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New low power pulse compressed ionosonde at Gibilmanna Ionospheric Observatory

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Abstract
A digital low power pulse compressed ionosonde was developed at the Istituto Nazionale di Geofisica e Vulcanologia (INGV), Rome, Italy. The aim of this Advanced Ionospheric Sounder, AIS-INGV, is to reduce the transmitted power and, consequently, weight, size, power consumption and hardware complexity. To compensate the power reduction the most advanced HF radar techniques such as the pulse compression and a phase coherent integration are used. The ionosonde is completely programmable and a PC supports the data acquisition, control, storage and on-line processing. The first prototype was installed at Gibilmanna Ionospheric Observatory (Sicily), an interesting location in the center of Mediterranean area. The new ionosonde will contribute to ionospheric database and real time knowledge of South European ionospheric conditions for space weather applications. In this work the first results (ionograms and autoscaled characteristics) are presented and briefly discussed.

Key words *ionosonde – automatic ionogram scaling – ionospheric data – vertical soundings*

1. Introduction

Ionospheric observations contributed to the knowledge of physical phenomena such as the radio propagation in ionised media, physical and chemical processes in upper atmosphere, ionosphere and magnetosphere coupling, solar-terrestrial relations, etc. Nowadays the scientific interest remains but the ionospheric observations are much more focused on radio propagation forecasting. To achieve this objective the new ionospheric sounders should have some distinctive characteristics especially oriented towards routine service with network link and automatic scaling of the ionograms.

Like other recent sounders, AIS-INGV ionosonde is practically built around a PC that constitutes the most important part (fig. 1). This ionosonde has been designed to fulfil certain physical characteristics such as the power reduction (around 200 W against several kilowatts of traditional systems) and consequently weight, size, power consumption and hardware complexity. It exploits the computer resources to manage the sounding, real time signal processing, data storing and sharing; it also has the capability to be remotely programmed.

The basic work of this prototype is to generate an ionogram from which virtual heights and critical frequencies can be scaled. This basic system allows future expansions including polarization measurement and doppler analysis.

This first prototype has been installed at INGV Gibilmanna Ionospheric Observatory located in the centre of the Mediterranean area where no systematic ionospheric observations have been performed. In recent years the growing interest in real time mapping and short term forecasts produced efforts to achieve real time scal-

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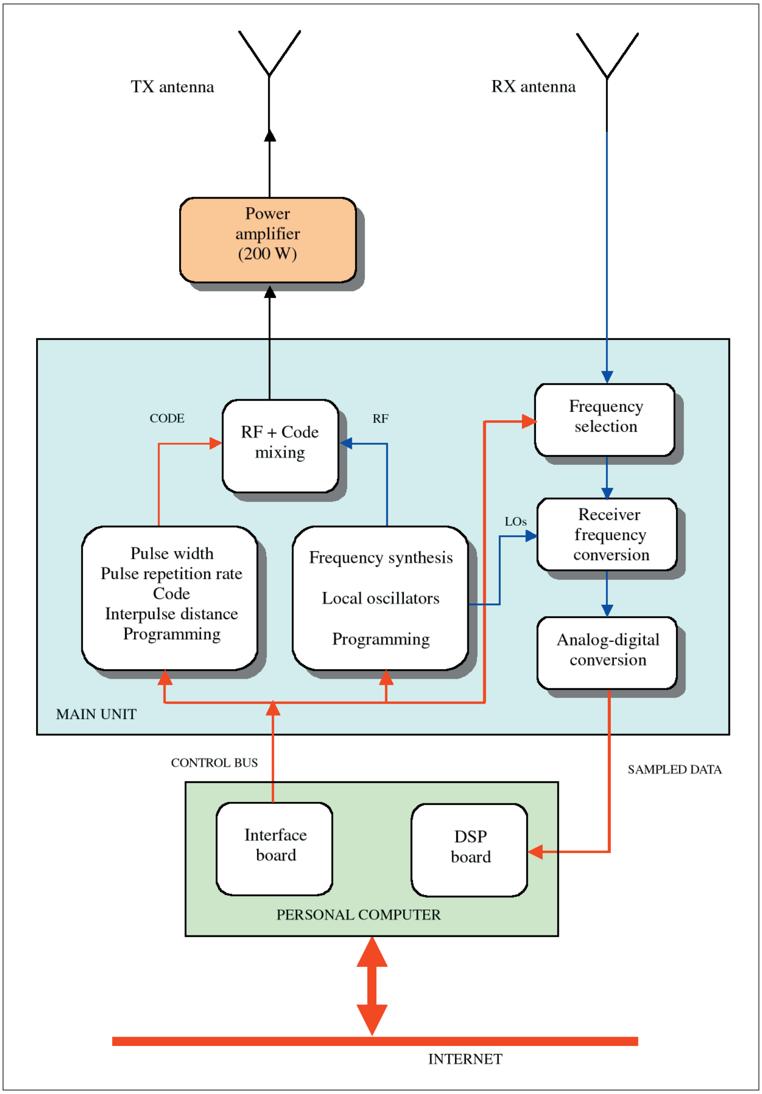

Fig. 1. Block diagram of the AIS-INGV ionosonde: red lines are digital signals while blue lines are analog.

ing of ionograms which led to many softwares (*e.g.*, Reinisch and Huang, 1983; Fox and Blundell, 1989; Igi *et al*., 1993; Tsai and Berkey, 2000). Among these, widely used and tested (Gilbert and Smith, 1988) is the ARTIST system, developed at the University of Lowell, Center for Atmospheric Research.

The INGV ionospheric laboratory designed and developed software to scale ionospheric parameters *foF*2 and MUF(3000)*F*2 automatically within a few minutes after every sounding. To date, autoscaled characteristics as well as ionograms are available real time at the site <http://eskimo.ingv.it>.

2. Description of the basic principle and system characteristics

The specifications of the new system are reported in Zuccheretti *et al*. (2003) and Arokiasamy *et al*. (2002). The new ionosonde was designed on the base of radar systems theory (Skolnik, 1980, 1997) applied to the study of the ionosphere (Hunsucker, 1991).

We exploited the information of the transmitted code, as in other phase-coded HF-VHF radars, to perform the pulse compression and the coherent integration (a more detailed description of the mathematical processes is given in Bianchi *et al*., 2003).

According to a general radar equation (Le Chevalier, 2002) the received power P_r is

$$P_r = \frac{P_t G_t}{4\pi \cdot r^2} \cdot \frac{1}{L_p} \frac{\lambda^2 G_r}{4\pi} \tag{2.1}$$

where P_t is transmitted power, r is the range, G_t and G_r are the transmitting and receiving antenna gain, λ is the wavelength, and L_p represents all the losses.

The bandwidth of the receiver, being less than the thermal noise, can be neglected with respect to the environmental noise N. The minimum S/N useful for detection is

$$S/N = \frac{P_r \cdot G_a \cdot G_{\text{process}}}{N} \tag{2.2}$$

where G_a includes all the analog gain in the receiver chain and G_{process} is the processing gain.

To achieve the desired S/N, the processing gain $G_{process}$ must be greater than 20-30 dB, because of various factors like poor antenna gain (less than 2 dB$_\text{i}$), the reduced transmitted power and the maximum required range. This constraint imposes limits on the system parameters like the Pulse Repetition Frequency (PRF), pulse width T, subpulse number M, phase-code and modulation characteristics (Bianchi *et al*., 2003). A 16 chips bi-phase complementary code has been employed (Golay, 1961); this particular code theoretically eliminates the side lobes as they are opposite in phase (fig. 2). The processing gain after the pulse compression, expressed as S/N, is given by $10\log(M)$ that for $M=16$ is approximately 12 dB. A further contribution to the gain comes from the integration process based on the ionospheric coherence.

The process of the phase coherent integration, depending on the ionospheric variability, can be performed till the phase of echoes sequence differs less than $\pi/2$, which limits the number N of the integrations. At Gibilmanna Ionospheric Ob-

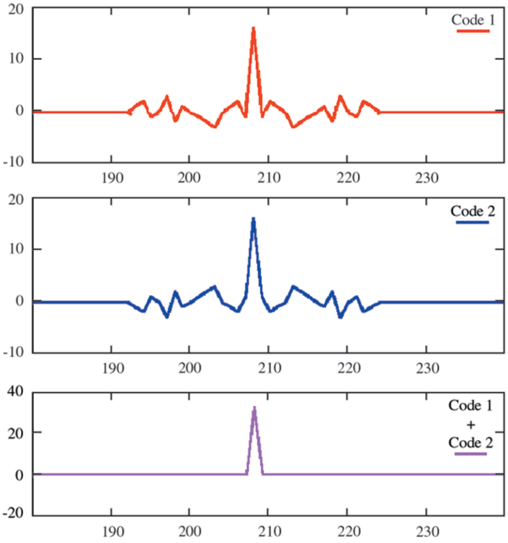

Fig. 2. Correlation results for code 1, code 2 and their addition. On x axis distance of an echo in km is indicated, while on y axes an arbitrary scale is used.

Table I. Processing and phase code features.

Code	Specifications
Type	Bi-phase complementary
Code length T	480 μs
Subpulse number M	16
Subpulse length τ	30 μs
Pulse Repetition Frequency (PRF)	30 Hz
Processing gain due to the correlation M	12 dB
Processing gain due to the integration N	8-18 dB

Table II. AIS-INGV programming parameters.

Parameter	Requirement
Height range	(90–750) km
Distance resolution	5 km
Peak transmitted power (medium power)	200 W (5~10 W)
Receiver sensitivity	~–85 dBm for 0 dB *S*/*N*
Input dynamic range	~80 dB
Frequency range	(1–20) MHz
Frequency resolution	25 kHz, 50 kHz, 100 kHz
Scan duration (1.5 MHz-20 MHz, 50 kHz step)	3 min
Acquisition sampling rate	100 kHz
Acquisition quantization	8 bit
Storage data rate (max)	60 kbytes (with 50 kHz step)

servatory different tests suggested a maximum number of integrations of 30. Table I summarizes the main parameters of the phase code and processing gain; other parameters have been chosen on the basis of the radar techniques.

Assuming light speed as the radio wave velocity and 750 km as the range, the maximum PRF should be around 200 Hz, but processing time limits this parameter to 30 Hz; this value of PRF still makes the integration process advantageous.

Other design parameters are related to spatial resolution and minimum detectable distance from the ground (Arokiasamy *et al*., 2002). A pulse width of 480 μs and 16 chips code with a chip length of 30 μs lead to a minimum range of 72 km and a radar resolution of around 5 km (table II).

3. The INGV software for automatic scaling of ionograms

The INGV software is based on a technique of image recognition and is able to work without polarization information. Hence it can be used

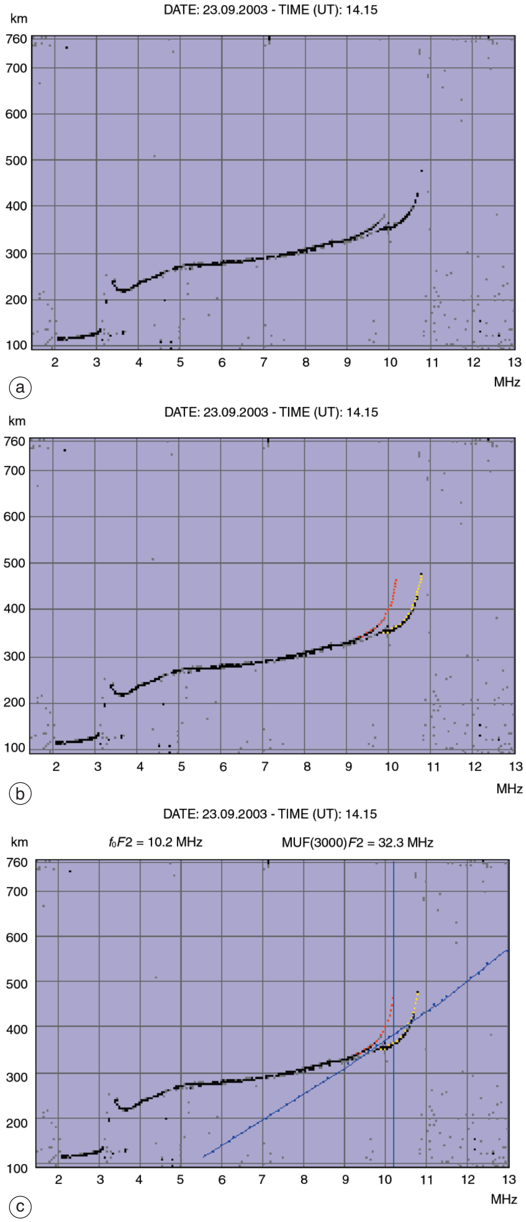

Fig. 3a-c. a) A typical AIS-INGV ionogram. b) Selected element of the family of functions superposed on the ionogram. The automatically detected traces are reported (in red the ordinary trace and in yellow the extraordinary trace). c) Vertical asymptote and tangent transmission curve of the automatically ordinary trace detected in correspondence of which *foF*2 and MUF(3000)*F*2 are calculated.

with both single antenna system and crossed antenna system. A family of empirical functions having the typical shape of the *F*2 trace is considered. A particular element of this family is selected by a maximum contrast technique and it is assumed as representative of the *F*2-layer trace. The vertical asymptote of the selected function corresponds to the critical frequency *foF*2; the MUF(3000)*F*2 is calculated numerically finding the transmission curve tangent to the selected function (fig. 3a-c). Using different families of empirical functions this method can in principle be applied for the identification of the other ionospheric layers. For radiopropagation purposes the real time scaling of *E* sporadic and *F*1-layers would also be important.

With respect to the previous version of INGV software for automatic scaling of ionograms (Scotto and Pezzopane, 2002), two main improvements have been introduced:

1) The parameterization of the girofrequency that makes this version able to scale ionograms recorded in any location.

2) The capability to identify ionograms with sufficient information, to make them properly scaled. If the ionogram is identified by the software to have insufficient information it is discarded by the program and neither the *foF*2 nor the MUF(3000)*F*2 are given as an output.

To test the software a comparison between the values scaled by an operator and by the program was performed considering 1124 ionograms recorded by the AIS-INGV installed at Gibilmanna Ionospheric Observatory in 2002 from December 1st to December 15th.

3.1. *Quantitative estimation of the software's capability to identify ionograms with sufficient information*

To test the capability of the software to properly identify the ionograms with sufficient information, the processed ionograms were divided into two subsets: subset S, that contains the ionograms considered by the program with sufficient information, hence scaled, and subset N containing ionograms considered by the program with insufficient information, hence discarded.

For each subset we considered: a) the number of ionograms for which the operator was able to scale neither the *foF*2 nor the MUF(3000)*F*2; b) the number of ionograms for which the operator was able to scale *foF*2 only; c) the number of ionograms for which the operator was able to scale MUF(3000)*F*2 only; d) the number of ionograms for which the operator was able to scale both *foF*2 and MUF(3000)*F*2.

The results of this analysis are reported in table III. It can be observed that 9 ionograms are considered with sufficient information without having it, while 7 ionograms are improperly considered with insufficient information.

This shows that the error percentage in recognising the trace of the ionogram by the software is 1.4% (16 out of 1124). With reference to this it is important to emphasize that for the software the lack of trace near the *F*2 region asymptote makes the choice of a particular element of the family of functions more difficult. This lack of trace sometimes leads the software to discard the ionogram even if an operator could scale MUF(3000)*F*2. On the contrary if the trace near the *F*2 region asymptote is clearly visible the program scales the ionogram for both while an operator could scale only *foF*2.

We can therefore conclude that the software capability to identify ionograms with sufficient information is quite good.

3.2. *Test of accuracy and acceptability of the automatically scaled parameters*

In this work an accurate value is considered to lie within ±0.1 MHz of the value obtained by the operator for *foF*2 and ±0.5 MHz for MUF(3000)*F*2. An acceptable value is considered to lie within ±0.5 MHz for *foF*2 and ±2.5 MHz for MUF(3000)*F*2. Limits of acceptability have been adopted in accordance with the URSI limits of ±5 Δ (Δ is the reading accuracy).

With reference to the ionograms scaled by the INGV software, the following three subsets have been considered (see table III): subset A, containing the ionograms in which the operator was able to scale both the critical frequency *foF*2 and the MUF(3000)*F2*; subset B, containing the ionograms in which the operator was

Table III. Test results of the software capability in identifying ionograms with sufficient information.

	No. of cases scaled by the INGV software (subset S)	No. of cases discarded by the INGV software (subset N)
The operator scaled neither *foF*2 nor MUF(3000)*F*2	9	46
The operator scaled both *foF*2 and MUF(3000)*F*2	847 (subset A)	7
The operator scaled MUF(3000)*F*2	only 182 (subset B)	21
The operator scaled *foF*2 only	12 (subset C)	0
Total	1050	74

Table IV. Subset A, subset B and ubset C: acceptability and accuracy percentages of autoscaled parameters.

	Subset A				Subset B		Subset C	
	*foF*2		MUF(3000)*F*2		MUF(3000)*F*2		*foF*2	
	N°	[%]	N°	[%]	N°	[%]	N°	[%]
Total	847	100.0	847	100.0	182	100.0	12	100.0
Acceptable	833	98.3	847	100.0	179	98.5	9	75.0
Accurate	638	75.3	827	97.5	170	93.5	6	50.0

able to scale the MUF(3000)*F*2 only; subset C, containing the ionograms in which the operator was able to scale the *foF*2 only.

A quantitative comparison between the values scaled automatically and manually has been performed and the results of the comparison are reported in table IV.

4. Observatory and data management

The software performs all the system operations and data management. Sounding parameters, number of integrations and sounding time scheduling, can be remotely changed at any time writing a new configuration file downloadable by the ionosonde, so remote control is also possible.

The system is completed with a device able to turn the amplifier on and to connect the antenna system just during the sounding time, in order to use less energy and to protect the system against ESD due to storms. At present the ionosonde performs soundings every fifteen minutes using a frequency range from 1.5 MHz to 13.0 MHz with a step of 50 kHz. At the end of every sounding the acquired data file is immediately available on <ftp://relay.ingv.it>, while processed ionograms and autoscaled data are available at the web site <http://eskimo.ingv.it> within few minutes as GIF file and TXT file respectively. The research team makes also a manual validation of the hourly data that can be shared on demand.

5. Conclusions

Nowadays ionosondes are intended to be ionospheric conditions monitoring systems, rather than being just scientific instruments for studying the physics of the ionosphere.

In fact short-term ionospheric forecasts are based on real-time data from vertical sounders and best results could be obtained connecting several ionosondes in a net covering an area and obtaining data from it. This means that a modern efficient ionosonde has to be low cost, easy to install and remotely programmable; in addition it should have the possibility to automatically scale the main characteristics giving a contribution to have reliable forecasts within few minutes after sounding.

The AIS-INGV ionosonde has been designed taking into account simplicity and flexibility to be installed even in a remote observatory. Moreover the automatic scaling of *foF*2 and MUF(3000)*F*2 suggests that the system can be a node of a possible net for space weather purposes.

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