A method for automatic scaling of F1 critical frequencies from ionograms

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Received 4 July 2007; revised 3 October 2007; accepted 11 October 2007; published 22 March 2008.

[1] This work describes a method that has been developed to automatically assess whether the F1 layer is present or not on an ionogram trace, and, if present, to scale the F1 critical frequency *foF1*. The ionograms in which the information related to the F1 trace is insufficient are identified and considered separately. In order to test the performance of this method and the conditions in relation to which it could be improved, a data set of ionograms recorded from September 2005 to June 2006 by the AIS-INGV ionosonde installed at Rome was used. The values obtained automatically by Autoscala, with the addition of this new F1 layer routine, were compared with those obtained by the standard manual method.

Citation: Pezzopane, M., and C. Scotto (2008), A method for automatic scaling of F1 critical frequencies from ionograms, *Radio Sci.*, 43 , RS2S91, doi:10.1029/2007RS003723.

1. Introduction

[2] The F1 layer is the lower part of the daytime F layer. It extends from about 140 to 240 km above the Earth, and it exists only during daylight hours, disappearing at night; it is more pronounced during the summer than during the winter, and at low sunspot numbers. The maximum electron density of the F1 layer occurs approximately at local noon when the solar zenith angle is minimum. Daytime summer ionograms generally show a well developed F1 cusp which allows an accurate manual scaling of the critical frequency *foF1* of the F1 layer.

[3] From the point of view of the electron density profile a description for the F1 layer was developed and introduced in the IRI model [*Reinisch and Huang*, 1999]. In this description the electron density depends on a single parameter D_1. The diurnal variation of D_1 showed a systematic behavior from zero (which describes the profile when the F1 layer is not present) at sunrise through a maximum at noon and then to zero again at sunset. A proposed task for the ionosonde community is to establish the necessary database to determine the diurnal behavior of D_1 as a function of latitude, season and solar activity. Although this approach can give a description of the long term behavior of D_1, it cannot provide good enough results for real time applications. This is mainly due to the difficulties arising from modelling the cut-off zenith angle that sets D_1 to zero.

[4] For the application of an electron density model to the real time data obtained from an ionosonde, it is important to have a reliable automatic scaling procedure for the F1 trace. By studying the ability of ARTIST [*Reinisch and Huang*, 1983] to characterise the F1 region, *Jacobs et al.* [2004] showed this is by no means a simple task. The automatic trace identification made by ARTIST, which uses information on wave polarization, starts by finding the center of the F trace, defined as the frequency/range domain where the change of h' with frequency is small and the echo amplitudes are strong. Then a first rough trace is constructed by sliding a searching window from the trace center toward higher and lower frequencies. This process is also able to successfully trace the F_1/F_2 transitions. An appropriate smoothing is then applied maintaining the cusp at the F_1/F_2 transition. Once this cusp has been identified, ARTIST gives as output for *foF1* either a value or N/A (Not Available). N/A is however given as output both when the F1 layer is not present on the ionogram and when the ionogram information is not sufficient to establish whether an F1 layer is present or not.

[5] In reality, a procedure must at least be able to reliably identify whether the F1 layer is observable in the ionograms, providing the appropriate critical frequency *foF1* as output. Furthermore, cases in which F1 is not actually present should be separated from cases for which the ionogram information is not sufficient to establish whether an F1 layer is present or not.

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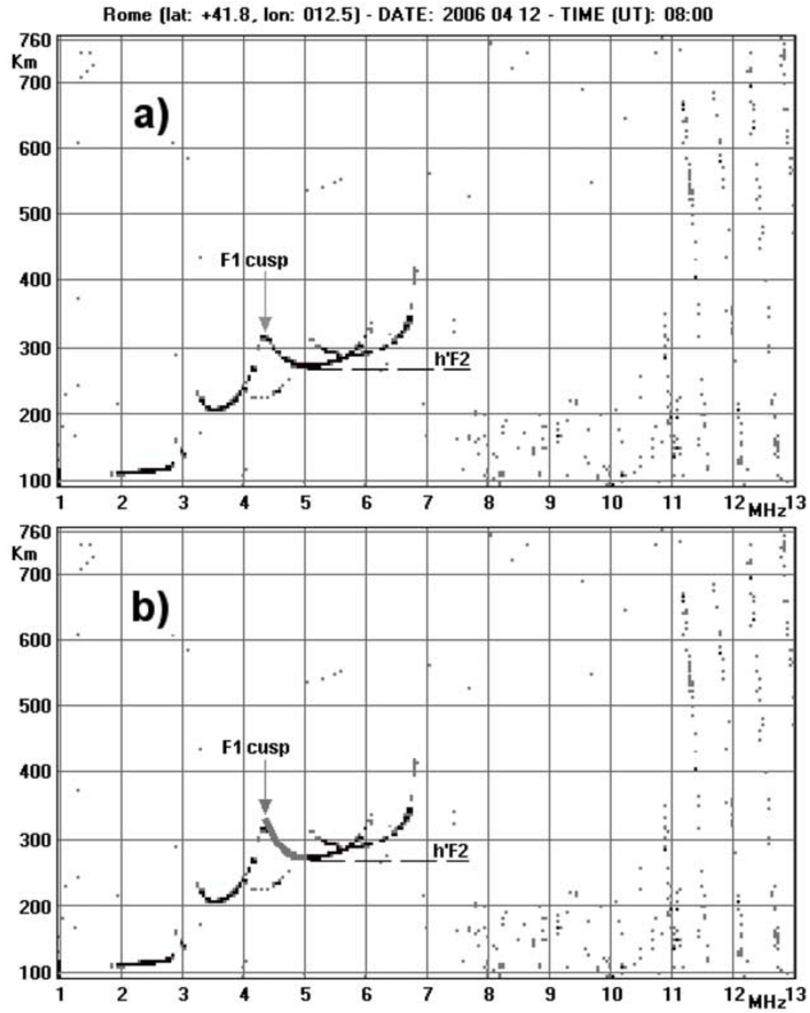

Figure 1. (a) Ionogram recorded on 12 April 2006 at 08:00 UT by the AIS-INGV installed at Rome. The F1 cusp and the lowest virtual height of the F2 layer ordinary trace are highlighted. (b) The ionogram trace, that the F1 layer autoscaling procedure described in this paper tries to identify, is shown in grey.

[6] This work describes an automatic scaling procedure to automatically scale the F1 layer, designed to satisfy the above requirements. This method, which can be applied to any kind of digital ionogram, tries to identify the trace from the F1 cusp to the lowest virtual height of the F2 layer ordinary trace (see Figure 1), which has previously been identified by the F2 layer autoscaling routine [*Pezzopane and Scotto*, 2007]. To test the performance of this procedure a data set of ionograms recorded from September 2005 to June 2006 by the AIS-INGV ionosonde (built by the Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy [*Zuccheretti et al.*, 2003]) installed at Rome was used. The values obtained automatically by Autoscala [*Scotto and Pezzopane*, 2002, 2007; *Pezzopane and Scotto*, 2004, 2005], with the addition to the code of the F1 routine, were compared with those obtained manually by an experienced operator.

2. Automatic Scaling Method for the F1 Layer

[7] The behavior of the F1 layer is quite regular. *DuCharme et al.* [1973] (here abbreviated DC) found a very comprehensive expression which is able to predict *foF1* assuming limits for the presence of the layer as a

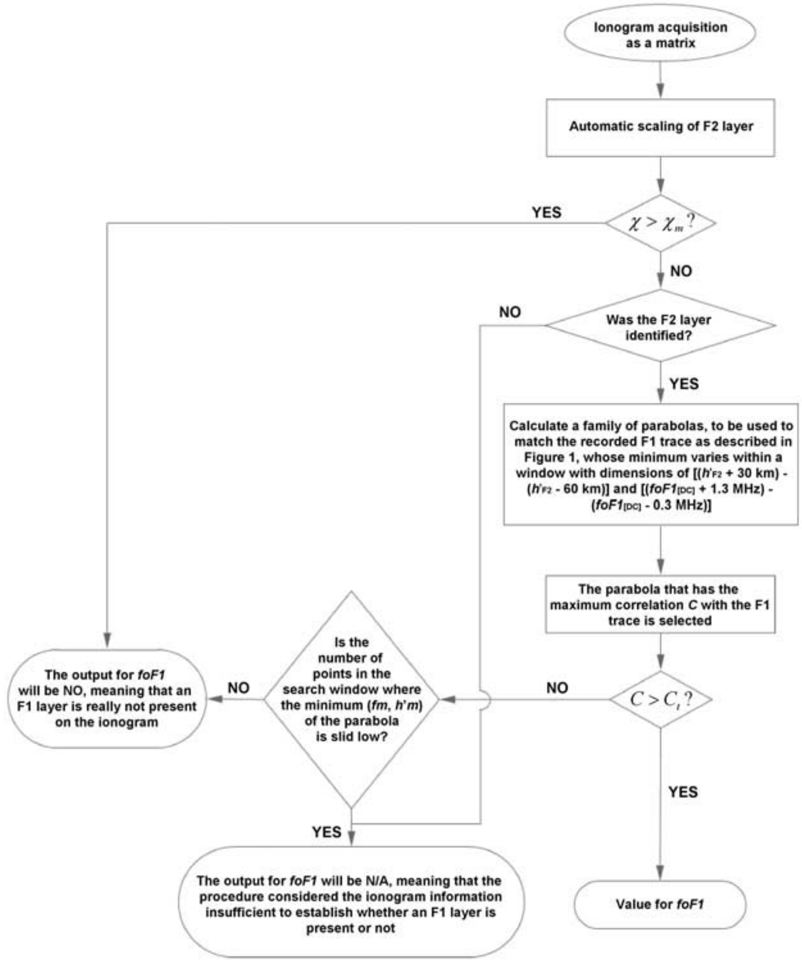

Figure 2. Flowchart of the algorithm described in this paper to automatically scale the F1 layer.

function of the solar zenith angle and of solar activity provided by the R12 index. However, in many cases, the F1 layer is observable well outside such limits. Also in these cases the DC formula is able to predict *foF1* with good accuracy [*Scotto et al.*, 1997]. For this reason the main requirement for an automatic scaling method for the F1 layer is to correctly distinguish the cases in which the F1 layer exists from the cases in which the F1 layer is absent. The secondary requirement is to correctly scale *foF1*. The algorithm developed to automatically identify the F1 layer is very similar to the one currently used for the scaling of *foF2* and *MUF(3000)F2*. It is based on an image recognition technique, does not use information on polarization, and can therefore be applied to both single antenna systems and crossed antenna systems [*Pezzopane and Scotto*, 2007]. Figure 2 illustrates the flowchart of the algorithm described in this paper.

[8] 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:

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

and

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

where f_f, h'_f, f_0, h'_0, and Δf are respectively the final frequency, the final virtual height, the initial frequency, the initial virtual height, and the frequency step of the sounding; $\Delta h'$ is the height resolution of the ionosonde.

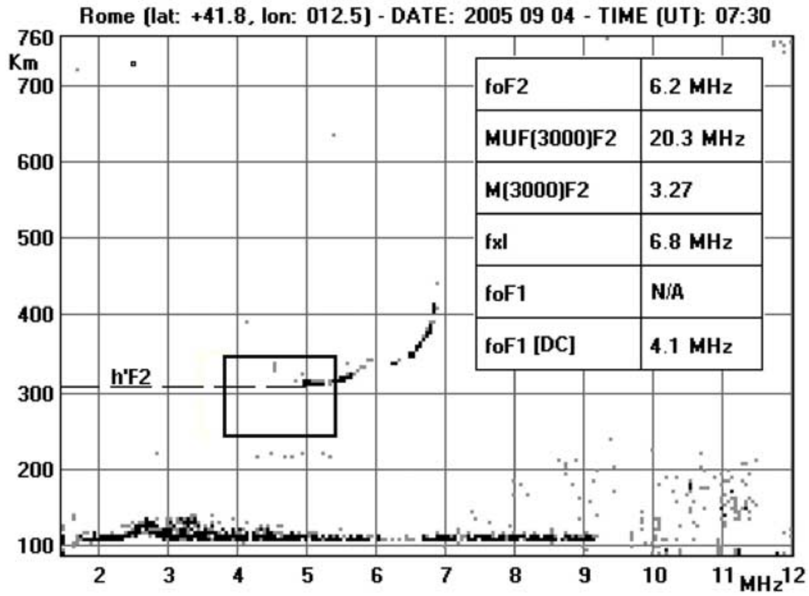

Figure 3. Ionogram recorded on 4 September 2005 at 07:30 UT by the AIS-INGV installed at Rome. Autoscala succeeded in scaling the F2 layer and the DC model forecasts *foF1* as 4.1 MHz. The F1 autoscaling routine gives as output N/A for *foF1* because the window (represented by the rectangle in the figure) where the minimum (f_m, h'_m) of the parabola is slid, contains too few points to establish whether the F1 trace is present or not. The dashed line depicts the virtual height h'_{F2} of the lowest frequency ordinary point identified by the F2 routine with respect to which the upper and lower border of the rectangle are defined.

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 higher the value, the stronger the echo amplitude received by the ionosonde. This value is retrieved directly from the binary file recorded by the AIS-INGV ionosonde, and then normalized to 254.

[9] Unlike the F2 layer autoscaling procedure, which is based on the identification of both ordinary and extraordinary rays, this procedure tries to identify only the F1 ordinary ray. Tests using different polynomial curves showed that a parabola is sufficient to effectively perform the fitting described in Figure 1. The parametric form of this parabola is

$$\begin{cases} f = \mathrm{int}[(f_v - f_0)/\Delta f] \\ h' = \mathrm{int}\left[\left(\left(af_v^2 + bf_v + c\right) - h'_0\right)/\Delta h'\right], \end{cases} \tag{2}$$

where f_v is the parameter.

[10] The coefficients a, b, and c of (2) are calculated imposing a parabola minimum at (f_m, h'_m) and passing through the point ($f_m - A_p$, h'_p). According to these three conditions, the coefficients a, b, and c are expressed by the following formulas

$$a = \left(h'_p - h'_m\right)/A_p^2, \tag{3a}$$

$$b = 2f_m\left(h'_m - h'_p\right)/A_p^2, \tag{3b}$$

and

$$c = \left(f_m^2 h'_p + h'_m\left(A_p^2 - f_m^2\right)\right)/A_p^2. \tag{3c}$$

[11] The parabola is calculated in the parametrical interval:

$$f_m - \Delta f_{ord} \le f_v \le f_m. \tag{4}$$

[12] The parameters defining the shape of the parabola are then:

$$f_m, h'_m, A_p, h'_p, \text{ and } \Delta f_{ord}. \tag{5}$$

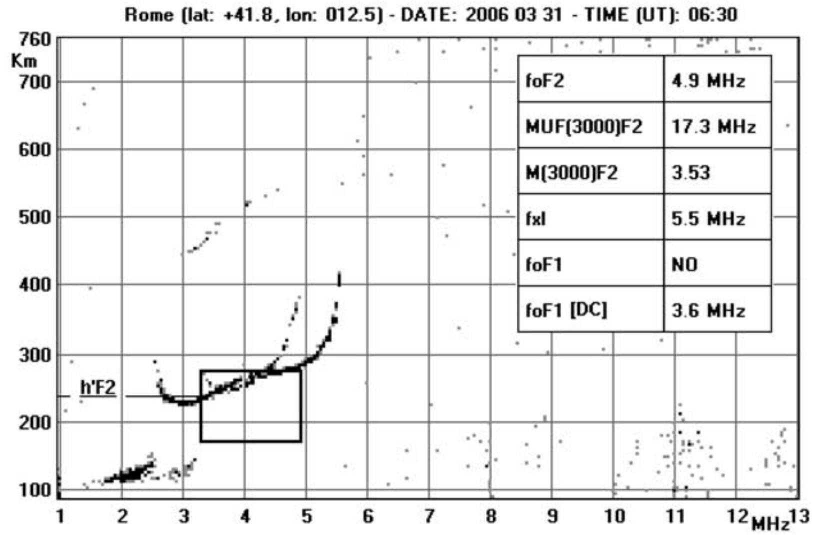

Figure 4. Ionogram recorded on 31 March 2006 at 06:30 UT by the AIS-INGV installed at Rome. Autoscala succeeded in scaling the F2 layer and the DC model forecasts *foF1* as 3.6 MHz. The F1 autoscaling routine gives as output NO for *foF1* because the window (represented by the rectangle in the figure) where the minimum (f_m, h'_m) of the parabola is slid, contains a number of points sufficient to establish that the F1 trace is not present. The dashed line depicts the virtual height h'_{F2} of the lowest frequency ordinary point identified by the F2 routine with respect to which the upper and lower border of the rectangle are defined.

f_m varies from ($foF1_{[DC]}$ − 0.3 MHz) ($foF1_{[DC]}$ is the monthly median value of *foF1* calculated by the DC model) to ($foF1_{[DC]}$ + 1.3 MHz); h'_m varies from (h'_{F2} − 60 km) to (h'_{F2} + 30 km), where h'_{F2} is the virtual height of lowest ordinary ray point identified by the F2 routine, A_p varies from 0.6 to 5.5 MHz, h'_p varies from 70 to 150 km, and Δf_{ord} varies from 0.1 to 2.0 MHz. This means calculating a family of parabolas, to be used to match the recorded F1 trace as described in Figure 1, whose minimum varies within a window with dimensions of [(h'_{F2} + 30 km) − (h'_{F2} − 60 km)] and [($foF1_{[DC]}$ + 1.3 MHz) − ($foF1_{[DC]}$ − 0.3 MHz)].

[13] For each parabola (2) the local correlation $C(f_m, h'_m, A_p, h'_p, \Delta f_{ord})$ with the recorded ionogram is then calculated making allowance for both the number of matched points and their amplitude. The parabola having the maximum value of C is then selected. If this value of C is greater than a fixed threshold C_t, the selected parabola is considered as representative of the F1 ordinary trace. *foF1* is then obtained by ($f_{m[\mathrm{MAX}]}$ − $\Delta f_{ord[\mathrm{MAX}]}$) where MAX indicates the values of f_m and Δf_{ord} maximizing C. On the contrary if C does not exceed C_t the procedure has two possible outputs:

[14] 1. If the number of points in the window where the minimum (f_m, h'_m) of the parabola is slid is low, the output will be N/A, meaning that the procedure considered the ionogram information insufficient to establish whether an F1 layer is present or not (Figure 3);

[15] 2. If the number of points in the window where the minimum (f_m, h'_m) of the parabola is slid is indeed significant, the output will be NO, meaning that an F1 layer is really not present on the ionogram (Figure 4).

[16] The possible outputs of the routine for the automatic scaling of the F1 layer can then be summarised as follows: (1) the F1 cusp is observed and a value is given for *foF1* as output; (2) the F1 cusp is not observed and NO is given for *foF1* as output; (3) the information is not sufficient to establish whether the F1 cusp is present or not and N/A is given for *foF1* as output.

[17] In order to avoid trivial mistakes and to reduce the processing time (~2 s on a computer with 2.5 GHz processor and 1 GB of RAM), the automatic scaling procedure for the F1 layer is not run for solar zenith angles at which it is not reasonable to expect an F1 layer. It is worth noting that the χ_m defined by DC is not considered as the maximum solar zenith angle for which the *foF1* is observed. Fixed solar zenith angles are set to 75° for winter months and to 87° for the rest of the year. Finally, it is important to emphasize that the routine developed is not able to function if the F2 layer is not identified. This is because the minimum virtual height in the F2 layer is used to define the window where the minimum (f_m, h'_m) of the parabola used to fit the F1 trace

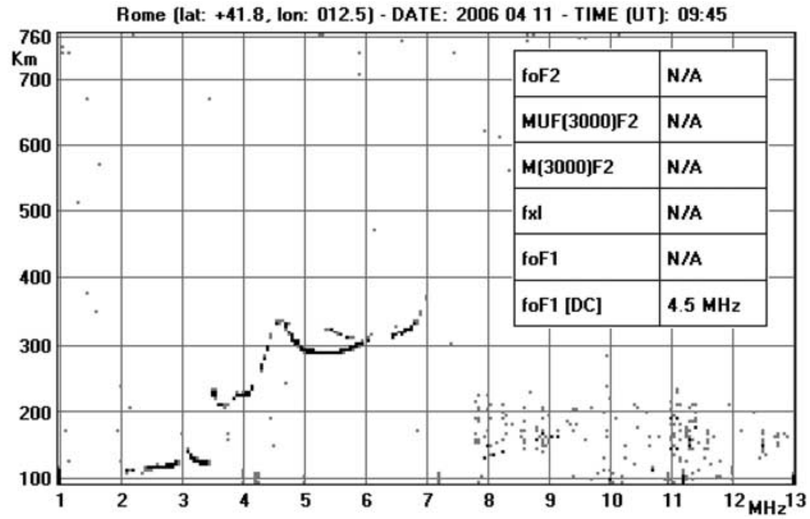

Figure 5. Ionogram recorded on 11 April 2006 at 09:45 UT by the AIS-INGV installed at Rome. Even if the DC model forecasts a monthly median value of *foF1*, the F1 autoscaling was not run because owing to interference no F2 ordinary ray was identified by the F2 autoscaling routine.

is slid. In these cases, if the DC model forecasts a monthly median value for *foF1*, the output for *foF1* is N/A, otherwise the output for *foF1* is NO. Autoscala has difficulty in identifying the F2 layer on ionograms for which the F2 traces near the critical frequency are not clearly recorded or partially obscured owing to absorption, interference or blanketing [*Pezzopane and Scotto*, 2005]. Figure 5 shows an example of an ionogram, with a weak F2 ordinary ray because of interference, for which Autoscala considered the information insufficient for identifying the F2 layer, and consequently the F1 autoscaling procedure was not run, even if the DC model forecasts a monthly median value of *foF1*. Figure 6 shows another example of an ionogram for which the F1 autoscaling procedure was not run, even if the DC model forecasts a monthly median value of *foF1*. In this

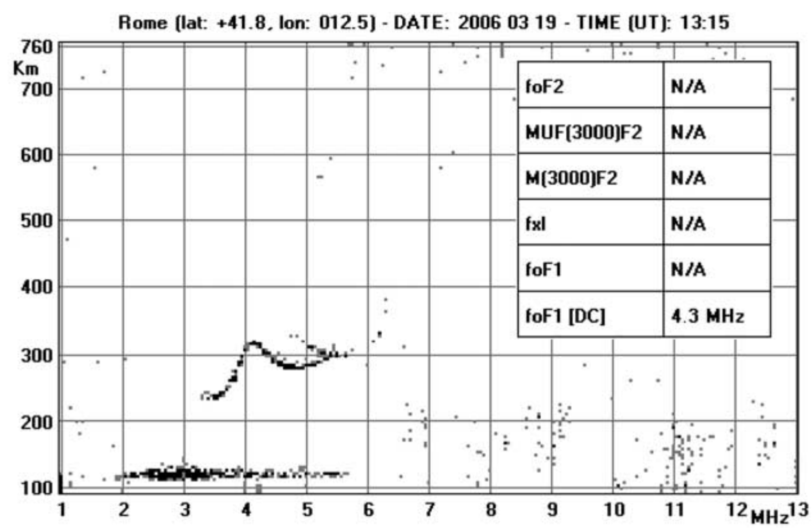

Figure 6. Ionogram recorded on 19 March 2006 at 13:15 UT by the AIS-INGV installed at Rome. Even if the DC model forecasts a monthly median value of *foF1*, the F1 autoscaling was not run because owing to Es blanketing no F2 ordinary ray was identified by the F2 autoscaling routine.

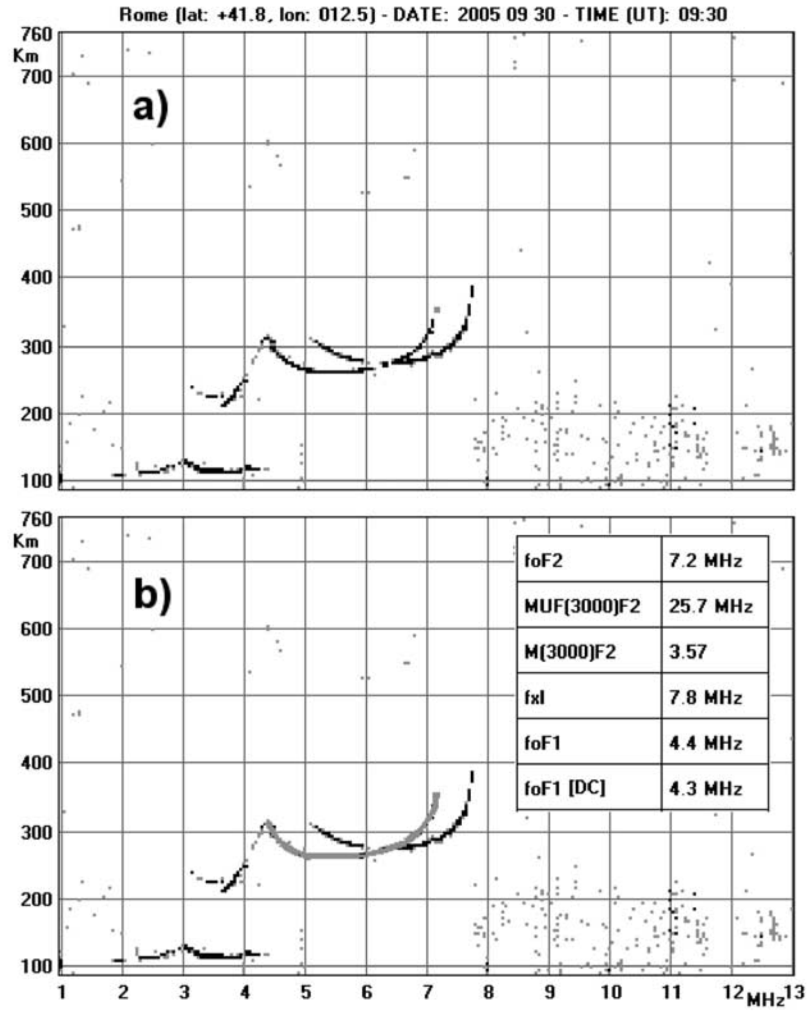

Figure 7. (a) Ionogram recorded on 30 September 2005 at 09:30 UT by the AIS-INGV installed at Rome and belonging to subset 1. (b) The F1 cusp is successfully scaled by Autoscala (in grey the ordinary trace identified by the software).

case the F2 layer was considered by Autoscala too weak to be identified because of sporadic E (Es) blanketing.

3. Comparison With the Manual Method

[18] The test was performed using a data set of ionograms recorded from September 2005 to June 2006 by the AIS-INGV ionosonde installed at Rome. This data set is only composed of ionograms for which Autoscala succeeded in autoscaling the F2 layer. The values obtained automatically by Autoscala were compared with those obtained manually by a well experienced operator according to the International Union of Radio Science (URSI) standard.

[19] With reference to the processing data set the following six subsets were considered: (1) subset 1, composed of ionograms for which the F1 cusp is very clear and the operator was able to scale *foF1* as a definite value, using neither descriptive nor qualifying letters (Figure 7); (2) subset 2, composed of ionograms for which the F1 cusp is not clearly recorded owing to interference, absorption, or blanketing, and the operator was able to scale *foF1* as a doubtful value (Figure 8); according to the URSI standard, in these cases the qualifying letter U is used followed by a descriptive letter (A blanketing, S interference, R absorption, Y Lacuna effect); (3) subset 3, composed of ionograms for which the F1 cusp is not visible at all owing to interference, absorption, or blanketing (Figure 3); (4) subset 4,

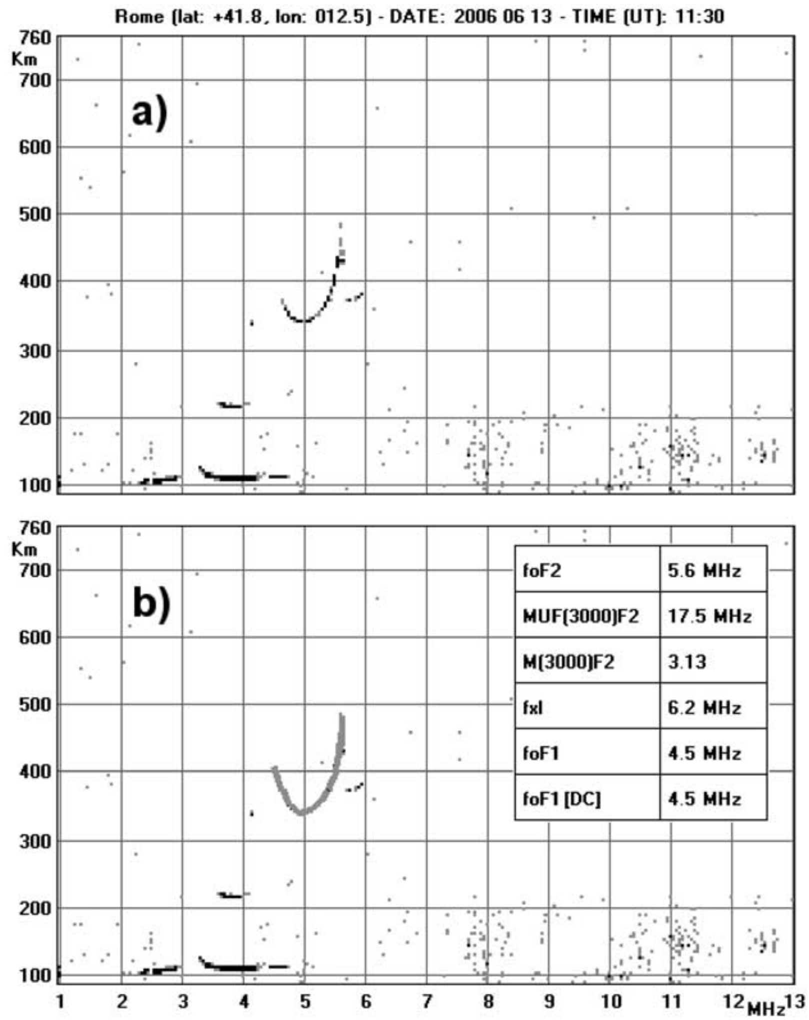

Figure 8. (a) Ionogram recorded on 13 June 2006 at 11:30 UT by the AIS-INGV installed at Rome and belonging to subset 2. (b) The F1 cusp is reasonably identified at 4.5 MHz by Autoscala (in grey the ordinary trace identified by the software).

composed of ionograms for which the F1 trace is not present even if the DC model forecasts a monthly median value for *foF1* (Figure 4); (5) subset 5, composed of ionograms for which the F1 layer is not fully formed and no clear cusp is observed between the F1 and F2 traces (Figure 9); for these ionograms the URSI standard suggests to express *foF1* only with the descriptive letter L; (6) subset 6, composed of ionograms for which the F1 cusp is neither typical nor clear (Figure 10). For these cases the URSI standard suggests to express *foF1* as the transition frequency between the F1 and the F2 trace, followed by the descriptive letter U and the qualifying letter L.

[20] For each subset we considered: (1) the percentage of ionograms for which the software detected the F1 trace and scaled an acceptable value of *foF1*; (2) the percentage of ionograms for which the software detected the F1 trace and scaled an unacceptable value of *foF1*; (3) the percentage of ionograms for which the software established that the ionogram information was sufficient to assume that the F1 trace was not present (the corresponding output is NO as in Figure 4); (4) the percentage of ionograms for which the software considered the ionogram information insufficient to assess whether the F1 trace was present or not (the corresponding output is N/A as in Figure 3).

[21] The results of the data analysis are reported in Table 1 where an acceptable value is considered to lie within ±0.5 MHz of the manual value. This limit of

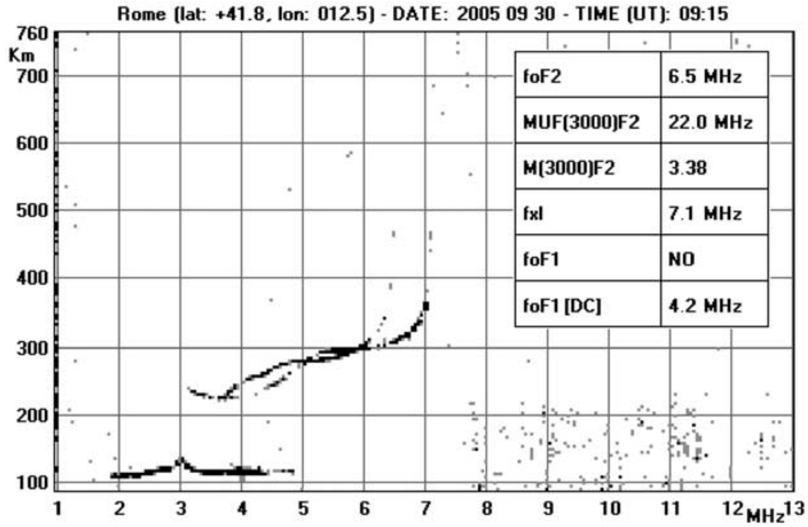

Figure 9. Ionogram recorded on 30 September 2005 at 09:15 UT by the AIS-INGV installed at Rome and belonging to subset 5. Even if the DC model forecasts a monthly median value of 4.2 MHz for *foF1*, Autoscala correctly detected no F1 layer.

acceptability was adopted in line with the URSI limit of $\pm 5\Delta$ (Δ is the reading accuracy).

4. Identification of Critical Ionogram Cases

[22] The results reported in Table 1 show that the F1 autoscaling procedure was successful for most of the ionograms, with very high percentages of good F1 layer detection and acceptable *foF1* values. However, two critical ionogram cases were identified for which the procedure needs to be improved. In this section we focus our attention on the description of these cases.

4.1. Ionograms for Which Only the Trace on the Left Side of the F1 Cusp is Well Defined

[23] Figure 11 shows a case of an ionogram belonging to subset 1. The F1 cusp is well visible but the F1 trace on the right side of the cusp is almost totally absent. Sometimes for this type of ionogram the procedure incorrectly gives as output N/A for *foF1*. This is because the algorithm described in paragraph 2 tries to identify the trace from the F1 cusp to the lowest virtual height of the F2 layer ordinary trace. As a consequence when this part of the trace is totally or nearly absent the procedure considers the ionogram information insufficient to establish whether an F1 layer is present or not. In order to avoid this kind of error, the ionogram information that might emerge from the trace on the left side of the F1 cusp should also be exploited, but this still needs to be developed and tested.

4.2. Ionograms Belonging to Subset 6

[24] Figure 12 shows a case of an ionogram, belonging to subset 6, characterized by an L condition. As shown in Table 1, for this type of ionogram the procedure does not succeed in detecting the F1 layer in 40% of cases and gives NO as output for *foF1*. At present the procedure is somewhat limited for these cases because the nearly flat shape of the trace on the right side of the F1 ledge prevents the correlation C from being larger than the threshold C_t, and at the same time in the window where the minimum (f_m, h'_m) of the parabola is slid, as described in paragraph 2, the number of points is indeed significant. In order to improve the autoscaling of such ionograms the threshold C_t could be decreased but this issue needs to be further studied and tested. Nevertheless, again for these ionograms the problem might be solved by trying also to exploit the ionogram information in the trace on the left side of the F1 cusp.

5. Summary

[25] This work described a new routine added to Autoscala able to perform an automatic scaling of the F1 region, necessary to compute a reliable electron density profile in real time. The results reported in Table 1 showed that this routine reliably succeeds in delineating the cases in which the F1 layer is present from the ones in which the F1 layer is not present.

[26] This procedure is able to separate ionograms in which the information is sufficient, but the F1 layer is not

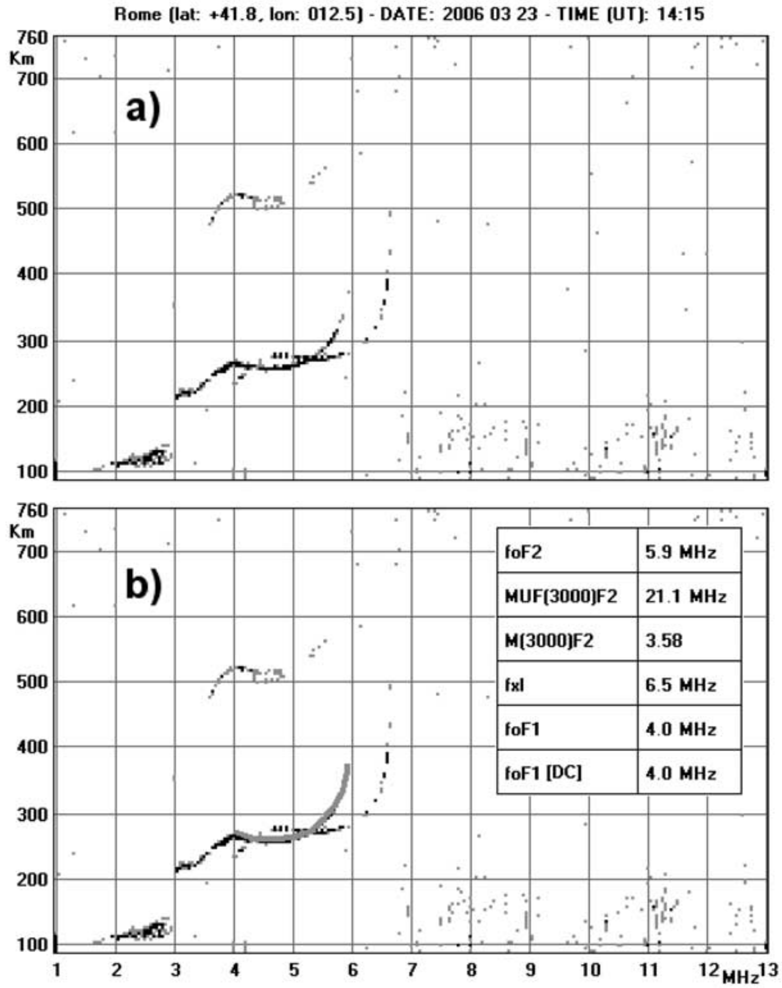

Figure 10. (a) Ionogram recorded on 23 March 2006 at 14:15 UT by the AIS-INGV installed at Rome and belonging to subset 6. (b) The transition frequency between the F1 and the F2 trace is correctly identified at 4.0 MHz by Autoscala (in grey the ordinary trace identified by the software).

Table 1. Behavior of the F1 Autoscaling Procedure Described in the Paper[a]

	Autoscala		
	F1 Layer Detected	Sufficient Information to State That the F1 Layer Is Not Present	Insufficient Information to State Whether the F1 Layer Is Present or Not
Subset 1 (580 ionograms)	Acceptable 89% Not Acceptable 0%	5%	6%
Subset 2 (765 ionograms)	Acceptable 75% Not Acceptable 2%	8%	15%
Subset 3 (356 ionograms)	3%	5%	92%
Subset 4 (235 ionograms)	3%	93%	4%
Subset 5 (346 ionograms)	2%	95%	3%
Subset 6 (634 ionograms)	Acceptable 46% Not Acceptable 2%	40%	12%

[a]The test was carried out on a data set of ionograms recorded at Rome from September 2005 to June 2006.

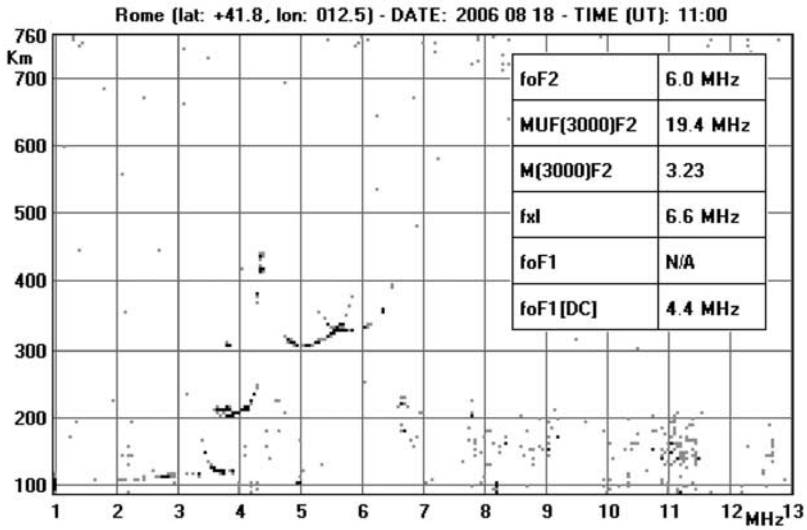

Figure 11. Ionogram recorded on 18 August 2006 at 11:00 UT by the AIS-INGV installed at Rome and belonging to subset 1. Autoscala incorrectly gave N/A as output for *foF1*.

present (the output in these cases is NO), from the ionograms where the information is insufficient to assess whether the F1 layer is present or not (the output in these cases is N/A). The output NO and N/A must not be confused. The identification of ionograms without sufficient information is useful for those who, for a post-autoscaling elaboration, want to use an F1 model for these cases. Moreover, for ionograms in which the operator scaled *foF1* as a certain value or as a doubtful value, the percentage of acceptable *foF1* values given as output by the program is high, as illustrated in Table 1 by subsets 1 and 2. On the contrary for ionograms characterized by an L condition like the one shown in Figure 12, the percentage of acceptable *foF1* values given as output by the software is low. This behavior may however be smoothed in the future by also making allowance for

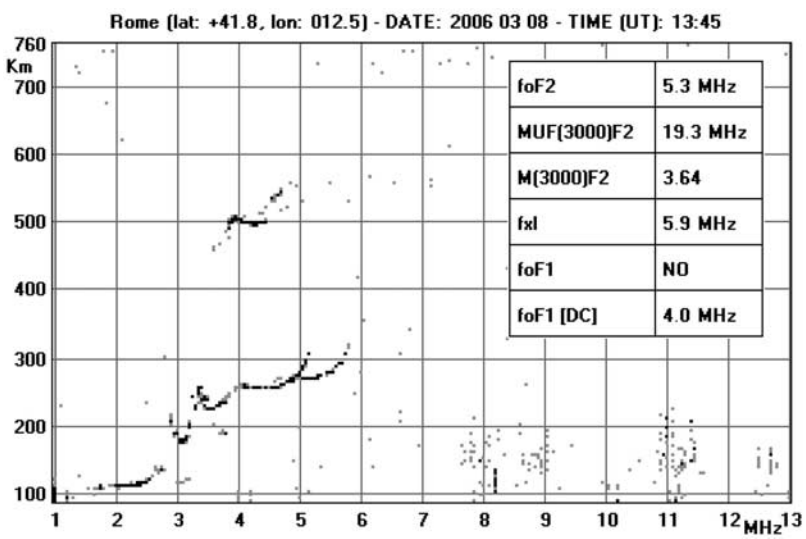

Figure 12. Ionogram recorded on 8 March 2006 at 13:45 UT by the AIS-INGV installed at Rome and belonging to subset 6. The transition frequency at 4.0 MHz between the F1 and the F2 trace was not detected by Autoscala, which incorrectly gave NO as output for *foF1*.

the ionogram information in the trace on the left side of the F1 ledge.

[27] The ionograms recorded at the Gibilmanna and Rome ionospheric stations by the ionosonde AIS-INGV and autoscaled by Autoscala to date, with the addition of the new F1 autoscaling routine, are available real time at the site http://ionos.ingv.it/spaceweather/start.htm.

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