Automatic scaling of critical frequency *foF2* and *MUF*(*3000*)*F2*: A comparison between Autoscala and ARTIST 4.5 on Rome data

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[1] The performances of Autoscala and ARTIST 4.5 were comparatively evaluated using a large database of 6098 ionograms recorded from September 2005 to June 2006 by the digisonde DPS4 at the Rome ionospheric station. Results of comparisons between automatically and manually scaled data are shown for both programs highlighting the different behaviors. The Autoscala and ARTIST 4.5 values of *foF2* and *MUF*(*3000*)*F2* both agree with the hand-scaled values for ∼95% of ionograms. For the other ∼5% of ionograms, which the manual scaler classed as unscalable, ARTIST 4.5 usually gave invalid results, whereas Autoscala usually gave no result. The data recorded by the ionosondes DPS4 (interpreted by ARTIST 4.5) and AIS-INGV (interpreted by Autoscala) during three geomagnetic storms were also analyzed. Ionograms with typical errors both for Autoscala and ARTIST 4.5 are displayed.

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1. Introduction

[2] The importance of real time ionospheric data to be used for space weather purposes has greatly increased over the past years. For this reason since the 1980s much work has been performed to develop computer programs able to automatically scale the ionograms giving as output the standard ionospheric characteristics [*Reinisch and Huang*, 1983; *Fox and Blundell*, 1989; *Igi et al.*, 1993; *Tsai and Berkey*, 2000]. Though much progress has been made, still today considerable effort is invested in continuously upgrading these programs in order to steadily improve the reliability of the automatically scaled data.

[3] The ARTIST system developed at the University of Lowell, Center for Atmospheric Research, is an automatic scaling program widely used and tested [*Reinisch and Huang*, 1983; *Gilbert and Smith*, 1988; *Jacobs et al.*, 2004; *McNamara*, 2006]. Recently the Istituto Nazionale di Geofisica e Vulcanologia (INGV) designed and developed an Advanced Ionospheric Sounder (AIS) along with a program, called Autoscala, to automatically scale ionospheric characteristics *foF2* and *MUF*(*3000*)*F2* from an ionogram [*Scotto and Pezzopane*, 2002; *Pezzopane and Scotto*, 2004]. The time required for ionogram scaling is approximately 50 s on a PC equipped with a 1.60 GHz processor and 512 Mb of RAM. ARTIST and Autoscala are based on completely different approaches. For the identification of the F2 trace, ARTIST is based on a hyperbolic trace fitting method and uses information on wave polarization, while Autoscala is based on an image recognition technique, described in Appendix A, and can operate without polarization information.

[4] A detailed comparison between automatically and manually scaled *foF2* and *MUF*(*3000*)*F2*, both for Autoscala program and for ARTIST system 4.01, was carried out: the data analysis showed that for this data set, Autoscala operated better than ARTIST 4.01, especially for ionograms characterized by a truncated ordinary ray [*Pezzopane and Scotto*, 2005].

[5] Recent improvements were introduced to the ARTIST algorithm significantly increasing the reliability of the autoscaled data, mostly in regards to ionograms with truncated traces [*Reinisch et al.*, 2005]. In September 2005 the Digital Portable Sounder 4 (DPS4) (produced by the University of Lowell, Massachusetts, United States) installed at the Rome ionospheric station (41.8 N, 12.5 E) was updated with this new version of ARTIST (release 4.5). Therefore a new test was neces-

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Table 1. The *foF2* Values Manually Scaled Compared to the Automatically Scaled Values Obtained by Autoscala and by ARTIST 4.5[a]

	Subset C			Subset D			Subset F			Subset T			Subset I	
	Acc	Not Acc	NS	Acc	Not Acc	NS	Acc	Not Acc	NS	Acc	Not Acc	NS	NS	S
Autoscala	4968	6	100	353	1	81	163	3	3	2	2	23	390	3
ARTIST	4919	86	69	409	16	10	165	2	2	9	17	1	149	244

[a]The comparison is separately performed for subsets C (definite values), D (doubtful values), F (spread F), T (truncated traces), and I (impossible scaling). The number of acceptable values (Acc), not acceptable values (Not Acc), not scaled ionograms (NS), and scaled ionograms (S) is shown. An acceptable value is considered to lie within ±0.5 MHz of the manual value.

sary to compare the performances of Autoscala and ARTIST 4.5.

2. Performance Comparison Between Autoscala and ARTIST 4.5

[6] The performances of Autoscala and ARTIST 4.5 are compared using 6098 hourly ionograms recorded at Rome observatory by the DPS4 from September 2005 to June 2006. These ionograms, that are now routinely automatically scaled by ARTIST 4.5, were also automatically scaled by Autoscala. The comparison is performed separately for *foF2* and *MUF*(*3000*)*F2* using as a reference the data obtained manually by a well experienced operator according to the International Union of Radio Science (URSI) standard. This method was already used to test the performances of Autoscala and ARTIST 4.01 [*Pezzopane and Scotto*, 2005]. 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 ±5Δ (Δ is the reading accuracy).

2.1. Test for the *foF2* Characteristic

[7] With reference to the processing data set of 6098 ionograms, the following subsets were considered:

[8] 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 qualifying letters.

[9] 2. Subset D (doubtful values). Composed of ionograms for which the operator scaled *foF2* as a doubtful value. This subset includes the following cases: (a) the trace near the critical frequency is not clearly recorded owing to interference, or absorption; (b) the ordinary trace is obscured by absorption, interference or blanketing while the extraordinary component is clearly visible; in these cases the URSI standard recommends deriving the critical frequency *foF2* of the ordinary trace from the extraordinary one.

[10] 3. Subset F (spread F). Composed of ionograms for which a spread F condition was observed.

[11] 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 a reliable value of *foF2* by extrapolation. This subset includes the ionograms for which the extrapolated frequency range is greater than 10% of *foF2*. For these ionograms the URSI standard suggests reporting the last recorded frequency followed by the qualifying letter D and the appropriate descriptive letter (S for interference or R for absorption).

[12] 5. Subset I (impossible). Composed of ionograms for which the operator was not able to observe the F2 trace for different reasons.

[13] The results of the comparison are reported for each subset in Table 1. It appears that Autoscala performs better than ARTIST 4.5 for subsets C, T, and I. On the contrary for subset D ARTIST 4.5 succeeds in scaling a number of ionograms greater than Autoscala and this represents an improvement with respect to ARTIST 4.01, for which the number of ionograms correctly scaled was lower than the corresponding number given by Autoscala [*Pezzopane and Scotto*, 2005]. On the other hand 16 unacceptable results were given as output by ARTIST 4.5 and only 1 by Autoscala.

[14] In Table 2, contingency tables are reported for each subset expressing the results in terms of correct or incorrect behavior of the two programs. For subsets C, D, and F, correct behavior of the programs is assumed for ionograms scaled with acceptable values given as output. For subset T the correct behavior of the programs is to discard the ionogram or to scale the ionogram giving an automatically scaled value exceeding the last recorded frequency by a percentage between 5% and 20%. For subset I the correct behavior of the programs is to discard the ionograms, giving no data as output.

[15] As already done to test Autoscala versus ARTIST 4.01, the McNemar test [*Huck*, 2004] was used to evaluate Autoscala versus ARTIST 4.5. In order to assess whether the two methods differ in a significant way the confidence level was set at 0.95. The results obtained are reported in Table 2 and confirm statistically that for subsets C, T and I Autoscala performs better than ARTIST

Table 2. Contingency Tables for *foF2*[a]

		Autoscala: Incorrect	Autoscala: Correct	Total
		$\chi^2 = 10521 \cdot 10^{-3}$, $p > 0.99$		
Subset C	ARTIST: Correct	85	4834	4919
	ARTIST: Incorrect	21	134	155
		106	4968	5074
		$\chi^2 = 32181 \cdot 10^{-3}$, $p > 0.99$		
Subset D	ARTIST: Correct	75	334	409
	ARTIST: Incorrect	7	19	26
		82	353	435
		$\chi^2 = 100 \cdot 10^{-3}$, $p < 0.25$		
Subset F	ARTIST: Correct	6	159	165
	ARTIST: Incorrect	0	4	4
		6	163	169
		$\chi^2 = 13067 \cdot 10^{-3}$, $p > 0.99$		
Subset T	ARTIST: Correct	0	10	10
	ARTIST: Incorrect	2	15	17
		2	25	27
		$\chi^2 = 239004 \cdot 10^{-3}$, $p > 0.99$		
Subset I	ARTIST: Correct	0	149	149
	ARTIST: Incorrect	3	241	244
		3	390	393

[a]The number of correct and incorrect scaling is separately reported for subsets C (definite values), D (doubtful values), F (spread F), T (truncated traces), and I (impossible scaling). Results obtained applying the McNemar χ^2 Test are reported. The confidence level is set at 0.95.

4.5. For subset F the behavior of the two programs does not differ, while for subset D ARTIST 4.5 performs better than Autoscala.

2.2. Test for the *MUF*(*3000*)*F2* Characteristic

[16] With reference to the processing data set of 6098 ionograms, the following three subsets were considered:

[17] 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.

[18] 2. Subset F (spread F). Composed of ionograms for which a spread F condition was observed.

[19] 3. Subset I (impossible). Composed of ionograms for which the operator was able to clearly observe neither the ordinary nor the extraordinary trace for different reasons.

[20] The results of the comparison are reported for each subset in Table 3. Autoscala performs better than ARTIST 4.5 for subset I while for subsets F and C significant differences are not evident.

[21] In Table 4, contingency tables are shown for each subset expressing the results obtained in terms of correct or incorrect behavior of the two programs. For subsets C and F the correct behavior is assumed for ionograms scaled with acceptable values given as output. In contrast for subset I the correct behavior of the programs is to discard the ionograms, giving no data as output.

[22] The McNemar test was used to evaluate Autoscala versus ARTIST 4.5 performances in order to assess whether the two methods differ in a significant way to a confidence level of 0.95. These results are reported in

Table 3. The *MUF*(*3000*)*F2* Values Manually Scaled Compared to the Automatically Scaled Values Obtained by Autoscala and by ARTIST 4.5[a]

	Subset C			Subset F			Subset I	
	Acc	Not Acc	NS	Acc	Not Acc	NS	NS	S
Autoscala	5311	18	182	163	3	3	412	6
ARTIST	5326	107	78	165	2	2	151	267

[a]The comparison is separately performed for subsets C (definite values), F (spread F), and I (impossible scaling). The number of acceptable values (Acc), not acceptable values (Not Acc), not scaled ionograms (NS), and scaled ionograms (S), is shown. An acceptable value is considered to lie within ±2.5 MHz of the manual value.

Table 4. Contingency Tables for *MUF*(*3000*)*F2*[a]

		Autoscala: Incorrect	Autoscala: Correct	Total
		$\chi^2 = 578 \cdot 10^{-3}$, $p < 0.25$		
Subset C	ARTIST: Correct	177	5149	5326
	ARTIST: Incorrect	23	162	185
		200	5311	5511
		$\chi^2 = 125 \cdot 10^{-3}$, $p < 0.25$		
Subset F	ARTIST: Correct	5	160	165
	ARTIST: Incorrect	1	3	4
		6	163	169
		$\chi^2 = 255094 \cdot 10^{-3}$, $p > 0.99$		
Subset I	ARTIST: Correct	2	149	151
	ARTIST: Incorrect	4	263	267
		6	412	418

[a]The number of correct and incorrect scaling is separately reported for subsets C (definite values), F (spread F), and I (impossible scaling). Results obtained applying the McNemar χ^2 Test are reported. The confidence level is set at 0.95.

Table 4 and confirm in a statistical way that for subsets C and F there is no significant difference between the two programs, while for subset I Autoscala performs better than ARTIST 4.5.

3. Critical Ionogram Cases

[23] In paragraph 2, statistical analysis gave us an overall view of the performances of Autoscala and ARTIST 4.5 on different ionogram subsets defined according to the URSI standard. This section goes into more detail, devoting attention to some critical ionogram cases and discussing the differences between the approaches adopted by the two programs.

3.1. Ionograms With Gaps Belonging to Subset C

[24] In many ionograms the F2 ordinary trace presented some gaps but the critical frequency could be easily scaled by an operator. For these cases ARTIST 4.01 often gave as *foF2* the frequency of the last recorded ionospheric echo of the ordinary trace before a gap, significantly underestimating the real value of *foF2*. ARTIST 4.5 showed a remarkable improvement in the automatic scaling of such traces increasing considerably the performance of the system. This is due to a refining of the ARTIST algorithm [*Reinisch et al.*, 2005] that in this case it proved to be successful. Figure 1 shows a case of an ionogram with a gap correctly scaled by ARTIST 4.5.

3.2. Ionograms Having Weak or Absent F1 Trace and Weak F2 Trace

[25] In many ionograms (belonging to subsets C or D) the F2 trace was not clearly recorded. Again for these cases ARTIST 4.5 showed a remarkable improvement with respect to the previous version. Figure 2 is one of these cases in which ARTIST 4.5 demonstrated an excellent capability in recognizing the F2 trace, even if it is very weak and truncated, giving as output a correct extrapolated value for *foF2*; on the contrary Autoscala considered the trace too weak to be elaborated and no data was given as output. At the moment, for these cases Autoscala is somewhat limited because the weakness of the F2 trace often prevents the correlation C from being larger than the threshold C_t (see Appendix A). This is due to the fact that Autoscala was initially designed for scaling strong traces noise-embedded [*Scotto and Pezzopane*, 2002]. On the contrary, for these cases the ARTIST 4.5 algorithm proved to be better than Autoscala. In order to improve the autoscaling of Autoscala for low noise ionograms with weak F2 trace, the threshold C_t value could be decreased but this issue needs to be further studied and tested.

3.3. Ionograms Having Clear F1 Trace and Weak or Absent F2 Trace

[26] In many ionograms the F1 trace was clearly recorded while the F2 trace was very weak (ionograms belonging to subsets C or D) or absent (ionograms belonging to subset I). In these cases Autoscala discarded the ionograms while ARTIST 4.5 often wrongly scaled the critical frequency *foF2* from the F1 trace as shown in Figure 3. Autoscala succeeds in discarding most of these ionograms because it uses the *DuCharme et al.* [1973] model for calculating the monthly median value of *foF1* as a function of the solar index R_{12}, the geomagnetic latitude, and the solar zenith angle. Once the monthly median value of *foF1* is calculated, the technique described in Appendix A is not applied to

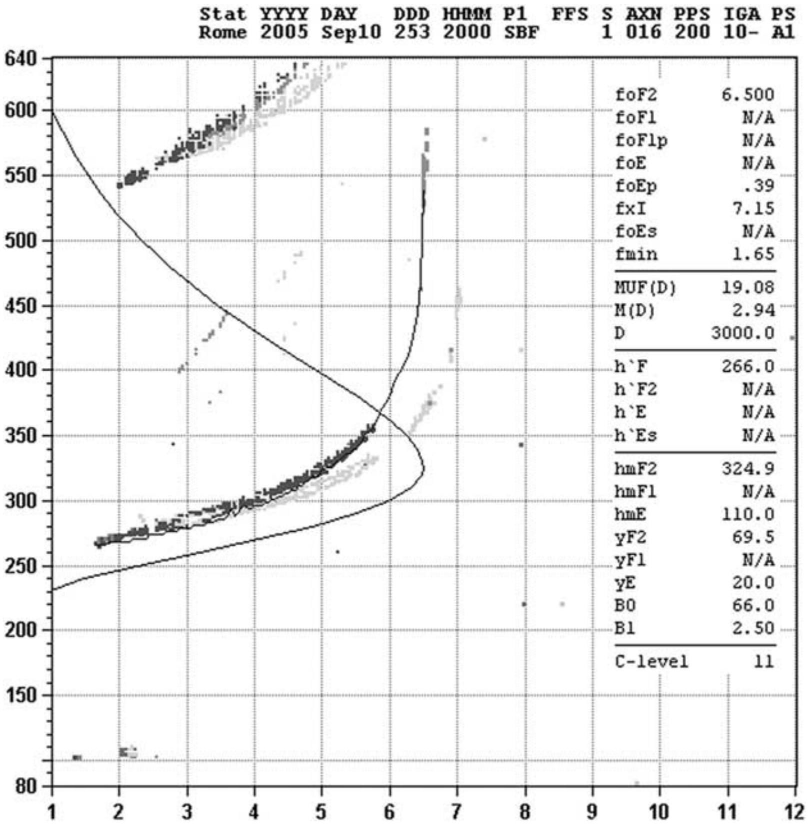

Figure 1. Ionogram recorded on 10 September 2005 at 20:00 UT by the DPS4 with a gap on the ordinary trace between 5.7 MHz and 6.5 MHz for which ARTIST 4.5 successfully scaled *foF2*.

curves having an asymptote a_{ord} smaller or too close to this value, therefore avoiding errors like that one shown in Figure 3.

3.4. Ionograms Belonging to Subset T

[27] In some ionograms the F2 trace was strongly truncated preventing the operator from extrapolating a reliable value of *foF2*, as already mentioned in section 2.1. With respect to the previous version, ARTIST 4.5 did not exhibit significant improvements, while Autoscala confirmed its reliability in discarding such ionograms, as shown in Figure 4. The ARTIST 4.5 algorithm is quite able to identify a F2 trace with gaps, on condition that the cusp region of the trace is well defined, as in Figure 1. When the F2 cusp region is totally absent as in Figure 4, ARTIST 4.5 often incorrectly forces the corresponding trace representation. This is why the hyperbolic trace fitting does not have sufficient subsets of anchor points in the cusp region of the F region baseline defined by *Reinisch and Huang* [1983], and the algorithm is consequently deceived. On the contrary, the technique illustrated in Appendix A lets Autoscala estimate whether the number of identified points is sufficient to reconstruct a reliable complete F2 trace or not. For ionograms as the one shown in Figure 4 this technique often establishes that the identification of the F2 trace is not possible, because the threshold C_t is never exceeded, and consequently no output is produced since it is considered unreliable.

3.5. Es Layer Blanketing Echoes From F2 Layer

[28] Tables 1 and 3 show that a large number of ionograms belongs to subset I, and also that there are significant differences between the two programs concerning the scaled and not scaled ionograms. This is due to the frequent occurrence of sporadic E (Es) layer blanketing the reflection from the F2 layer. The different behavior of Autoscala and ARTIST 4.5 with regard to these cases is highlighted in Figure 5 presenting the 15-min *foF2* plots for 28 September 2005, 19 May 2006, and 17 June 2006. Observing these plots it would seem that ARTIST 4.5 recorded some positive ionospheric

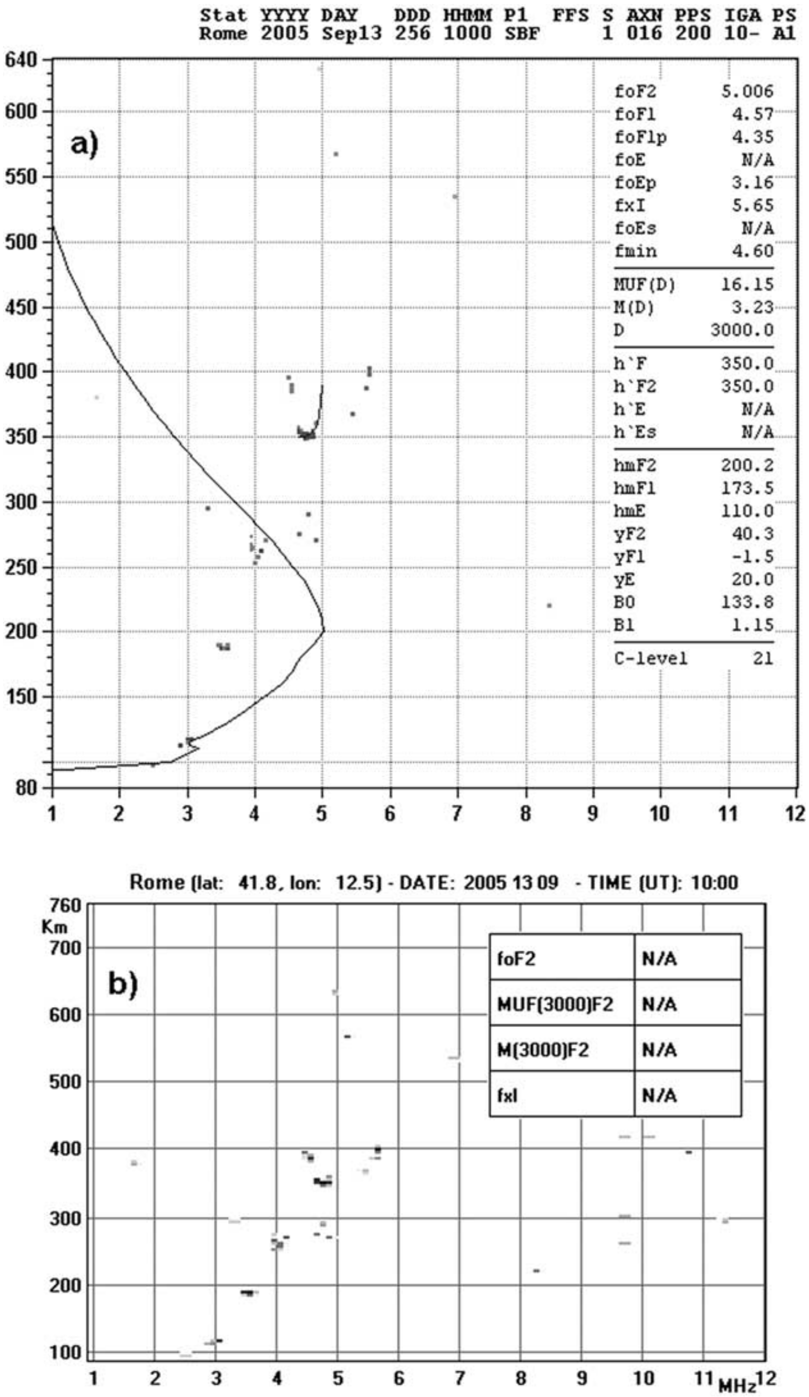

Figure 2. Ionogram recorded on 13 September 2005 at 10:00 UT by the DPS4 and autoscaled by (a) ARTIST 4.5 and (b) Autoscala. Autoscala considered the trace too weak and discarded the ionogram giving no data as output. On the contrary, ARTIST 4.5 showed an excellent capability in recognizing the trace although it is truncated and very weak.

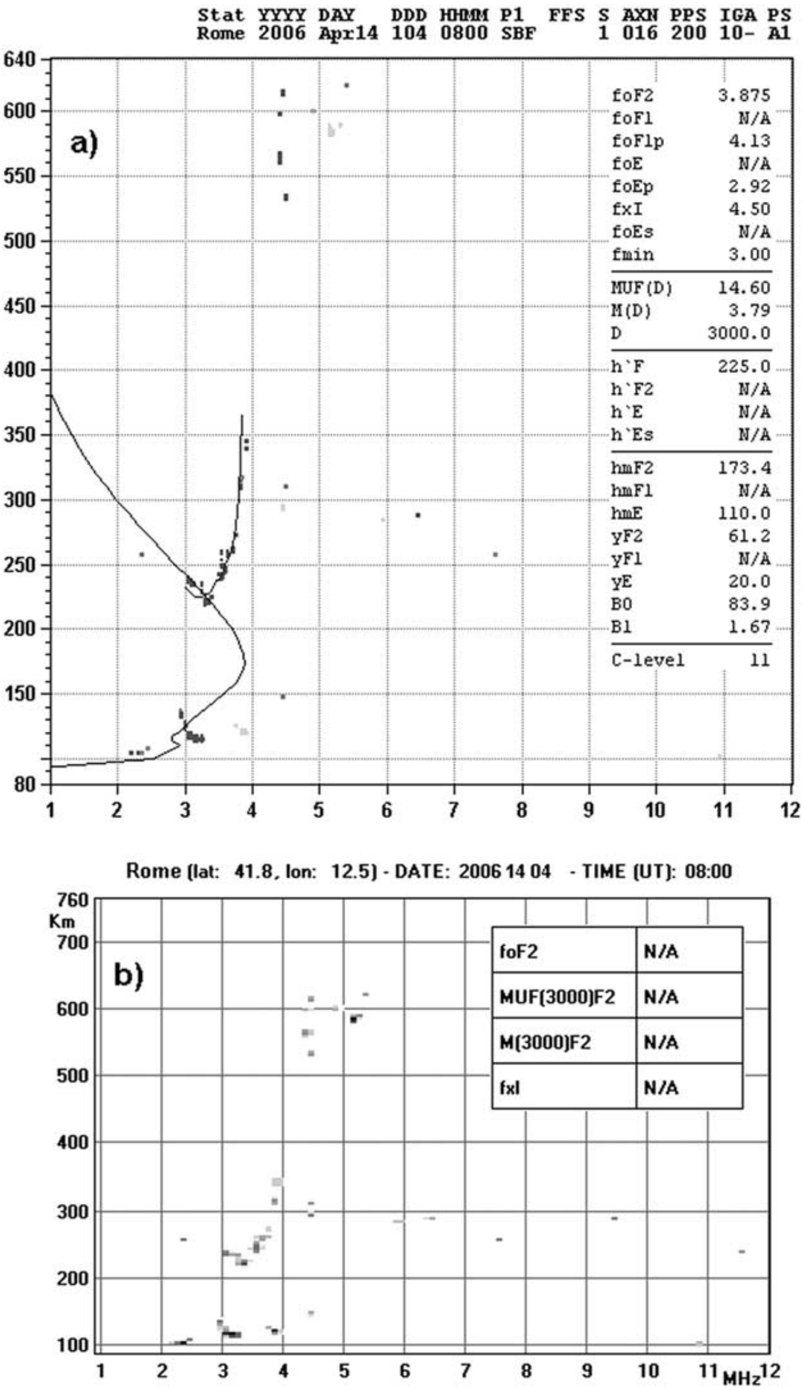

Figure 3. Ionogram recorded on 14 April 2006 at 8:00 UT by the DPS4. The F2 trace is very weak, while the F1 trace is very clear. In this case, (a) ARTIST 4.5 wrongly scaled the critical frequency *foF2* in correspondence of the F1 trace, while (b) Autoscala correctly discarded the ionogram.

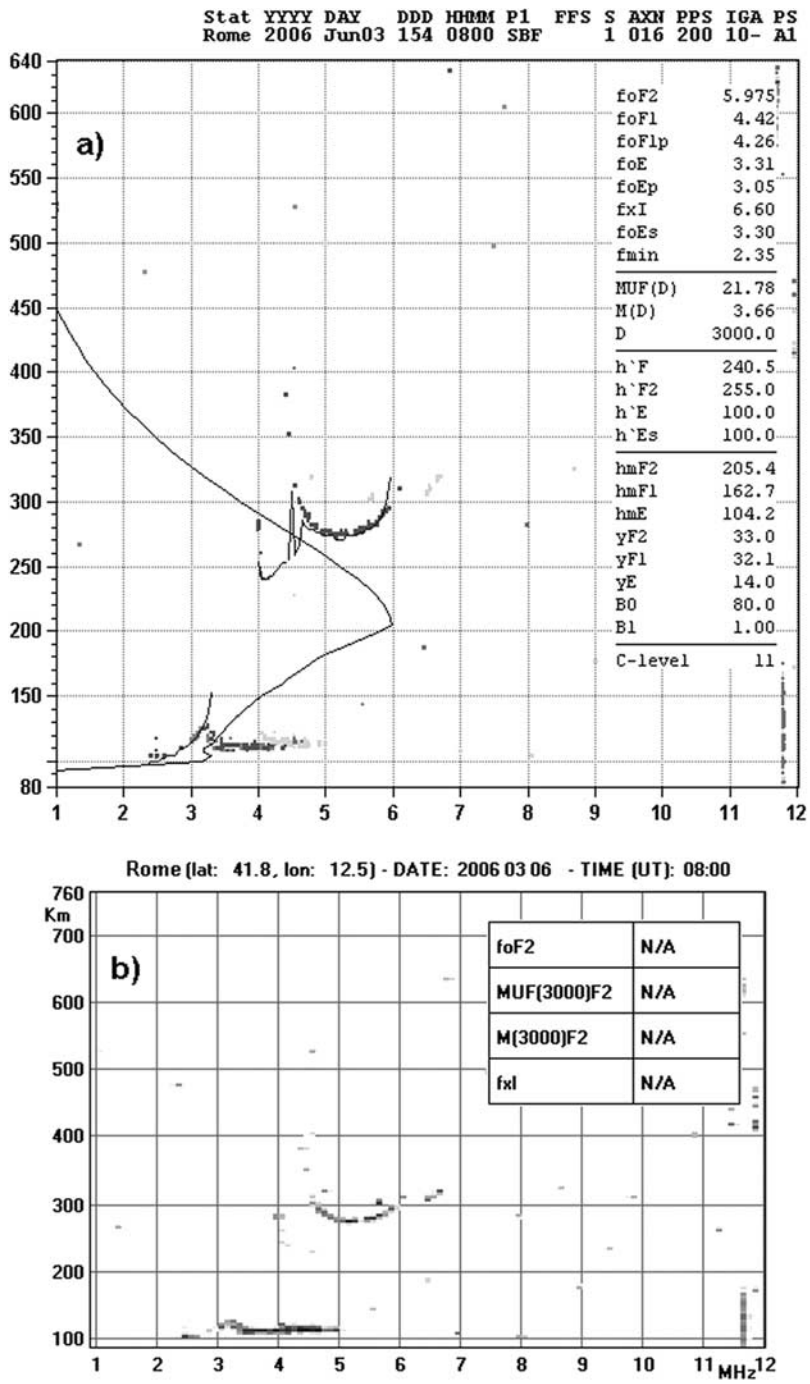

Figure 4. Ionogram recorded on 3 June 2006 at 8:00 UT by the DPS4. This ionogram has a truncated F2 trace preventing an operator from extrapolating a value for *foF2*. (a) ARTIST 4.5 wrongly scaled *foF2* as the last frequency recorded. (b) Autoscala correctly discarded the ionogram.

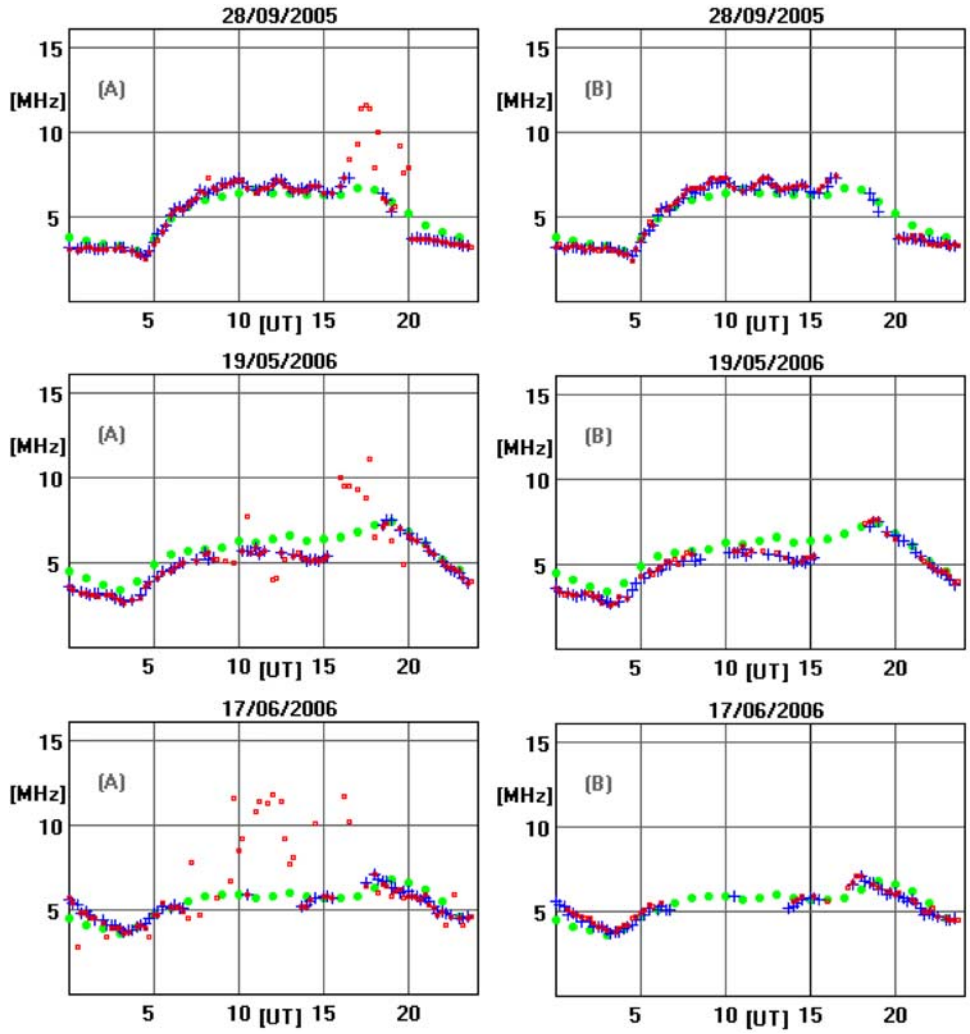

Figure 5. The *foF2* 15-min plots as obtained by (a) ARTIST 4.5 and by (b) Autoscala for 28 September 2005, 19 May 2006, and 17 June 2006. Values manually scaled, values obtained automatically, and predicted hourly median values, here assumed as quiet values, are indicated by blue crosses, red squares and green circles, respectively. While Autoscala displays data gaps, ARTIST 4.5 recognizes the second reflection of the Es layer as part of the F2 trace, displaying wrong data indicating positive ionospheric disturbances that are not actually occurring.

disturbances while Autoscala for the same periods displayed gaps. Actually these differences are due to the fact that ARTIST 4.5 often recognized the second-order echoes reflected from the Es layer as echoes reflected from the F2 layer while Autoscala correctly discarded these ionograms by detecting the total absence of the F2 layer. An example of an ionogram depicting this issue is displayed in Figure 6. ARTIST 4.5 often treats the second reflection of the Es layer as the F2 region baseline trace and incorrectly forces the F2 trace representation even if this is not visible at all. This is why the automatic trace identification made by ARTIST often seems not to be able to make out that the echo amplitudes belonging to the second reflection of the Es layer do not belong to the center of the F trace, defined by *Reinisch and Huang* [1983] as the frequency/range domain where the change of virtual height with frequency is small and the echo amplitudes are strong. On the contrary, in these cases Autoscala is always able to understand that the F2 trace is not present, because the

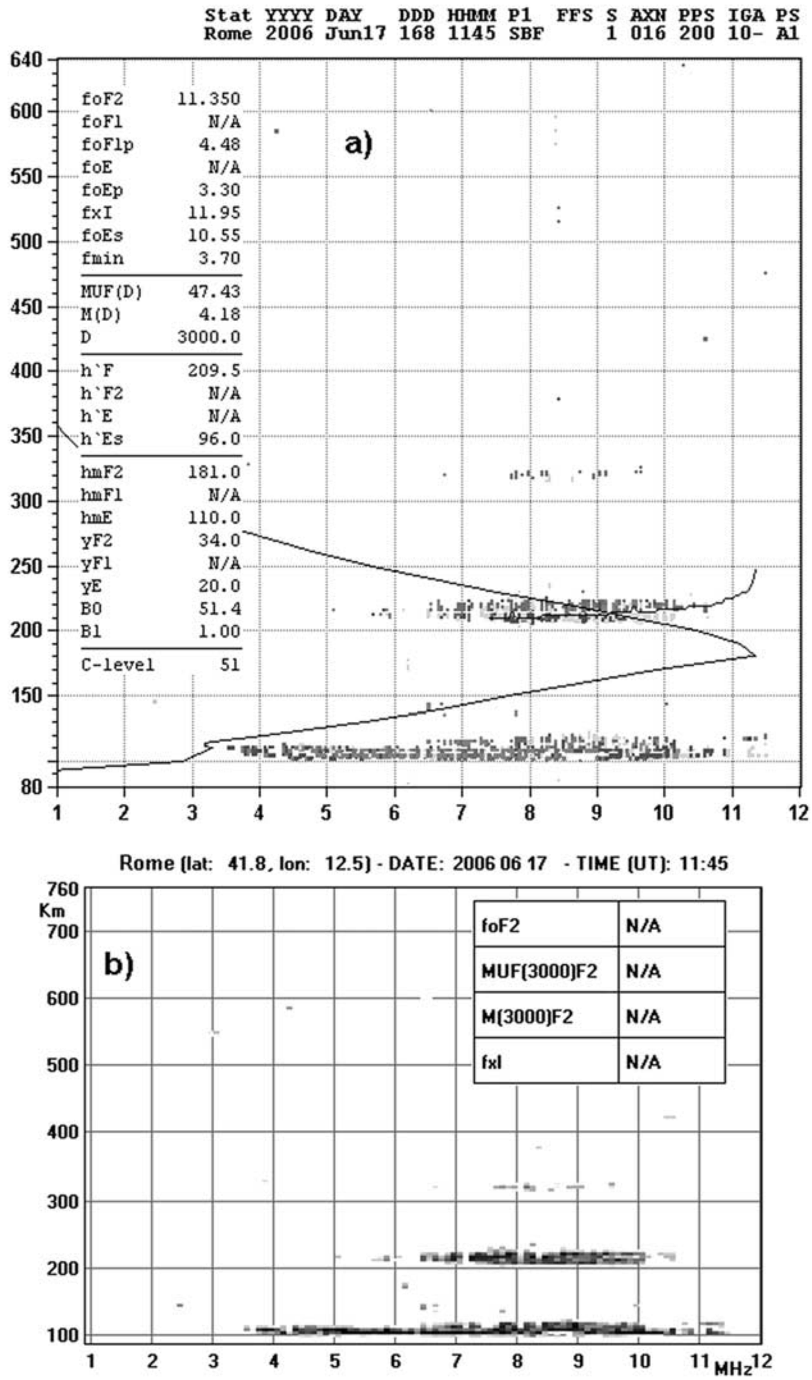

Figure 6. Ionogram recorded on 17 June 2006 at 11:45 UT by the DPS4. (a) ARTIST 4.5 recognized the second-order echoes reflected from the Es layer as echoes reflected from the F2 layer, giving as output an erroneous value for *foF2*, while (b) Autoscala correctly considered the F2 layer trace absent giving no data as output.

shape of the empirical curves T_1 and T_2 is such that the threshold C_t is never exceeded when the correlation is calculated between the ionogram matrix and different sets of T_1 and T_2 (see Appendix A).

3.6. Misleading Polarization Tagging

[29] The digisonde DPS4 is able to separate the recorded information of the ordinary and extraordinary waves in terms of polarization. Using a cross antenna system like DPS4 does, it is possible to tag the polarization of the ordinary and extraordinary wave coding the echo amplitude recorded by the digisonde. This polarization tagging is evident in the DPS4 ionogram pictures where the ordinary ray is depicted in red while the extraordinary ray is depicted in green. The polarization tagging of an ionogram certainly represents a significant aid for the autoscaling methods, like ARTIST, relying on such information. Nevertheless, in certain cases errors in the polarization tagging can occur and such autoscaling systems are deceived with a consequent incorrect identification of the ordinary trace. On the contrary, Autoscala not relying on this tagging, is not affected by this kind of errors. Figure 7 is an example of an ionogram (belonging to subset C) characterized by a misleading polarization tagging, being the ordinary and the extraordinary rays depicted with the same red colour. ARTIST 4.5 is deceived and identifies the extraordinary ray as the ordinary one. This because the ARTIST system recognizes red points as belonging to the ordinary ray and consequently the F region ordinary baseline is constructed sliding a searching window from the center of the F trace towards higher frequencies until it finds red points. On the contrary, the only criterion on which Autoscala is based to differentiate the ordinary from the extraordinary ray is that $a_{ord} < a_{ext}$, as explained in Appendix A. Hence Autoscala is never deceived by such a misleading polarization tagging, as shown in Figure 7.

4. Performances of Autoscala and ARTIST 4.5 for Disturbed Ionospheric Conditions: Three Case Studies

[30] Within the period of time considered for the analysis discussed in the previous paragraphs, three significant geomagnetic storms occurred: (1) from 11 to 13 September 2005 (Kp = 8−); (2) from 18 to 20 March 2006 (Kp = 6+); (3) from 13 to 16 April 2006 (Kp = 7).

[31] Figures 8, 9, and 10 show the corresponding 15-min *foF2* plots during which positive and negative ionospheric phases took place. In these figures the automatically scaled values obtained by DPS4-ARTIST 4.5 and AIS-INGV-Autoscala systems are compared to the corresponding values obtained by an operator. In the same plots also the hourly median values, calculated using the Simplified Ionospheric Regional Model [*Zolesi et al.*, 1996], and here assumed as quite-day values, are drawn. The behavior of the two programs is generally very similar but for some days there are significant differences. Focusing on particular time intervals of 11 September 2005 (between 5 UT and 15 UT), 19 March 2006 (between 8 UT and 11 UT), and 14 (between 6 UT and 10 UT), 16 (between 6 UT and 13 UT), April 2006 highlights how Autoscala correctly discarded most of the ionograms while ARTIST 4.5 gave wrong data as output misrepresenting the actual ionospheric conditions.

[32] These errors fall within the ones already discussed in paragraph 3.3 and illustrated in Figure 3. They are due to the fact that absorption made the F2 trace very weak and ARTIST 4.5 wrongly scaled the critical frequency *foF2* from the F1 trace.

5. Conclusions

[33] The results obtained in the study carried out can be summarized as follows:

[34] 1. For subset D contrary to what happened for the previous ARTIST version [*Pezzopane and Scotto*, 2005], ARTIST 4.5 performs better than Autoscala.

[35] 2. For subset C Autoscala demonstrates better capability than ARTIST 4.5 to output reliable values for *foF2* and *MUF*(*3000*)*F2*.

[36] 3. The ionograms with a very weak trace are usually discarded by Autoscala. In these cases ARTIST 4.5 sometimes demonstrates an excellent capability to produce good output values for *foF2*, but often wrongly scales the critical frequency *foF2* from the F1 trace. This error causes a misrepresentation of the actual ionospheric conditions mostly during geomagnetic storms when an F2 layer absorption is likely to occur.

[37] 4. For ionograms with Es layer multiple reflections, Autoscala detects the total absence of the F2 layer trace and produces no output data, while ARTIST 4.5 often identifies the second reflection of the Es layer as the baseline of the F region. This error alters the *foF2* plot displaying data indicating positive ionospheric disturbances that are not actually occurring.

[38] Point 3 underlines the different approach used by the two methods. Regardless of the clearness of the trace, ARTIST 4.5 often scales the ionospheric characteristics. In this way it effectively limits interruptions in the data sequence, but incorrect data may be produced. On the contrary Autoscala is designed to limit incorrect data. Thus in many cases, when the trace is not well defined, it discards the ionogram producing an interruption in the data sequence.

[39] To date, the ionograms recorded at the Gibilmanna and Rome ionospheric stations by the ionosonde AIS-INGV and autoscaled by Autoscala are available real

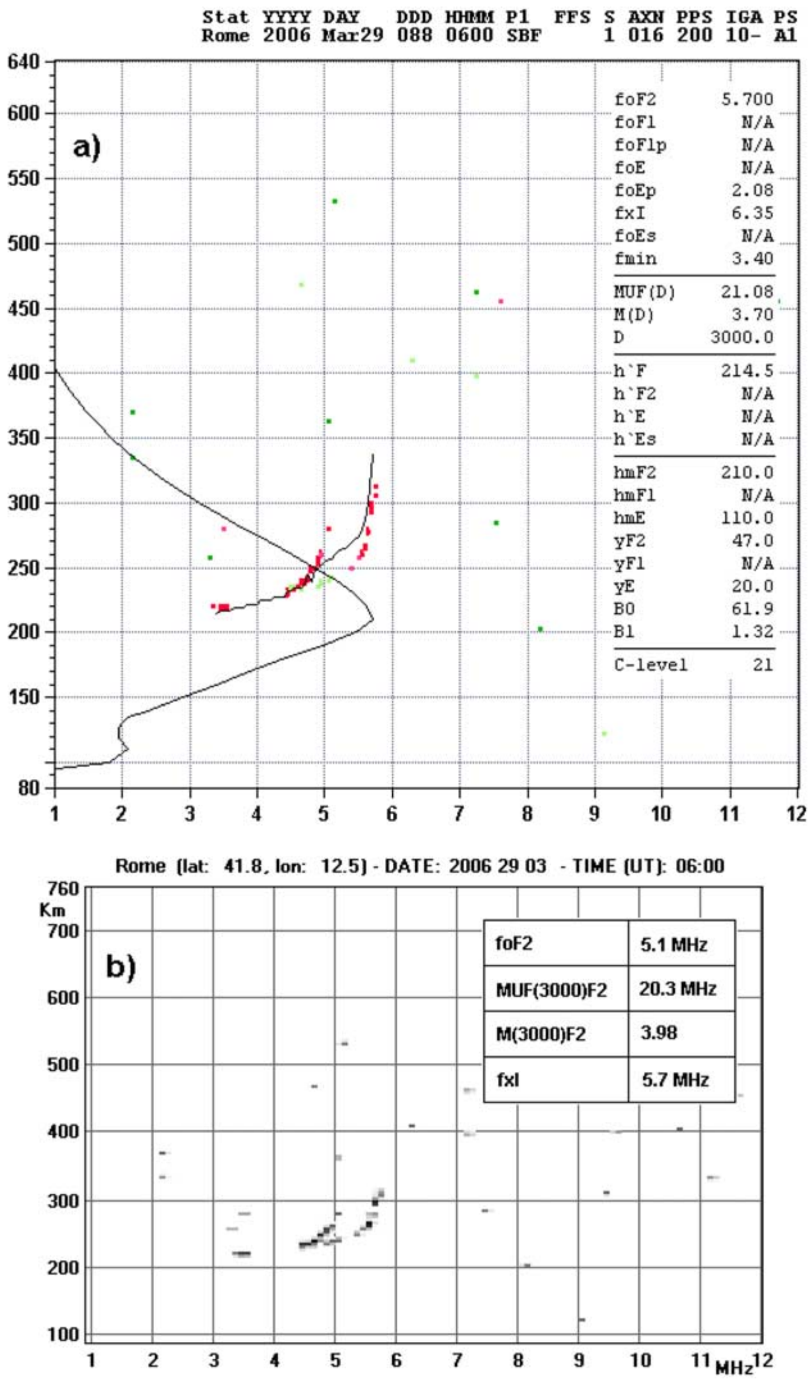

Figure 7. Ionogram recorded on 29 March 2006 at 06:00 UT by the DPS4 characterized by a misleading polarization tagging as it is evident from the same red colour of both traces. (a) ARTIST 4.5 recognized the extraordinary ray of the ionogram as the ordinary one, giving as output an erroneous value for *foF2*, while (b) Autoscala correctly identified the ordinary ray, giving as output a correct value for *foF2*.

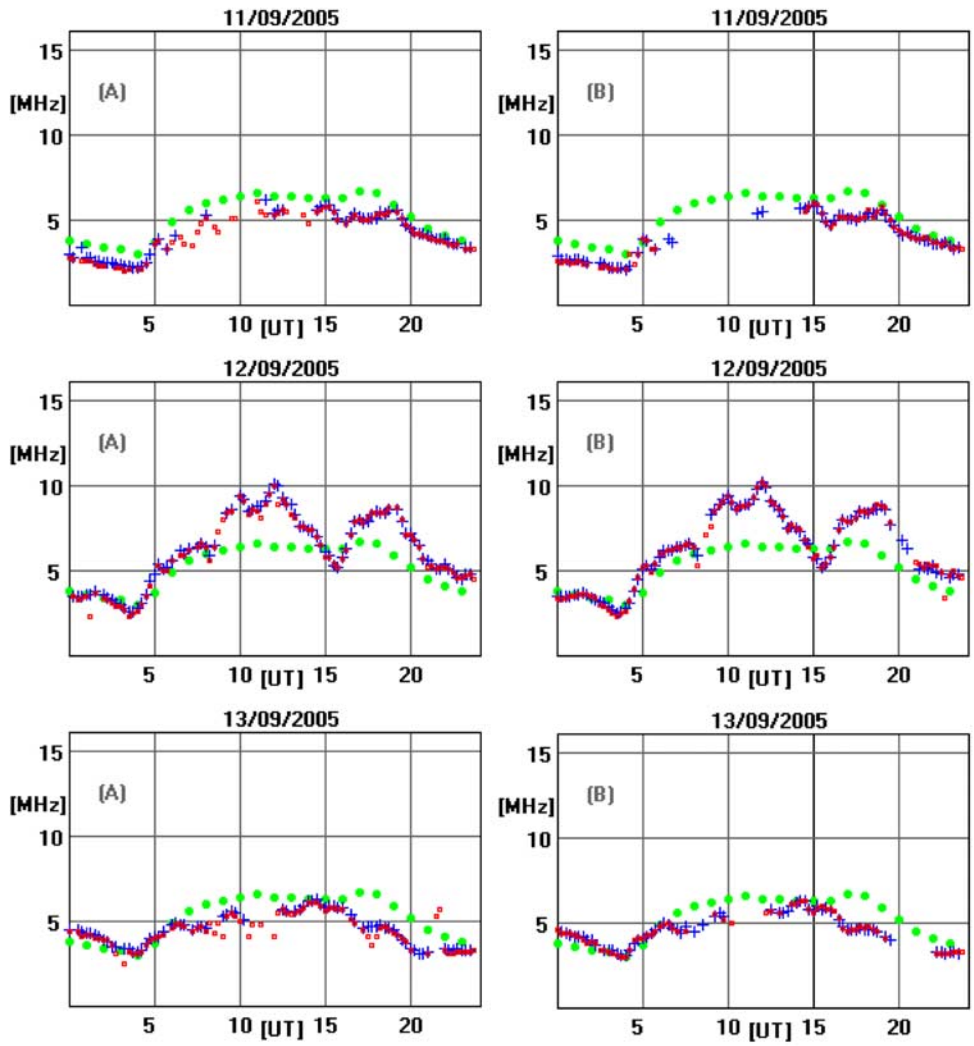

Figure 8. The 15-min *foF2* plots from 11 to 13 September 2005 as obtained by the ionograms recorded by the (a) DPS4-ARTIST 4.5 and (b) AIS-INGV-Autoscala systems installed at Rome observatory. Values manually scaled, values obtained automatically, and predicted hourly median values, here assumed as quiet values, are indicated by blue crosses, red squares and green circles, respectively. In correspondence to the deterioration of the F2 trace associated with the negative ionospheric phase that occurred on 11 September from 7 to 15 UT Autoscala correctly discarded most of the ionograms while ARTIST 4.5 often wrongly scaled *foF2* from the F1 trace. Therefore, while the *foF2* plot given by Autoscala displays a data gap, the corresponding plot given by ARTIST 4.5 misrepresents the actual ionospheric conditions.

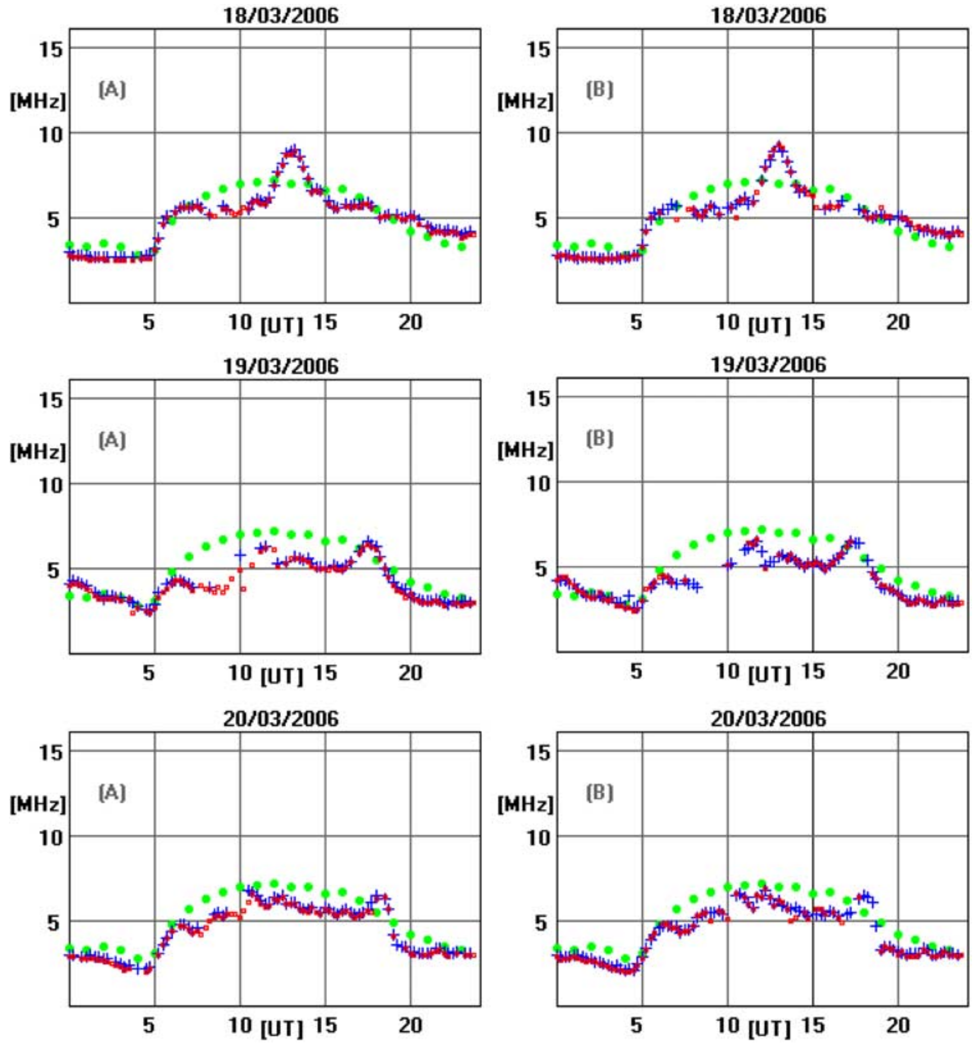

Figure 9. The 15-min *foF2* plots from 18 to 20 March 2006 as obtained by the ionograms recorded by the (a) DPS4-ARTIST 4.5 and (b) AIS-INGV-Autoscala systems installed at Rome observatory. Values manually scaled, values obtained automatically, and predicted hourly median values, here assumed as quiet values, are indicated by blue crosses, red squares and green circles, respectively. In correspondence to the deterioration of the F2 trace associated with the negative ionospheric phase that occurred on 19 March from 8 to 11 UT, Autoscala correctly discarded most of the ionograms while ARTIST 4.5 often wrongly scaled *foF2* from the F1 trace. Therefore, while the *foF2* plot given by Autoscala displays a data gap, the corresponding plot given by ARTIST 4.5 misrepresents the actual ionospheric conditions.

Figure 10. The 15-min *foF2* plots from 13 to 16 April 2006 as obtained by the ionograms recorded by the (a) DPS4-ARTIST 4.5 and (b) AIS-INGV-Autoscala systems installed at Rome observatory. Values manually scaled, values obtained automatically, and predicted hourly median values, here assumed as quiet values, are indicated by blue crosses, red squares and green circles, respectively. In correspondence to the negative ionospheric phases that occurred on 14 April from 6 to 10 UT and on 16 April from 6 to 12 UT, Autoscala correctly discarded most of the ionograms while ARTIST 4.5 often wrongly scaled *foF2* from the F1 trace. Therefore, while the *foF2* plot given by Autoscala displays a data gap, the corresponding plot given by ARTIST 4.5 misrepresents the actual ionospheric conditions.

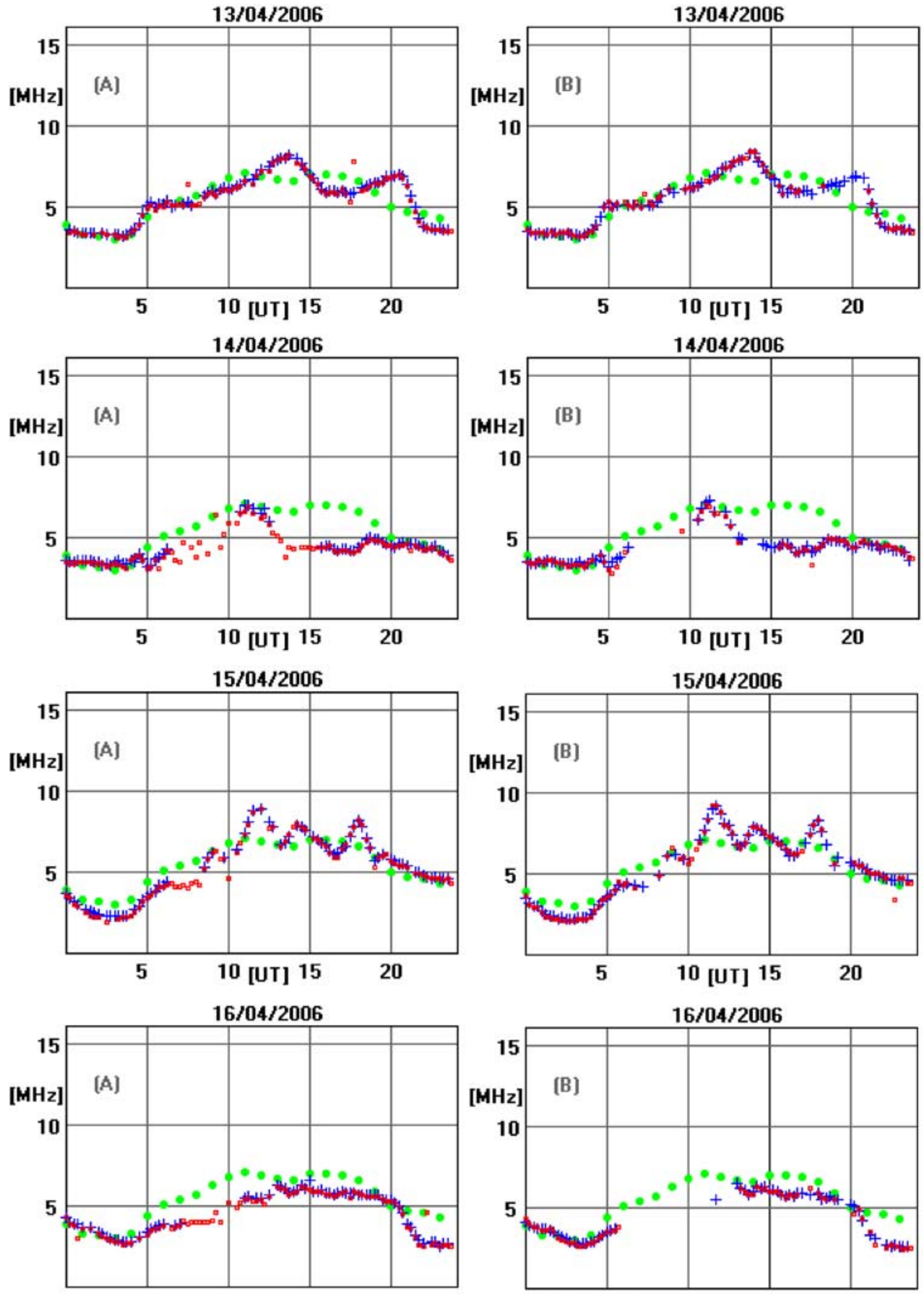
13/04/2006
(A)
(B)
14/04/2006
15/04/2006
16/04/2006
15
[MHz]
10
5
5
10 [UT] 15
20

Figure 10

time at the site http://ionos.ingv.it/spaceweather/start.htm.

Appendix A

[40] In this appendix we describe the basic idea on which Autoscala was designed. Initially the ionogram is memorized by Autoscala as a matrix A of m rows and n columns whose numbers are defined by the following formulas:

$$m = \mathrm{int}\left[\left(h'_f - h'_0\right)/\Delta h'\right] + 1 \tag{A1a}$$

and

$$n = \mathrm{int}\left[\left(f_f - f_0\right)/\Delta f\right] + 1, \tag{A1b}$$

where f_f, f_0, Δf, h'_f, h'_0 and $\Delta h'$ are respectively the final frequency, the initial frequency, the frequency step, the final virtual height, the initial virtual height, and the virtual height resolution of the sounding. h'_0 and $\Delta h'$ are fixed values depending on the construction of the ionosonde. For the AIS-INGV h'_0 is 90 km and $\Delta h'$ is 4.5 km. The element a_{ij} (with $i = 1,\ldots, m$ and $j = 1,\ldots, n$) of the matrix A is an integer varying from 0 to 254, the larger is the value, the stronger is the echo amplitude received by the ionosonde. This value is retrieved directly from the binary file recorded by the ionosonde or indirectly from the colour pixel depth in the ionogram picture, and then normalized to 254. Once the ionogram is memorized as a matrix of elements a_{ij}, two empirical curves T_1 and T_2 that are able to fit the typical shape of the F2 trace are defined. The curves are defined by the following parametric form

$$T_1 = \begin{cases} f_1 = a_{ord} - k \\ h'_1 = \mathrm{int}\left\{H_{ord} + A_{ord}\tan\left[\frac{\pi}{2}\cdot\frac{\Delta x - k}{\Delta x}\right]\right\} \\ 0 \le k \le \Delta x \end{cases} \tag{A2a}$$

for the curve used for the investigation of the ordinary ray and

$$T_2 = \begin{cases} f_2 = a_{ext} - k \\ h'_2 = \mathrm{int}\left\{H_{ext} + A_{ext}\tan\left[\frac{\pi}{2}\cdot\frac{\Delta x - k}{\Delta x}\right]\right\} \\ 0 \le k \le \Delta x \end{cases} \tag{A2b}$$

for the curve used for the investigation of the extraordinary ray. In (A2a) and (A2b) the frequencies and the virtual heights of T_1 and T_2 are expressed as integers and correspond to the indices i and j of the matrix A. The parameters defining the two curves are:

$$H_{ord}, H_{ext}, a_{ord}, a_{ext}, A_{ord}, A_{ext} \text{ and } \Delta x. \tag{A3}$$

[41] H_{ord} and H_{ext} are integers varying from 1 to (m-30) and correspond to the values of the horizontal asymptote for T_1 and T_2. a_{ord} and a_{ext} are integers varying from 1 to n, with the condition $a_{ord} < a_{ext}$, and correspond to the values of the vertical asymptote for T_1 and T_2. A_{ord} and A_{ext} are two decimals coefficients. Δx is an integer varying from 6 to 30 representing the frequency interval, expressed in pixels, where T_1 and T_2 develop. Once Δx is set, the curves start from frequencies ($a_{ord} - \Delta x$) and ($a_{ext} - \Delta x$) and extend up to a_{ord} and a_{ext}. k is an integer varying from 0 to Δx. For small values of a_{ord} and a_{ext} it can happen that f_1 and f_2 are negative, but these values are intercepted and neglected by the algorithm as they correspond to negative values of the frequency.

[42] For each set of curves T_1 and T_2 the local correlation $C(H_{ord}, H_{ext}, a_{ord}, a_{ext}, A_{ord}, A_{ext}, \Delta x)$ with the recorded ionogram is calculated making allowance for both the number of matched points and their amplitude (from 0 to 254). The set of curves T_1 and T_2 having the maximum value of C is then selected. If this value of C is greater than a fixed threshold C_t the selected curves are considered as representative of the F2 trace. *foF2* is thus obtained as the frequency of the vertical asymptote a_{ord} of T_1 while *MUF*(*3000*)*F2* is numerically calculated by finding the transmission curve tangent to T_1. On the contrary if C does not exceed C_t the routine assumes the F2 trace is not present on the ionogram.

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