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Software for the automatic scaling of critical frequency f_0F2 and MUF(3000)$F2$ from ionograms applied at the Ionospheric Observatory of Gibilmanna

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Abstract
Software for the automatic scaling of critical frequency f_0F2 and MUF(3000)$F2$ from ionograms was developed and applied to the ionograms produced by the new Advanced Ionospheric Sounder installed at the Ionospheric Observatory of Gibilmanna. A test based on 1124 ionograms recorded in normal ionospheric condition was performed comparing the automatically scaled parameters with the corresponding ones obtained by the standard manual method. The results of a preliminary test performed during a strong magnetic ionospheric storm are also presented.

Key words *ionograms – automatic scaling – ionosonde*

1. Introduction

Ionospheric observations are performed by a high frequency radar know as an ionosonde. The ionosonde sends short pulses of radio waves vertically into the ionosphere. These pulses are refracted back towards the ground and the ionosonde records the time delay between transmission and reception of the pulses. By varying the frequency of the pulses from 1 to 20 MHz, a record is obtained of the time delay at different frequencies. This record is referred to as an ionogram and is usually presented in the form of a graph.

From the ionogram an experienced operator is able to obtain the most important ionospheric parameters, in particular the critical frequency of the $F2$ layer (f_0F2) and the Maximum Usable Frequency on a distance of 3000 km (MUF(3000)$F2$).

Because of the growing interest in real time mapping and short term previsions, in recent years efforts have been made to develop software to achieve real time scaling of ionograms (*e.g.,* Fox and Blundell, 1989; Igi *et al.*, 1993; Tsai and Berkey, 2000). 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).

The National Institute of Geophysics and Vulcanology (INGV) developed a low power pulse compressed ionosonde to be used for standard ionospheric soundings. This instrument – called an Advanced Ionospheric Sounder (AIS-INGV) designed for minimally attended, remotely controlled operation – was installed in the INGV Ionospheric Observatory of Gibilmanna (37.9N-14.0E). A program (called Autoscala) for the automatic scaling of f_0F2 and MUF(3000)$F2$ was developed to provide scaled

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data within a few minutes the ionogram being produced. To date, these data are available real time on the internet at the site <http://www.ingv.it/~zscotto/latest.html>.

2. The INGV software for automatic scaling of ionograms

The INGV software is based on an image recognition technique and can operate without polarization information. Hence it can be used both with single antenna systems and crossed antenna systems. Using a family of functions with the typical *F*2 layer shape, and applying a maximum contrast technique, a particular element of this family is then selected and defined as representative of the *F*2 layer trace. The vertical asymptote of the selected function corresponds to the critical frequency f_0F2; the MUF(3000)*F*2 is calculated numerically establishing the transmission curve tangent to the selected function.

Compared to the previous version of the INGV software (Scotto and Pezzopane, 2002) for automatic scaling of ionograms some improvements have been made.

1) The main routine has been redesigned, with improvements in CPU time required and parametrizing the girofrequency, which means that this version will be able to scale ionograms recorded in any location.

2) In a significant percentage of the recorded ionograms it is not possible to scale a value for the considered ionospheric characteristic (MUF(3000)*F*2 and f_0F2). This can be due to different reasons, that are well known and classified by the standard URSI. The most common cases are reported below.

a) No *F*2 trace is observed owing to blanketing by the *E* sporadic layer. In these cases the standard URSI recommends the use of the descriptive letter *A* on bulletins substituting the value of ionospheric characteristic f_0F2.

b) The trace near the critical frequency is not clearly recorded for different reasons. In these cases the standard URSI recommends to scale the most reliable value of f_0F2 by extrapolation, hypothetically extending the traces up to the most probable value of the critical frequency. If the extrapolated frequency range is greater than 10%, it is recommended to report the highest frequency of the recorded trace, followed by the qualifying letter *D* (greater than) and the descriptive letter associated to the reason why the trace is not clearly recorded (*S* interference, *R* absorption, *C* equipment).

The software for automatic scaling of ionograms recognizes the trace and outputs both the values of the characteristics. This version has been improved and a method for identifying ionograms without sufficient information has been introduced and tested. If an ionogram is considered to lack sufficient information it is discarded by the program and neither the f_0F2 nor the MUF(3000)*F*2 are given as output.

3. Test: INGV software compared with the manual method during normal ionospheric conditions

The test was performed using 1124 ionograms recorded from December 1 to December 15, 2002 by the AIS-INGV installed in the Ionospheric Observatory of Gibilmanna. The period selected is composed by magnetically quiet days in order to test the performance of the software in normal ionospheric conditions.

3.1. *Test of the method to identify and separate ionograms with sufficient or insufficient information*

The set of 1124 ionograms was divided into two subsets. The subset *S*, containing the ionograms scaled by the program, and subset *N* containing the ionograms discarded by the software because of insufficient information.

For each subset we considered:

a) The number of ionograms for which the operator was able to scale neither the f_0F2 nor the MUF(3000)*F*2.

b) The number of ionograms for which the operator was able to scale f_0F2 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 f_0F2 and MUF(3000)*F*2.

Table I. The behavior of the method to identify and separate ionograms with sufficient or insufficient information.

	Scaled by the INGV software No. of cases	[%]	Discarded by the INGV software No. of cases	[%]
The operator scaled neither the f_0F2 nor the *MUF(3000)F2*	9	0.9%	46	62.1%
The operator scaled both f_0F2 and *MUF(3000)F2*	847 (subset *A*)	80.7%	7	9.5%
The operator scaled *MUF(3000)F2* only	182 (subset *B*)	17.3%	21	28.4%
The operator scaled f_0F2 only	12 (subset *C*)	1.1%	0	0.0%
Total	1050	100.0%	74	100.0%

Table II. The few cases (9 out of 1124, equal to 0.8%) in which the program scales values but the operator is not able to read a value. A comparison between the output of Autoscala and the corresponding manual scaling performed by a very experienced operator according to the standard URSI is reported.

Day and time	MUF(3000)$F2$ (software) [MHz]	MUF(3000)$F2$ (operator) [MHz]	f_0F2 (software) [MHz]	f_0F2 (operator) [MHz]
5 December 2002 22.00	8.3	*A*	3.1	*A*
6 December 2002 13.00	26.1	*R*	8.1	8.4 *DR*
7 December 2002 07.45	30.4	*R*	9.1	8.9 *DR*
7 December 2002 08.45	29.0	*S*	8.6	8.2 *DS*
7 December 2002 12.45	18.1	*S*	4.7	9.7 *DS*
8 December 2002 09.00	32.1	*R*	10.6	9.8 *DR*
8 December 2002 11.00	31.2	*S*	9.6	9.6 *DS*
11 December 2002 14.00	30.2	*S*	9.8	9.4 *DS*
12 December 2002 03.30	30.3	*S*	9.8	8.6 *DS*

The results of this analysis are reported in table I and they confirm the general robustness of the overall system. The ionograms not discarded by the software and for which the operator was not able to scale any value constitute the most critical cases. These cases are very few (9 out of 1124, equal to 0.8%) and are reported in table II where a comparison between the output of Autoscala and the corresponding manual scaling performed by a very experienced operator is shown. This comparison highlights that 8 out of 9 critical cases occurred for ionograms characterized by a truncated trace.

On the other hand, it is also important to underline that the software does not discard ionograms that present a trace sufficiently defined for an operator. This can be inferred observing that the cases discarded by the software in which the operator was able to scale both f_0F2 and MUF(3000)$F2$ are very few (7 out of 1124, equal to 0.6%).

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

With reference to the ionograms scaled by the INGV software, the following three subsets were considered (see table I):

1) Subset *A*, containing the ionograms in which the operator was able to scale both the critical frequency f_0F2 and the MUF(3000)$F2$.

2) Subset *B*, containing the ionograms in which the operator was able to scale the MUF(3000)$F2$ only.

3) Subset *C*, containing the ionograms in which the operator was able to scale the f_0F2 only.

Table IIIa-c. Acceptable and accurate values (with corresponding percentage) for the test carried out on the ionograms recorded in Gibilmanna from December 1 to December 15, 2002. In (a) the 847 ionograms for which the operator was able to scale both f_0F2 and MUF(3000)$F2$ are considered (subset *A*). In (b) the 182 ionograms for which the operator was able to scale only the MUF(3000)$F2$ are considered (subset *B*). In (c) the 12 ionograms for which the operator was able to scale only the f_0F2 are considered (subset *C*).

(a)

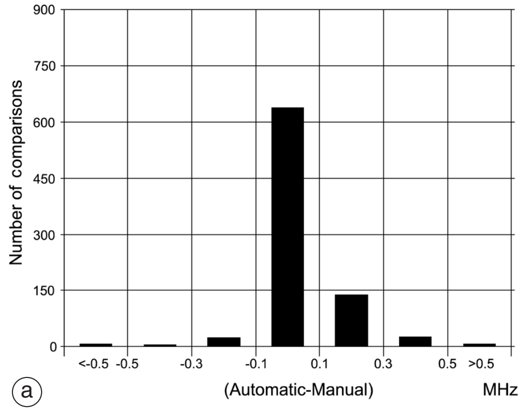
	f_0F2		MUF(3000)$F2$	
	No.	[%]	No.	[%]
Total	847	100.0	847	100.0
Acceptable	833	98.3	847	100.0
Accurate	638	75.3	827	97.5

(b)

	MUF(3000)$F2$	
	No.	[%]
Total	182	100.0
Acceptable	179	98.5
Accurate	170	93.5

(c)

	f_0F2	
	No.	[%]
Total	12	100.0
Acceptable	9	75.0
Accurate	6	50.0



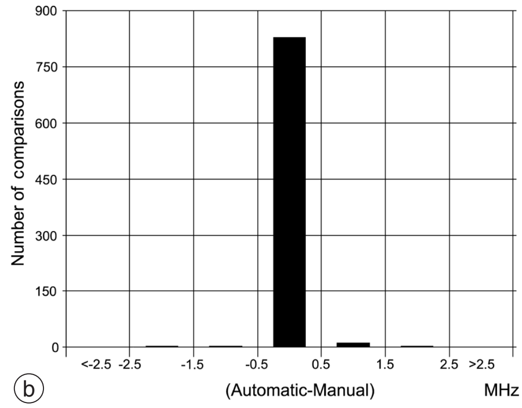


Fig. 1a,b. a) Differences (δ) between the values of f_0F2 scaled by Autoscala and by the standard manual method considering ionograms for which the operator was able to scale both f_0F2 and MUF(3000)$F2$ (subset A). Out of 847 cases it results: for 638 cases (-0.1 MHz $\leq \delta \leq 0.1$ MHz); for 139 cases (0.1 MHz $< \delta \leq 0.3$ MHz); for 24 cases (-0.3 MHz $\leq \delta <$ < -0.1 MHz); for 26 cases (0.3 MHz $< \delta \leq 0.5$ MHz); for 6 cases (-0.5 MHz $\leq \delta < -0.3$ MHz); for 7 cases ($\delta > 0.5$ MHz); for 7 cases ($\delta < -0.5$ MHz). b) Differences between the values of MUF(3000)$F2$ scaled by Autoscala and by the standard manual method considering ionograms for which the operator was able to scale both f_0F2 and MUF(3000)$F2$ (subset *A*). Out of 847 cases it results: for 827 cases (-0.5 MHz $\leq \delta \leq 0.5$ MHz); for 11 cases (0.5 MHz $< \delta \leq 1.5$ MHz); for 3 cases (-1.5 MHz $\leq \delta < -0.5$ MHz); for 4 cases (1.5 MHz $< \delta \leq 2.5$ MHz); for 2 cases (-2.5 MHz $\leq \delta < -1.5$ MHz); for 0 cases ($\delta > 2.5$ MHz); for 0 cases ($\delta < -2.5$ MHz).

A quantitative comparison between the values scaled automatically and manually was performed and the results of the comparison are reported in table IIIa-c. In this work an accurate value is considered to lie within ± 0.1 MHz of the value obtained by the operator for f_0F2 and ± 0.5 MHz for MUF(3000)$F2$. An acceptable value is considered to lie within ± 0.5 MHz for f_0F2 and ± 2.5 MHz for MUF(3000)$F2$. Limits of acceptability have been adopted in line with the URSI limits of $\pm 5\Delta$ (Δ is the reading accuracy). For the subset *A* and *B* (constituted by a sufficient number of elements), the results of the comparison are presented in form of a histogram in figs. 1a,b and 2. This analysis shows that the INGV software for automatic scaling gives acceptable values in more than 98% of cases both for f_0F2 and MUF(3000)$F2$.

The ionograms belonging to subset *B* show the ionogram trace abruptly truncated, but the software considers the information sufficient to identify the trace, and a value of f_0F2 is given. The test gives us an evaluation of the capability of the software to scale these cases. An example

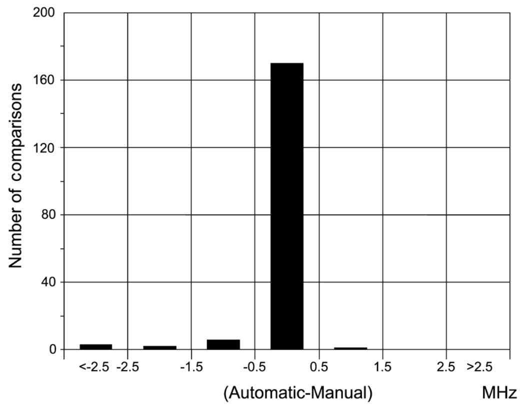


Fig. 2. Differences between the values of MUF(3000)$F2$ scaled by Autoscala and by the standard manual method considering ionograms for which the operator was able to scale only the MUF(3000)$F2$ (subset *B*). Out of 182 cases it results: for 170 cases (-0.5 MHz $\leq \delta \leq 0.5$ MHz); for 1 case (0.5 MHz $< \delta \leq 1.5$ MHz); for 6 cases (-1.5 MHz $\leq \delta < -0.5$ MHz); for 0 cases (1.5 MHz $< \delta \leq 2.5$ MHz); for 2 cases (-2.5 MHz $\leq \delta < -1.5$ MHz); for 0 cases ($\delta > 2.5$ MHz); for 3 cases ($\delta < -2.5$ MHz).

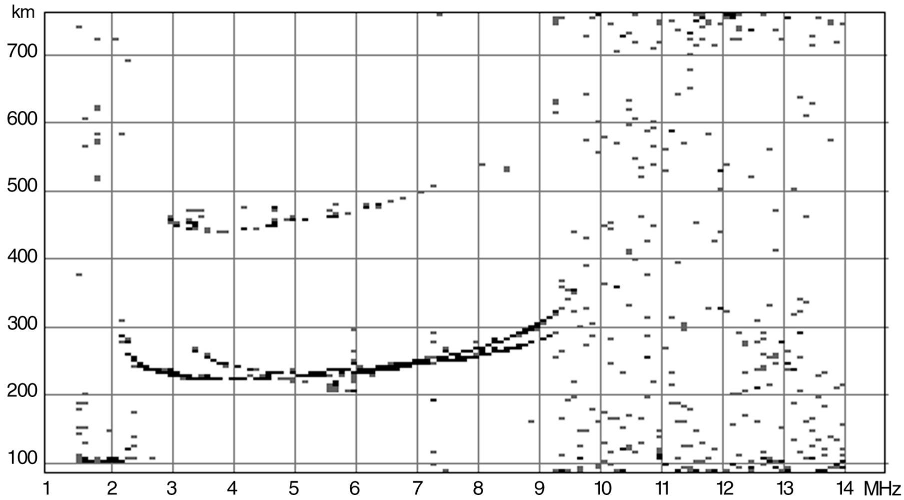


Fig. 3. An example of ionogram belonging to the subset *B*. The ionogram trace is abruptly truncated, so the operator is not able to scale the critical frequency f_0F2. In this case the software identifies the trace correctly and so the MUF(3000)$F2$ is correctly scaled (33.0 MHz the value automatically scaled, and 33.0 MHz by the operator). The value of $f_0F2 = 10.3$ MHz given by the program is reasonable.

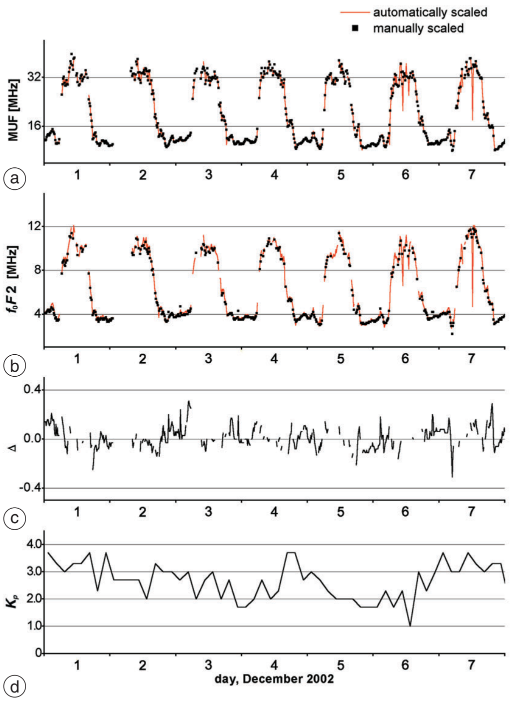


Fig. 4a-d. With reference to the days from 1 to 7 December 2002: a) comparison between MUF(3000)$F2$ manually scaled (black square) and automatically scaled data (red line); b) comparison between f_0F2 manually scaled (black square) and automatically scaled data (red line); c) plot of $\Delta=(f_0F2_{\text{measured}}+-f_0F2_{\text{median}})/f_0F2_{\text{measured}}$, used as an index of the ionospheric disturbance; d) plot of the geomagnetic activity index Kp.

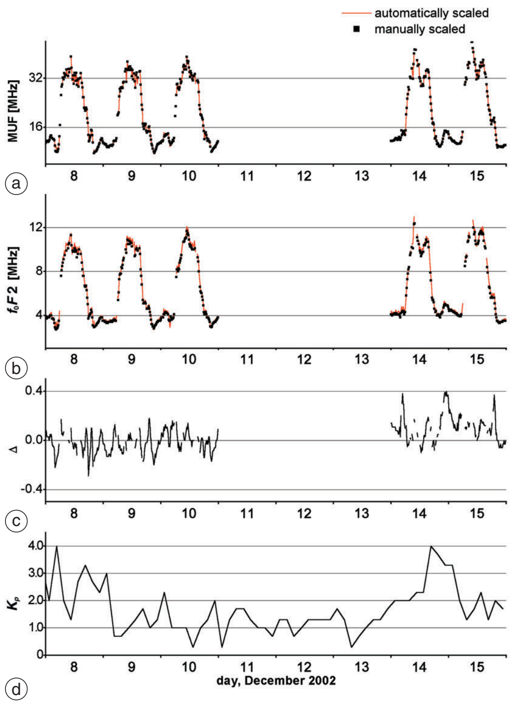


Fig. 5a-d. With reference to the days from 8 to 15 December 2002: a) comparison between MUF(3000)$F2$ manually scaled (black square) and automatically scaled data (red line); b) comparison between f_0F2 manually scaled (black square) and automatically scaled data (red line); c) plot of $\Delta=(f_0F2_{\text{measured}}+-f_0F2_{\text{median}})/f_0F2_{\text{measured}}$, used as an index of the ionospheric disturbance; d) plot of the geomagnetic activity index Kp.

of an ionogram from subset *B* is shown in fig. 3. The ionogram trace is abruptly truncated, so the operator is not able to scale the critical frequency f_0F2, but the software identifies the trace correctly. The MUF(3000)$F2$ is correctly scaled (33.0 MHz is the value automatically scaled, and 33.0 MHz scaled by the operator) and the value of $f_0F2=10.3$ MHz given by the program is reasonable.

Figures 4a and 5a report the plot of the MUF(3000)$F2$ values obtained by Autoscala and the plot of corresponding values obtained by a well experienced operator. Figures 4b and 5b report the same plots for f_0F2. Figures 4c and 5c report the plot of the parameter $\Delta=(f_0F2_{\text{measured}}-f_0F2_{\text{median}})/f_0F2_{\text{measured}}$ (where f_0F2_{measured} is the value obtained by an experienced operator), that is considered an index of the ionospheric disturbance. Figures 4d and 5d report the plot of the geomagnetic activity index Kp.

From figs. 4a-d and 5a-d one can observe qualitatively that the plots of the automatically scaled data are very close to the data obtained by an operator. Therefore we can conclude that the performance of Autoscala is stable for not disturbed magneto-ionospheric conditions ($Kp<=4$).

4. Performance of INGV software for disturbed ionospheric conditions: a case study

On October 29 2003, the sudden commencement of a strong magnetic storm was observed. Approximately at 6 UT the arrival of a large high-speed solar wind shock front was detected by the solar wind monitoring satellite. The geomagnetic field disturbance was observed in some regions until 7 UT. The AIS-INGV of Gibilmanna recorded the start of the initial phase of the associated ionospheric storm at 8.45 UT by an increase in the critical frequency f_0F2.

Figure 6a,b reports the plot of the f_0F2 values obtained from the ionograms recorded in Gibilmanna; the values obtained by Autoscala are compared with the corresponding ones scaled by a well experienced operator. Figure 6a,b also reports the plot of the f_0F2 values obtained from the ionograms recorded in Rome; the values obtained by ARTIST system are compared with the corresponding ones scaled by a well experienced operator.

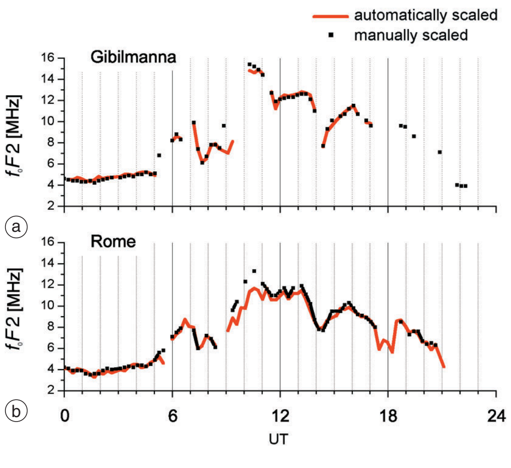


Fig. 6a,b. a) Plot of f_0F2 values, from the ionograms recorded in Gibilmanna on 29 October 2003, obtained by a well experienced operator (black square) compared to the corresponding plot obtained by Autoscala (red line); b) plot of f_0F2 values, from the ionograms recorded in Rome on 29 October 2003, obtained by a well experienced operator (black square) compared to the corresponding plot obtained by ARTIST (red line).

Comparing the two plots it is observed that during the morning the commencement of the storm causes the deterioration of the ionograms trace for both digisondes. Autoscala is able to detect this condition and does not give data that would be wrong. The system AIS-INGV detects the ionospheric storm as soon as the ionogram trace is sufficiently clear. On the contrary, ARTIST does not detect this condition so the real time data of the digisonde of Rome are wrongly given in output. As a result the real time data of Rome between about 9 and 11 UT are highly underestimated and consequently the plot dissemble the ionospheric effect of the storm.

5. Conclusions

The results of the test performed can be summarized observing that considering the subset A (constitued by good quality ionograms, for which the operator is able to scale both f_0F2 and MUF(3000)$F2$) the percentage of acceptable values automatically scaled is very high (>98%).

For medium quality ionograms (for which the operator is able to scale only MUF(3000)$F2$) the percentage of acceptable values automatically scaled is also good (>98%). Hence we can conclude that for normal ionospheric conditions Autoscala is able to provide good quality data.

For disturbed ionospheric conditions a preliminary test has been performed showing good results. A study performed during the strong ionospheric storm of october 2003 showed that Autoscala better demonstrated the evolution of the ionospheric storm than the ARTIST system.

6. Further developments

The tests performed are not able to give information on the performance of Autoscala for spread F conditions as this case was not observed in the period considered at the ionospheric station of Gibilmanna. A separate study on this item would be necessary.

Autoscala has definitively been applied at the ionospheric station of Gibilmanna since April 2003 and to date more than 20000 ionograms have been produced. Tests based on larger datasets comprehensive of different seasons and solar conditions are necessary. Extensive comparative studies of Autoscala with other automatic scaling software (with particular reference to ARTIST system) would be also interesting.

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