TRACKING OF RADIO STARS
WITH THE
MINITRACK SYSTEM

by

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Scope of the Report

This report will discuss the possibilities of using the Minitack system with a wider predetection Bandwidth in conjunction with the Narrow Band Tracking Filter for the tracking of Radio Stars.

Reasons for Tracking Radio Stars

The importance of being able to track Radio Stars with the Minitrack is twofold: First, Radio Stars can be used to calibrate the Minitrack stations replacing, or at least reducing the need of the frequent airplane calibrations needed today thus providing a a way for a daily check of that part of the system not calibrated by the Internal Calibrator of the system, i.e.: Antennas, cables and cable connectors. Second, the Minitrack system could be used to find more accurately the position of the radio stars. One observation may not be enough but taking a number of observations from one station, the effects of ramdom deviations due to either system noise or ionospheric effects would be minimized and the positioning error would be as low as the accuracy of the system. A number of observations can be taken from different stations of the Network, then by taking their average the error would be reduced even more. The large number of stations in the network would be a positive advantage over other interpherometer system used so far.

Limitations of the Present Equipment

The Minitrack system as it stands now has a predetection bandwidth of 10 Kc and a postdetection bandwidth of 10 cps. Its sensitivity for noise sources is limited to radio stars with a field strength of 10^{22} watt/m^2/cps or larger. Most of Radio Stars have field strength at least 10 db weaker than this with the exception of Cassiopia A with 1.3 X 10^{-22} watts/m^2/cps and Cygnus A with 10^{-22} watts/m^2/cps. At this signal strength the phase output of the system has a peak to peak deviation larger than 500 counts (0.5 wavelength) which makes impossible to process the data with the available digital equipment. The analogue phase output can be hand smoothed at stations with relative large latitud North (these sources are located at a declination of 58°32'N and 40°34'N respectively) but the residual error of the observation is larger than desirable.

The Minitrack with the Narrow Band Tracking Filter

The development of the Narrow Band Tracking Filter (1) (2) (NBTF) opened the possibilities of the Minitrack system for the tracking of the stronger Radio Stars (Cassiopia A and Cignus A) with the potencial accuracy of the system. The filter narrows the post detection BW (bandwidth) from 10 cps to 0.03 cps which effectively increases the integration time from 30 milliseconds to 10 seconds. Former peak to peak deviations of 500 counts are reduced to 30 counts. The NBTF time is placed before the automatic digital equipment and does not change the nature of the signal (the phase of 100 cps signal), thus allowing the use of the existing automatic digital equipment and the computer programs to process the information. Sampling every 10 or 20 seconds is sufficiently frequent for the new integration time, and if 30 points are taken and digitally smoothed the integration time is effectively increased to 300 sec increasing the "precision" of the observation to ± 3 counts of probable error. This error is of the order of the "accuracy" of the syste. The effects of refraction due to small scale irregularities in the ionosphere (scintillation) is also smoothed out since the most part of frequency spectrum of the phase deviation produced by them is outside the effective BW that corresponds to the effective 300 seconds integration time. The use of the NBTF for the tracking of Radio Stars was evaluated at Blossom Point. Cygnus A and Cassiopia were tracked and the results conformed very well with the expected performance. More tests are being carried at the East Grand Forks station. An intent was made at Lima to track Cignus A with no success. At Lima this source is 53° North from Zenith and is almost out of the main beam of the antenna.

The NBTF works on the detected signal in the way described above but does not improve the detecting threshold of the system still is not able to detect signal levels much weaker than 10^{-22} watts/m^2/cps*, therefore its use would be limited to Northern Hemisphere stations with relatively high latitudes where Cygnus A and Cassiopia A are in the main beam of the antennas (Table I) So it is of no use in the Southern Hemisphere or in tracking signals of other Radio Stars.

Effects of a Wider Predetection BW

An increase in predetection BW effectively increases the amount of power being received from the noise source. Although it also increases the amount of noise from the receiver front end, the end result is an improvement on the signal to noise ratio proportional to the square root of the BW. This is due to the fact that the signals received at two different antennas of an interferometer from a discrete noise source are coherent and produces an interference signal (the 100 cps signal in the case of the Mod. I Minitrack) directly proportional to the bandwidth, where the noise signal produced at the two different front ends are incoherent and produce noise at the interference signal output of

* NOTE : The system still shows traces of signals 2 to 4 db lower than 10^{-22} watts/m^2/cps depending on the conditions of the front end.

the interferometer with an amplitude proportional only to the square root of the BW.

What has been expressed above can be expressed mathematically by saying that:

$$\bar{\theta} = K\sqrt{\Delta w\,\tau}$$

Where $\bar{\theta}$ error is the standard deviation of the phase output of the interferometer, Δw is the predetection Bnadwidth, τ post detection integration time, and K constant of proportionality.

The actual effects of a wider predetection bandwidth in the tracking of radio stars has been tested experimentally at the Lima station using the Mod. I Telemetry IF amplifiers instead of the 10 Kc IF amplifiers of the Minitrack System. Two bandwidths have been tried: 300 Kc and 1 Mc.

System Hook up for 300 Kc Predetection BW

Two different schemes were tried using 300 Kc pre-detection BW. In one scheme the two different outputs of the two Minitrack "Pre-amp Converters" (3), one converted to 20.700 Mc and the other to 20.7001 Mc., were summed by a hybrid adder. The output of the Adder with an interference pattern of 100 cps was fed to the Mod. I Telemetry 2nd Converter (4) and converted to a center frequency of 3.2 Mc. It was then fed to the 2nd Mod. I telemetry IF set at 300 Kc BW. The AM detected output (100 cps) of the 2nd IF was fed to two phase measuring channels of the Minitrack Phase Measuring System. One channel with a 100 cps 2 cps BW filter and the other with the NBTF set at 0.03 cps BW. Both analog phase outputs were recorded in the Sanborn Recorder. The 0.03 cps BW output was also recorded digitally on tape by the Digital Recording System. In the second scheme, the outputs of the two different front ends were independently fed to two different 2nd converters and to two different 2nd IF's. The amplified output of both IF's was fed to a cross-product detector in which the coherent noise signals received at the two front ends (converted to two different nominal frequencies of 3.2 Mc. and 3.1999 Mc) produce a 100 cps beat note with a phase carrying the interferometer information. This signal was fed into the phase measuring system in equal manner as in the previous case. This second way turn out to be slightly better than the first way but not enough to justify the extra equipment needed.

Experimental Sensitivity of the System with 300 Kc Predetection BW and NBTF.

Fig. 1 shows the extra sensitivity achieved by the wider predetection bandwidth 300 Kc (curve B) and by the combination of a wider predetection BW and the narrower postdetection BW of the NBTF (curve C). The abcisas show the relative signal strength with respect to an arbitrary level and the ordinates the peak to peak deviations of the phase output of the system in thousands of a wavelength (counts). The strength of a quiet sun with approximately 10^{-22}watts/m^2/cps has been marked in order to give an idea of the relative strength that corresponds more or less to the signal strength of the source Cygnus A when in the center of the beam of the antenna. The signal strength and the corresponding phase deviations of the sources TAURUS A and CYGNUS A as they are received at Lima are also shown. Notice that these sources, the strongest at Lima are 10 db weaker than the unmodified system threshold, and that, with the help of the NBTF and a wider predetection BW,.they can be tracked with peak to peak deviations in the order of 40 counts or 10 counts r.m.s. If the mean of 30 data points is taken it would have a standard deviation of

$$\frac{10}{\sqrt{30}} \simeq 2 \text{ counts r.m.s.}$$

which is below the order of the accuracy of the system.

The curves shown in Figure 1 were obtained by calibrating the system with a noise generator set at +18 db in series with a 37 db gain pre-amp, a variable attenuator and a power divider with 39 db attenuation. The relative signal strength shown on the abcisa corresponds to the setting of the attenuator and can be converted to equivalent antenna temperature. The -16 db point would correspond to 0 db with respect to the noise generated by a matched resistor at 300° Kelvin (134 dbm for 10 Kc BW). This (134 dbm for 10 Kc BW) figure could be used to compare the sensitivity of this system with other Radio Interferometers. Fig. 2 shows the original analogue record from which the curves in figure 1 were obtained.

1 Mc Predetection BW Hook up

Tests were run at 1 Mc predetection BW. Although extrasensitivity was not necessary, this BW was more convenient to be used because of the equipment available. The hook up was similar to the 300 Kc BW but the first IF of the Mod. I telemetry receiver was used instead. This IF did not have any frequency conversion and was found very convenient specially when the crossproduct detector was used and no need of a common local oscillator for conversion was necessary as in the case of 300 Kc BW. Most of the tracking of Radio Stars was done on this BW and all Radio Star records included in this report were taken at this predetection BW.

Experimental Results Using 1 Mc BW and the NBTF

Fig. **2** shows the relative sensitivity of the system for noise signals with 1000 Kc predetection BW with and without the NBTF in comparison with the normal 10 Kc BW of the system. Fig. 4 and 5 are original records from which the curves on Fig. **2** were obtained. With the 1000 Kc predetection and the NBTF at 0.03 the system is able to track sources 30 db weaker than it would be able to track with the normal BW for the same standard deviation. Figure 2 also shows the relative signal strength of the Radio Stars Centaurus A, Virgo A, Taurus A, Cignus A and the Quiet Sun as they are being received at Lima. Fig. 3 also shows the signal strength of Cignus A as it would be received by a system with this source overhead. Notice that at this signal strength the phase deviations are of the order of a few counts even without the use of the NBTF. Fig. y, and EWF record of a Quiet Sun, gives an idea of the amount of noise to be expected on the phase output at these signal levels. Cassiopia A would also produces similar records at high Northern latitudes.

Figures 7,8,9,10 are EWF analogue records of the transit of Cignus A, Taurus A, Virgo A and Centaurus A respectively with, 1000 Kc predetection BW with and without the NBTF. Their relative signal strengths reported on figure 3 have been obtained from the peak to peak deviations of the 1000 Kc predetection and 2 cps postdetection BW record channel. Centaurus A is the strongest Radio Star in the Southern hemisphere. It has a latitude of -42°46' and possibly the only star that could be tracked at the Woomera, Santiago and Johannesburg stations. Figure 10 shows that, at Lima, Centaurus produces a phase signal output with 30 counts peak to peak deviation or 8 counts standard deviation. Taking 30 data points the mean would have a standard deviation of:

$$\sigma_m = \frac{8}{\sqrt{30}} \approx 2 \text{ counts}$$

This source was not tracked at 300 Kc predetection BW, but knowing the signal strength and with the help of Fig. 1, the precision of the observation at this BW can be deduced. Taking 30 data points the standard deviation of the mean would be σ_m = 3 counts. The observation of this star made by stations farther south than Lima would have slightly more precision since the star would be closer to the center of the antenna beam.

General Comments

As it has been said the 1000 Kc BW was used only for convenience but the 300 Kc BW would be sufficient to track the mentioned sources. It is convenient to use a narrower predetection BW from the accuracy point of view. The accuracy of the system depends among other factors, on the accuracy of the distance in wavelength between the two interferometer antennas. The wavelength used is the one that corresponds to the center frequency. This center frequency, and consequently the distance in between antennas, is more uncertain as the BW gets wider. The 300 Kc BW seems to be a good compromise between accuracy and sensitivity for the southern hemisphere.

The effect of irregularities in the ionosphere (Radio Scintillations) is not noticeable most of the time and never during the day. At night, there are times where the phase deviations are larger than it would be expected for a particular signal strength. This phenomena has been noticed before with satellite signals and can be very pronounced specially at latitudes near the Magnetic Equator. In fact, this is an important phenomena to which most Radio Interferometers are dedicated for the study of the ionosphere. Fig. 11 is a record of a transit of Virgo A showing such a phenomena. The effect can be more pronounced.

In order to obtain the performance expected with the wider predetection BW, it was found necessary to increase the pre-amplifier gain to 60 db before the first conversion. Although the 30 db pre-amp gain that the system normally has, proves to be sufficient for a predetection BW of 10 Kc, it is not sufficient with the 300 and 1000 Kc BW. A possible explanation is that the noise introduced by the two first "Local Oscillators" is coherent and increases proportionally to the BW. The coherence of the noise could be explained by the common origin of these two "local oscillator" frequencies.

Conclusions

Radio Stars with a signal strength larger than 5X10^{-24}watts/m^{2}/cps can be tracked with the Minitrack System with very little extra equipment. Stations as far South as Lima would be able to track at least four Radio Stars plus the Sun, and all of them including Santiago, at least one. The extra equipment needed for two channels are two complete 300 Kc BW IF strips specially designed for the purpose and a two channel NBTF's like the prototype used in this experiment or like the ones built in the SFAAC system. The NBTF would not necessarily be extra equipment for the purpose of tracking Radio Stars since it can be fully justified for the tracking of weak satellite signals. The precision of the observations taking 30 data points and using 300 Kc predetection BW and 0.03 cps postdetection BW is of the order of ± 3 counts rms for sources as weak as 5 X 10^{-24}watts/m^{2}/cps and in the beam of the antennas. No effort has been made to evaluate the accuracy of the observation. It has been left for the time a prototype subsystem is built. It is recommended that such a prototype is built.

*

TABLE 1

Coordinates and Signal Strength of Main Radio Sources*

RADIO STAR	R. A h	 m	 s	δ	Watts/m^2/cps $X10^{-24}$at 136Mc	ANGULAR SIZE	LIMA ANGL FROM ZENI	
CASSIOPIA	23	21	12	58°32.1'	130	3' X 4'	71°	N
CIGNUS	19	57	45	40°35'	100	3' X .5'	53°	N
TAURUS	05	31	35	22°04'	10.5	3.5'X5.5'	35°	N
CENTAURUS	13	22	30	-42°46'	15	3' X6.5'	30°	S
VIRGO	12	28	18	12°37'	10	2.5'X 5'	25°	N

* From Cosmic Radio Waves by Shklovsky.

1) R. Woodman - A Phase-Locked Phase Filter for the Minitrack System. NASA TN-D-1419

2) R. Woodman - Report on the Narrow Band Tracking Filter to the head of the Phase Techniques Section of NASA Goddard Space Flight Center, Data & Tracking Division, dated August 14, 1962. Not published.

3) Goddard Space Flight Center - Instruction Manual for 136 Mc Minitrack Interferometer System.

4) Goddard Space Flight Center - Instruction Manual for 136 Mc Telemetry Receivers.

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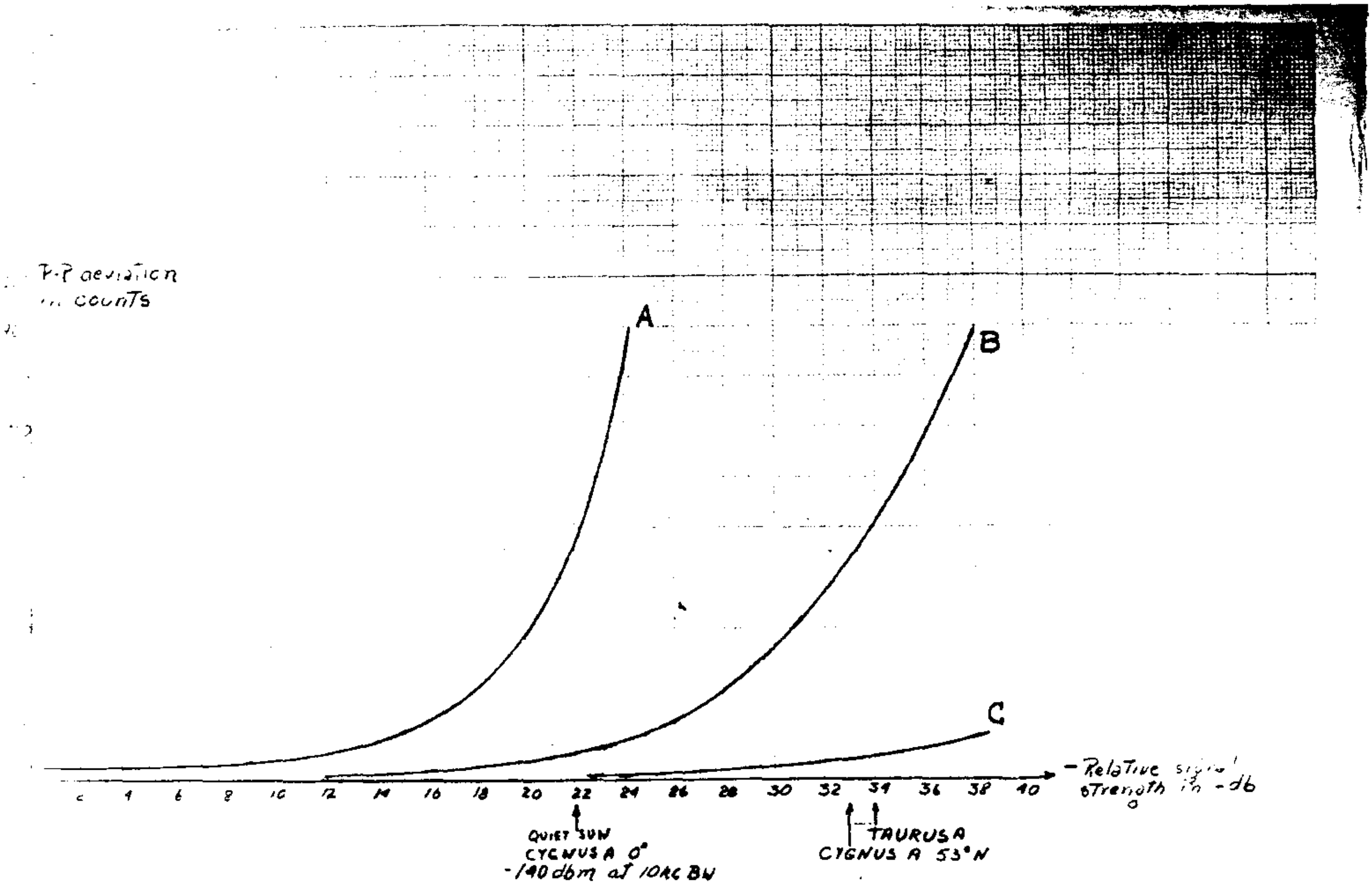
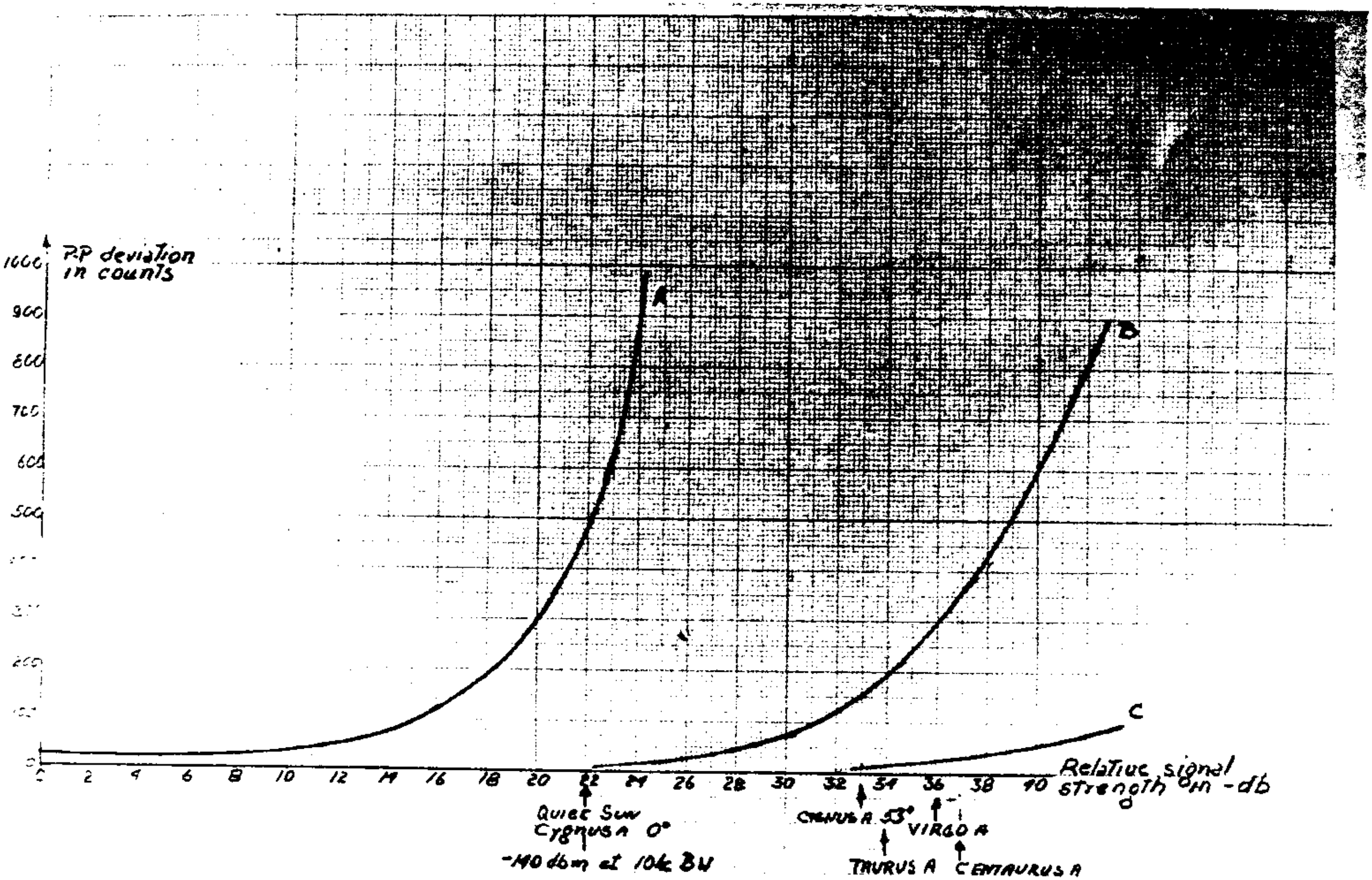


Relative System Sensitivity of the Minitrack System for Noise Sources with:

A) 10 Kc. pre-detection 10 cps post-detection BW
B) 300 Kc. pre-detection 2 cps post-detection BW
C) 300 Kc. pre-detection 0.03 cps post-detection BW

Fig. 1



Relative System Sensitivity of the Minitrack System for Noise Sources with:
- A) 10 Kc. pre-detection 10 cps post-detection BW
- B) 1000 Kc. pre-detection 2 cps post-detection BW
- C) 1000 Kc. pre-detection 0.03 cps post-detection BW

Fig. 2

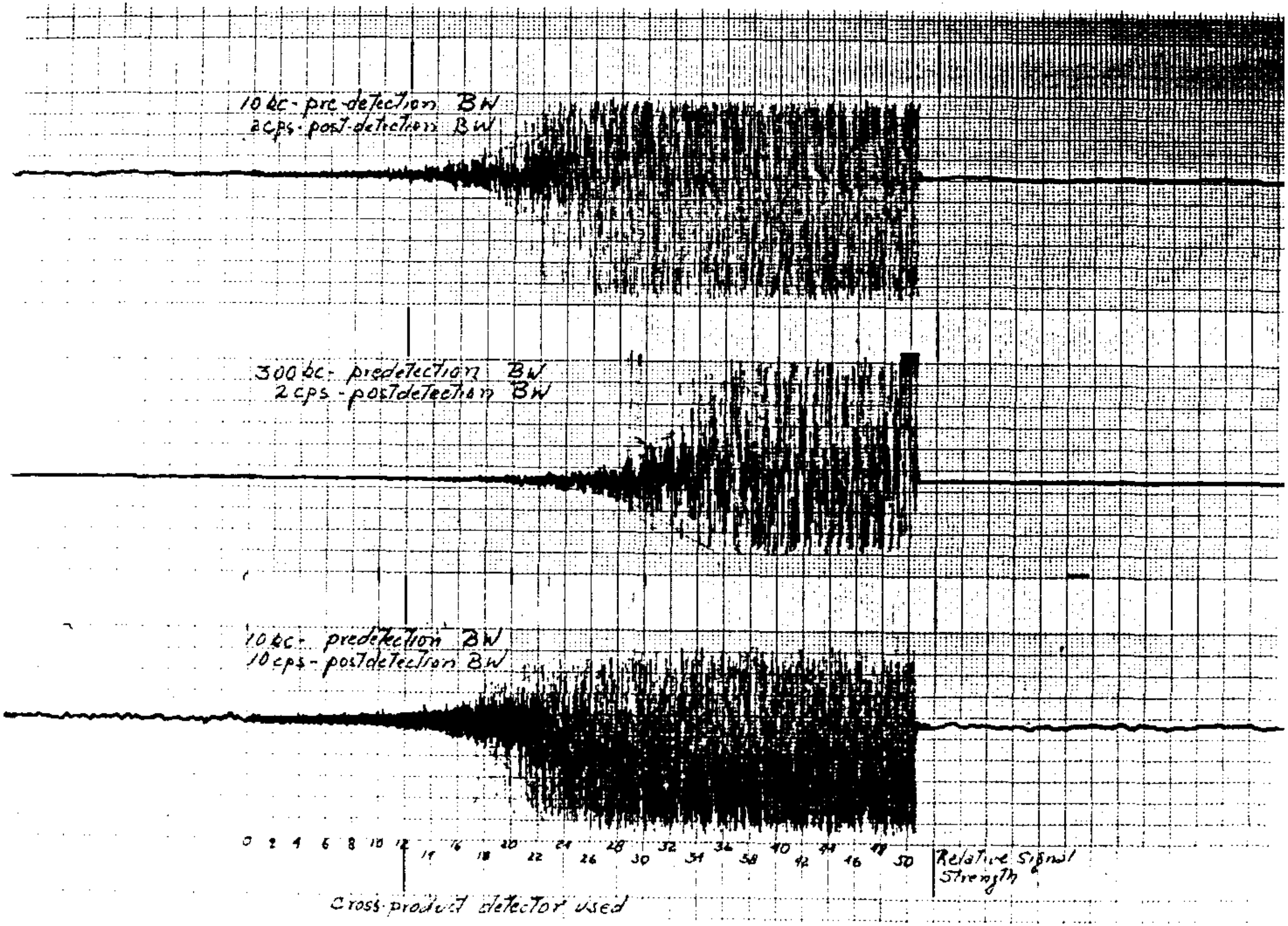

10 kc - pre-detection BW
2cps - post-detection BW
300 kc - predetection BW
2 cps - postdetection BW
10 kc - predetection BW
10 cps - postdetection BW
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50
Relative Signal Strength
Cross-product detector used

Fig. 3

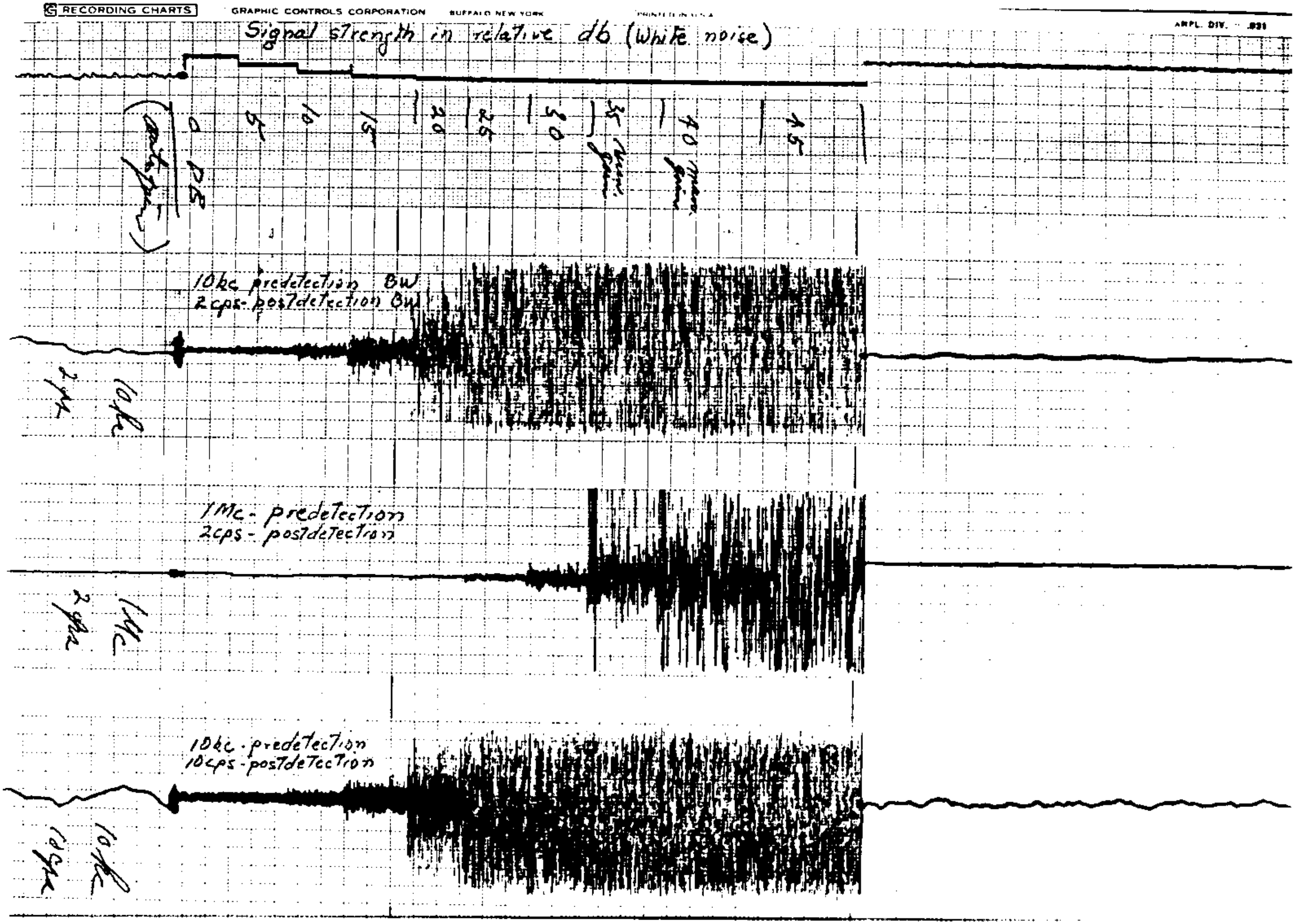

RECORDING CHARTS
GRAPHIC CONTROLS CORPORATION
BUFFALO NEW YORK
PRINTED IN U.S.A.
Signal strength in relative db (White noise)
0 PB
(auto gain)
5
10
15
20
25
30
35 max. gain
40 max. gain
45
10kc predetection BW
2cps-postdetection BW
10kc
2cps
1Mc - predetection
2cps - postdetection
1Mc
2cps
10kc - predetection
10cps - postdetection
10kc
10cps

Fig. 4

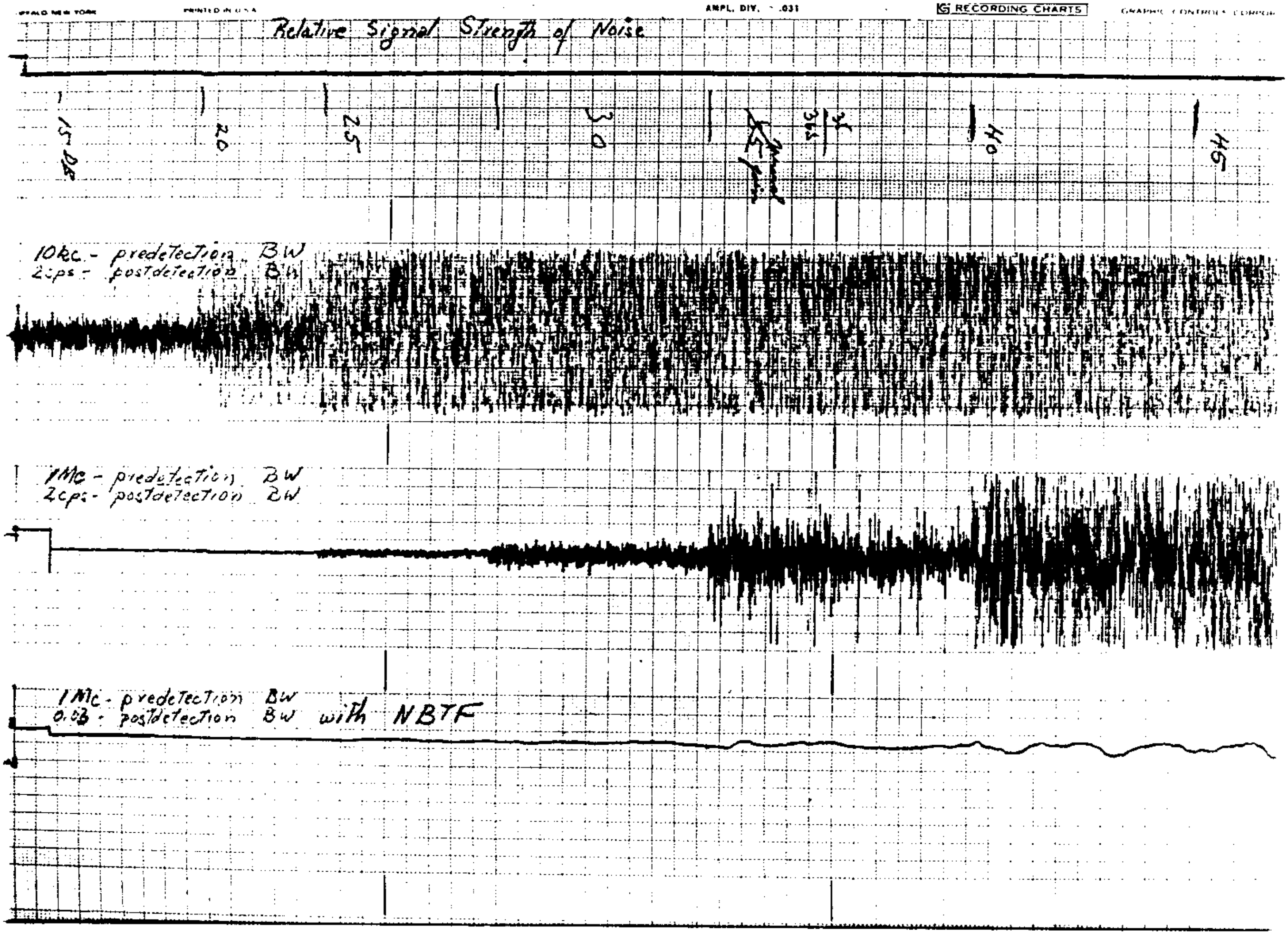
PRINTED IN U.S.A.
AMPL. DIV. .031
RECORDING CHARTS
GRAPHIC CONTROLS CORPOR
Relative Signal Strength of Noise
15 DB
20
25
30
35
40
45
10kc - predetection BW
2cps - postdetection BW
1Mc - predetection BW
2cps - postdetection BW
1Mc - predetection BW
0.03 - postdetection BW with NBTF

Fig. 5

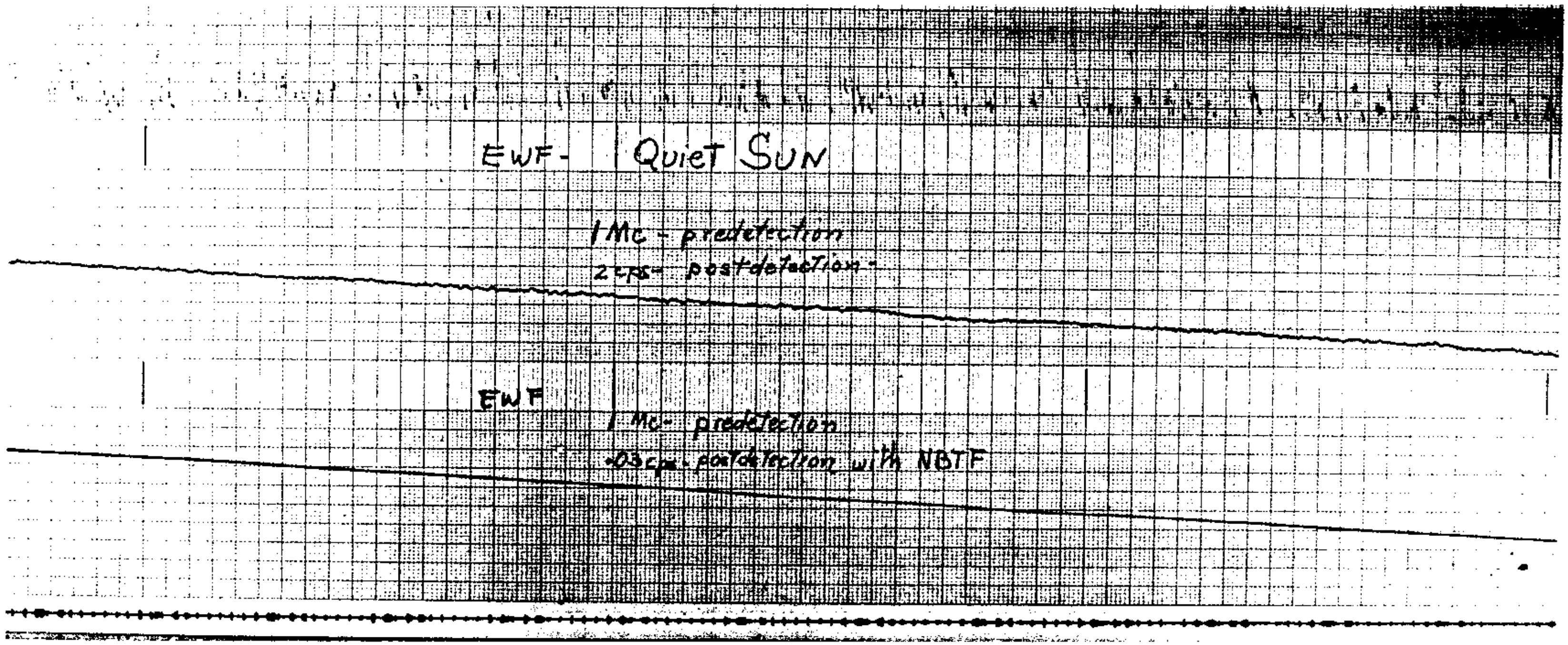

EWF - Quiet SUN
1Mc - predetection
2cps - postdetection -
EWF
1 Mc - predetection
.03cps - postdetection with NBTF

Fig. 6

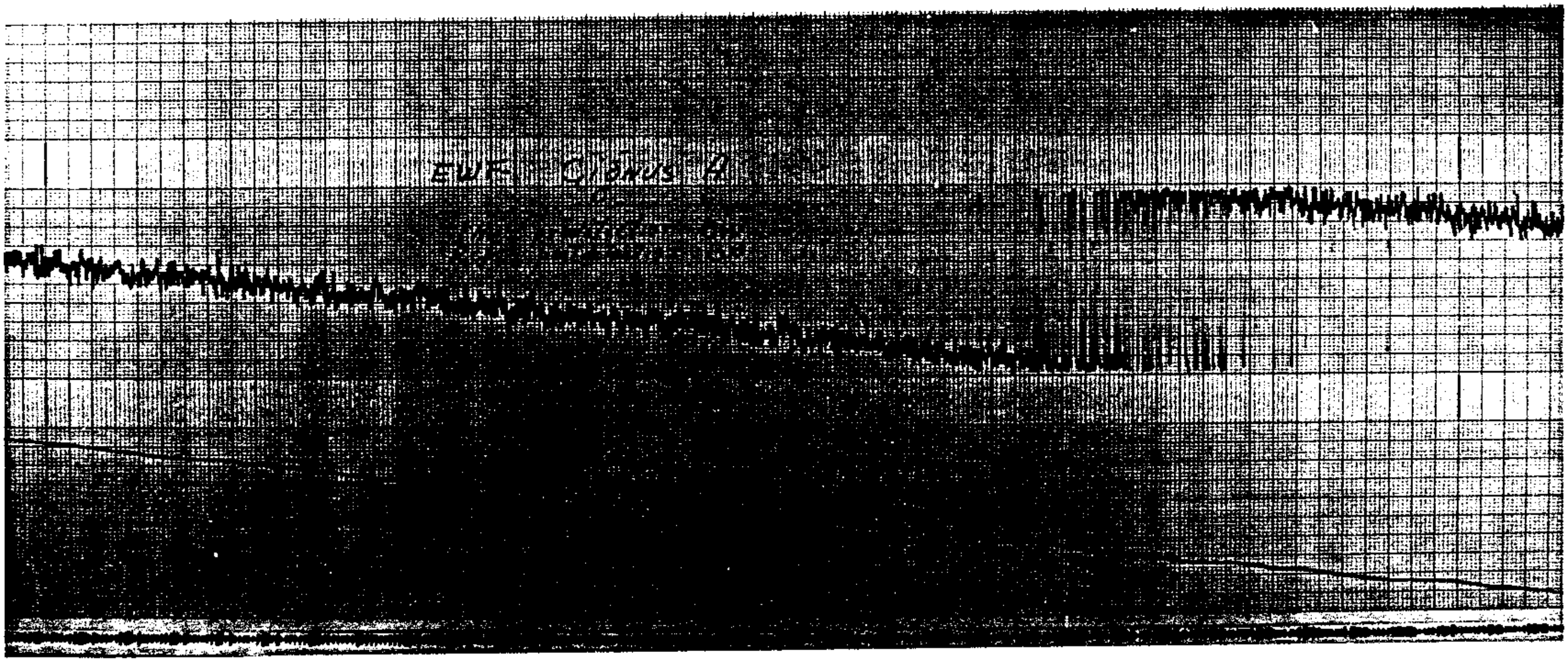


Fig. 7

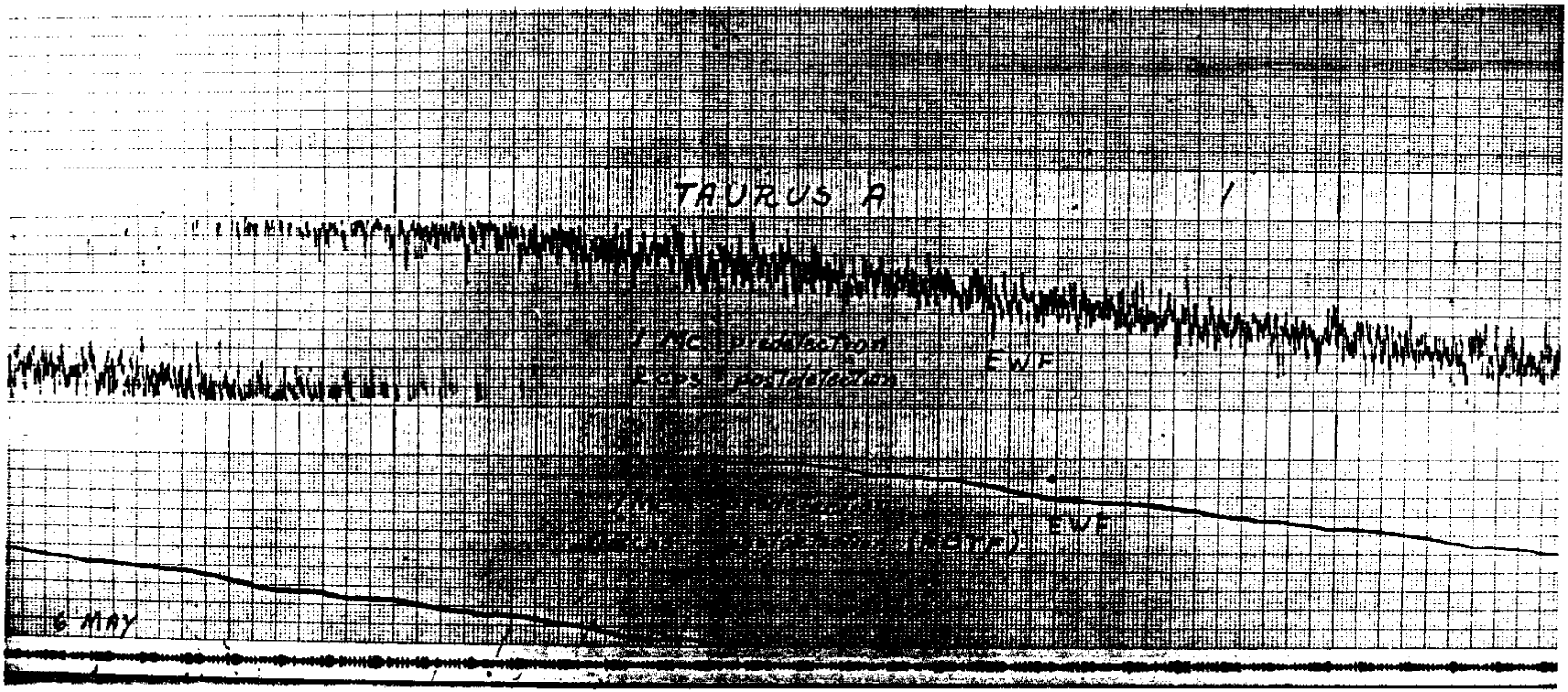


Fig. 8

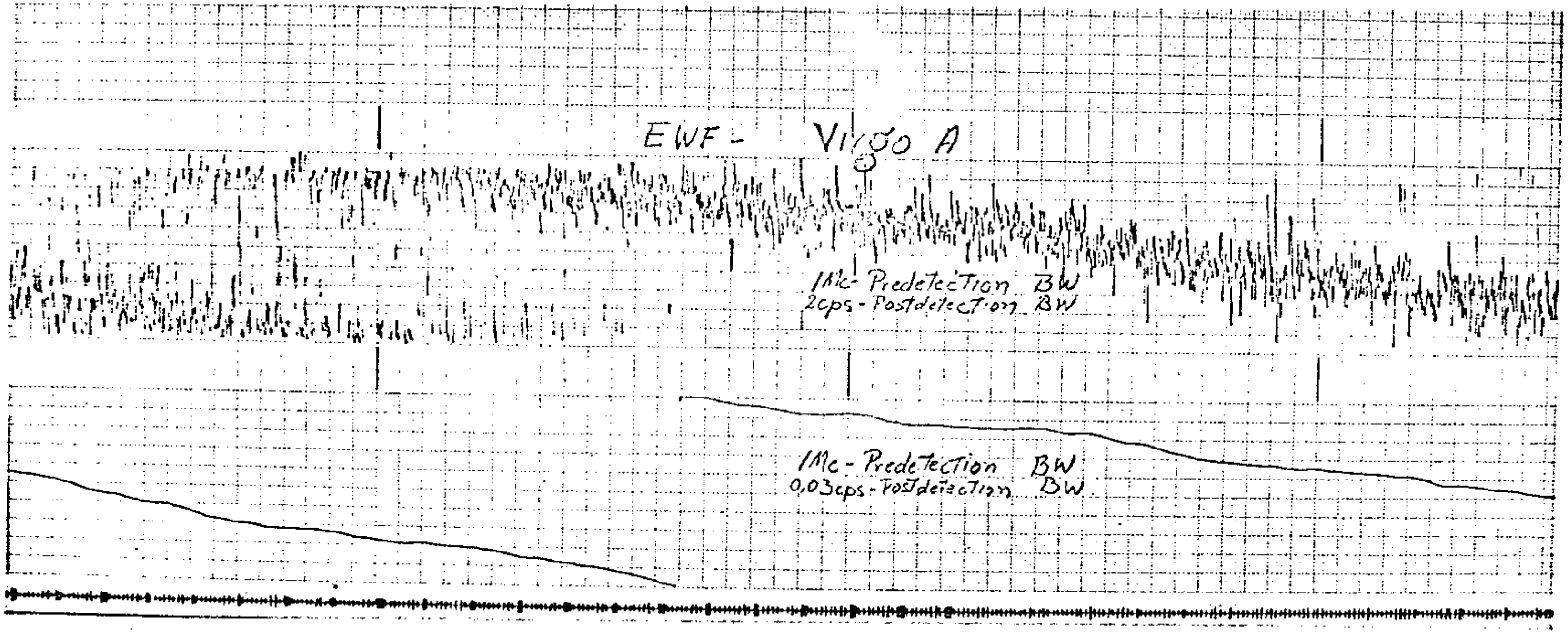

EWF - Virgo A
1Mc - Predetection BW
2cps - Postdetection BW
1Mc - Predetection BW
0,03cps - Postdetection BW

Fig. 9

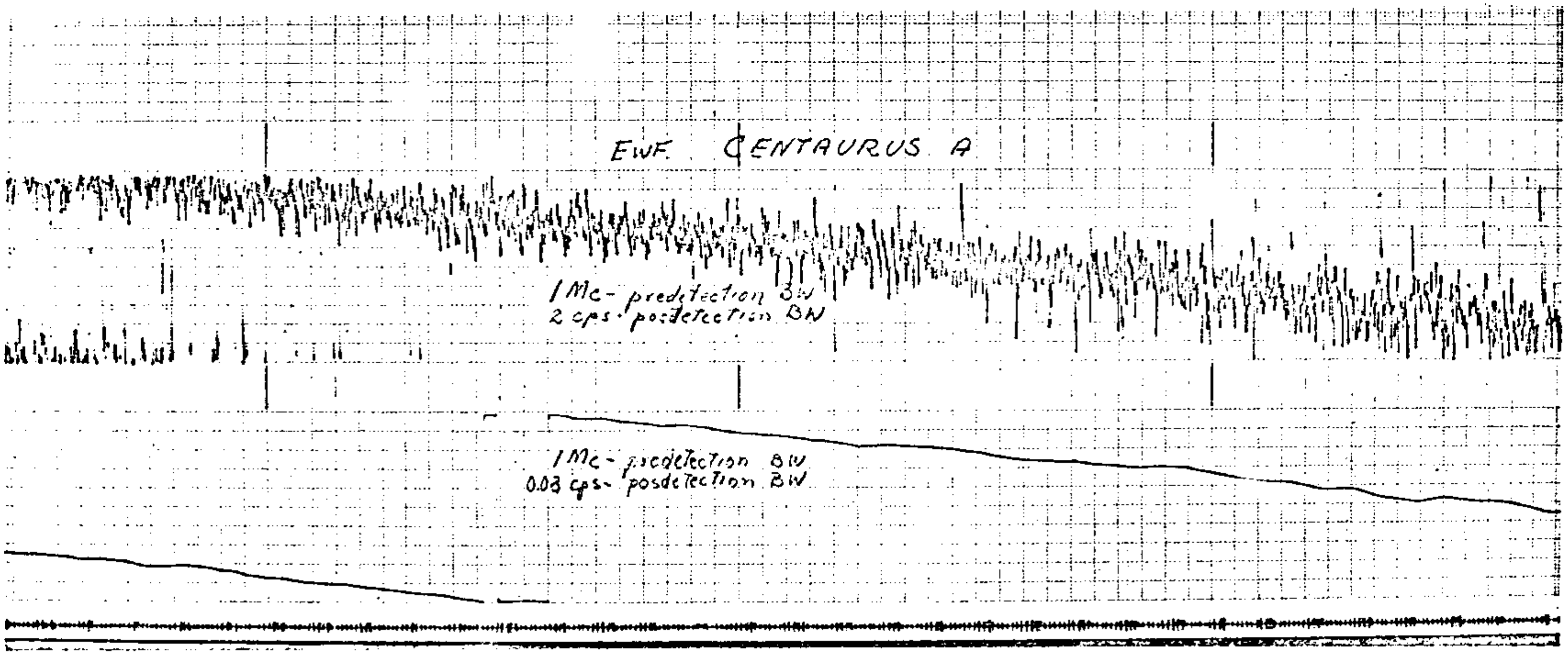

EWF CENTAURUS A
1Mc- predetection BW
2 cps- posdetection BW
1Mc- predetection BW
0.03 cps- posdetection BW

Fig. 10

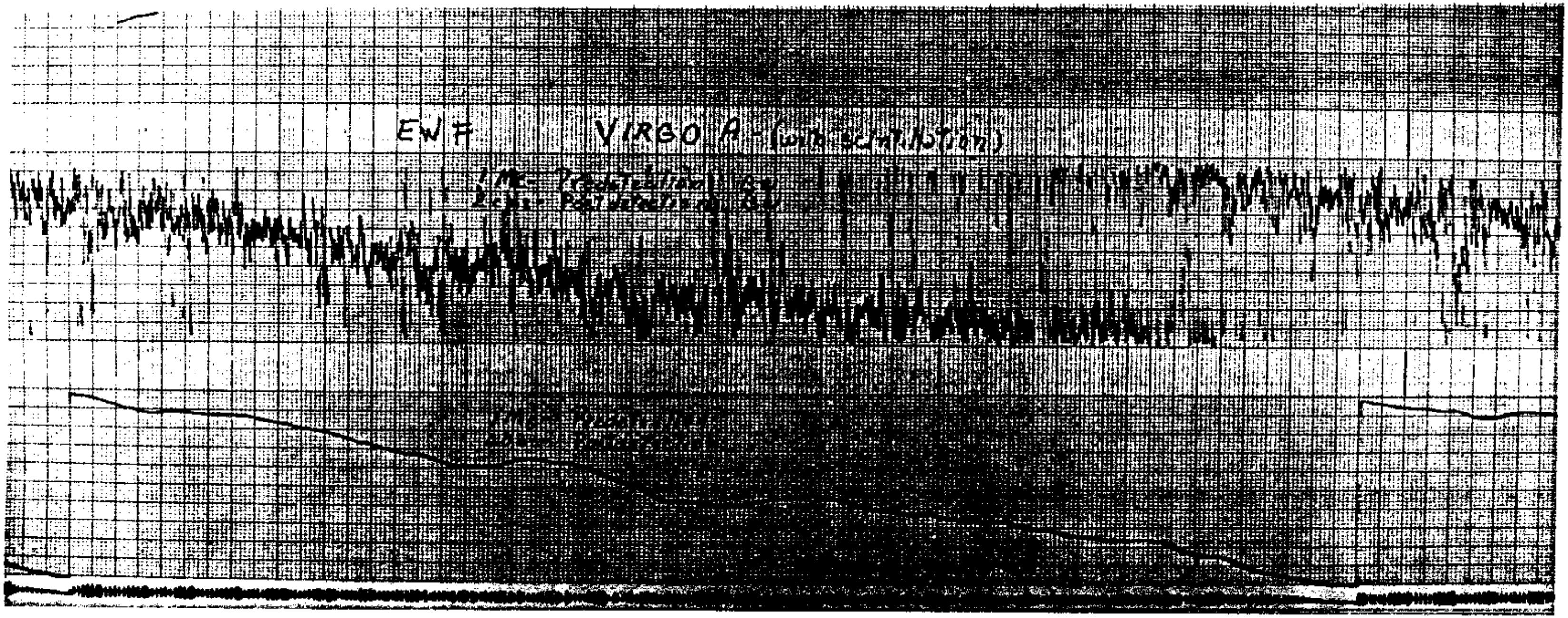


Fig. 11