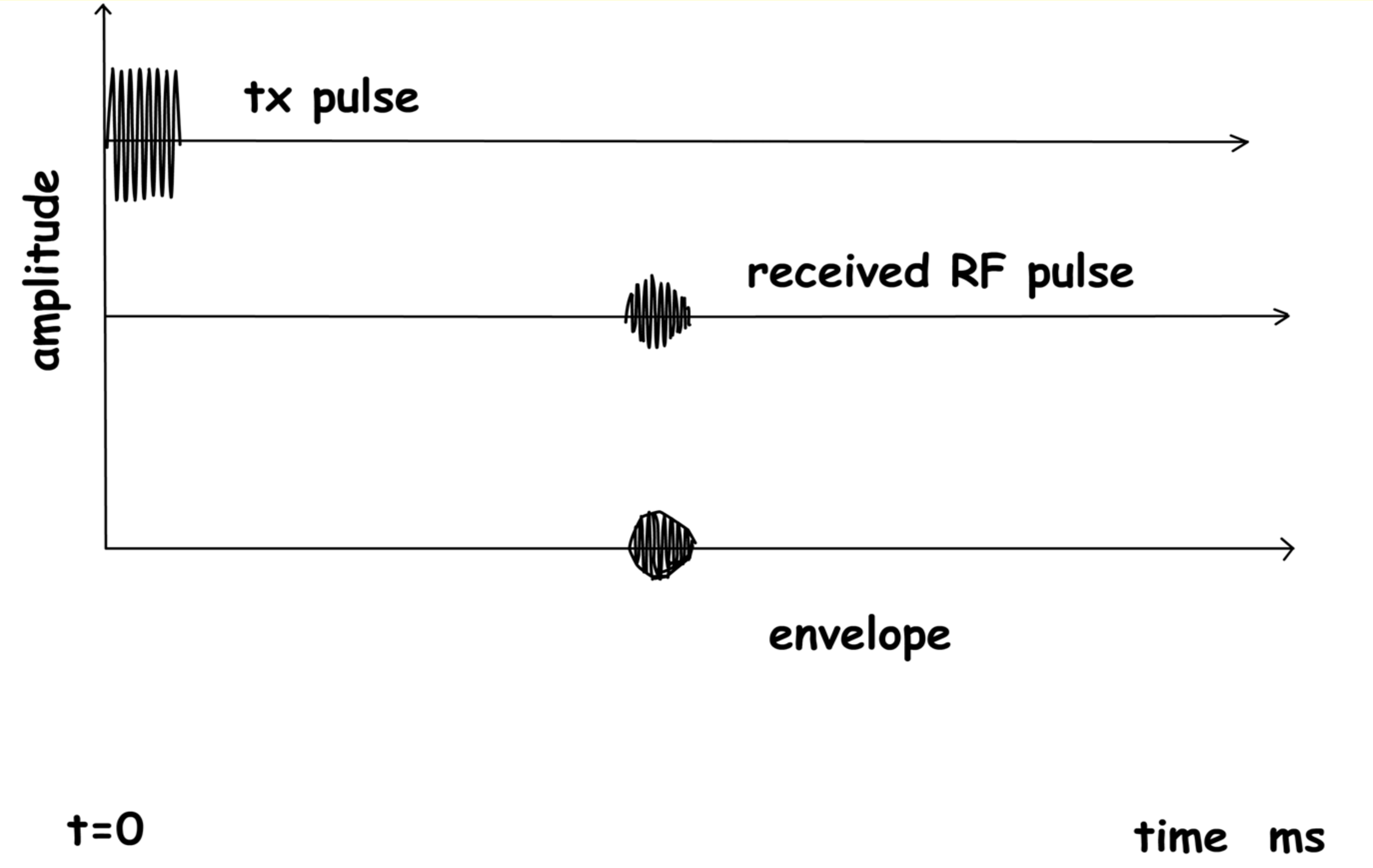
# ionosonde

- Ionosonde is a variable frequency bi-static radar

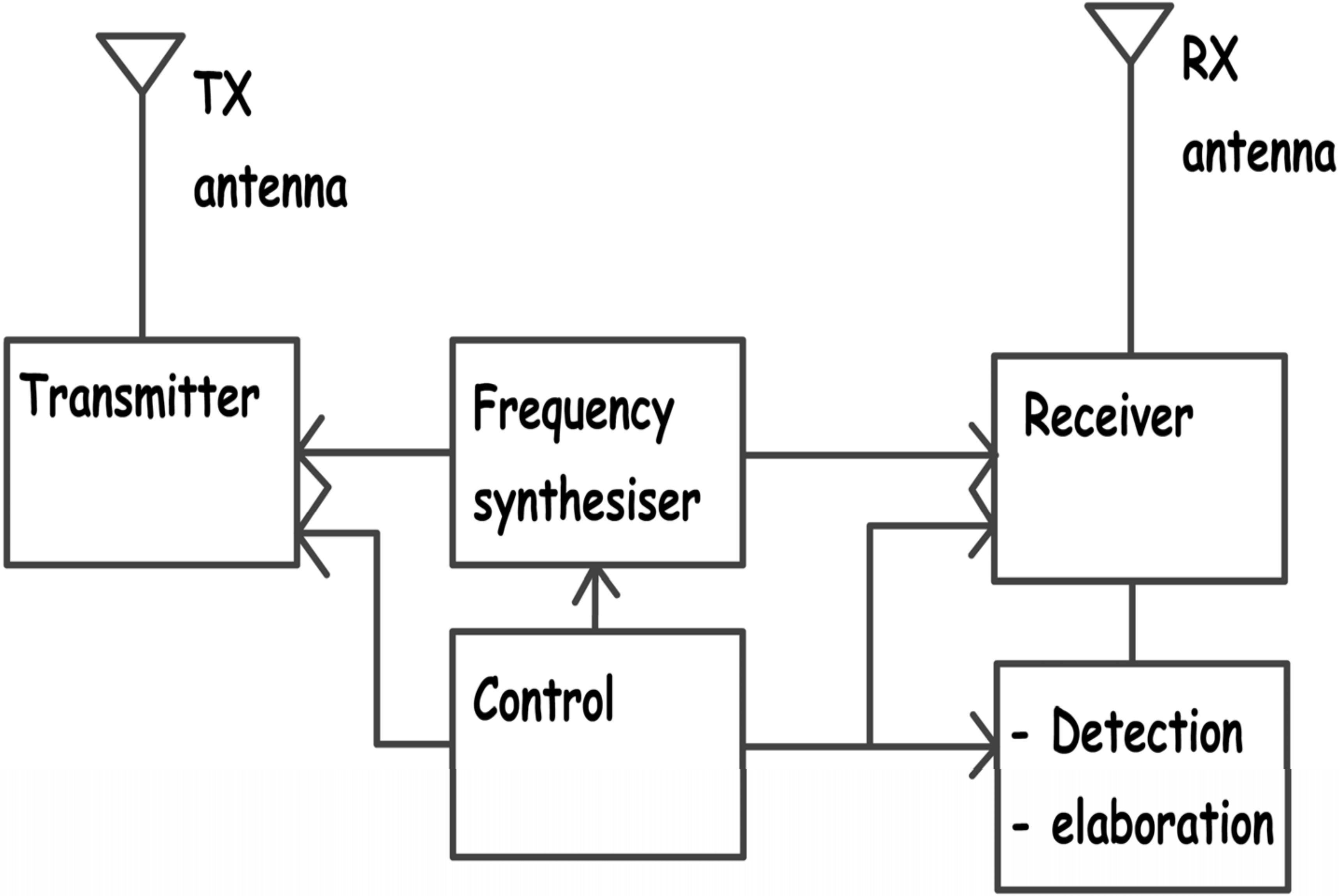
- Frequency of operation (about in the HF band)

- Target (Coherent reflector constitute by electronic density surfaces)

# Envelope detector ionosonde or HF Radar

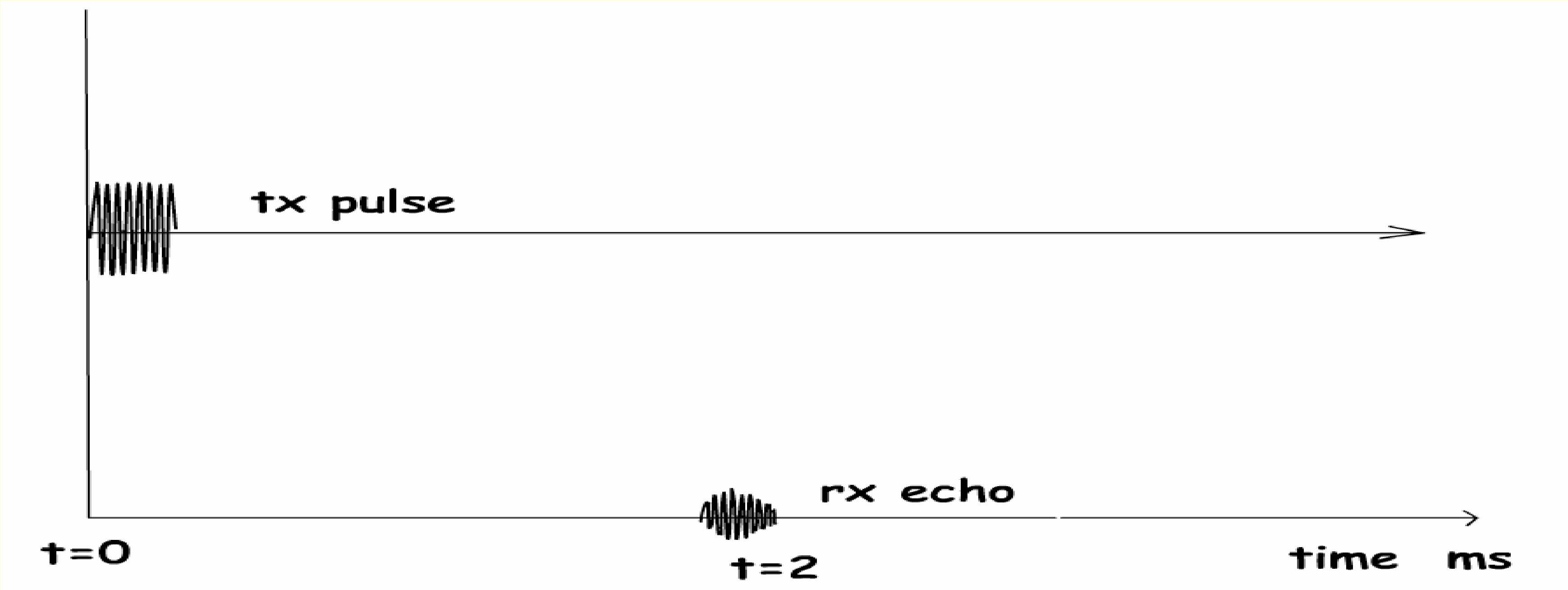


# ionosonde block-diagram



- The frequency measurement is assured by the receiver selectivity always tuned with the transmitted frequency

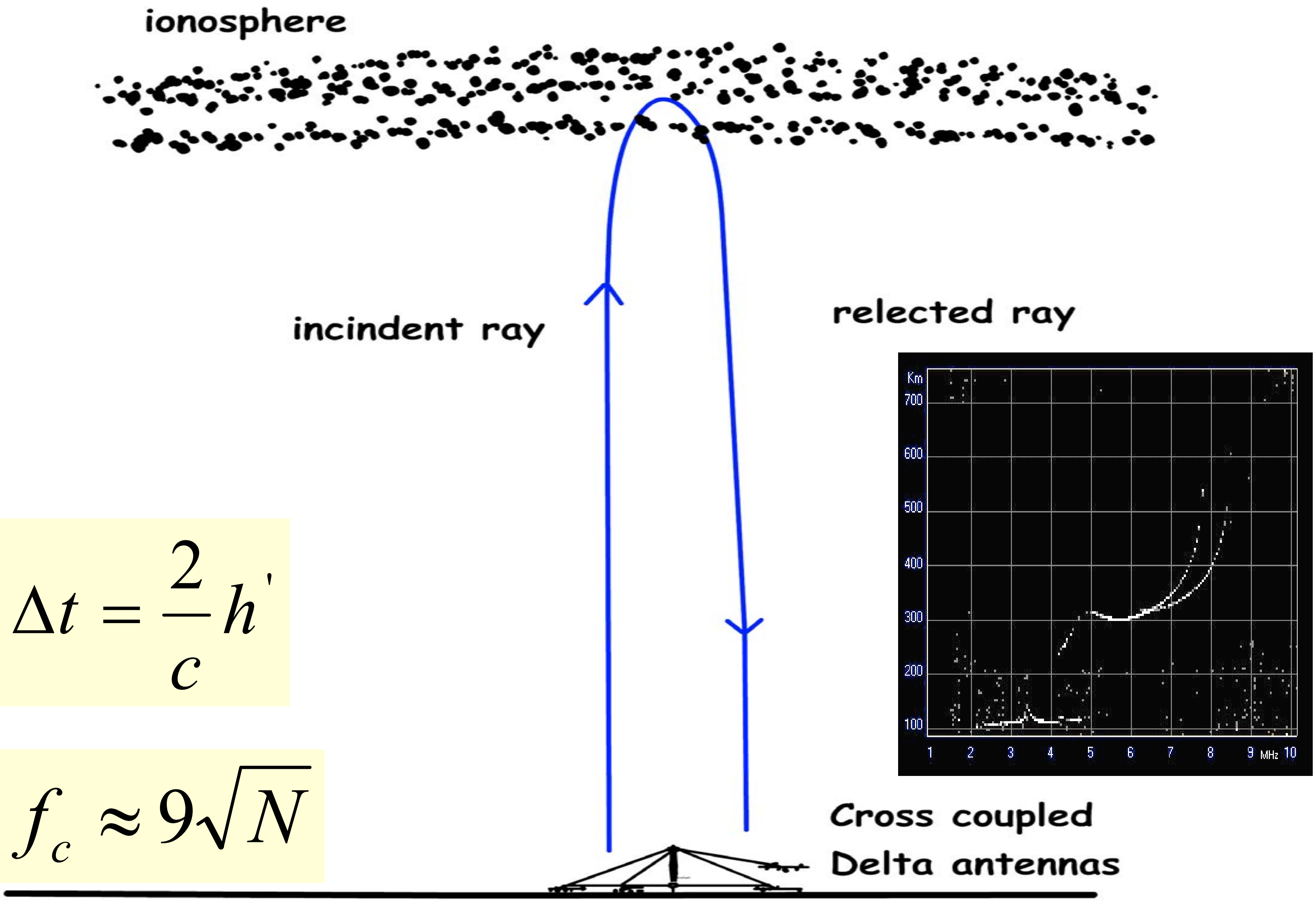
In practical is the same frequency synthesizer that steers both transmitter and receiver




Delay

- Vertical sounding are performed by a high frequency radar known as ionosonde. The ionosonde sends short pulses of radio energy vertically into the ionosphere. These pulses are reflected back towards the ground and the ionosonde records the time delay between transmission and reception of pulses. By varying the carrier frequency of pulses from 1 to 20 MHz, the time delay at different frequencies is recorded.

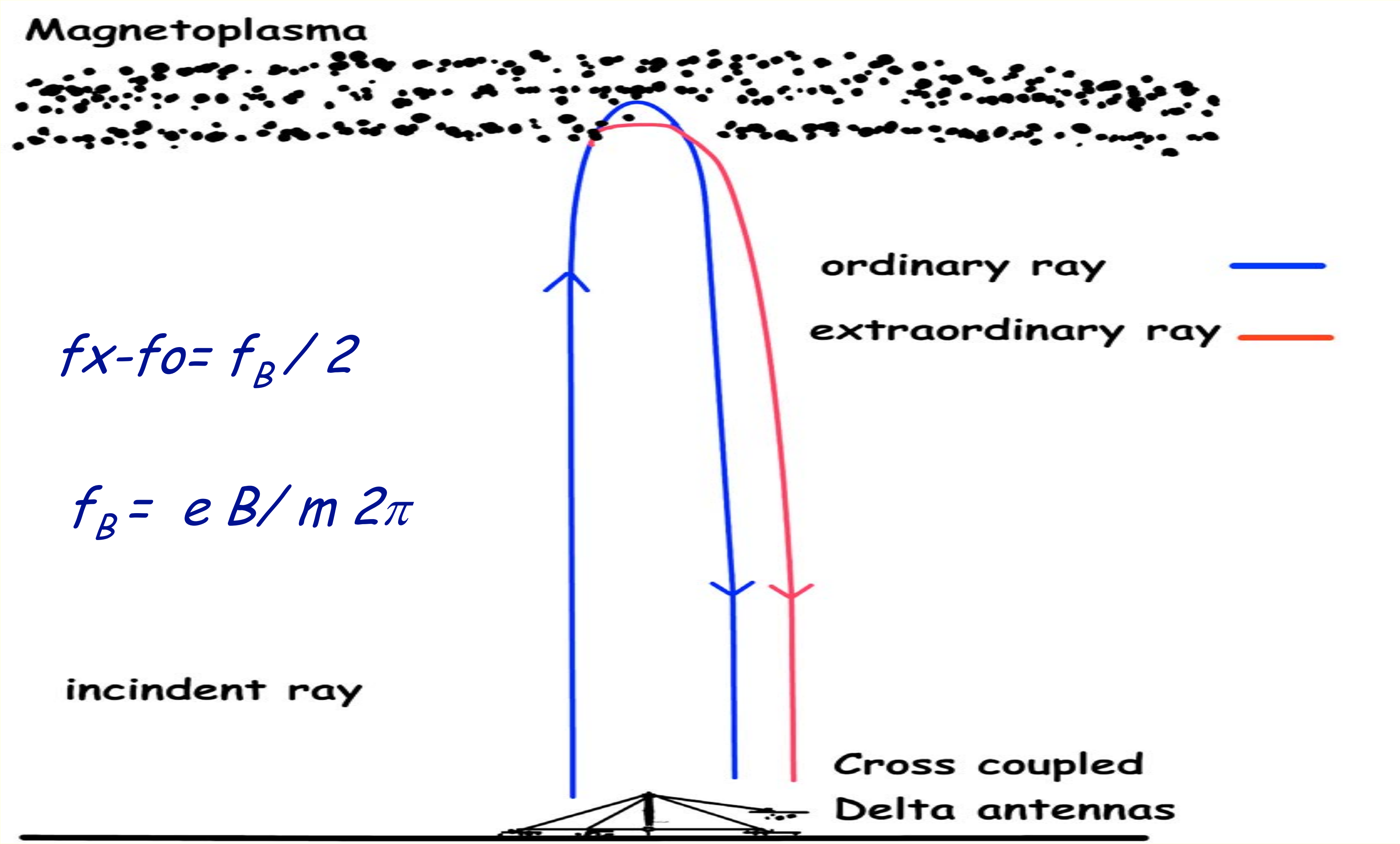
Vertical sounding




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

$$f_c \approx 9\sqrt{N}$$

# Magnetoplasma separate the wave into two components




$$fx - fo = f_B / 2$$

$$f_B = eB / m2\pi$$

# Ionospheric plasma

$f_p$, $\nu$ and $f_B$

- the plasma frequency *fp* is:

$$f_p = \frac{1}{2\pi}\sqrt{\frac{Ne^2}{m\varepsilon_0}}$$

-The frequency of collision between electrons and neutral molecules ($\nu$) is:

$$\nu = 1/\tau$$

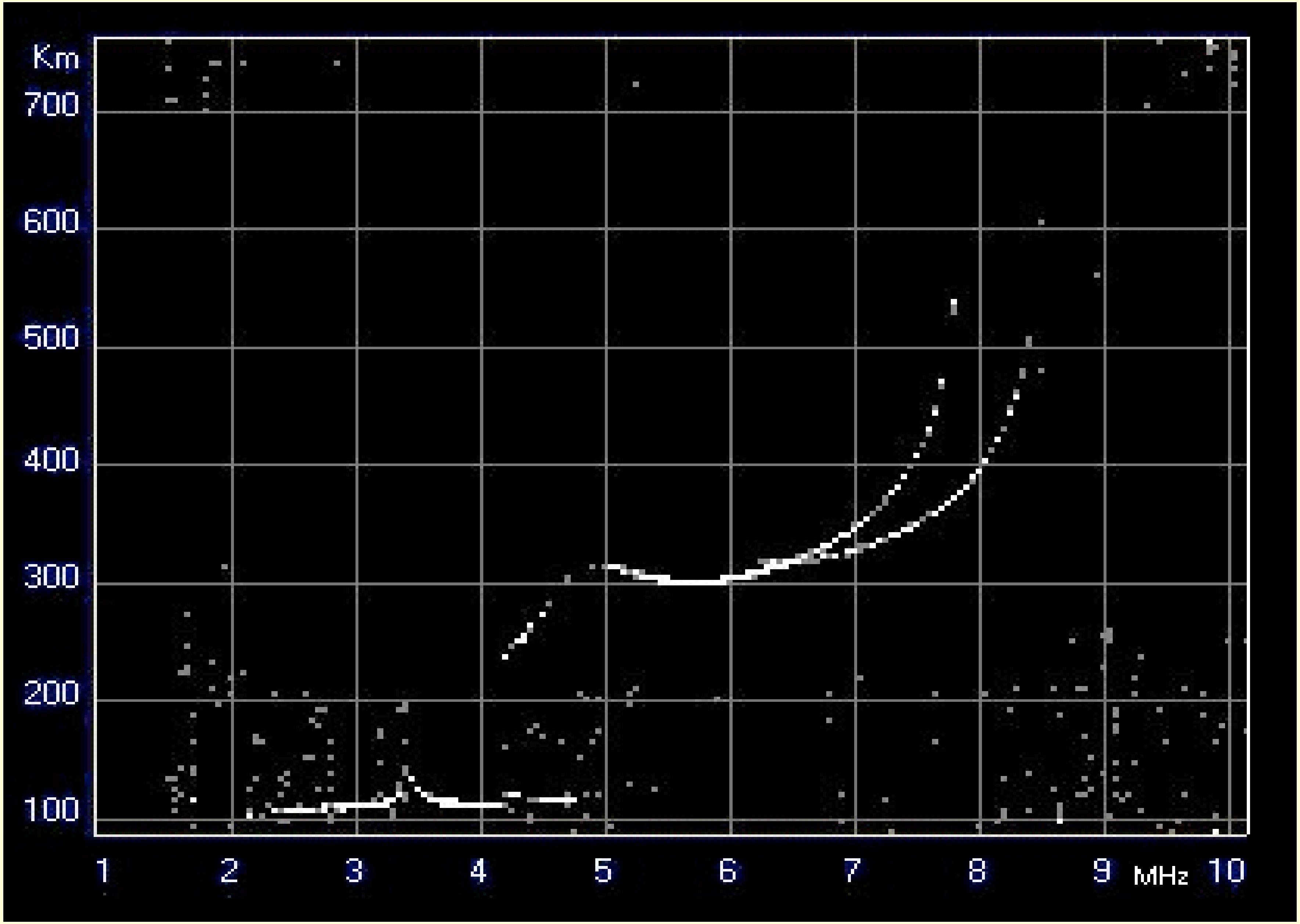
being $\tau$ is the average time between collisions

-frequency of cyclotron ($f_B$)

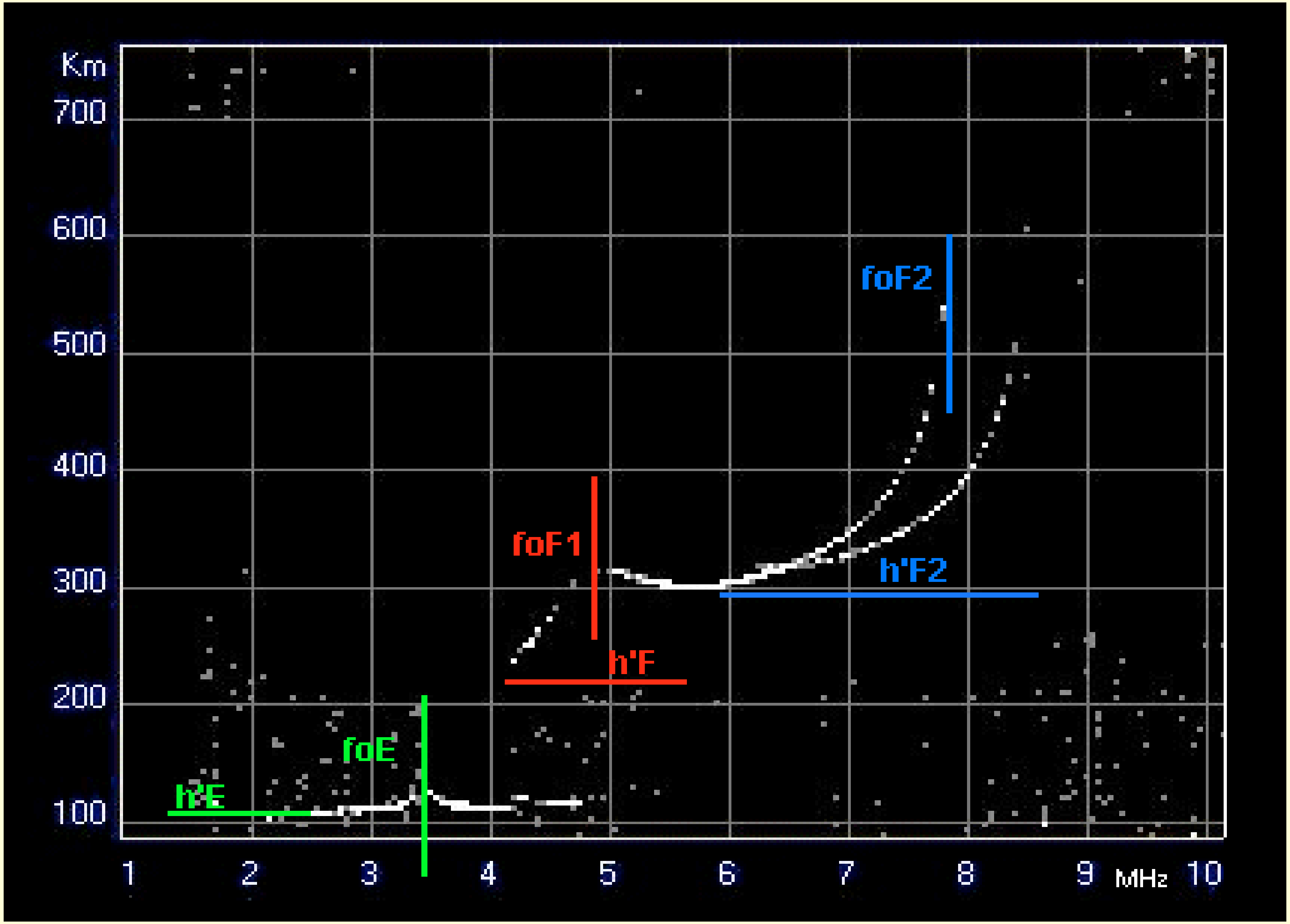
$$f_B = e B / m\, 2\pi$$

establishes the condition of propagation of the wave through the magnetized ionospheric plasma.

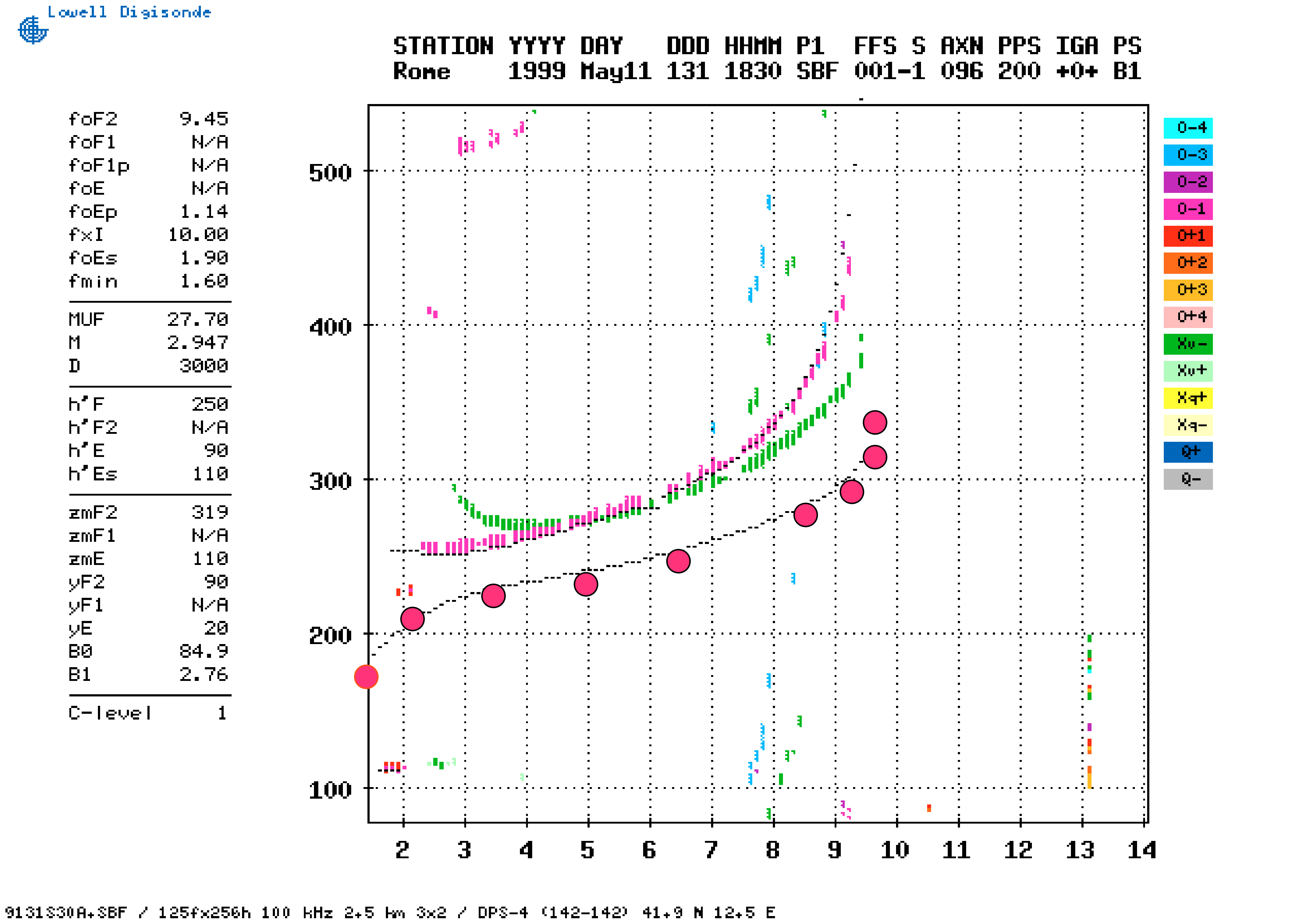
# ionogram



# Ionogram's characteristics



# Bottom profile (post-process)



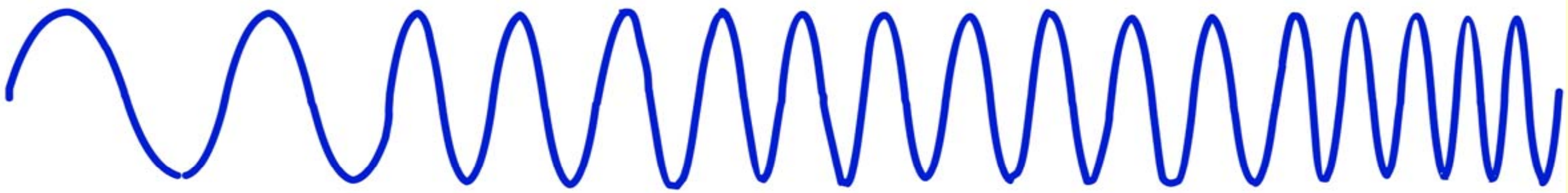
# CHIRP

Chirp: typical phase coding or modulation applied to the range pulse of a radar designed to achieve a large time-bandwidth product. The resulting phase is quadratic in time, which has a linear derivative. Such coding is often called linear frequency modulation, or linear FM.

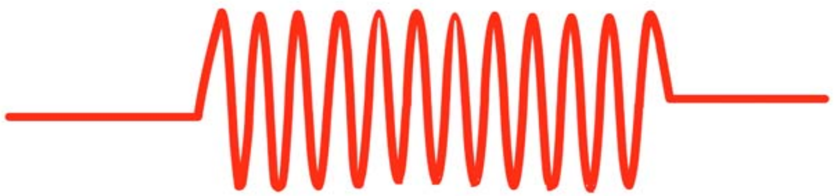
- The most significant advantages of the chirp techniques over other pulse HF system are:
- the reduced vulnerability to narrow-band interference
- the use of low power due to the ability to transmit with a nearly unit duty cycle.

# Chirp modulation (CW-FM)

**Continuos wave -frequency modulated**

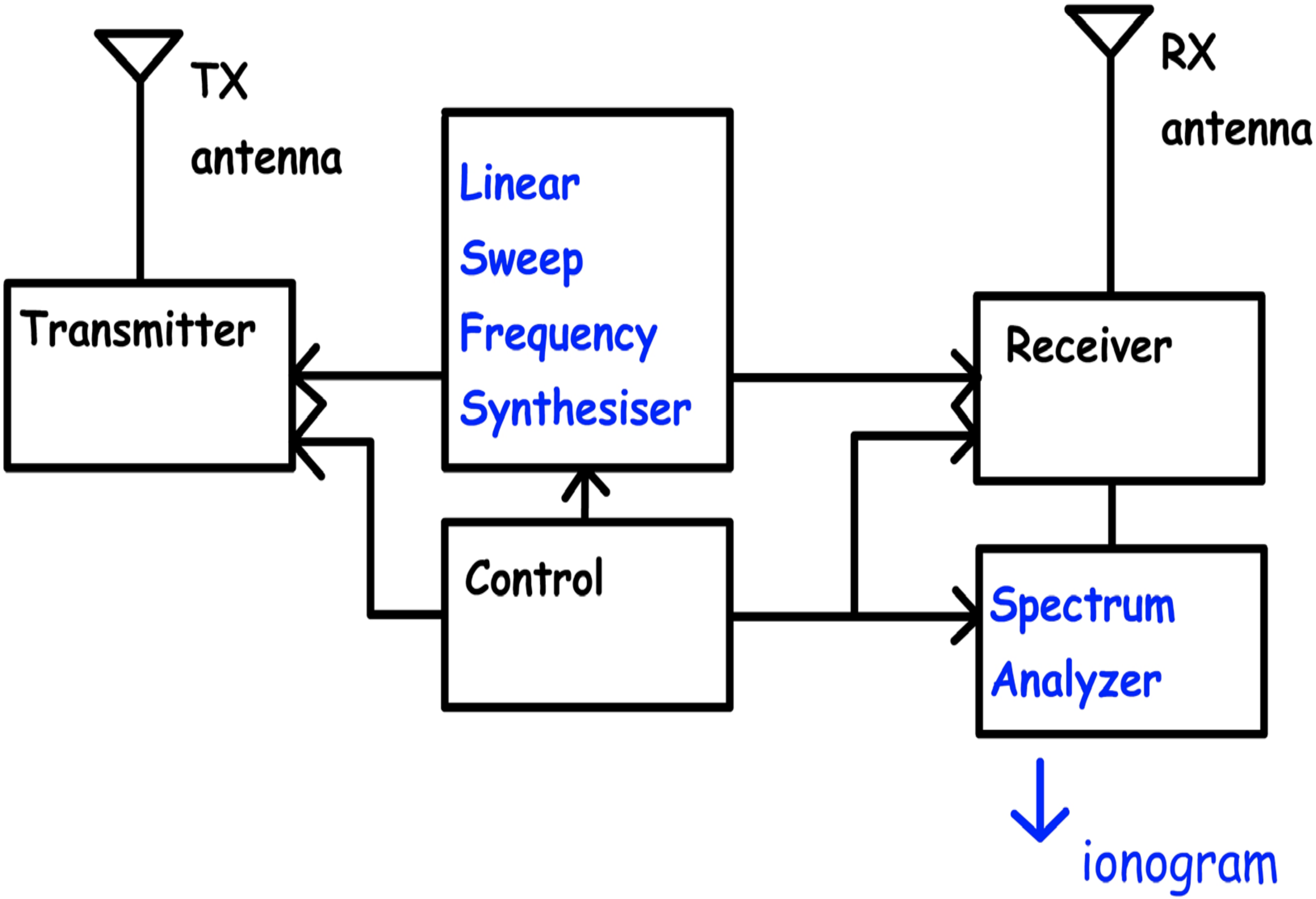


**The frequency increases linearly with time**

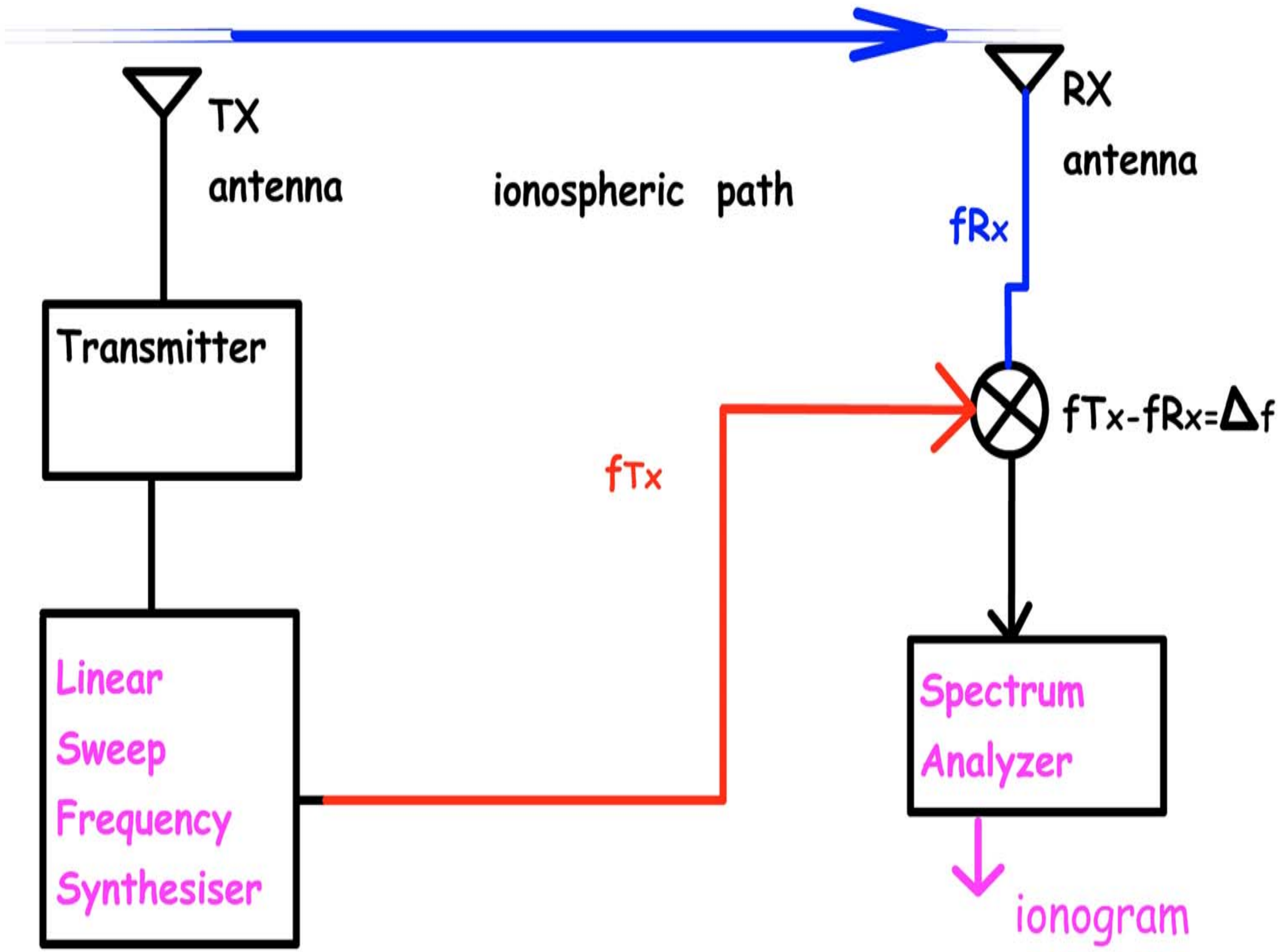


**Pulsed technique**

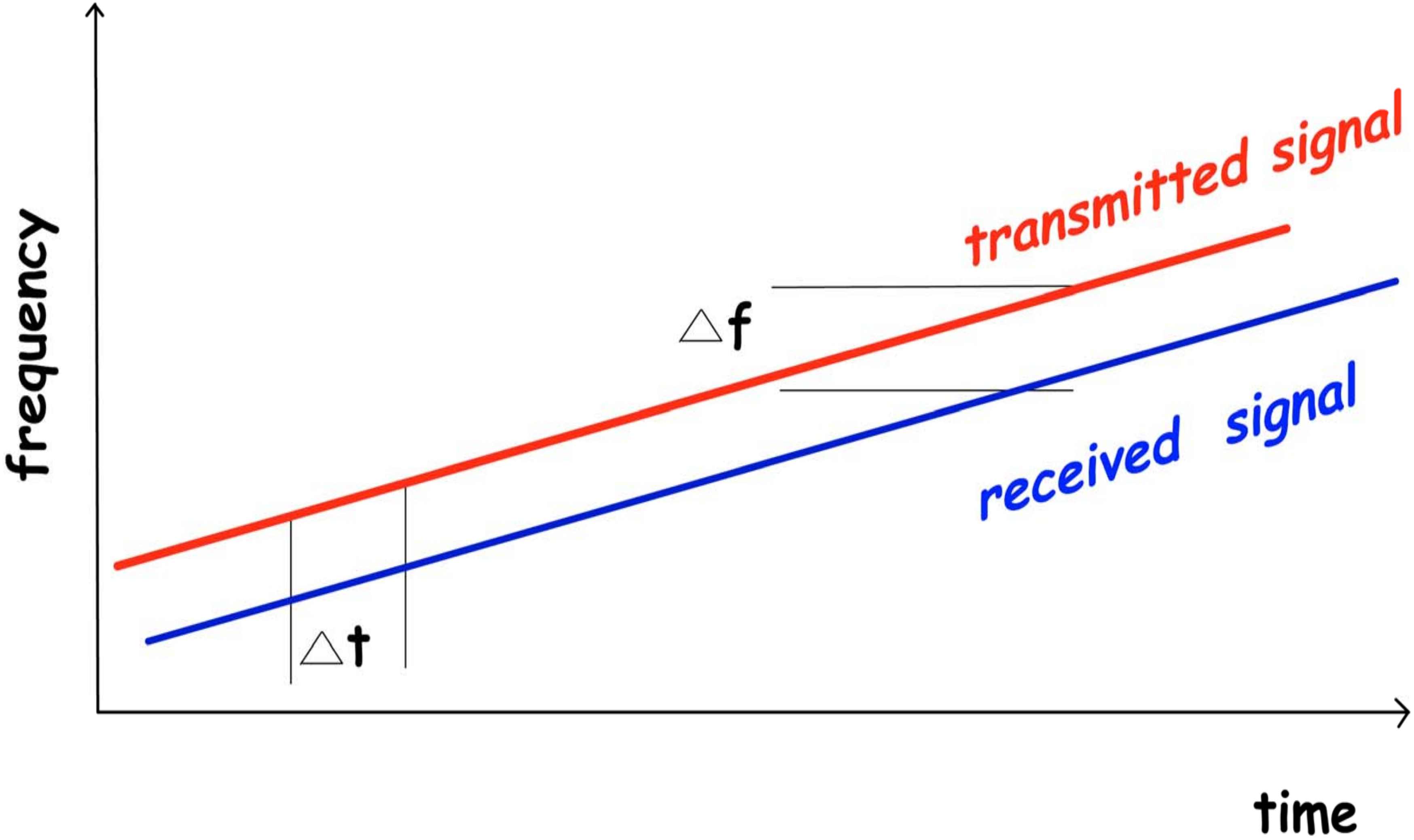
# Chirp Ionosonde



# Chirp Ionosonde principle

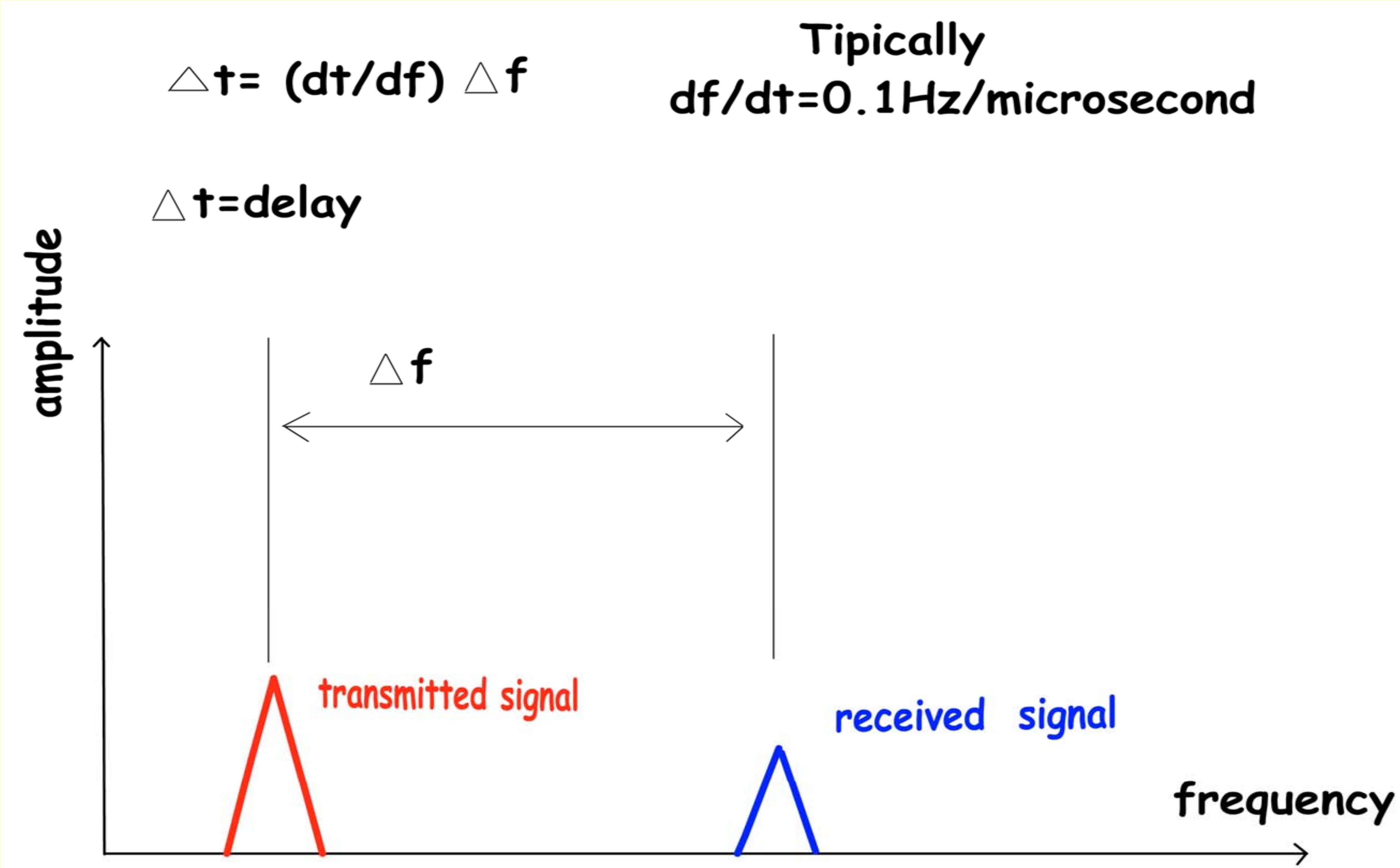


# Chirp techniques1




$\triangle f = (df/dt) \triangle t$

# Chirp techniques2



- Frequency analysis of the de-chirped signal is known to be identical to a matched filter in pulse compression radar. The pulse compression ratio G is given by:

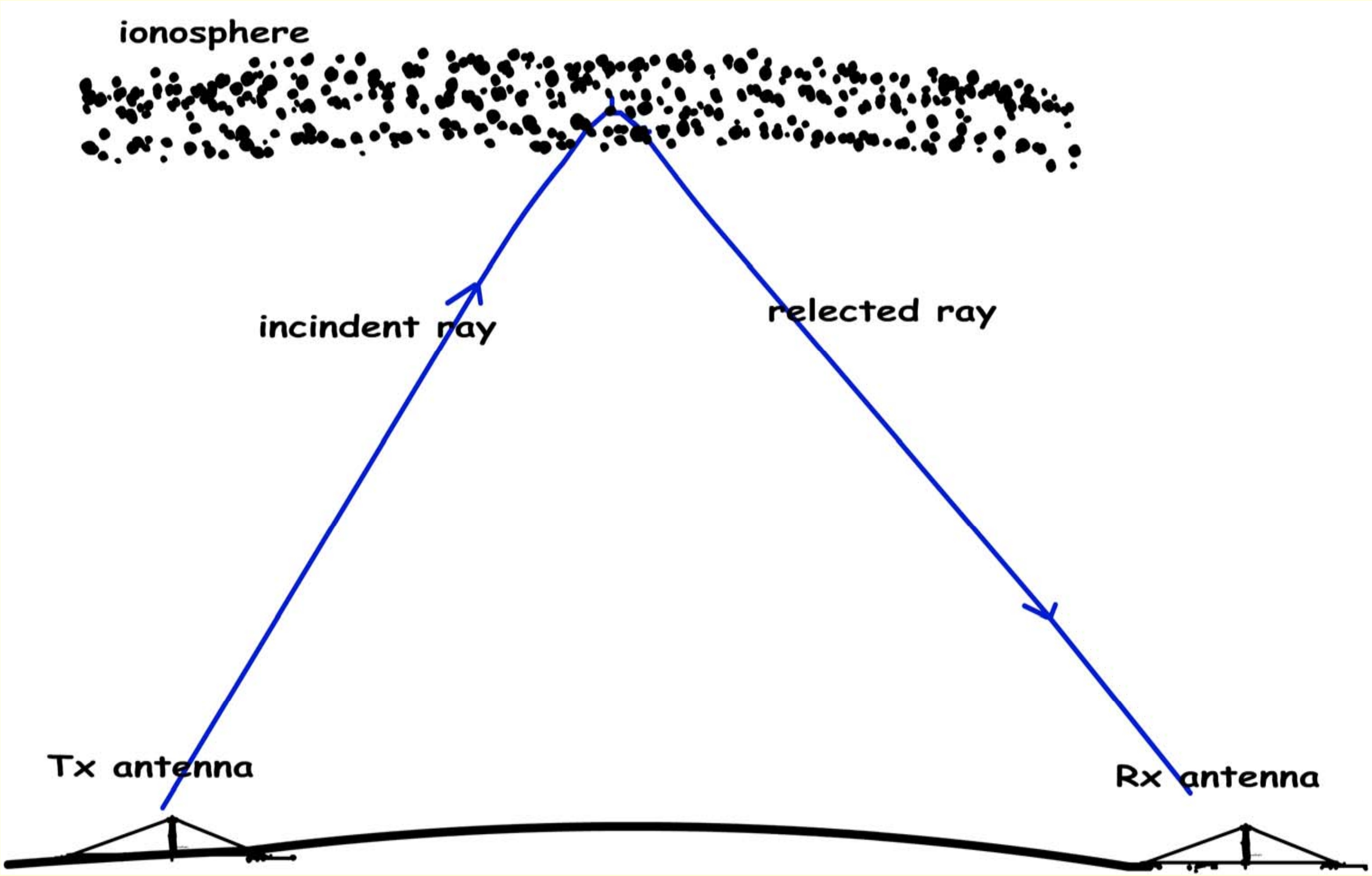
$$G = BT$$

where B is the frequency sweep range and T is the time duration for one spectrum analysis]. Range resolution $\Delta r$ is given by:

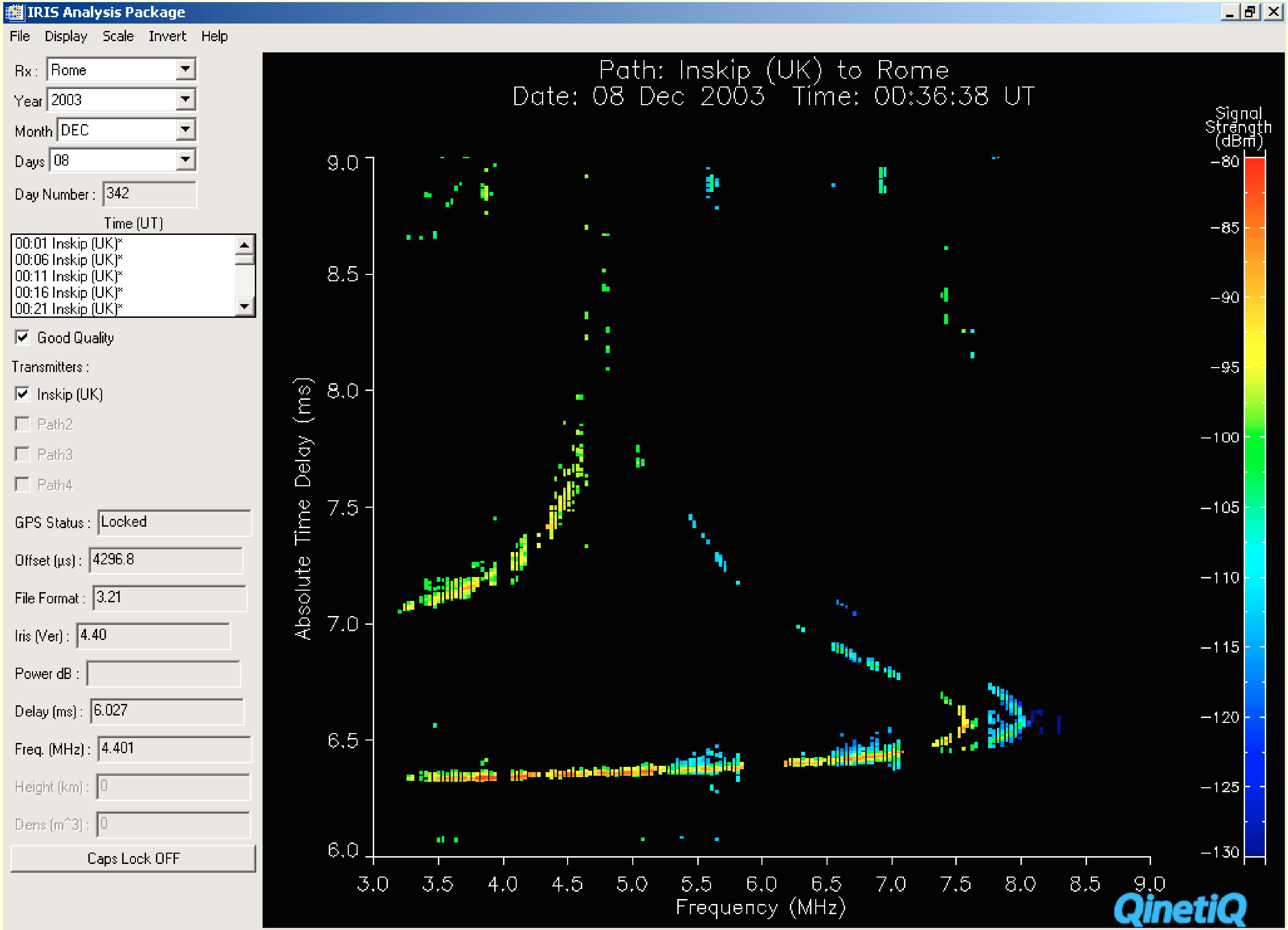
$$\Delta r = c / 2B$$

where c is the velocity of light.

Oblique sounding

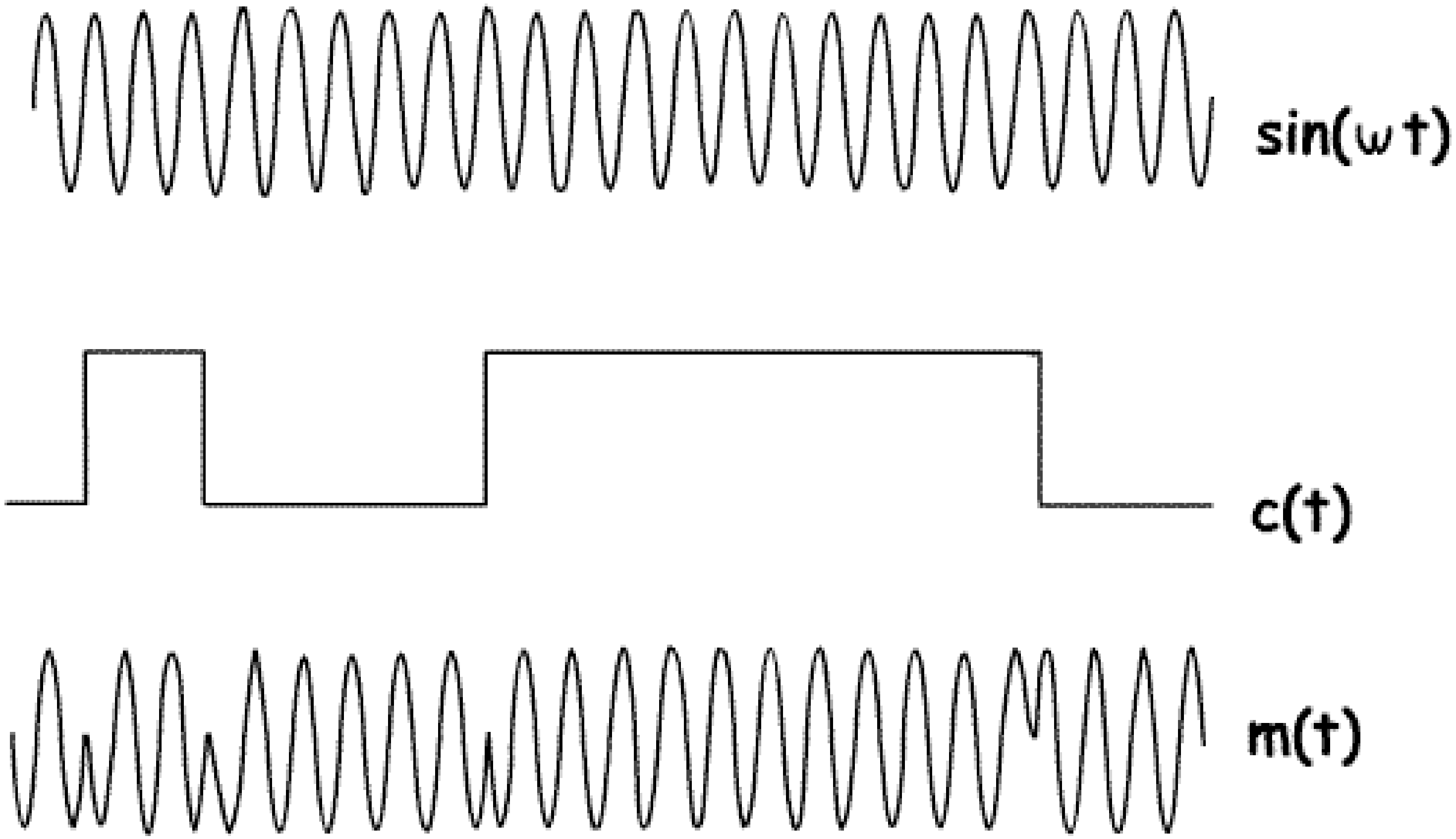


# Oblique ionogram



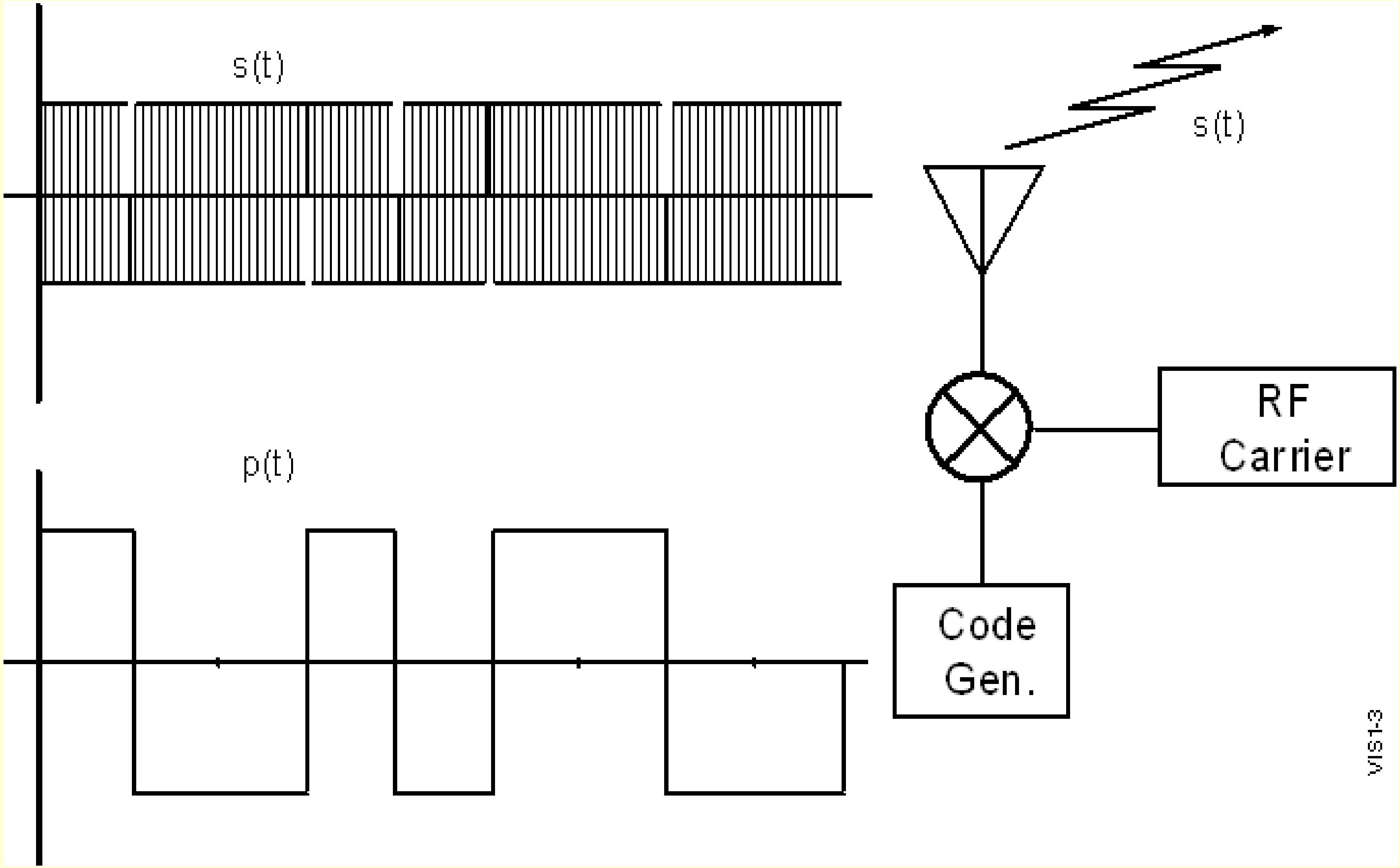
# Pulse compressed ionosondes

# Phase-coded ionosonde

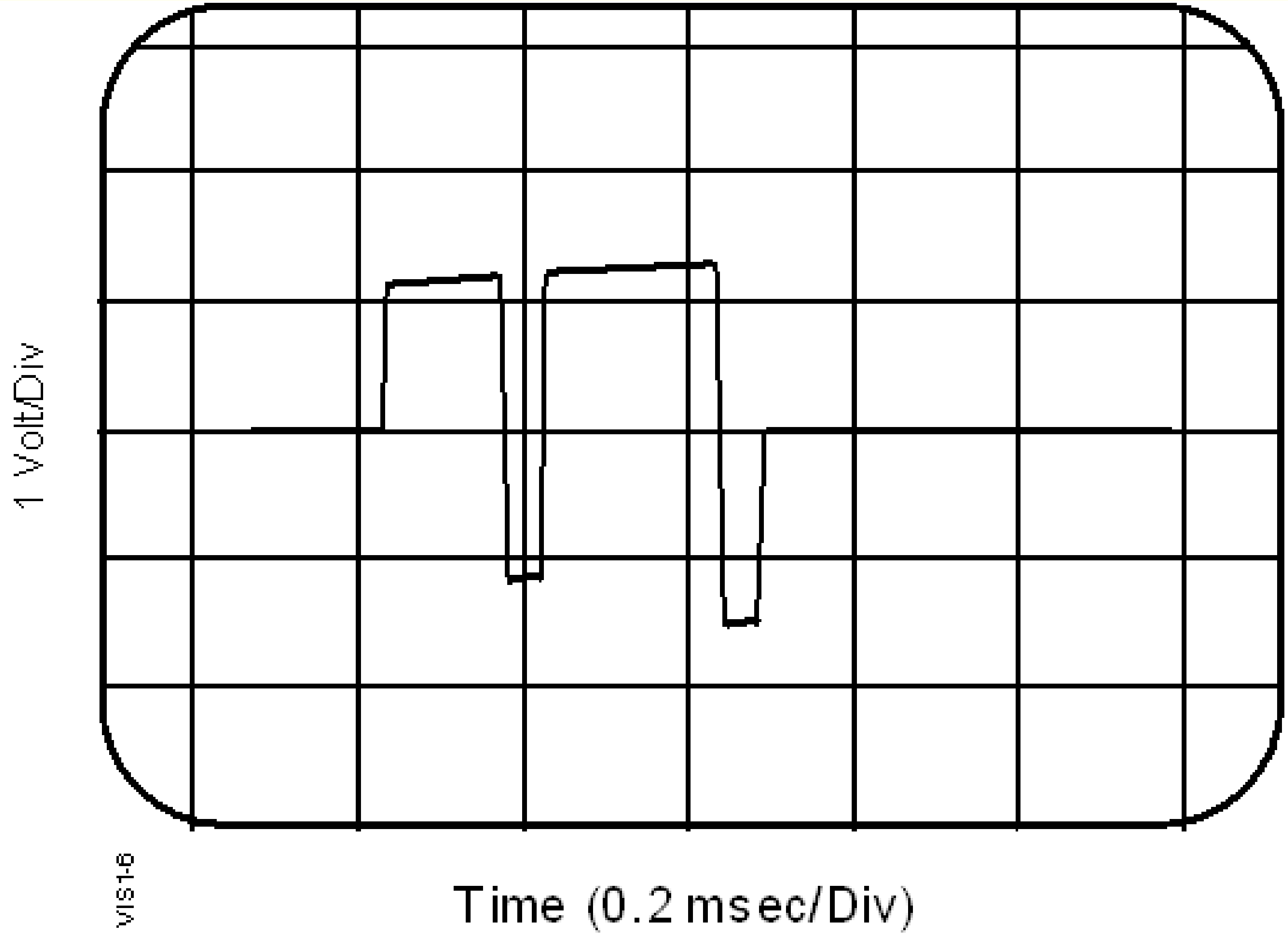



Phase-coded waveform

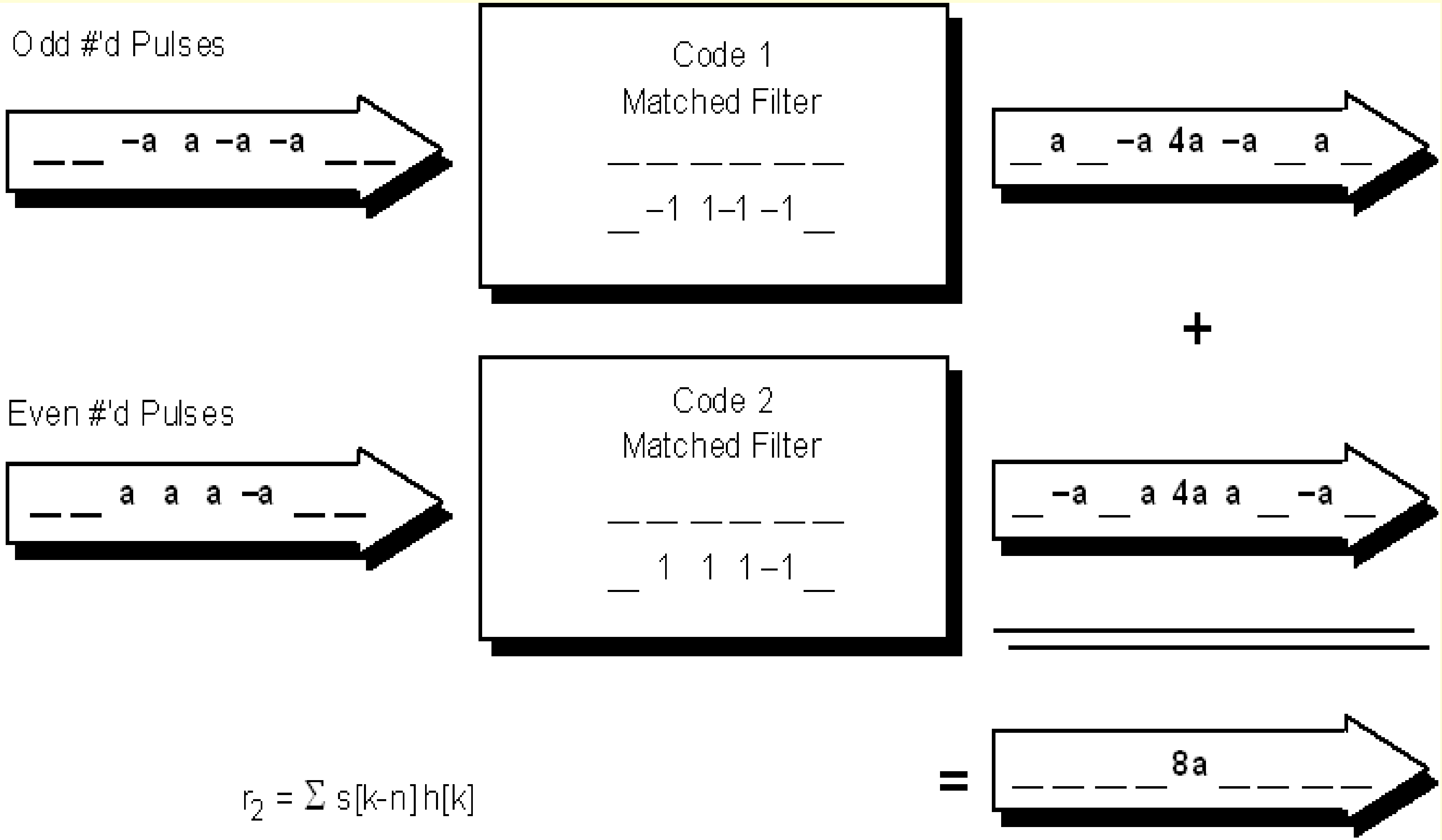
# Code generation



# baseband



# Time-domain correlation



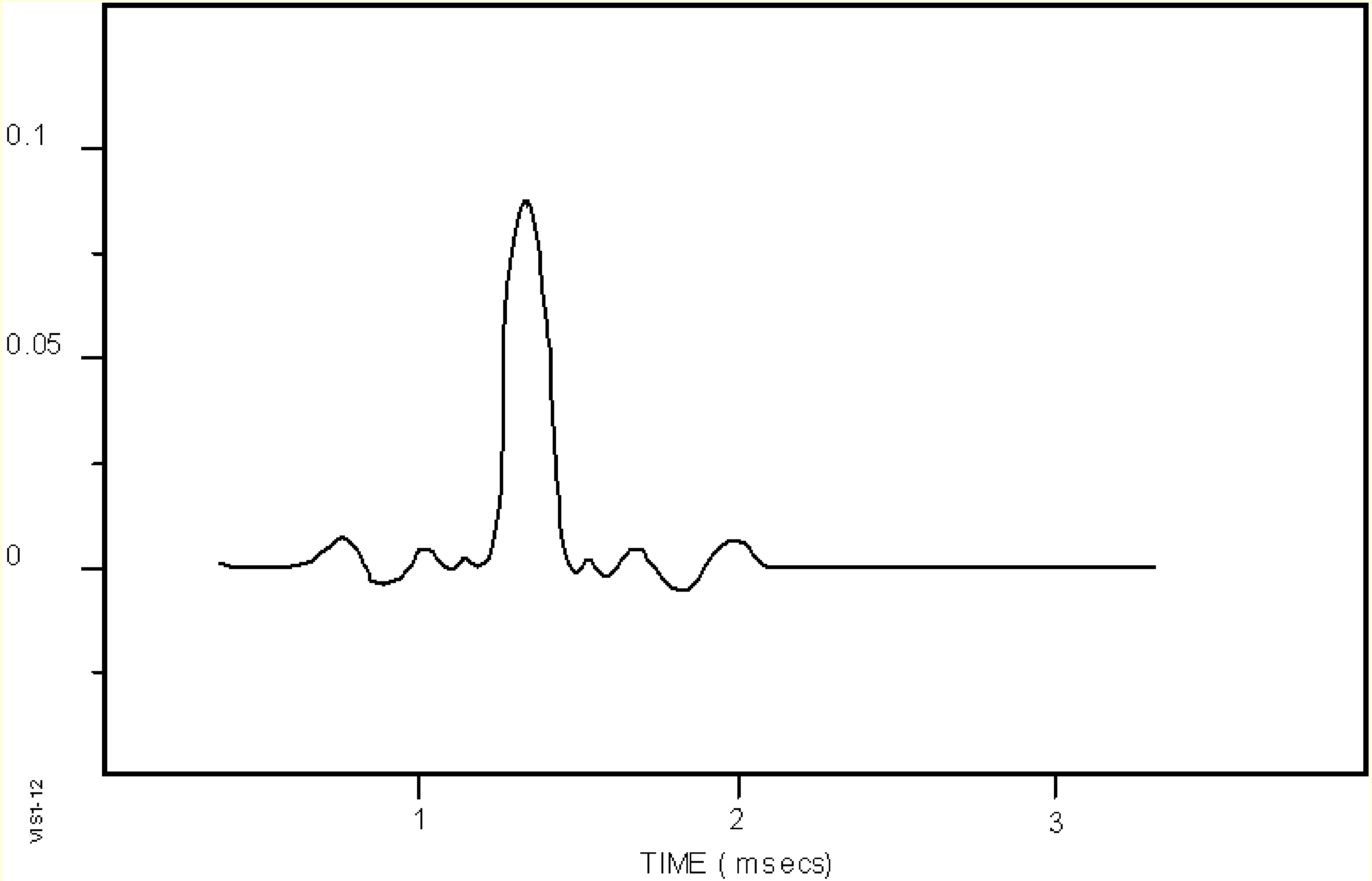

$$r_2 = \Sigma\, s[k-n]\, h[k]$$

$$y_1 = \Sigma\, a\, p_1[k-n]\, p_1[k]$$

$$y_2 = \Sigma\, a\, p_2[k-n]\, p_2[k] \qquad r_2 = y_1 + y_2$$

VIS 1-7

# Pulse compression



# Processing gain

- More or less 30 dB
- About 15 dB due to correlation process
- About 15 dB due to phase coherent integration

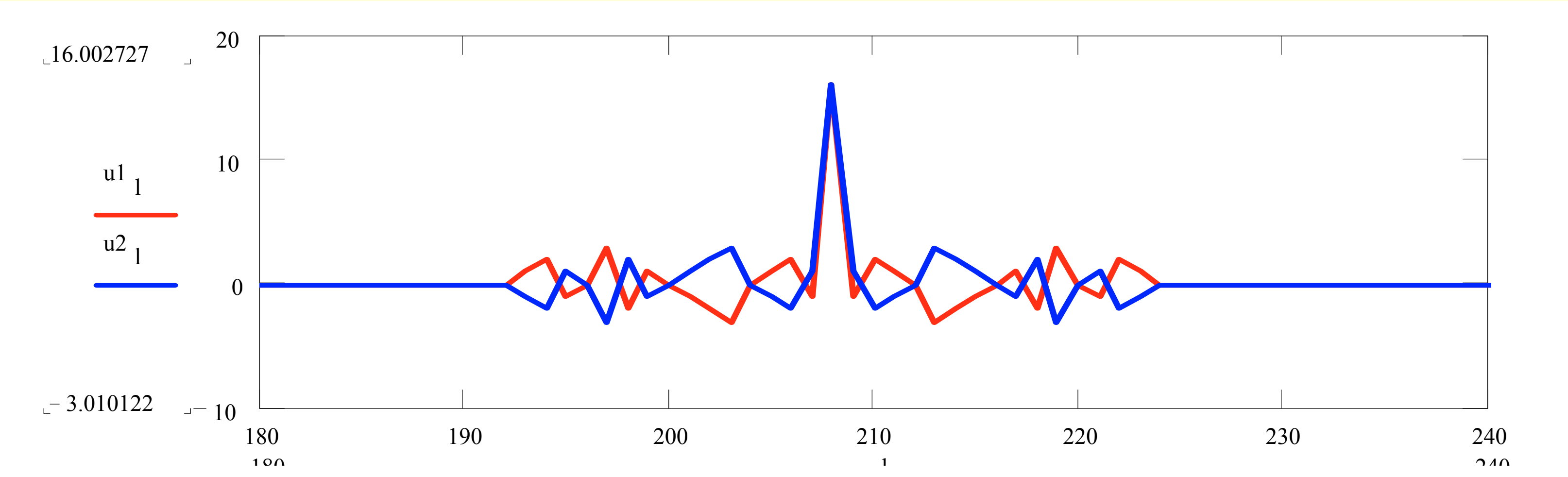
# Code reconstruction

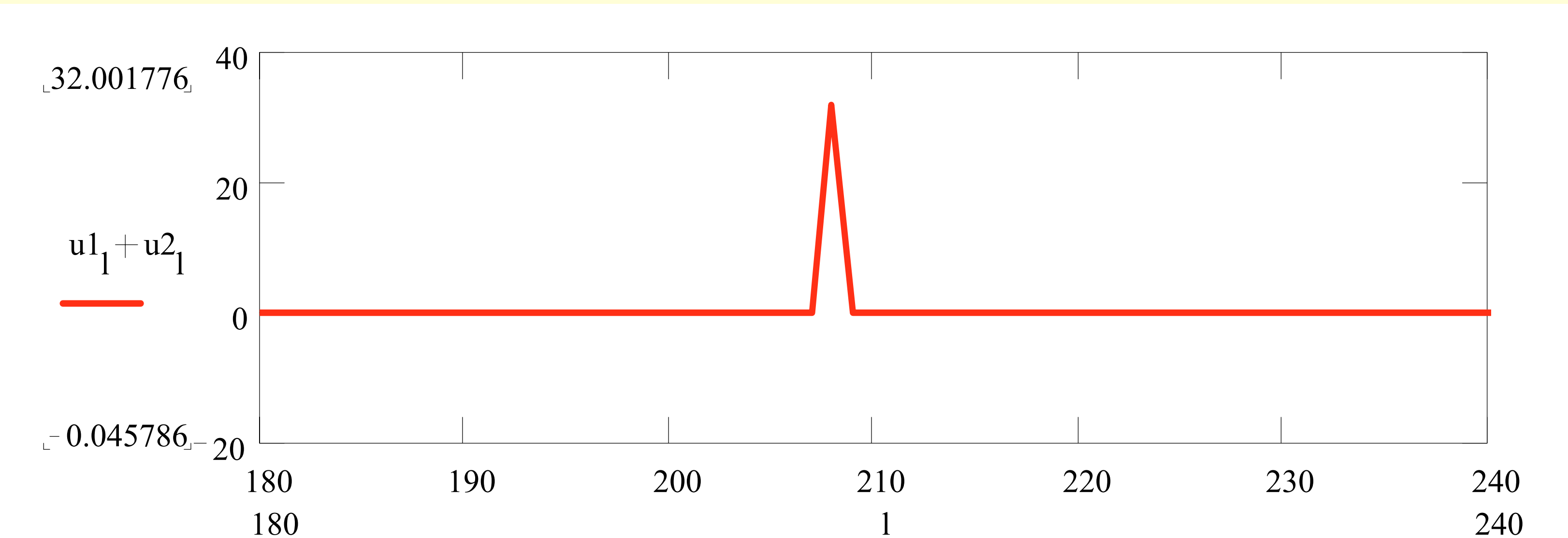
**The reconstruction of the code, baseband, starting from the echo signal is the following:**

- **the analog signal at the output of the IF ( typically 100 kHz) is sampled both in phase and quadrature at the same frequency**
- **the quadrature sampling allows to obtain the amplitude and, more important, the phase of the signal to reconstruct the baseband**
- **after the A/D conversion the signal is fed through the digital matched filer implemented on the DSP board**
- **the process is repeated for the even and odd code if complementary code is used.**

# Complementary code

In the complementary phase code the side lobes of the correlation process and in a certain measure the noise superimposed to the signal



# Pulse compression technique

The energy (E) of the echo signal from the ionosphere, under certain propagative condition, is proportional to the transmitted power (P) and the pulse length (T)

$E=P\cdot T$

In the old ionosonde the power P was of the order of 10000 W while the pulse length, to have the desired high resolution, was 30 $\mu$s, so the energy was of the order of 0.3 J.

The phase coded HF radar uses a pulse length of about 500 $\mu$s and a power of 200 W and the energy of the pulse is 0.1 J (same order of magnitude). The resolution is maintained because an adequate number of sub-pulse $\tau$ constitute the pulse length T.

- The particular sequence of the sub-pulses that is what we say a code. The pulse compression consists to input the pulse T (subpulse sequence) in a matched filter, which is sensitive only to the chosen code, whose output concentrate its energy in a time $\tau$.

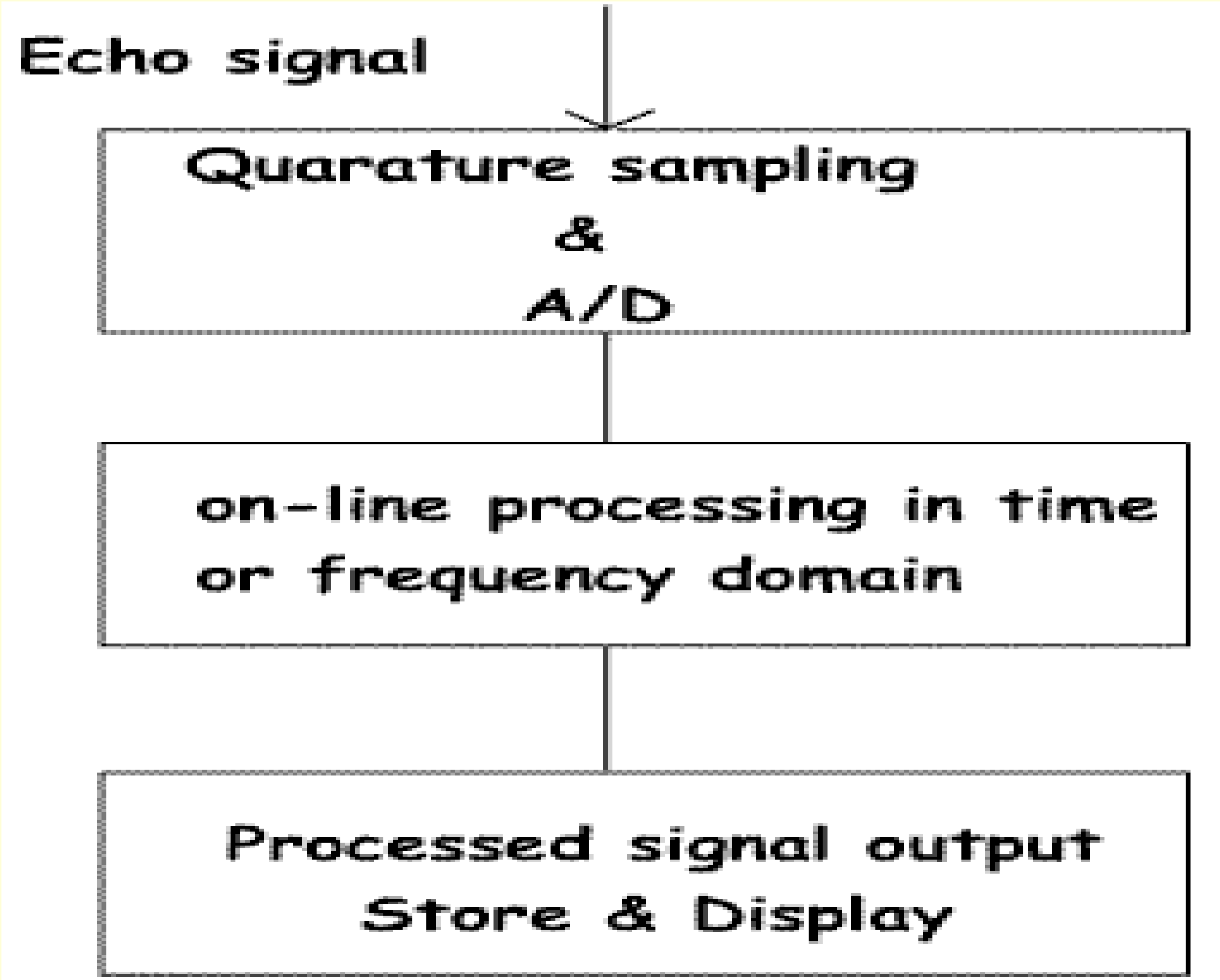
- So the matched filter magnifies only the segment of the signal that contains the code sequence.

# Filtering and integration

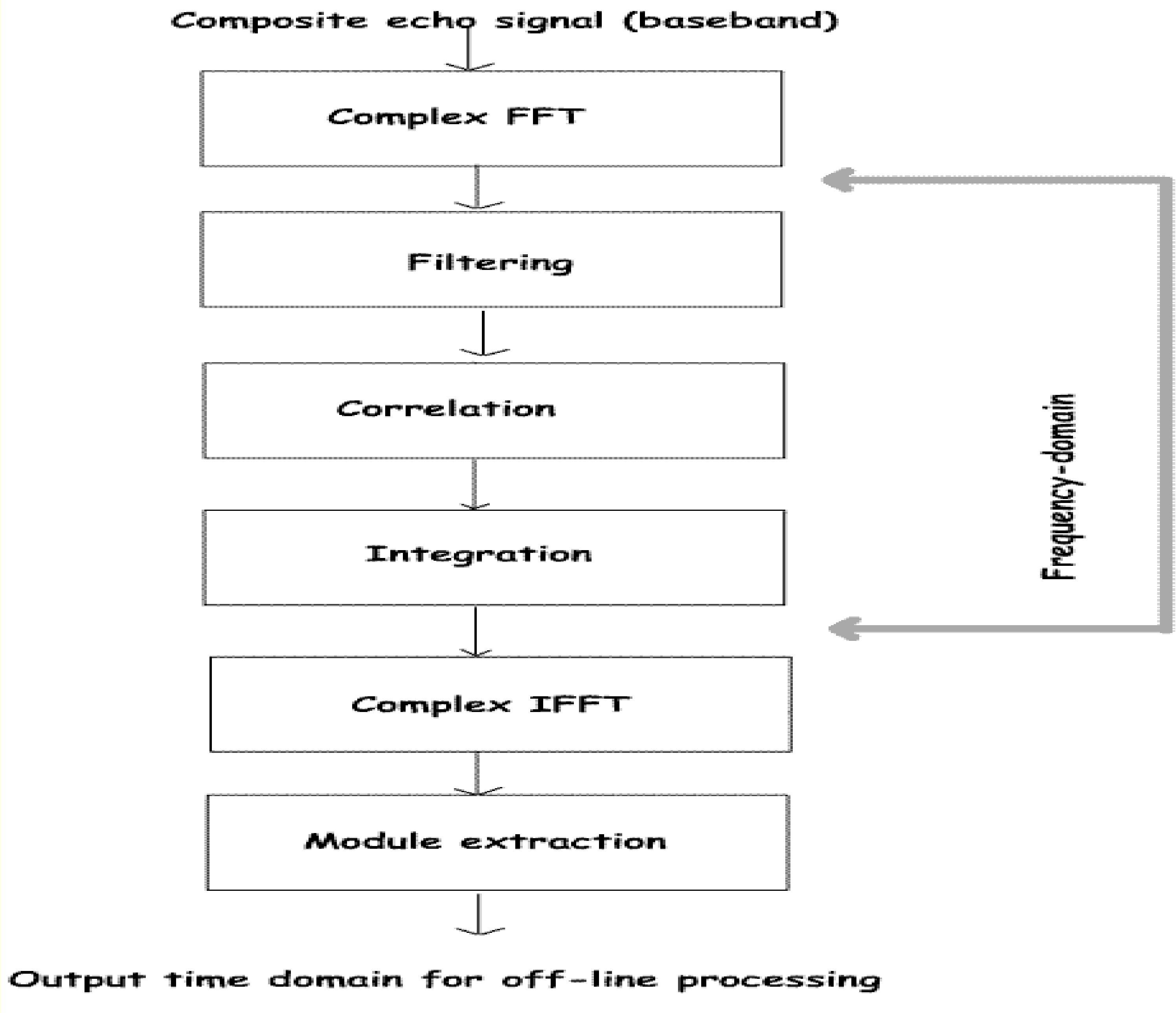
- After the FFT a digital filter to reduce the amplitude of the strongest frequency component, can be implemented. This filter cut out the frequency of the interfering radio broadcasting etc.. This filter follows empirical criteria and can be modified according to the particular sounding site.

- The phase coherent integration is a sum in the frequency domain lasting till the phase difference between the first and the last echoes of the incoming signal is less than 90 degrees. After that the integration process is not useful. This process takes into account the time coherence of the reflection process in the ionosphere.

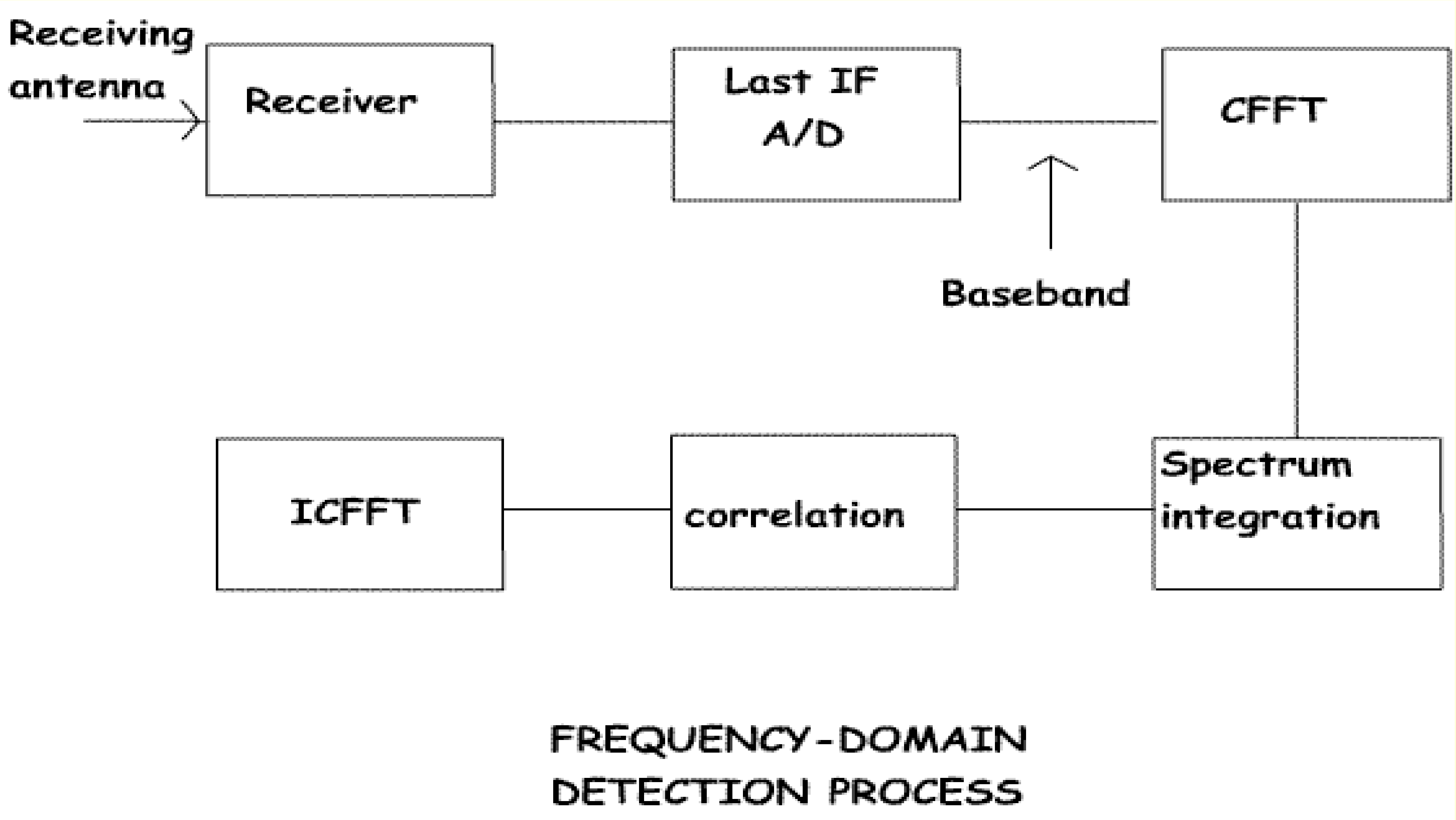
# Digital signal processing 1



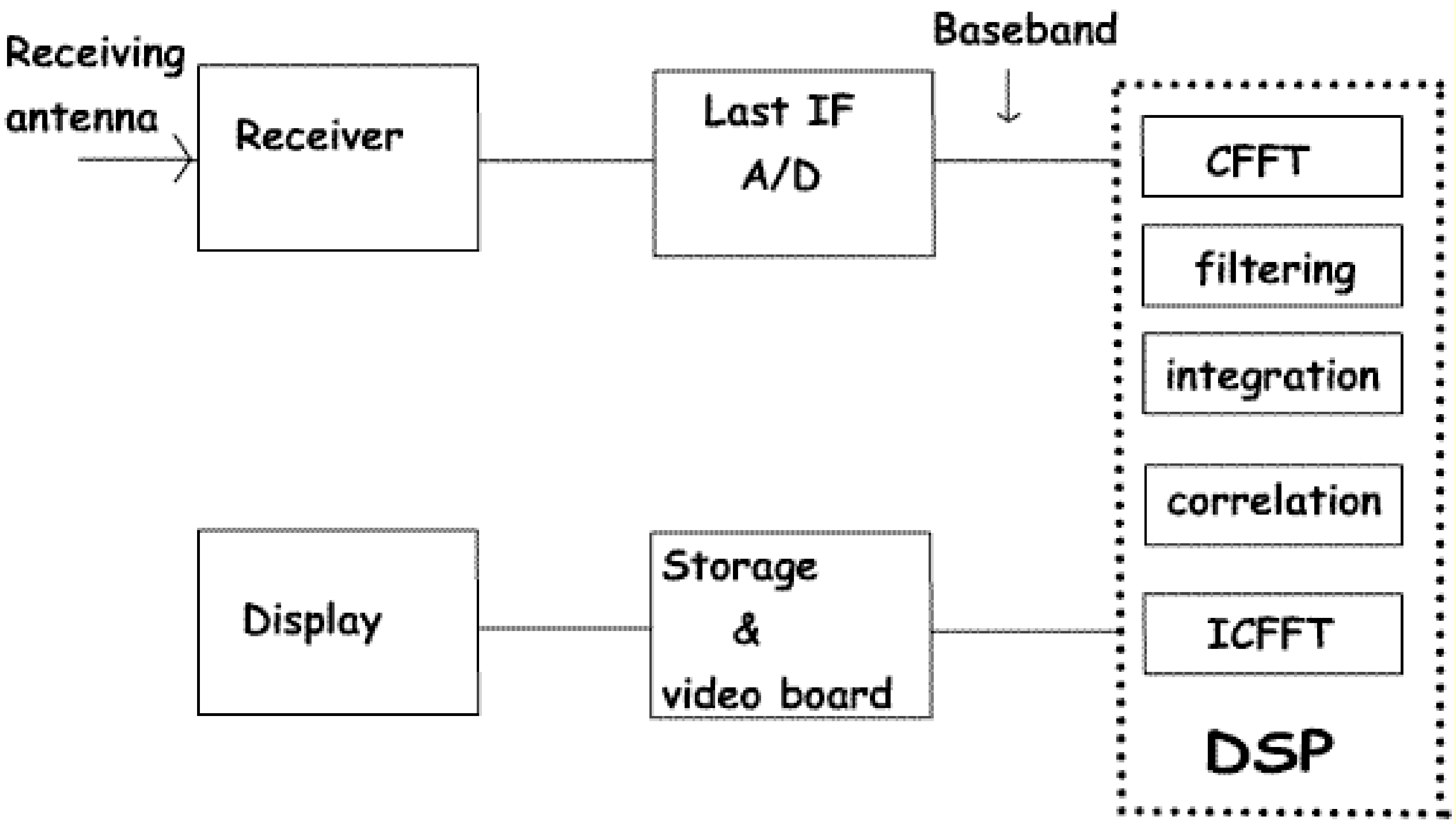
# Digital signal processing 2



# Digital signal processing 3



# Digital signal processing 4




Block diagram of the receiving system and detection process

# Incoherent scatter radar system

Incoherent Scatter Radar systems are among the most powerful of modern radars. They typically operate in the VHF-UHF frequency range and are used to study the Earth's ionosphere and near space environment.

These high-power (megawatts) radar systems transmit and receive using large antennas and require precision radio receivers to acquire their data.

They use frequencies greater than the critical frequency and penetrate deeply in the ionospheric plasma.

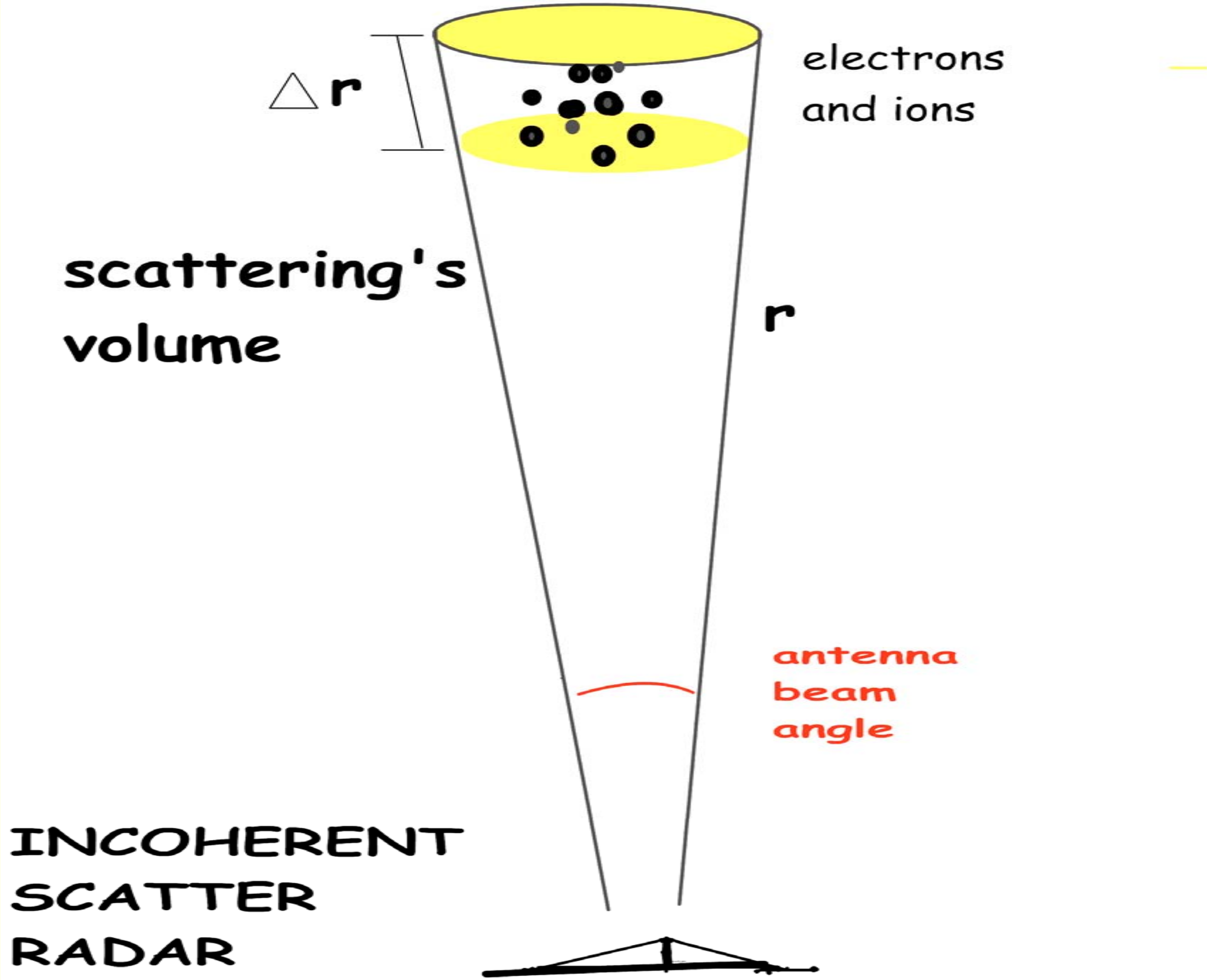
These radar systems transmit with millions of watts of peak power and use large antennas (steerable) for their operations.

# Why millions of watts?

The radar equation below shows that the received power, a part from other quantity, is function of the cross section $\sigma$ and the distance ( $1/r^4$).
The radar cross section is very small and the system is a very point-scatter radar that obeys to the following equation:

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

# Radar cross section

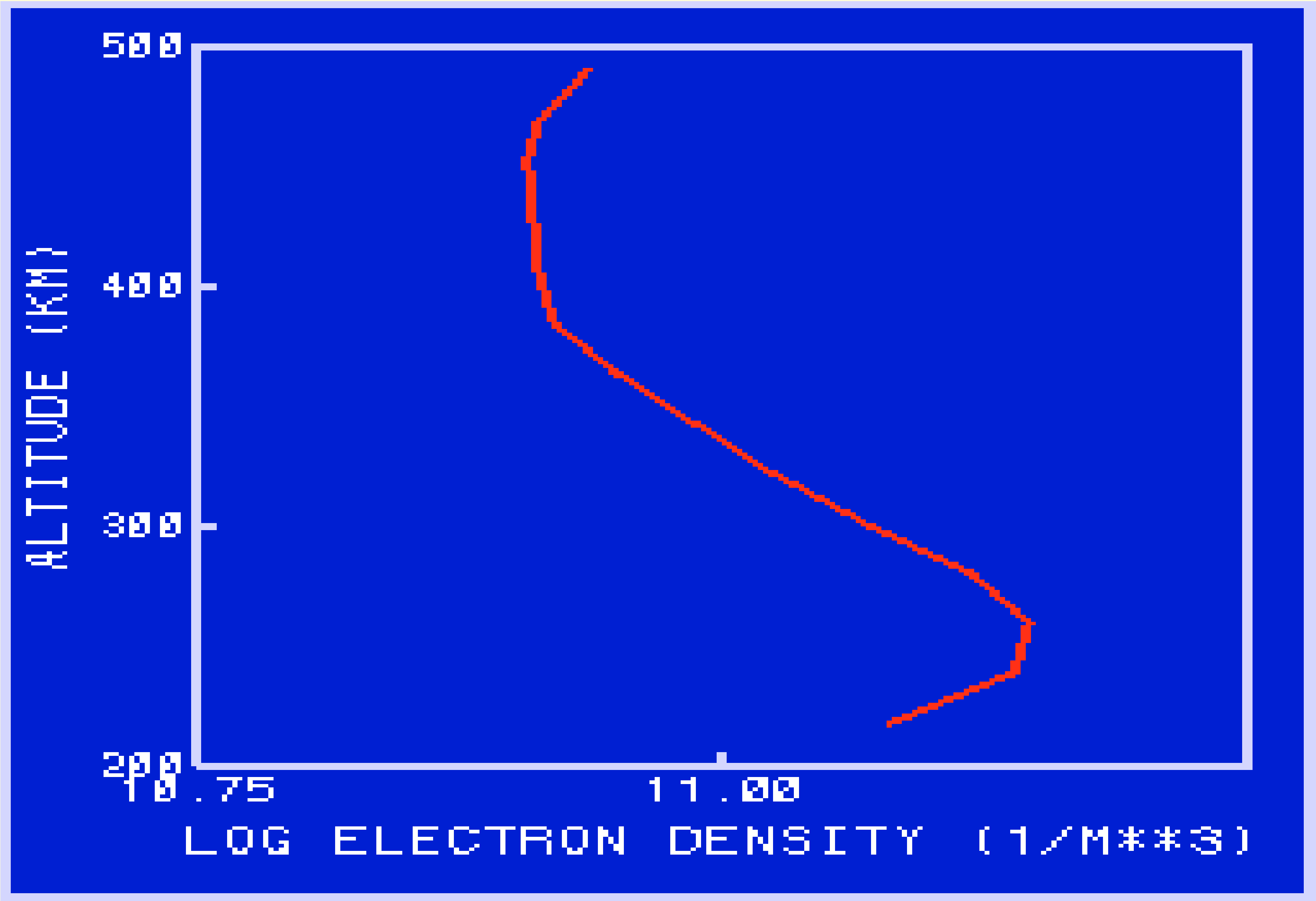


# What it measures?

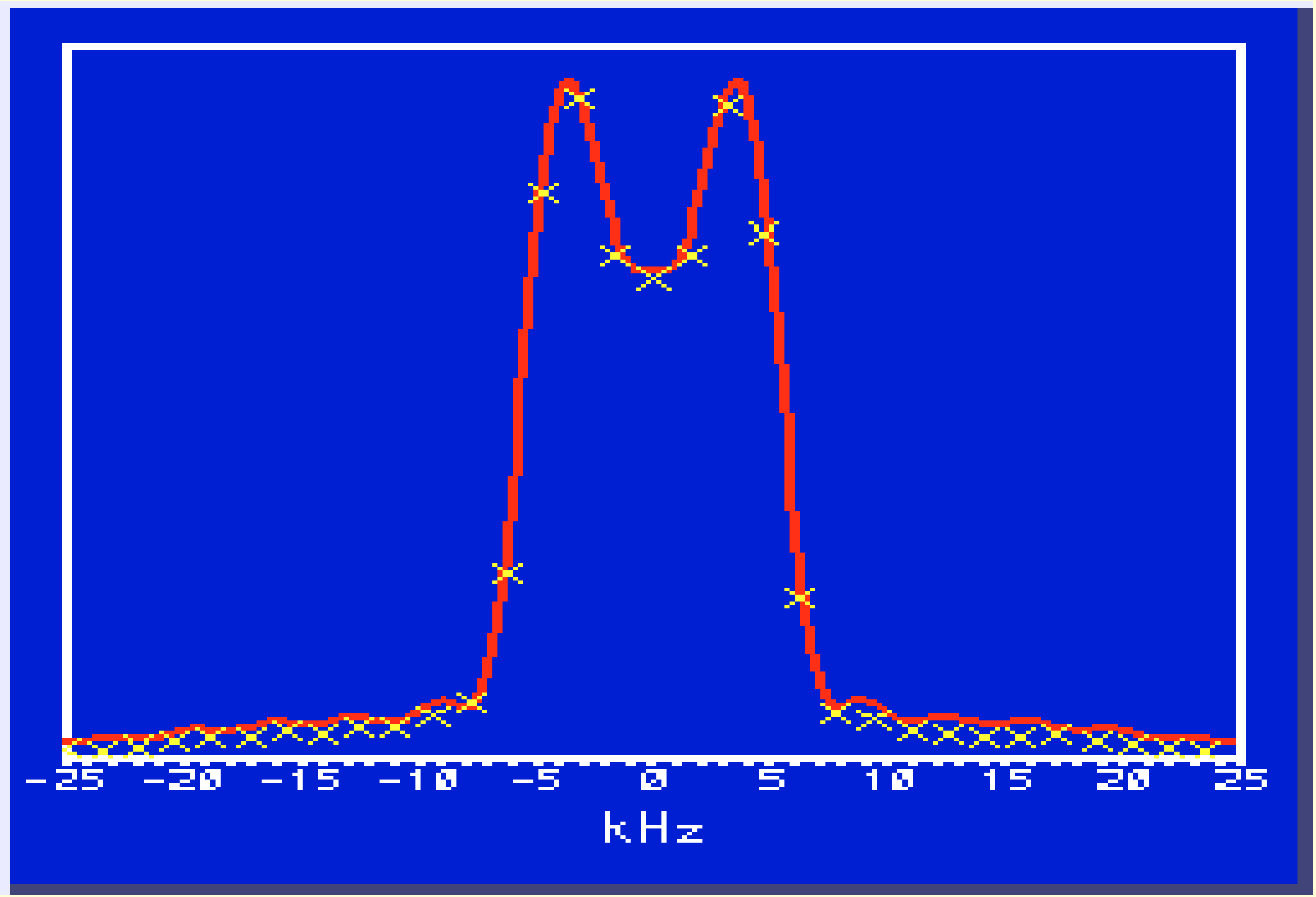
- An incoherent scatter echo comes from a very large number of electrons. These are not stationary, but rather are in random thermal motion. Thus the echo will not be at a single frequency, but instead will contain a range or spectrum of frequencies near the transmitter frequency.

As the temperature increases, the average velocity of the electrons increases, and the range of velocities increases. For this reason, the width of the spectrum increases. The width of the spectrum is then a measure of the temperature of the ionosphere, and the incoherent scatter radar functions as a thermometer.

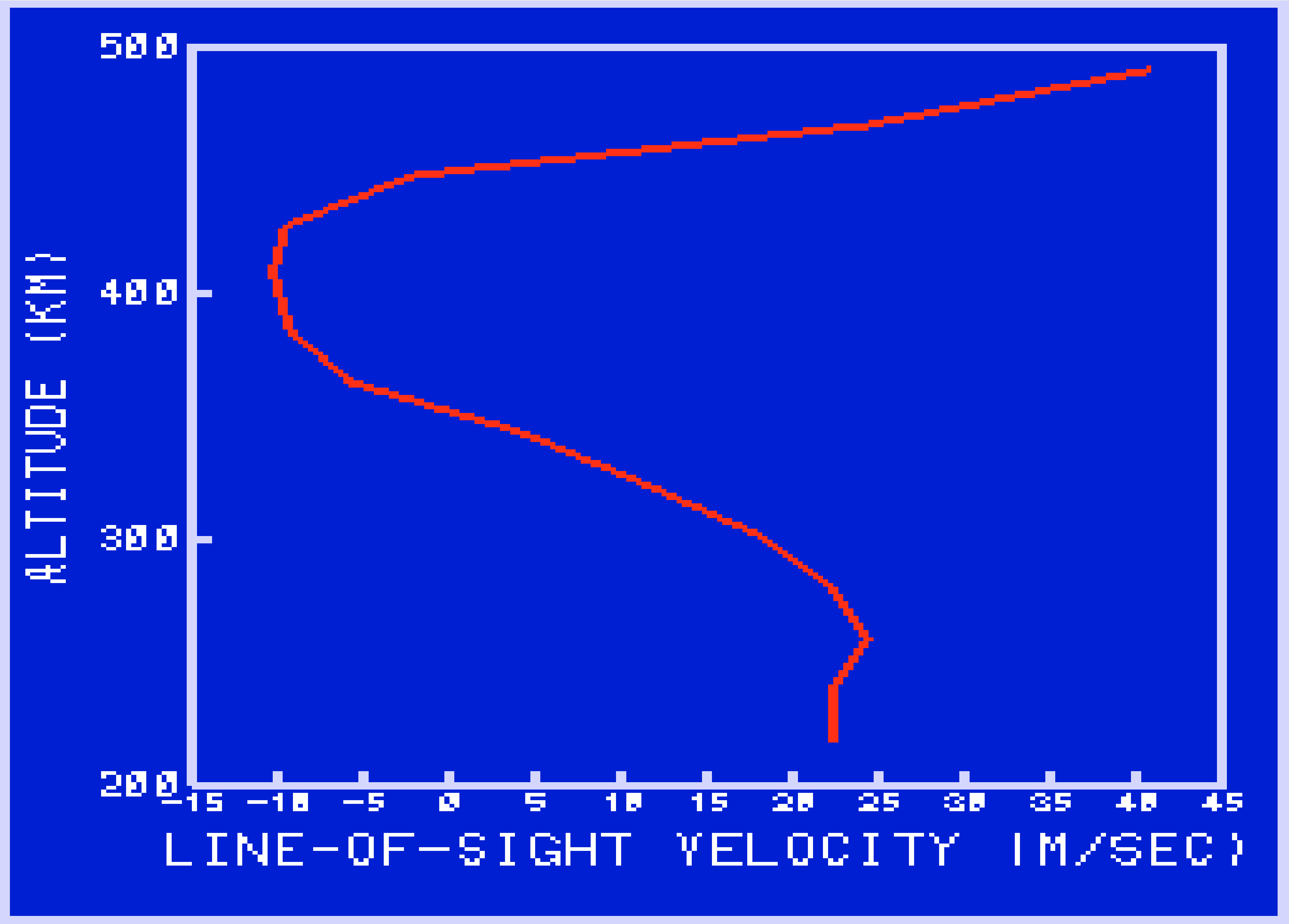
# Direct electronic density profile



# Spectral analysis



# Drift velocity



# TEC Measurement

Direct

Differential phase techniques (GPS, NNSS receiver)

VHF Incoherent Radar

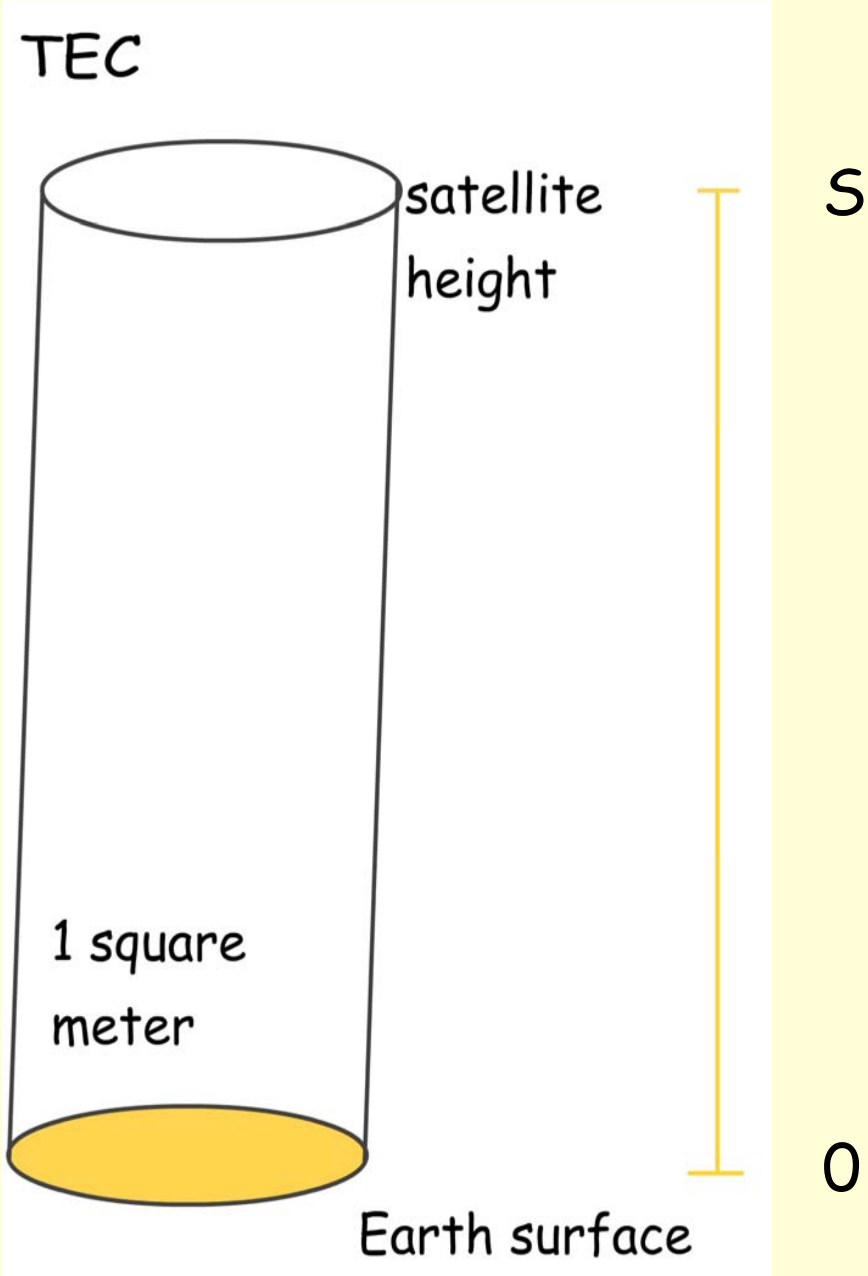
Derived

HF radar or ionosonde (below $N_{max}$)

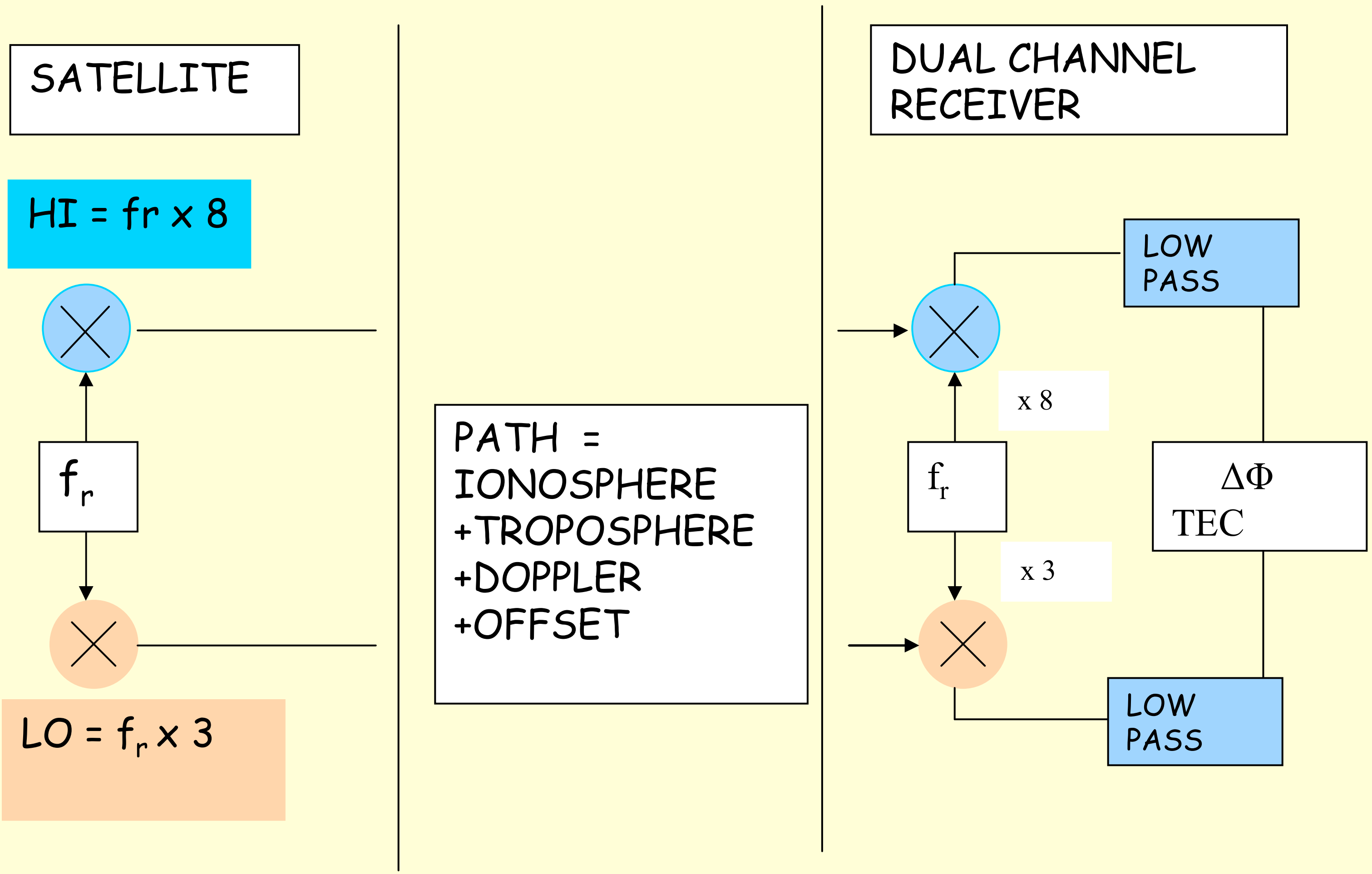
# Total electron content

One unit of TEC is $1 \times 10^{16}$ electron $/m^2$

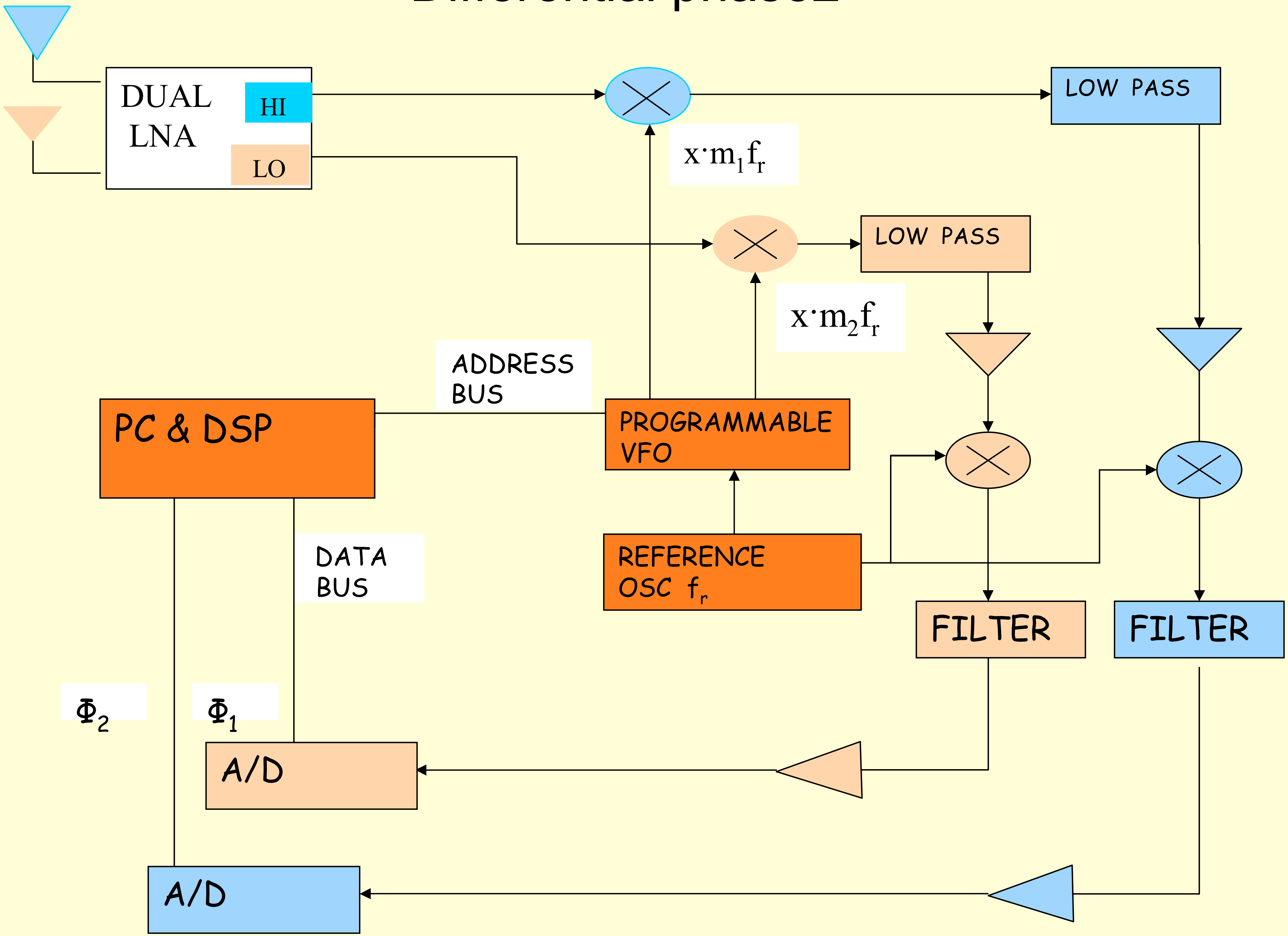
$$\int_{S}^{0} N_e ds = TEC$$



# Differential phase1



# Differential phase2



The electric field E of a propagating radio wave can be described as:

$$E(r,t)=E_o(r,t)e^{-j\Psi(r,t)}$$

$$\Psi(r,t) = \omega t - kz = \omega t - \frac{\omega}{c} l$$

Phase path

$$l = \int_S^0 n(r)\,dr$$

From the magnetoionic theory the phase refractive index is:

$$n^2 = 1 - \frac{X}{1 - jZ - \frac{Y_T^{\,2}}{2(1 - X - jZ)} \pm \sqrt{\frac{Y_T^{\,4}}{(1 - X - jZ)^2} + Y_L^{\,2}}}$$

where,

$X = f_p^{\,2} / f^{\,2}$

$Z = \nu / f$

$Y_T = f_{BT} / f$

$Y_L = f_{BL} / f$

$fp$ is the plasma frequency given by:

$$f_p = \frac{1}{2\pi}\sqrt{\frac{Ne^2}{m\varepsilon_0}}$$

$f_B$ is the frequency of cyclotron given by: $f_B = e\,B/\,m\,2\pi$

$\nu$ is the frequency of collision between electrons and neutral molecules

($\nu = 1/\tau$ being $\tau$ is the average time between collisions).

These three frequencies establishes the condition of propagation of the wave through the magnetised ionospheric plasma.

Now being $Y_T < 0.14\ 10^{-3}$ and $Z < 0.3\ 10^{-6}$ the following approximation is possible

$$n^2 = 1 - X$$

$$n = \sqrt{1 - X}$$

Expanding in terms of Taylor serie we obtain

$$n \approx 1 - \frac{1}{2} X$$

The phase path *l*

$$l = \int_S^0 n(r)\,dr$$

will be

$$l = \int_S^0 \left(1 - \frac{40.3\,N(r)}{f^2}\right) dr = l_o - \frac{40.3}{f^2}\,TEC$$

If the satellite emits two frequencies $f_1$ and $f_2$, the two related phase path $l_1$ and $l_2$ will be:

$$l_1 = l_o - \frac{40.3}{f_1^2} TEC$$

$$l_2 = l_o - \frac{40.3}{f_2^2} TEC$$

and the difference delta $\Delta l$ is:

$$\Delta l = 40.3 \cdot TEC\left(\frac{f_2^2 - f_1^2}{f_2^2 f_1^2}\right)$$

$$\Delta\phi = 40.3/f\,c\,(1/q_1^2 - 1/q_2^2)\ \mathrm{TEC}\quad \text{(cycles)}$$