Spectral analysis of the f_0F_2 data obtained at five PRIME sites during a 15 minute campaign in June 1993

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Abstract
During the COST 238: PRIME project there was a campaign of 15-min intervals of the f_0F_2 soundings at Kandilli, Rome, Sofia, Poitiers and Lannion. The campaign took place for one month in June 1993. The spectral analysis of the data using a Fast Fourier Transform (FFT) algorithm proved a relatively easy method to reconstruct the original data at the confidence level of $\alpha = 0.05$.

Key words *spectral analysis – f_0F_2 data – PRIME*

1. Introduction

A Polish made Vertical Ionosonde (VI) was installed at the Kandilli Observatory where it worked successfully for almost one year between 6 May 1993 and 21 April 1994 (Rokicki *et al.*, 1993). During this period there was a mutual agreement among several scientists to hold a measurement campaign of 15-min intervals in addition to the usual measurement interval of every half hour. The purpose of the whole exercise was to improve the instantaneous mapping and modeling of the ionospheric critical frequencies (f_0F_2) over Europe as to fulfill one of the objectives of the COST 238: PRIME project (Bradley, 1991).

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2. Method of analysis

The f_0F_2 data were obtained at equal intervals of time, that is, either at every fifteen minutes or on the half hour continuously. However, due to several reasons the available data had breaks in a random manner. Therefore, it is a difficult task to employ a standard FFT algorithm in the spectral analysis of the f_0F_2 data. However, the algorithm referred to as «clean spectrum» by Roberts *et al.* (1987) here takes care of the data gaps. In this algorithm the successive data gaps in time are treated as windows. That is, the available valid data between two successive data gaps are treated as windowed. The length of the rectangular window is determined each time by the existing data gap.

The results of the analysis are presented here in two groups: i) the Discrete Fourier Transform (DFT) analysis of the 15-min long f_0F_2 data obtained at Kandilli (41°N-29°E); Rome (42°N-13°E); Sofia (43°N-23-°E); Poitiers (47°N-0°E) and Lannion (49°N-3°E).

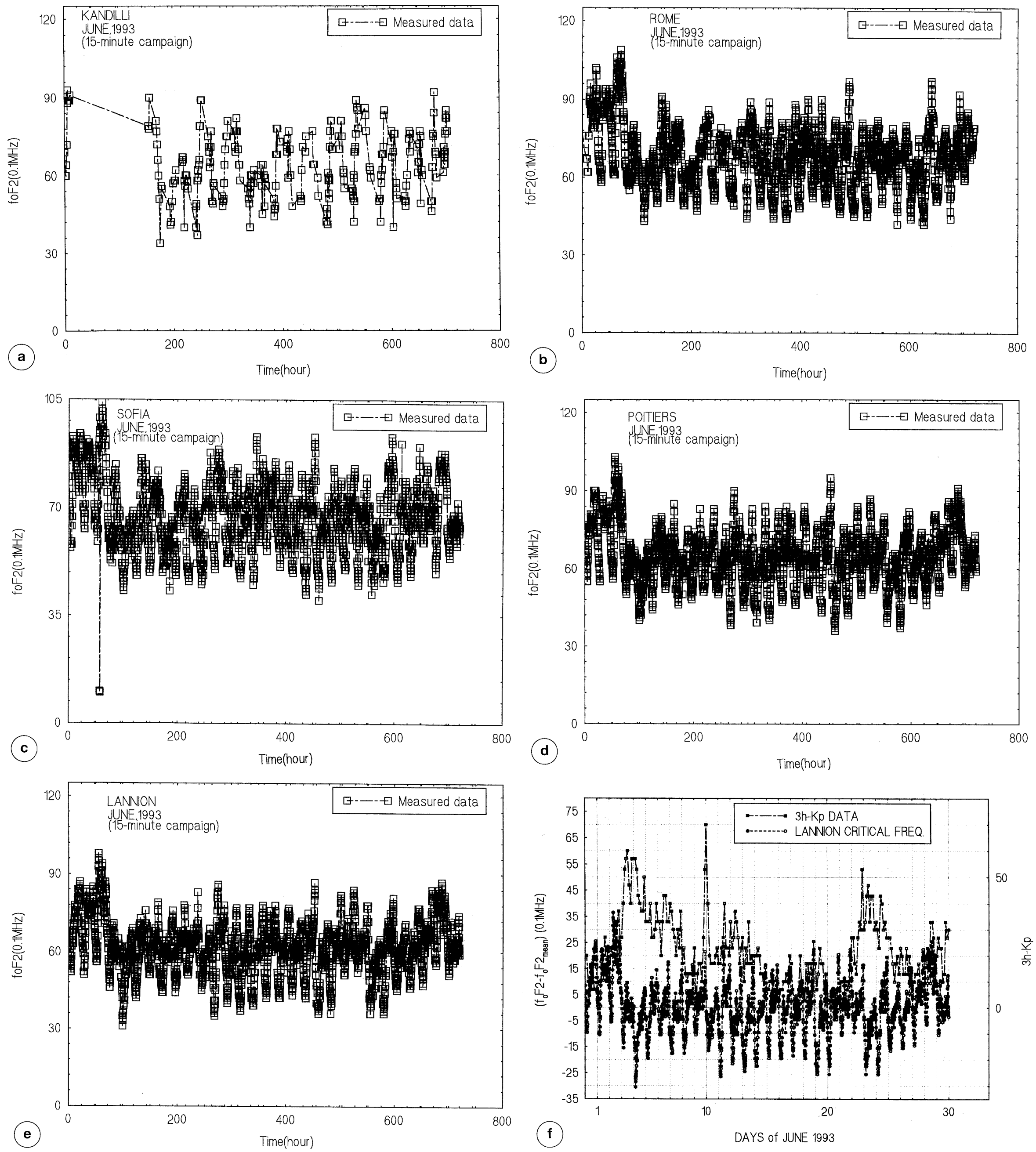

Fig. 1a-f. The f_0F_2 values obtained in June 1993 during the 15-min campaign and superimposed are the computed (synthetic) f_0F_2 values as obtained by the inverse DFT by Roberts *et al.* (1987) for: a) Kandilli; b) Rome; c) Sofia; d) Poitiers; e) Lannion; f) (f_0F_2-f_0F_2 mean) for Lannion and the planetary 3h-K_p values *vs.* the days of June 1993.

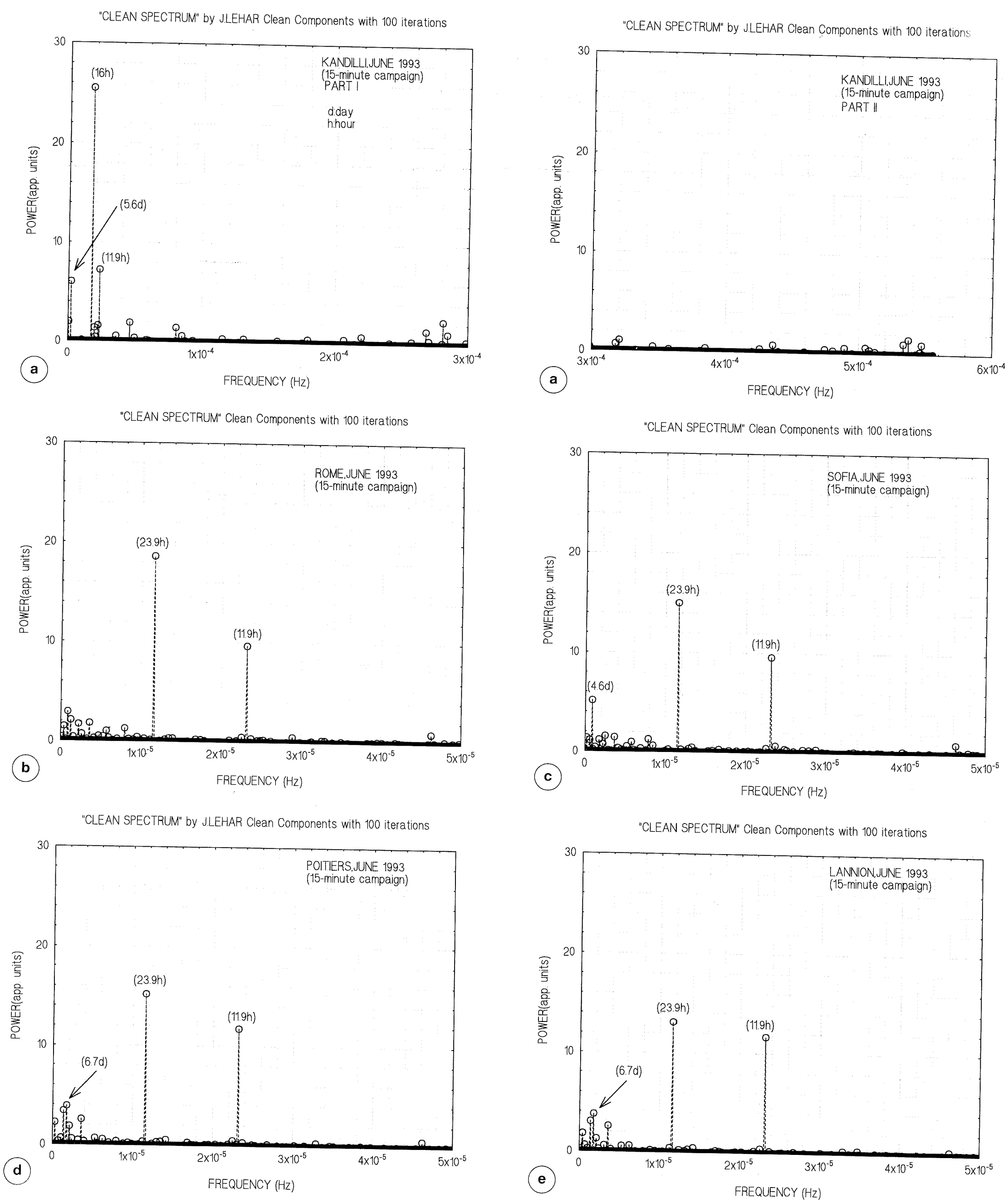

Fig. 2a-e. The spectrum of the f_0F_2 values obtained in June 1993 during the 15-min campaigns for: a) Kandilli; b) Rome; c) Sofia; d) Poitiers; e) Lannion. The DFT program employed is due to Roberts *et al.* (1987).

These stations, geographically, cover a latitudinal zone of (41°N-49°N) and longitudinal zone of (3°W-29°E). The dipole magnetic coordinate coverage of these stations are between 41°N and 52°N; and between 80°E and 104°E; ii) DFT analysis of the half hourly f_0F_2 data obtained at Kandilli.

3. Results

3.1. *Results of the 15-min campaign in June 1993*

Figure 1a-e illustrates the f_0F_2 values during the 15-min campaign in June 1993. Except for Kandilli, the data coverage is very good. How-

Table Ia. The spectrum of the f_0F_2 values obtained during the 15-min campaign at five PRIME stations. The periods corresponding to «power» amplitudes greater than 5.5 in appropriate units are listed in hours or days.

Period		Station names				
		Kandilli (41°N-29°E)	Rome (42°N-13°E)	Sofia (43°N-23°E)	Poitiers (47°N-0°E)	Lannion (49°N-3°W)
Hour	Day (approx.)	% rel. power	% rel. power	% rel. power	% rel. power	% rel. power
0.5		5.8				
0.93		9.132				
0.9		9				
3.4		6				
6		7		7		
11.9		28	52	64	90	89
12.4		6				
16		100				
23.9			100	100	100	100
34.7	1.4		7			
35.1	1.5			8		
47.9	2			7		
48.8	2		6			
75.8	3.2			10		
77.8	3.2		10		16.6	20
110.7	4.6			10		
125.2	5.2		9			
130.9	5.5				13	10
134.4	5.6	24				
159.9	6.7			8	26	28
205.6	8.6				23	23
221.5	9.2		11			
319.8	13.3		16	8		
479.8	20			8		
564.4	23.5	8				
719.7	30		8		9.6	14
1439.5	60			9		

Table Ib. The spectrum of the f_0F_2 values of the Kandilli data which were obtained between 6 May 1993 and 21 April 1994.

Period		Kandilli
Hour	Day (approx.)	% rel. power
7.9		7
11.9		10
12		11
12.1		7
12.11		12
12.2		6
23,5		8
23.8		100
23.9		13
24.1		6
24.2		66
716	29.9	6
16109	671	10

ever, in the case of Kandilli, there are several missing f_0F_2 values. As seen in fig. 1b-e the highest f_0F_2 values were observed in the beginning of June 1993. In the beginning of June 1993 there was a considerably large magnetic storm as marked with the 3-h planetary magnetic index (3h-K_p). The (3h-K_p) index was 6 on 4 June 1993 between 12-14.9 h UT. The storm continued on 5 June 1993 and gradually died out on 7 June 1993. During this period an important reduction in the f_0F_2 values is very clear in fig. 1f. It is thought that this reduction in the f_0F_2 values was due to that ongoing substorm activity. In fig. 1f the Lannion f_0F_2 values were chosen to illustrate how the f_0F_2 and the planetary 3h-K_p indices varied in June 1993. Later in that month, on June 24, there was another substorm and the 3h-K_p value was 5- between 9-11.9 h UT. In a similar way, the f_0F_2 values exhibited a reduction with respect to their general daily variation again.

Figure 2a-e shows the results of the DFT analysis by the algorithm «clean spectrum» of Roberts *et al.* (1987). The data employed were those which had been obtained during the 15-min campaigns. The «power» may be in any appropriate units. The «power» spectrum exhibited several important maxima in the frequency domain as seen in these figures. Table Ia,b summarizes some numerical results of the analysis. The periods corresponding to power amplitudes greater than 5.5 in appropriate units are listed either as hours or days for the five stations mentioned. The power amplitudes are normalized with respect to the maximum amplitude obtained by the «clean spectrum» program of Roberts *et al.* (1987). The power amplitudes, then expressed as percents in table Ia,b. The fundamental period is 23.9 h for all the stations except Kandilli. The second harmonic is observed at 11.9 h for all five stations. The scarcity of the Kandilli f_0F_2 data during the 15-min campaign is thought to be the reason for the Kandilli harmonics obtained to appear different in hierarchy from those of the other four stations.

Figure 3a-e exhibits those frequencies whose power amplitudes were greater than 5.5 in appropriate units. This time, the relative powers are indicated in time domain on logarithmic scales so that they can be investigated separately.

Figure 4a-d illustrate the scatter diagrams of the f_0F_2 values during the 15-min campaigns which took place in June 1993. On the figures, the Rome, Sofia, Poitiers and Lannion f_0F_2 values are plotted *vs.* Kandilli f_0F_2's. Number of the data points making the scatter diagram and the cross correlation coefficients are also indicated in the figures. At the significance level of $\alpha = 0.05$ the cross correlation coefficients calculated are slightly more significant for (Rome-Kandilli); (Sofia-Kandilli); than those of obtained for (Poitiers-Kandilli); and (Lannion-Kandilli). This might be due to the effect of the geographical separation of the stations with respect to each other. Table II summarizes the results which can be stated based on the output of fig. 4a-d.

Figure 5a-e exhibits the scatter diagrams of the observed f_0F_2 values during the 15-min campaign and the f_0F_2 values generated by the inverse Fourier transform by the «clean spectrum » program Roberts *et al.* (1987). The generated data are referred to as «synthetic» in the figures. The number of iteration steps in obtaining the clean spectrum was 100. The

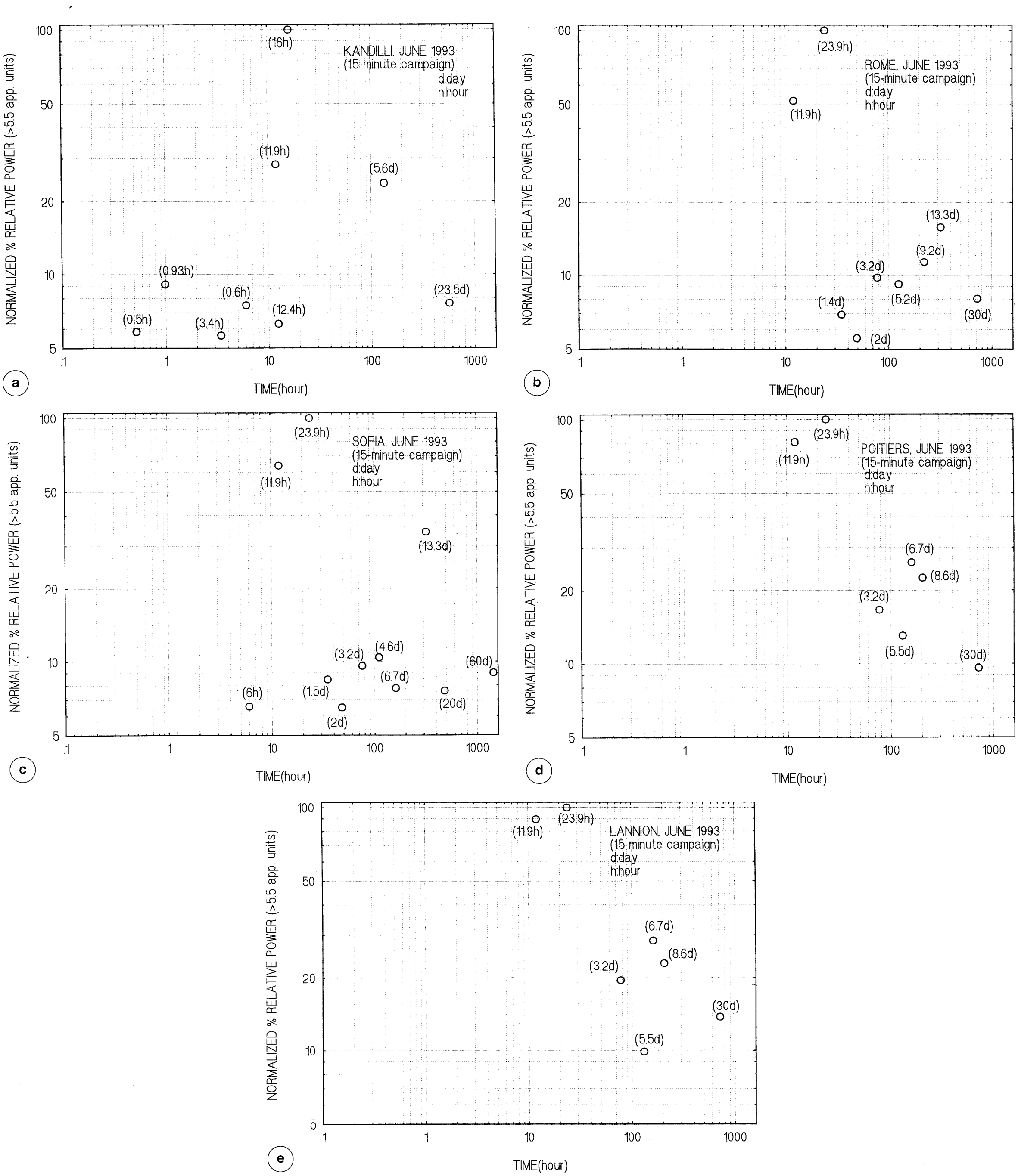

Fig. 3a-e. The normalized per-cent relative power of the major harmonics of those displayed in fig. 2a-e *vs.* time in hours, for: a) Kandilli; b) Rome; c) Sofia; d) Poitiers; e) Lannion.

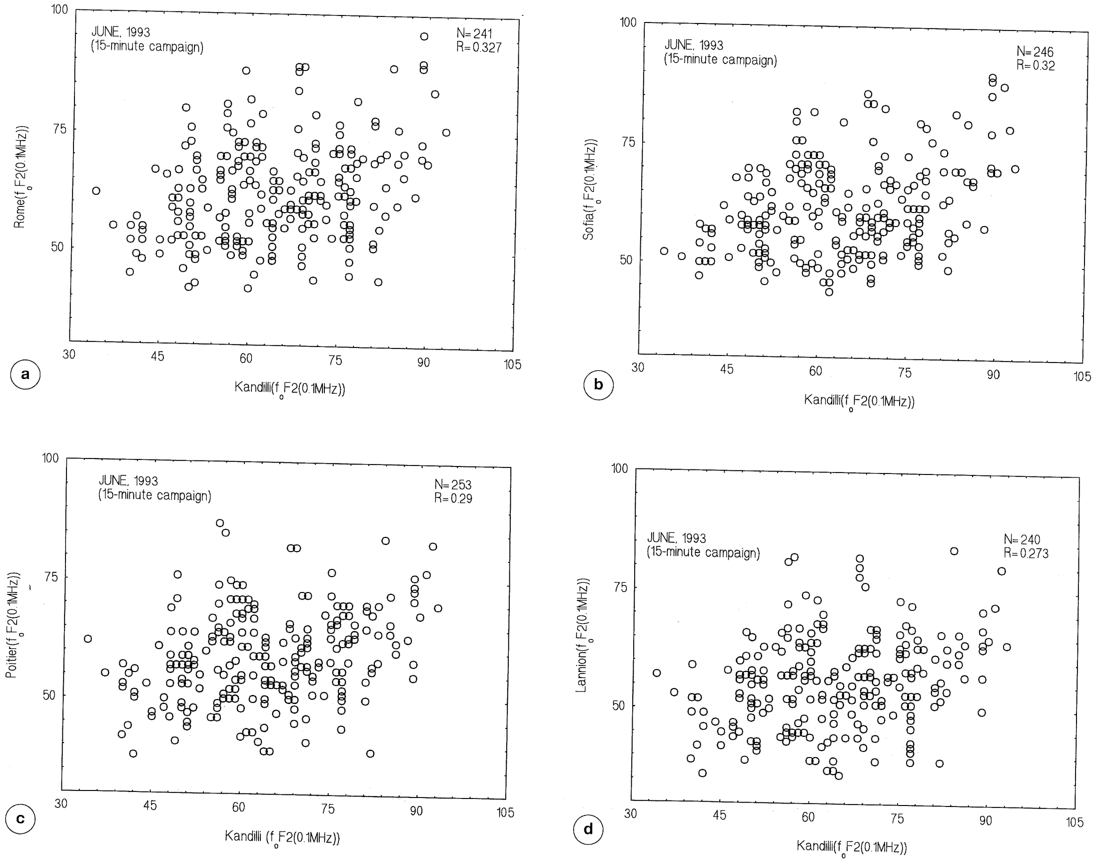

Fig. 4a-c. The scatter diagrams constructed between f_0F_2 values for: a) Rome; b) Sofia; c) Poitiers; d) Lannion. Number of the common data points and the cross correlation coefficients for each case are exhibited above the figures.

Table II. The cross correlation coefficients between critical frequencies obtained at several PRIME stations during the 15-min campaign.

Station	No.	Kandilli	Rome	Sofia	Poitiers	Lannion
Kandilli	264	1	0.33	0.32	0.29	0.27
Rome	2680	0.33	1	0.75	0.86	0.84
Sofia	2642	0.32	0.75	1	0.73	0.73
Poitiers	2744	0.29	0.86	0.73	1	0.96
Lannion	2673	0.27	0.84	0.73	0.96	1

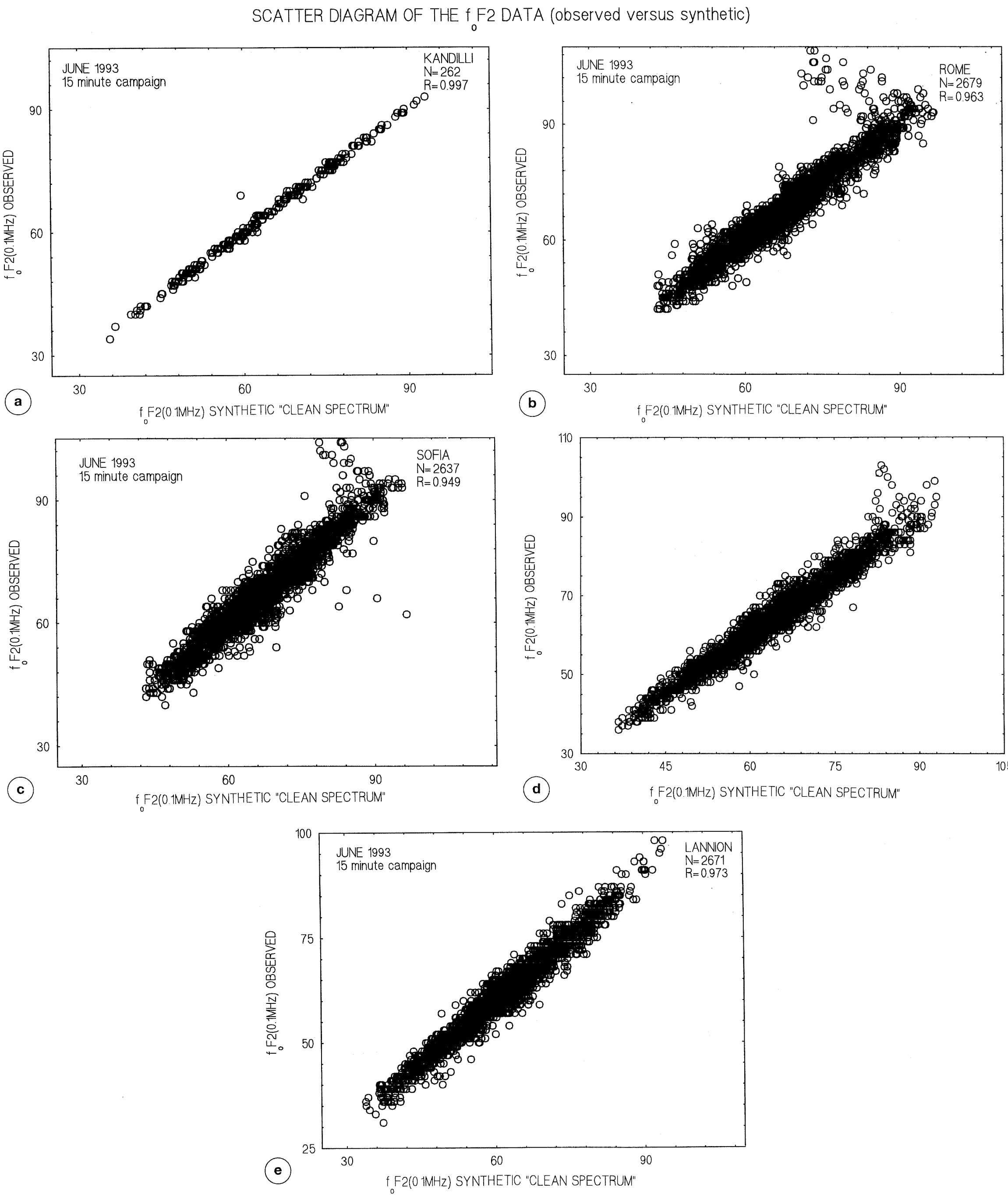

Fig. 5a-e. The observed f_0F_2 values are plotted *vs.* the f_0F_2 values computed by the DFT program of Roberts *et al.* (1987) for: a) Kandilli; b) Rome; c) Sofia; d) Poitiers; e) Lannion in June 1993. Number of data employed during the analysis and the cross correlation coefficients are also indicated separately in the figures.

Table III. The cross correlation coefficients between critical frequencies obtained at several PRIME stations and their generated data (synthetic).

Station	Cross correlation coefficient
Kandilli-Kandilli	0.997
Rome-Rome	0.963
Sofia-Sofia	0.949
Poitiers-Poitiers	0.973
Lannion-Lannion	0.973

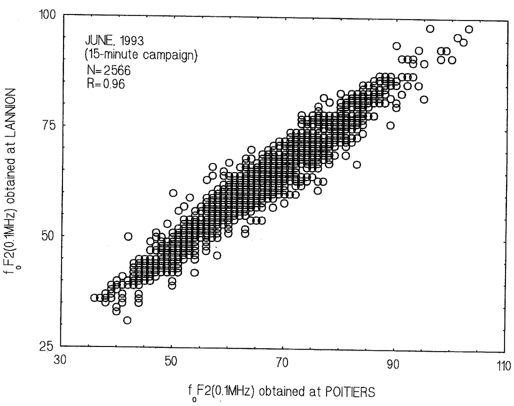

Fig. 6. The highest cross correlation coefficient is obtained between the f_0F_2 values at Lannion and those of Poitiers. This figure exhibits this fact as a scatter diagram during the 15-min campaign in June 1993.

highest cross correlation coefficient for this exercise was obtained for the case of Kandilli since the observed, available data were as small as 264. Table III summarizes the results which can be stated based on the output of fig. 5a-e.

Table III summarizes the cross correlation coefficients of the f_0F_2 values obtained at the pairs of the PRIME stations of interest. From the cross correlation coefficients exhibited in this table, at the significance level of $\alpha = 0.05$, there seems to be not much difference between Kandilli, Rome, Sofia, Poitiers and Lannion. Figure 6 is a typical good example to illustrate how well the f_0F_2 values of Lannion and Poitiers resemble each other at the significance level of $\alpha = 0.05$.

3.2. *Results of the analysis using the f_0F_2 data obtained every half hour at Kandilli*

Figure 7 shows the results of the DFT analysis by using the «clean spectrum» program of Roberts *et al.* (1987) for the, almost one year long f_0F_2 values of Kandilli. The fundamental

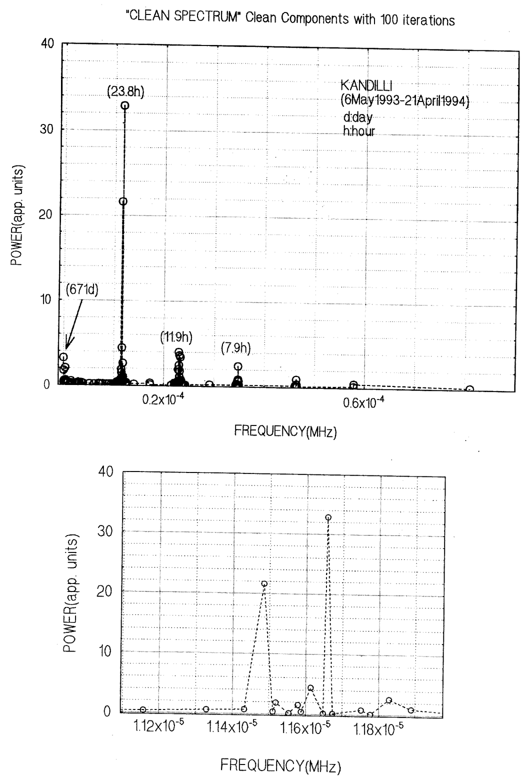

Fig. 7. The DFT spectrum of the f_0F_2 values obtained at Kandilli between 6 May 1993 and 21 April 1994 at every half hour. The algorithm and the program is due to Roberts *et al.* (1987). The portion of the figure around 0.1×10^{-4} MHz is magnified to resolve the harmonics in the small frame below.

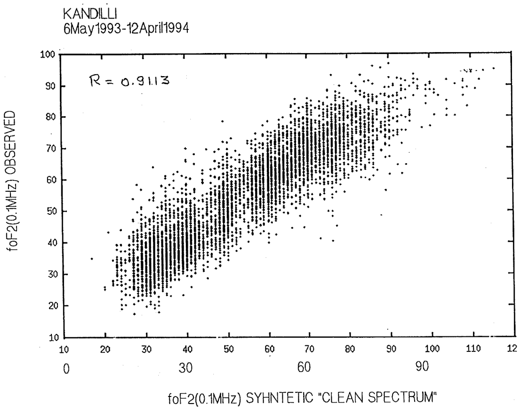

Fig. 8. The observed f_0F_2 values of Kandilli between 6 May 1993-21 April 1994 and the ones generated (synthetic) by the inverse DFT of Roberts *et al.* (1987) are scattered in this figure.

period in the Kandilli data turns out to be 23.8 h almost in agreement with those of the other four stations of interest. The spectrum results of the Kandilli data are exhibited in table Ib.

Figure 8 shows the scatter diagram of the observed Kandilli f_0F_2 values and those computed (synthetic) by the inverse DFT by the program of Roberts *et al.* (1987).

4. Conclusions

There are several very good DFT algorithms available. However, most of these programs take care of the data of a time series which are sampled continuously during the period of interest. The VI experiments made the f_0F_2 available at equal sampling periods. Yet due to the reasons which are not relevant here there are always gaps in time in the data. Therefore, the «clean spectrum» by Roberts *et al.* (1987) has the advantage over most of the other similar algorithms. This DFT program takes care of any data which are sampled at even intervals with data gaps.

The ultimate goal of this work is to be able to provide the user with an analytical expression or «model», so that, by putting in the independent variable time, one can obtain which frequency to use within the limitations of statistics.

This paper provides a preliminary «model» which only depends on time. The «model» is made by using the DFT coefficients for the major eighteen frequencies obtained in 100 iterations of the «clean spectrum» program of Roberts *et al.* (1987).

Table IV shows the major frequencies in (1/h) (or periods in hour); the corresponding DFT coefficients a's and b's for Kandilli, Rome, Sofia, Poitiers, Lannion; and both their means and medians for the cases if there are more than one entry. By using the median values and the mean DC component of 61.02 MHz the analytical expression of the «model» is expressed in eq. (4.1):

$$f_0F_2(t) = 61.02 + \\ +2\sum_{i=1}^{18} 2[a_i \cos(2\pi f_i t) - b_i \sin(2\pi f_i t)] \\ (\times 0.1)\ \text{MHz}. \qquad (4.1)$$

A very preliminary test of eq. (4.1) is made by computing the f_0F_2 values for Lannion, in June 1993 at 15-min intervals.

Figure 9 shows the observed f_0F_2 values for Lannion in June 1993. Superimposed are the f_0F_2 values computed using eq. (4.1). There were N = 2763 data points involved in the analysis. The cross correlation coefficient between the measured and the computed f_0F_2 values is R = 0.67. At the significance level of $\alpha = 0.05$, it seems that both the computed and the observed f_0F_2 values do come from the same population. One may thus conclude that, although there are differences in details, the general tendency of the curve obtained by the «model» is very similar to the observed one. Therefore, it seems very encouraging to improve eq. (4.1) further along the lines mentioned in this paper.

Table IV. The eighteen major frequencies (1/h) (or periods in hour); the corresponding DFT coefficients of a_i's and b_i's; their means, medians for the five PRIME stations of interest.

Frequency (1/h) (×10E-4)	Period (h)		Kandilli	Rome	Sofia	Poitiers	Lannion	MEAN	MEDIAN
84.03	11.9	*a*	2.68	− 0.37	− 3.08	− 2.46	0.52	− 0.54	− 0.37
		b	0.24	− 3.09	− 0.33	2.33	3.38	0.51	0.24
41.84	23.9	*a*		− 3.75	− 3.87	− 2.71	− 1.19	− 2.88	− 3.23
		b		− 2.14	− 0.18	2.62	3.42	0.93	1.22
28.82	34.7	*a*		− 0.57				− 0.57	− 0.57
		b		− 0.98				− 0.98	− 0.98
28.49	35.1	*a*			− 0.77			− 0.77	− 0.77
		b			− 0.82			− 0.82	− 0.82
20.88	47.9	*a*			0.35			0.35	0.35
		b			0.92			0.92	0.92
20.49	48.8	*a*		− 0.62				− 0.62	− 0.62
		b		0.81				0.81	0.81
13.19	75.8	*a*			1.09			1.09	1.09
		b			− 0.49			− 0.49	− 0.49
12.85	77.8	*a*		1.32		1.31	1.31	1.31	1.31
		b		− 0.28		− 0.81	− 0.92	− 0.67	− 0.81
9.03	110.7	*a*			1.19			1.19	1.19
		b			− 0.39			− 0.39	− 0.39
7.99	125.2	*a*		− 0.22				− 0.22	− 0.22
		b		− 1.29				− 1.29	− 1.29
7.64	130.9	*a*				− 0.99	− 0.91	− 0.95	− 0.95
		b				− 0.92	− 0.68	− 0.80	− 0.8
6.25	159.9	*a*			0.95	1.91	1.92	1.59	1.91
		b			0.52	0.27	0.15	0.31	0.27
4.86	205.6	*a*				− 1.49	− 1.52	− 1.51	− 1.505
		b				− 0.98	− 0.82	− 0.90	− 0.9
4.51	221.5	*a*		− 1.29				− 1.29	− 1.29
		b		− 0.66				− 0.66	− 0.66
3.13	319.8	*a*		1.62	2.04			1.83	1.83
		b		0.55	0.97			0.76	0.76
2.08	479.8	*a*			− 0.31			− 0.31	− 0.31
		b			− 1.02			− 1.02	− 1.02
1.39	719.7	*a*		− 1.19		− 1.17	− 1.33	− 1.23	− 1.19
		b		0.29		0.05	0.19	0.18	0.19
0.69	1439.5	*a*			− 0.59			− 0.59	− 0.59
		b			0.99			0.99	0.99

$$f_0F_2(t) = 61.02 + 2\sum_{i=1}^{18} 2\,[a_i \cos(2\pi f_i t) - b_i \sin(2\pi f_i t)]$$

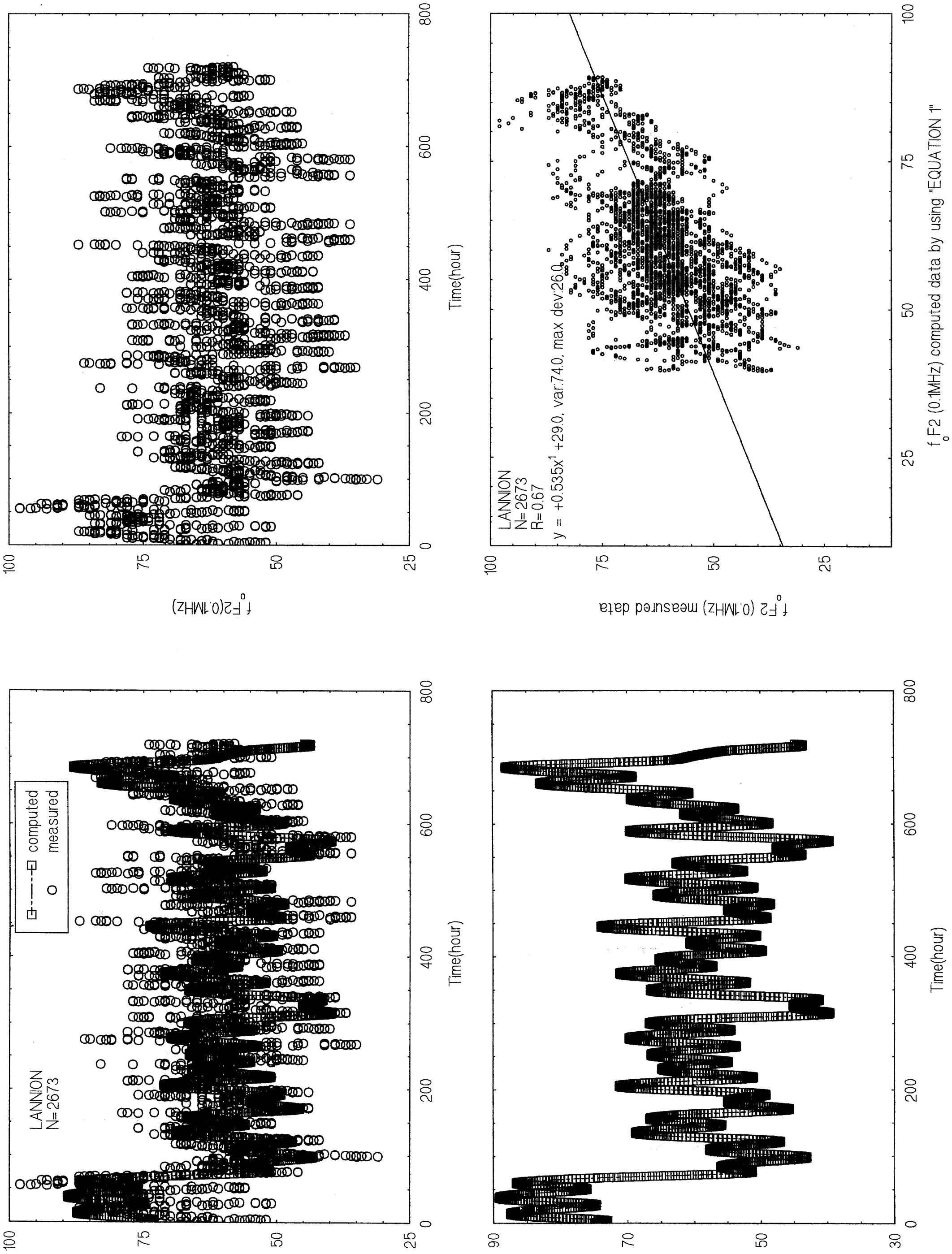

Fig. 9. The observed f_0F_2 values at Lannion in June 1993 during the 15-min campaign, superimposed is the data calculated by using eq. (4.1). The cross correlation coefficient between the observed data and the calculated data is exhibited along with the number of data points employed in the figure.

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