

TECHNICAL PROGRESS REPORT

SEPTEMBER 1993

DEVELOP ADVANCED NONLINEAR SIGNAL ANALYSIS
TOPOGRAPHICAL MAPPING SYSTEM

NASA CONTRACT NO. NAS8-39393

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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NONLINEAR SIGNAL ANALYSIS
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Technical Progress Report (AI
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DEVELOP ADVANCED NONLINEAR SIGNAL ANALYSIS TOPOGRAPHICAL MAPPING SYSTEM (NASA CONTRACT NO. NAS8-39393)

The SSME has been undergoing extensive flight certification and developmental testing, which involves some 250 health monitoring measurements. Under the severe temperature, pressure, and dynamic environments sustained during operation, numerous major component failures have occurred, resulting in extensive engine hardware damage and scheduling losses. To enhance SSME safety and reliability, detailed analysis and evaluation of the measurements signal are mandatory to assess its dynamic characteristics and operational condition. Efficient and reliable signal detection techniques will reduce catastrophic system failure risks and expedite the evaluation of both flight and ground test data, and thereby reduce launch turn-around time.

The basic objective of this contract are threefold:

- (1) Develop and validate a hierarchy of innovative signal analysis techniques for nonlinear and nonstationary time-frequency analysis. Performance evaluation will be carried out through detailed analysis of extensive SSME static firing and flight data. These techniques will be incorporated into a fully automated system.
- (2) Develop an advanced nonlinear signal analysis topographical mapping system (ATMS) to generate a Compressed SSME TOPO Data Base (CSTDB). This ATMS system will convert tremendous amount of complex vibration signals from the entire SSME test history into a bank of succinct image-like patterns while retaining all respective phase information. High compression ratio can be achieved to allow minimal storage requirement, while providing fast signature retrieval, pattern comparison, and identification capabilities.
- (3) Integrate the nonlinear correlation techniques into the CSTDB data base with compatible TOPO input data format. Such integrated ATMS system will provide the large test archives necessary for quick signature comparison.

This study will provide timely assessment of SSME component operational status, identify probable causes of malfunction, and indicate feasible engineering solutions. The final result of this program will yield an ATMS system of nonlinear and nonstationary spectral analysis software package integrated with the Compressed SSME TOPO Data Base (CSTDB) on the same platform. This system will allow NASA engineers to retrieve any unique defect signatures and trends associated with different failure modes and anomalous phenomena over the entire SSME test history across turbopump families.

REPORTS

In addition to monthly technical progress reports, informal analysis results of SSME test are prepared and presented at irregular intervals. Software routines and database are provided for application on MSFC computers. The final report will document all analysis results, new techniques and computer software generated under this contract.

TECHNICAL PROGRESS

This is September 1993 monthly technical progress report on the subject contract for the development of an advanced nonlinear signal analysis topographical mapping system (ATMS) for SSME diagnostic evaluation. Specific tasks performed in this reporting period are summarized as follows:

Several high amplitude Sync RMS spikes were observed on the external acceleration measurements of High Pressure Oxygen Pump (HPOP) during a series of ATD (Alternate Turbopump Development) engine tests. To validate the analysis techniques to be implemented in the ATMS system, a number of signal analysis were performed to investigate the vibration characteristics of these Sync spike anomalies.

Figure 1 shows the RMS tracking of the turbine end external acceleration measurements HPOT RAD 126 for test 904-164. The figures on the left column are the composite RMS tracking between harmonics, while the ones on the right are the Sync/Harmonics RMS tracking. Notice that there is a strong spike in the RMS tracking for Sync "N" which occurred at S+280 second. This Sync spike represents a typical example of the Sync spike anomaly to be investigated. The first major objective is to find any other signature that might be correlated with this Sync spike phenomenon. However, the RMS tracking of all the other components in figure 1 do not show any of such correlation in terms of the timing of events or trends.

Figures 2-a and 2-b show the PSDs of measurements HPOT RAD 42 and HPOT RAD 126 at S+100 second. The peaks marked "N", "2N", "3N" and "4N" are the Sync frequency component and its harmonics. The harmonics of the 60 Hz line noise are also presented at 180 Hz, 200 Hz, 420 Hz and 540 Hz. The only anomaly observed in this PSD is the peak marked "ORP" at 2267 Hz which is corresponding to the Outer Roller Pass (ORP) frequency of the Turbine End roller bearing (which has 14 rollers). This ORP component was observed in most of this test series and its relationship with respect to the Sync spikes anomaly will first be examined.

Figures 3-a, 3-b and 3-c show the instantaneous envelop signal of Sync N, its second harmonic 2N, and the ORP component. Again, Sync spike is shown in its envelop signal in figure 2-a. Interestingly enough, the envelop signal of the ORP component in figure 3-c exhibits a strong periodicity which indicates that the ORP is subjected to an amplitude modulation motion. In addition, the frequency of the envelop signal is not constant. Figure 4 shows the isoplot of this envelop signal. At the time when the Sync spike occurs at s+280, the frequency of the envelop happens to shift up to a higher frequency and then shift down to a lower frequency latter on. Even though this is not a strong evidence to prove the ORP component is correlated with the Sync spike anomaly, it does indicate that the turbine end roller bearing is the first candidate to be further looked into.

The frequency of the ORP component is simply 14 times of the cage frequency or the rotational frequency of the roller train. The presence of any cage frequency component (C) or its harmonics (2C, 3C, 4C, ...) in such an external casing measurement typically indicates bearing-related defects such as bearing wear. Therefore, cage-related signal would be the next critical signature to search for. The cage frequency C should be at 42.5% of the Sync frequency N. However, the cage frequency component is not observable at all in its raw PSDs as shown in figure 2. Therefore, signal enhancement was

performed next in order to dig out any hidden cage signature that might be corrupted by noise.

Figure 5 shows the results of a two-stage signal enhancement process from this HPOT RAD 126 measurement. Figure 5-a shows the PSD of the first-stage enhancement where all the sync-related components were "discretized". This "discretized" procedure will provide better frequency resolution and will enhance any component that is correlated with Sync (it will not enhance a non-sync-related component). Compare to its original raw PSD in figure 2-b, "3N", "5N", and "6N" components become observable. With all the sync-related components being "discretized", a second-stage enhancement process will then provide a further enhancement on any discrete component. Figure 5-b shows the result of this second enhancement. Compared to figure 5-a, the "3N", "5N", and "6N" components are further enhanced. In addition, several other components start to show up. The most significant components are the peaks marked "3C", "4C", "5C", and "6C". These components turn out to be the harmonics of the cage component. Therefore, additional roller bearing related signatures were found which indicates a potential roller bearing problem. However, this result does not provide any timing information of event or trending that is corresponding to the Sync spike at S+280 since the enhancement technique is performed over a long period of time where instantaneous signatures or events are averaged out. Therefore, again, it still doesn't provide a strong evidence to prove the Sync spike anomaly is correlated with the turbine-end roller bearing problem.

With all the identified anomalous signatures being directed to the turbine end roller bearing, the next objective of this investigation is to identify whether there exist any significant event which occurred before the Sync spike as a potential precursor. To do so, the frequency of the analysis window is open up to 50 KHz from the regular 5 KHz. Figure 6 shows the 50 KHz PSD of measurement HPOT RAD 126 at S+100. Most of the PSD peaks are just higher harmonics of Sync of HPOP (N) or Sync of HPFP (N'), and some high frequency line noise. No significant component is found to be particularly suspicious. However, the RMS tracking time history of this 50 KHz data reveals an interesting phenomenon. Figure 7 depicts the composite RMS trackings over five frequency bands which are: (0-10 KHz), (10-20 KHz), (20-30 KHz), (30-40 KHz), and (40-50 KHz). Several RMS spikes start to show up in the frequency band of 30 KHz to 40 KHz. The timings of these spikes (S+80 to S+160) are quite earlier than the Sync spike which is at S+280. Referring to the 50 KHz PSD as shown in figure 7, a broad peak is present in this 30 to 40 KHz band which is corresponding to the resonant frequency of the accelerometer. Figures 8 and 9 show the raw time histories of the 50 KHz data during the spike (S+125) and after the spike (S+200), respectively. An apparent amplitude modulation phenomenon is clearly observed during the spike, while it disappears after the spike. In order to identify the source of these anomalous spikes, envelop detection analysis is performed to further study this modulation phenomenon.

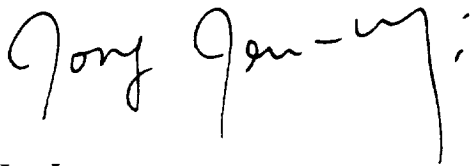
The objective of envelop detection is to extract a low-frequency characteristic or event which is initiating, acting upon, or modifying a high-frequency signal. It is commonly applied to rolling element bearing analysis where a low-frequency periodic motion, such as a roller striking a race, excites a high-frequency structural or sensor resonance. In this event, each impact will ring the structure at the resonant frequency, and the waveform will repeat itself with a repetition rate equal to the low-frequency periodic impact rate. The time history shown in figure 8 indeed reveal such amplitude modulation waveform.

To obtain the envelope of a complex signal, the signal is first bandpass filtered over the frequency band of the structural resonance. Hilbert Transform (HT) is then performed whose transfer function $H(w)$ has unity gain with 90 degree phase shift. The envelop signal can be obtained from the original signal and the 90-degree phase shifted signal from

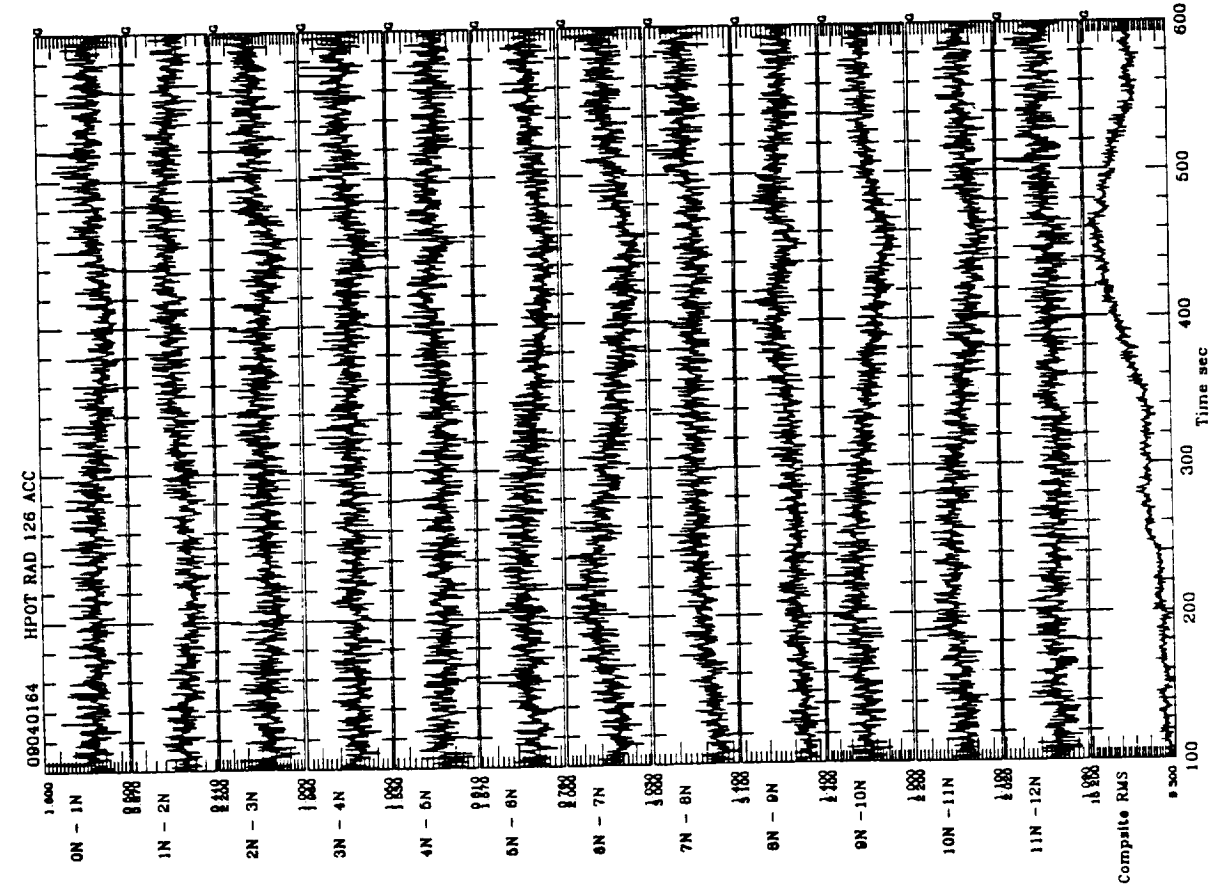
the Hilbert Transform. Figure 10 shows the PSD of 32 KHz to 40 KHz bandpass filtered signal which contains the accelerometer's resonant response. Figure 11 shows the TOPO of the resulting envelop signal. Two apparent peaks Marked "3N" and "4N" corresponding to the third and fourth harmonics of Sync of HPFP are seen throughout the test. These Sync harmonics in the envelop signal are considered irrelevant to the Sync spike anomaly. However, several interesting activities start to show up in the low-frequency region (0 to 1000 Hz) between S+60 to S+160. The zoomed-in isoplot in this time/frequency region as shown in figure 12 depicts a better picture of such activities. Several spikes occurred in this newly transformed envelop signal whose PSD is shown in figure 13. The frequencies of these spikes turn out to be at the Cage frequency of the turbine end roller bearing and its harmonics. This indicates that during the time when these cage spikes occurred, some striking motion from the rolling elements was present whose signal is imbedded in the sensor's resonant response in the form of amplitude modulation. Figure 14 shows the RMS tracking of the envelop signal for cage component "C" and its harmonics.

Even though the timing of these cage spikes still do not match that of the Sync spike, this result clearly indicates the bearing condition went through some significant change before the Sync spike. Whether or not the cage spikes acted as a precursor to the Sync spike is not clearly known yet. High frequency analysis of other engine tests with Sync spike anomalies is currently under investigation. The results will be reported in the next progress report.

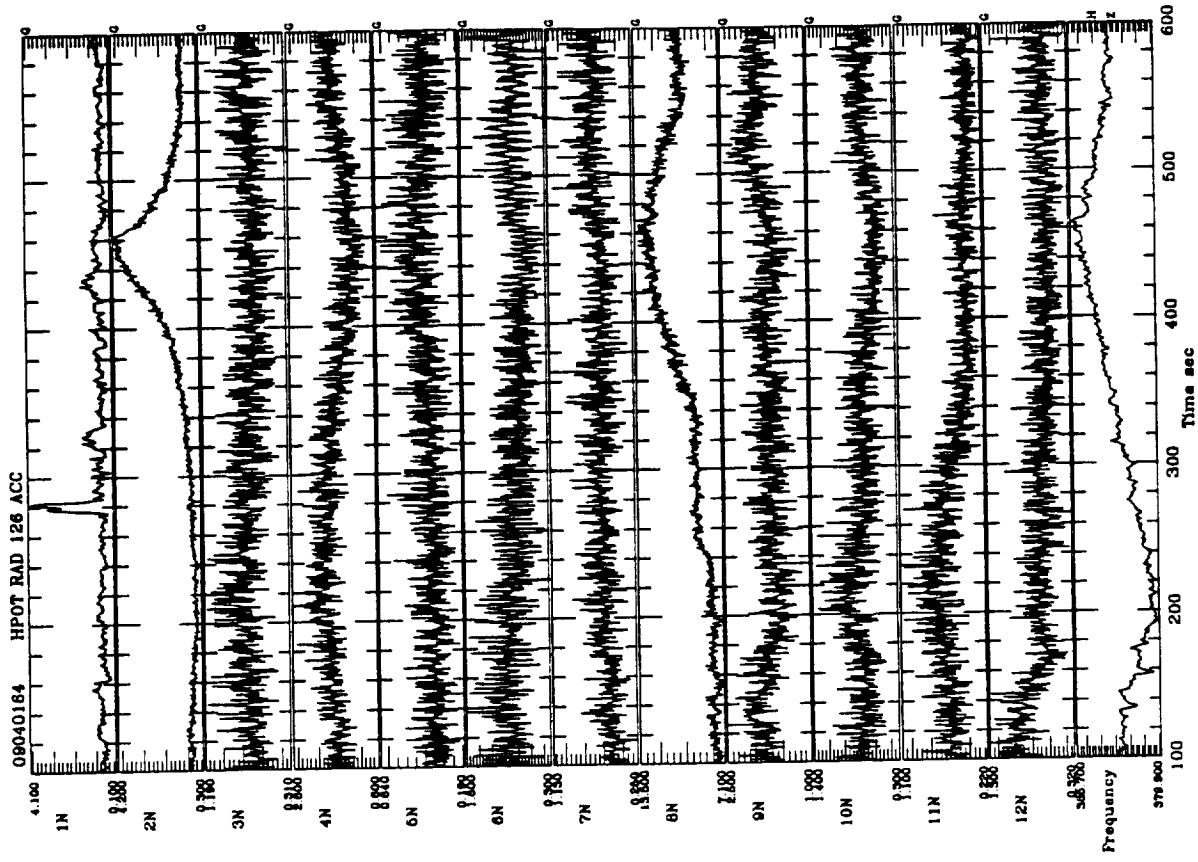
Prepared and approved by

A handwritten signature in black ink, appearing to read "Jen Jong", with a stylized flourish at the end.

Jen Jong
Program Manager



Between Harmonic RMS Tracking



Sync/Harmonic RMS Tracking

Figure 1

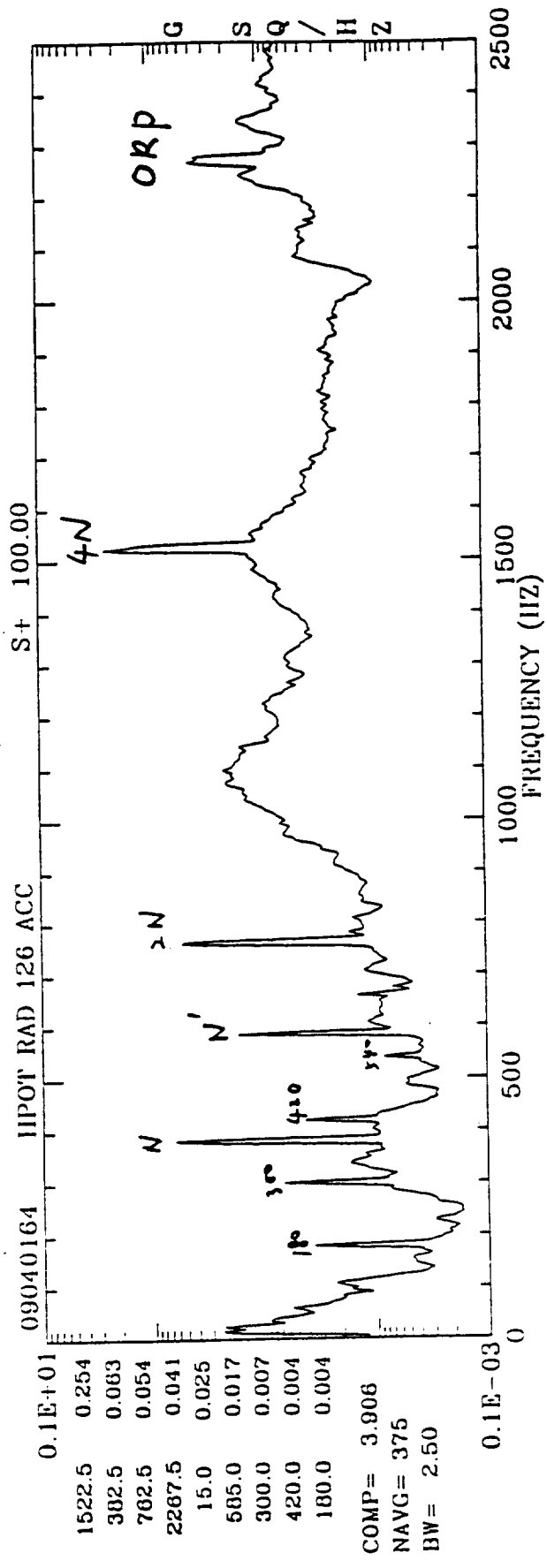
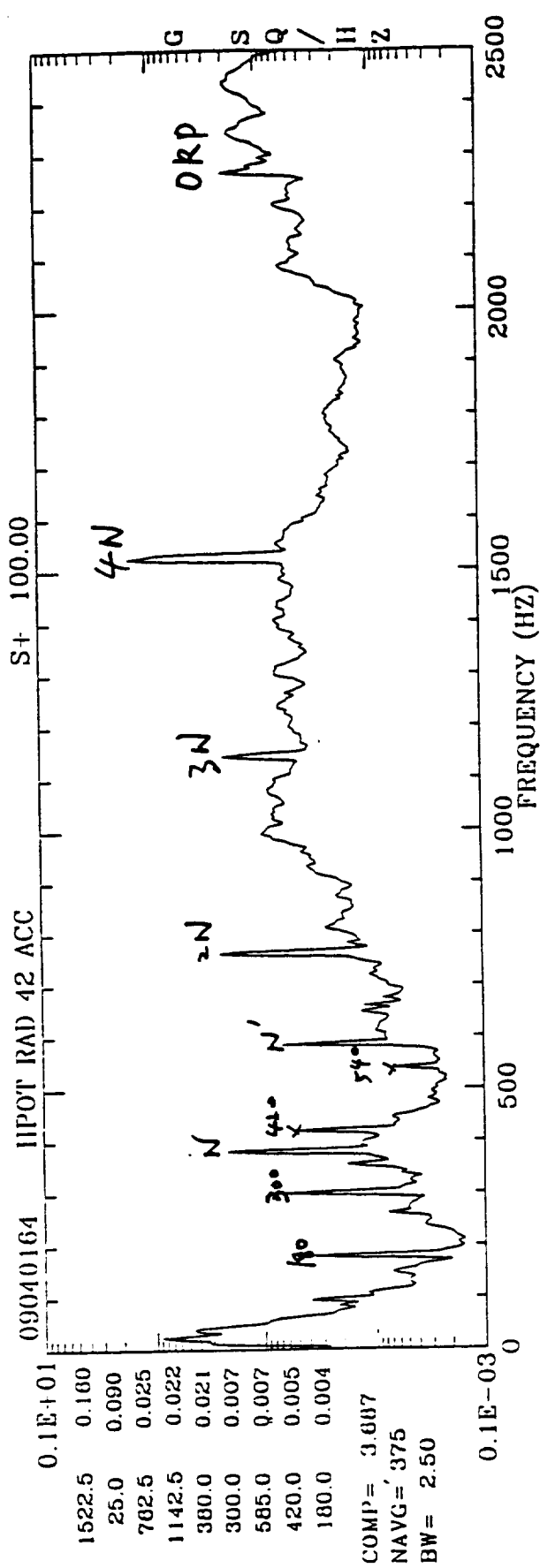


Figure 2

09040164 HPOT RAD 126

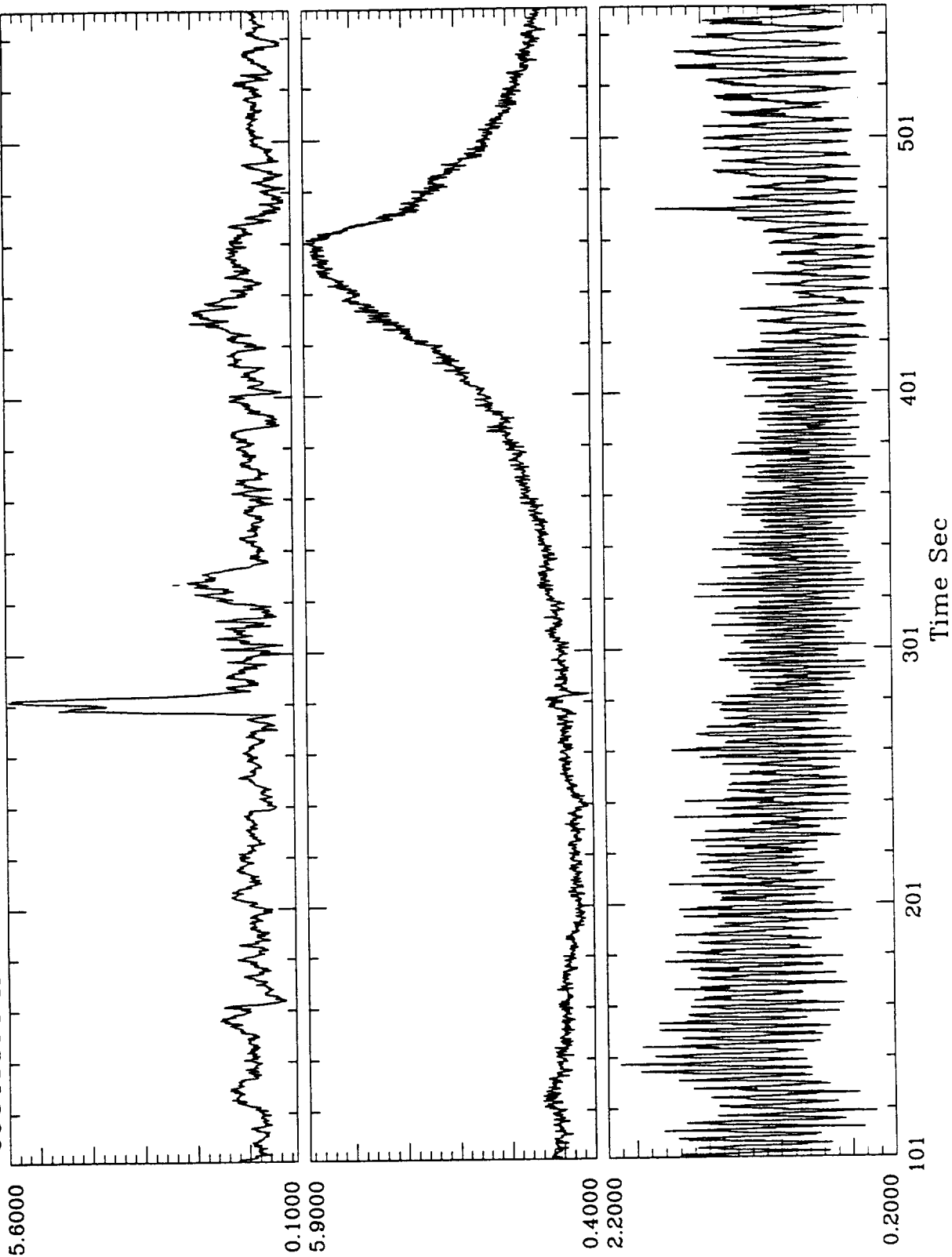


Figure 3

BW= 0.020 ORP-AMP Channel 1 09/03/93
 Y-INC=.640E+01 sec <ED23>
 PLOT CLIP LEVEL = .303E+01 V-SQ/Hz LINEAR Freq. Range = 0.0 - 0.8
 OVR LPS = 8

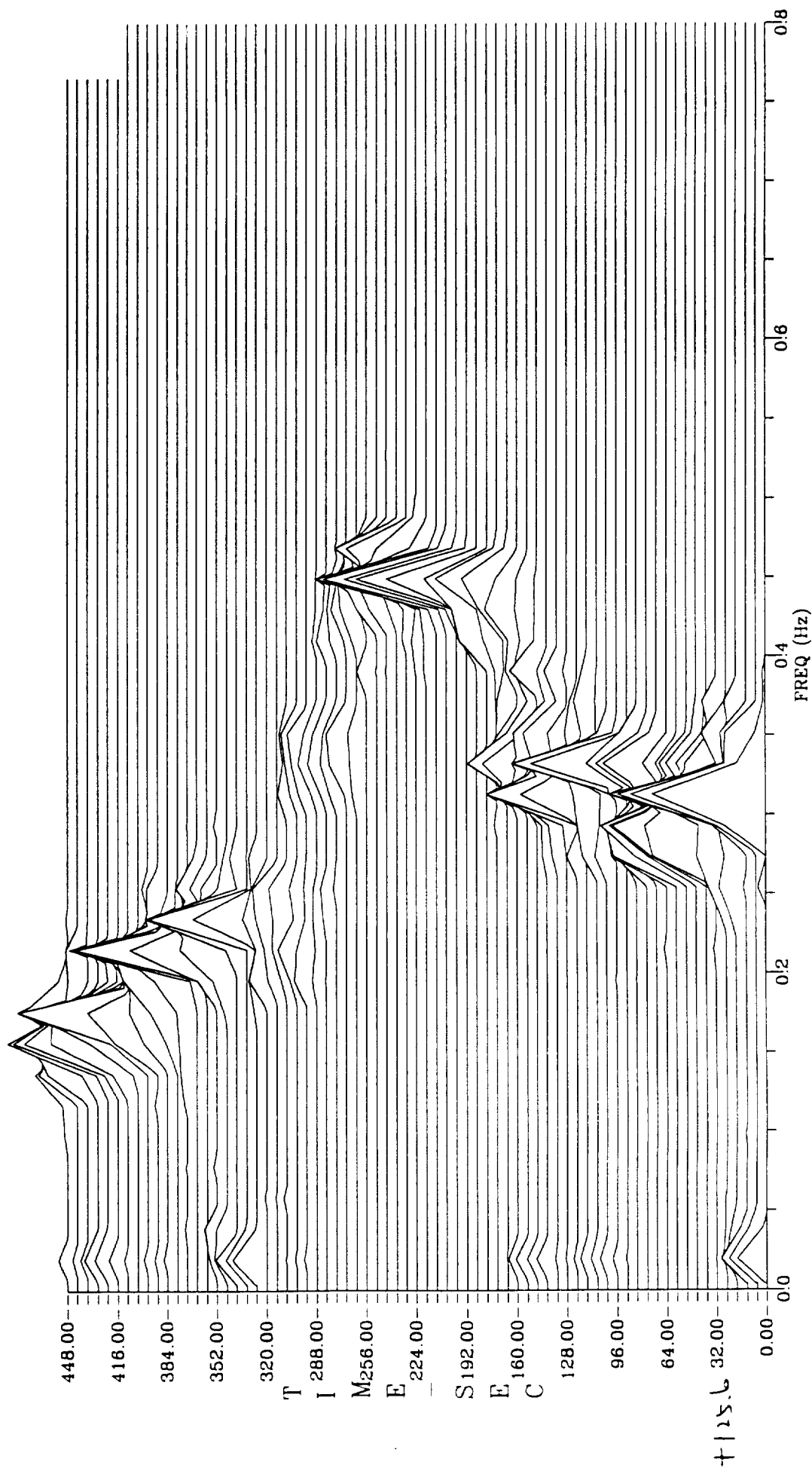


Figure 4

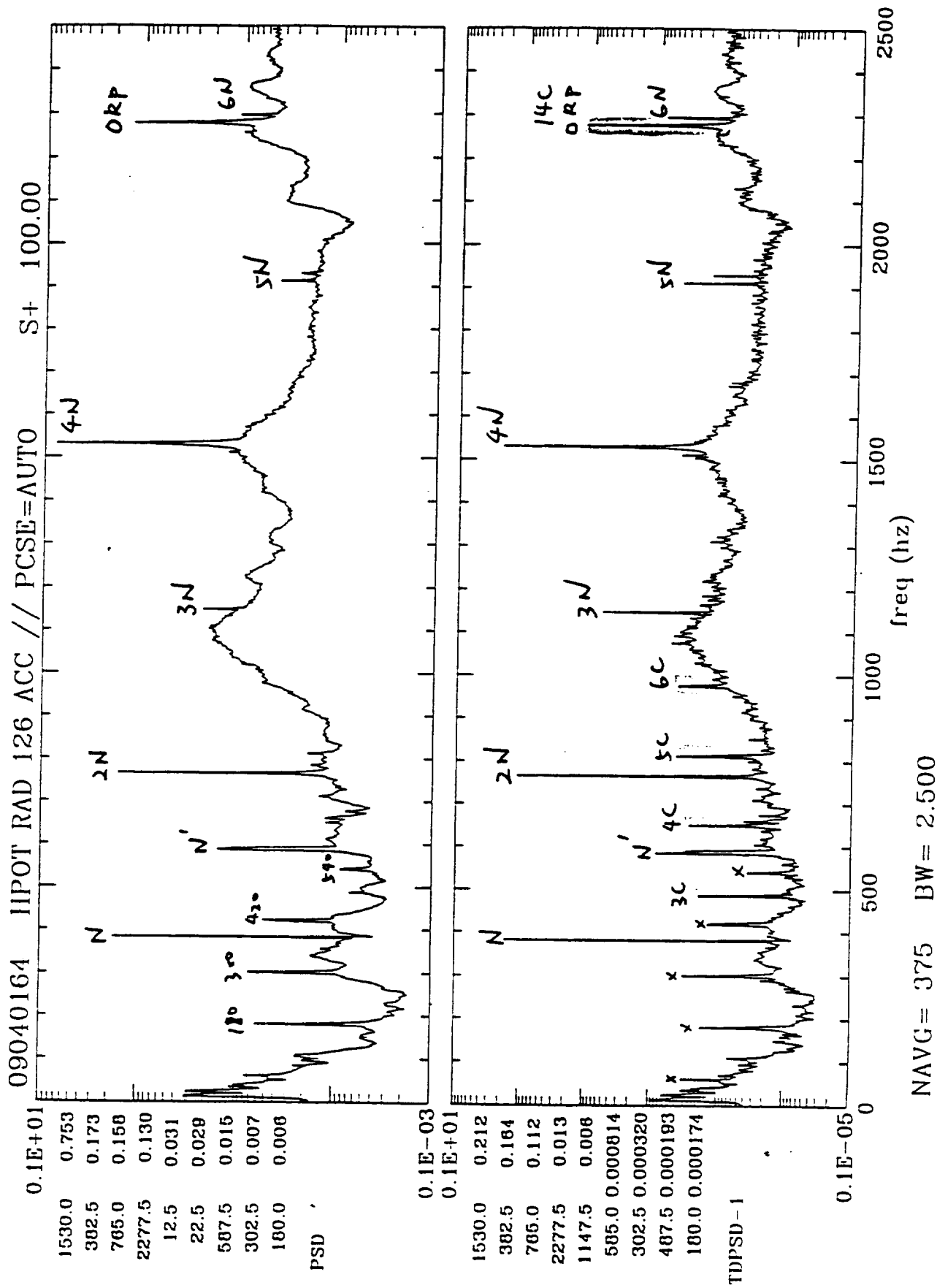


Figure 5

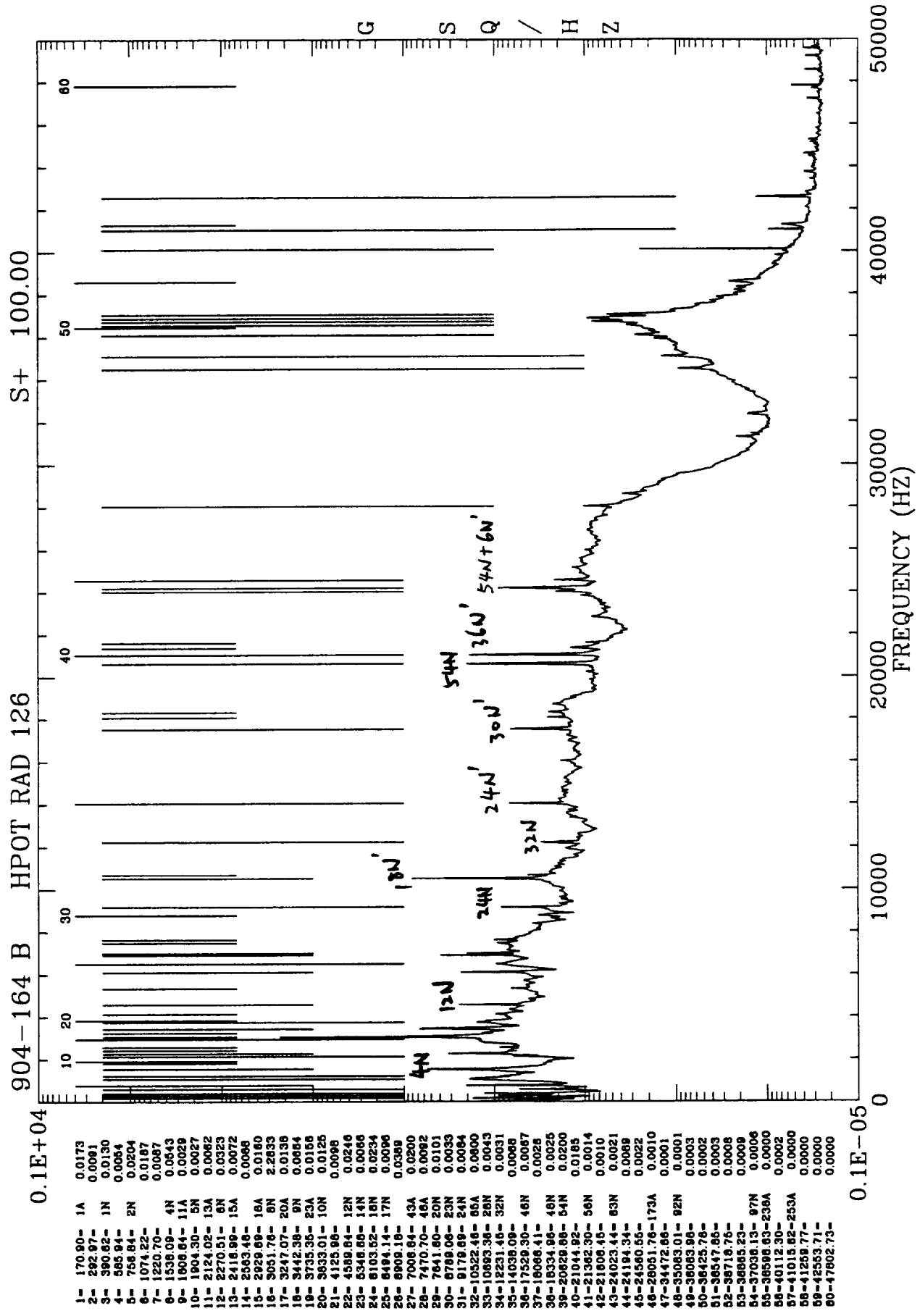
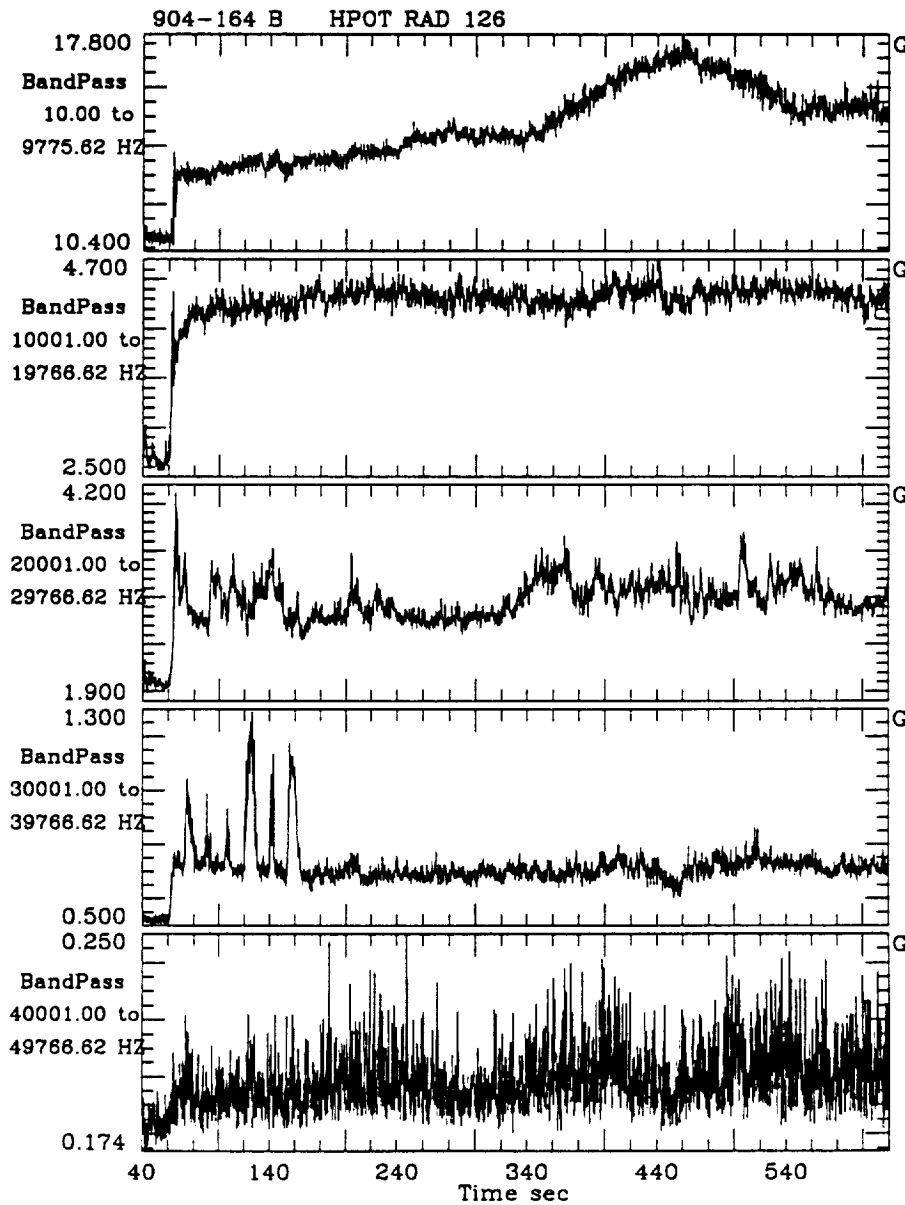
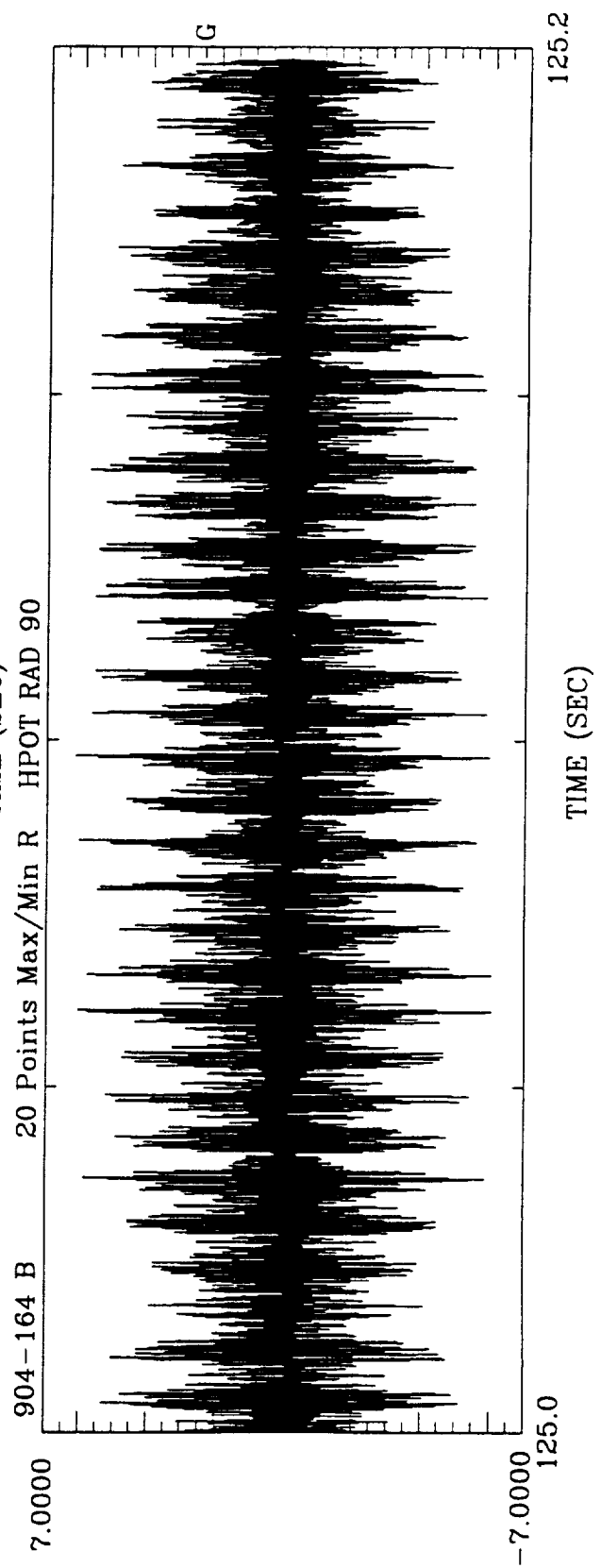
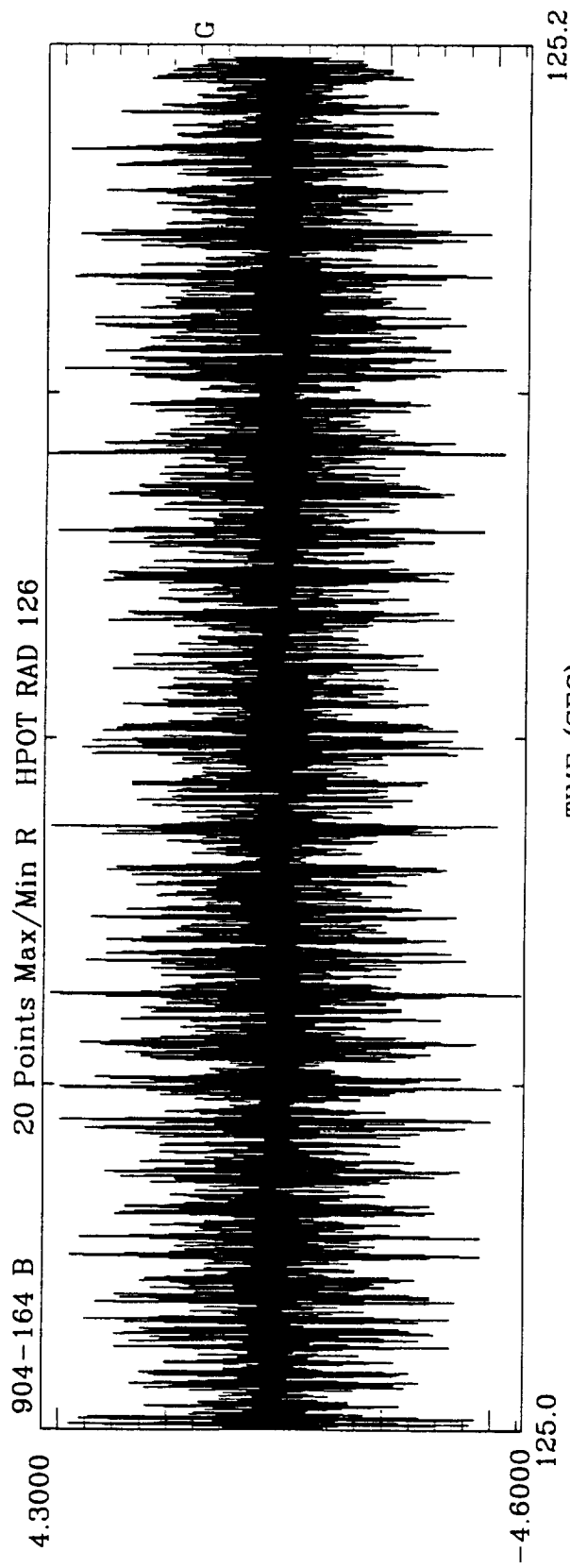


Figure 6



RMS Amplitude Tracking

Figure 7



ENVELOP SIGNAL = CAGE

Figure 8

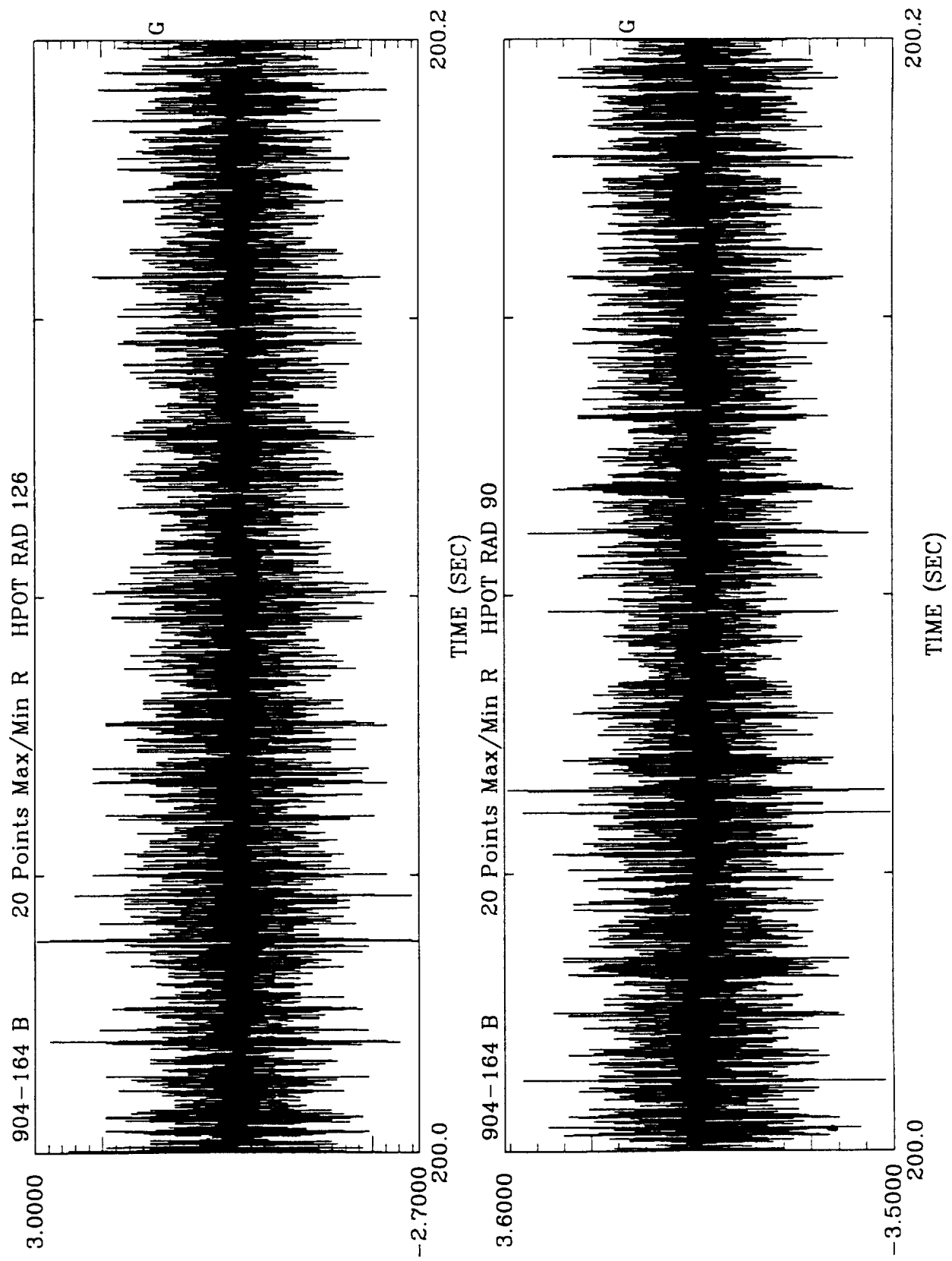


Figure 9

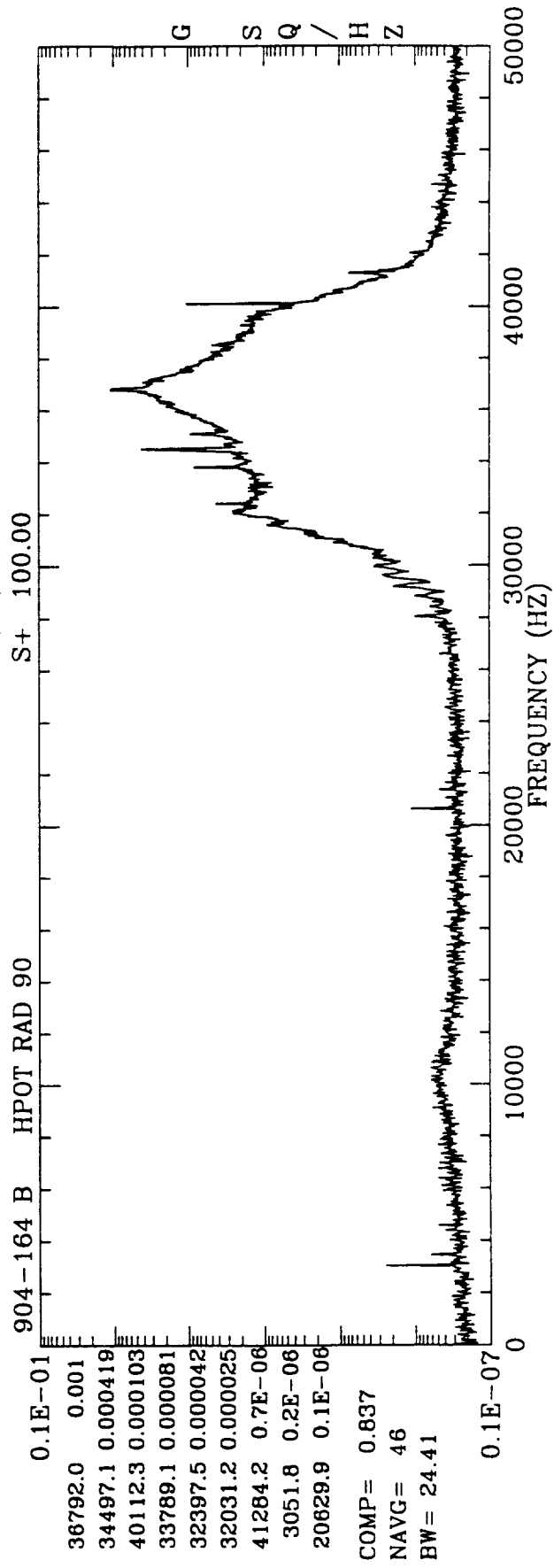
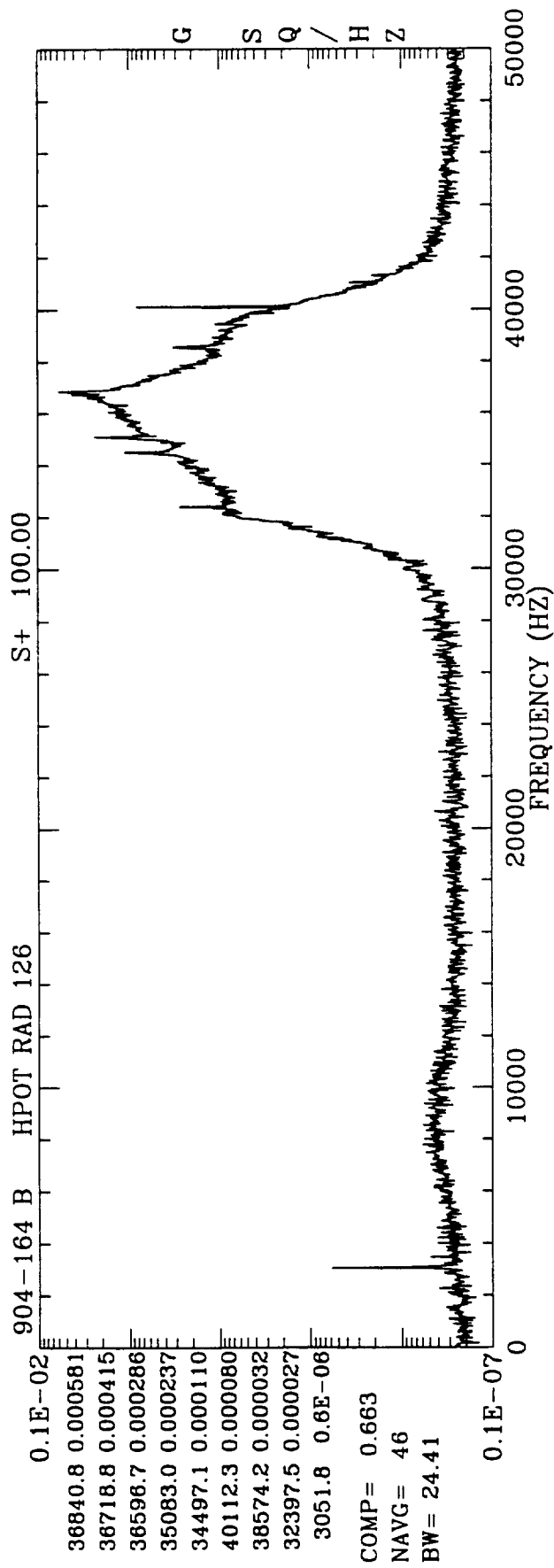


Figure 10

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904-164/ENV

HPOT RAD 126

npk = 100
isp = 4
neigh = 12
ipara = 8
mx = 0
my = 0

nPSDs = 441
nAVGs = 4
BW = 3.1

TIME - sec

s.p.k.e $\Rightarrow$ 160

s.p.k.e $\Rightarrow$ 120

09/22/93

ED23

s.p.k.e $\Rightarrow$ 80

600
560
520
480
440
400
360
320
280
240
200
160
120
80
40
0

FREQ (Hz)

3u'

4u'

Figure 11

BW = 3.052 904-164/ENV HPOT RAD 126 09/22/93
 Y-INC=.164E+01 sec 5 PSDs AVERAGED <ED23>
 PLOT CLIP LEVEL = .100E-01 G-SQ/Hz LINEAR Freq. Range = 50.0 - 1050.0

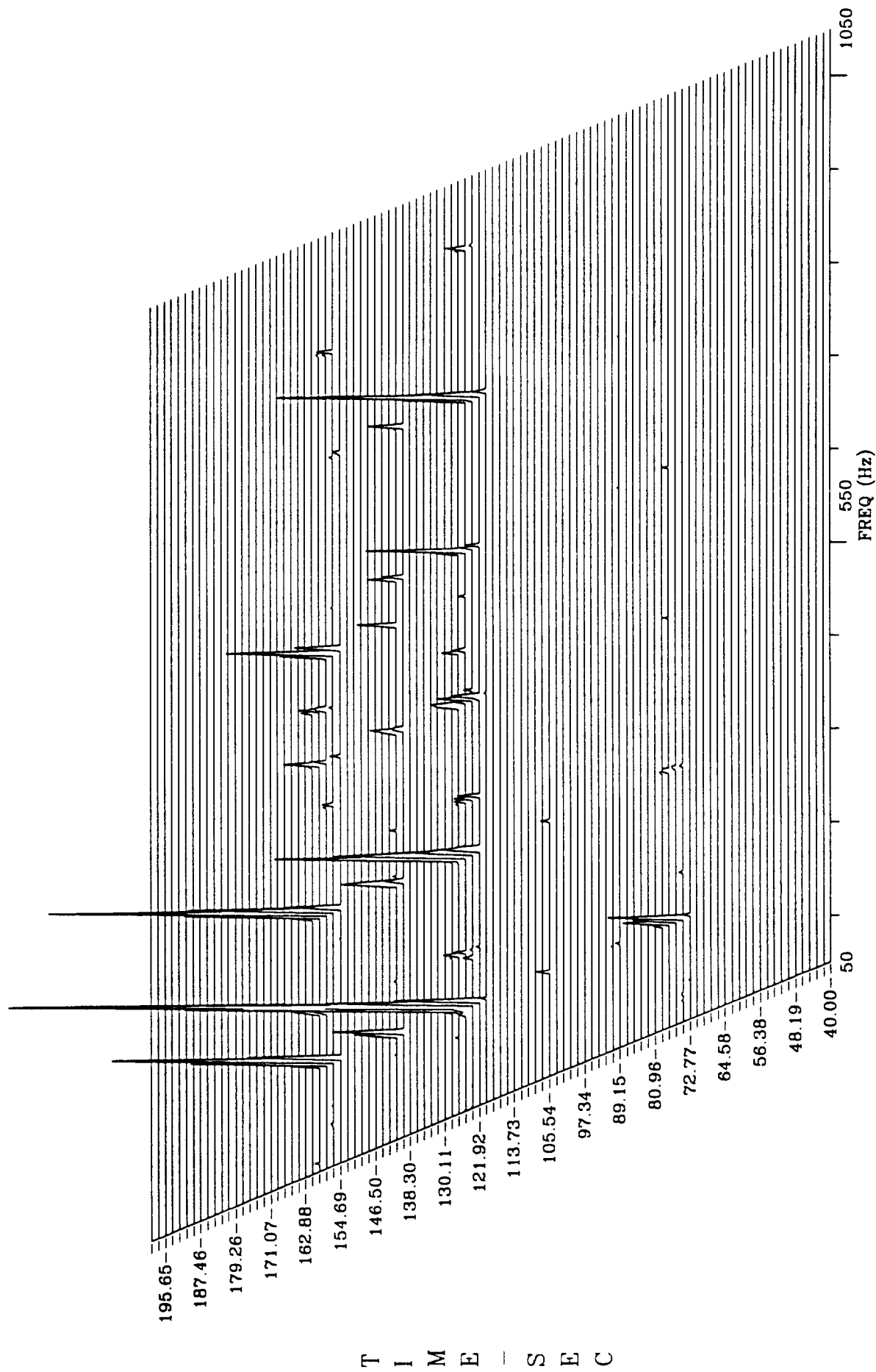
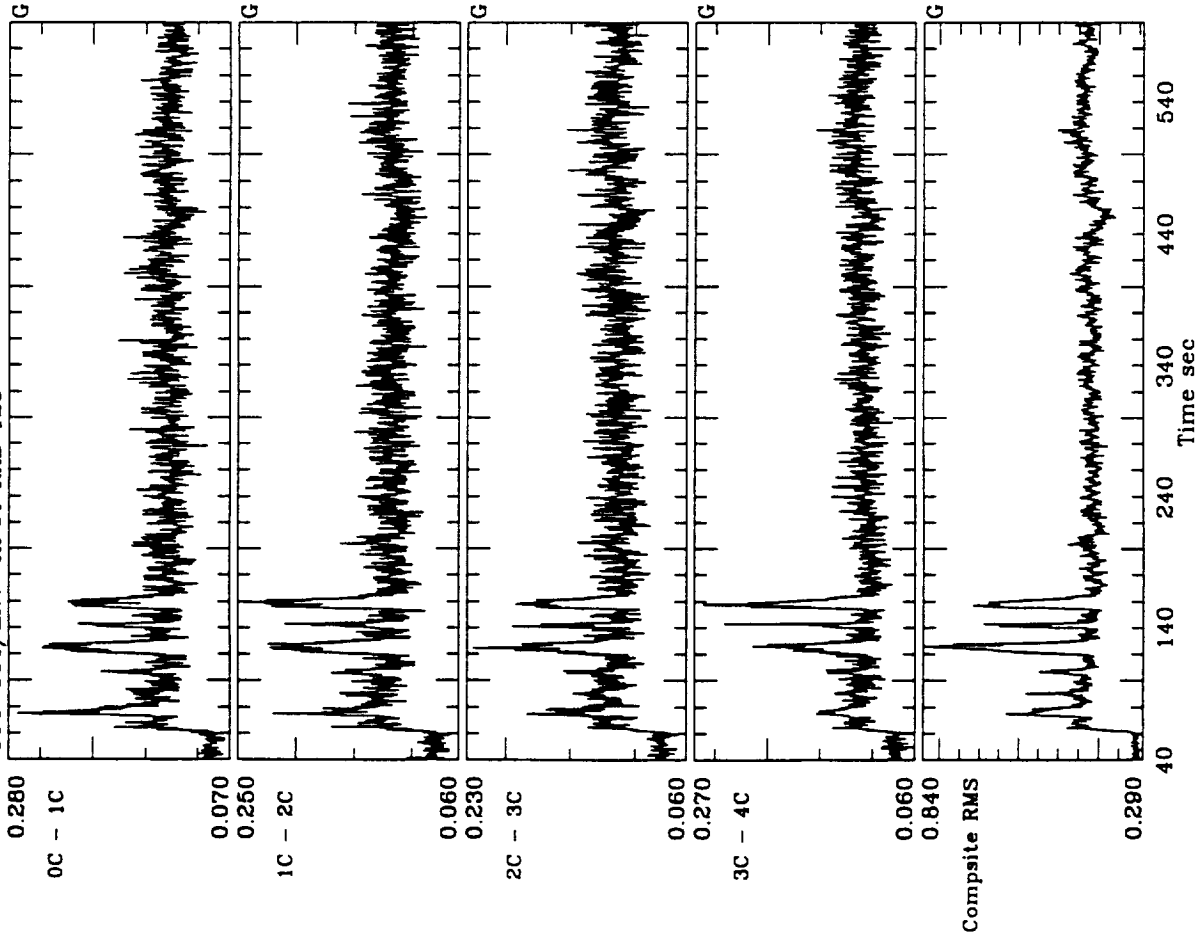


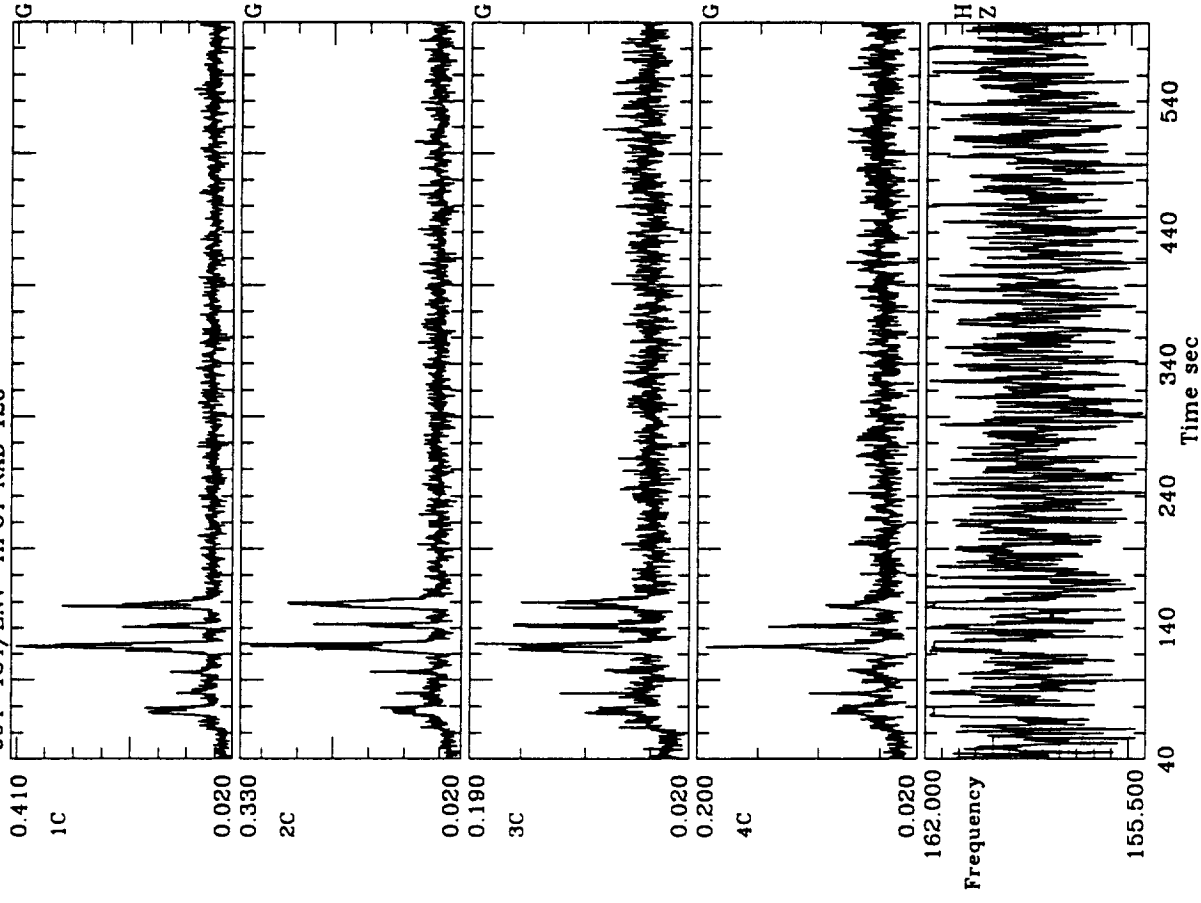
Figure 12

904-164/ENV HPOT RAD 126



Between Harmonic RMS Tracking

904-164/ENV HPOT RAD 126



Sync/Harmonic RMS Tracking

Figure 14

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