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The INGV software for the automatic scaling of foF2 and MUF(3000)F2 from ionograms: A performance comparison with ARTIST 4.01 from Rome data

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Abstract

The performance of a computer program, called Autoscala, for the automatic scaling of foF2 and MUF(3000)F2 from ionograms has been extensively tested. Results of comparisons between automatically and manually scaled data are shown both for Autoscala and for ARTIST (release 4.01). Particular attention has been paid to the cases in which the ionograms have a truncated trace. The problem of the rejection of bad quality ionograms has been also considered. The analysis of data shows that the reliability of values automatically given as output by Autoscala is good. For the data set considered Autoscala seems to operate better than ARTIST.

Keywords: Ionosonde; Ionogram scaling; Automatic scaling; Ionosphere monitoring

1. Introduction

Recently the INGV (Istituto Nazionale di Geofisica e Vulcanologia) developed an ionosonde, called AIS (Advanced Ionospheric Sounder), with minimum transmitted power (less than 200 W) and consequently less weight, size, power consumption, and hardware complexity. In November 2002 this ionosonde was installed at the ionospheric station of Gibilmanna (Zuccheretti et al., 2003; Bianchi et al., 2003).

In the last years, due to the growing interest in real time mapping and short term predictions, the need for immediate availability of good scaled data became more and more important. For this reason, together with the ionosonde, the INGV developed a computer program, called Autoscala, for the automatic scaling of critical frequency foF2 and MUF(3000)F2 from ionograms. The main characteristic of Autoscala is that it is based on image recognition technique, and does not use information on polarization. Thanks to these characteristics Autoscala can be easily applied to any kind of ionosonde.

Another important characteristic of Autoscala is that in the case of a truncated trace, if the digital information of the ionogram is considered sufficient, the software is able to reconstruct it, giving more reliable foF2 and MUF(3000)F2 output values. This characteristic of Autoscala is shown here for a case of an artificially truncated trace correctly reconstructed by the software.

Since the first phase of Autoscala development attention has been paid to the quantitative evaluation of the performance of the algorithms by comparing the output from Autoscala with the corresponding result obtained by a well experienced operator. This kind of evaluation has demonstrated the reliability of the

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software for quiet conditions (Kp$\leqslant$4) (Scotto and Pezzopane, 2002, 2004).

In this article, the performance of Autoscala and ARTIST (Reinisch and Huang, 1983; Gilbert and Smith, 1988), are comparatively evaluated using as a reference the data obtained according to the standard URSI interpretation. The used data set is constituted by 4326 ionograms, including a wide range of ionospheric conditions, recorded by the DPS4 (Digital Portable Sounder 4, produced by University of Lowell, Massachusetts, USA) installed at the ionospheric station in Rome and autoscaled by ARTIST. These ionograms were automatically scaled by Autoscala and manually scaled by a well experienced operator. Autoscala uses ionograms in RDF file format as input (Pezzopane, 2004) and so, before applying Autoscala to ionograms recorded by the ionosonde DPS4, a format change was necessary. In this change of format the information on polarization was also removed.

In addition, a comparison between Autoscala and ARTIST was performed for disturbed conditions on the occasion of the strong ionospheric storm which occurred on 29 October 2003.

2. Autoscala: reconstruction of truncated traces

The trace of the F2 region can appear on ionograms basically in three different ways, identifying three different classes:

(1) the trace is very clear and foF2 can be easily scaled from the vertical asymptote (Fig. 1a);
(2) the trace near the critical frequency is not clearly recorded owing to interference, absorption or scattering (Fig. 1b);
(3) the trace is completely lost due to defects of the ionosonde or some ionospheric reasons (Fig. 1c).

For the ionograms belonging to class (1) the software limits itself to identifying the trace. For the ionograms belonging to class (3) the program establishes that the identification of the trace is not possible and consequently no output is produced.

As regards the ionograms belonging to class (2), Autoscala is designed to reconstruct (when possible) the truncated trace giving as output MUF(3000)F2 and an extrapolated value of foF2. In order to test the capability of the software to do this reconstruction we carried out a study by artificially truncating some good traces. As an example of the procedure, Fig. 2a shows a good quality ionogram with the values of foF2 and MUF(3000)F2 correctly scaled by Autoscala; Fig. 2b shows the same ionogram artificially truncated, and Fig. 2c the reconstructed trace with the corresponding autoscaled values. From Figs. 2a and c the correspondence of the values can be seen as evidence of a correct reconstruction by Autoscala.

3. Performance comparison between Autoscala and ARTIST 4.01

A test was performed using a wide data set of 4326 ionograms recorded from January 1 to June 30, 2003 by the ionosonde DPS4 installed at the ionospheric station in Rome and autoscaled by ARTIST. These ionograms, including of a wide range of ionospheric conditions, were automatically scaled by Autoscala and manually scaled by an operator.

The tests were performed separately for the two characteristics produced as output from Autoscala.

3.1. Test for the foF2 characteristic

With reference to the processing data set of 4326 ionograms, the following five subsets were considered:

(1) Subset C (definite values). Composed of ionograms for which the operator was able to scale foF2 as a definite value, using neither descriptive nor qualificative letters.
(2) Subset D (deteriorated traces). Composed of ionograms for which the traces were deteriorated but the operator was able to scale foF2; this subset includes the following separate cases:
    (a) the trace near the critical frequency is not clearly recorded owing to interference, or absorption; in this case the operator scaled foF2 as a doubtful value;
    (b) the ordinary trace is obscured by absorption, interference or blanketing and an extraordinary component is clearly visible; in these cases the standard URSI (International Union of Radio Science) recommends deriving the critical frequency foF2 of the ordinary trace from the extraordinary one.
(3) Subset F (spread F). Composed of ionograms for which a spread F condition was observed.
(4) Subset T (truncated traces). Composed of ionograms for which the trace near the critical frequency is not clearly recorded owing to interference or absorption. In these cases it is possible to obtain the most reliable value for foF2 by extrapolation. This subset includes the ionograms for which the extrapolated frequency range is greater than 10% of foF2.
(5) Subset I (impossible). Composed of ionograms for which the operator was not able to observe the F2 trace for different reasons.

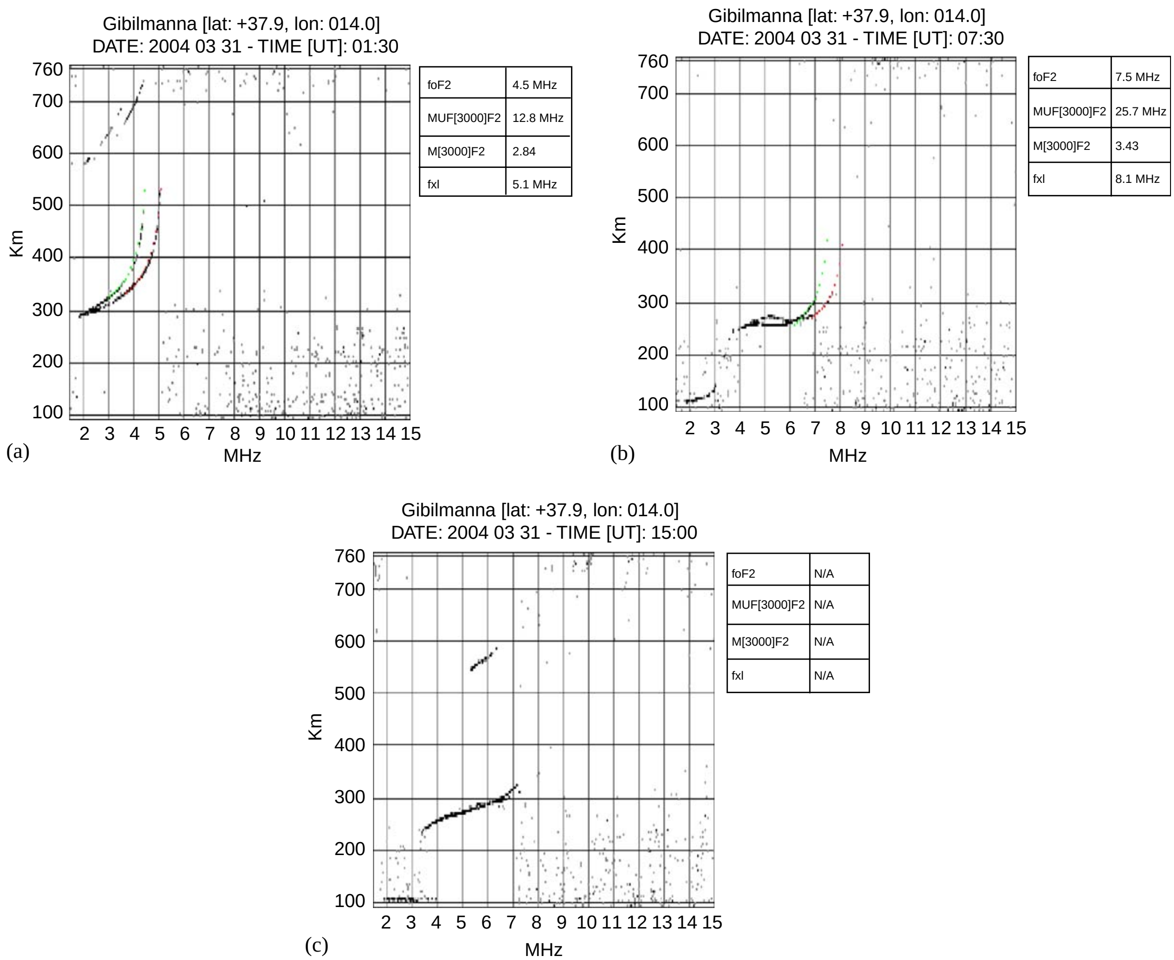


Fig. 1. (a) Good quality ionogram. The F2 trace is very clear up to the critical frequency therefore foF2 can be easily scaled from the vertical asymptote and MUF(3000)F2 is determined by the tangent transmission curve. Autoscala is designed to recognize the trace giving as output MUF(3000)F2 and foF2. The automatically detected traces are reported (in green the ordinary trace and in red the extraordinary trace). (b) Medium quality ionogram. The F2 trace near the critical frequency is not clearly recorded owing to interference, absorption or scattering. Autoscala is designed to reconstruct the truncated trace determining MUF(3000)F2 by the tangent transmission curve and foF2 by extrapolation. The automatically reconstructed traces are reported (in green the ordinary trace and in red the extraordinary trace). (c) Bad quality ionogram. The F2 trace is completely lost. Autoscala is designed to discard these cases giving no value as output.

For each of these subsets the data obtained manually by the operator was compared separately to the data given in output by Autoscala and by ARTIST.

In this work an acceptable value is considered to lie within ± 0.5 MHz of the manual value for foF2 and ± 2.5 MHz for MUF(3000)F2. Such limits of acceptability were adopted in line with the URSI limits of $\pm 5\Delta$ (Δ is the reading accuracy).

In Table 1 contingency tables are reported for each subset expressing the results obtained in terms of correct or incorrect behaviour of the two programs.

For subsets C, D, and F the correct behaviour of the programs is assumed for ionograms scaled with acceptable values given as output. On the contrary, for subset I the correct behaviour of the programs is to discard the ionograms, giving no data as output. For subset T (truncated traces), if the extrapolated frequency range exceeds 10% of foF2, the URSI standard suggests reporting the last recorded frequency followed by the qualifying letter D and the appropriate descriptive letters (S for interference or R for absorption). Consequently, the correct behaviour of the programs for this subset is to discard the ionogram or to scale the ionogram giving an automatically scaled value that exceeds the last recorded frequency by a percentage between 5% and 20%.

The McNemar test (see Appendix A) was used to evaluate Autoscala vs. ARTIST performance. In order

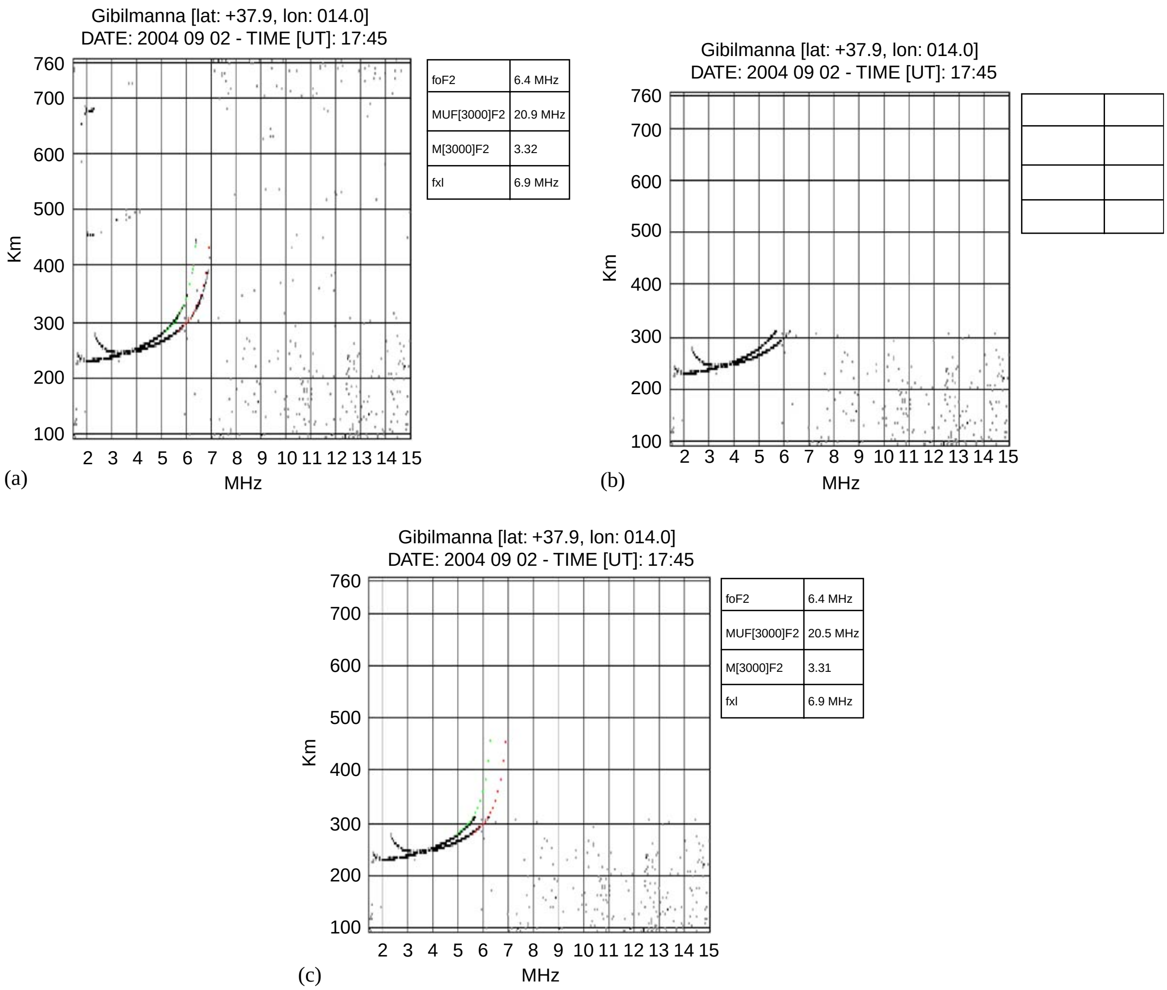


Fig. 2. (a) A good quality ionogram with the values of foF2 and MUF(3000)F2 correctly scaled by Autoscala. The automatically detected traces are reported (in green the ordinary trace and in red the extraordinary trace). (b) The same ionogram reported in Fig.2a artificially truncated. (c) Starting from the artificially truncated ionogram reported in Fig. 2b Autoscala automatically reconstructs the traces giving as output foF2 and MUF(3000)F2. Note the consistence of these values with the ones scaled from the original ionogram reported in Fig. 2a. The automatically reconstructed traces are reported (in green the ordinary trace and in red the extraordinary trace).

to assess whether the two methods differ in a significant way the confidence level was set at 0.95. The results obtained (see Table 2) show that for subsets C, D, T, and I Autoscala performs better than ARTIST, while for subset F the behaviour of the two programs does not differ.

As an example, Fig. 3a shows a case of an ionogram for which ARTIST wrongly scaled foF2 as the last frequency recorded on the truncated trace; Fig. 3b shows the same ionogram with the trace correctly reconstructed by Autoscala and a reasonable value of foF2 given as output. Fig. 4a illustrates another case of an ionogram for which ARTIST wrongly scaled foF2 as the last frequency recorded on the truncated trace, while in Fig. 4b the same ionogram is correctly discarded by Autoscala.

Moreover, for subsets C, D, and F the ionograms that were acceptably scaled by both programs were considered. The following mean square differences between the automatically scaled values and the corresponding values scaled by the operator were calculated separately for each class:

$$\bar{\delta}_{\text{Autoscala}} = \sum_{i=1}^{N} (\text{foF2}_{i(\text{autoscaled})} - \text{foF2}_{i(\text{operator})})^2/N \tag{1a}$$

and

$$\bar{\delta}_{\text{ARTIST}} = \sum_{i=1}^{N} (\text{foF2}_{i(\text{autoscaled})} - \text{foF2}_{i(\text{operator})})^2/N. \tag{1b}$$

Table 1
Autoscala vs. ARTIST

		Autoscala: Incorrect	Autoscala: Correct	
Subset C	ARTIST: Correct	7	2064	2071
	ARTIST: Incorrect	12	109	121
		19	2173	2192
Subset D	ARTIST: Correct	45	1104	1149
	ARTIST: Incorrect	37	142	179
		82	1246	1328
Subset F	ARTIST: Correct	8	123	131
	ARTIST: Incorrect	5	4	9
		13	127	140
Subset T	ARTIST: Correct	8	34	42
	ARTIST: Incorrect	46	253	299
		54	287	341
Subset I	ARTIST: Correct	4	234	238
	ARTIST: Incorrect	14	73	87
		18	307	325

Test for foF2: contingency tables for each subset.

Table 2
Autoscala vs. ARTIST

Subset	χ^2	p
C	$87\,940 \times 10^{-3}$	>0.99
D	$49\,283 \times 10^{-3}$	>0.99
F	750×10^{-3}	<0.70
T	$22\,8107 \times 10^{-3}$	>0.99
I	$60\,052 \times 10^{-3}$	>0.99

Test for foF2: χ^2 McNemar test for each subset.

The paired t-test (see Appendix B) was applied to determine whether $\bar{\delta}_{\text{Autoscala}}$ and $\bar{\delta}_{\text{ARTIST}}$ differ in a significant way. The results of this further analysis are reported in Table 3. It is possible to conclude that, for the ionograms scaled acceptably by both programs, $\bar{\delta}_{\text{Autoscala}}$ and $\bar{\delta}_{\text{ARTIST}}$ do not differ to a statistically significant degree.

3.2. *Test for the MUF(3000)F2 characteristic*

With reference to the processing data set of 4326 ionograms, the following three subsets were considered:

(1) Subset C (definite values). Composed of ionograms for which the operator was able to scale MUF(3000)F2 as a definite value; this data set includes the following cases:
   (a) the ordinary trace is clearly observed and the tangent transmission curve is easily determined;
   (b) the ordinary trace is partially lost but the tangent transmission curve can however be determined observing the extraordinary trace that is indeed well defined;
(2) Subset F (spread F). Composed of ionograms for which a spread F condition was observed;
(3) Subset I (impossible). Composed of ionograms for which the operator was able to clearly observe neither the ordinary trace nor the extraordinary one for different reasons.

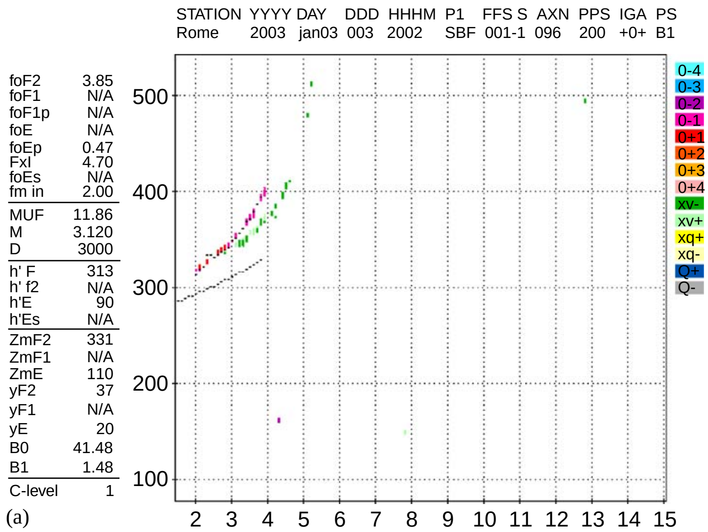
In Table 4 contingency tables are reported for each subset expressing the results obtained in terms of correct or incorrect behaviour of the two programs.

For subsets C and F the correct behaviour of the programs is assumed for ionograms scaled with acceptable values given as output. On the contrary for subset I the correct behaviour of the programs is to discard the ionograms, giving no data as output.

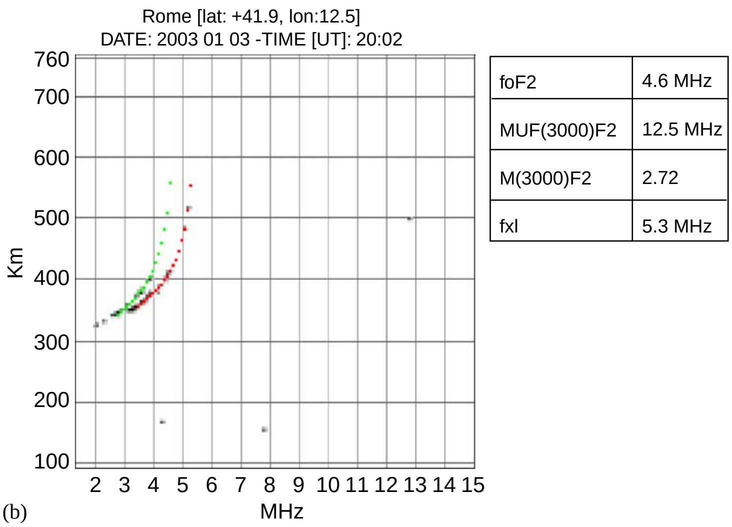
The McNemar test was used to evaluate Autoscala vs. ARTIST performance. Again, in order to assess whether the two methods differ in a significant way the confidence level was set at 0.95. The results obtained (see Table 5) show that for subsets C and F there is not significant difference between the two programs, while for subset I Autoscala performs better than ARTIST.

As for the foF2 study, a paired t-test for the ionograms that were acceptably scaled by both programs was performed (considering in this case the subsets C and F). The mean square differences between the automatically scaled values and the corresponding ones scaled by the operator were calculated separately for each class applying Eqs. (1a) and (1b) in which foF2 was substituted with MUF(3000)F2.

Again it can be concluded that, for the ionograms scaled acceptably by both programs, $\bar{\delta}_{\text{Autoscala}}$ and $\bar{\delta}_{\text{ARTIST}}$ do not differ to a statistically significant degree (see Table 6).



(a)



(b)

Fig. 3. (a) A case of truncated ionogram (subset T) for which ARTIST wrongly scaled foF2 as the last frequency recorded. (b) The same ionogram reported in Fig. 3a, with the trace correctly reconstructed by Autoscala. As output a reasonable extrapolated value for foF2 is given. The automatically reconstructed traces are reported (in green the ordinary trace and in red the extraordinary trace).

4. Performance of autoscala for disturbed ionospheric conditions in comparison with ARTIST system 4.01: a case study

A severe magnetic storm occurred from 29 to 31 October 2003. The arrival of a large high-speed solar wind shock front was detected by the solar wind monitoring satellite on 29 October at approximately 6 UT. The geomagnetic field disturbance was observed in some regions until 7 UT.

In Fig. 5 the foF2 values from Rome are reported. The values obtained by hand are compared with the corresponding ones scaled by ARTIST (Fig. 5a) and by Autoscala (Fig. 5b).

The onset of the storm causes the deterioration of the ionogram traces and comparing the two plots it can be seen that Autoscala is able to detect this condition. In some cases Autoscala correctly reconstructed the trace or discarded the ionogram giving no data as output. On the contrary ARTIST did not detect this condition and so the real time values of foF2 were wrongly given as output. As a consequence, from Fig. 5a it can be noted that the real time data given by ARTIST between about 9 and 11 UT are highly underestimated and consequently the plot dissembles the ionospheric effect of the storm. Therefore Fig. 5 would seem to indicate that the performance of Autoscala during this extreme event was better than that of ARTIST.

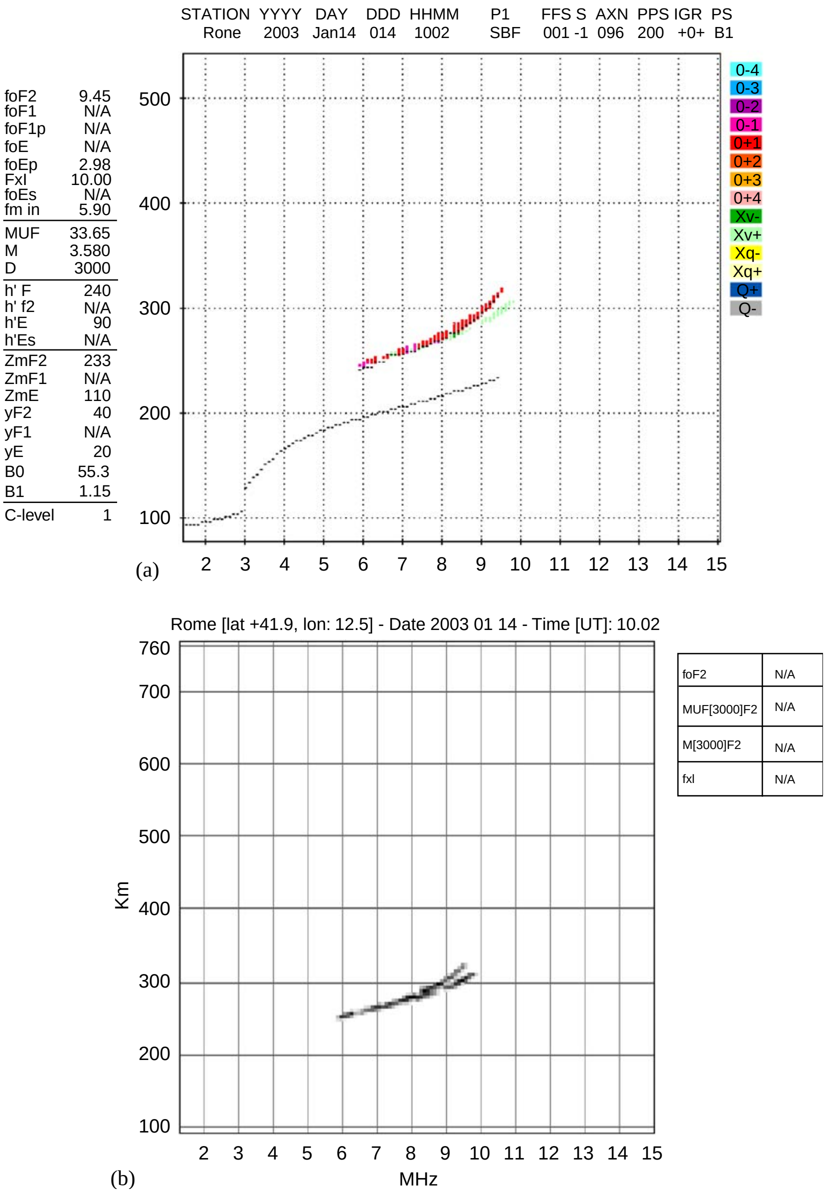


Fig. 4. (a) A case of truncated ionogram (subset T) for which ARTIST wrongly scaled foF2 as the last frequency recorded. (b) The same ionogram reported in Fig. 4a, correctly discarded by Autoscala.

Table 3
Autoscala vs. ARTIST

Subset	$\overline{\delta}_{\text{Autoscala}}$	$\overline{\delta}_{\text{ARTIST}}$	t	p
C	1.6×10^{-2}	2.1×10^{-2}	9.5×10^{-2}	<0.75
D	2.5×10^{-2}	3.8×10^{-2}	12.3×10^{-2}	<0.75
F	6.1×10^{-2}	4.5×10^{-2}	4.1×10^{-2}	<0.75

Test for foF2: paired t-test for ionograms acceptably autoscaled by both softwares.

Fig. 6a shows an ionogram recorded on 29 October 2003 in which the trace has some gaps. In this case ARTIST wrongly gave foF2 = 8.25 MHz as output. Fig. 6b shows the same ionogram as Fig. 6a elaborated by Autoscala; the missing parts of the traces are correctly reconstructed and the value foF2 = 10.8 MHz given as output is more appropriate.

In Fig. 7a another ionogram recorded on 29 October 2003 has its trace abruptly truncated. In this case ARTIST wrongly gave foF2 = 9.75 MHz as output.

Table 4
Autoscala vs. ARTIST

		Autoscala: Incorrect	Autoscala: Correct	
Subset C	ARTIST: Correct	114	3373	3487
	ARTIST: Incorrect	26	116	142
		140	3489	3629
Subset F	ARTIST: Correct	2	124	126
	ARTIST: Incorrect	0	4	4
		2	128	130
Subset I	ARTIST: Correct	29	248	277
	ARTIST: Incorrect	62	228	290
		91	476	567

Test for MUF(3000)F2: contingency tables for each subset.

Table 5
Autoscala vs. ARTIST

Subset	χ^2	p
C	4×10^{-3}	<0.10
F	167×10^{-3}	<0.50
I	$152\,545 \times 10^{-3}$	>0.99

Test for MUF(3000)F2: χ^2 McNemar test for each subset.

Table 6
Autoscala vs. ARTIST

Subset	$\overline{\delta}_{\mathrm{Autoscala}}$	$\overline{\delta}_{\mathrm{ARTIST}}$	t	p
C	6.8×10^{-2}	36.4×10^{-2}	61.6×10^{-2}	<0.75
F	26.7×10^{-2}	41.9×10^{-2}	5.2×10^{-2}	<0.75

Test for MUF(3000)F2: paired t-test for ionograms acceptably autoscaled by both softwares.

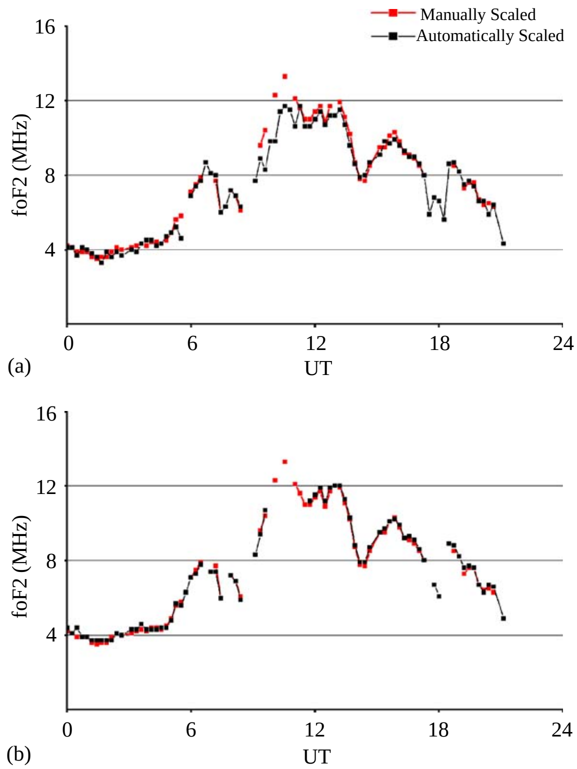


Fig. 5. (a) Plot of foF2 values, referring to the ionograms recorded in Rome on 29th October 2003, scaled by an experienced operator (in red) compared to the corresponding plot of foF2 automatically scaled by ARTIST (in black). (b) Plot of foF2 values, referring to the ionograms recorded in Rome on 29th October 2003, scaled by an experienced operator (in red) compared to the corresponding plot of foF2 automatically scaled by Autoscala (in black).

Fig. 7b shows the same ionogram as Fig. 7a discarded by Autoscala because of the many gaps in the traces.

5. Conclusions

The results obtained in the test carried out (including the comparison with ARTIST 4.01) showed that Autoscala performs well for the automatic scaling of the ionospheric parameters foF2 and MUF(3000)F2. The behaviour of Autoscala can be summarized as follows:

(a) for ionograms with a clear and not truncated trace Autoscala demonstrates good capacity to output reliable values for foF2 and MUF(3000)F2;
(b) for truncated ionograms with adequate trace quality, along with the capability of outputting good MUF(3000)F2 values, Autoscala is also able to extrapolate reliable foF2 values;
(c) for bad quality ionograms Autoscala does not compute any values.

For these reasons the ionosonde AIS-INGV together with the Autoscala software can be proposed as an ionospheric monitoring system. Real time ionograms recorded and autoscaled by the AIS-INGV/Autoscala

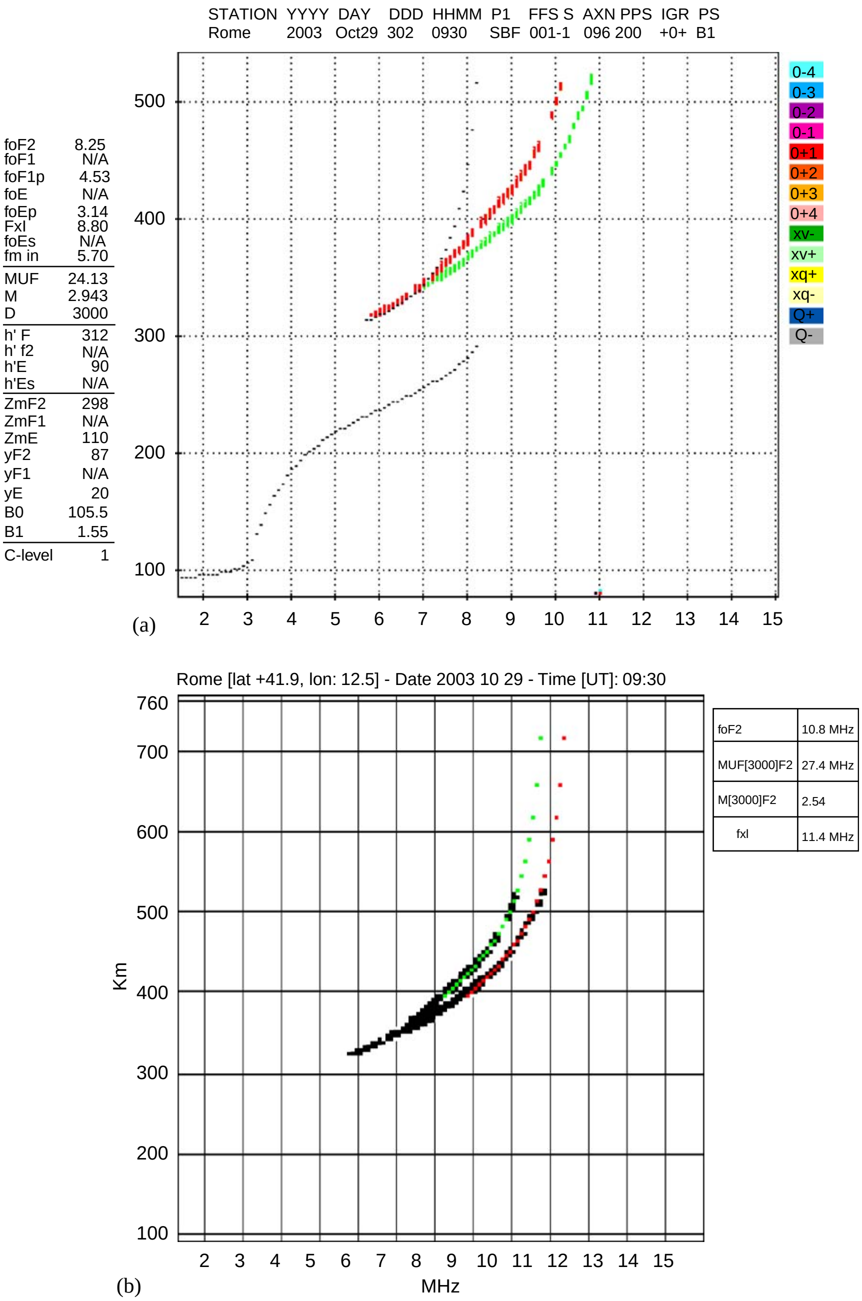


Fig. 6. (a) A case of ionogram occurred during the magnetic storm of 29th October 2003 for which ARTIST wrongly scaled foF2 as the last frequency recorded before the first significative gap of the recorded trace. (b) The same ionogram reported in Fig. 6a elaborated by Autoscala. The lacking parts of the traces are correctly reconstructed and the value of foF2 is correctly extrapolated. The automatically reconstructed traces are reported (in green the ordinary trace and in red the extraordinary trace).

system installed at the ionospheric station of Gibilmanna can be seen on Internet (go to http://ionos.ingv.it/spaceweather/start.htm, and click the “Gibilmanna Autoscaled Ionograms” link).

Appendix A. McNemar test

The McNemar test assesses the significance of the difference between two dependent samples when the

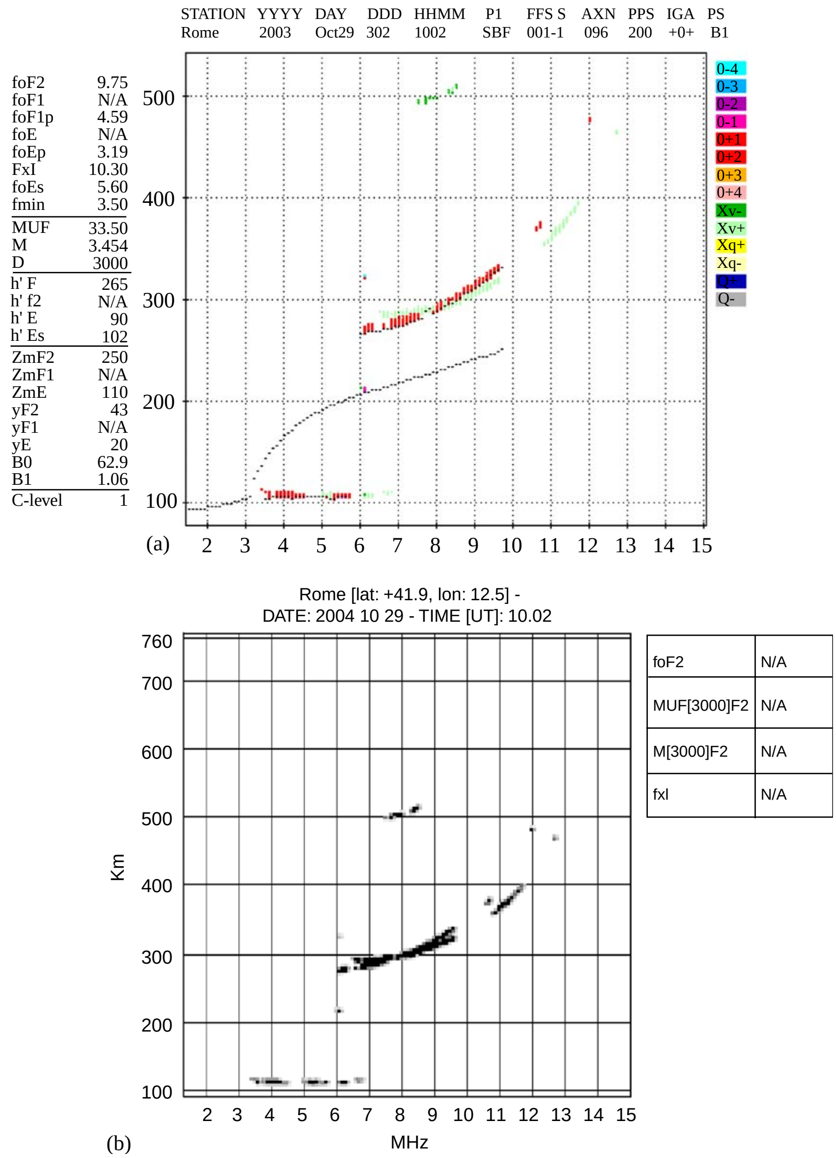


Fig. 7. (a) A case of ionogram occurred during the magnetic storm of 29th October 2003 for which ARTIST wrongly scaled foF2 as the last frequency recorded on the truncated trace. (b) Because of many lacks of the traces the same ionogram reported in Fig. 7a was discarded by Autoscala.

variable of interest is a dichotomy. It is used primarily in biology in before-after studies to test for an experimental effect. It is also used in computer science for deciding whether the difference in error rates between two algorithms tested on the same data is statistically significant.

Consider Table 7 that summarizes agreement between two raters on a dichotomous outcome. The McNemar statistic is calculated as:

$$\chi^2 = \frac{(|b-c|-1)^2}{b+c}.$$

Table 7
Summary of binary ratings by rater 1 (rows) and rater 2 (columns)

	Incorrect	Correct	
Incorrect	a	b	a + b
Correct	c	d	c + d
	a + c	b + d	total

The value χ^2 can be viewed as a χ^2 statistic with 1 degree of freedom. Statistical significance is determined by evaluating the probability of χ^2 using a table of cumulative probabilities of the χ^2 distribution or a comparable computer function. A significant result implies that the two samples are different.

Appendix B. Paired *t*-test

Given two sets X_i and Y_i of n measured values, the paired t-test determines whether they differ from each other in a significant way. The assumptions are that the paired differences are independent and normally distributed.

Let

$$t = (\bar{X} - \bar{Y})\sqrt{\frac{n(n-1)}{\sum_{i=1}^{n} (\hat{X}_i - \hat{Y}_i)^2}}$$

with

$$\hat{X}_i = X_i - \bar{X}$$

and

$$\hat{Y}_i = Y_i - \bar{Y},$$

where $\bar{X}$ and $\bar{Y}$ are the means of X_i and Y_i, respectively.

It is possible to demonstrate that this statistic has a Student's t-distribution with n-1 degrees of freedom. A table of cumulative probabilities of Student's t-distributions or a comparable computer function is used to assess the significance level at which two distributions differ.

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