Modern radio techniques for probing the ionosphere

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 ways with the electromagnetic waves.

The radio techniques for probing the ionosphere are spread in nearly all ranges of radio frequency.

We explore the structure of the ionosphere by bouncing radio waves of different frequencies on it, and using special receivers to detect how the reflected waves have changed from the transmitted waves.

We also examine the changes of the radio waves from satellites transmitted through the ionosphere etc.
Techniques

- vertical soundings + Doppler shift measurement
- incoherent scatter radar
- TEC measurement
Range of frequency and recent employed techniques

- VLF range
  - VLF receiver
  - MF-HF receiver
  - ENVELOPE RADARS (old ionosondes)
  - CODED RADARS (advanced ionosondes)

- MF-HF range
  - MF-HF receiver

- VHF range
  - VHF receiver
  - POLARIMETERS & RHIOMETERS
  - INCOHERENT RADARS

- Microwave
  - SATELLITE RADIO BEACONS
  - NNSS and GPS RECEIVER
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, amplifying and demodulating AM, FM, phase coded waves, etc.

- Ability to tune to a specific signal

- Amplify the signal that is picked up
Radio Receiver

Schematic diagram of simple radio receiver

- Radio wave
- Antenna
- L1
- L2
- C1
- C2
- Headphone
Superherodyne receiver

antenna

RF amplifier

Mixer

Intermediate Frequency stages

Detector

Local oscillator

Low frequency amplifier
sections

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

Filter Switch

Low noise amplifier (LNA)

RF stage

to the Intermediate frequency
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.

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

Input modulated signal

Envelope detector

audio out

c

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

Coherent (synchronous): frquencies

Non-coherent (asynchronous): envelope detection

Two types
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:

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

where $K$ is the Boltzmann constant ($J/\text{Hz}$) and $B$ is the band of frequency considered.

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

By definition the noise factor $F$ is:

$$\text{Signal-to-noise ratio (input)} / \text{Signal-to-noise ratio (output)}$$
In the receiver it is useful to define the noise factor $F$ in quantitative way as:

$$F = \frac{P_i / K T o B}{G P_i / (G K T o B + P_A)}$$

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

magnetospheric cavity

ionospheric cavity

atmospheric noise

ELF - HF

man made noise

terrestrial electromagnetic environment

magnetic noise ULF-ELF

cosmic noise VHF-UHF
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.
Mono static radar
Frequency synthesizer

Variable Frequency Oscillator

fr = reference frequency
Direct Digital Synthesis

Computer or micro controller

Address bus

DDS

Reference Frequency

OUT

Radio Frequency OUTPUT
The radar equation represents the physical dependences of between the transmitted power and received power.

\[ P_r = \frac{(\lambda G_d)^2 \sigma P_{rad}}{(4\pi)^3 r^4} \]
### Radar eq

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

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_r )</td>
<td>Power received by the radar antenna</td>
<td>watts (W)</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>Wavelength of signal received by radar antenna</td>
<td>meters (m)</td>
</tr>
<tr>
<td>( G_d )</td>
<td>Directive gain of antenna (measure of the concentration of the radiated power in a particular direction)</td>
<td>unitless</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>Radar cross section (characterizes the target’s ability to scatter or reflect energy)</td>
<td>square meters (m²)</td>
</tr>
<tr>
<td>( P_{rad} )</td>
<td>Power dissipated through the characteristic impedance, ( R_{rad} ), of the TX radar antenna</td>
<td>watts (W)</td>
</tr>
<tr>
<td>( r )</td>
<td>Distance measured from the radar to the target</td>
<td>meters (m)</td>
</tr>
</tbody>
</table>
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:

\[ \sigma \equiv 4 \pi r^2 \left( \frac{|E_s|}{r} \right)^2 = 4 \pi \left( \frac{|E_s|}{|E_i|} \right)^2 \]
Envelope detector ionosonde or HF Radar

- tx pulse
- received RF pulse
- envelope

$t=0$
ionosonde block-diagram

TX antenna

Transmitter

Frequency synthesiser

Control

Receiver

RX antenna

- Detection
- elaboration
- 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.
• 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.

\[ f_x - f_0 = \frac{f_B}{2} \]

\[ f_B = \frac{eB}{m} 2\pi \]

Incident ray

Ordinary ray

Extraordinary ray

Cross coupled Delta antennas
Ionospheric plasma

- The plasma frequency $f_p$ is:

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

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

$$\nu = \frac{1}{\tau}$$

being $\tau$ is the average time between collisions

- Frequency of cyclotron ($f_B$)

$$f_B = \frac{e B}{m 2\pi}$$

establishes the condition of propagation of the wave through the magnetised ionospheric plasma.
Ionogram’s characteristics
Bottom profile (post-process)

foF2  9.45
foF1  N/A
foF1p N/A
foE   N/A
foEp  1.14
fxI   10.00
foEs  1.90
fmin  1.60

NMF  27.70
M    2.947
D    3000

h'F   250
h'F2  N/A
h'E   90
h'Es  110

zmF2  319
zmF1  N/A
zmE   110
yF2   90
yF1   N/A
yE    20
B0    84.9
B1    2.76

C-level 1

STATION YYYY DAY DDD HHMM P1 FFS S AXN PPS IGA PS
Rome 1999 May11 131 1830 SBF 001-1 096 200 +0+ B1

0-4
0-3
0-2
0-1
0+1
0+2
0+3
0+4
Xu-
Xu+
Xt+
Xt-
O-
Q-

9131S30A+SBF / 125fx256h 100 kHz 2.5 km 3x2 / DPS-4 (142-142) 41.9 N 12.5 E
Pulse compressed ionosondes
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

Diagram of a chirp ionosonde system:
- TX antenna
- Transmitter
- Linear Sweep Frequency Synthesiser
- Control
- Receiver
- Spectrum Analyzer
- ionogram
Chirp Ionosonde principle

TX antenna  ionospheric path  RX antenna

Transmitter

Linear Sweep Frequency Synthesiser

$\Delta f = f_{Tx} - f_{Rx}$

Spectrum Analyzer

ionogram
Chirp techniques

$\Delta f = (df/dt) \Delta t$
Chirp techniques

\[ \Delta t = \left( \frac{dt}{df} \right) \Delta f \]

Typically
\[ \frac{df}{dt} = 0.1 \text{Hz/microsecond} \]

\[ \Delta t = \text{delay} \]

Transmitted signal

Received signal

amplitude

frequency
• 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:

$$\Delta r = \frac{c}{2B}$$

where $c$ is the velocity of light.
Oblique sounding
Phase-coded ionosonde

\[ \sin(\omega t) \]

\[ c(t) \]

\[ m(t) \]

Phase-coded waveform
Time-domain correlation

Odd #’d Pulses

Even #’d Pulses

Code 1
Matched Filter

Code 2
Matched Filter

\[ r_2 = \sum s[k-n]h[k] \]

\[ y_1 = \sum a p_1[k-n] p_1[k] \]

\[ y_2 = \sum a p_2[k-n] p_2[k] \]

\[ r_2 = y_1 + y_2 \]
Pulse compression

The phase path $P$ is given by
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 filter 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 µs, so the energy was of the order of 0.3 J.

The phase coded HF radar uses a pulse length of about 500 µs 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

Echo signal

Quadrature sampling & A/D

On-line processing in time or frequency domain

Processed signal output

Store & Display
Digital signal processing 3

FREQUENCY-DOMAIN DETECTION PROCESS
Digital signal processing 4

Block diagram of the receiving system and detection process