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SOLAR RADIO FLUXES AS INDICES OF SOLAR ACTIVITY

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Abstract—The daily solar radio flux values at 9400, 3750, 2000 and 1000 MHz and at 2800 MHz observed since 1957 at Toyokawa and Ottawa, respectively, have been used to provide new information on the solar radio fluxes as indices of solar activity. After an examination of the yearly mean values at each frequency, another investigation based on mean ratios during periods of 18 or 6 months indicates that a close connection is observed between the radio fluxes in the cm region and that anomalies related to calibration problems can be detected. The regression analysis of the daily values of the fluxes during at least 25 years and a special test on the sensitivity may provide final information on the stability of the data with respect to time and solar activity. The method is capable of detecting long-term trends corresponding to instrumental drifts. Such information is essential to our understanding of anomalies detected in the observations of u.v. and X-ray irradiances. However, such a method is based on a linear relationship. When a quadratic form, as it is observed in the decimeter region, is adopted, the effect of the various levels of activity in a solar cycle must be considered.

1. INTRODUCTION

Since the introduction by Wolf in 1847 of the so-called Relative Sunspot Number, a great many investigations of the variations in solar activity have been made. Also, for many years, other methods for evaluating the characteristics of sunspots have been adopted; these include the projected and corrected areas of spots, which have been determined at Greenwich since 1874, the studies of the classification and evolution of spots carried out at the Zurich Observatory and the investigations of the complex magnetic field in and near spot groups that have been undertaken at the Mount Wilson Observatory. In addition, all the solar phenomena that can be observed by optical means at ground level have been considered as indices of solar activity; these include photospheric faculae, H-alpha and Ca^+ flocculi appearing as chromospheric plages, prominences (dark filaments when projected on the solar disk) and, more recently, the green (5303 Å) and the red (6374 Å) coronal lines.

The essential problem is to find which of the various observable solar phenomena that vary with changes in the level of solar activity can be reduced to numerical indices representing these changes as closely as possible. Such indices must be suitable also as indicators of the level of solar activity in studies of various geophysical phenomena. It is necessary also to have indices which represent the way in which geophysical phenomena are influenced by changes in solar activity; in this field, the reviews prepared by Mayaud (1980) for geomagnetic indices and by Minnis (1964) for ionospheric indices are well known.

Nowadays, rockets and satellites make it possible to observe solar radiation in the u.v. and X-ray regions. It seems possible that information on these radiations might also be obtained indirectly by the observations of solar events known to be related to various spectral irradiances. However, many more observations will be needed before it becomes possible to form a complete picture of the periodicities associated with the Sun and, in particular, with those relating to its projected surface as seen from the Earth: the solar disk.

Another method for studying changes in solar activity has proved to be fruitful; this is the use of solar radio emissions in the cm and dm wavebands, which originate at different levels between the chromosphere and the corona and which can form the basis of solar radio indices. The radio fluxes can be regarded as fairly objective indices of solar activity, so long as it is accepted that they refer to the disk as a whole and not to specific features. The characteristics of the radio fluxes in the region between 3 and 30 cm have been closely studied, and the present article is concerned mainly with the most relevant correlations between the different fluxes, and with the accuracy of the observational data.

2. OBSERVATIONAL DATA

Extensive solar radio flux observations have been conducted since 1946 at a wavelength of 10.7 cm (2800 MHz) at Ottawa by the National Research Council of

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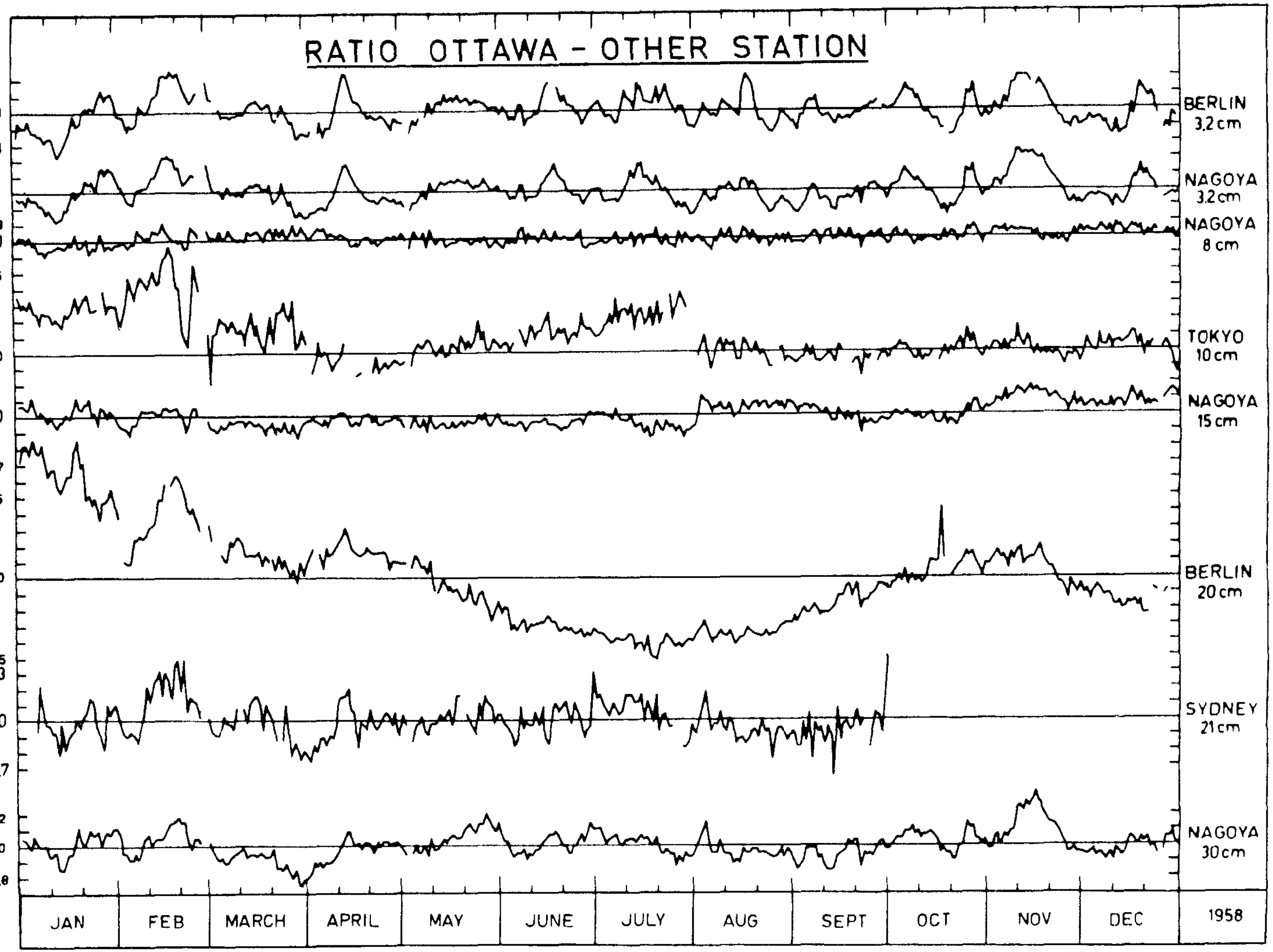

FIG. 1. RATIO OF SOLAR RADIO-EMISSIONS AT 3, 8, 10.7, 15, 20, 21 AND 30 cm IN 1958 TO THE SOLAR RADIO-EMISSION AT 10.7 cm (OTTAWA) WHEN THE AVERAGE RATIO FOR THE WHOLE YEAR IS 1 (NICOLET, 1960).

Canada, and since November 1951 at 8 cm (3750 MHz) at Toyokawa by the Institute of Atmospherics of Nagoya University. Other regular observations have been made at Toyokawa at 3.2 cm (9400 MHz) since May 1956 (Tanaka and Kakinuma, 1956), and at 15 cm (2000 MHz) and 30 cm (1000 MHz) since just before the International Geophysical Year (Tanaka and Kakinuma, 1958).

In the early days of monitoring solar radiation in the cm and dm bands, the accuracy of the daily calibrations was generally poor, and several years elapsed before final and successful conclusions were reached concerning the absolute values of the radio flux. In his analysis of the various causes of temperature variations at the thermopause, Nicolet (1960) pointed out that the radiation fluxes at certain radio frequencies were not reliable indices. The correlation, or the lack of correlation, between various atmospheric parameters and several published values of radio fluxes were spurious because of drifts of instrumental origin (Nicolet, 1960, 1961). It appeared also that, when the errors in the calibration of certain radio measurements were eliminated, the radio fluxes at all wavelengths between 3 and 30 cm varied in almost the same way with changes in solar activity. Nevertheless, it is possible that systematic errors are also present; for example, when a periodic seasonal variation arises because of the assumption of constant sky temperature. Other systematic errors may have been introduced, particularly at the shortest wavelengths, by variations in the attenuation of the lower atmosphere. Finally, in any series of routine observations, sporadic fluctuations that are not related to the solar radiation may occur.

Before the International Geophysical Year, an effort was made at Nagoya and at Ottawa to estimate the internal consistency and the absolute accuracy of the measured radio fluxes in the microwave region (Tanaka and Kakinuma, 1953, 1956, 1958; Covington and Medd, 1954; Tanaka, 1955; Medd and Covington, 1958). At 3, 8 and 10 cm, the errors reached 10% and were even greater at 15 and 30 cm. An analysis of the correlation between the solar radio flux and the temperature of the upper atmosphere made by Nicolet (1963) indicated that certain systematic errors were associated with differences in behaviour at a few wavelengths. At various other observatories (Fig. 1) it was found that several radio fluxes between 3 and 30 cm were affected by inaccuracies in the daily calibrations, arising from instrumental effects (Krüger *et al*., 1964). As a result, for example, Priester and Martin (1959) found spurious correlations between atmospheric densities deduced from satellite drag and the 20 cm flux as observed in Berlin (see Fig. 1), while Nicolet (1963) was using the correct data from Nagoya and Ottawa.

Finally, a paper was published jointly by Tanaka (Japan), Castelli (U.S.A.), Covington (Canada), Krüger (DDR), Landecker (Australia) and Tlamicha (Czechoslovakia): Tanaka *et al.* (1973). This paper contains a complete history of the problems of absolute calibrations, so as to avoid confusion, and it includes correction factors designed to convert the published routine observations of flux into consistent series of values. This led to the publication of two booklets of practical value:

(a) *Complete Summary of Daily Solar Radio Flux at Toyokawa Observatory* by Tanaka (Nagoya University, February 1975). This contains a list of corrected absolute values from the beginning of the observations up to December 1974.

(b) *A Working Collection of Daily 2800 MHz Solar Flux Values 1946–1976* by Covington (National Research Council of Canada, August 1977). In this, all the important errors that had been detected were removed (Covington, 1948, 1953, 1966).

We have used these two publications, and the subsequent monthly supplements, as the basis for our study of the behaviour of solar radio fluxes in the microwave region from 3 to 30 cm during a period of more than 25 years, between 1957 and 1983.

3. GENERAL TRENDS IN RADIO SOLAR FLUXES

One of the first investigations of the variations in radio flux must be to study the yearly mean values. These are listed in Table 1 for the period 1957–1983 and are expressed in the usual units: 10^{-22} Wm^{-2} Hz^{-1}. The values quoted are those actually observed; for example, those for Ottawa correspond to the yearly mean values at 2800 MHz (Series C) observed daily at 1700 h UT. The relative sunspot numbers are given in the last column of Table 1 so as to illustrate the relation between the radio flux and the oldest of all the indices of solar activity. The minimum values of the Wolf number (10 and 13) occur in 1964 and 1976. In this connection, it is worth pointing out that the Relative Sunspot Number (R) is defined by the relation $R = 0.6\,(10g+f)$, where g is the number of spot groups and f is the number of individual spots; the constant factor 0.6 has been introduced by the Swiss Federal Observatory (Waldmeier, 1966). The minimum possible value of R is obviously zero, but the next lowest value is 7, since one isolated spot gives $R = 0.6\,(10+1) = 6.6$ Similarly, the number 10 would result from one spot group containing 6 or 7 spots, and 13 from two groups each containing only one spot.

Table 1 shows that the minima and the maxima in the yearly mean values occur simultaneously at all

TABLE 1. MEAN ANNUAL VALUES (10^{-22} Wm^{-2} Hz^{-1}) OF THE SOLAR RADIO FLUXES AT 1 ASTRONOMICAL UNIT

Year	3 cm	Ratio	8 cm	Ratio	10 cm(*)	Ratio	15 cm	Ratio	30 cm	Ratio(**)	Wolf Number
1957	374	1.44	230	2.88	249	3.44	198	3.73	151	3.49	206
8	359	1.38	211	2.64	232	3.18	184	3.47	146	3.40	185
9	350	1.35	196	2.45	210	2.88	165	3.11	131	3.05	159
1960	327	1.26	154	1.93	162	2.22	130	2.45	105	2.44	112
1	282	1.09	107	1.34	105	1.44	84	1.58	63	1.47	54
2	270	1.04	95	1.19	90	1.23	71	1.34	56	1.30	37
3	264	1.01	87	1.09	81	1.11	61	1.15	49	1.14	28
4	261	1.00	79	1.00	73	1.00	53	1.00	43	1.00	10
5	268	1.03	82	1.03	76	1.04	56	1.06	47	1.09	15
6	284	1.09	103	1.29	102	1.40	78	1.47	64	1.49	47
7	308	1.18	137	1.71	143	1.96	113	2.13	89	2.07	94
8	311	1.20	143	1.79	149	2.04	118	2.23	96	2.23	106
9	317	1.22	148	1.85	151	2.07	123	2.32	94	2.19	105
1970	317	1.22	154	1.93	156	2.14	130	2.45	98	2.28	105
1	290	1.12	119	1.51	118	1.62	94	1.77	73	1.69	67
2	291	1.12	122	1.53	121	1.66	97	1.73	76	1.77	69
3	271	1.04	97	1.21	93	1.27	72	1.36	58	1.26	38
4	270	1.04	92	1.15	87	1.19	67	1.26	53	1.23	34
5	261	1.00	83	1.04	76	1.04	59	1.11	47	1.09	16
6	259	1.00	80	1.00	73	1.00	56	1.06	46	1.03	13
7	267	1.03	91	1.14	87	1.19	68	1.28	56	1.30	27
8	306	1.18	142	1.76	143	1.96	119	2.24	90	2.09	92
9	336	1.29	182	2.27	192	2.63	161	3.04	123	2.86	155
1980	335	1.29	184	2.30	198	2.71	164	3.09	126	2.93	155
1	340	1.31	188	2.35	203	2.78	168	3.17	127	2.95	140
2	325	1.25	167	2.09	175	2.40	144	2.72	110	2.56	116
3	286	1.10	118	1.48	120	1.64	98	1.85	81	1.88	67
MEAN (27 years)	300		132		134(*)		108		84		82

* For conversion in absolute units, 10 cm flux must be multiplied by 0.9. Thus, 121 instead of 134.
** The "amplification factor" at a given frequency is defined as the ratio of the ratio of the flux in a given year to the flux in 1964, when solar activity was at its minimum (quiet Sun year).

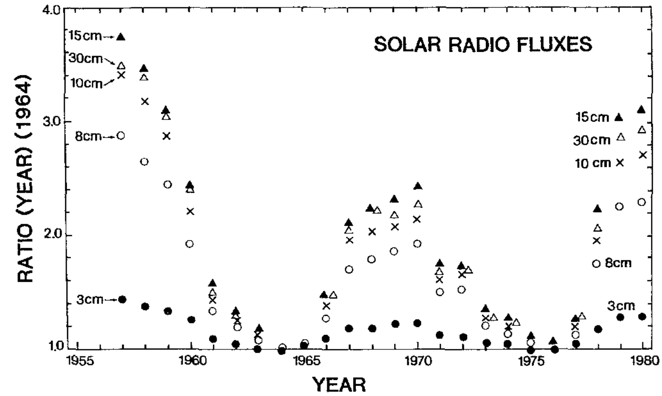

FIG. 2. RATIO OF SOLAR RADIO FLUXES (ANNUAL AVERAGE) TO FLUXES IN 1964 (QUIET SUN) AT 3, 8, 10.7, 15 AND 30 cm.

wavelengths: in 1964 and 1976 for the minima, and in 1957–1958, 1969–1970 and 1979–1981 for the maxima. It can be concluded that, even though the sunspot and the radio flux cycles may not be identical, the yearly minima and the maxima coincide with each other.

For the period 1957–1980, Fig. 2 shows the ratio of the yearly mean flux values to the mean for 1964; minima occurred in 1964 and 1976. As in Table 1, it can be seen that the amplitude of the variations at 3 cm is small as compared with the amplitudes at other wavelengths; the greatest amplitude is at 15 cm. The general character of the yearly mean variation is the same at all frequencies between 10,000 and 1000 MHz. On the other hand, if the yearly mean values of the radio fluxes are compared with each other, it becomes clear that the relations are not identical. The fluxes at 10 cm are compared with those at 3 cm in Fig. 3, and with those at 8, 15 and 30 cm in Fig. 4; as can be seen, the scatter of the points is much greater at 30 cm than at 3 cm. The yearly mean values at 3 cm can be expressed, in terms of the values at 10 cm, by a linear regression with an accuracy better than 2%, except for the year 1960. Figure 5 shows the linear regressions between the yearly mean fluxes at 3 and at 8 cm, and here also there is a discrepancy for the year 1960. It is concluded that there must have been an error in the final adjustment of the instruments at 3 cm, and this question will be discussed later. Small systematic differences, which occur between 1965 and 1969, should also be considered as anomalous results related to calibration problems.

Figure 4 illustrates the increase in the scatter of the points as the wavelength is increased from 8 cm (less than $\pm 3\%$) to 30 cm (greater than $\pm 5\%$); this may be attributed partly to a decrease in the accuracy of the measurements, and partly to real differences in the flux variations as a function of wavelength.

It seems necessary, therefore, to analyse the data in other ways and to try to determine whether there are systematic differences in behaviour during certain

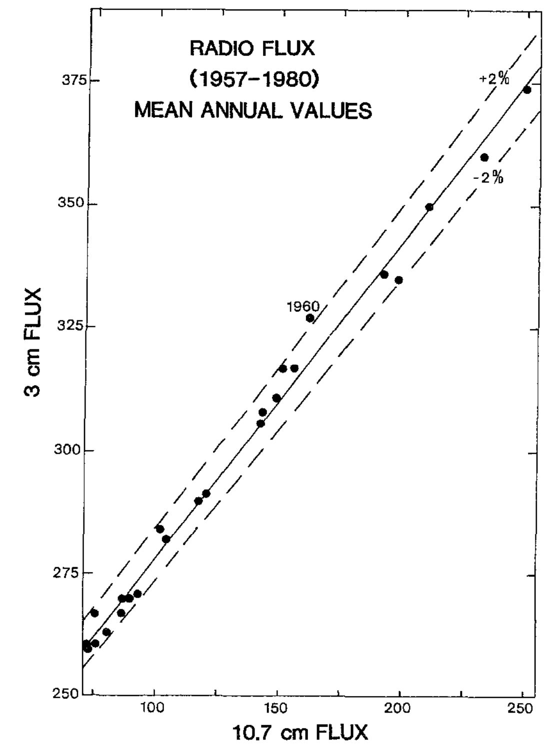

FIG. 3. LINEAR REGRESSION BETWEEN ANNUAL MEAN VALUES OF RADIO FLUXES AT 3 AND 10 cm FROM 1957 TO 1980. Relationship better than $\pm 2\%$ except in 1960.

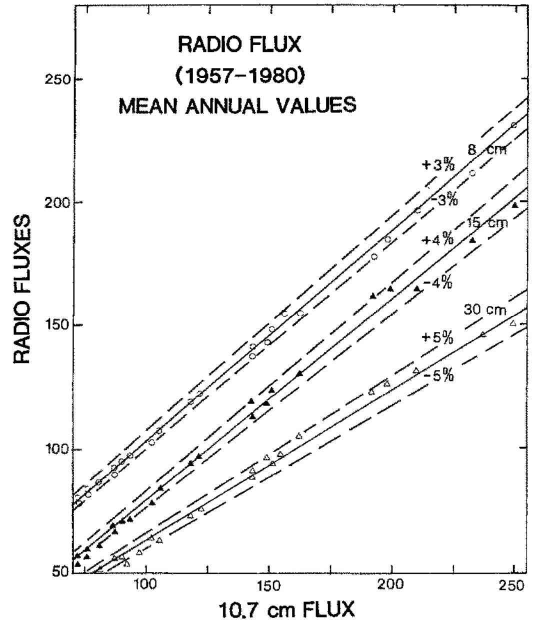

FIG. 4. LINEAR REGRESSION BETWEEN ANNUAL MEAN VALUES OF RADIO FLUXES AT 8, 15 AND 30 cm AND THE RADIO FLUX AT 10 cm FROM 1957 TO 1980.

Relationship better than $\pm 3\%$ at 8 cm. Relationship better than ± 4 and $\pm 5\%$ at 15 and 30 cm, respectively, except at low and high values of the solar flux corresponding to a quadratic relationship.

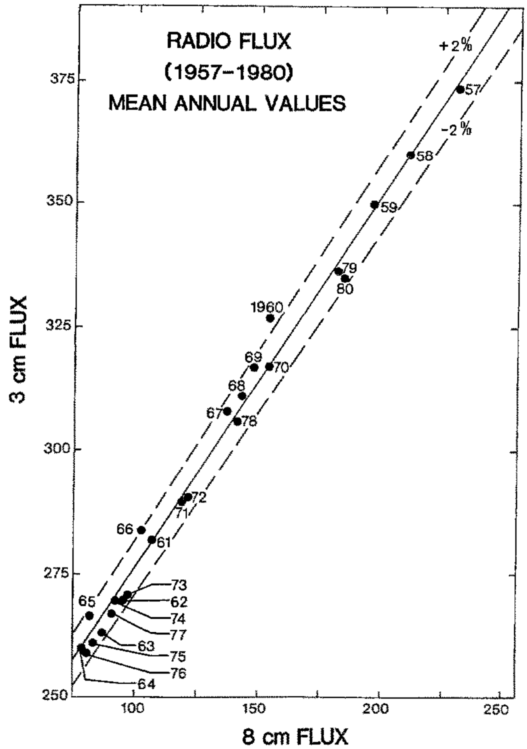

FIG. 5. LINEAR REGRESSION BETWEEN ANNUAL MEAN VALUES OF RADIO FLUXES AT 3 AND 8 cm FROM 1957 TO 1980.

Relationship better than $\pm 2\%$ as illustrated in Fig. 3. Anomalous result in 1960, but normal values in 1959 and 1961. Also systematic differences occur from 1965 to 1969.

periods. In order to avoid introducing spurious annual or seasonal effects into the analysis, we have first divided the data into 16 periods of 18 months between 1 July 1957 and 30 June 1981. The first period corresponds to the IGY: 1957–1958. In order to provide a common basis for comparing the different radio fluxes, we have constructed Tables 2a and b which refer to the 10.7 cm flux measured at Ottawa, but adjusted to a Sun–Earth distance of 1 AU, for the period 1957–1980. All the flux values have been divided into activity classes of width ± 5 units in Table 2a and ± 10 units in Table 2b. Each of the numbers in these tables represents a "period ratio"; i.e. the ratio of the flux for a given period in a given activity class to the mean value for all the periods within the same activity class. In Table 2a, all the ratios lie within the range 1 ± 0.01, except for a very few cases where the departure reaches 0.02. In Table 2b, the departure from unity at very low levels of solar activity are greater because of the greater width of the activity classes whence because there are real differences between 18-month periods at low solar activity; all these differences are included in the range 75 ± 7.5 ($= \pm 10\%$).

The above analysis of the behaviour of the flux at 10.7 cm shows that it can be used as a reference in studies of the fluxes at other wavelengths. Therefore the fluxes observed at Toyokawa at 8 and 15 cm have been analysed by calculating period ratios in the same way as for the 10.7 cm flux at Ottawa. Note that the activity classes used in Tables 2–6 are all defined in terms of the flux at 10.7 cm. In Tables 2a–6a, the width of the classes is 10 units, while in Tables 2b–6b the width is 20 units. Tables 3a and b correspond to Tables 2a and b, respectively, but they refer to the 8 cm flux at Toyokawa (vs the 10.7 cm flux at Ottawa). The period ratios in Tables 3a and b are uniformly distributed for all levels of solar activity over the whole 24-year period with a variation of ± 0.02, except for a few periods where they reach 1.04 and 1.06. Nevertheless, it appears that there are some small systematic variations in the ratios with time; the smallest values occur in Periods 1–16, and the largest in Periods 9 and 11. Otherwise the general uniformity is excellent, and even the maximum departures from unity are small. Tables 4a and b

TABLE 2a. RATIOS (%) OF THE MEAN FLUX FOR AN 18-MONTH PERIOD TO THE MEAN FLUX FOR ALL PERIODS IN THE SAME ACTIVITY CLASS*

10.7 cm[(1)]	070	080	090	100	110	120	130	140	150	160	170	180	190	200
PERIOD[(2)]														
01											100	100	100	
02							100	100	100	100	100	100	100	
03			102	100	100	100	100	100	100	100	100	100	100	
04	102	101	099	099	100	099	099							
05	099	100	099	099										
06	101	099	101	100	099									
07			102	100	100	100	100	100	099	100	100	099		
08						101	100	100	100	099	100	100	100	100
09				102	100	100	100	100	100	100	099	100	100	
10			102	101	100	100	100	099	100	100	099	100		
11	102	102	101	100	100	099	100	100	099	100				
12	100	100	099	099	101	099								
13	099	099	098											
14	101	101	099	100	101	100	101	099	100	099				
15					099	100	100	101	100	100	100	100	100	100
16								100	101	100	101	100	100	100

* Wavelength 10.7 cm; class width 10 flux units.
(1) *10.7 cm classification*: xxx $\pm$ 5.
(2) 18 months $\times$ 16 = 24 years.

TABLE 2b. RATIOS (%) OF THE MEAN FLUX FOR AN 18-MONTH PERIOD TO THE MEAN FLUX FOR ALL PERIODS IN THE SAME ACTIVITY CLASS*

10.7 cm[2]	1[1] 0001 0547	2 0548 1095	3 1096 1643	4 1644 2191	5 2192 2739	6 2740 3287	7 3288 3835	8 3836 4383	9 4384 4931	10 4932 5479	11 5480 6027	12 6028 6575	13 6576 7123	14 7124 7671	15 7672 8219	16 8220 8647	10.7 cm[3]
075				1.04	0.98	1.00					1.06	1.00	0.98	1.02			75.80
095			1.03	0.98	0.97	1.00	1.03			1.04	1.01	0.98	0.96	0.98			95.05
115			1.00	0.98		0.96	1.01	1.05	1.03	0.99	0.99	1.00		1.01	1.00		114.85
135		1.03	1.00	0.96			0.98	1.01	1.00	1.00	1.00	0.97		1.00	1.01	1.02	135.09
155		1.01	1.01				1.00	0.99	1.00	0.98	0.99			1.00	1.00	1.01	155.35
175	1.02	1.01	0.99				1.00	1.00	0.99	0.99				1.01	1.00	1.00	175.18
195	1.00	1.00	0.99				1.00	1.00	1.00	0.99					0.99	1.00	195.02
215	1.00	1.00	1.00				0.99	0.99	0.99						0.99	1.00	215.37
235	1.00	1.00													0.99	1.00	234.63
255	1.00	1.00														1.00	253.86
275	1.00	1.00														1.00	274.03
295	1.00																294.21
315		1.00															313.78

* Wavelength 10.7 cm; class width 20 flux units.
(1) 16 periods × 18 months = 24 years; 0001–0547 January 1957–June 1958; 8220–8647 July 1979–December 1980.
(2) 10.7 cm classification xxx ± 10.
(3) Average for all periods.

TABLE 3a. RATIOS (%) AS IN TABLE 2a, BUT FOR WAVELENGTH 8 cm*[(2)]

10.7 cm[(1)]	070	080	090	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250
PERIOD[(3)]																			
01												098	098	098	098	099	099	099	098
02								098	099	098	098	099	098	099	099	099	101	101	102
03			102	100	099	099	099	100	100	098	100	099							
04	102	101	100	102	102	104													
05	099	099	100	103															
06	101	099	101	101	101														
07			100	098	098	098	097	098	098	100	100	100							
08						099	099	099	099	098	100	101	100	100					
09				102	101	102	101	101	102	103	102	104	105						
10			101	101	100	101	101	101	103	101	104								
11	102	103	101	100	101	102	102	102	105										
12	101	101	100	104	101														
13	099	100	099																
14	100	100	099	100	101	101	103	102	102	101									
15					099	100	101	101	100	101	101	101	102	103	103	102	101	100	
16								097	099	098	098	098	097	099	099	099	100	100	101

* Class width 10 flux units.
(1) 10.7 cm classification: xxx $\pm$ 5.
(2) Ratio 8 cm 18 months/24 years.
(3) 18 months $\times$ 16 = 24 years; 1957–1981.

TABLE 3b. RATIOS AS IN TABLE 2b, BUT FOR WAVELENGTH 8 cm*

10.7 cm[(2)]	1[(1)] 0001 0547	2 0548 1095	3 1096 1643	4 1644 2191	5 2192 2793	6 2740 3287	7 3288 3835	9 3836 4383	9 4384 4931	10 4932 5479	11 5480 6027	12 6028 6575	13 6576 7123	14 7124 7671	15 7672 8219	16 8220 8647	8 cm[(3)]
075				1.03	0.98	1.00					1.06	1.01	0.98	1.01			81.94
095			1.02	0.99	0.99	1.00	1.00			1.03	1.00	0.99	0.98	0.98			98.15
115			0.99	1.00		0.98	0.98	1.02	1.04	0.99	1.00	1.03		1.02	1.00		115.16
135		1.00	0.99	1.01			0.96	1.00	1.02	1.01	1.02	1.00		1.02	1.02	0.99	131.92
155		0.99	0.99				0.99	0.98	1.02	1.00	1.02			1.02	1.00	0.99	150.29
175	0.99	0.99	0.99				1.00	1.00	1.02	1.01				1.04	1.01	0.98	167.07
195	0.98	0.99	0.99				1.05	1.01	1.04	1.03					1.02	0.98	184.03
215	0.99	0.99	1.04				1.02	1.00	1.07						1.02	0.99	199.81
235	0.99	1.00													1.00	0.99	216.07
255	0.99	1.01														1.00	234.27
275	1.00	1.02														1.00	254.07
295	1.00																271.23
315		1.02															298.00

* Class width 20 flux units.
(1) 16 periods × 18 months = 24 years; 0001–0547 January 1957–June 1958; 8220–8647 July 1979–December 1980.
(2) 10.7 cm classification xxx ± 10.
(3) Average for all periods.

TABLE 4a. RATIOS (%) AS IN TABLE 2a BUT FOR WAVELENGTH 15 cm*[(2)]

10.7 cm[(1)]	070	080	090	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250
PERIOD[(3)]																			
01												100	099	099	099	100	100	101	100
02								102	100	100	100	099	098	098	098	097	097	097	097
03			103	101	100	100	098	099	099	097	096	100	099						
04	106	103	100	102	102	101	100												
05	096	097	094	095															
06	099	096	097	095	088														
07			101	098	098	099	098	096	095	096	096	094							
08						100	100	098	098	097	097	095	094	096	098				
09					105	102	103	102	102	102	100	100	099	100					
10			104	103	100	099	099	099	100	100	098	096							
11	104	104	101	100	102	100	100	100	099	099									
12	101	102	099	099	098	097													
13	100	100	098																
14	104	102	101	101	100	101	105	103	101	100									
15					101	102	103	104	103	103	103	104	104	104	104	103	103	102	
16								106	194	103	103	102	103	103	103	103	101	103	

* Class width 10 flux units.
(1) 10.7 cm classification: xxx $\pm$ 5.
(2) Ratio 15 cm 18 months/24 years.
(3) 18 months $\times$ 16 = 24 years: 1957–1981.

TABLE 4b. RATIOS AS IN TABLE 2b, BUT FOR WAVELENGTH 15 cm*

10.7 cm[2]	1[1] 0001 0547	2 0548 1095	3 1096 1643	4 1644 2191	5 2192 2739	6 2740 3287	7 3288 3835	8 3836 4383	9 4384 4931	10 4932 5479	11 5480 6027	12 6028 6575	13 6576 7123	14 7124 7671	15 7672 8219	16 8220 8647	15 cm[3]
075				1.06	0.95	0.98					1.09	1.01	0.99	1.04			57.27
095			1.04	0.99	0.92	0.95	1.02			1.06	1.01	0.98	0.94	0.99			74.36
115			1.00	0.99		0.85	0.99	1.04	1.06	0.99	1.00	0.98		1.01	1.02		91.86
135		1.05	0.98	0.96			0.96	1.00	1.02	0.98	1.00	0.93		1.04	1.04	1.08	109.73
155		1.01	0.98				0.96	0.97	1.02	0.99	0.98			1.00	1.03	1.04	127.04
175	1.02	1.00	0.97				0.95	0.96	1.00	0.96				1.00	1.04	1.03	153.56
195	0.99	0.98	0.97				0.95	0.94	0.99	0.95					1.04	1.03	158.63
215	1.00	0.98	0.95				0.93	0.97	0.97						1.03	1.03	172.83
235	1.01	0.97													1.02	1.02	188.12
255	1.01	0.98														1.02	200.25
275	1.00	0.98														1.01	213.28
295	1.00																227.43
315		0.98															242.72

* Class width 20 flux units.
[1] 16 periods × 18 months = 24 years; 0001–0547 January 1957–June 1958; 8220–8647 July 1979–December 1980.
[2] 10.7 cm classification xxx ± 10.
[3] Average for all periods.

TABLE 5a. RATIOS (%) AS IN TABLE 2a, BUT FOR WAVELENGTH 30 cm*[(2)]

10.7 cm[(1)]	070	080	090	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250
PERIOD[(3)]																			
01												110	107	107	106	104	103	104	103
02								112	111	112	109	107	104	101	102	099	098	099	098
03			101	098	096	095	095	096	101	100	099	102	098						
04	104	100	099	098	097	093													
05	096	096	091	089															
06	100	098	096	092	084														
07			108	104	103	103	100	096	093	093	092	089							
08						109	104	101	100	098	095	092	091	089	088				
09					110	106	104	101	099	099	095	093	090	089					
10			107	105	101	097	094	092	095	092	089	086							
11	107	107	102	101	100	099	095	096	094	093									
12	101	101	097	096	091	091													
13	100	099	094																
14	106	104	103	102	101	099	099	098	094	090									
15					104	101	102	104	103	102	100	101	100	100	098	096	094	095	
16								116	110	107	106	104	104	103	101	099	101	096	097

* *Class width 10 flux units.*
(1) 10.7 cm classification: xxx ± 5.
(2) Ratio 30 cm 18 months/24 years.
(3) 18 months × 16 = 24 years; 1957–1981.

TABLE 5b. RATIOS AS IN TABLE 2b, BUT FOR WAVELENGTH 30 cm*

10.7 cm[2]	1[1] 0001 0547	2 0548 1095	3 1096 1643	4 1644 2191	5 2192 2739	6 2740 3287	7 3288 3835	8 3836 4383	9 4384 4931	10 4932 5479	11 5480 6027	12 6028 6575	13 6576 7123	14 7124 7671	15 7672 8219	16 8220 8647	30 cm[3]
075				1.04	0.94	0.99					1.12	1.01	0.98	1.06			46.76
095			1.00	0.97	0.89	0.94	1.08			1.08	1.02	0.96	0.90	1.02			59.41
115			0.96	0.95		0.80	1.04	1.14	1.11	0.98	0.99	0.91		1.00	1.03		72.17
135		1.15	0.95	0.90			0.98	1.03	1.02	0.93	0.96	0.79		0.98	1.04	1.19	87.64
155		1.12	1.01				0.93	0.98	0.99	0.93	0.93			0.92	1.03	1.09	99.75
175	1.12	1.08	1.00				0.90	0.94	0.94	0.87				0.87	1.01	1.05	111.51
195	1.07	1.03	0.96				0.88	0.90	0.90	0.84					1.00	1.03	122.76
215	1.05	1.00	0.97				0.83	0.90	0.88						0.97	1.00	132.65
235	1.03	0.98													0.95	0.99	143.28
255	1.03	0.98														0.97	150.36
275	1.01	0.98														0.96	158.29
295	1.01																165.62
315		0.97															168.39

* Class width 20 flux units.
[1] 16 periods × 18 months = 24 years; 0001–0547 January 1957–June 1958.
[2] 10.7 cm classification: xxx ± 10.
[3] Average for all periods.

Table 6a. Ratios (%) as Table 2a, but for wavelengths 3 cm*[(2)]

10.7 cm[(1)]	070	080	090	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250
PERIOD[(3)]																			
01												099	099	099	100	100	100	099	100
02								100	099	099	100	100	100	099	100	099	101	102	101
03			101	100	101	100	101	102	104	102	103	104	106						
04	100	100	099	099	099	097	098												
05	100	099	099	100															
06	102	102	102	102	101														
07			103	101	102	101	100	100	101	101	100	102							
08						100	100	100	100	099	100	101	102	100	101				
09					102	101	101	100	100	101	101	100	102	103					
10			102	100	100	099	099	099	099	098	099	099	099						
11	100	100	100	099	099	099	099	100	102	102									
12	100	100	100	100	101	098													
13	099	099	099																
14	099	099	099	100	100	099	100	100	100	099									
15				101	101	100	099	099	099	099	099	100	101	100	101	099	100		
16							097	098	098	098	098	097	099	098	098	099	099	099	

* Class width 10 flux units.
[(1)] 10.7 cm classification: xxx ± 5.
[(2)] Ratio 3 cm 18 months/24 years.
[(3)] 18 months × 16 = 24 years; 1957–1981.

TABLE 6b. RATIOS AS IN TABLE 2b, BUT FOR WAVELENGTH 3 cm*

10.7 cm[2]	1[1]	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	3 cm[3]
	0001	0548	1096	1644	2192	2740	3288	3836	4384	4932	5480	6028	6576	7124	7672	8220	
	0547	1095	1643	2191	2739	3287	3835	4383	4931	5479	6027	6575	7123	7671	8219	8647	
075				1.00	0.99	1.02					1.01	1.00	0.99	0.99			262.12
095			1.01	0.99	0.99	1.02	1.02			1.01	0.99	1.00	0.98	0.99			274.43
115			1.01	0.98		1.00	1.01	1.01	1.02	0.99	0.99	1.00		0.99	1.01		288.48
135		1.01	1.02	0.97			1.00	1.00	1.00	0.99	1.00	0.99		1.00	1.00	0.98	302.69
155		1.00	1.03				1.01	0.99	1.01	0.98	1.02			1.00	0.99	0.98	315.89
175	1.00	1.00	1.03				1.01	1.01	1.00	0.99				1.02	0.99	0.98	328.17
195	0.99	1.00	1.06				1.05	1.01	1.02	1.00					1.00	0.98	339.43
215	1.00	1.00	1.02				1.02	1.01	1.06						1.00	0.98	349.74
235	1.00	1.01													0.99	0.99	362.37
255	1.00	1.00														0.98	375.01
275	1.00	1.02														0.99	394.67
295	1.00																409.36
315		1.02															432.39

* Class width 20 flux units.
[1] 16 periods × 18 months = 24 years; 0001–0547 January 1957–June 1958; 8220–8647 July 1979–December 1980.
[2] 10.7 cm classification: xxx ± 10.
[3] Average for all periods.

(Toyokawa, 15 cm) were constructed in the same way as Table 3; the general behaviour of the ratios is similar, and the majority lie within the range 1.00 ± 0.05 for the activity classes of ±5 units. However, during Periods 3 and 4, near the minimum of the solar cycle, there are important differences which can best be seen in Table 4b. If the amplitude of the differences found at 15 cm were due to a wavelength effect, even greater differences would be expected at 30 cm; this expectation is confirmed by the ratios in Tables 5a and b where the scatter is much greater than in Tables 3 and 4. Ratios in a range as great as 1.00 ± 0.10 confirm that the behaviour at 30 cm is not comparable with that at the shorter wavelengths. Other methods of treating the data must be used if conclusions are to be drawn concerning either the accuracy of the measured data or the physics of the Sun. The various anomalies described above will be examined in greater detail later.

At the short-wave limit of the radio fluxes examined here, the flux at 3 cm is of special interest because, as pointed out earlier, the variation of the yearly mean values during the solar cycle is much smaller than for the other wavelengths. Tables 6a and b show clearly that the ratios remain within the range 1.00 ± 0.02 except for the abnormally high values in Period 3. This period corresponds to the year 1960 for which an anomaly has already been indicated in the discussion on the yearly mean values.

From this general study of the radio fluxes in the range 3–30 cm, it is concluded that the observations made over a sufficiently long period at Ottawa and Toyokawa can be used as indices of solar activity provided one accepts uncertainties of between ±2 and ±5%, for mean values corresponding to several months.

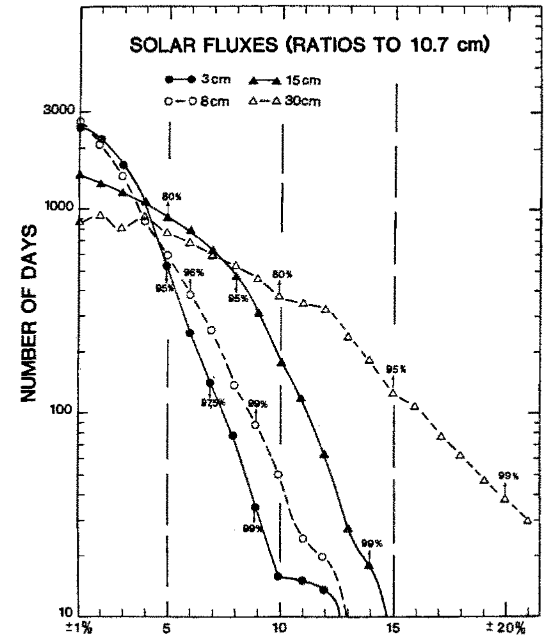

FIG. 6. FREQUENCY DISTRIBUTIONS OF THE DIFFERENCES BETWEEN THE "DAILY RATIOS" AT 10.7 cm AND THOSE AT 3, 8, 15 AND 30 cm (SEE SECTION 4).

4. GENERAL DISTRIBUTION OF DAILY RADIO FLUXES

In order to examine more closely the behaviour of the cm and dm radio fluxes, we have repeated the calculations described in Section 3. However, instead of calculating the "period ratio", which refers to the mean flux during a period of 18 months, we have calculated, for the wavelengths 3–30 cm, the "daily ratio": i.e. the ratio of the flux on a given day to the mean flux for all the days in the same activity class. These calculations refer to the 8646 days in the interval 1957–1980, or to the 9741 days in the interval 1957–1983.

The degree of similarity between the ratio on a given day at 10 cm and the ratios for the same day at the other four wavelengths is illustrated in Fig. 6; for the wavelengths 3, 8, 15 and 30 cm, Fig. 6 shows the frequency distribution of the number of days on which the difference between the daily ratio at 10 cm at the wavelength in question equalled ±1, ±2%, etc. As can be seen, 95% of the ratios at 3 cm and 96% at 8 cm do not differ from the ratios at 10 cm by more than ±5%. At 15 and 30 cm, 95% of the ratios lie within ±8 and ±15%, respectively.

The number of days on which the ratios for 3, 8, 15 and 30 cm differed from those for 10 cm by a given percentage or less is illustrated in Fig. 7. At 30 cm, only 95% of the ratios are within ±15% of that for 10 cm, and only 80% are within 10%. On the other hand, 99% of the ratios at 15 cm are within ±15%, while at 3 and 8 cm, 99% are within 10%.

Figure 8 is similar to Fig. 6, but it shows positive and negative differences separately. The similarity between the distributions for 3 and 8 cm is obvious; all the ratios agree within ±10%, except for 0.2% contained in a tail that extends from 10 to 12%. The width of the distributions increases with wavelength and attains 15% at 15 cm, and 20% at 30 cm on a small number of days. If differences of ±10% are considered as random differences between 3, 8 and 10 cm daily values, such fluctuations should occur in any analysis of the relation between solar activity and solar radio fluxes.

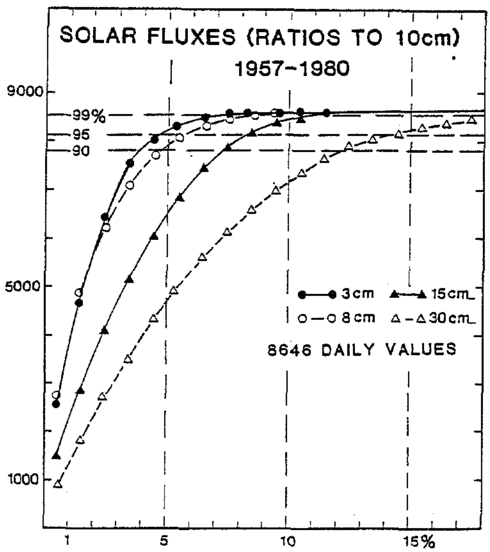

FIG. 7. THE CURVES SHOW THE NUMBER OF DAYS ON WHICH THE DIFFERENCES BETWEEN THE "DAILY RATIOS" AT 10.7 cm AND THOSE AT 3, 8, 15 AND 30 cm WERE EQUAL TO OR LESS THAN A GIVEN PERCENTAGE (SEE SECTION 4).

5. REGRESSION ANALYSIS OF DAILY RADIO FLUXES

In order to obtain numerical relations between the daily values of the fluxes, a regression analysis of the daily fluxes (F) and of their 27-day running means ($\bar{F}$)

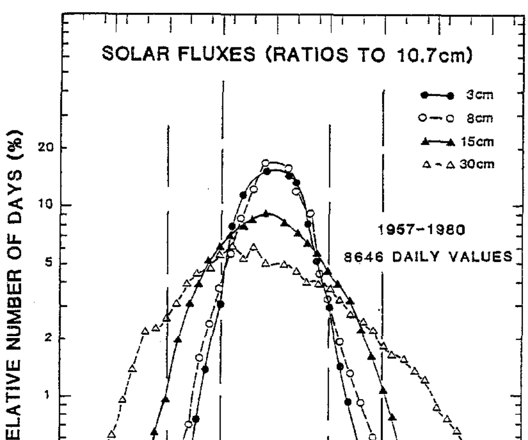

FIG. 8. AS FOR FIG. 6, EXCEPT THAT POSITIVE AND NEGATIVE DIFFERENCES ARE SHOWN SEPARATELY (SEE SECTION 4).

has been made. The relations 1–4 below express the flux at a given wavelength as a function of the flux at 10.7 cm; CC represents the correlation coefficient and D the standard deviation:

Equation	CC	D	
$F_3 = 254\left[1+0.26\left(\frac{F_{10.7}-65}{1000}\right)\right]$	0.970	7.5	(1a)
$\bar{F}_3 = 255\left[1+0.26\left(\frac{\bar{F}_{10.7}-65}{100}\right)\right]$	0.985	4.9	(1b)
$F_8 = 72\left[1+1.20\left(\frac{F_{10.7}-65}{100}\right)\right]$	0.993	4.2	(2a)
$\bar{F}_8 = 73\left[1+1.17\left(\frac{\bar{F}_{10.7}-65}{100}\right)\right]$	0.998	2.3	(2b)
$F_{15} = 50\left[1+1.66\left(\frac{F_{10.7}-65}{100}\right)\right]$	0.992	4.5	(3a)
$\bar{F}_{15} = 50\left[1+1.69\left(\frac{\bar{F}_{10.7}-65}{100}\right)\right]$	0.996	3.0	(3b)
$F_{30} = 43\left[1+1.37\left(\frac{F_{10.7}-65}{100}\right)\right]$	0.974	6.6	(4a)
$\bar{F}_{30} = 41\left[1+1.52\left(\frac{\bar{F}_{10.7}-65}{100}\right)\right]$	0.989	4.1	(4b)

As can be seen, the use of the 27-day running mean increases the correlation coefficients and reduces the scatter.

In Figs. 9–12, the daily values of the flux at 30, 15, 8 and 3 cm respectively are plotted against the flux at 10 cm. Figure 9 shows that, at 30 cm, only 80% of the values lie within ±10% of the values given by the regression line. A quadratic regression represents the distribution somewhat better, but the problem of the scatter of the points remains. It must be accepted that the data available at 30 cm are unsuitable for making direct valid comparisons with those at the other wavelengths. A more detailed analysis is required.

At 15 cm (Fig. 10) the scatter of the points is much less than that at 30 cm; the linear regression line gives the values to within ±10% for over 95% of the points, and a quadratic regression makes little difference to the correlation coefficient or the scatter.

Table 7 lists the flux values given by the linear and the quadratic relations for each of the four wavelengths for given values of the flux at 10.7 cm. Clearly the linear relation is inapplicable at 30 cm, and it can be applied only partially at 15 cm because of the considerable departures at low and high fluxes. At 3 and 8 cm, the linear regression is completely satisfactory. Figure 11 shows that, at 8 cm, 99% of the points are within ±10% of the regression line represented by equation (2a). There are a few isolated points and, in particular, those

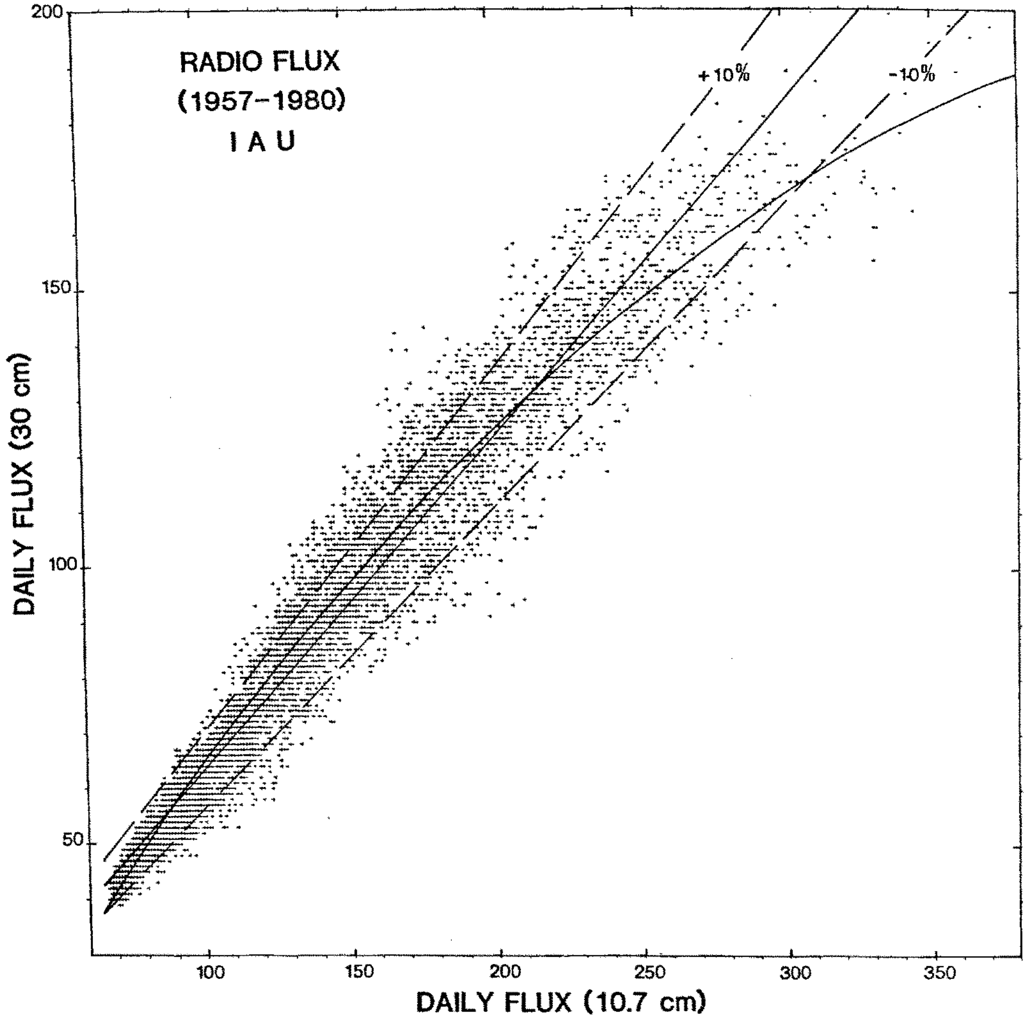

FIG. 9. SCATTER DIAGRAM LEADING TO THE DETERMINATION OF THE CORRELATION BETWEEN OBSERVED DAILY FLUXES AT 30 cm AND 10.7 cm.

The linear regression line indicated in this diagram is also shown in Fig. 4 and is given by formula (4a). As can be seen, the dispersion of the points above and below the linear regression line may exceed 10%. A quadratic regression curve is also shown.

at $F_{10.7} = 91$ and 261 correspond to 21 September 1963 and 28 June 1957. Comparisons with all the observational data lead to the conclusion that the value 91 at 10.7 cm ought to be 121, a value which is consistent with the value at 8 cm, namely 141. Similar detailed comparisons could lead to corrections to other abnormal daily values. However, since our objective is to determine solar activity indices that are applicable over longer periods, no further attention will be given to abnormal values which may often be interpreted as typographical errors.

For the relation at 3 cm, shown in Fig. 12, 95% of the points lie within $\pm 5\%$ of the regression line, 97.5% within 7.5% and more than 99% within $\pm 9\%$. As for 8 cm, the isolated points at $F_{10.7} = 91$ and 261 can again be seen. Another isolated point occurs at $F_{10.7} = 190$ and $F_3 = 438$ on 14 November 1960. This abnormality is due partly to the fact that this date coincided with the maximum activity in a 27-day period, and partly to the systematic positive errors in 1960 already mentioned.

When discussing Figs. 4 and 5, we have already pointed out that, for 3 cm, the mean value for 1960 is

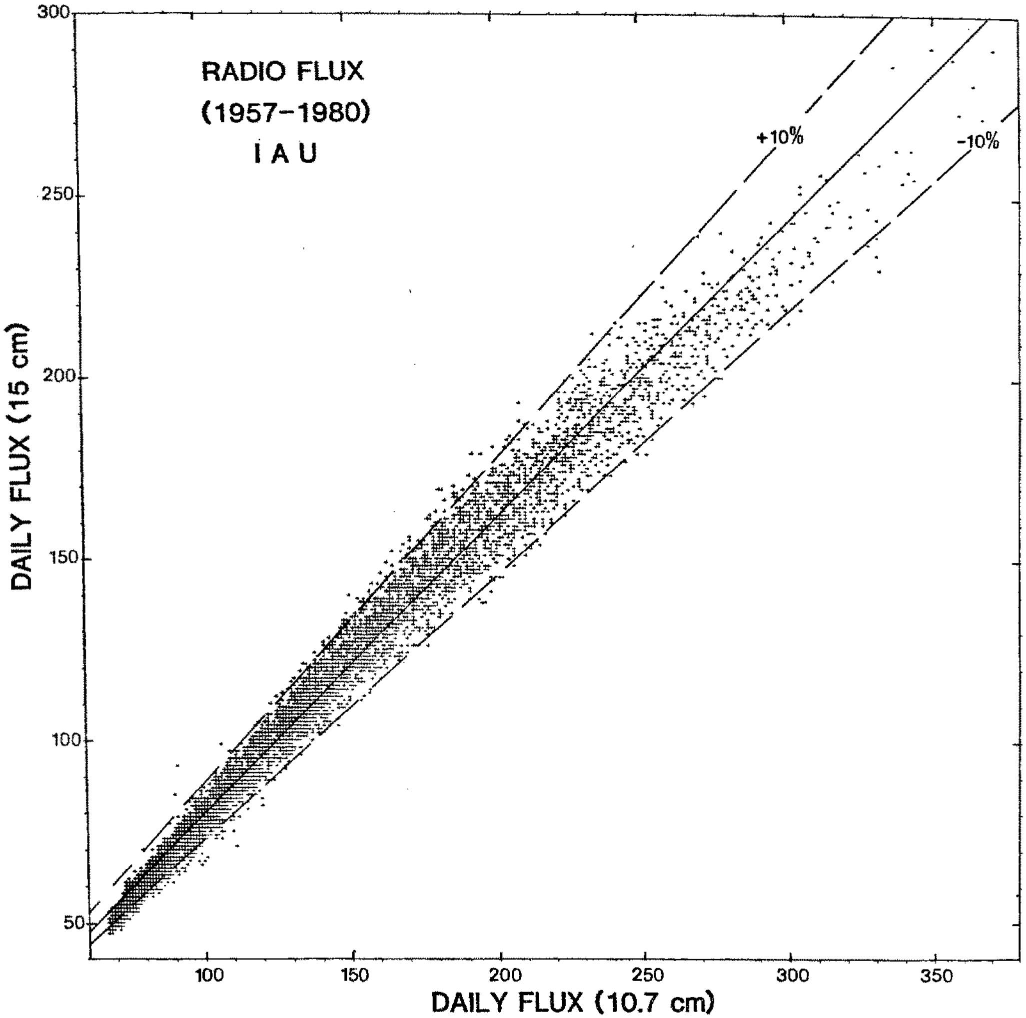

FIG. 10. SCATTER DIAGRAM LEADING TO THE DETERMINATION OF THE CORRELATION BETWEEN OBSERVED DAILY FLUXES AT 15 AND 10.7 cm.

The regression line indicated in this diagram is also shown in Fig. 4 and is given by formula (3a). As can be seen, the dispersion of the points above and below the linear regression line seldom exceeds 10%. A quadratic regression curve is possible (see Table 7).

displaced from the values for the years 1957, 1958, 1961 and 1962 (Fig. 5), and indeed in relation to all the data for the period 1957–1981. In 1960, the daily variations of the flux at 3, 8, 10, 15 and 30 cm indicate that the amplitude of the changes in the flux during the course of the 27-day cycles cannot be the same for all wavelengths. Moreover, variations of 5–10% from one day to the next may be attributable to differences in the times at which the observations are made. Also the corrections that are applied when the period of observation includes a burst may mask the true mean values. Assuming that there is an average error of about 3% in 1960, based on averages deduced from observations made over a decade, it is concluded that the error reaches 4% during the second half of the year. Thus most of the points on the scatter diagram that lie outside the 10% limits (between $F_{10.7} = 150$ and 200) must be corrected by using the values of the flux at 3 cm as given by the linear relation, equation (1a).

Finally, for the years 1959–1962, we have determined the linear regression lines relating the daily flux at 3 and 8 cm, and at 3 and 10.7 cm, and also the correlation

TABLE 7. LINEAR AND QUADRATIC APPROXIMATIONS OF SOLAR RADIO FLUXES AT 3, 8, 15 AND 30 cm V THE FLUX AT 10.7 cm

10.7	Linear 3	Linear 8	Linear 15	Linear 30	Quadratic (*) 3	Quadratic (*) 8	Quadratic (*) 15	Quadratic (*) 30 cm
65	256	73	50	42	256	73	47	38
115	288	115	91	72	288	115	93	74
165	320	158	132	102	320	158	135	106
215	352	201	173	132	352	201	174	133
265	385	244	214	162	385	245	209	155
315	417	287	256	192	417	289	241	173
365	449	329	297	222	448	334	270	187
Correlation coefficient	0.97	.99	.99	.98	.97	.99	.99	.98
Standard deviation	9	6	6	8	9	5	5	7

* The quadratic effect should be considered at 15 cm and it is important at 30 cm.

coefficients (CC):

1959

$F_3 = 182+0.86\,F_8$ with $CC = 0.95$ and $F_3 = 180+0.81\,F_{10}$ with $CC = 0.91$

1960

$F_3 = 216+0.72\,F_8$ with $CC = 0.80$ and $F_3 = 233+0.58\,F_{10}$ with $CC = 0.72$

1961

$F_3 = 198+0.79\,F_8$ with $CC = 0.91$ and $F_3 = 208+0.70\,F_{10}$ with $CC = 0.90$

1962

$F_3 = 208+0.64\,F_8$ with $CC = 0.91$ and $F_3 = 216+0.60\,F_{10}$ with $CC = 0.90$.

These results show that the correlation coefficient is usually greater than 0.90, but that in 1960 it falls to 0.80 and 0.72 for 8 and 10.7 cm, respectively. This confirms that the anomaly in the 3 cm fluxes in 1960 appears in all the analyses and cannot be assumed to have a physical origin.

6. DETECTION OF DRIFTS IN RADIO FLUXES

In order to show how an abnormality or drift can be detected, the daily values of the observed flux at 10.7 cm have been placed in 16 classes each having a width of ± 5 units and extending from 70 ± 5 units to 220 ± 5 units; the values above 225 units have not been classified because there are too few of them. The values corresponding to each class are plotted in Fig. 13. In order to separate the various classes, the ordinates have been incremented by 20 from $F_{1\,AU}(10\,\mathrm{cm}) = 70\pm 5$ up to 220 ± 5; i.e. for 16 classes, $N = 0$ for the class 70 ± 5, $N = 2$ for the class 80 ± 5 and $N = 15$ for the class 220 ± 5 units. Therefore, the relation between the plotted values of the flux (F_{ORD}) and the observed values (F_{OBS}) is

$$F_{ORD}(10\ \mathrm{cm}) = F_{OBS}(10\ \mathrm{cm}) + 20\,N. \qquad (5)$$

The first of the 16 classes just mentioned (70 ± 5) corresponds to the minimum in the solar activity cycle: $F_{1\,AU}(10.7\ \mathrm{cm}) = 65$ units. In Fig. 13, the abscissa represents the number of days counting from 1 May 1957 and extending up to 31 December 1980. Ideally, the points in each of the horizontal bands ought to be distributed uniformly within the limits of ± 5 units. Sinusoidal variations are actually found and correspond to the semiannual variation in the Sun–Earth distance; the resulting variation in the irradiance of $\pm 3.3\%$ can be easily detected in the figure and is a test of the sensitivity of the method. If the observed values are

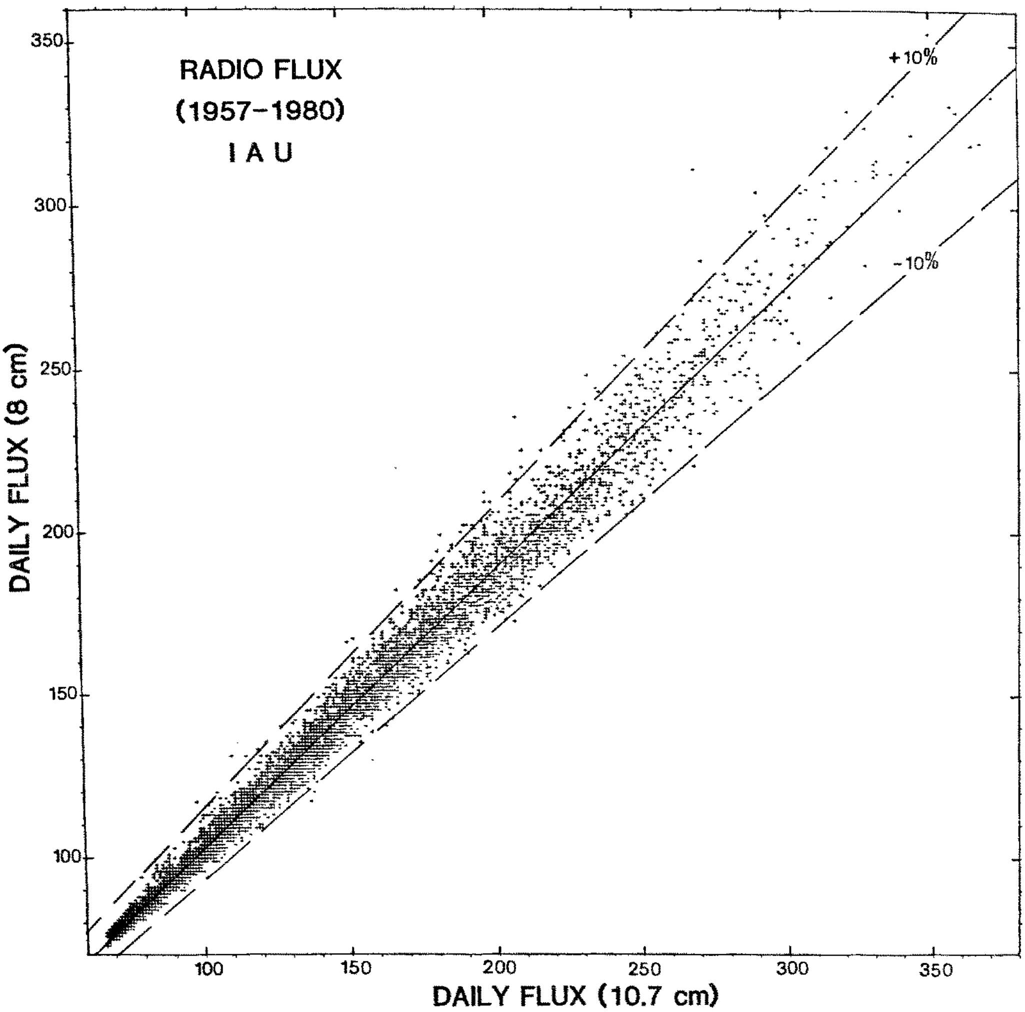

FIG. 11. PLOT OF DAILY FLUXES AT 8 cm VS THOSE AT 10.7 cm AS IN FIGS. 9 AND 10.
As can be seen, the dispersion of the points above and below the linear regression line corresponds to $\pm 10\%$.

first adjusted to what they would be for a Sun–Earth distance of 1 AU, then the sinusoidal variations must disappear leaving horizontal bands as shown in Fig. 14 where:

$$F_{\mathrm{ORD}}(10) = F_{1\,\mathrm{AU}}(10) + 20\,N. \tag{6}$$

The points included in Figs. 13 and 14 are reproduced in a different form in Fig. 15 in which the relation between the observed flux at 10.7 cm is plotted against the flux adjusted to 1 AU; the scatter of the points lies in the range $\pm 3.3\%$ and illustrates the semiannual variation in the Sun–Earth distance.

Figures 16 and 17 have been constructed in the same way as Figs. 13 and 14 respectively, but they refer to the daily flux at 3 cm. In Fig. 16, the relation between the plotted values of the flux (F_{ORD}) and the observed values (F_{OBS}) is given by:

$$F_{\mathrm{ORD}}(3) = F_{\mathrm{OBS}}(3) + 100\,N \tag{7}$$

indicating that the ordinates are incremented by 100 when the 10.7 cm flux at 1 AU increases by one class, from 70 ± 5 ($N = 0$) to 220 ± 5 ($N = 15$).

In Fig. 17, the observed values have been adjusted to correspond to 1 AU and, as before, the sinusoidal variations due to the changing Sun–Earth distance have been eliminated. The values of F_{ORD} in Fig. 17 are

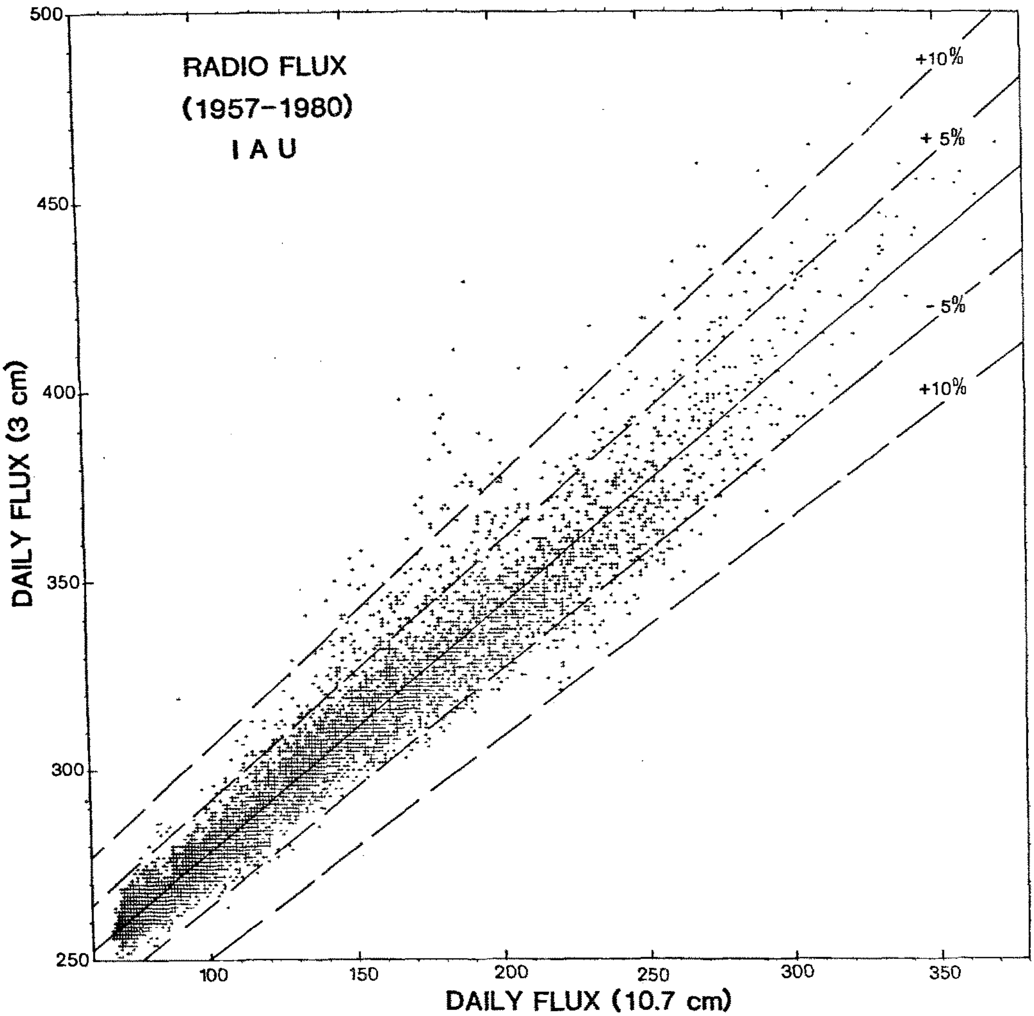

FIG. 12. PLOT OF DAILY FLUXES AT 3 cm VS THOSE AT 10.7 cm AS IN FIGS. 9, 10 AND 11. As can be seen, except at medium and high levels of solar activity, the dispersion of the points above and below the regression line is usually less than about 5%.

given by:

$$F_{\mathrm{ORD}}(3) = F_{1\,\mathrm{AU}}(3) + 100\,N. \qquad (8)$$

However, a more detailed examination of Fig. 17 shows that the bands of points are not completely horizontal for a period of several hundred days between Days 1000 and 1500; a systematic increase in the flux values (underlined) can be seen. This anomaly corresponds to a drift in the observational data at 3 cm during 1960. Thus the anomaly at 3 cm in 1960, which was found earlier during the analysis of the yearly means and the daily values, appears again in the form of a systematic trend at all levels of solar activity in 1960.

The comparison between the fluxes at 8 and 10 cm, illustrated in Figs. 11 and 18, shows that practically all the fluctuations are less than $\pm 10\%$. It is possible, therefore, to say that the observations made at these two wavelengths ought to be used simultaneously in the search for correlations between various phenomena and solar activity.

Figure 19 is analogous to Figs. 14 and 17, but it refers to the daily values of the flux at 15 cm during the 4400 days from 1969 to 1980. Although the points tend to form horizontal bands for each level of solar activity, there are several departures from the horizontal. There appears to be a peak near Day 500, followed by a

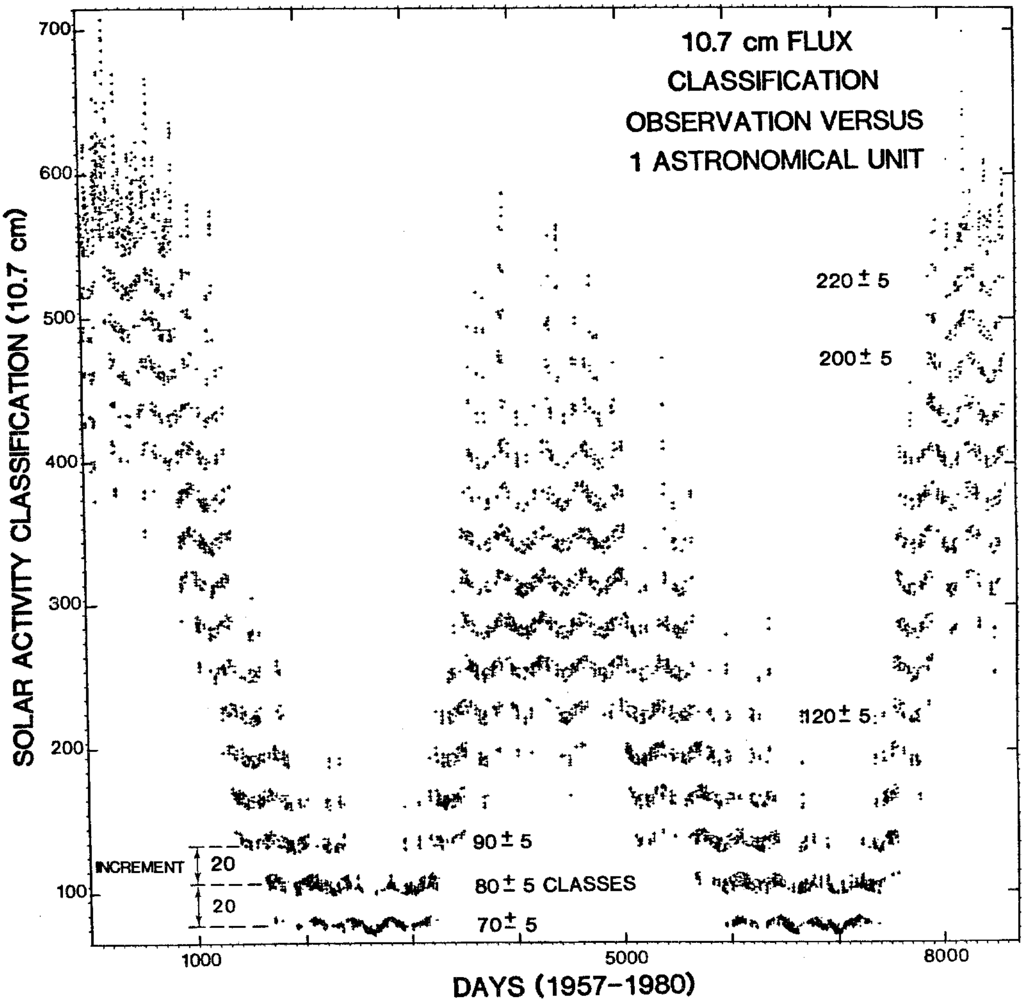

FIG. 13. DAILY VALUES OF THE OBSERVED SOLAR FLUX AT 10.7 cm PLOTTED IN A SERIES OF CLASSES OF WIDTH 70 ± 5, $80\pm5\ldots220\pm5$ FLUX UNITS.

The plot for each class is separated from those immediately above and below by 20 flux units. The semi-annual oscillation of $\pm3.3\%$ arises from the variation in the Sun–Earth distance.

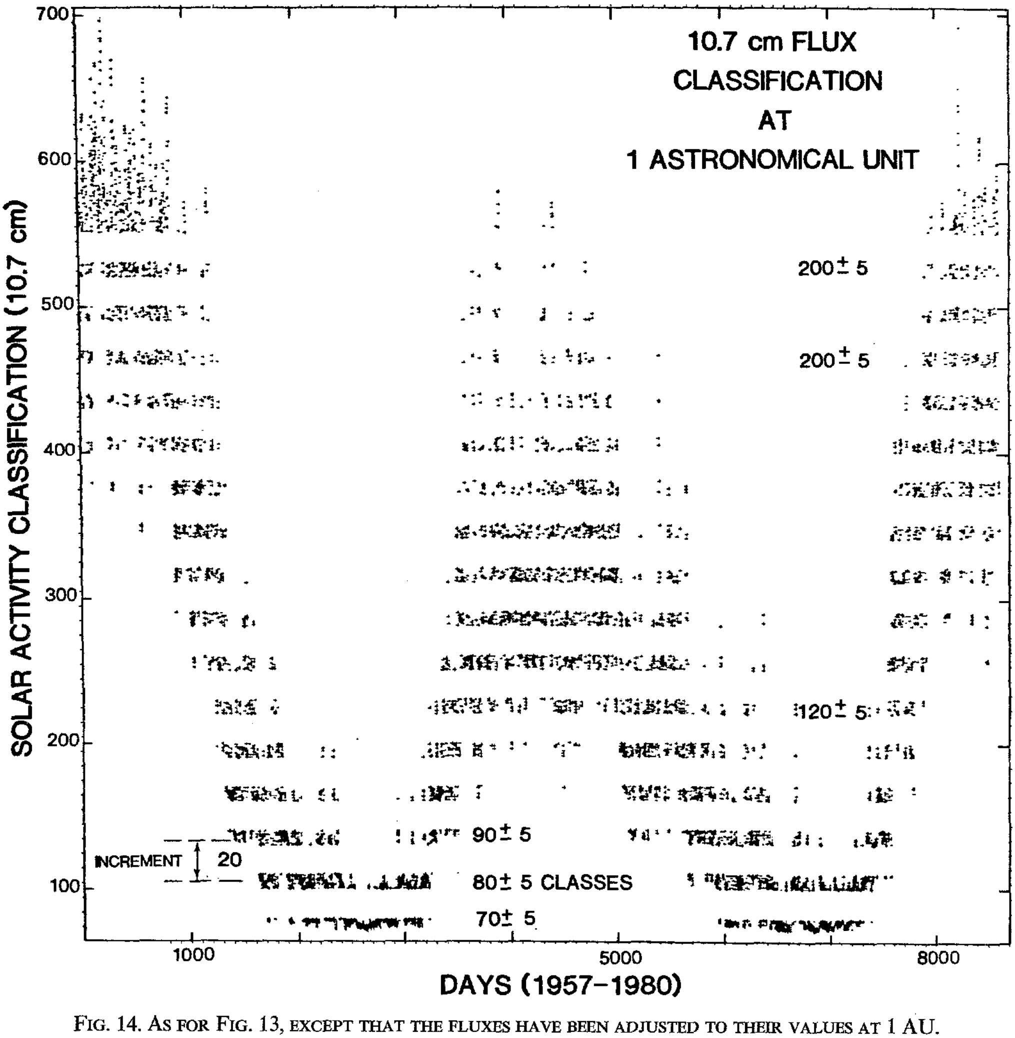

FIG. 14. AS FOR FIG. 13, EXCEPT THAT THE FLUXES HAVE BEEN ADJUSTED TO THEIR VALUES AT 1 AU.

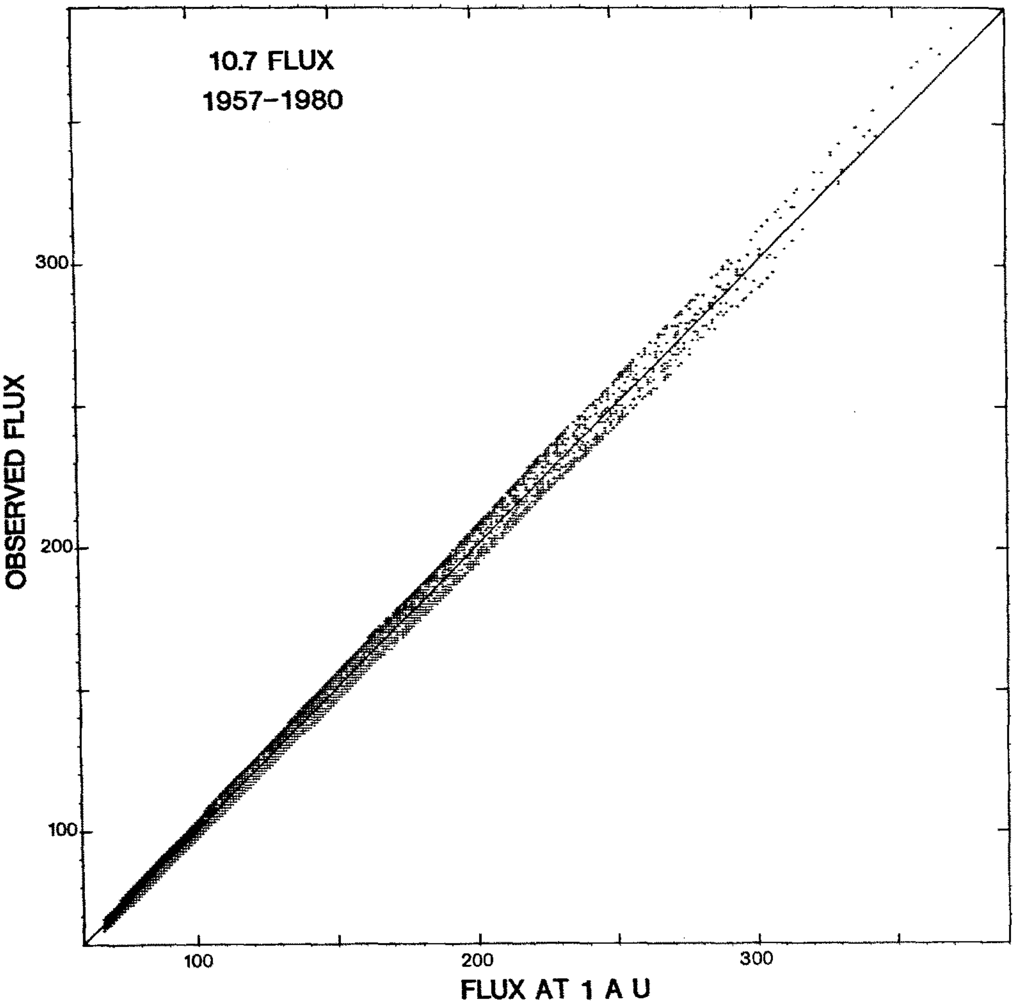

FIG. 15. REGRESSION LINE RELATING THE OBSERVED FLUX (INCLUDING THE 3.3% DISPERSION) TO THE FLUX ADJUSTED TO A SUN–EARTH DISTANCE OF 1 AU

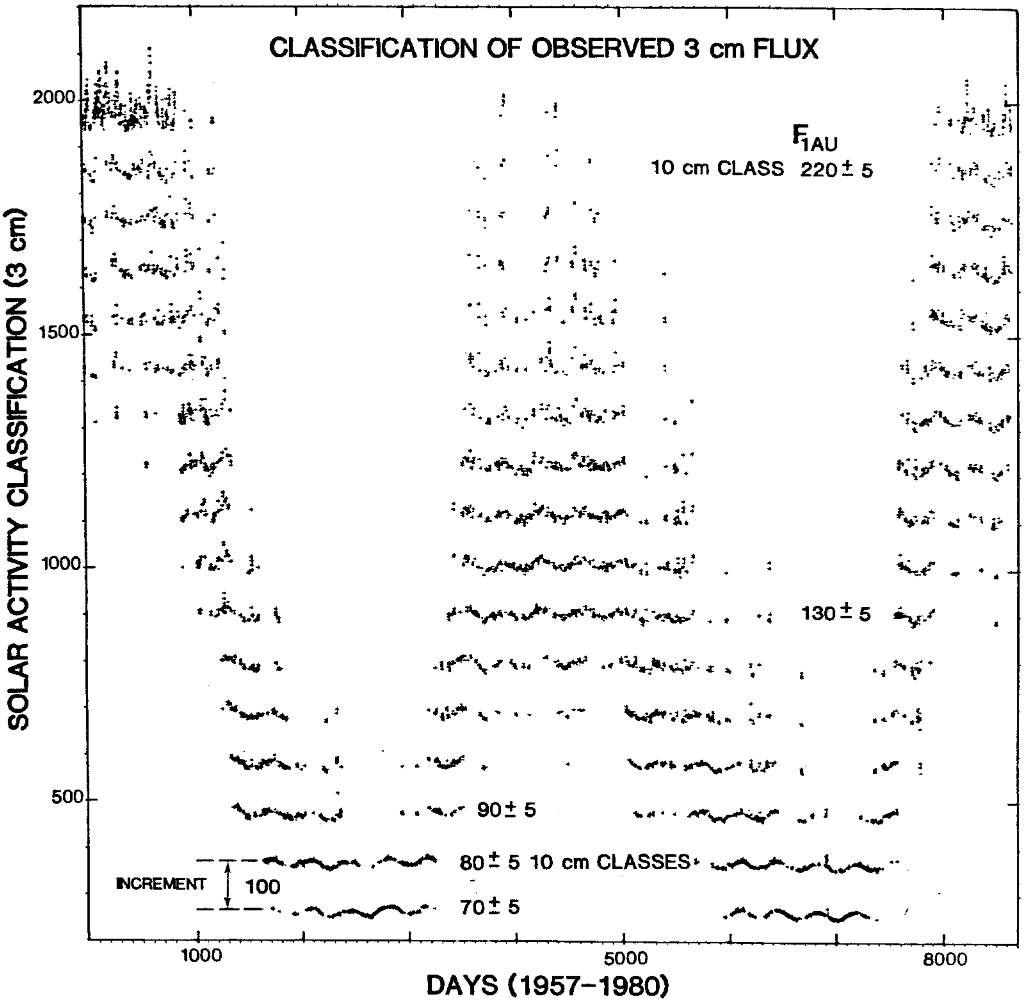

FIG. 16. AS FOR FIG. 13, FOR 3 cm INSTEAD OF 10.7 cm AND FOR SEPARATION OF THE CLASSES OF 100 FLUX UNITS INSTEAD OF 20.

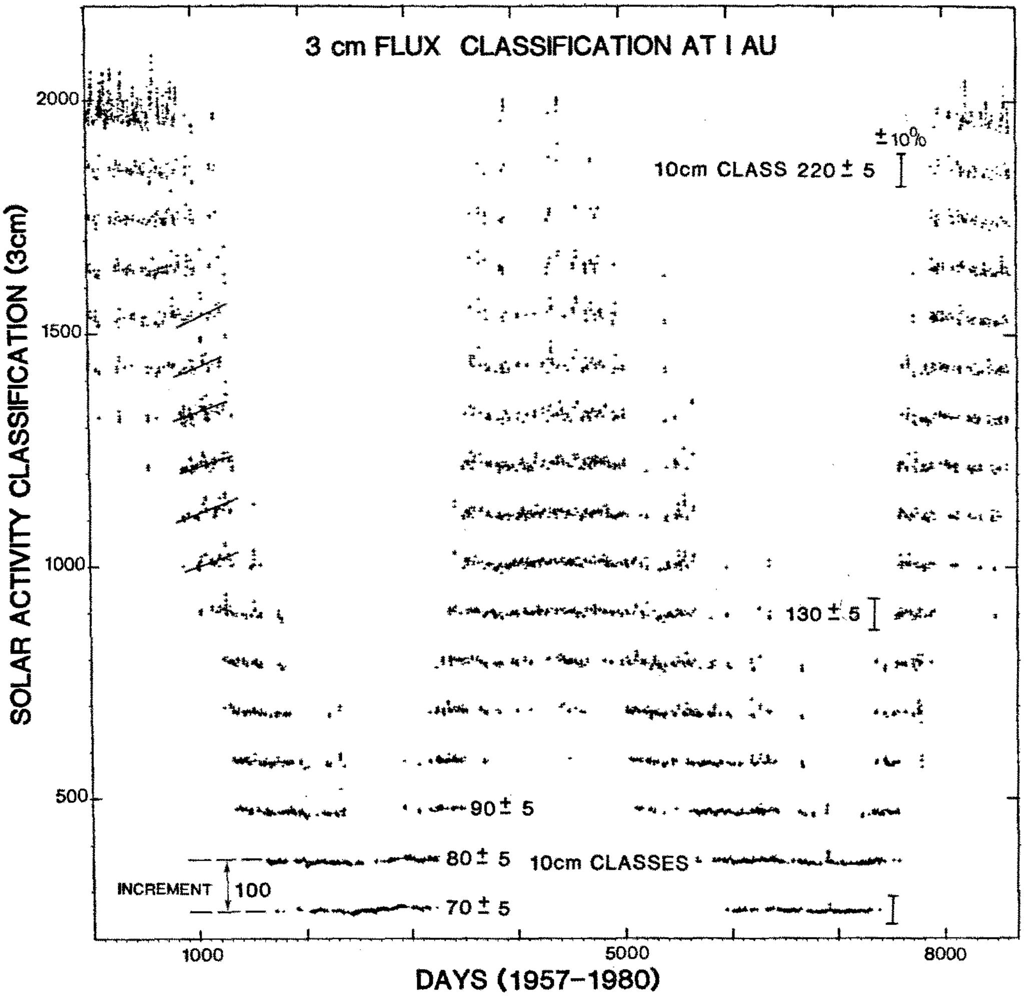

FIG. 17. AS FOR FIG. 16, EXCEPT THAT THE FLUXES HAVE BEEN ADJUSTED TO THEIR VALUES AT 1 AU.

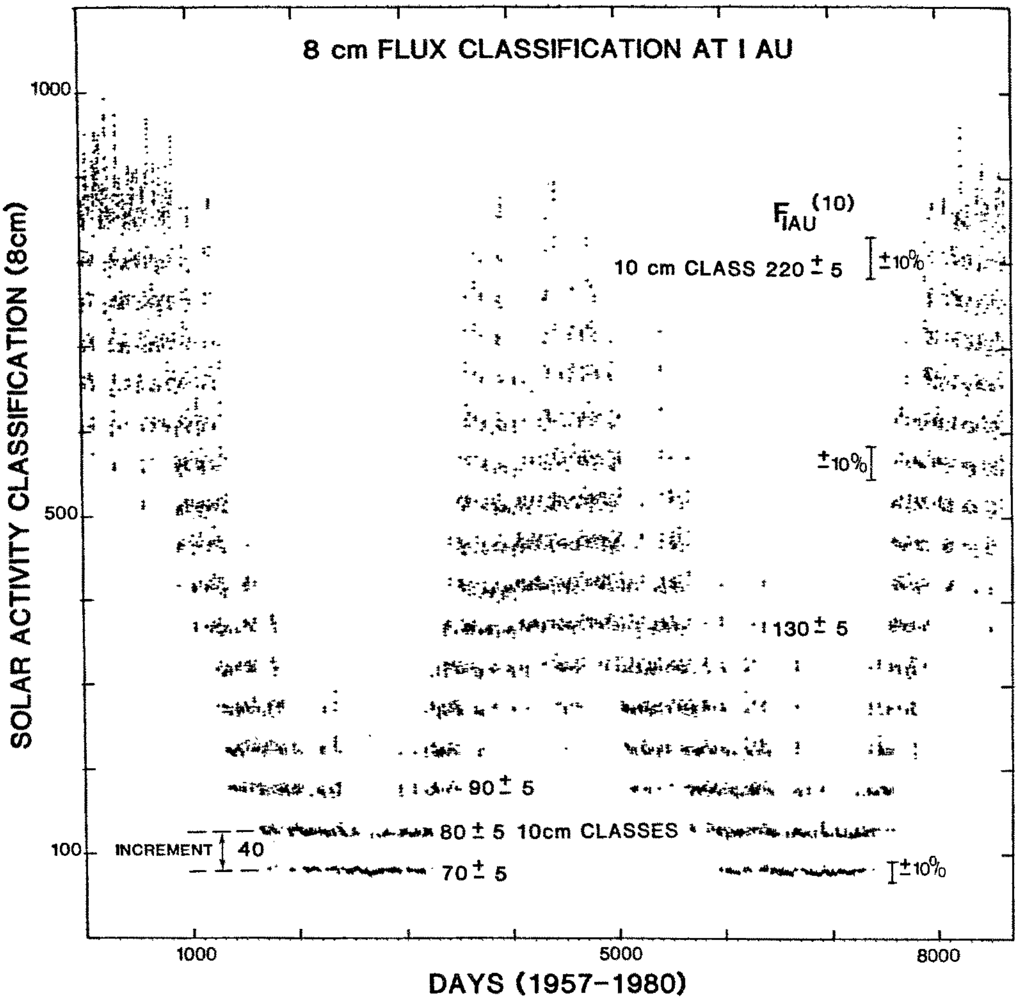

FIG. 18. DAILY VALUES OF THE SOLAR FLUX AT 8 cm, ADJUSTED TO 1 AU, PLOTTED IN A SERIES OF CLASSES OF WIDTH 70 ± 5, $80 \pm 5 \ldots 220 \pm 5$ FLUX UNITS.

The plot for each class is separated from those immediately above and below by 40 units.

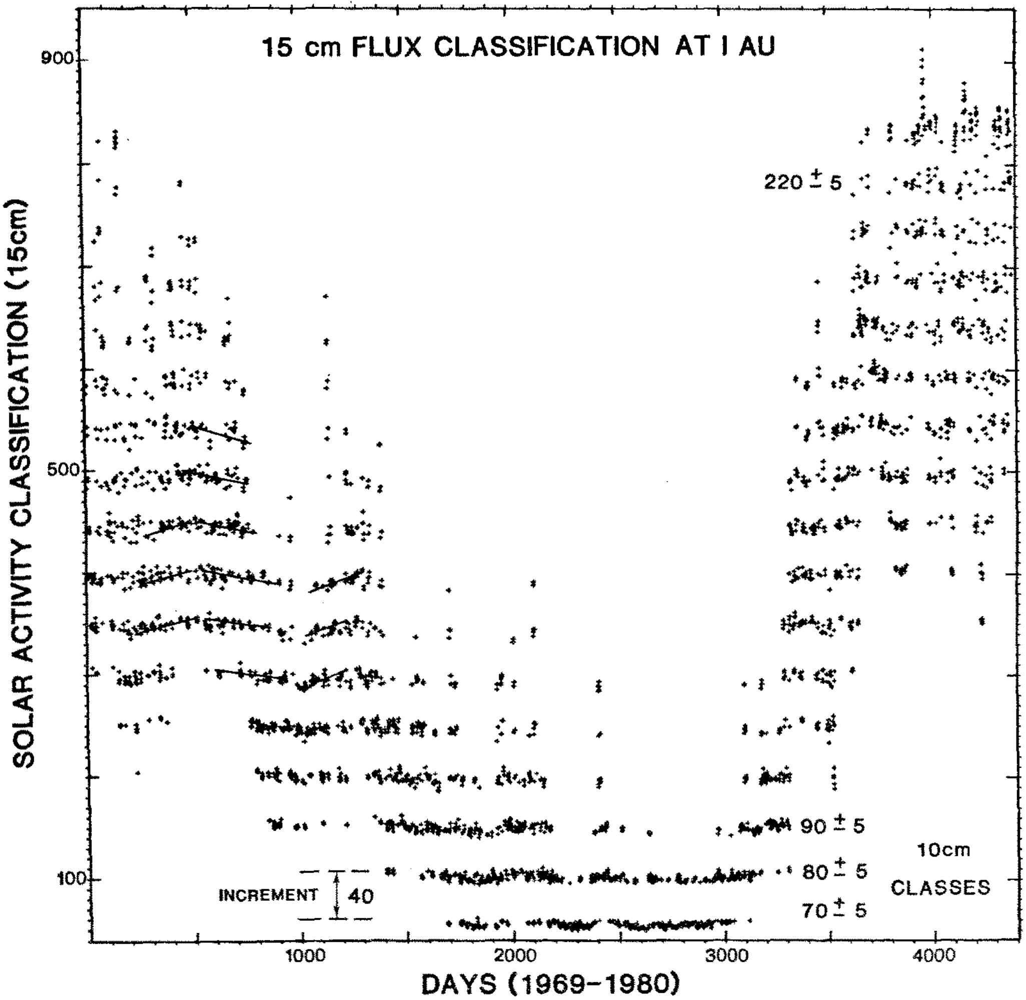

FIG. 19. DAILY VALUES OF THE SOLAR FLUX AT 15 cm, ADJUSTED TO 1 AU, PLOTTED IN A SERIES OF CLASSES OF WIDTH $70 \pm 5, 80 \pm 5 \ldots 220 \pm 5$ FLUX UNITS.

The plot for each class is separated from those immediately above and below by 40 flux units.

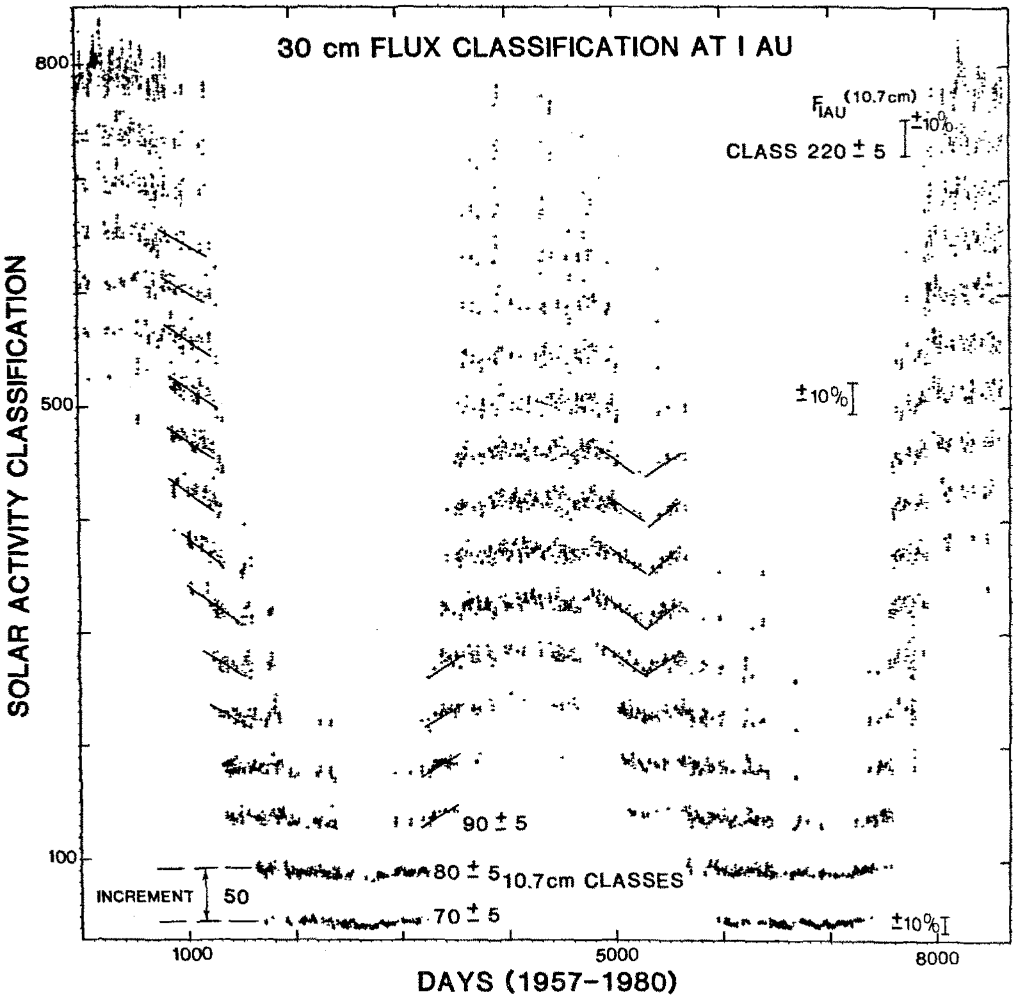

FIG. 20. AS FOR FIG. 19, FOR 30 cm INSTEAD OF 15 cm AND FOR SEPARATION OF CLASSES OF 50 UNITS INSTEAD OF 40.

minimum near Day 1000, and then a further rise in the values. This proves that the problems of calibration that were pointed out by those who made observations at 15 cm have not been completely resolved and that, in spite of the corrections introduced (Tanaka *et al.*, 1973), errors still remain which perhaps may give rise to the systematic trends just mentioned.

Finally, Fig. 20 is analogous to Figs. 17–19 except that it refers to the flux at 30 cm where the problems of calibration are most difficult. Instead of horizontal bands, there is a downwards trend in the values from Day 1000, a rise after Day 3000 and a minimum after Day 5000 (underlined in Fig. 20). In consequence, there is a need for a more detailed analysis of the flux values at 30 cm taking these trends into account. In view of the considerable scatter of the flux values at 30 cm, and also of the fact that the apparent temperature at this wavelength is of the order of 200,000 K, and that the radiation temperature at the centre of the disk is of the order of 125,000 K, a simple relationship cannot be deduced directly. In any case, since a linear relationship with the 10.7 cm must be replaced by a quadratic form, a special analysis is required.

7. ANALYSIS OF MEAN VALUES FOR 6-MONTH PERIODS

The results of the analyses described in the preceding paragraphs have been tested using another method. The year has been divided into two 6-month periods: Summer (from the spring to the autumn equinox) and Winter (from the autumn to the spring equinox). For each period, the mean value of the flux at 3, 8, 10, 15 and 30 cm has been calculated and the results are shown in Table 8 for the years 1957–1983. The mean values of the Wolf Sunspot Number are also given since they will be referred to in a subsequent analysis. Special attention has been given to the fluxes at 3, 8 and 10 cm because, at these wavelengths, linear regression analysis can be applied without large error. As can be seen in Figs. 21 and 22, comparisons of the flux at 3 cm with those at 8 and 10 cm disclose certain anomalies; for example the points relating to 1960 lie outside the 2% dispersion range which is characteristic of the other years. In order to examine in more detail all the possible anomalies of this kind, we have calculated the percentage difference between the observed flux at 3 cm and the values given

TABLE 8. SIX-MONTHLY MEAN VALUES (S = SUMMER, W = WINTER) OF THE SOLAR RADIO FLUXES AT 1 AU

YEAR	DAYS	3 cm	8 cm	10 cm	15 cm	30 cm	SUNSPOTS	P	n
1957	121 - 273	366	280	235	187	141	189	S	1
57-58	274 - 090	377	230	253	201	155	211	W	2
1958	091 - 273	363	216	237	187	149	189	S	3
58-59	274 - 090	368	211	227	177	141	179	W	4
1959	091 - 273	353	200	217	170	134	167	S	5
59-60	274 - 091	322	162	172	139	116	119	W	6
1960	092 - 274	332	160	169	135	110	122	S	7
60-61	275 - 090	304	122	125	99	75	70	W	8
1961	091 - 273	286	112	111	88	65	63	S	9
61-62	274 - 090	272	99	95	76	58	41	W	10
1962	091 - 273	272	95	90	72	57	38	S	11
62-63	274 - 090	262	86	80	62	49	25	W	12
1963	091 - 273	266	89	84	62	50	33	S	13
63-64	274 - 091	259	83	77	57	45	26	W	14
1964	092 - 274	261	78	71	51	42	7	S	15
64-65	275 - 090	265	80	74	54	44	12	W	16
1965	091 - 273	269	83	77	57	48	14	S	17
65-66	274 - 090	269	86	81	60	49	22	W	18
1966	091 - 273	287	105	105	80	66	50	S	19
66-67	274 - 090	304	128	131	104	81	84	W	20

TABLE 8 (*continued*)

YEAR	DAYS	3 cm	8 cm	10 cm	15 cm	30 cm	SUNSPOTS	P	n
1967	091 - 273	307	133	140	110	87	83	S	21
67-68	274 - 091	310	145	155	121	97	106	W	22
1968	092 - 274	308	138	144	114	94	107	S	23
68-69	275 - 090	316	147	150	122	96	111	W	24
1969	091 - 273	317	148	150	121	95	103	S	25
69-70	274 - 090	316	152	154	128	93	105	W	26
1970	091 - 273	321	155	156	131	101	108	S	27
70-71	274 - 090	306	141	143	117	87	83	W	28
1971	091 - 273	289	114	113	91	71	62	S	29
71-72	274 - 091	286	119	119	95	71	71	W	30
1972	092 - 274	297	126	126	103	80	75	S	31
72-73	275 - 090	278	105	103	81	64	47	W	32
1973	091 - 273	273	100	96	75	60	41	S	33
73-74	273 - 090	264	86	81	61	50	25	W	34
1974	091 - 273	272	95	90	70	55	41	S	35
74-75	274 - 090	266	87	81	62	49	23	W	36
1975	091 - 273	262	84	78	60	47	18	S	37
75-76	274 - 091	259	81	74	56	46	12	W	38
1976	092 - 274	259	80	74	56	46	12	S	39
76-77	275 - 090	258	81	75	58	48	15	W	40
1977	091 - 273	268	92	87	68	55	28	S	41
77-78	274 - 090	285	114	112	92	72	56	W	42
1978	091 - 273	307	141	143	118	89	90	S	43
78-79	274 - 090	326	170	176	149	112	131	W	44
1979	091 - 273	329	172	180	151	117	146	S	45
79-80	274 - 091	338	185	200	167	128	164	W	46
1980	092 - 274	333	183	197	163	126	155	S	47
80-81	275 - 090	339	187	201	167	126	146	W	48
1981	091 - 273	342	190	205	169	127	141	S	49
81-82	274 - 090	344	191	203	169	125	146	W	50
1982	091 - 273	316	158	165	136	105	108	S	51
82-83	274 - 090	308	144	149	124	100	87	W	52
1983	091 - 273	290	126	128	105	85	79	S	53

by the following two linear relations (for 8 and 10.7 cm respectively):

$$F_{3\,\mathrm{cm}} = 254\left[1+0.30\left(\frac{F_8-72}{100}\right)\right] \tag{9}$$

and

$$F_{3\,\mathrm{cm}} = 254\left[1+0.26\left(\frac{F_{10}-65}{100}\right)\right]. \tag{10}$$

The results are shown in Fig. 23, and it is clear that, whatever the absolute value of the flux at 3 cm, most of the differences lie within $\pm 2\%$ of the values given by equations (9) and (10). Besides the anomaly in 1960 which has already been noted, others are now apparent: 1965 S, 1966 and 1980 S. Since the anomalies in 1960 (Periods 7 and 8) occur at two different levels of solar activity, as defined by the fluxes at 10 and 8 cm (Tables 9 and 10, respectively) it is concluded that the

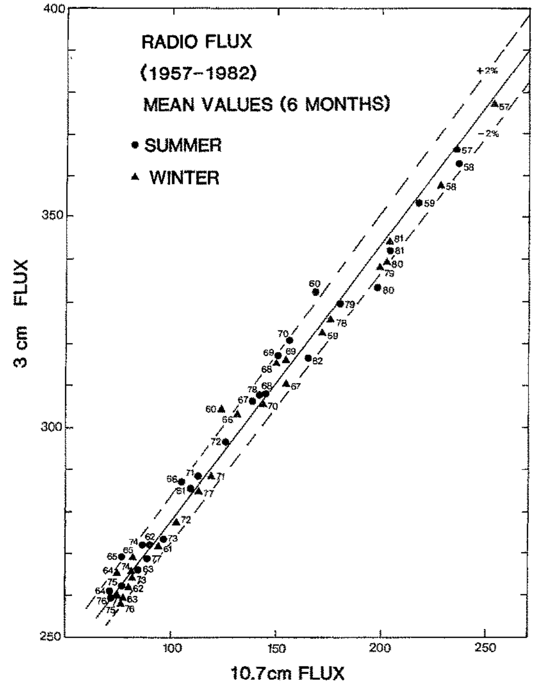

FIG. 21. MEAN VALUES OF THE 3 cm SOLAR RADIO FLUX VS THE MEAN VALUES AT 10.7 cm BETWEEN 1957 AND 1981.
Six-month average values for Summer (between spring and autumn solstices) and for Winter (between autumn and spring equinoxes).

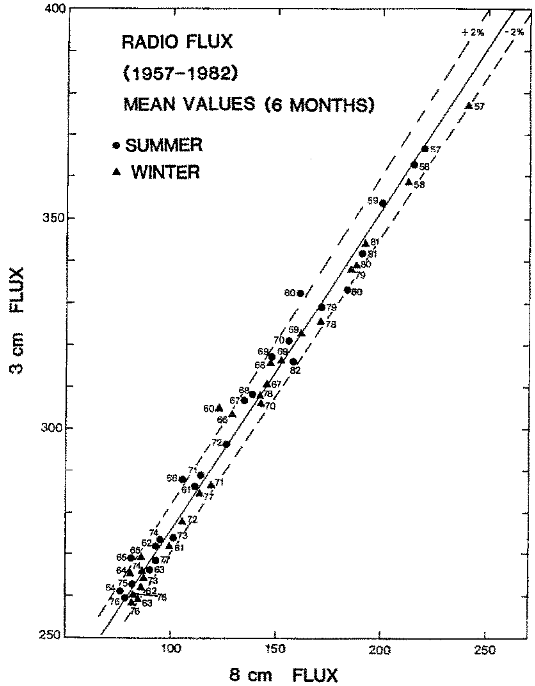

FIG. 22. MEAN VALUES OF THE 3 cm SOLAR RADIO FLUX VS THE MEAN VALUES AT 8 cm.
As for Fig. 21.

problem is one of calibration and not of the structure of the solar atmosphere. It should be noted that the high values of the 3 cm flux in 1960, 1965 and 1966 have an influence on the regression line (Fig. 23); but the influence of the values in the 1970s and 1980s is opposite in character since the values are less than those given by the regression line (Figs. 5, 21, 22). A comparison, as in Table 11, of the values of the flux at 8 cm with the corresponding values at 10.7 cm shows, for example, small anomalies during Periods 21 and 22 (−3%) and Periods 26 and 27 (+3%). Figure 24 shows that the 6-month mean values of the fluxes at 8 and 10.7 cm agree to within ±3%. As can be seen from Fig. 25, these limits fall to ±2% if the anomalous periods are excluded: Periods 21 and 22, 1967 S and W, and Periods 26 and 27, 1969 W and 1970 S. Figure 25 shows also that the sequence of differences between 1967 and 1970 corresponds to a total change of 5 or 6%: 1967 S (−2.5%), 1967 W (−3%), 1968 S (−1.5%), 1968 W (+1.0%), 1969 (+2%), 1969 W (+2.5%) and 1970 S (+3.5%). Such a trend over an interval of 3 years demonstrates the effects of systematic differences arising from the conditions of observation, and not

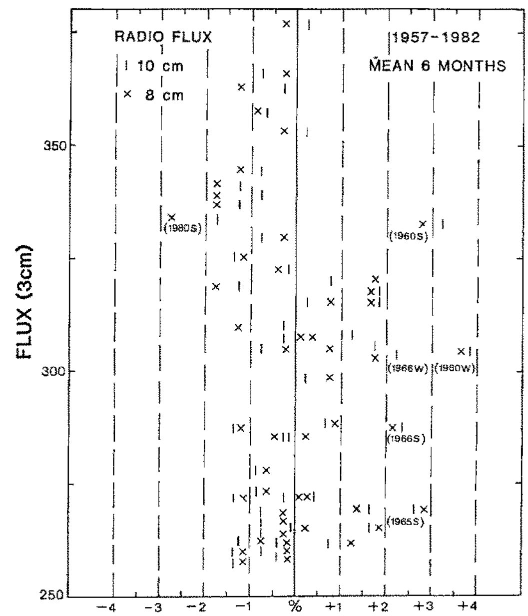

FIG. 23. DISTRIBUTION OF DIFFERENCES (%) BETWEEN THE OBSERVED SOLAR RADIO FLUXES AT 3 cm AND THOSE CALCULATED BY THE LINEAR REGRESSIONS: EQUATIONS (9) AND (10) FOR 8 AND 10 cm.
Figure 23 is based on the data illustrated in Figs. 21 and 22.

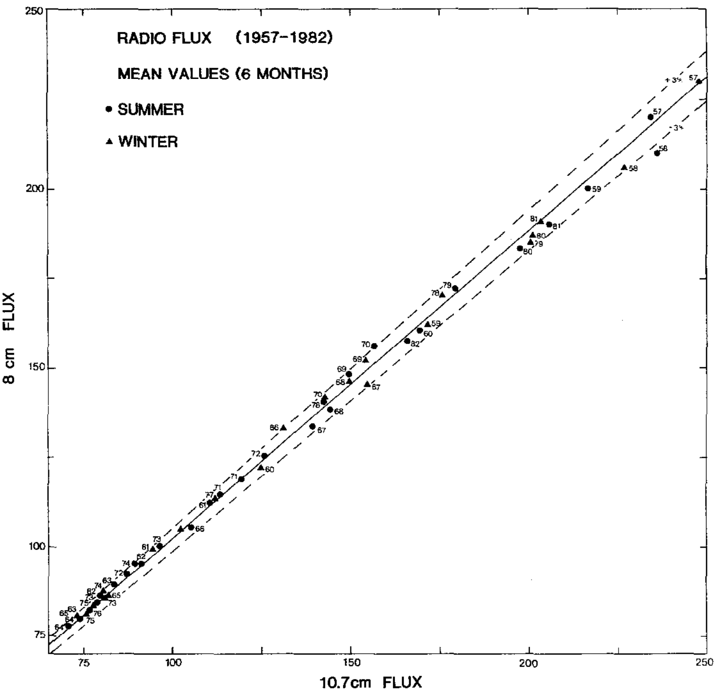

FIG. 24. MEAN VALUES OF THE 8 cm SOLAR RADIO FLUX VS THE MEAN VALUES AT 10.7 cm BETWEEN 1957 AND 1981. Six-month average values for Summer (between spring and autumn equinoxes) and for Winter (between autumn and spring equinoxes).

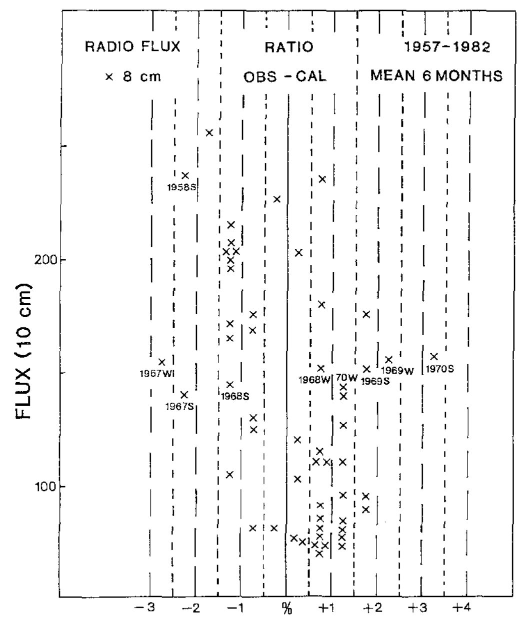

FIG. 25. DISTRIBUTIONS OF DIFFERENCES (%) BETWEEN THE OBSERVED SOLAR RADIO FLUXES AT 8 cm AND THOSE CALCULATED BY THE LINEAR RELATION (2a) WITH 10.7 cm. Figure 25 corresponds to the data illustrated in Fig. 24.

from variations in either solar activity or the incidence of various solar phenomena. The evidence confirms that some caution must be exercised in studies of the relations between different solar and terrestrial phenomena; this is especially important when the observational data have been obtained using rockets and satellites, because of the increased risk of changes in the calibration and in the rate of instrumental drift, neither of which can easily be checked.

The concept of the least-squares regression line linking two parameters can easily be extended to a line in three-dimensional space linking three parameters, namely the daily values of the flux at 3, 8 and 10 cm. Assuming that the errors at the three frequencies are comparable, it is required to find the line that corresponds to the minimum value of $S = \Sigma d_i^2$ where d_i is the distance between the line and the point P_i which represents the three flux values on day i. In the subsequent discussion, in references to the line defined in this way, the term "space line" will be used for the sake of brevity (see the Appendix). The projections of the space line on the three planes defined by 3, 8 and 10 cm axes define the three two-dimensional regression lines already discussed. Starting from the basic observational data in Table 8, it is then possible to derive the

TABLE 9. RATIOS OF THE MEAN FLUX AT 3 cm AS IN TABLE 6b, BUT FOR A 6-MONTH PERIOD*

	075	095	115	135	155	175	195	215	235	255	275	295	315	335(1)	
01(2)						099	098	100	101	103	102	102(3)			1005(4)
02						100	100	101	099	099	100	100		100	998
03							100	100	100	099	099	099			995
04						098	098	100	098	100	101	099	107		994
05						100	100	099	102	101	102				1003
06				100	098	100	100	100	095						994
07				103	103	103	104	102							1030
08		102	102	103	105	111									1034
09		101	100	100											1003
10	100	100	098	097											993
11	101	100	098												1001
12	100	096													991
13	100	099	100												995
14	098	098													984
15	100														995
16	101														1011
17	102	101													1024
18	102	101	099												1016
19		102	102	102											1023
20		102	102	101	101	104									1018
21		102	101	100	101	100	105	102							1003
22			100	098	099	098	100	100							990
23			102	100	099	101	100								1001
24				101	101	104	103	102							1013
25			102	101	101	101	103		108						1018
26			101	100	100	100	103								1007
27			102	101	102	102	102	104							1017
28		103	100	099	099	099	100								994
29		102	100	101	097										1005

30		100	099	097	096										986
31		101	100	100	102										1004
32	101	099	098	103											994
33	101	099	098	097											994
34	100	098													995
35	101	100	100												1005
36	100	100		098											998
37	100	098	096												992
38	099	099													987
39	099														990
40	099	096													985
41	100	099	099												997
42	102	099	100	099	101	101									996
43		103	101	100	100	099									1000
44				099	099	099	100	100							995
45				100	100	100	100	102	099						999
46				099	098	098	099	099	098						988
47				098	098	099	097	097	099	096					979
48					098	098	099	099	099	099	101				988
49				098	097	098	100	100	100	101	097				989
50				099	099	099	101	101	100	100	100	100			999
51			097	099	098	098	098	098	106						985
52				099	101	100	101		103						1008
103	262(6)	274	288	302	315	326	339	350	363	376	393	409	432	444	

* Class width 20 at 10.7 cm.
(1) 10.7 cm classification: xxx ± 10.
(2) Six-month periods; from 1957 to 1982.
(3) Ratio 3 cm (6 months)/26 years; 102 = +2%; 99 = −1%.
(4) Average value of the ratio for each period; 1005 = +0.5%; i.e. ‰.
(5) Columns 2–15: classifications for each level of solar activity defined by 10.7 cm.
(6) Mean values at 3 cm corresponding to the classification of solar activity at 10.7 cm.

Table 10. Ratios of the mean flux at 3 cm as in Table 9, but for a class width 16 at 8 cm

	078	094	110	126	142	158	174	190	206	222	238	254	270	286	302	318(1)	
01(2)							098	099	101	100	099	101	099	101(3)			997(4)
02						100	101	102	101	100	101	100	100	101	101	098	1005
03							102	101	100	100	100	100	100				1001
04						099	099	099	099	099	099	100	100				993
05						100	101	100	101	102	100	101					1006
06				101	099	100	099	101	100	097							999
07				103	104	103	105	106	102	099							1032
08		103	102	102	106	106	108										1038
09		102	100	099	100												1000
10	100(5)	099	098	096													987
11	101	100	099	095													999
12	100	098															989
13	100	098	100														992
14	098	098															984
15	100																998
16	102																1014
17	103	102															1024
18	102	101	100														1014
19		103	102	102	104												1027
20		103	102	102	101	101	102										1017
21		103	102	101	101	101	101	101	102								1012
22			102	099	100	099	099	099	101								998
23			102	101	100	099	101										1004
24				102	100	101	104	103									1012
25			103	101	101	101	100	100									1012
26			102	100	100	099	100	101	104								1001
27			103	101	100	101	100	101	099								1007
28			101	100	099	099	099	098									993

29		103	100	100	100												1006
30		100	099	098	096												983
31		102	100	099	100	102	099										998
32		100	098	097													996
33	100	100	098	096													989
34	100	099	097														995
35	100	100	100	099													999
36	100	100	099	098													998
37	100	098	097														990
38	099	100															989
39	099	098															992
40	099	097															986
41	100	099	099	096													991
42		100	099	099	099	099											995
43			102	100	100	099	098	098									999
44				100	098	098	100	098	098	100							988
45					100	100	099	100	100	100							996
46				100	100	099	100	100	100	100							997
47				099	099	099	099	098	098	098	098		096				984
48					099	099	100	099	098	099	100	098					991
49					098	098	099	100	100	100	100	101					993
50				100	100	099	099	101	100	099	104	100					999
51			098	099	098	100	099	098	099	105							987
52				100	100	100	102	101									1009
3 cm	261 (6)	270	284	298	309	320	331	344	353	366	378	393	408	421	434	453	

(1) 8 cm classification: xxx ± 8.
(2) Six-month periods; from 1957 to 1982.
(3) Ratio 3 cm (6 months)/26 years; 101 = +1%; 099 = −1%.
(4) Average value of the ratio for each period; 997 = −0.3%; 1005 = +0.5%, i.e. in ‰.
(5) Columns 2–17: classifications for each level of solar activity defined by 8 cm.
(6) Mean values at 3 cm corresponding to the classifications of solar activity at 8 cm.

TABLE 11. RATIOS OF THE MEAN FLUX AT 8 cm AS IN TABLE 3b, BUT FOR A 6-MONTH PERIOD

	075	095	115	135	155	175	195	215	235	255	275	295	315	335(1)	
01(2)						100	099	100	101	104	103	103(3)			1012(4)
02						098	098	098	099	097	099	099		100	983
03							098	099	099	097	098	100			985
04					101	099	098	101	099	102	101	098	103		1000
05						099	099	098	100	100	102				990
06				100	099	099	100	100	099						993
07				101	100	099	098	104							997
08		101	099	097	100	102									997
09		102	100	101											1009
10	105(5)	101	099	101											1022
11	104	099	100												1008
12	103	096													1013
13	102	099	099												1010
14	100	097													997
15	095														950
16	098														982
17	100	097													998
18	101	099	098												1006
19		101	098	098											998
20		102	100	099	099	104									1001
21		100	097	095	099	099	104	102							970
22			101	096	098	098	101	099							979
23			101	100	098	099	097								993
24				101	100	102	101	100							1010
25			103	101	101	101	104		111						1019
26			104	101	101	103	105								1023
27			105	102	104	103	105	106							1033
28		109	100	103	100	101	102								1012

29		102	099	102	101										1004
30		103	100	100	102										1009
31		104	101	101	102										1017
32	109	100	098	107											1004
33	106	100	101	102											1018
34	100	097													994
35	104	100	103												1020
36	100	099		100											998
37	099	098	104												991
38	097	098													974
39	098														977
40	099	093													985
41	104	097	103												1016
42	109	099	101	101	102	102									1005
43		104	100	102	101	103									1013
44				100	102	101	103	103							1019
45				104	100	101	100	103	101						1012
46				100	099	097	099	100	097						986
47				098	098	098	099	102	098						987
48					098	098	099	098	100	102	100				990
49				100	097	099	100	100	099	101	096				990
50				100	099	099	101	102	102	101	101	101			1004
51			097	103	098	100	100	099	103						997
52				100	102	098	101		099						1004
8 cm	082 (6)	098	115	132	150	167	184	200	216	235	254	271	298	311	

(1) 10.7 cm classification: xxx $\pm$ 10.
(2) Six-month periods; from 1957 to 1982.
(3) Ratio 3 cm (6 months)/26 years; 103 = +3%; 99 = −1%.
(4) Average value of the ratio for each period; 1012 = +1.2%; 983 = −1.7%, i.e. in ‰.
(5) Columns 2–15: classifications for each level of solar activity defined by 10.7 cm.
(6) Mean values at 8 cm corresponding to the classifications of solar activity at 10.7 cm.

departure of each of the 6-month averages from the space line, and to make the appropriate corrections. The results are presented in Table 12 which gives the percentage correction to be applied to the fluxes at 3, 8 and 10 cm for each of the 6-month periods, and also the standard deviation $((\Delta x^2 + \Delta y^2 + \Delta z^2)/N)^{1/2}$ of the departure of the daily values from the space line. Six cases of corrections equal to or greater than 2% occurred at 3 cm, and none at 8 or 10 cm. Taking all three wavelengths, 23% of the corrections lay between 1.0 and 1.9%, and as many as 73% did not exceed 1%.

From the above discussion, it is concluded that the fluxes in the range 3–10.7 cm can be used as indices of solar activity. To a first approximation they represent the variations in the irradiance originating over the whole of the solar disk and reaching ground level.

Corr. (%)	3	8	10	
		(cm)		
$\geqslant 2$	6	0	0	6
1.0–1.9	15	12	10	37
0–0.9	32	41	43	116
Total	53	53	53	159

As for the fluxes at 15 and 30 cm, their relations to the flux at 10 cm are represented better by quadratic regression curves (Figs. 26 and 27).

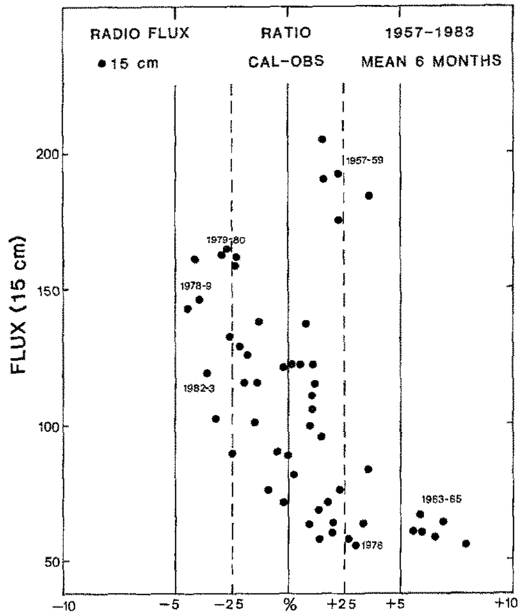

FIG. 26. DISTRIBUTION OF DIFFERENCES (%) BETWEEN THE CALCULATED SOLAR RADIO FLUXES DETERMINED BY THE LINEAR REGRESSION WITH 10.7 cm EQUATION (3a) AND THE OBSERVED VALUE AT 15 cm.

The deviation from a least-squares line is shown by differences greater than 2.5 and 5% in 1976 and 1963–1965, respectively; these dates correspond to two minima of the solar activity (see Table 7). Differences between the values given by a linear and a quadratic least-squares fit occur also at high solar activity. As far as 1982–1983 is concerned, it seems to be due to an anomaly.

8. A THREE-DIMENSIONAL COORDINATE SYSTEM FOR SOLAR RADIO FLUXES AT 3, 8 AND 10 cm

The preceding paragraph described how a regression line in three-dimensional space (the "space line") could be used to determine the anomalies in the 6-monthly averages of the fluxes of 3, 8 and 10.7 cm. The same technique has been applied to the study of the 9741 daily values for years 1957–1983: a total of 29,223 flux measurements for the three wavelengths. Table 13 shows that only 32 of these required corrections of 10% or greater, and this figure falls to eight if the anomalous 3 cm fluxes in 1960 are excluded. These remaining anomalies can be explained if the published fluxes are examined. For example, in September 1963, the observed fluxes were as follows:

September	8	3	10.7
		(cm)	
20	130	295	109
21	141	316	90
22	117	296	105
23	111	288	99

It is obvious from a comparison of the other values that the value of 90 at 10 cm on 21 September is unrealistic and requires correction: the corresponding anomalous point stands out clearly in Figs. 11 and 12 (at 90 on the x-axis).

Figure 28 shows the frequency distributions of the percentage deviations from the space line of the fluxes at 3, 8 and 10.7 cm. The first conclusion is that, at 8 and 10.7 cm, at least 90% of the fluxes lie within ±3% of the value given by the space line; at 3 cm, this figure falls to 85%. Alternatively, it can be said that 99% of the values lie within ±7% at 3 cm, ±6% at 10.7 cm and ±5% at 8 cm.

In Fig. 28, the anomalous values at 3 cm for deviations exceeding −6% originate mainly from the 32 cases of deviations which occurred in 1960. In fact, however, only 1.5% of the 3 cm fluxes observed during 25 years differed by more than 6% from the value given by the space line.

It is concluded that the daily flux values at 3, 8 and 10.7 cm, when considered together, can be used to

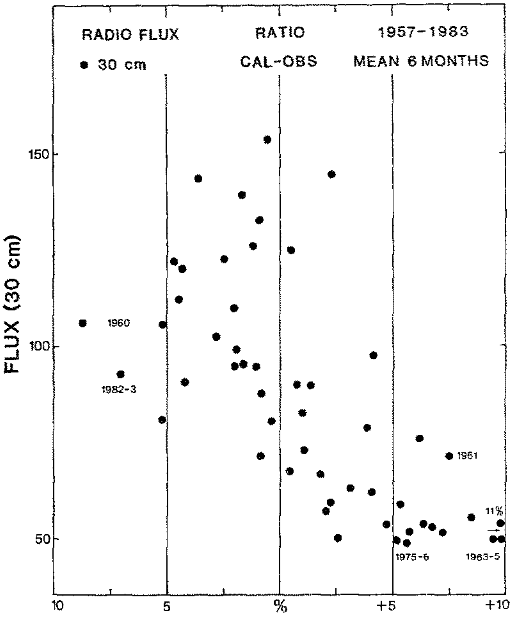

FIG. 27. DISTRIBUTIONS OF DIFFERENCES (%) BETWEEN THE CALCULATED SOLAR RADIO FLUXES DETERMINED BY THE LINEAR REGRESSION WITH 10.7 cm AND THE OBSERVED VALUE AT 30 cm. The differences between the linear and the quadratic regressions give rise to differences in the ratios which exceed +5% for quiet Sun periods, namely in 1963–1965 and 1975–1976. Anomalies are detected in 1960–1961 where the difference varies from 7.5% in 1960 to +7.5 in 1961. The period 1982–1983 seems also to correspond to another anomaly. The general behaviour of the differences, which vary from +5 to −5% and then to 0% with increasing solar activity, corresponds to the difference between the linear and the quadratic regressions. See also Fig. 29.

indicate the level of solar activity to within ±5% in most cases, and to within ±10% in all cases where the fluxes have been correctly measured. It is then possible to adopt linear relations connecting the fluxes at 3, 8 and 10.7 cm:

$$F_3 = 254\left[1+0.30\left(\frac{F_8-72}{100}\right)\right] \tag{11}$$

$$F_3 = 254\left[1+0.26\left(\frac{F_{10.7}-65}{100}\right)\right] \tag{12}$$

$$F_8 = 72\left[1+1.82\left(\frac{F_3-254}{100}\right)\right] \tag{13}$$

$$F_8 = 72\left[1+1.20\left(\frac{F_{10.7}-65}{100}\right)\right] \tag{14}$$

$$F_{10.7} = 65\left[1+2.31\left(\frac{F_3-254}{100}\right)\right] \tag{15}$$

$$F_{10.7} = 65\left[1+1.78\left(\frac{F_8-72}{100}\right)\right]. \tag{16}$$

Equation (12) is practically identical to equations (1a) and (10).

The flux values at 15 and 30 cm cannot be related to those at the three lower wavelengths by using a simple linear regression line; Figs. 9 and 10, and also Table 7, show that a quadratic relationship is required. The method used above for the detection of anomalies, illustrated in Figs. 13–20, cannot be applied here without taking into account the different levels of solar activity, since a systematic variation could be attributable to a deviation from a linear relationship. Nevertheless, when such a variation appears over a wide range of levels of solar activity, it can only be regarded as a real anomaly. The above points are illustrated in Fig. 29 which refers to the comparison between 6-month average values of the fluxes at 30 and 10.7 cm; the procedure used is analogous to that of Table 12 except that the space line refers to 8, 10.7 cm and 30 cm. Two conclusions can be drawn: (a) all the values of the 30 cm flux are within ±10% of the values given by the space line, (b) there is a tendency for the points to follow the variation (dashed line) represented

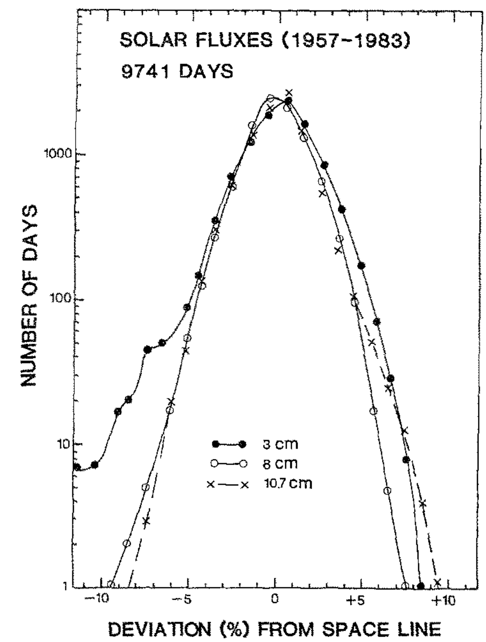

FIG. 28. DEVIATIONS (%) FROM THE SPACE LINE IN THE RECTANGULAR COORDINATE SYSTEM 8, 3 AND 10.7 cm. Number of days in a total of 9741 days. The anomaly at 3 cm (between −6 and −10%) corresponds mainly to 1960 (32 days), 1969 (12 days), 1981 (17 days) and 1982 (24 days).

TABLE 12. SOLAR RADIO FLUXES AT 3 cm, 8 cm AND 10.7 cm. SIX-MONTH MEAN VALUES FROM 1957 TO 1983

	PERIODS(1) YEAR	DAYS	3 cm CORRECTIONS (± %)(2)	8 cm CORRECTIONS (± %)(2)	10.7 cm CORRECTIONS (± %)(2)	RMS(3)	3 cm ADJUSTED VALUES(4)	8 cm ADJUSTED VALUES(4)	10.7 cm ADJUSTED VALUES(4)
1	57-57	121-273	0.2	- 0.4	0.3	0.6	367	219	236
2	57-58	274- 90	0.1	0.9	- 0.9	1.2	377	232	251
3	58-58	091-273	0.8	1.0	- 1.3	1.9	366	217	233
4	58-59	274- 90	0.9	- 0.1	- 0.3	0.9	361	211	226
5	59-59	091-273	0.6	0.7	- 0.7	1.0	354	202	215
6	59-60	274-091	0.5	0.7	- 0.8	1.1	324	163	170
7	60-60	092-274	- 2.7	1.0	0.0	2.9	323	162	169
8	60-61	275-090	- 3.5	1.0	0.1	3.6	294	123	125
9	61-61	091-273	- 0.4	- 0.4	0.4	0.7	285	112	111
10	61-62	274-090	0.9	- 1.1	0.7	1.5	274	98	95
11	62-62	091-273	- 0. 2	- 0.6	0.5	0.8	272	95	91
12	62-63	274-090	1.0	- 0.7	0.4	1.3	264	85	80
13	63-63	091-273	0.5	- 0.8	0.6	1.1	267	89	84
14	63-64	274-091	1.4	- 0.6	0.2	1.5	263	83	77
15	64-64	092-274	- 0.8	- 0.5	0.6	1.1	259	77	71
16	64-65	275-090	- 1.7	- 0.4	0.6	1.8	261	80	75
17	65-65	091-273	- 2.4	- 0.1	0.5	2.5	263	83	77
18	65-66	274-090	- 1.4	0.1	0.2	1.5	265	86	81
19	66-66	091-273	- 2.2	0.7	- 0.1	2.4	281	106	105
20	66-67	274-090	- 1.9	0.4	0.2	1.9	298	129	131
21	67-67	091-273	- 1.2	1.4	- 0.9	2.1	303	135	138
22	67-68	274-091	0.5	1.5	- 1.5	2.2	312	147	152
23	68-68	092-274	- 0.5	0.8	- 0.6	1.1	306	140	143
24	68-69	275-090	- 1.5	- 0.2	0.6	1.6	311	146	151
25	69-69	091-273	- 1.6	- 0.7	1.1	2.1	311	146	151
26	69-70	274-090	- 0.5	- 1.0	1.1	1.6	314	150	156

27	70-70	091-273	- 1.3	- 1.5	1.7	2.7	317	153	159
28	70-71	274-090	0.3	- 1.0	0.7	1.2	306	140	144
29	71-71	091-273	- 0.7	- 0.3	0.4	0.9	286	114	114
30	71-72	274-091	1.3	- 0.4	0.0	1.4	290	119	119
31	72-72	092-274	- 0.5	- 0.7	0.7	1.1	295	125	127
32	72-73	275-090	0.5	- 0.4	0.2	0.7	279	104	103
33	73-73	091-273	0.7	- 0.9	0.6	1.3	275	99	97
34	73-74	274-090	0.3	- 0.1	0.0	0.3	265	86	81
35	74-74	091-273	- 0.3	- 1.1	1.0	1.5	271	94	91
36	74-75	274-090	- 0.2	- 1.0	0.8	1.3	265	86	81
37	75-75	091-273	0.4	- 0.9	0.7	1.2	263	84	79
38	75-76	274-091	0.1	- 0.9	0.6	1.2	261	80	75
39	76-76	092-274	0.3	- 0.6	0.4	0.8	260	79	74
40	76-77	275-090	1.1	- 0.3	0.0	1.1	261	81	75
41	77-77	091-273	0.5	- 0.6	0.4	0.8	269	92	88
42	77-78	274-090	0.2	- 0.5	0.3	0.6	286	113	113
43	78-78	091-273	- 0.4	- 0.8	0.7	1.1	307	140	144
44	78-79	274-090	0.8	- 1.1	0.7	1.5	328	168	177
45	79-79	091-273	0.4	- 0.4	0.2	0.6	331	171	180
46	79-80	274-091	1.2	0.8	- 1.2	1.9	342	187	198
47	80-80	092-274	2.1	0.5	- 1.3	2.5	340	184	195
48	80-81	275-090	1.3	0.5	- 1.0	1.7	343	188	199
49	81-81	091-273	1.2	0.6	- 1.0	1.7	346	191	203
50	81-82	274-090	0.5	- 0.1	- 0.1	0.5	345	191	203
51	82-82	091-273	1.3	0.1	- 0.5	1.4	320	158	164
52	82-83	274-090	0.4	0.4	- 0.4	0.7	310	144	149
53	83-83	091-273	2.0	0.0	- 0.6	2.1	296	126	128

(1) 53 periods of 6 months from 1957 to 1983; $N = 1$ from day 121 to day 273 in 1957 and $N = 53$; $N = 53$ from day 91 to day 273 in 1983.
(2) Corrections in $\pm\%$ to fit the space least-squares line for 3, 8 and 10.7 cm.
(3) Standard deviation = root-mean-square of the x–y–z deviations.
(4) Values deduced from the least-squares line.

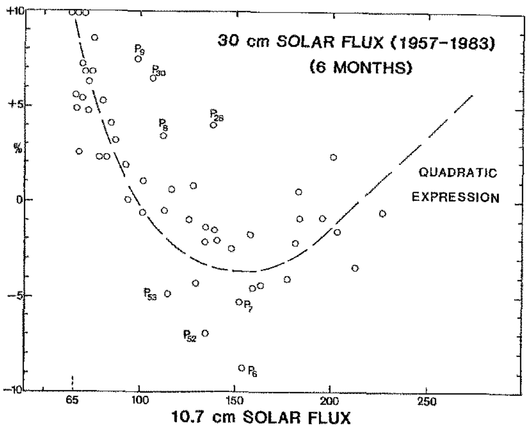

FIG. 29. DEVIATIONS (%) FROM THE SPACE LINE IN THE RECTANGULAR COORDINATE SYSTEM 8 AND 10.7 cm WITH 30 cm FOR 53 PERIODS OF 6 MONTHS BETWEEN 1957 AND 1983.
The curve represents the positive and negative differences (%) between the linear and quadratic expressions used to represent the daily values at 30 cm compared with 10.7 cm. Anomalies such as P6 and P26 correspond to peculiar trends in the 30 cm observations.

by a quadratic expression. In other words, when the Sun is quiet, the linear relation gives values that are about 10% too high; but at middle levels of activity the values are about 5% too low. In Fig. 29, the anomalous points P_6, P_8 etc. refer to Periods 6, 8 etc. in Table 8. P_6 and P_9 occur in 1959–1960, while P_{26} and P_{30} relate to the period near Day 5000 where anomalous values can be seen in Fig. 20.

The solar radio flux observed between 1957 and 1983 at wavelengths in the range 3–10 cm can be represented with good accuracy by a linear space line. As already indicated by Tanaka (1964), the accuracy for wavelengths less than 15 cm is greater than for those in the decimetric band as a whole.

However, the plots of the daily value above 15 cm shows that the linear relationship is no longer valid and that a quadratic relation gives a better representation of the variations during a complete solar cycle. This fact could be borne in mind when solar radio noise fluxes are used as indices of the level of solar activity in studies of variations in the u.v. irradiance of the Sun.

Finally, it is possible to adopt the following quadratic relations connecting the fluxes at 15 and 30 cm with that at 10.7 cm.

$$F_{15} = 47\left[1+2.02\left(\frac{F_{10.7}-65}{100}\right)-0.145\left(\frac{F_{10.7}-65}{100}\right)^2\right]$$

$$\begin{matrix} CC & D \\ 0.993 & 5.3 \end{matrix} \qquad (17)$$

and

$$F_{30} = 38\left[1+2.03\left(\frac{F_{10.7}-65}{100}\right)-0.260\left(\frac{F_{10.7}-65}{100}\right)^2\right]$$

$$\begin{matrix} CC & D \\ 0.979 & 6.8 \end{matrix} \qquad (18)$$

9. 27-DAY MODULATION

A full analysis of the solar irradiance in the centimetric and decimetric wavebands would require a detailed study of its variations during the 27-day synodic rotation periods and during a complete solar cycle. Such a project would require greater accuracy than that needed for statistical studies of the variations during the solar cycle. Corrections would be necessary for the elimination of abnormal values associated with rapid fluctuations in solar activity. Such a study was not one of our objectives, but a simplified approach to the question of the 27-day modulation has led to several conclusions; these are based on the 53 periods in Table 8 which cover the 25 years from 1957 to 1983. For each of these periods, the ratio of the daily value of the flux to the 27-day moving average was calculated for 3, 8, 10.7, 15 and 30 cm. The four highest and the four lowest ratios were then selected but, in order to avoid possible anomalies in the extreme values, only the second and third highest $V2$ and $V3$ (max) and the second and third lowest values $V2$ and $V3$ (min) were retained for further treatment. For each period of 6 months, the "amplification factor" was defined as the ratio of the average value of $V2+V3$ (max) to the average $V2+V3$ (min). In Fig. 30, the amplification factor has been plotted against the ratio of the mean flux for the corresponding 6-month period to the flux for the quiet sun. The curve for each wavelength passes through the median values of the amplification factors observed during the period 1957–1983.

The first conclusion is that the 27-day modulation is least for the fluxes at 30 and 3 cm. Moreover, the variability in the flux during the solar cycle is least at 3 cm; the 6-month mean value never exceeds the quiet sun value by a factor of more than 1.7 as compared with a factor of more than 3.5 at the other wavelengths. The second conclusion relates to the maxima in the amplification factors at 8, 10.7 and 15 cm (1.6 approximately) which occur when the mean 6-month flux is about 2 to 2.5 times as great as the value at the solar minimum.

This concise survey of the 27-day modulation of the fluxes between 3 and 30 cm demonstrates that the amplification factor increases very rapidly at the

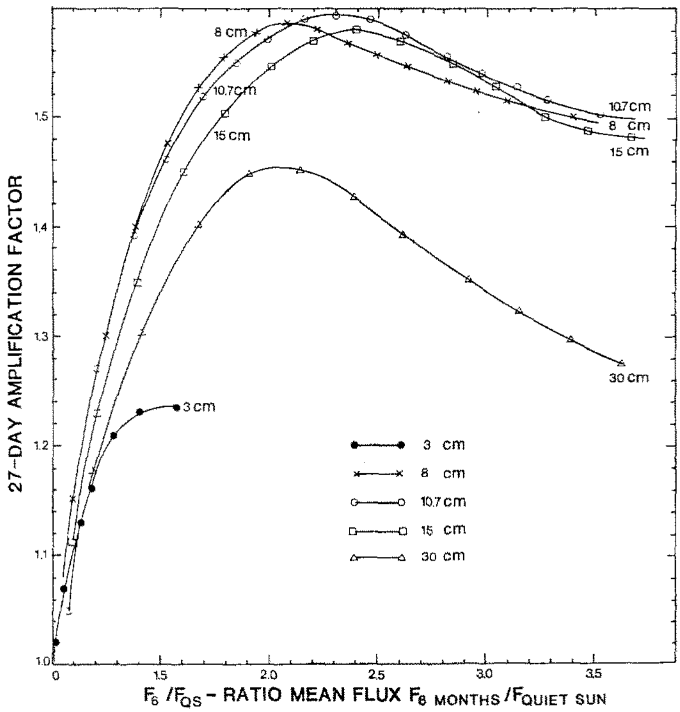

FIG. 30. AMPLIFICATION RATIO FOR THE 27-DAY MODULATION VS THE RATIO OF THE 6-MONTH MEAN SOLAR FLUX F_6 AND THE FLUX F_{QS} FOR A QUIET SUN AT 3, 8, 10.7, 15 AND 30 cm RESPECTIVELY.
The curves correspond to median curves deduced from the 53 6-month periods between 1957 and 1983.

beginning of a solar cycle, and then stabilizes near a limiting value. When the flux increases by a factor of 1.5 as compared with the solar minimum value, the amplification factor increases just as rapidly. However, when the flux lies between 1.5 and 3.5 times its minimum value, the amplification factor remains at about 1.5 1.6 for 8, 10.7 and 15 cm wavelengths. It is important to remember that these conclusions do not apply to particular cases; they are valid only for the typical mean conditions that occur during a solar cycle. In short, the 27-day modulation of the fluxes at centimetre and decimetre wavelengths is particularly sensitive to changes in solar activity when the general level of activity is low, i.e. when the flux is less than 1.5 times the minimum value of the flux; above this limit, the modulation tends to be independent of the level of solar activity. However, it is necessary to take account of the scatter of the data above and below such mean values which include only 80–90% of the values with a scatter of less than ±10%.

CONCLUSIONS

A detailed analysis has been made of the solar radio fluxes in the wavelength range 3–30 cm as observed at Toyokawa and Ottawa between 1957 and 1983. These have been published in corrected form in 1977 (Ottawa) and 1975 (Toyokawa) for the years preceding these dates, and monthly thereafter. From this analysis it is concluded that the various calibrations adopted from time to time are sufficient to ensure a general consistency of the radio fluxes in the centimetre range.

However, an examination of the yearly mean values at various wavelengths has shown up an anomaly in the observed fluxes at 3 cm in 1960. Another investigation, based on the mean ratios of the fluxes to those at 10.7 cm during periods of 18 or 6 months between 1957 and 1983, confirms the abnormality of the data for certain periods. The differences take the form of ratios that are too great or too small by several percentage points. Nevertheless, the conclusion is that there is no important long-term trend in the data, and this indicates that there is normally a close connection between the radio fluxes in the centimetre region. The same conclusion cannot be reached for the decimetre region since there is quadratic effect at 15 and 30 cm.

The regression analysis of the daily values of the flux for at least 25 years also leads to various conclusions such as the existence of anomalous values due to numerical errors, or to differences relating to specific wavelengths. Day-to-day variations may differ from one wavelength to another, particularly when the observational data were not obtained simultaneously, where they were corrected for a burst effect, or when they are not daily averages. In such cases the accuracy of the data is relatively low and cannot be better than $\pm 10\%$.

A study of the series of over 8000 daily values of the flux between 1957 and 1980 has been made. This was designed to test the stability of the data with respect to time and solar activity, and led to the conclusion that various trends corresponding to drifts of specific origin may occur. For example, the 3 cm data for 1960 appear to be abnormal. At 15 cm, positive and negative drifts have been detected, and these are even more apparent at 30 cm; this suggests that these two wavelengths ought not yet to be used directly as a basis for studies of solar activity. A special analysis is required since a quadratic relationship must replace the linear expressions used for 3, 8 and 10 cm. A three-dimensional least-squares line representing the fluxes at 3, 8 and 10.7 cm can be determined which corresponds to the two-dimensional relations between 3 and 8 cm, 3 and 10.7 cm and 8 and 10.7 cm.

In conclusion, the combination of the radio fluxes at 3, 8 and 10 cm could form a good basis for a permanent solar activity index based on solar radio emissions in the centimetre band.

Acknowledgements—The authors are deeply indebted to Dr. C. M. Minnis for discussing and editing the test. They are grateful to Drs. Covington and Tanaka for providing their solar radio data since the beginning of the International Geophysical Year, and also thank the National Research Council of Canada and the Toyokawa Observatory for their monthly publications which led to discussions of the solar radio emissions at cm and dm wavelengths. All of this information is vital to the understanding of solar–terrestrial relationships. A first version of this paper was written when the authors were at the Royal Meteorological Institute of Belgium. It was presented with the title "Solar radio flux models for the study of trends in solar u.v. irradiances" (*IAGA-IAMAP Symp. Middle Atmosphere Sci.*, IUGG XVIII General Assembly, Hamburg, 15–27 August 1983, p. 314). The final solar irradiances (1957–1983) which have been adopted can be made available by contacting the Belgian Space Aeronomy Institute, c/o J. Palange.

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APPENDIX

Least-square fitting of a straight line when all the data contain errors of comparable magnitude.

We consider N sets of M simultaneous measurements which define N points P in a vector space V^M. This will be the case when the measurements refer to the same physical quantity.

The origin of the coordinates is placed at the centre of gravity of the points, and the vectors OP_i are designated by $\mathbf{x}_i$.

The problem is to find the unit vector $\mathbf{v}$ which defines the

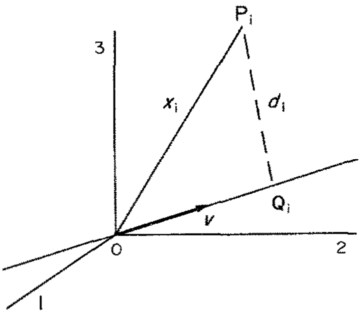

Fig. A1.

straight line passing through the origin, and such that the sum of the squares of the distances of the points P_i from the straight line is a minimum.

The vector $\mathbf{d}_i = P_iQ_i$ is

$$\mathbf{d}_i = \mathbf{x}_i - (\mathbf{x}_i \mid \mathbf{v})\mathbf{v} \tag{A1}$$

and the problem is to minimize

$$S \equiv \frac{1}{2}\sum_i (\mathbf{d}_i \mid \mathbf{d}_i) \tag{A2}$$

given the condition that

$$(\mathbf{v} \mid \mathbf{v}) = 1. \tag{A3}$$

Introducing the Lagrange multiplier λ, and omitting the summation signs, the problem is to minimize

$$\begin{aligned} S &= \tfrac{1}{2}[(\mathbf{d} \mid \mathbf{d}) + \lambda(\mathbf{v} \mid \mathbf{v})] \\ &= \tfrac{1}{2}[(\mathbf{x} \mid \mathbf{x}) - 2(\mathbf{x} \mid \mathbf{v})^2 + (\mathbf{x} \mid \mathbf{v})^2(\mathbf{v} \mid \mathbf{v}) + \lambda(\mathbf{v} \mid \mathbf{v})] \end{aligned} \tag{A4}$$

the normal equations of which are, in vector form,

$$\mathbf{f} \equiv \frac{\partial S}{\partial \mathbf{v}} = [\lambda\mathbf{v} + (\mathbf{x} \mid \mathbf{v})^2\mathbf{v} - (\mathbf{x} \mid \mathbf{v})\mathbf{x}] = \mathbf{0}. \tag{A5}$$

On multiplying scalarly with $\mathbf{v}$, we see that $\lambda = 0$ in the present case. In consequence, the normal equations reduce to

$$\mathbf{f} = (\mathbf{x} \mid \mathbf{v})^2\mathbf{v} - (\mathbf{x} \mid \mathbf{v})\mathbf{x} = \mathbf{0} \quad \text{with} \quad (\mathbf{v} \mid \mathbf{v}) = 1. \tag{A6}$$

These equations become homogeneous in $\mathbf{v}$ on the formation of antisymmetrical expressions

$$g_{jk} \equiv v_j f_k - v_k f_j = (\mathbf{x} \mid \mathbf{v})(x_j v_k - x_k v_j) = 0 \tag{A7}$$

which on writing

$$(\mathbf{x} \mid \mathbf{v}) = x_j v_j + x_k v_k + \Sigma\, x_m v_m \quad (m \neq j, k)$$

takes the form

$$x_j x_k v_k^2 + (x_j^2 - x_k^2) v_j v_k - x_j x_k v_j^2 = \Sigma\,(x_k x_m v_j - x_j x_m v_k) v_m. \tag{A8}$$

The system of equations $g_{jk} = 0$ is redundant; it is sufficient, for example, to put $j = 1$ and the equations $g_{1k} = 0$ give $M-1$ normal equations where the products x_p, x_q and x_p^2 are the components of the covariance matrix of the data.

When $M = 2$, the set of equations (A8) reduces to the single equation

$$x_1 x_2 v_2^2 + (x_1^2 - x_2^2) v_1 v_2 - x_1 x_2 v_1^2 = 0 \tag{A9}$$

the solution of which is the root which has the same sign as $x_1 x_2$ and the values of v_1 and v_2 are obtained from

$$v_1^2 + v_2^2 = v_1^2\left(1 + \frac{v_2^2}{v_1^2}\right) = 1. \tag{A10}$$

When $M > 2$, the solution of the equations (A8) can be obtained as follows: put $v_1 = 1$, omit the right side of (A8) and solve the equations in the same way as equation (A9); then insert the results in the right sides and proceed by iteration. The final values of the v_js are determined by the condition in equation (A3).