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TUNE MEASUREMENTS FOR THE AGS AND THE BOOSTER

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Summary

Different methods for processing signals to obtain the betatron tune of the transverse motion will be discussed. The present tune meter for the AGS, based on the so-called gated counter method, will be reviewed shortly. Next the different possibilities of measuring the tune with the help of Fast Fourier Transforms (FFT) will be discussed. A final section gives a proposal for systems to be implemented for the AGS as well as the Booster.

The AGS Tune Meter

The tune meter consists of kicker magnets with associated power supplies for each transverse plane to excite coherent betatron motion and signal processing equipment to measure the frequency of this coherent motion and deduce a number for the betatron tune.

The present system for the AGS is based on the so-called gated counter method after a survey by Raka.[1] In short, after kicking the beam in the horizontal or vertical plane, the difference signal from a PUE station is fed into a bandpass filter such that only one component from the harmonic spectrum present in that signal is transmitted to a frequency counter. From this frequency the fractional part 'q' of the betatron frequency can be deduced. A description of the system and a users guide can be found in Ref. 2. The accuracy of the tune meter fully depends on the length of the coherence of the input signal. In the vertical plane, where the chromaticity is small in general, the tunes can be determined with a precision of $\pm$ 0.001. In the horizontal plane, where in most cases only a 10 μs long measuring time is available, the precision is three to four times worse.

Although the tune meter has been used extensively during the last year, a tune measurement with the present system is far from a push button operation. The main reasons for this are summarized below:

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1. E.C. Raka, AGS Tech. Note 185 (December 1982)
2. W.K. van Asselt, Operations Note 8 (March 1986)

- A gate has to be generated during which the electronic frequency counter acquires the frequency of the input signal, see Figure 1c (this figure has been reproduced from Ref. 2 for convenience). As long as there is nice coherent motion as in Figure 1b, there is no problem. When the coherence lasts only for a short time, however, or when there is beating in the signal as in Figure 1a, it is impossible to have an automatic procedure for generating this gate. Full control of chromaticity and coupling is required to overcome this difficulty.

- For proper operation, the electronic counter requires input signal levels greater than 0.5 V p-p. The electronic bandpass filter requires signals smaller than a few volts p-p, otherwise the signal will deteriorate due to leakage of the filter. With the large variation in intensities in the AGS, this means that signal levels have to be adjusted carefully at the start of measurement periods. Remote control of setting the gain of PUE amplifiers, in terms of beam intensity, would be the easiest solution to this.

- The microprocessor in the A-10 house, which controls the tune meter, determines the fractional part of the tune from the coherent frequency and the rf frequency, which both have to be measured independently. The speed of data transfer between the PDP-10 and the microprocessor is unpredictable, which makes it difficult to generate automatic procedures to switch the counter between the two signals. A solution to this would be to use the counter in a ratio mode. At CERN this has been done by using a high harmonic of the rf frequency, instead of the rf itself, in order to obtain the required resolution.[3]

Tune Measurements with FFT

A digital oscilloscope with built-in spectrum analysis capabilities by means of FFT and with a bandwidth considerably greater than the frequency range of interest for the tune meter recently became available. This device has become an alternative for the signal processing equipment mentioned above for obtaining the betatron tunes. A typical frequency spectrum (obtained with signal averaging) is shown in Figure 2, where the FFT spectrum of a 1250 point time record is plotted. Because the time signal is not filtered, all the sidebands $|n \pm q|$ of the betatron tune are present in the spectrum. Although obtaining the tune in this way principally has become a manual operation, the ease of operation compensates for this. Further there are a number of other advantages to using this device:

- Input signal levels may vary over a factor of 10 for a given input attenuation, while getting reliable results. The input attenuation next increases the dynamic range with orders of magnitude.

- Signal or spectrum averaging makes it possible to measure the tune of very noisy signals, see Figure 3. The top trace is the time domain signal, the lower trace is the FFT spectrum. The middle trace is the average of 16 FFT spectra. It is seen that even in these circumstances very clean frequency spectra can be obtained.

3. G.C. Schneider, CERN/MPS/SR 73-4 (1973).

Besides the sidebands of the betatron tune, other spectral lines may be present. Bunch-to-bunch amplitude modulation will, for instance, show up as strong lines at the revolution frequency and its harmonics. This is illustrated in Figure 4, where the upper trace shows the spectrum of a gently kicked heavy ion beam. In the lower trace the beam has been kicked so hard that part of one or two bunches was lost, causing the strong revolution lines. When there are frequency components above the Nyquist frequency, which is half the sampling frequency, these lines will appear as lower frequency components, an effect called aliasing. Figure 5a shows an example of this effect. Because of the aliasing, it becomes very difficult to recognize the spectral lines. Figure 5b shows that by increasing the Nyquist frequency (to 12.5 MHz) the spectrum becomes recognizable again at the cost of resolution. The rf and its second harmonic are easily identifiable, the line at 7.2 MHz is the alias of the fourth harmonic of the rf. In Figure 5c a low pass filter at 500 kHz was used to avoid aliasing, also resulting in a recognizable spectrum (the bump at 50 kHz is yet unexplained, but is not related to the coherent motion, see Figure 6).

An even more powerful application of FFT's for tune measurements can be realized by locking the frequency of the digitizer to the revolution frequency, as used with the beam position monitor system of the Tevatron.[4] Because the Nyquist frequency will be half the revolution frequency, the spectral line q will alias at the 1-q position and so on. As a result the whole spectrum will consist of only one line. To verify this for AGS conditions, signals have been digitized, while using the rf/12 as a clock. These waveforms have been spectrum analyzed off-line. Figure 7a shows the digitized vertical difference signal as a function of the turn number, where the beam has been kicked at roughly the 130th turn. The corresponding frequency spectrum is shown in Figure 7b, where the x-axis runs from 0 to 0.5 times the revolution frequency. It is evident that the tune can be deduced very accurately from a spectrum like this. Figures 7c and d give the result for a beam kicked and sampled in the horizontal plane, where the coherence of the signal lasts less than 100 turns. As a result, the peak is less well defined. However, with some arithmetic or by signal averaging, it should be easy to deduce the tune from spectra like this. Note, in Figure 7d that also coherence in the vertical plane is observed and in Figure 7c that the coherence of the horizontal signal reappears after roughly 500 turns, apparently the synchrotron period.

Sampling at the revolution frequency has additional advantages. Amplitude modulation effects as in Figure 3 become invisible for instance. More important, aliasing from the rf, like in Figure 5, also becomes invisible. Figure 6a again shows the effect of aliasing of the rf. In Figure 6b the spectrum is shown after the difference signal was sampled at the revolution frequency. Figure 6c was obtained without kicking the beam, showing that the two bumps below 0.2 apparently relate to the frequency response of the PUE amplifiers.

On-Line Tune Measurements of the AGS and Booster

It is proposed that signal processing systems are built, which obtain the tune from the FFT of turn-to-turn digitized signals. This sampling frequency determines the Nyquist frequency at $f/f_{rev} = 0.5$, the precision of the frequency determination is determined by the size of the FFT. This is

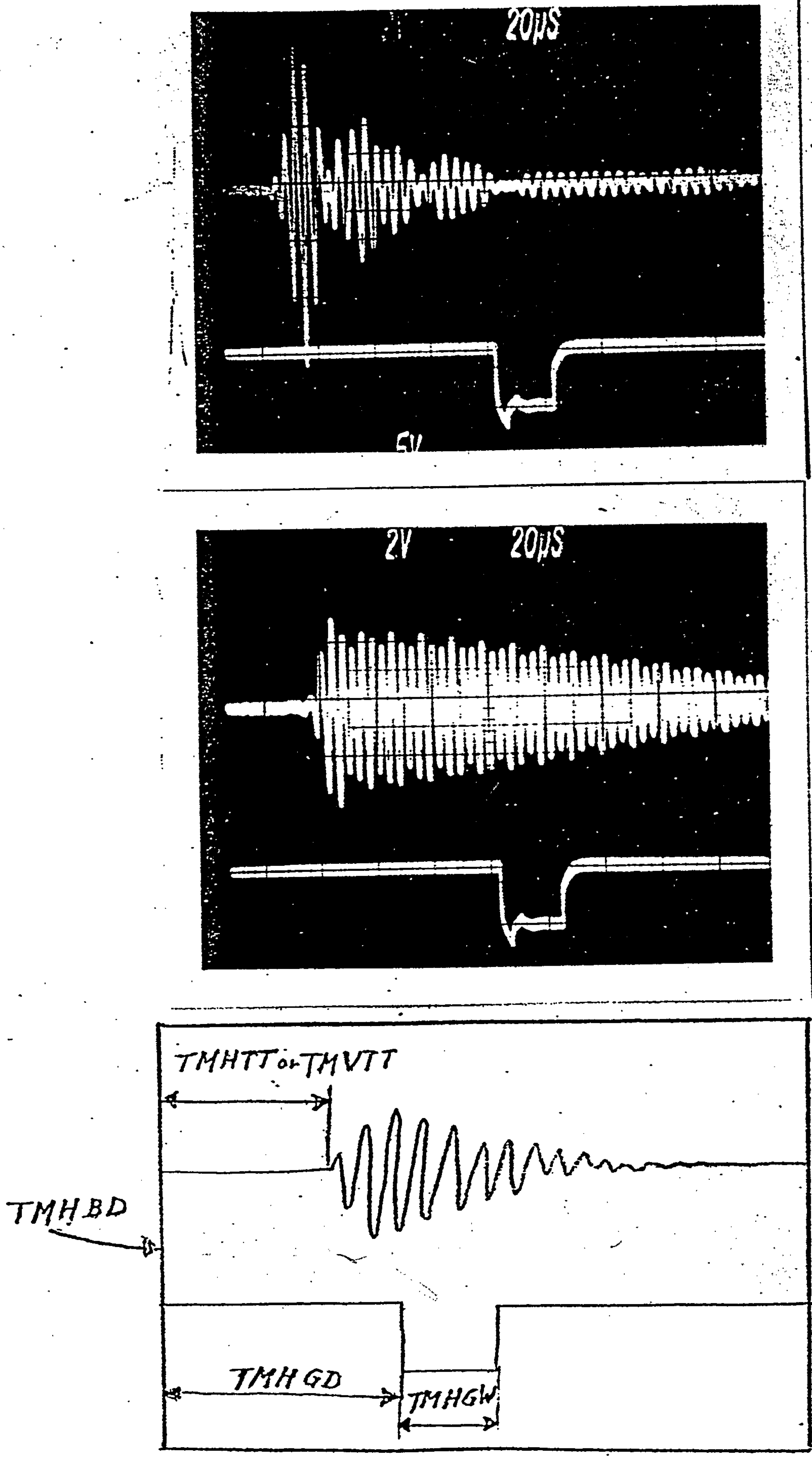
4. R.E. Shafer, et al., Proc. XII Intern. Conf. High Energy Accelerators, Fermilab, 609 (1983)

illustrated in Figure 8. Figure 8a shows a difference signal, digitized during 4096 turns. Figure 8b shows the signal expanded. In the rest of the figure (expanded) FFT spectra or respectively 4096, 2048, 1024, and 512 points of this time record are given. In the last two spectra the coherent frequency is all contained within one frequency bin. The maximum precision is thus obtained with transform sizes of 2k and up. In Figure 9 similar results are given for a signal which remains coherent for less than 100 turns, showing that in this case the precision is not increased with the transform size. Since there are commercially available FFT processor cards for transform sizes up to 1024 points (processing time for a 1024 point spectrum less than 10 ms), this size is a reasonable compromise. With such a transform size the precision with which the fractional part of the tune can be determined is 0.001.

For the AGS, the signal processing system can be used with the present kicker magnets and power supplies, which were designed to kick one full turn. Some caution is necessary when heavy ions with the low frequency rf system are accelerated, because at the lowest frequency only one bunch is being kicked, so to get the tune that bunch has to be sampled.

That it is sufficient to kick only one bunch for tune measurements may simplify the design of a power supply for the kicker magnet of the booster significantly, because the pulse length does not need to be variable. When the pulse length is chosen to be the revolution time at the highest frequency it will be roughly 55 degrees of an rf period at the lowest frequency. Therefore the kicker pulse should be locked very accurately to a bunch.

FIGURE 1



a
HOR.

b
VERT.

c

Figure 1

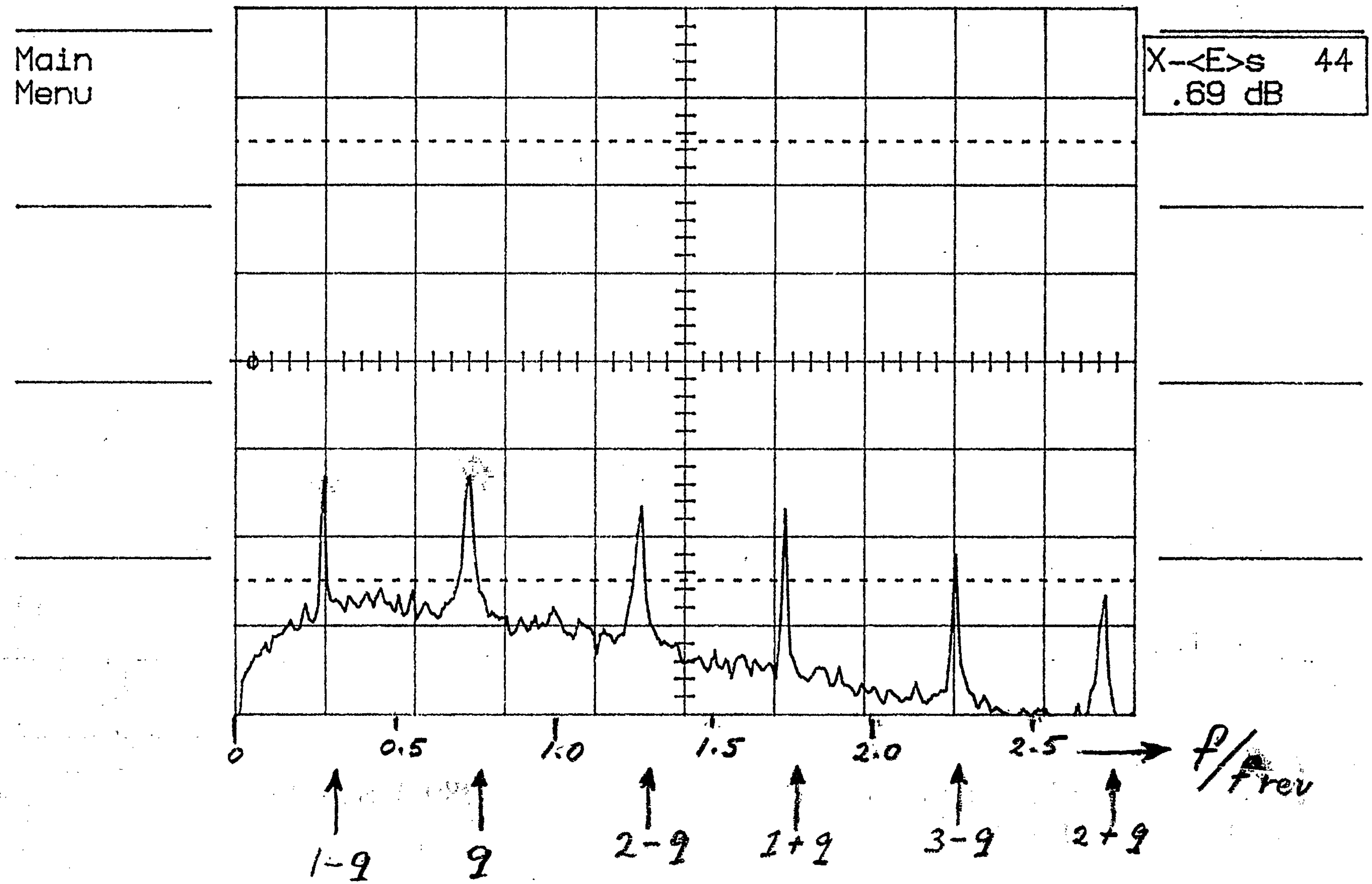


Figure 2

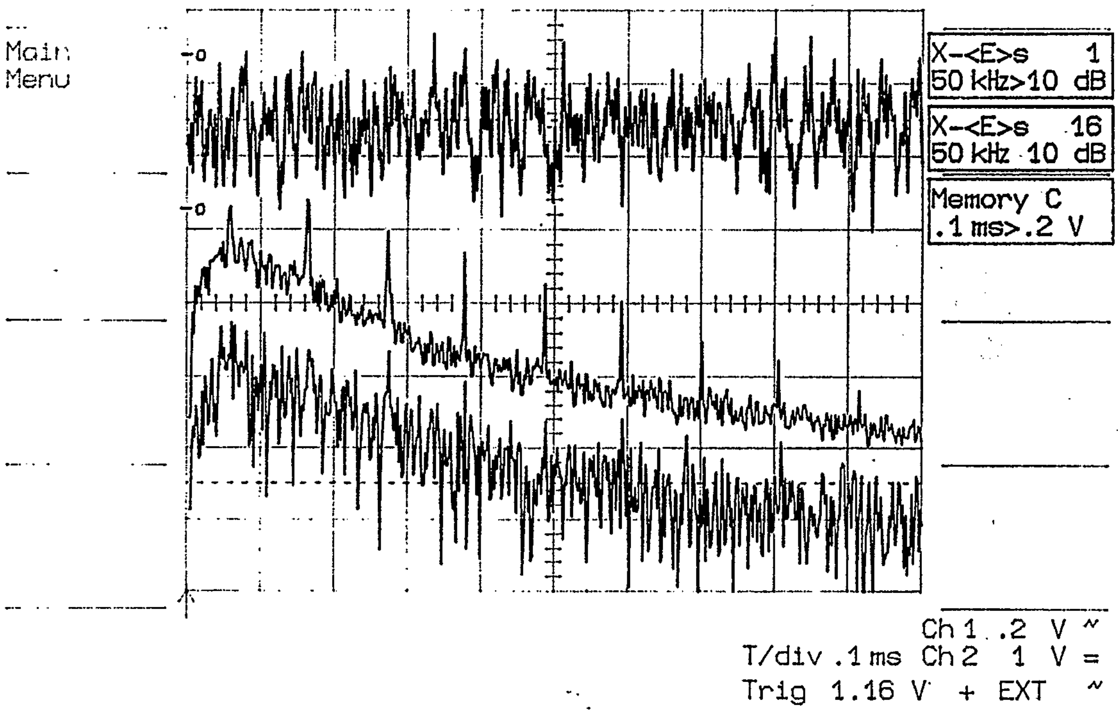


Figure 3

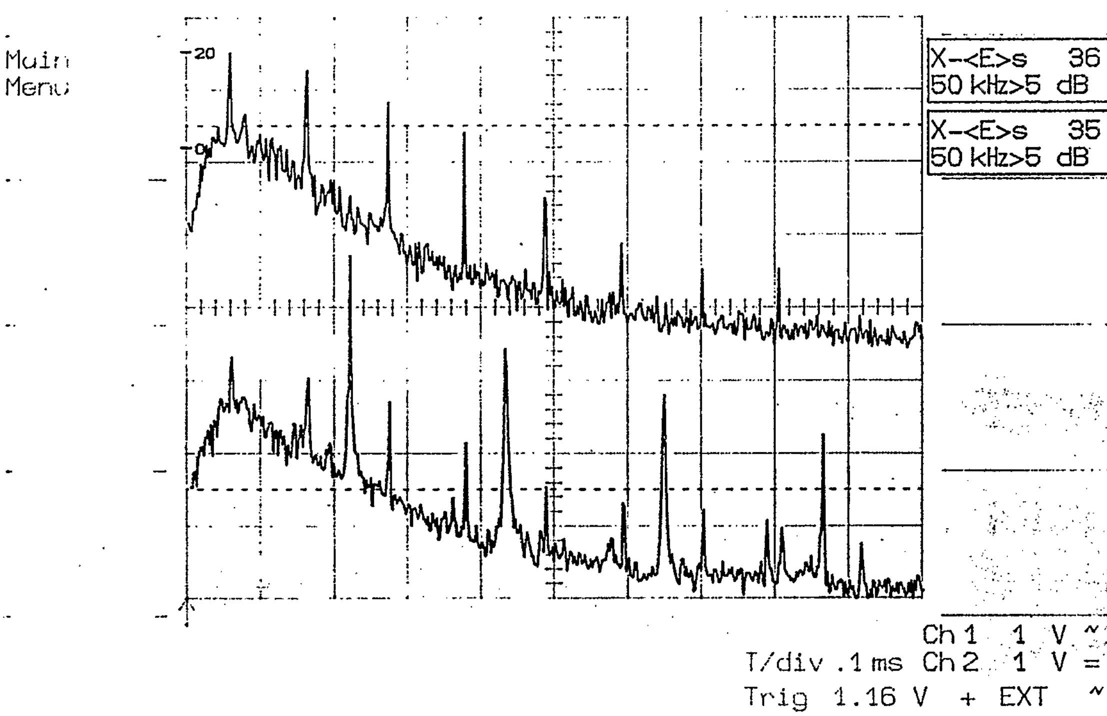


Figure 4

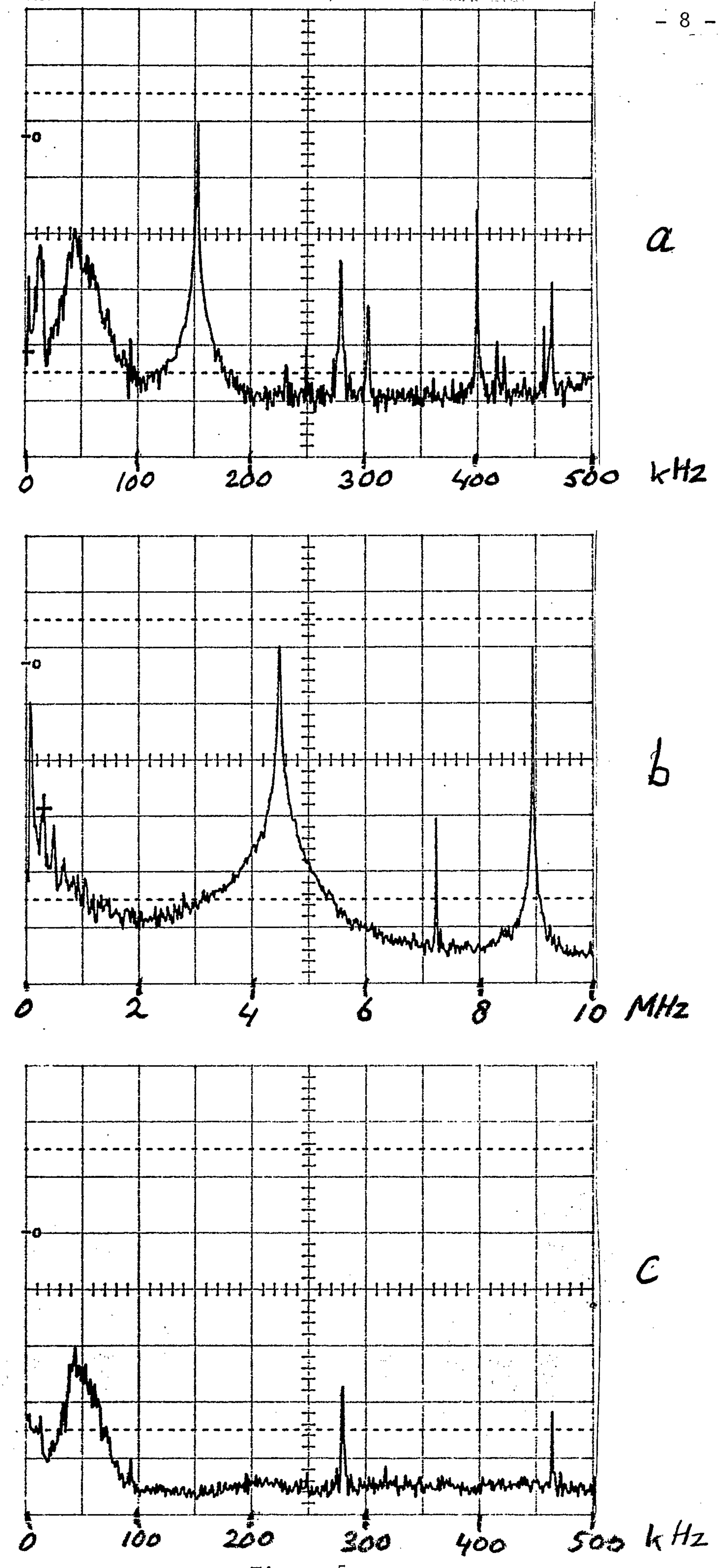

a
0 100 200 300 400 500 kHz
b
0 2 4 6 8 10 MHz
c
0 100 200 300 400 500 kHz

Figure 5

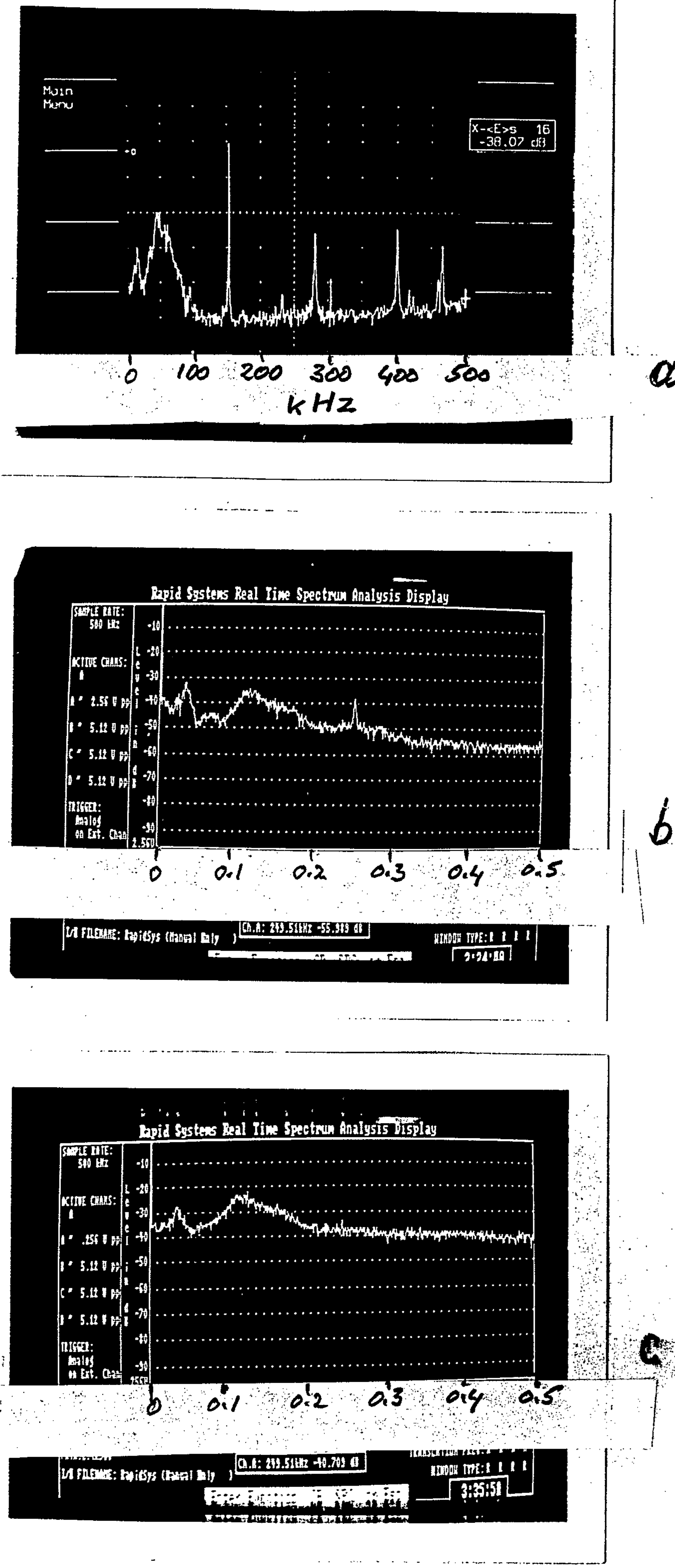

Main
Menu
X-<E>s 16
-38.07 dB
0 100 200 300 400 500
kHz
a
Rapid Systems Real Time Spectrum Analysis Display
SAMPLE RATE:
500 kHz
ACTIVE CHANS:
TRIGGER:
Analog
on Ext. Chan
0 0.1 0.2 0.3 0.4 0.5
b
Rapid Systems Real Time Spectrum Analysis Display
SAMPLE RATE:
500 kHz
ACTIVE CHANS:
TRIGGER:
Analog
on Ext. Chan
0 0.1 0.2 0.3 0.4 0.5
c
3:35:51

Figure 6

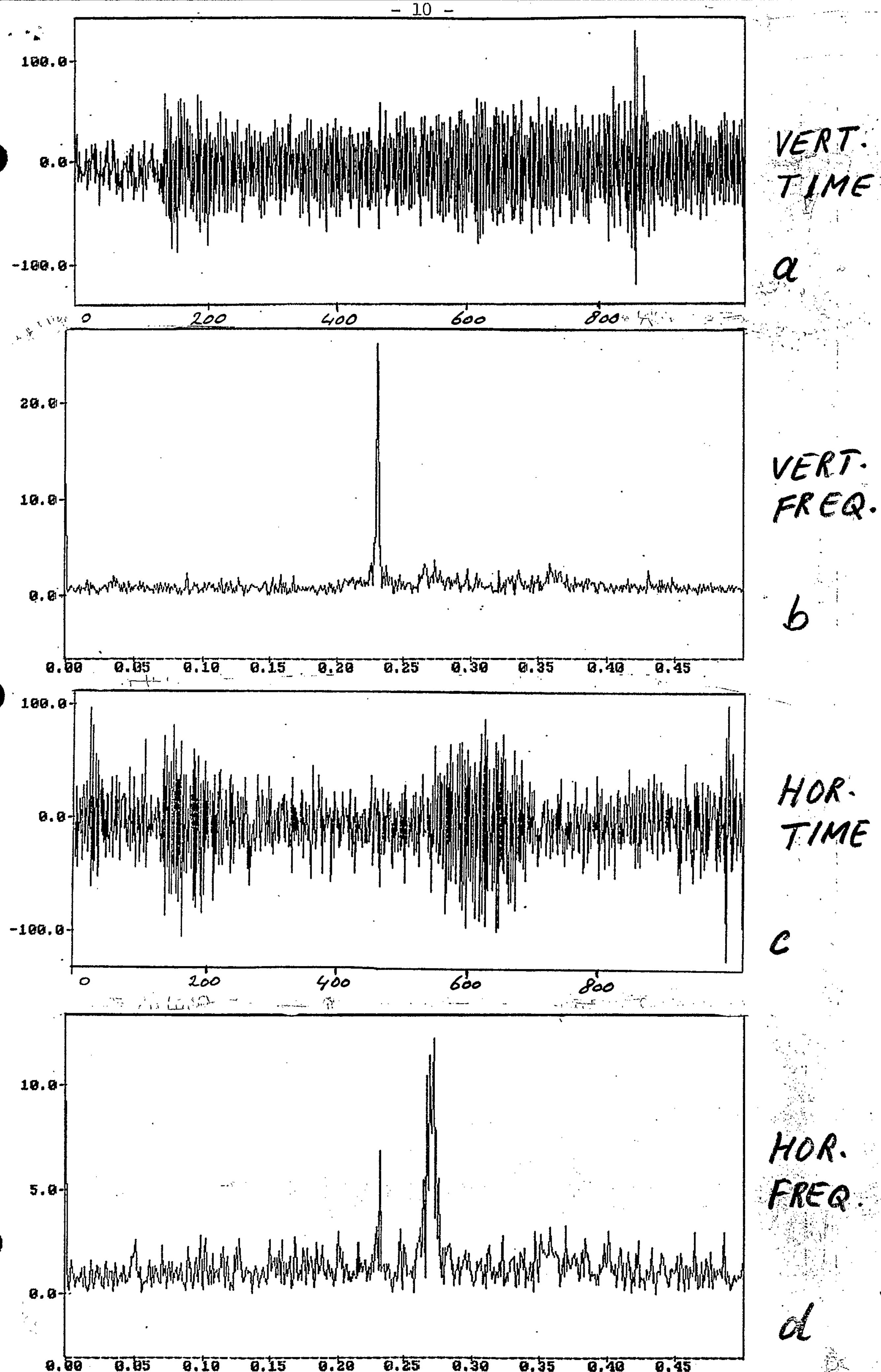

100.0
0.0
-100.0
0
200
400
600
800
VERT.
TIME
a
20.0
10.0
0.0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
VERT.
FREQ.
b
100.0
0.0
-100.0
0
200
400
600
800
HOR.
TIME
c
10.0
5.0
0.0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
HOR.
FREQ.
d

Figure 7

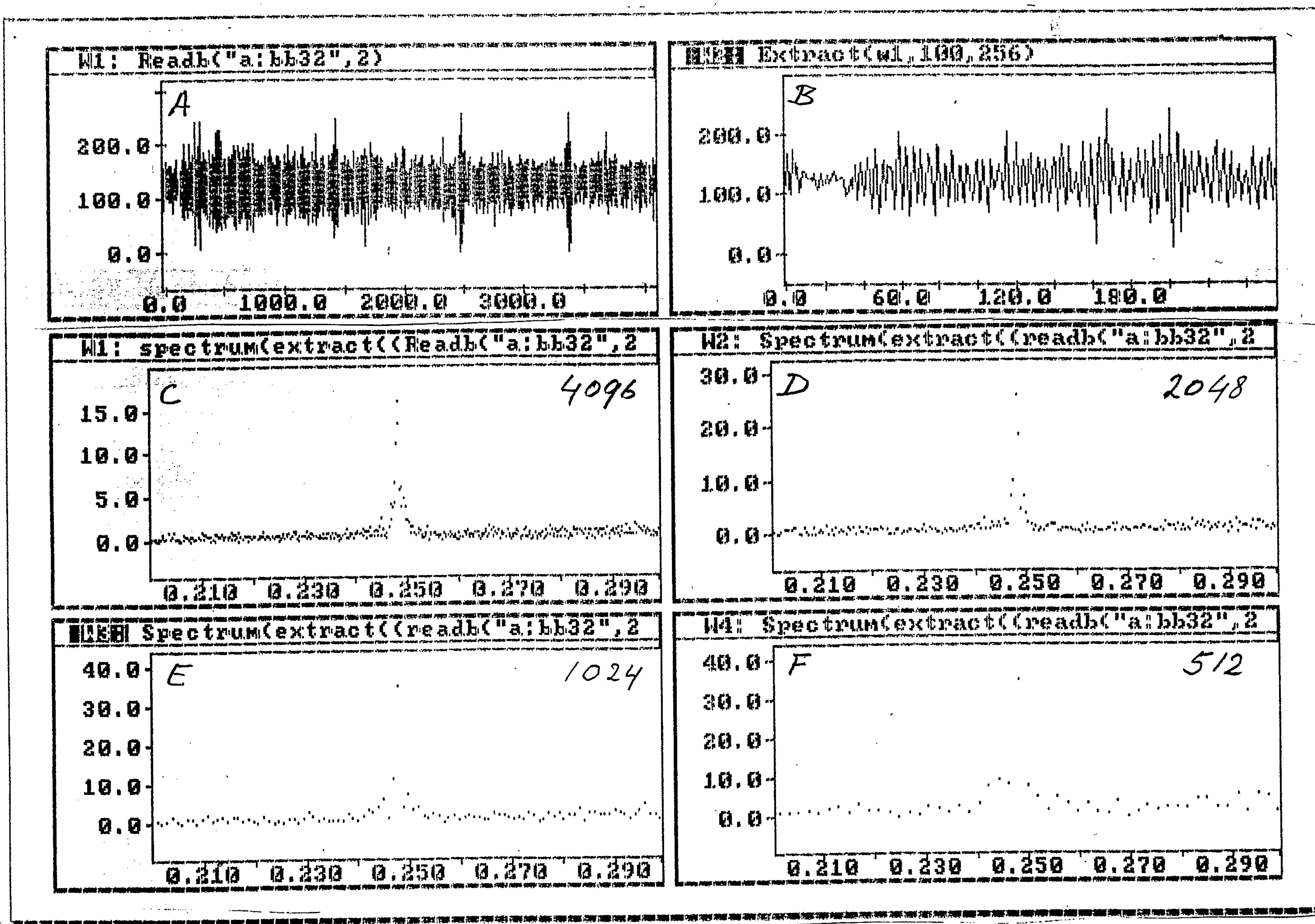

W1: Readb("a:bb32",2)
A
200.0
100.0
0.0
0.0
1000.0
2000.0
3000.0
Extract(w1,100,256)
B
200.0
100.0
0.0
0.0
60.0
120.0
180.0
W1: spectrum(extract((Readb("a:bb32",2
C
4096
15.0
10.0
5.0
0.0
0.210
0.230
0.250
0.270
0.290
W2: Spectrum(extract((readb("a:bb32",2
D
2048
30.0
20.0
10.0
0.0
0.210
0.230
0.250
0.270
0.290
Spectrum(extract((readb("a:bb32",2
E
1024
40.0
30.0
20.0
10.0
0.0
0.210
0.230
0.250
0.270
0.290
W4: Spectrum(extract((readb("a:bb32",2
F
512
40.0
30.0
20.0
10.0
0.0
0.210
0.230
0.250
0.270
0.290

Figure 8

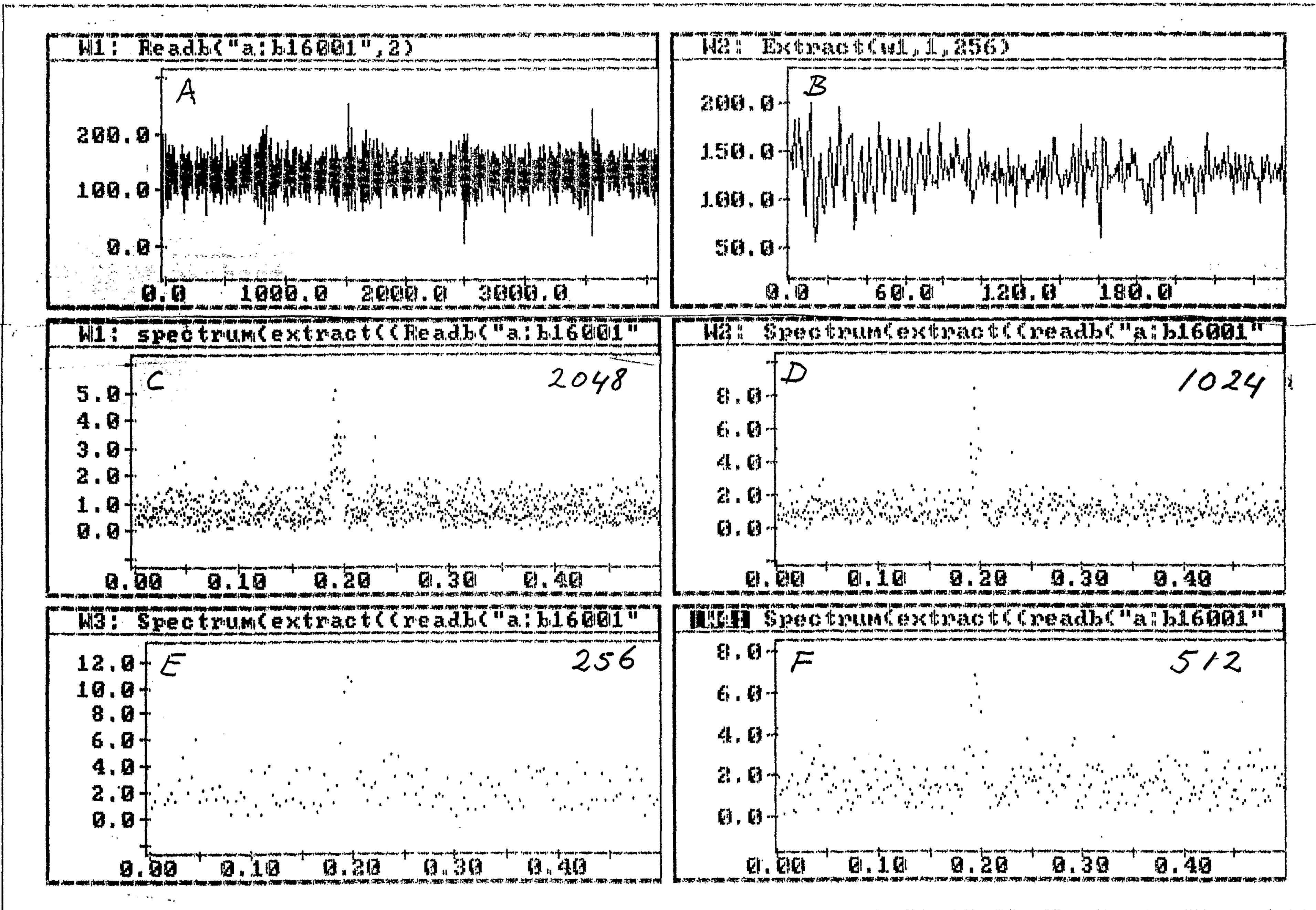

W1: Readb("a:b16001",2)
A
200.0
100.0
0.0
0.0 1000.0 2000.0 3000.0
W2: Extract(w1,1,256)
B
200.0
150.0
100.0
50.0
0.0 60.0 120.0 180.0
W1: spectrum(extract((Readb("a:b16001"
C
2048
5.0
4.0
3.0
2.0
1.0
0.0
0.00 0.10 0.20 0.30 0.40
W2: Spectrum(extract((readb("a:b16001"
D
1024
8.0
6.0
4.0
2.0
0.0
0.00 0.10 0.20 0.30 0.40
W3: Spectrum(extract((readb("a:b16001"
E
256
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0.00 0.10 0.20 0.30 0.40
Spectrum(extract((readb("a:b16001"
F
512
8.0
6.0
4.0
2.0
0.0
0.00 0.10 0.20 0.30 0.40

Figure 9