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TECHNICAL PROGRESS REPORT

DECEMBER 1993

DEVELOP ADVANCED NONLINEAR SIGNAL ANALYSIS TOPOGRAPHICAL MAPPING SYSTEM

NASA CONTRACT NO. NAS8-39393

N94-24856
Unclas
G3/43 0198514

(NASA-CR-194785) DEVELOP ADVANCED NONLINEAR SIGNAL ANALYSIS TOPOGRAPHICAL MAPPING SYSTEM Technical Progress Report (AI Signal Research) 16 p

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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AI SIGNAL RESEARCH TECHNICAL REPORT TR-4002-93-12

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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 December 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:

. As reported in the monthly technical progress report for July 1993, a new signal analysis technique called "Instantaneous Frequency Correlation (IFC)" for time delay estimation was developed which will be incorporated into the ATMS system. In this report, a different technique for time delay estimation called "Phase Difference Time Derivative Estimator (FDTDE)" will be discussed. The FDTDE technique does not replace the IFC method since their application conditions are different. The IFC technique can estimate the time delay between two spectral components of two measurement signals when the center frequency of the component are constant. While the FDTDE method can provide accurate time delay estimation when the frequency of the subject component changes linearly such as during engine startup or shut-down. The major advantage of the IFC technique is that it can estimate time delay from the newly generated Instantaneous Frequency Variation (IFV) signal without being subjected to the ambiguity limitation due to the 2π phase wrapped around effect. However, the condition for the IFC technique to be applicable is quite restrictive. This is due to the frequency of the newly generated IFV signal for correlation analysis is greatly reduced from the original waveform. As a result, high signal to noise ratio and large number of ensemble average is required in order to reduce the statistical variation of the correlation function estimation. In addition, long period of stationary signal is required in order to generated a accurate estimation of Instantaneous Frequency Variation (IFV) signal. On the other hand, by taking advantage of a special property of signal when its frequency changes linearly, time delay information can be identified directly from the signal's FFT phase slope by the FDTDE method. As a result, the signal condition requirement would not be as restrictive as the IFC method.

Time delay estimation is an important task in machinery diagnostics. When an anomalous frequency component is observed at various measurement locations, it is always highly desirable to be able to identify the source of the anomaly by determining the wave propagation path from the time lead/lag information of these measurement signal. The conventional approach for time delay estimation of a stationary discrete spectral component is by using either the cross-correlation function of the band-passed signal in the time domain or the phase difference of the transfer function in the frequency domain. However, a critical limitation exists for these conventional techniques. The time delays estimated from these two methods are subjected to a 2π phase wrapped around effect, which introduces ambiguities in the delay estimation. Therefore, these techniques are only valid when the time lag/lead involved is small and is within the 2π window.

As well known, the phase difference between two spectral components is directly related to their time delay within an unknown integer multiple of 2π. However, if the frequency of the subject spectral component changes linearly, such phase wrapping ambiguity can be avoided from the time derivative (or slope) of phase difference information. To demonstrate this, let's consider the following FM signal:

$$x(t) = \cos[\, 2\pi\, (0.5\, f'\, t^2 + f_o\, t) + Px\,] \qquad (1)$$

The instantaneous frequency f(t) of x(t) is:

$$f(t) = f'\, t + f_o \qquad (2)$$

let y(t) be a time delayed version of x(t):

$$\begin{aligned} y(t) &= x(t-\tau) \\ &= \cos[\, 2\pi\, (0.5\, f'\, (t-\tau)^2 + f_o\, (t-\tau)\,) + Px\,] \\ &= \cos[\, 2\pi\, (0.5\, f'\, (t-\tau)^2 + f_o\, (t-\tau)\,) + Px + \\ &\qquad 2\pi\, (0.5\, f'\, \tau^2 - f_o\tau - f'\tau t)\,] \qquad (3) \\ &= \cos[\, 2\pi\, (0.5\, f'\, (t-\tau)^2 + f_o\, (t-\tau)\,) + Py\,] \end{aligned}$$

The phase difference between x(t) and y(t) becomes:

$$Pxy = Py-Px = 2\pi\, (0.5\, f'\, \tau^2 - f_o\tau - f'\tau t) \qquad (4)$$

Phase difference Pxy can be directly estimated from the FFT of the signal, and the time delay τ can be obtained from equation (4). However, this estimation is subjected to a 2π ambiguity due to the phase wrapping. Notice that, the time derivative of the phase difference P'xy (or the phase slope) still retains the desired time delay information since:

$$P'xy = d(Pxy)/dt = -\, 2\pi\, f'\tau \qquad (5)$$

Equation (5) states that, there exists a unique relationship between the phase slope P'xy and the time delay τ when the frequency of signal changes linearly. (such relationship no longer exists if the signal's frequency stays constant since its frequency slope f' would become zero). The major advantage provided by such relationship is that the phase slope P'xy is no longer subjected to the phase wrapping effect. As a result, the 2π phase ambiguity in the resulting time delay estimation will be removed.

A computer simulation is performed in order to demonstrate this technique. An FM signal with linearly varying frequency is generated as below:

$$x(t) = \cos[\,2\pi\,(0.5\,f'\,t^2 + f_o\,t)\,]$$

The initial frequency f_o is 2000 Hz with frequency slope f' being 4.54545 Hz/sec. The sampling frequency used is 10,240 Hz. Figure 1 shows the PSD isoplot of the simulation signal. Notice that, the required linearly varying frequency is apparent. Three time delay versions are artificially generated by delaying the reference signal by 5, 20, and 100 samples respectively. Figure 2 shows the time histories of the reference signal along with these three time delayed signals. Figure 3 shows their corresponding PSDs at S+1 second. Figure 4 shows (a) the frequency tracking of the spectral component, (b) the RMS amplitude of the component of the reference signal, (c) the RMS amplitude of the component of the 5-point delay signal, and (d) the FFT phase difference time data between the reference and the 5-point delay signal. The two required parameters f_o and f' can also be calculated directly from the frequency tracking plot in figure 4-a. Figure 5 and 6 show the same information between the reference and the 20-point, the 100-point delay signals respectively.

Notice that, the phase difference time data indeed shows an apparent linear trend which is directly related to the time delay τ. This phase slope P'xy can be obtained from this linear trend of the phase difference time data as shown in figure 4-d, 5-d and 6-d. These parameters of P'xy are: 0.0139, 0.055676, and 0.2788 rad/sec for the three delayed signals. From this information, the time delays τ can then be estimated based on the relationship of equation (5).

The values of f', P'xy , the estimated time delay τ, and the estimated time delay D in samples for the three cases in figure 4, 5, and 6 are shown below:

	ref/5-point	ref/20-point	ref/100-point	Unit
f'	-4.5454	-4.5454	-4.5454	Hz/sec
P'xy	0.0139	0.055676	0.2788	rad/sec
τ	0.4882	1.952	9.766	msec
D	5	20	100	sample

The estimated time delay in sample (D) of 5, 20, and 100 indeed correctly recover their corresponding true time delays for these three cases.

This simulation study indicates that the FDTDE technique can correctly estimate time delay from the phase slope of signal with linearly varying frequency without being subjected to the ambiguity limitation due to the 2π phase wrapping effect. In addition, the condition for this technique to be applicable is not as restrictive as the IFC method. As shown above, this process only requires the standard FFT operation and the phase difference tracking. Unlike the IFC method which requires "instantaneous" information (i.e. IFV) estimation, the signal to noise ratio requirement is less strict for the FDTDE method since the FFT phase information is processed in "block" operation.

Figure 7 shows an example in a laboratory environment suitable for application of the FDTDE time delay estimation. The data is taken from a test of a series of air flow tests at the MSFC air flow facility (AFF). As shown in the isoplot in figure 7-a, an anomalous frequency component was observed whose frequency changes linearly from 4400 Hz to 4260 Hz from S+10 to S+50 second. Figure 7-b show the PSDs at two measurement locations. The purpose of these tests is to characterize the facility generated noise. In order to identify the source of this anomaly, the wave propagation direction of this anomaly along the air flow pipe must first be determined.

Figure 8 shows (a) the frequency tracking of the anomaly, (b) the RMS amplitude of the anomaly at measurement XB03, (c) the RMS amplitude of the anomaly at a down stream measurement FH03, and (d) the FFT phase difference time data between these two measurements. Notice that, the phase difference time data indeed shows an apparent linear trend (phase slope) which is directly related to their time delay. The two required parameters f_0 and f' can be calculated from the frequency tracking plot in figure 8-a. This phase slope $P'xy$ is obtained from the phase difference time data in figure 8-d. From this information, the time delay is then estimated based on the relationship of equation (5). The resulting time delay estimated is 1.7 msec. This time delay corresponds to a distance of 2 feet based on an average acoustic speed of 1180 ft/sec. This distance is close to the actual physical length between these two measurement locations. In addition, the positive phase slope shown in figure 8-d clearly indicates that the anomaly in XB03 is leading the FH03. This lead/lag information is critical in determining the source of anomaly. More detailed analysis and application by using the FDTDE technique for the AFF test will be continued in the next reporting period.

Prepared and approved by

Jong Jen-Yi

Jen Jong
Program Manager

BW= 2.500 TIMELAG Reference 12/22/93
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PLOT CLIP LEVEL = .269E+00 V-SQ/Hz LOG/ 77.% Freq. Range =1500.0 - 2500.0

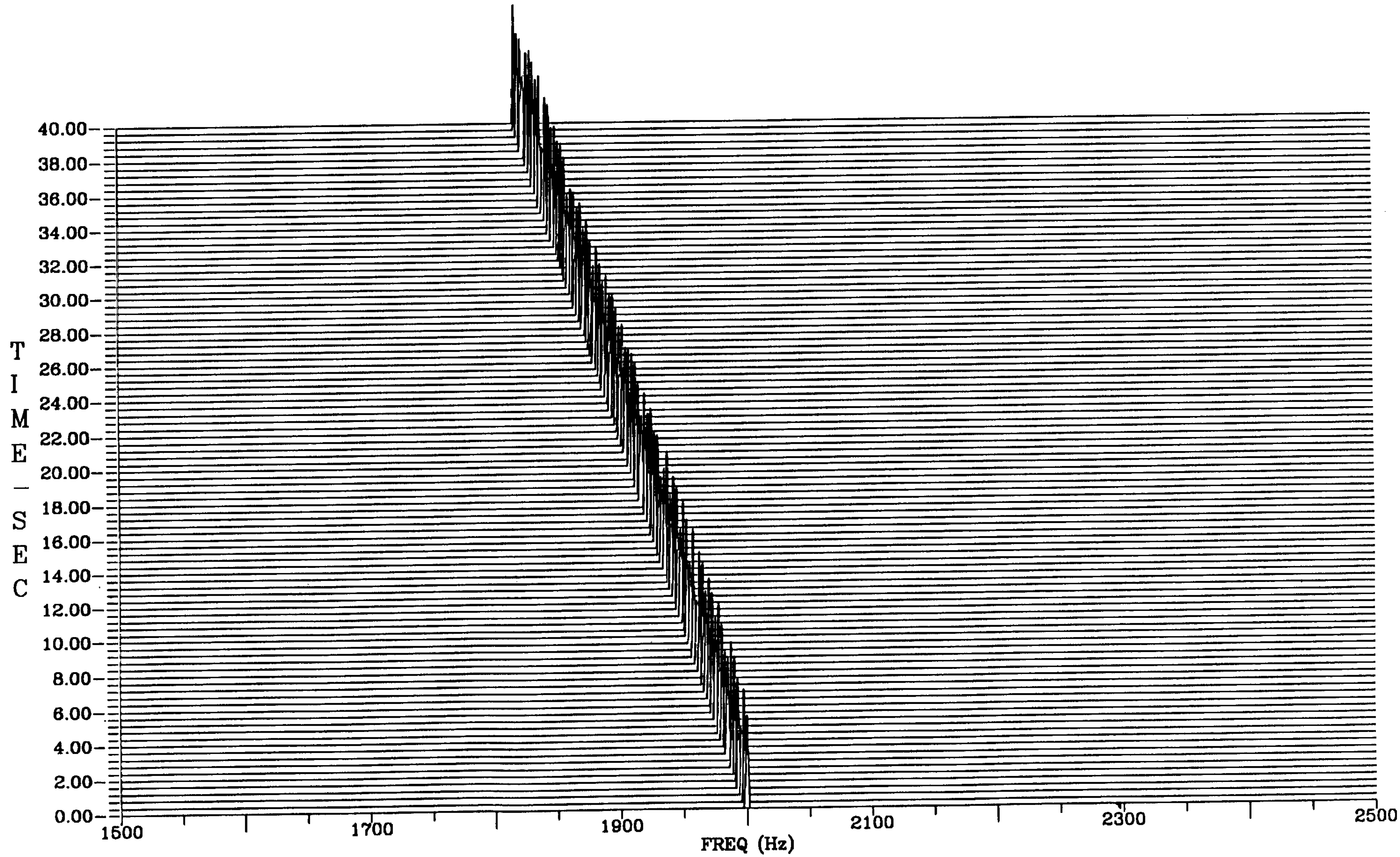


Fig -1

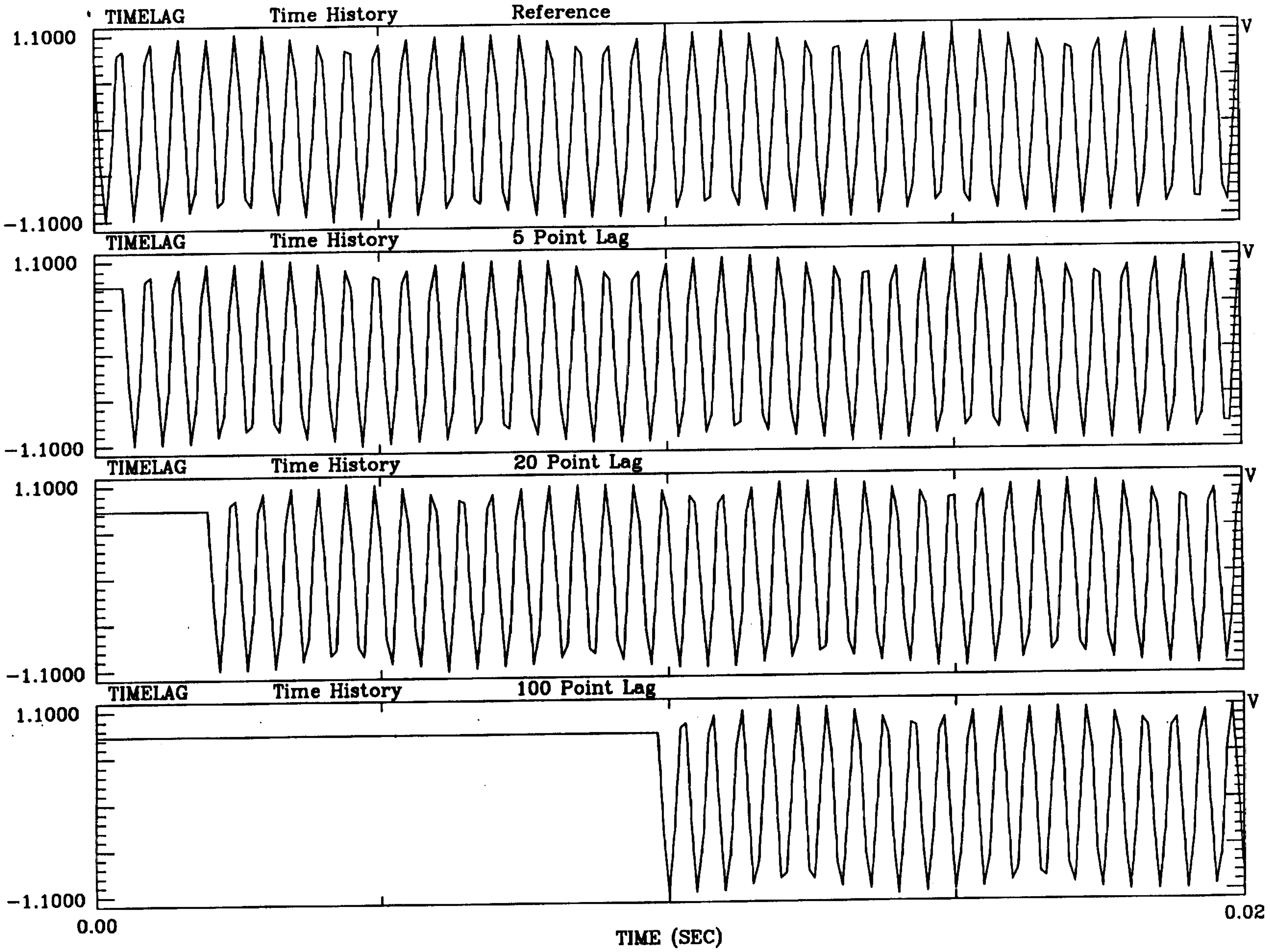
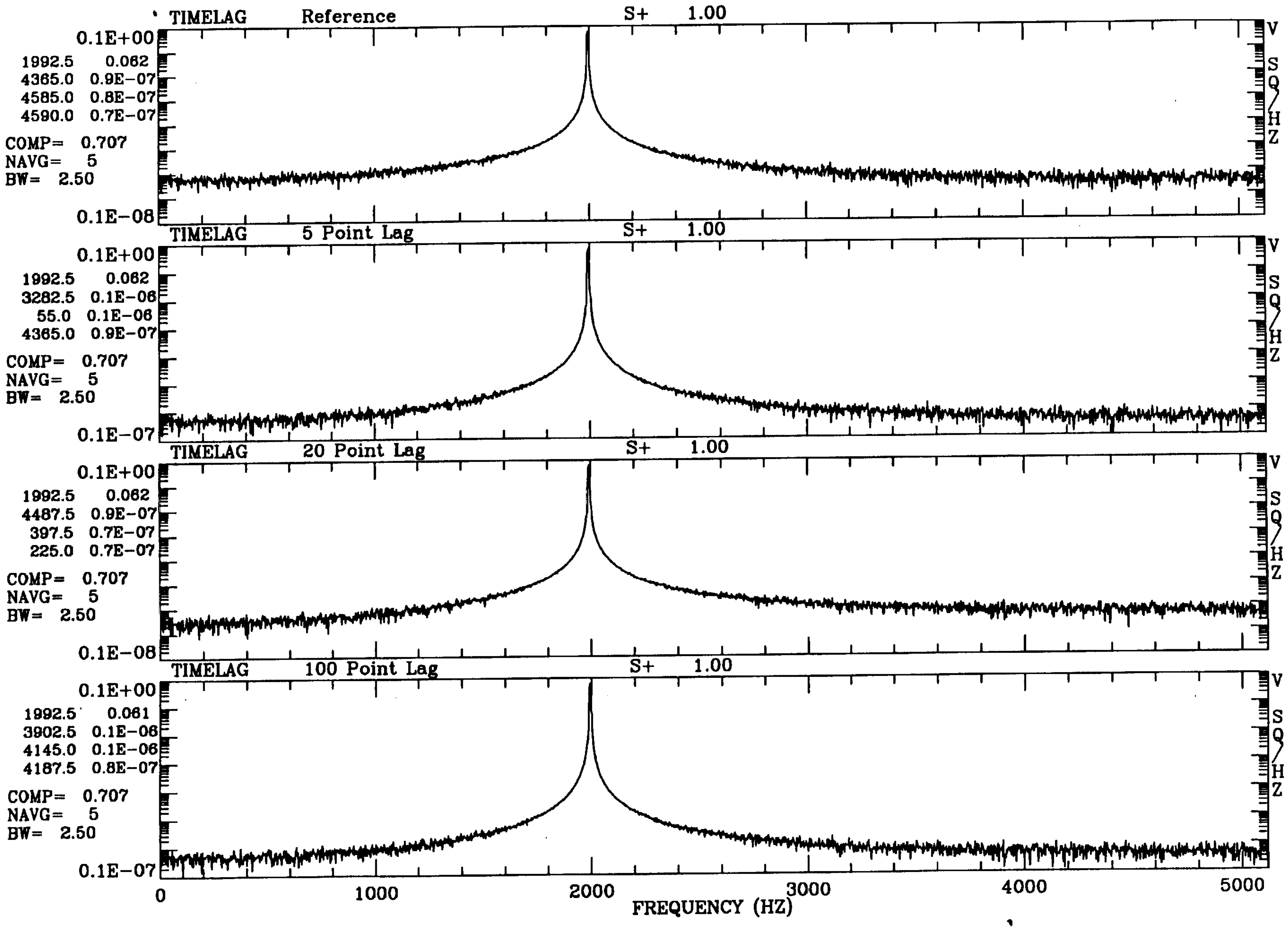

TIMELAG
Time History
Reference
TIMELAG
Time History
5 Point Lag
TIMELAG
Time History
20 Point Lag
TIMELAG
Time History
100 Point Lag
1.1000
-1.1000
V
0.00
0.02
TIME (SEC)

Fig -2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NAVG= 5
BW= 2.50
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0.1E+00
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397.5 0.7E-07
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NAVG= 5
BW= 2.50
0.1E-08
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0.1E+00
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4145.0 0.1E-06
4187.5 0.8E-07
COMP= 0.707
NAVG= 5
BW= 2.50
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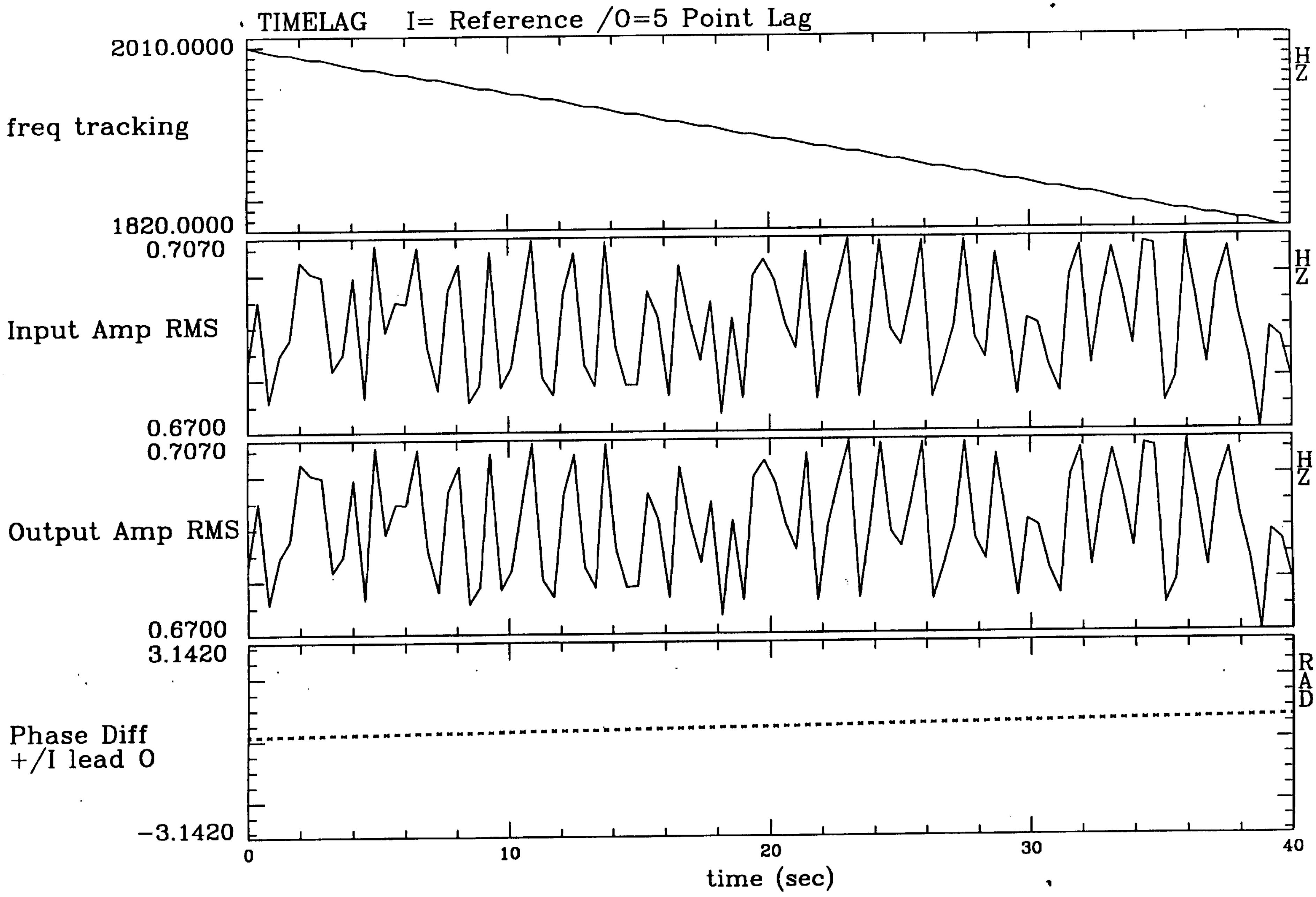
V
S
Q
H
Z
0
1000
2000
3000
4000
5000
FREQUENCY (HZ)

Fig-3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1820.0000
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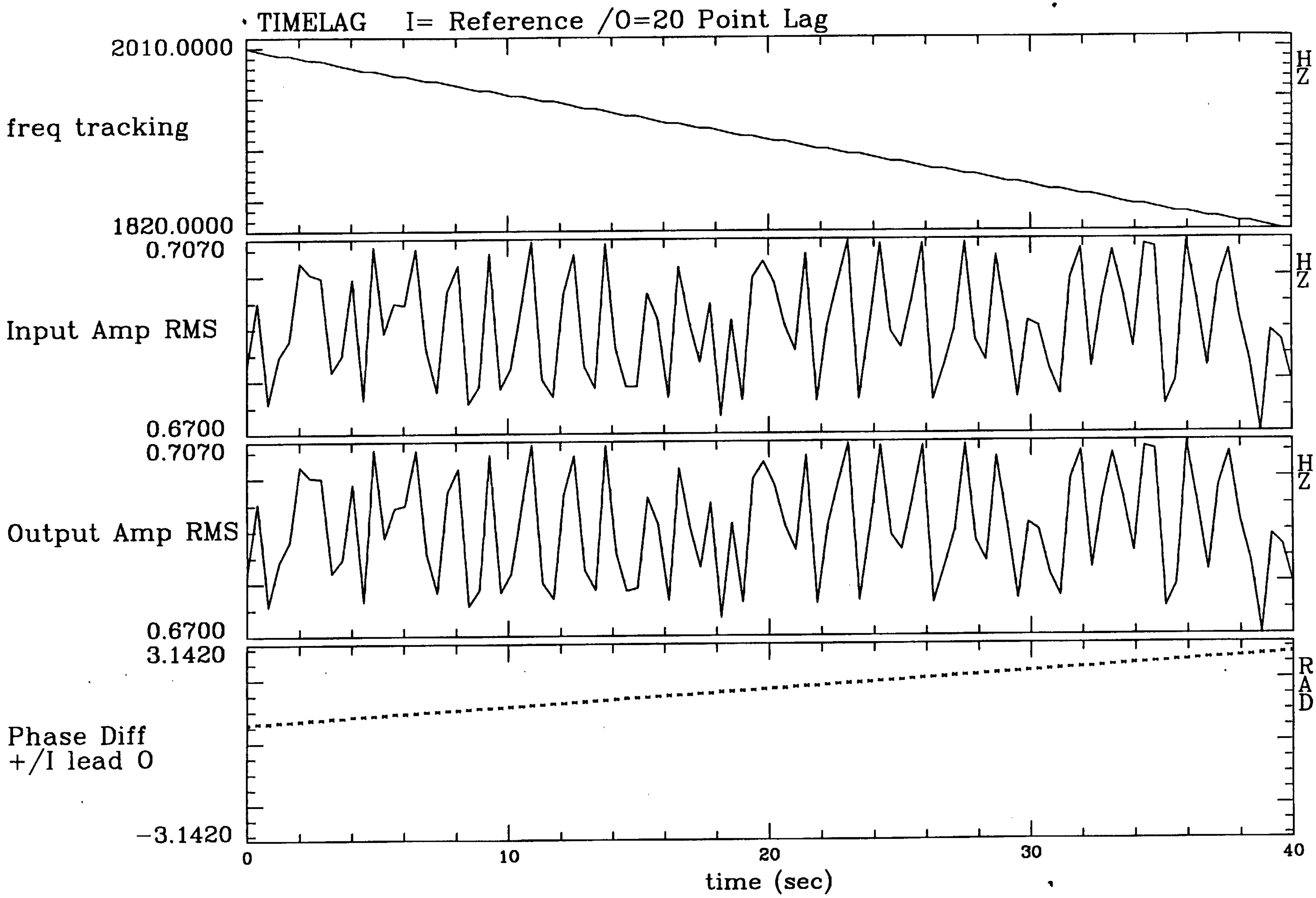
HZ
0.7070
Output Amp RMS
0.6700
HZ
3.1420
Phase Diff
+/I lead O
-3.1420
RAD
0
10
20
30
40
time (sec)

Fig-4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Input Amp RMS
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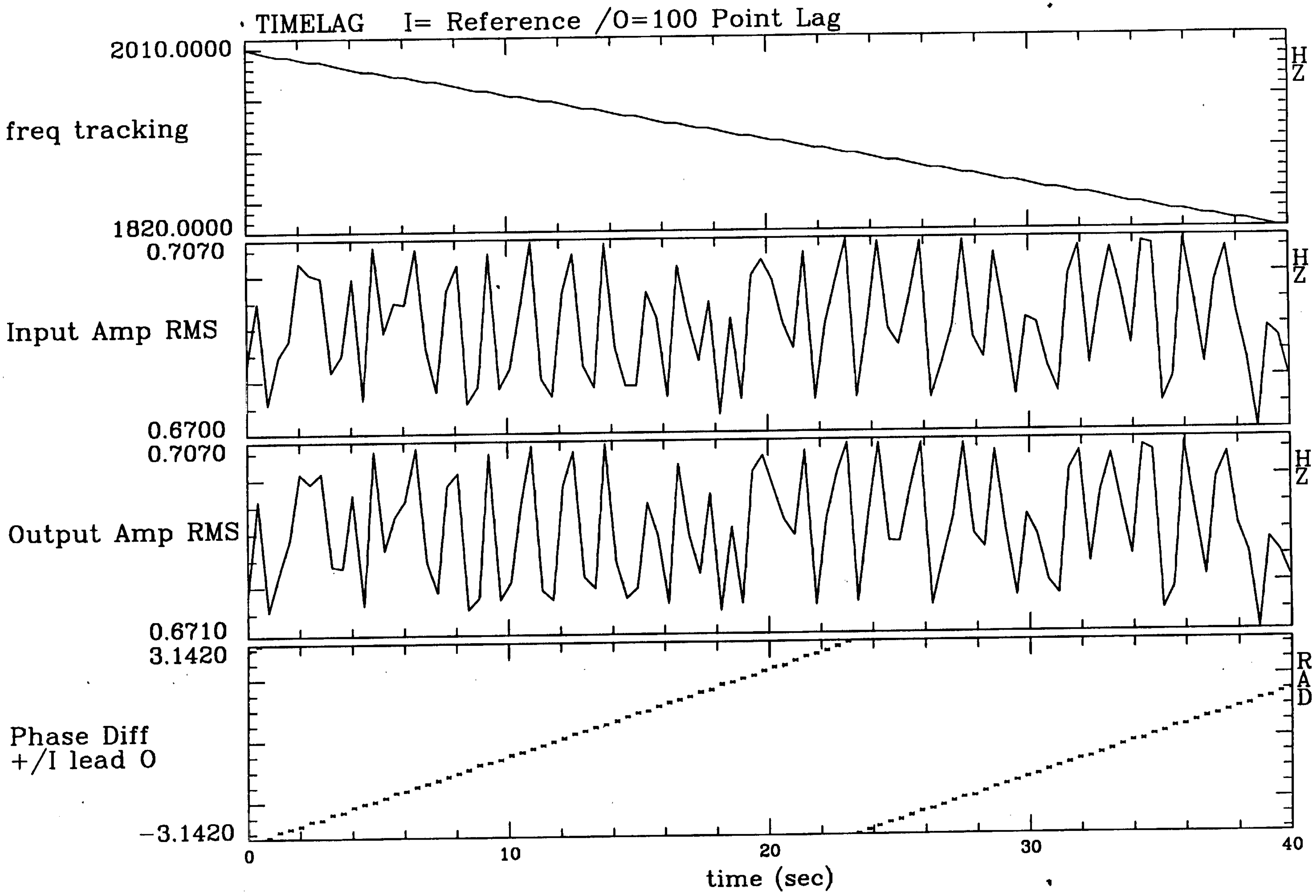
HZ
0.7070
Output Amp RMS
0.6700
HZ
3.1420
Phase Diff
+/I lead O
-3.1420
RAD
0
10
20
30
40
time (sec)

Fig-5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freq tracking
1820.0000
HZ
0.7070
Input Amp RMS
0.6700
HZ
0.7070
Output Amp RMS
0.6710
HZ
3.1420
Phase Diff
+/I lead O
-3.1420
RAD
0
10
20
30
40
time (sec)

Fig -6

BW= 4.999 AFD21-719/0A XB03 12/23/93
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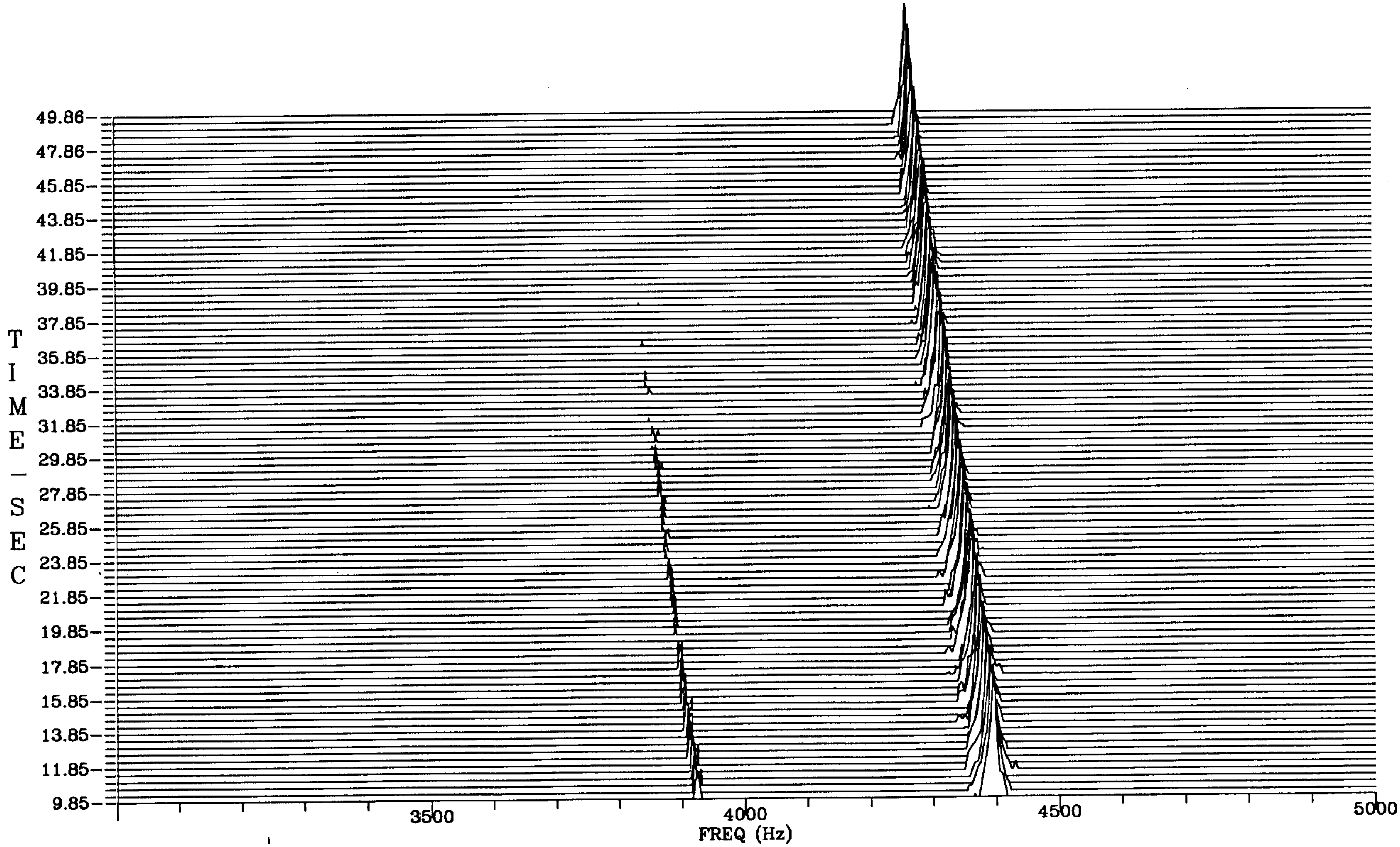
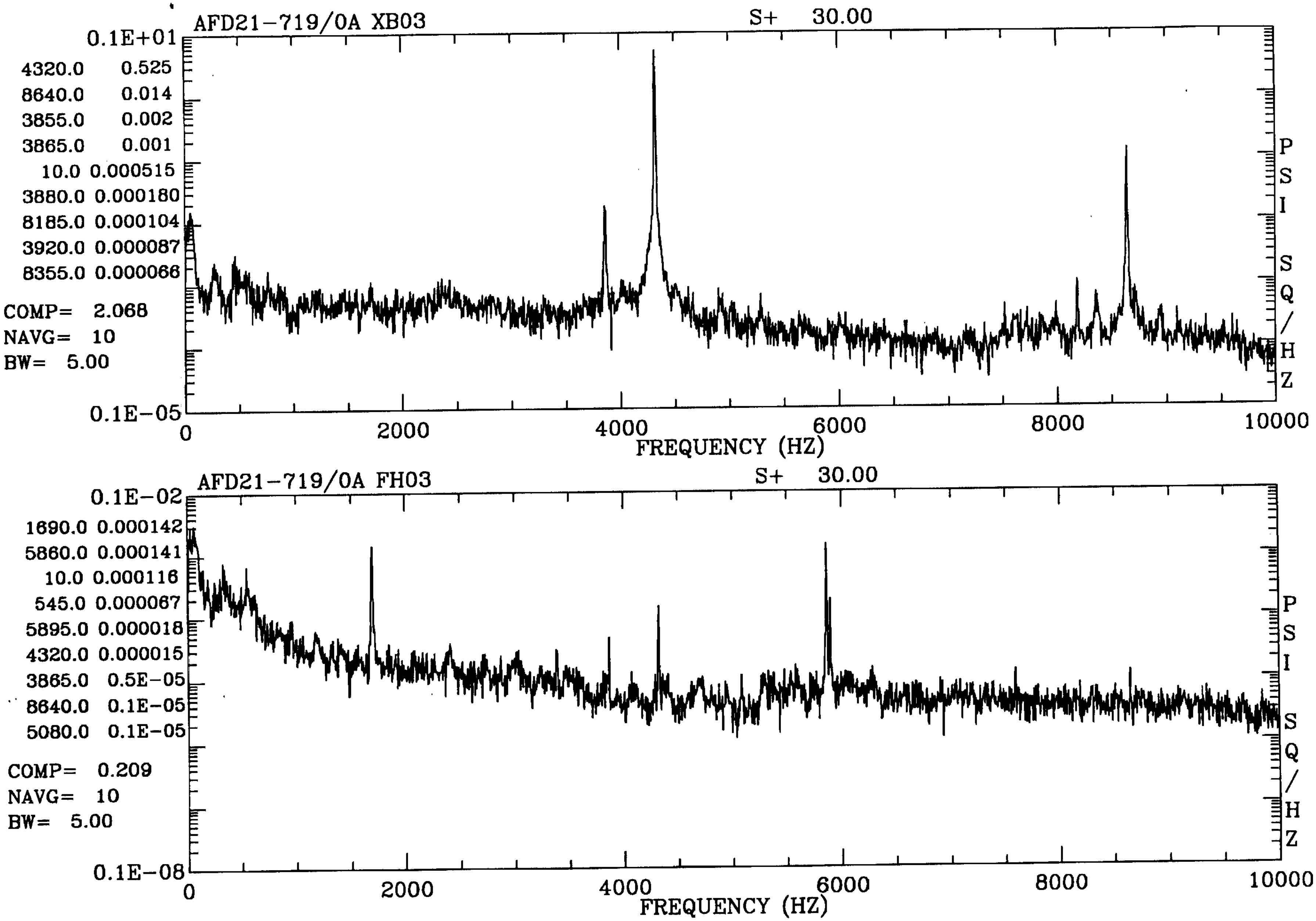


Fig 7a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8355.0 0.000066
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NAVG= 10
BW= 5.00
0.1E-05
0
2000
4000
6000
8000
10000
FREQUENCY (HZ)
PSI SQ/HZ
AFD21-719/0A FH03
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NAVG= 10
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2000
4000
6000
8000
10000
FREQUENCY (HZ)
PSI SQ/HZ

Fig F6

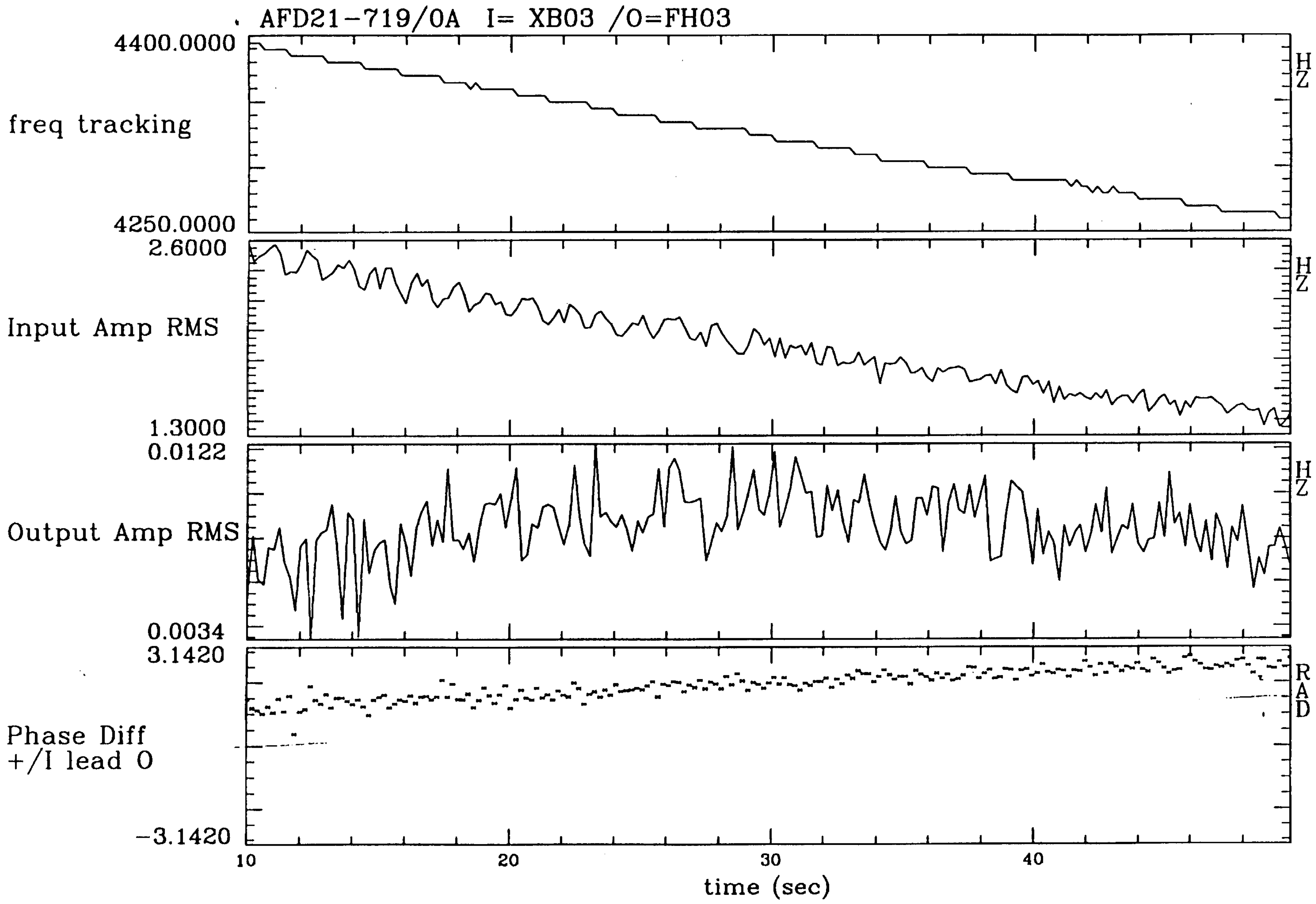

Fig 8

$$\frac{d\phi}{dt} = +\frac{1.5^r}{40s} = +0.038^r/s$$

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
December 31, 1993

3. REPORT TYPE AND DATES COVERED
Monthly Report/December 1993

4. TITLE AND SUBTITLE
Develop Advanced Nonlinear Signal
Analysis Topographical Mapping System

5. FUNDING NUMBERS
NAS8-39393

6. AUTHOR(S)
Jen-Yi, Jong

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER
TR-4002-93-12

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Procurement Office, AP29-I
George C. Marshall Space Flight Center
NASA
Marshall Space Flight Center, AL 35812

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

As reported in the monthly technical progress report for July 1993, a new signal analysis technique called "Instantaneous Frequency Correlation (IFC)" for time delay estimation was developed which will be incorporated into the ATMS system. In this report, a different technique for time delay estimation called "Phase Difference Time Derivative Estimator (FDTDE)" will be discussed. The FDTDE technique does not replace the IFC method since their application conditions are different. The IFC technique can estimate the time delay between two spectral components of two measurement signals when the center frequency of the component are constant. While the FDTDE method can provide accurate time delay estimation when the frequency of the subject component changes linearly such as during engine startup or shut-down.

14. SUBJECT TERMS

15. NUMBER OF PAGES
14

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT

18. SECURITY CLASSIFICATION OF THIS PAGE

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT