

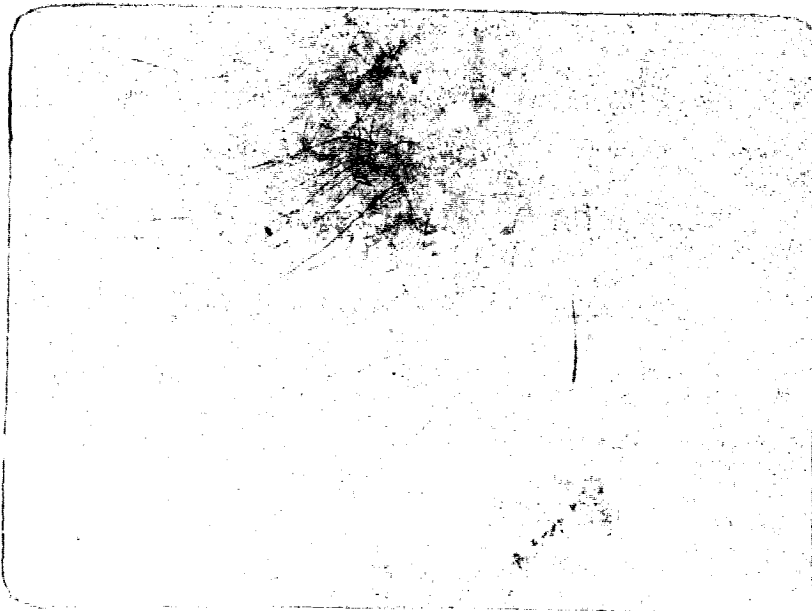
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(NASA-TM-84715) MICROWAVE AND HARD X-RAY  
OBSERVATIONS OF A SOLAR FLARE WITH A TIME  
RESOLUTION OF BETTER THAN 100 MS (NASA)  
17 p HC A02/MF A01

N82-30215

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1. Publication Nº <i>INPE-2336-PRE/083</i>	2. Version <i>1 st.</i>	3. Date <i>Feb., 1982</i>	5. Distribution <input type="checkbox"/> Internal <input checked="" type="checkbox"/> External  <input type="checkbox"/> Restricted
4. Origin <i>CAS/DAS</i>			Program <i>Rádio Astron. Fís. Solar</i>
6. Key words - selected by the author(s); <i>Solar bursts</i> <i>multi-structured bursts</i> <i>time delay X-ray, microwaves</i>			
7. U.D.C.: <i>523.03</i>			
8. Title  <i>MICROWAVE AND HARD X-RAY OBSERVATIONS OF A SOLAR FLARE WITH A TIME RESOLUTION OF BETTER THAN 100MS</i>		10. Nº of pages: <i>17</i>	
		11. Last page: <i>16</i>	
		12. Revised by  <i>Pierre Kaufmann</i>	
9. Authorship  <i>P. Kaufmann</i> <i>F.M. Strauss</i> <i>J.E.R. Costa</i> <i>B.R. Dennis **</i> <i>A. Kiplinger**</i> <i>K.J. Frost**</i> <i>L.E. Orwig**</i>		13. Authorized by  <i>Nelson de Jesus Parada</i> <i>Director</i>	
Responsible author			
14. Abstract/Notes - <i>Simultaneous microwave and X-ray observations are presented for a solar flare detected on 1980 May 8 starting at 1937 UT. The X-ray observations were made with the Hard X-Ray Burst Spectrometer on the Solar Maximum Mission and covered the energy range from 28-490 keV with a time resolution of 10 ms. The microwave observations were made with the 5 and 45 foot antennas at the Itapetinga Radio Observatory at frequencies of 7 and 22 GHz, with time resolutions of 100 ms and 1 ms respectively. Detailed correlation analysis of the different time profiles of the event show that the major impulsive peaks in the X-ray flux preceded the corresponding microwave peaks at 22 GHz by about 240ms. For this particular burst the 22 GHz peaks preceded the 7 GHz by about 1.5s. Observed delays of the microwave peaks are too large for a simple electron beam model but they can be reconciled with the speeds of shock waves in a thermal model.</i>			
* In memoriam (1942-1981) ** NASA/GSFC			
15. Remarks - <i>Research supported partially by FINEP and FAPESP. Submitted to Solar Physics.</i>			

**MICROWAVE AND HARD X-RAY OBSERVATIONS OF A SOLAR FLARE WITH A TIME  
RESOLUTION OF BETTER THAN 100 MS**

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**ABSTRACT**

Simultaneous microwave and X-ray observations are presented for a solar flare detected on 1980 May 8 starting at 1937 UT. The X-ray observations were made with the Hard X-Ray Burst Spectrometer on the Solar Maximum Mission and covered the energy range from 28-490 keV with a time resolution of 10 ms. The microwave observations were made with the 5 and 45 foot antennas at the Itapetinga Radio Observatory at frequencies of 7 and 22 GHz, with time resolutions of 100 ms and 1 ms respectively. Detailed correlation analysis of the different time profiles of the event show that the major impulsive peaks in the X-ray flux preceded the corresponding microwave peaks at 22 GHz by about 240 ms. For this particular burst the 22 GHz peaks preceded the 7 GHz by about 1.5s. Observed delays of the microwave peaks are too large for a simple electron beam model but they can be reconciled with the speeds of shock waves in a thermal model.

**\* In memoriam (1942-1981)**

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**\*\* INPE operates CRAAM and Itapetinga Radio Observatory**

## 1. INTRODUCTION

Accurate measurements of timing and flux relationships between hard X-rays and short wavelength radio emission from solar bursts are crucial for the understanding of the impulsive stage of solar flares. Extensive discussions on thermal and non-thermal interpretations of early phases of bursts have been published (e.g. Kahler 1975, Kane et al. 1980, Brown and Smith 1980), but the results are still far from conclusive. Continuation of these researches depend on new and more refined simultaneous measurements in different energy ranges with better spatial, temporal and spectral resolution. Some basic questions such as whether hard X-rays and microwaves are emitted by the same population of energetic electrons and if they are emitted at the same spatial location can be addressed by precise timing measurements.

Present knowledge of temporal relationships between emission at different microwave frequencies and between microwave and hard X-ray emission has, until recently, been restricted by timing accuracies of no better than a second. Uralov and Nefed'ev (1976) and Wiehl et al. (1980) have presented observations showing the lower frequency microwave emission delayed by several seconds compared to the higher frequency emission. Kaufmann et al. (1980a) showed that, for a complex burst, the general time structures were delayed by ~2s at 7 GHz compared to similar structures observed at 22 GHz. Other flares, however, show delays either for the lower frequency emission or for the higher frequency emission in the region of mm-cm wavelengths (Kaufmann et al. 1982a). Previous hard X-ray observations have shown good correlations with the microwave emission within the 1-2 s time resolution generally available (Parks and Winckler 1969, Kane and Anderson 1970, Mätzler et al. 1978). Crannell et al. (1978) have, however, pointed out that hard X-rays are likely to occur 1-2 s prior to the microwave emission. Crannell et al. (1980; 1982) have also shown that, for one particular flare, the microwave emission was delayed at all frequencies compared to the X-ray emission and that the amount of the delay was dependent on the absolute value of the

difference between the observed frequency and the frequency at which the flux was a maximum, with the longer delay for the greater difference.

We discuss in this paper the first example of a burst observed simultaneously in microwaves and hard X-rays with sub-second time resolution.

## 2. OBSERVATIONS

The solar flare of 8 May 1980 at 1937 UT was the first event that was observed with the Hard X-ray Burst Spectrometer (HXRBS) on the Solar Maximum Mission with 10 ms time resolution and simultaneously with the Itapetinga microwave antennas at frequencies of 22 and 7 GHz. Details of the instruments used to make the observations are given Table I. The flare was classified as SB in H $\alpha$  and M2 in soft X-rays; it was located at S22W29 in the NOAA active region 2418 (Hale number 16815) (NOAA, 1980).

In Figure 1 we display flux-versus-time profiles for the complete event in microwaves at 7 and 22 GHz, and in hard X-rays. The burst had no linear polarization component at 22 GHz and had a 40 percent left-handed polarization at 7 GHz. Major peaks 2 to 3 s in duration repeat at an average time interval of 5.5 s. A more slowly varying component appears to underly these major peaks. Some significant ultra-fast structure on a time scale of less than 1 s can be distinguished at 22 GHz and also in the X-ray emission (see also Figure 3).

## 3. TEMPORAL ANALYSIS

In order to determine the temporal relationship between the 7 GHz and the 22 GHz emission, the data covering the total duration of the event at these two frequencies were cross-correlated. The resulting cross-correlation coefficient is plotted

in Figure 2 as a function of the delay of the 7 GHz data. This plot shows clearly the 5.5 s quasi-periodicity (also evident in Figure 1 and the X-ray power spectrum) and also the overall 1.54 s delay of the 7 GHz emission compared with the 22 GHz emission. This delay can be seen directly in Figure 3 where the major peaks in the three data sets are plotted on an expanded time scale.

The small rapid variations in the 22 GHz flux shown in Figure 3 are all of solar origin; the instrumental rms deviation is only 0.03 sfu. They may be of the same nature as the ultra-fast time structures reported previously by Kaufmann et al. (1980b). Any such features at 7 GHz would be smoothed out by the poorer time resolution (100 ms) and lower sensitivity (rms deviation of 2 sfu) at this frequency. Some of the rapid variations in the X-ray counting rate are also of solar origin as indicated by the statistical uncertainties shown in Figure 3. Note that many of the fast structures seen at 22 GHz are also present in the X-ray data. Moreover, Figure 3 reveals a delay in the overall microwave time profile compared to the X-ray time profile. Direct measurements at the half intensity levels of the major peaks indicate that the 22 GHz emission is delayed by ~ 250 ms and that the 7 GHz emission is delayed by ~ 1.66 s both with respect to the X-ray emission.

A more quantitative method of determining the delay of the 22 GHz emission is to cross-correlate the 7 s of hard X-ray and 22 GHz data covering the major peak of the event from 19<sup>h</sup>37<sup>m</sup>12<sup>s</sup> to 19<sup>h</sup>38<sup>m</sup>19<sup>s</sup> UT (shown in Figure 3). After averaging the data into 30 ms samples, the two data sets were cross-correlated using two different methods of data preparation.

The first method renders the cross-correlation function (CCF) sensitive to the relatively slowly varying component in the data sets. Two such calculations involving subtracting either the means of the data sets or quadratic trends gave peaks in the CCF corresponding to microwave lags of 300 and 240 ms, respectively. The second method of data preparation renders the CCF sensitive to the more rapidly varying structures in the data sets. In this method the data in each set was first smoothed with a running-mean filter and then this

smoothed data were subtracted from the original. Two CCFs were computed on the resulting differences, one for a 31 point (0.93 s) running mean and the other for a 17 point (0.051 s) running mean. Both gave microwave lags of 240 ms. The uncertainties in these different cross-correlation techniques are of the order of the 30 ms time resolution used. Consequently, we conclude that both the fast features and the more slowly varying component of the 22 GHz emission lag the X-ray emission by 200 to 300 ms.

#### 4. DISCUSSION

The major result of the simultaneous hard X-ray and microwave observations with sub-second time resolution is that the peaks in hard X-rays precede similar peaks at 22 and 7 GHz. The dynamic spectrum for the observed burst on 1980 May 8 at 1937 UT is as follows: (a) the 22 GHz time structures are delayed by about 240 msec with respect to the corresponding hard X-ray structures; (b) the 7 GHz time structures are delayed by about 1.5 sec with respect to the 22 GHz structures; (c) the maximum time at 2.8 GHz reported by Ottawa, NRS (NOAA, 1980) is delayed a further 2 sec with respect to the 7 GHz maximum. Note that this time sequence of emission at microwave frequencies observed for this event is not a general rule valid for all bursts (Kaufmann et al. 1982a).

Time structures in hard X-ray bursts with time scales of seconds are well known (Frost, 1969, van Beek et al., 1974). Quasi-periodicities of several to tens of seconds in hard X-ray and microwave bursts were also well known (Parks and Winckler 1969, Janssens et al. 1972). They are probably of the same nature as those presented here.

The repetitive character of the superimposed time structures can be attributed to a number of possible primary mechanisms (Brown and Smith, 1980). They might be considered as independent superimposed bursts, the so called "Elementary Flare Bursts", irrespective of the primary mechanisms which produce them (van Beek



et al. 1976; de Jager and de Jonge, 1978).

The currently best accepted models describing hard X-ray and microwave production in the impulsive phase of a flare are the so called thermal and non-thermal models (see, for example, Brown 1976, Rust and Emslie 1979, Brown and Smith 1980). In a hybrid model (Emslie and Vlahos, 1980), X-rays are in part produced by thermal bremsstrahlung from trapped electrons near the top of a magnetic loop, and in part by thick-target bremsstrahlung from fast electrons streaming down and interacting with the denser chromospheric plasma at the foot-points of the loops. Microwaves would arise from gyro-synchrotron emission from the trapped electrons contained by anomalous conduction fronts moving away from the top of the magnetic loop at relatively slow speeds near the ion-acoustic phase velocity. Without going into details, all models appear to predict hard X-ray emission coincident or preceding microwave emission. On the observational standpoint, however, more events have to be analysed with high time resolution in order to establish whether or not hard X-rays always precede microwaves, irrespective to their dynamic spectra.

In attempting to interpret the present observational results, we must discard, initially at least, a plasma response to a beam of fast relativistic electrons since the observed delays are too large. The observed time sequence for the burst analysed here, in which hard X-rays precede mm-waves which in turn precede cm-waves, poses geometric problems for both models.

In non-thermal models one might expect X-rays and microwaves to be closely correlated in time. The observed large delays could be an indication of plasma oscillations produced by an m.h.d. shock resulting from the primary explosion, similar to the metric type II mechanism. However, the primary source must be placed deeper in the chromosphere to explain the observed time sequence of the mm and cm waves.

A thermal model with the primary explosion producing a m.h.d. expanding shock front moving upwards from the lower chromosphere

was used by Uralov and Nefed'ev (1976). Wiehl et al. (1980) assumed the formation of a collisionless conduction front in a similar geometry. Such a conduction front moves upwards with a speed of about  $1000 \text{ km s}^{-1}$  in the lower chromosphere where the electron density is assumed to decrease exponentially with height. In such a model the free-free absorption cutoff frequency decreases with height, and radio emission will appear at progressively lower frequencies as observed. With such a geometry, the observed delays between mm and cm waves are easily explained.

An upward moving front would result in time displacements of the initial increase in flux at different frequencies. This was not found in the event presently analysed. Note that, in Figure 3, as the 22 GHz flux increased from 6 s.f.u. to 13 s.f.u., the 7 GHz flux also increased from 52 s.f.u. to 60 s.f.u.

The assumption of a primary source deep in the chromosphere does not correspond to the geometry most frequently used by various authors (Sturrock and Smith, 1968; Strauss and Papagiannis, 1971; Brown et al., 1979; Rust and Emslie, 1979; Emslie and Vlahos, 1980, etc.). Kundu and Vlahos (1979), discussing polarization characteristics of cm-wave bursts, have placed the primary source lower in a magnetic arch, but with the anomalous conduction front moving downwards. An extension of the thermal model reconciled with the present evidence is being prepared for publication (Costa and Kaufmann, 1982).

A remaining problem is the delay of the 22 GHz emission with respect to the X-ray emission. This can be explained from the difference in the lifetime of the electrons which produce the different types of radiation. The electrons which produce the X-rays at the loop footpoints have very short lifetimes  $< 1 \text{ s}$  whereas at least some of the electrons which produce the microwaves are trapped near the top of the loop for a longer time  $> 1 \text{ s}$ . Thus, the microwave time profile is the integral of the X-ray profile with a time constant of the order of the average electron trapping time. It is still curious, however, that emission from the initial electron beam is not detected before it

produces X-rays at the footpoints in spite of the high sensitivity of the observations. This might be attributed to the very small fraction of fast electrons with small pitch angles which actually escape to the footpoints (Brown 1976, Kundu and Vlahos 1979).

#### ACKNOWLEDGEMENTS

Observations at the Itapetinga Radio Observatory received technical help from R.E.Schaal and C. Laporte. This research was partially supported by the Brazilian research agencies FAPESP and FINEP. The hard X-ray data were analysed and the cross-correlation analysis was carried out using computer programs written by T. Chewning, H. Dennis and K. Talbert of Computer Sciences Corporation.

TABLE 1

X-RAY OBSERVATIONS

Instrument	Hard X-ray Burst Spectrometer on SMM
Energy Range	28 - 490 keV
Beam width	Whole Sun ( $40^\circ$ FWHM)
Time resolution	10 ms - no spectral resolution 128ms-15 channel spectral information
Absolute timing accuracy	< 5 ms
Reference	Orwig <u>et al.</u> (1980)

RADIO OBSERVATIONS

Instruments	Dish antennas at Itapetinga, Brazil	
Antenna diameter	5 ft (1.5 m)	45 ft (13.7 m)
Frequency	7 GHz	22 GHz
Wavelength	4.3 cm	1.35 cm
Time resolution	100 ms	1 ms
Absolute timing accuracy	< 100 $\mu$ s	< 100 $\mu$ s
Sensitivity	2 sfu	0.03 sfu
Polarization	circular	two orthogonal linear components
Beam width	Whole sun $2^\circ$ HPBW	4' HPBW
Reference	Kaufmann <u>et al.</u> (1982b)	

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### FIGURE CAPTIONS

Figure 1: The hard X-ray and microwave time profiles of the solar flare on 1980 May 8 at 1937 UT. Seven seconds of data covering the major peak, indicated by vertical dashed lines, are shown in Figure 3 on an expanded time scale.

Figure 2: The result of the cross-correlation of the 7 and the 22 GHz data for the complete event from  $19^{\text{h}}36^{\text{m}}50.00^{\text{s}}$  to  $19^{\text{h}}38^{\text{m}}38.40^{\text{s}}$  UT. The cross-correlation coefficient is plotted as a function of the delay of the 7 GHz data. Both sets of data were digitally filtered prior to the analysis to eliminate frequency components close to zero and to the Nyquist frequency. The analysis was carried out using standard techniques and formulae for the coefficients and uncertainties (IBM 1968, Bevington 1969). The 5.5 s quasi-periodicity is indicated together with the 1.54 s delay of the 7 GHz emission.

Figure 3: The major peak of the 1980 May 8 event on an expanded time scale showing the time delays of the 7 and 22 GHz emission with respect to the hard X-rays. The instrumental noise has an rms deviation of 0.03 sfu at 22 GHz and 2 sfu at 7GHz. The error bars shown on the X-ray data points are  $\pm$  one standard deviation calculated from the square root of the number of counts observed in each 50 ms interval. The time resolution is 50 ms for the X-rays, 1 ms at 22 GHz and 100ms at 7 GHz. Note that some of the ultra-fast time structure at 22 GHz has corresponding structure in X-rays but with a translation in time.



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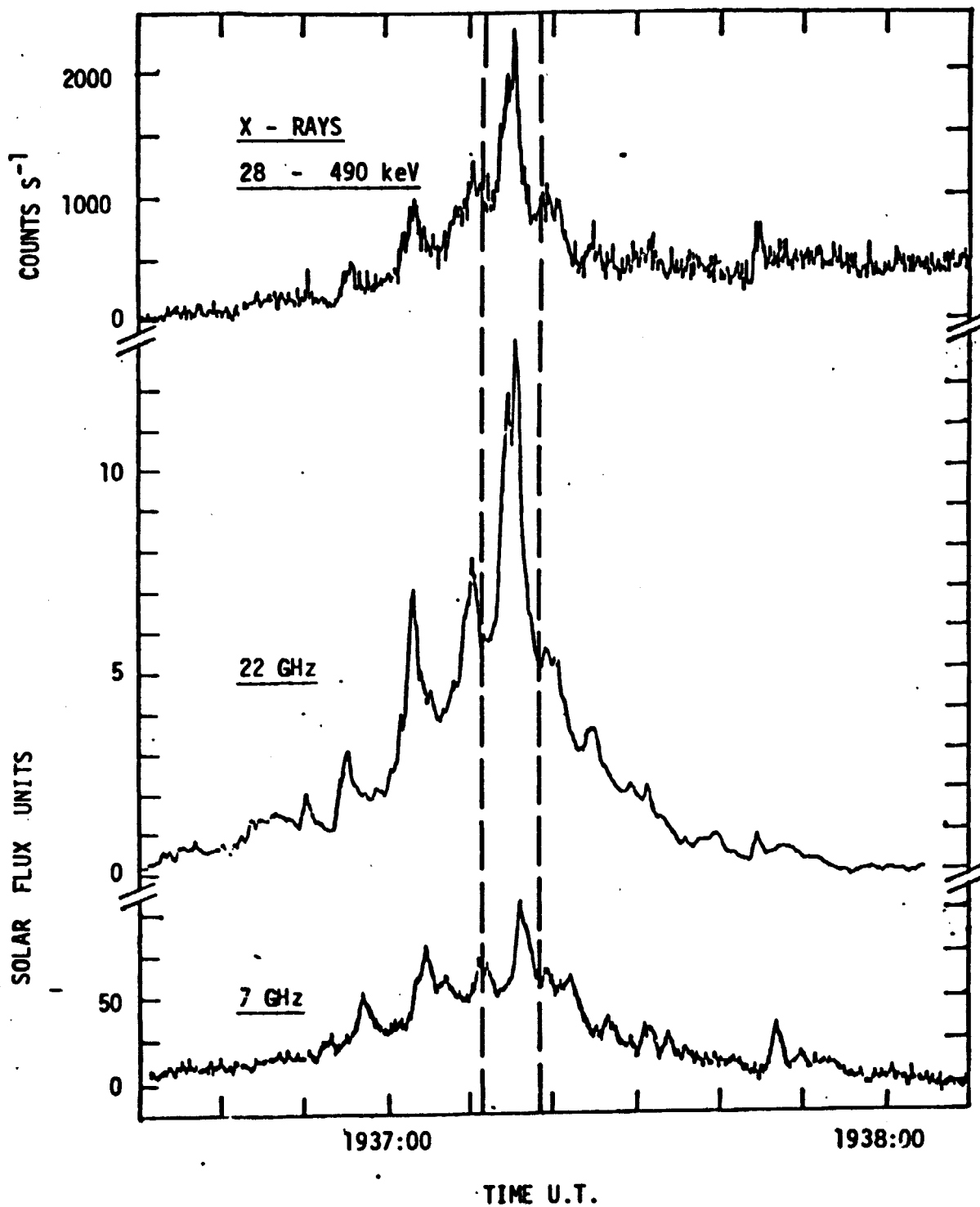


Fig.1

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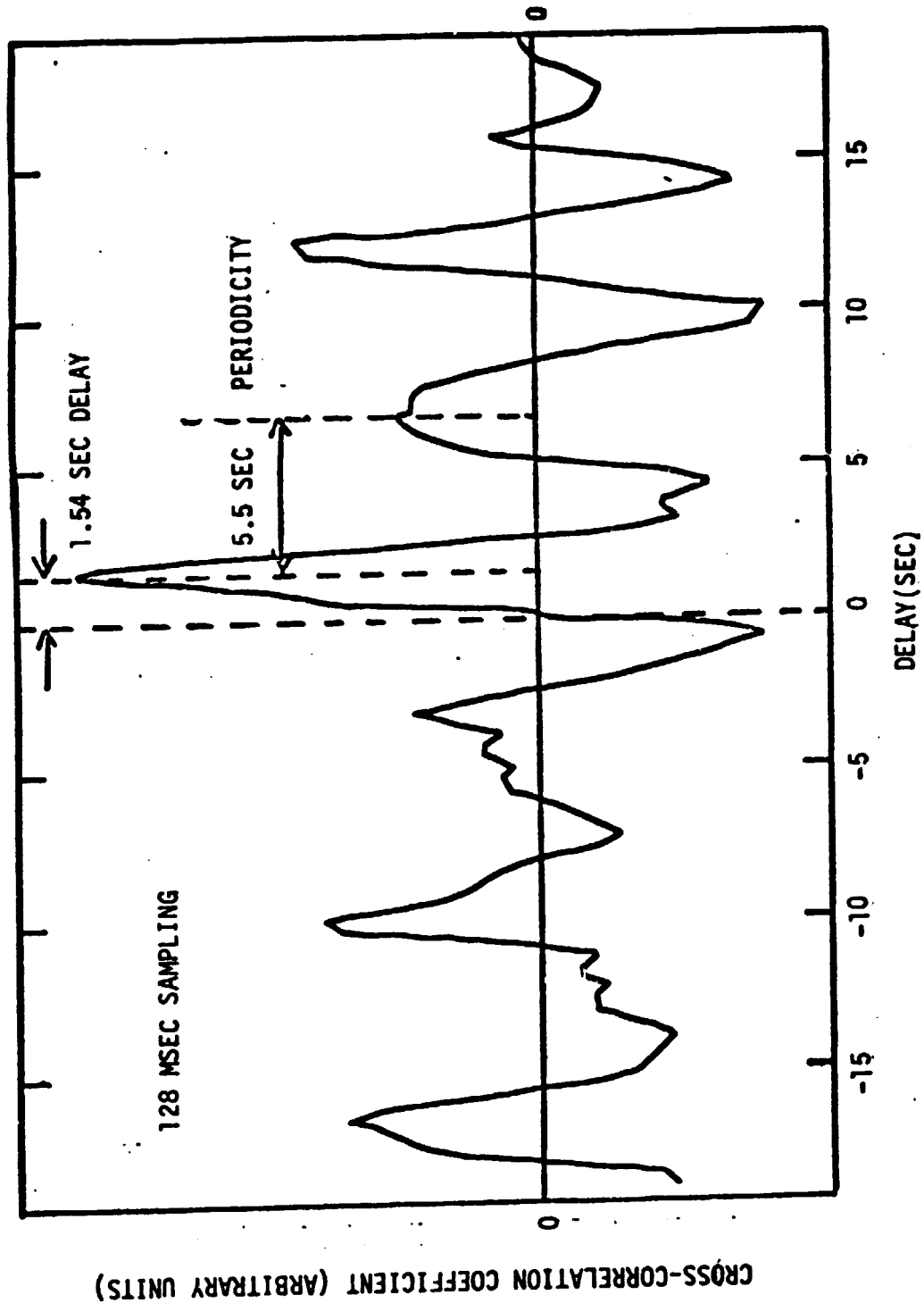


Fig. 2

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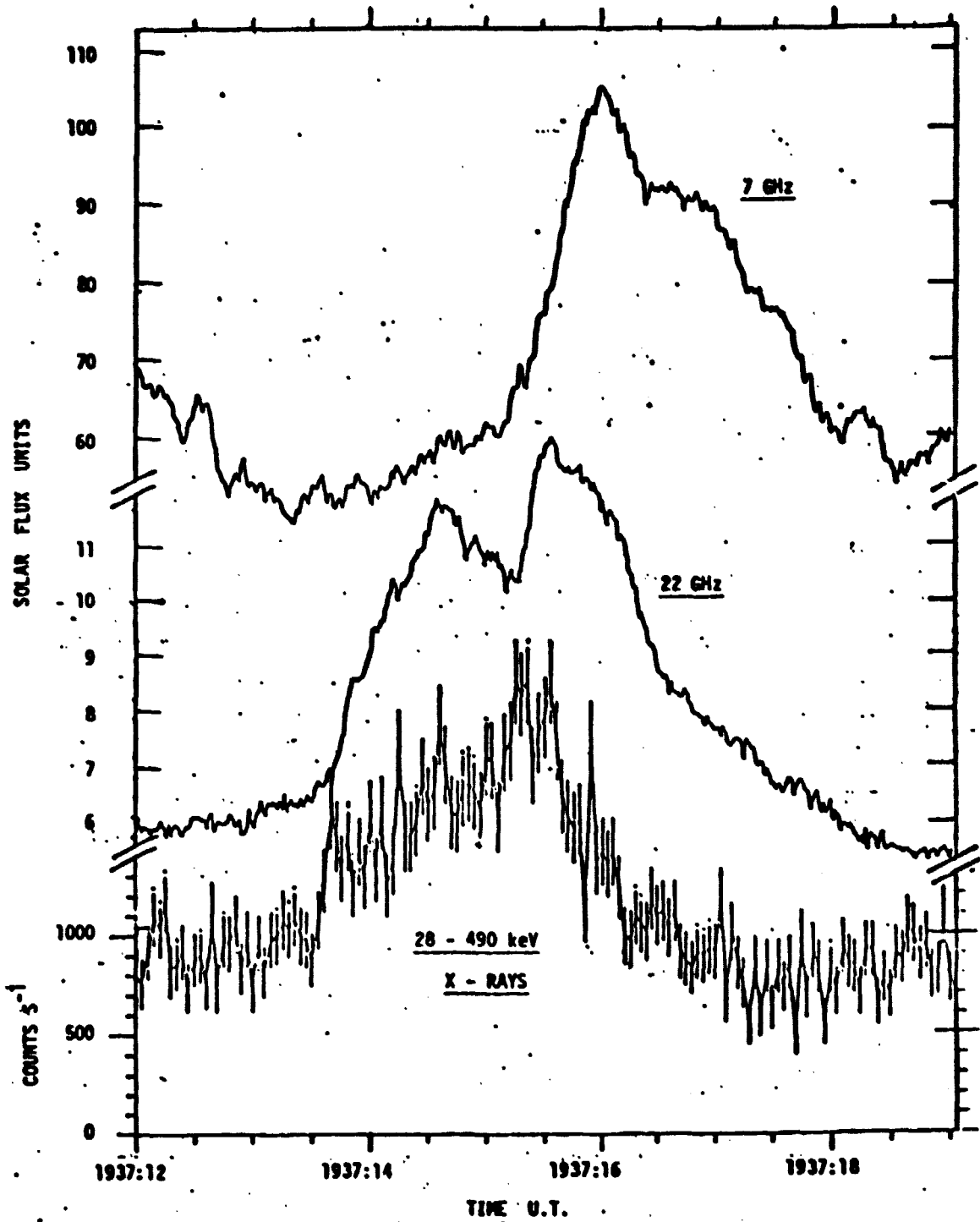


Fig.3