AFFDL-TR-70-76

OPTICAL DATA PROCESSING STUDY

DR. DENIS HANKINS

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OPTICAL DATA PROCESSING STUDY

DR. DENIS HANKINS

TRW SYSTEMS GROUP

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FOREWORD

This report was prepared by TRW, Inc., TRW Systems Group, Redondo Beach, California, for the Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, under contract F33615-70-C-1057. The contract was initiated under Project No. 8219, Stability and Control Investigations, Task No. 821903 Flight Control Data, administered by the AFFDL, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, Mr. N. V. Loving, (FDTE) Project Engineer.

This report covers work performed during the period 15 October 1969 to 28 April 1970. It was released by the author as TRW Report No. 14000-6006-T0-00 on 1 May 1970 and as a corrected final report on 15 July 1970. This effort was funded by the Air Force Flight Dynamics Laboratory Director's Fund.

This report benefited greatly from the assistance of Mr. G. E. Maddux of FDTR, Mr. E. H. Flinn of FDCC, Mr. C. E. Thomas of FDDS and Mr. W. P. Johnson of FDTE. Also, key technical information was provided by the Battelle-Northwest team of Dr. C. E. Elderkin and Mr. D. C. Powell who are performing FDTE-sponsored TOLCAT research.

Acknowledgement is made for the valuable assistance of Dr. D. Douthett and Dr. G. A. Bekey of TRW Systems Group.

This technical report has been reviewed and approved.

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ABSTRACT

An optical data processing study was performed to determine the value of the use of present day coherent optical processing techniques on selected AFFDL data processing problems. Optical, digital and analog implementation of Power Spectral Density, Cross Spectrum, Auto and Cross Correlation, Transfer Function, and Filtering (Convolution) were considered for a wide variety of input data: from low frequency Clear Air Turbulence (cycles/hour) to high frequency acoustic data (10 KHz).

A sample problem supplied by AFFDL was analyzed by in-house optical, digital and analog computers to demonstrate the degree of computational equivalence. Next a study of twelve processing areas at Flight Dynamics Laboratory was performed to uncover promising areas for Optical Processing. Although most requirements could be met all twelve users reported a dynamic range requirement 10 dB or more than that which is available in established optical processing technology. Areas in which optical processing shows advantages over digital processing, viz., two-dimensional Fourier transforms and high BT products were not desired nor within the current mission of the Laboratory.

Cost data for the three processing methods were generated. For large volume processing, the digital and optical implementations were found to be roughly equal and less than the cost of analog equipment for spectrum analysis. The digital method is found to be system cost effective in that once a special purpose Fast Fourier Transform (FFT) computer is purchased to generate power spectrum, the other functions can be calculated with negligible increase in cost.

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I. INTRODUCTION

The investigation of coherent optical processing techniques as applied to data processing problems within the Air Force Dynamics Laboratory is described in this report. The first step of the scheduled two phase study was to determine those processing areas in which cost-effective optical data processing could be applied to AFFDL requirements using present day technology. The second phase of the study would be to perform a System Analysis Study of the requirements identified in Phase I and to develop specifications for optical data processors to fulfill these needs.

The results of the Phase I effort indicate that use of present optical technology for AFFDL processing problems is not cost effective. Therefore no Phase II work was required nor performed. This Final Report then describes the Phase I results. System specifications for the various methods of implementation of the required processing functions are included as necessary for performance comparison.

To resolve the question of the value of optical data processing to the Flight Dynamics Laboratory, the work was divided into three task areas. First a sample problem was selected and supplied by AFFDL. This was solved by digital, analog and coherent optical processing methods to demonstrate the equivalence of these processing techniques. Task 2 pertained to the study of the Laboratory's data processing problems to determine those areas which are susceptible to optical data processing. Emphasis was placed on those areas in which optical data processing could be realistically applied using today's technology. Finally a cost effectiveness analysis was conducted on optical, analog and digital computing techniques in spectrum analysis, the processing area found most desirable under Task 2.

II. SUMMARY

This section describes the three task areas of the Phase I study effort and briefly highlights the results. Sections III, IV, and V give the detailed results of the study.

2.1 Task 1 - Sample Problem Analysis

This task, to process the AFFDL selected problem by digital, analog and coherent optical processing methods, showed the equivalence of the three processing methods. The sample problem was spectrum analyzed by each method. Three sinusoids at 200, 350 and 866 Hz in the input band 100-1000 Hz were determined.

Power Spectral Densities (PSD) were generated for two types of analyses. The first type was for 1000 spectral resolution elements per decade or equivalently a 1-Hz filter resolution analysis. The second type, a 250 resolution element (or 4-Hz) spectrum analysis, was run to correct a TRW error in the specification of the recording speed in which AFFDL was to record the sample problem.

These analyses demonstrated the equivalence of the three processing methods. In addition, the digital analyses were run with input dynamic range values of 24, 30, and 66 dB. This test proved that optical and digital processing at the lower dynamic range values are equivalent and will at least for the sample input problem, detect all signals. As made evident in paragraph 4.2.1, this conclusion is not valid for Take-Off and Landing Clear Air Turbulence (TOLCAT) data.

2.2 Task 2 - Identification and Classification of AFFDL Processing Problems

TRW studied the AFFDL data processing problems to identify characteristics and areas which might be susceptible to optical data processing problems. Emphasis was placed upon Clear Air Turbulence (CAT) problems, particularly TOLCAT, and researchers in these areas were interviewed and their reports, recommendations, and pertinent technical literature were studied. In addition, a questionnaire was circulated throughout the Laboratory. The respondees were FDTE (TOLCAT), FDDS, FDCC, FDFM, FDFE, FDFS, FDTS, and FDCS.

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The survey indicates that the processing most attractive to implement with optical techniques is that of power spectral density analysis. Large volume, high throughput rate processing is a key factor in the study. Users requiring the spectrum analysis of many channels of data on a daily basis would benefit by the fact that optical spectrum analyzers are capable of space-bandwidth products of sufficient magnitude to allow up to 100 channels of simultaneous processing. The nature of the data however presents a limited number of parallel channels that can be processed at the same time (analog tape recorders usually have only 7 to 14 channels of analog signals). Even with the optical computer operating substantially below the capacity of an optical transform lens, economies can be realized by this processing method.

On the other hand optical processing as it is known today has a limited input dynamic range with photographic film as the input recording medium.

The minimum input dynamic range for all groups responding to our survey was 40 dB, with a maximum of 75-80 dB. The maximum available dynamic range in optical processors available today is 20-30 dB. Dynamic range available in digital processing is from 60-90 dB depending on the number of analog-to-digital conversion bits. Analog spectrum analyzers are available with input dynamic range greater than 60 dB.

Other processing functions required at the Laboratory were found to be unsuited to optical techniques for reasons in addition to the dynamic range limitation. Time domain optical correlators compute the square of the correlation function. Without phase information, subsequent processing cannot determine the cross spectrum or transfer function.

The other method to optically implement cross-correlations (and cross-spectrum and transfer functions) requires the use of complex spatial filtering. Complex spatial filters require very tight optical alignment tolerances. High volume, high throughput rates would require a considerable effort to obtain. While optical correlators are useful for energy detection problems such as radar and matched filtering and two-dimensional problems in image enhancement, high volume processing of cross-correlation, cross spectrum or transfer functions are unlikely candidates for present day optical technology.

In defense of optical processing, areas in which optical techniques have their greatest advantage were not desired by the Laboratory. The BT products required come within a small fraction of that which is available by optical methods. Two dimensional Fourier analysis was not required and the number of one-dimensional channels to be analyzed simultaneously was about 1/10 capacity of an optical system.

Regarding TOLCAT, we find that digital processing becomes less expensive than optical processing as the input band lowers in frequency. This points to digital processing being less expensive than optical processing of turbulence data.

2.3 Task 3 - Cost Effectiveness Study

Optical processing of all the requirements studied under Task 2 were found to be lacking in at least one performance criteria. The spectrum analysis (PSD) computation was found to be deficient in only one area, viz., dynamic range. A cost performance study was performed for power spectrum analysis of 32 channels of data.

The results of this study reveal that there is no significant difference in cost between digital and optical processing for any of the PSD functions specified. The main difference is that while an optical processor can generate PSD, each additional function required (cross spectrum, transfer function, etc.) would require an additional (separate) optical computer to implement each function if it were feasible to do so. The digital Fast Fourier Transform (FFT) processor on the other hand, if purchased with a small general purpose computer can implement all the functions with the same equipment -- provided that one purchases one of the FFT processors that provides complex Fourier amplitudes as output. Under these conditions, FFT processing is highly cost effective over optical processing.

Digital processing is also cost effective over analog processing if large quantities of data are to be processed. Analog equipment purchase is generally lower, but the elapsed time required to perform the computations raises the total processing cost.

III. SAMPLE PROBLEM ANALYSIS

3.1 Description of Problem

Task 1 was to demonstrate the equivalence of optical, digital and analog methods of spectrum analysis computations on a sample problem defined and recorded by the Flight Dynamics Laboratory.

The data was recorded on 1/4 inch AM tape. To guarantee low aliasing errors in the digital analysis, the data was conditioned by 6-pole electronic filters limiting the data content to the decade 100-1000 Hz. The data was recorded in 6 segments, each of about 5 seconds duration and the beginning and end of the record contained a 500 Hz calibration signal corresponding to 1 volt rms. The data was specified by TRW to be recorded at 15 ips.

The optical processing subsystem which converts the analog signal to the photographic film mask for this study accepts data recorded at 15 ips and generates the film mask with a film transport velocity of 7.5 ips. With a 50 mm optical aperture the Fourier Transform time T in the optical window is

$$T = \frac{50}{7.5 \times 25.4} \cong 0.25 \text{ second}$$

The frequency resolution for the optically synthesized filters is given by $\Delta f \approx 1/T$ (as is the case for the digitally synthesized filter resolution); the 0.25 second window would yield a 4-Hz analysis or, equivalently, yield 250 spectral resolution elements in the 1000 Hz input frequency band.

In assessing the data processing problems prevalent at FDL, it is apparent that a 1-Hz (or T = 1 second in the optical window) frequency resolution is required. We re-recorded the data at 1/4 speed - 3 3/4 ips - to accomplish this finer resolution spectrum analysis. The re-recorded data played into the film subsystem would yield one second of data in the 50 mm optical aperture.

To compare the three processing techniques, we performed the following:

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Analysis of Original Recording at 15 ips	Analysis of Re-recorded Data at 3 3/4 ips
a) 1-Hz digital (Figure 1)	e) 1-Hz digital (Figure 4)
b) 4-Hz digital (Figure 2)	f) 1-Hz optical (Figure 5)
c) 4-Hz optical (Figure 3)	
d) 1-Hz analog (Figure 6)	

As mentioned above, the test tape contained 8 data records and calibration signals. The results in Figures 1 through 6 were computed on Record 2 and revealed sinusoids at 200, 350, and 866 Hz. It was found that the 1 Hz frequency resolution analysis was indeed needed to provide sufficient signal-to-noise gain to clearly detect the smallest sine wave at 866 Hz.

3.2 Results of Analysis Demonstration

Comparison of Figure 1 with Figure 2 shows, using the same digital FFT algorithm, the effect of broadening the filter resolution in the analysis of Record 2. Notice that although the 200 and 350 Hz signals are detectable, the 866 Hz signal is now down in the noise floor and in fact is less in magnitude than peak noise excursions (False Alarms) in the vicinity of 660 Hz. The loss of the small signal is explained by the fact that broadening the filter resolution from 1 Hz to 4 Hz resolution results in a processing loss of approximately 6 dB.

Comparison of Figure 3 with Figure 2 illustrates that the optical and digital computations are nearly identical. The optical and digital output spectra reflect the loss of the 866 Hz signal due to the 6 dB processing loss for both analyses. It is noticeable that the optical analysis has more processing noise in the 100-200 Hz region (this is leakage from d.c. noise). On the other hand there appears to be less noise in the mid-frequency region in the optical output plots. This latter fact would indicate that it would be desirable to increase the minimum spatial dimension in the optical frequency plane that corresponds to 100 Hz.

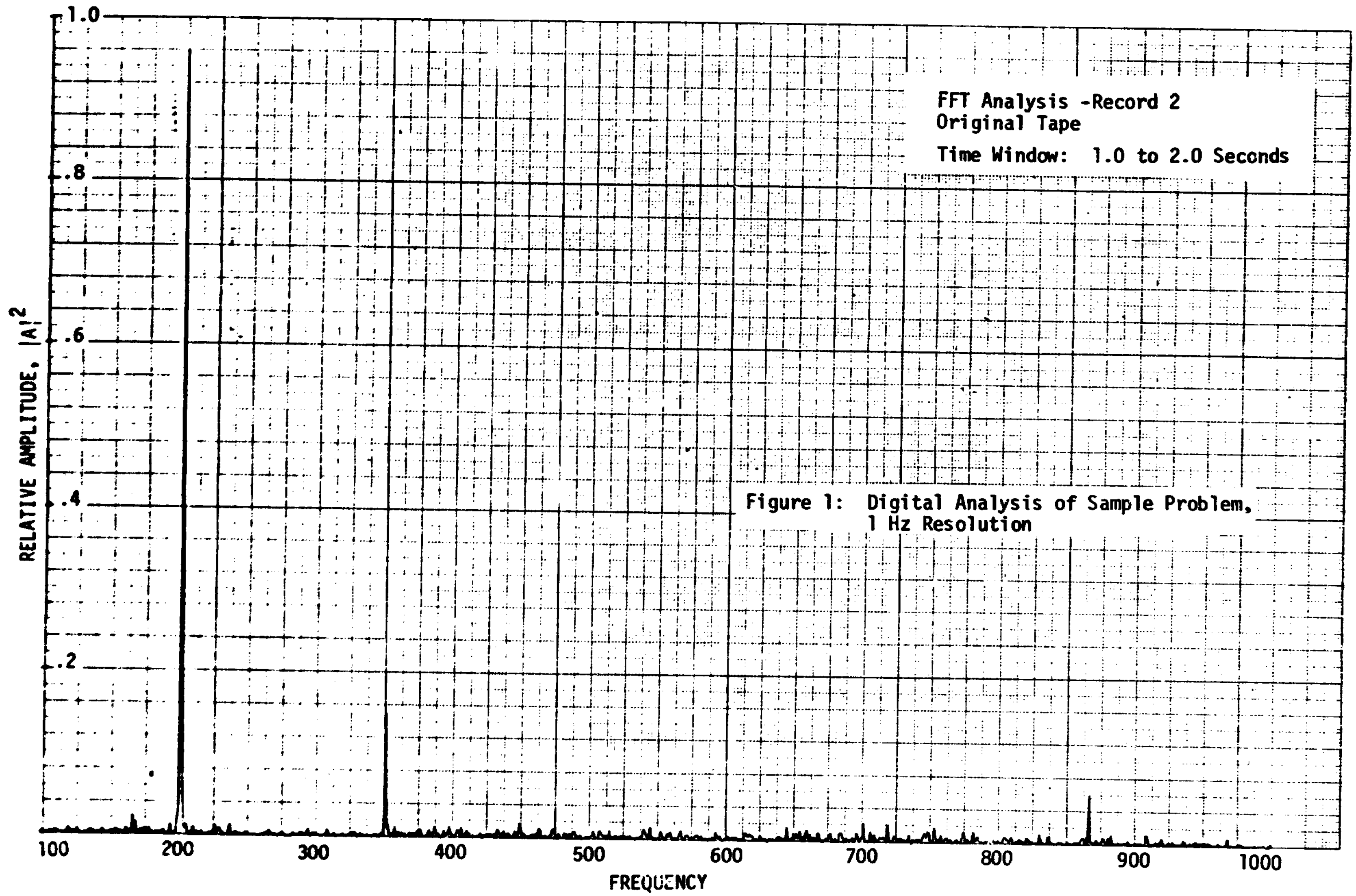

Figure 1: Digital Analysis of Sample Problem, 1 Hz Resolution

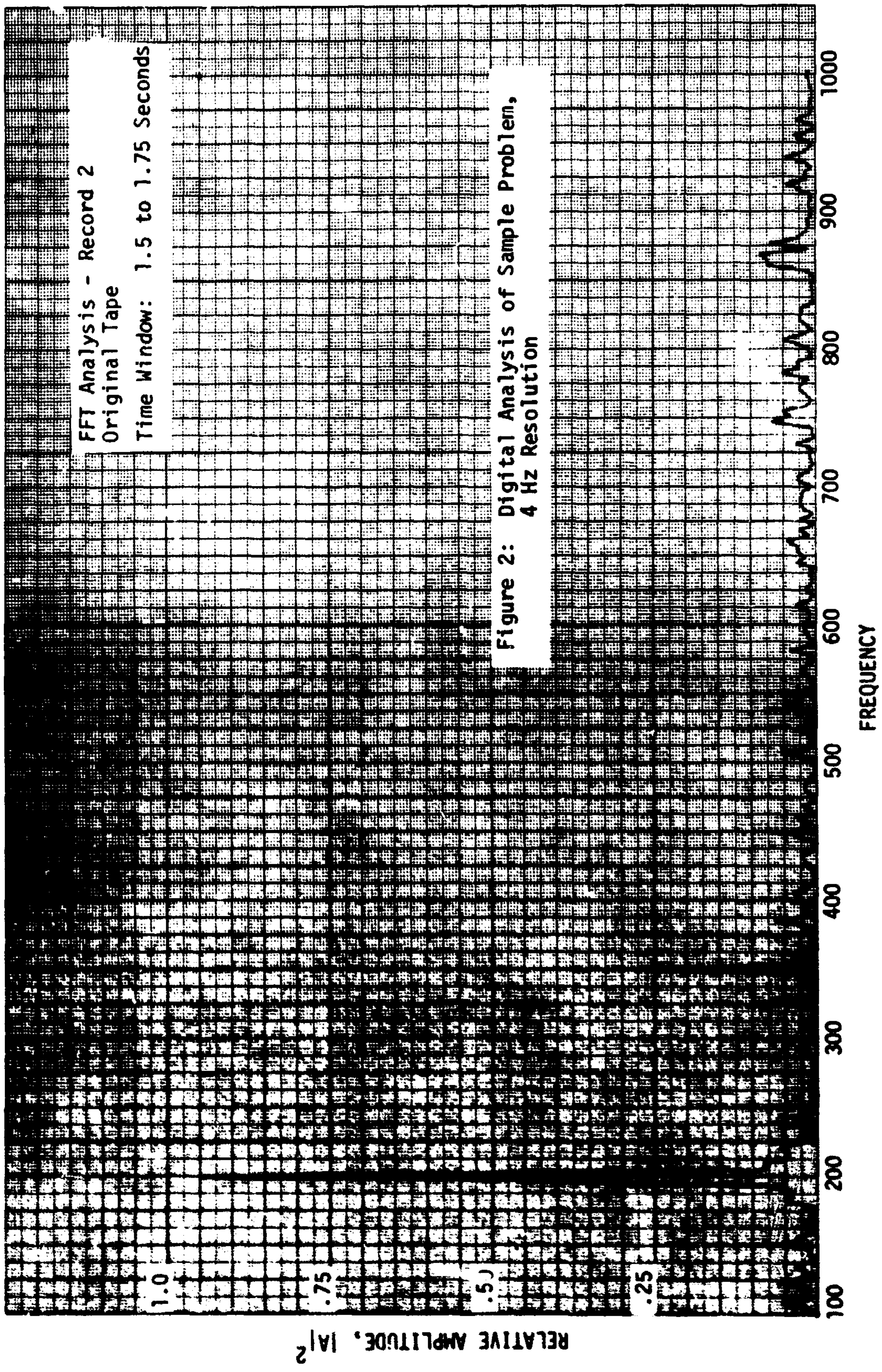

Figure 2: Digital Analysis of Sample Problem, 4 Hz Resolution

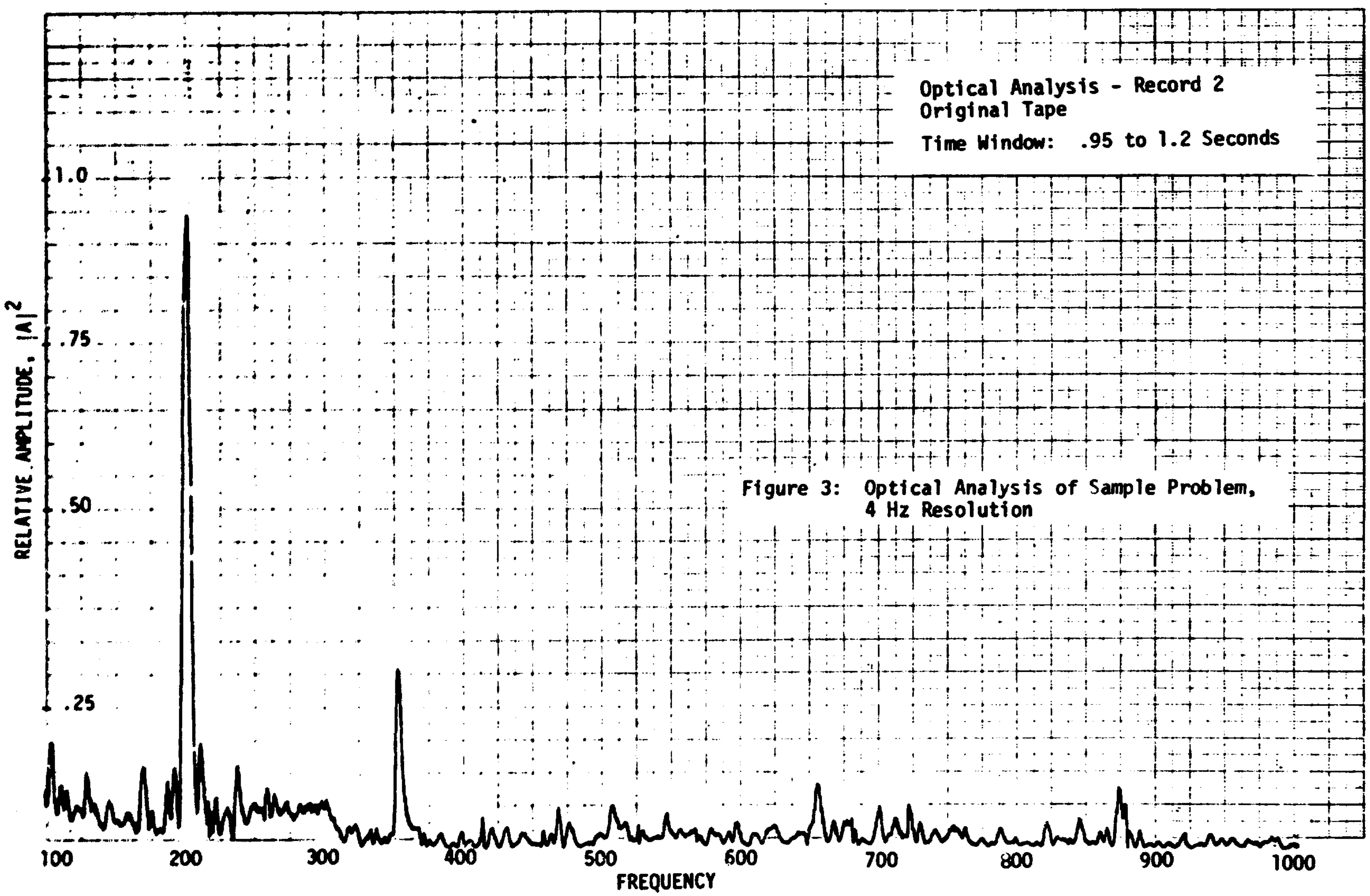

Figure 3: Optical Analysis of Sample Problem, 4 Hz Resolution

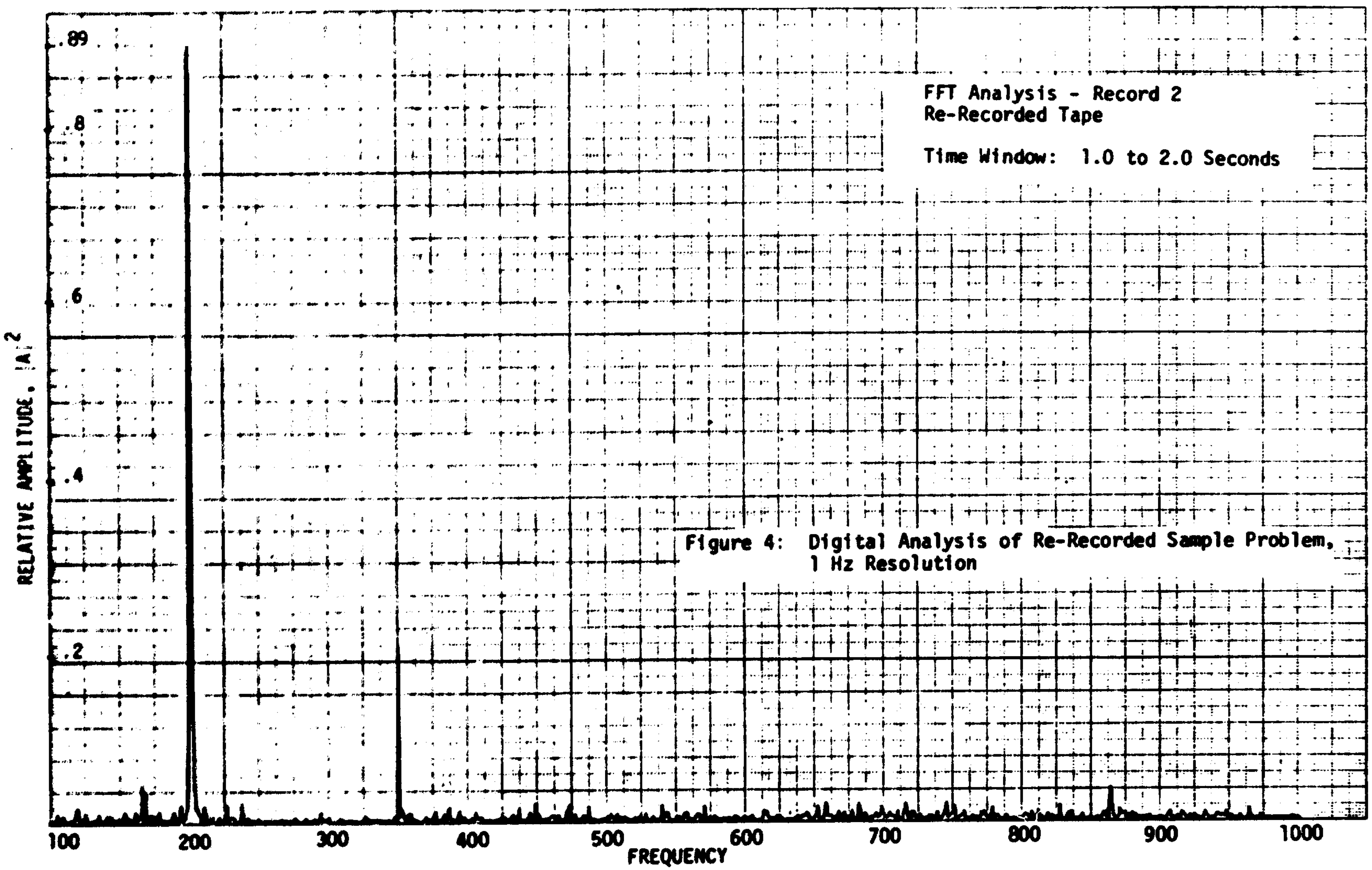

Figure 4: Digital Analysis of Re-Recorded Sample Problem, 1 Hz Resolution

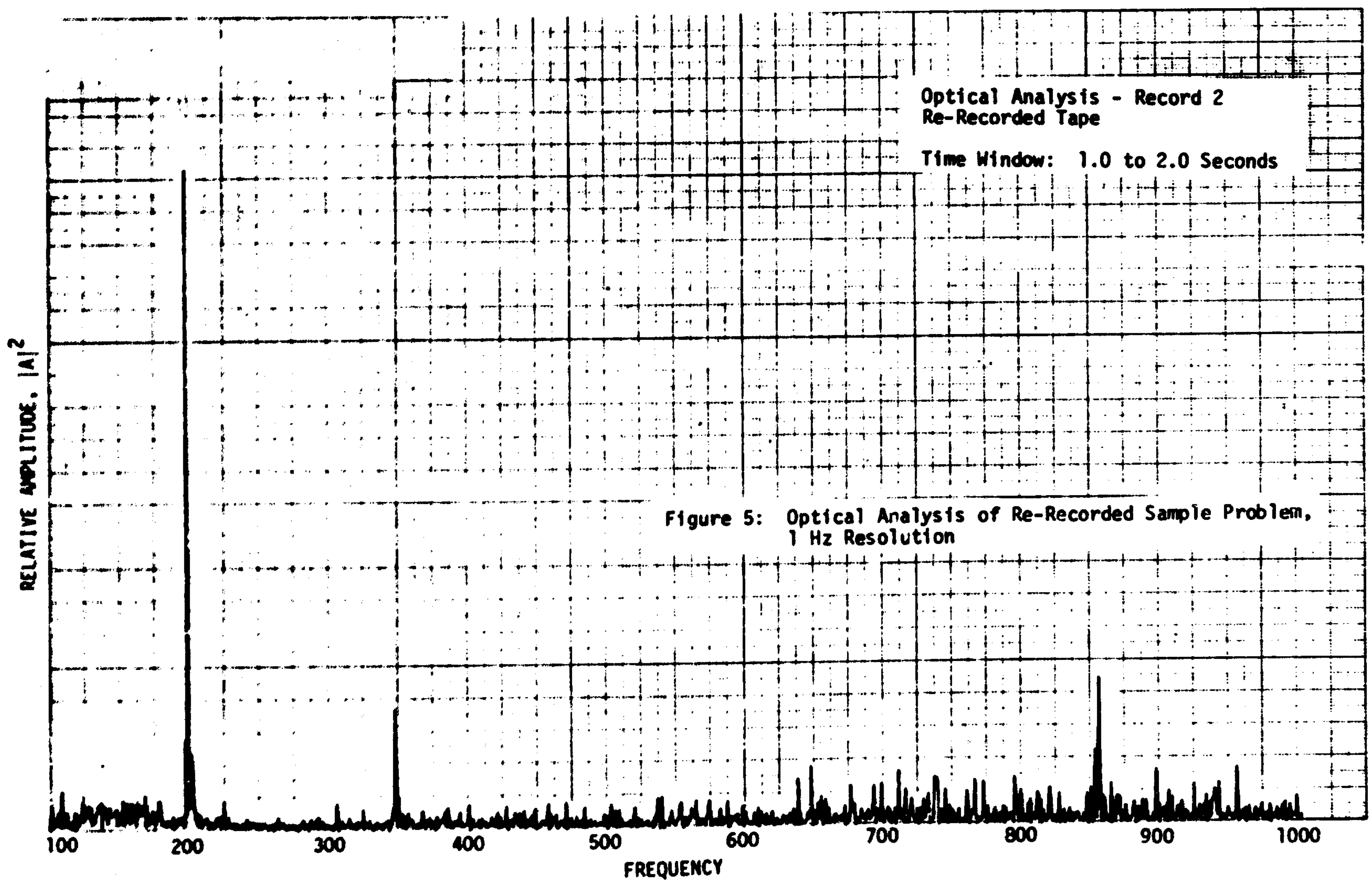

Figure 5: Optical Analysis of Re-Recorded Sample Problem, 1 Hz Resolution

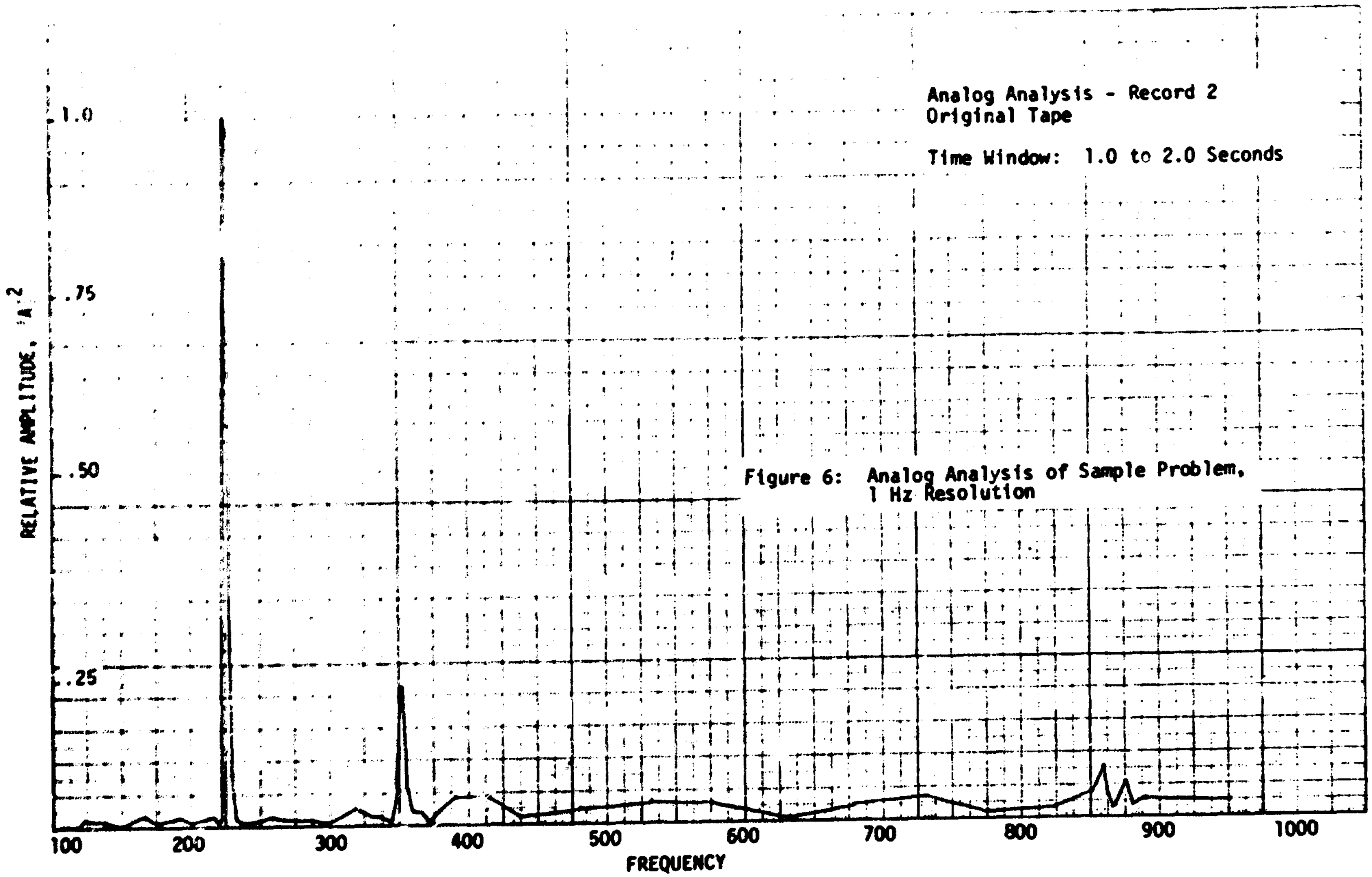

Figure 6: Analog Analysis of Sample Problem, 1 Hz Resolution

A comparison of a digital 1 Hz analysis on the original and a digital 1 Hz analysis on the re-recorded data is shown in Figures 1 and 4. Notice in Figure 4 that the noise background is slightly higher due to the second recording. The optical computation of the second recording in Figure 5 shows a good comparison with the digital computation of Figure 4, except for a gain factor at high frequencies. As explained in progress report no. 3 the optical results for the re-recorded input require recalibration in amplitude to adjust for the high-frequency emphasis in the film generating equipment.

Additional computations were made in the digital analyses to test for dynamic range required. Although it was found that the same results could be arrived at with input dynamic range of 24, 30, or 66 dB input dynamic range, it is felt that this was true because the test tape was not designed to reveal inaccuracies due to limited dynamic range.

The digital dynamic range tests were performed similarly to that which was performed by the Battelle Researchers on TOLCAT data, described in paragraph 4.2.1.

In summary, we conclude that digital, optical and analog spectrum analysis extracted essentially identical information from the test problem supplied to us.

IV. IDENTIFICATION AND CLASSIFICATION OF AFFDL DATA PROCESSING PROBLEMS

4.1 AFFDL Processing Requirements

4.1.1 Study Inputs

The processing requirements at AFFDL are summarized in Table I. These data represent the response to a questionnaire circulated throughout the Laboratory. Also included in this table are data concerning the FDTE-sponsored TOLCAT research, which was obtained by discussions with Dr. Charles E. Elderkin and Mr. David C. Powell at Battelle Northwest, Richland, Washington. The general headings in Table I are treated individually in the following six subparagraphs.

4.1.2 Mathematical Techniques Used

Almost all users indicate needs to calculate autocorrelations, cross correlations, power spectra (PSD), and cross power spectra. Convolutions, phase spectrum and transfer function analysis are all derived from the above with negligible effort. Two-dimensional Fourier analyses such as bispectra were not requested.

Part I of the questionnaire points out that one-dimensional multi-channel analysis capability for auto and cross correlation and PSD and cross power spectra* are a required baseline for the trade-off study. Low volume processing can best be performed with existing equipment.

4.1.3 Data Input Format

As only two users require a real time analysis, the data processing baseline will be considered mainly to operate on recorded data, both digital and analog. However, one of the key parameters in the trade-off will be the capability to analyze at a rate commensurate to that in which the data was acquired. If cost does not prohibit, data backlog will be avoided.

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* Hereafter, these functions may be referred to as the "4 baseline functions."

4.1.4 Data Input Band

One of the conclusions of this Task 2 study of AFFDL processing areas is that the low frequency data must be digitized at some time prior to processing of the "four baseline functions." This conclusion is supported by the fact that a wide variety of data input bands are required throughout the Laboratory. Attempts for equipment standardization would point to a desirability of all processing to be performed on digitized data.

For optical processors to operate on analog data, the input frequency must be greater than about 10 Hz to avoid D.C. noise.* Digitization of the data allows "real time" to be removed from the data. Higher frequency input frequency bands can be presented to the optical processor by reconstructing the data to analog form at a rate faster than the digitization rate. This technique has been used for both hybrid (Reference 1) and optical (Reference 2) processors.

4.1.5 Analysis Parameters

4.1.5.1 Dynamic Range

Dynamic range can be divided into two categories: those requiring 40 dB at the input and those requiring 60-80 dB dynamic range. Dynamic range is an important design limitation in optical processing. This parameter is treated in detail in paragraph 4.2.1.

4.1.5.2 Filter Response

A need for a flexible processor is evident here in that both a constant interval and logarithmically spaced (1/3 octave) power spectral density analysis is required. In addition, filter selectivity requirements vary from f^{-1} (unweighted Fourier transform) to shape factors of 2:1. The shape factor is the ratio of the filter width at the -60 dB point to the width at the -3 dB point. For 40 dB dynamic range systems, we will redefine the shape factor to be the ratio at -40 dB.

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* This is true for film recording at rates comparable to analog tape recording speeds (see paragraph 5.1.2.3).

TABLE I. AFFDL Processing Requirements

	FDTE	FDDS	FDDS	FDCC	FDFM
I. MATHEMATICAL TECHNIQUES USED					
1. Correlation	X	X	X		X
2. Cross-Correlation	X	X	X		X
3. Convolutions		X	X		
4. PSD	X	X	X		X
5. Cross Spectrum	X	X	X	X	X
6. Phase Spectrum	X				
7. Transfer Function		X	X	X	
8. Statistical Tests	X	X	X		X
a. Coherency	X				
b. Stationarity	X				
c. Amplitude Probability Density	X	X			
9. Bispectra		X			
II. DATA INPUT FORMAT					
1. Real time		X			
2. Playback	X	X	X	X	X
3. Digital	X	X	X		
4. Analog	X	X	X	X	X
III. DATA INPUT BAND					
1st Frequency Interval (Hz)	.001-1	0-10		0-5	
2nd Frequency Interval (Hz)	1-10	10-100			
3rd Frequency Interval (Hz)		100-1000			
4th Frequency Interval (KHz)		1-10 KHz	0-4 KHz		0-10 KHz
IV. ANALYSIS PARAMETERS					
1. BT Product	2000-4000	1000	60	450	100-500
2. Dynamic Range (dB)	40	75	40	60	60
3. Filter Response (and spacing if not constant Δf)	f^{-1}	2.5:1	f^{-10}		2.5:1
4. Data Analysis Interval (Time)	800 sec	10 sec	8 sec	90 sec	.01-10 sec
5. Cost Per Analysis Interval		8 min, $20.	4 min	$3.-5.	
V. DATA PRECONDITIONING TECHNIQUES					
1. Amplitude Compensation		X	X		X
2. Phase (Interchannel) Compensation		X	X		X
3. Prewhitening				X	
4. Notch Filtering					
VI. COMPUTER NOW IN USE	Univac 1108	G.R.1921 H'Well 1950	7094	7094	7094

FDFM	FDFM	FDFM	FDFE	FDFM	FDTS	FDDS	FDFE	FDCS
X	X	X	X	X		X	X	X
X	X	X		X			X	
		X	X	X			X	
X	X	X	X	X			X	
X	X	X		X		X	X	
				X			X	
		X	X	X			X	X
X	X		X					X
	X			REQUIREMENTS NOT DEFINED	REQUIREMENTS NOT DEFINED AS YET	REQUIREMENTS NOT DEFINED	X	
X							X X	X
X							X X	X
0-10 KHz	0-100 0-1000	0-100	5-300 300-1000 1-5 KHz				0-500 0-1000 0-2000 1-10 KHz	REQUIREMENTS NOT DEFINED AS YET
100-500 60		100 (Unknown)	60/120/240 40				Sine sweep/100/100/50 70-80	
2.5:1		(Unknown)	1/3 Oct.Spacing				2:1	
.01-10 sec	5 sec	20 sec (Unknown)	15/15/45 sec $4,4,12				22 min/ 30/30/30 sec 90/day;60,30,30/day	
X X			X				X	
		X X	X				X X >30dB rejection @23% bandwidth	
7094	PAR 101, 102	7094	7094	7094	7094	7094	7094	7094

4.1.5.3 BT Product

BT product requirements indicate that 3500 for TOLCAT and 1000 for any of the others would be a suitable design goal. It might be pointed out here that this requirement is substantially below that which is available in optical processing.

4.1.5.4 Data Analysis Interval (Time)

This entry indicates the amount of data the processor must accommodate at one time. For instance a user might run 10 minutes of data at a filter resolution of 0.1 Hz (measured at the -3 dB points of the filter). Thus, his data analysis interval would be 10 minutes based on an average of 60 power spectra estimates calculated in contiguous 10 second inputs ($\Delta f \cong 1/T$).

4.1.5.5 Cost Per Analysis Interval

This data is used as a comparison factor in the cost effectiveness Task 3 part of this optical data processing study.

4.1.6 Data Preconditioning Techniques

There was no strong indication of a need for prewhitening or notch filtering. Amplitude and phase compensation is performed on data in which the transfer function of the system prior to data acquisition is known. Phase compensation is particularly important in cross correlation measurements.

The TOLCAT processing has some unique preconditioning requirements. The data is acquired for wind velocities in three directions which have to be orthagonalized and rotated along the mean wind direction. Standard statistical procedures are then followed. The TOLCAT data preconditioning technique firmly requires that the data be converted to digital format.

4.1.7 Present Computational Equipment

This data was required for the cost effectiveness study. It is seen that most users at Wright Field use a centralized digital computer processing facility with its associated time delays to obtain results. For low volume processing, this procedure is probably best left unchanged.

4.2 Critical Areas in Performance Requirements

This paragraph discusses the critical performance areas in optical processing as applied to the requirements at AFFDL.

4.2.1 Input Dynamic Range Requirements

Before discussing dynamic range requirements it is necessary to define dynamic range in terms common to digital, optical, and analog computer processing. As analog spectrum analysis is the classic method we will define optical and digital dynamic range in analog terms.

4.2.1.1 Analog Dynamic Range

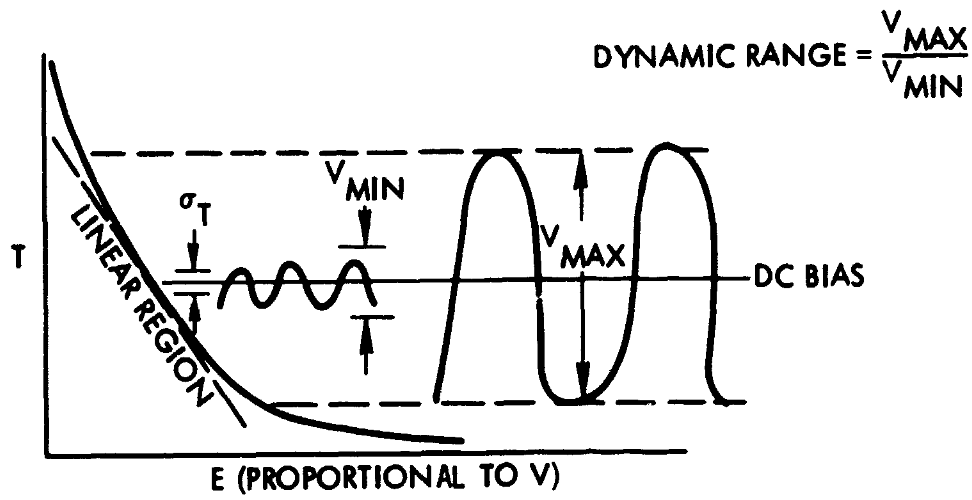
We define analog dynamic range (DR) as the ratio of the input voltages.

$$DR = V_{max}/V_{min} \tag{1}$$

where V_{max} is the amplitude of the full scale signal which is present at the input to the analog computer. A sinusoid with amplitude greater than V_{max} will be clipped or attenuated in some other way to render V_{max} as the full scale input. V_{min} is the minimum detectable signal present at the input.

4.2.1.2 Optical Input Dynamic Range

The analog signal(s) which are present at the input to an optical processor are converted onto a photographic film (see paragraph 5.1.3) having a transmission proportional to the spatial variation of the signal. This signal is written on the film signal mask by a laser writing beam which is governed by a device (Pockels Cell, for example) which modulates the writing beam as a function of the input voltage from the analog signal(s). The full scale analog signal which drives the modulator is adjusted such that the resulting film exposure lies on the linear region of the transmission vs. exposure energy curve of the photographic film. The dynamic range of this system then is shown pictorially as



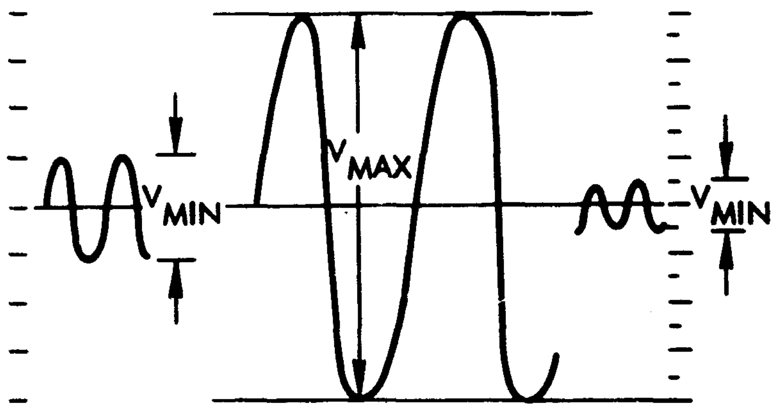
FILM DYNAMIC RANGE CONCEPT

V_{min} is the minimum signal measurably greater than the rms fluctuation in transmission, σ_T.

Typical values of dynamic range available on film range from 20 to 30 dB.

4.2.1.3 Digital Input Dynamic Range

The input transducer in a digital system is the analog-to-digital converter (ADC). For an n-bit converter $+V_{max}/2$ corresponds to all 1's, and $-V_{max}/2$ to all 0's in the ADC. V_{min} is that signal that can be detected at the least significant bit of the ADC. Pictorially, for a 3-bit (8-level) and a 4-bit (16-level) ADC we have



3-BIT ADC

$$DR = \frac{V_{MAX}}{V_{MIN}} \cong 4, \; (=12 \text{ dB})$$

4-BIT ADC

$$DR = \frac{V_{MAX}}{V_{MIN}} \cong 8, \; (=18 \text{ dB})$$

ADC DYNAMIC RANGE

Thus for the 3-bit ADC we have $20 \log_{10}(4) = 12$ dB, and for the 4-bit ADC we have $20 \log_{10}(8) = 18$ dB. In general we have the dynamic range relation for the n-bit ADC to be approximately

$$DR \doteq 6(n - 1) \text{ dB} \qquad (2)$$

where n = number of bits in the ADC.

Comparing (2) with that dynamic range available on film, it is seen that digital processing with a 5 or 6 bit ADC is equivalent to the dynamic range available in optical processing.

4.2.1.4 <u>Results of Investigation of Battelle Dynamic Range Requirement</u>

The survey of user requirements at FDL are summarized in Table I, paragraph 4.1. It is seen that the dynamic range requirements fall into two categories, viz., those requiring 40 dB at the input and those requiring 70-80 dB at the input. The Battelle Northwest research team in the TOLCAT area were at first uncertain of the requirement for their anemometer data. At that time they were using a digital data conversion of 12-bit resolution (66 dB) but stated that this dynamic range was chosen because it was the maximum available on their equipment.

To determine whether the use of optical processing with its upper limit of 30 dB dynamic range would yield to accurate results, a program to test for dynamic range was suggested.

The suggested plan was to perform all their standard processing (PSD, cross-correlation, cross spectra, phase spectra, etc.) on selected data with 12-bit input data. Using the same data they would then mask off the least significant bits to 42 dB (8-bits) and 30 dB (6-bits). With these two new sets of input data, they would calculate new PSD, correlation, etc. using the same computer program. Comparison would at least be a necessary (if not sufficient) condition to relax the input dynamic range to something less than 66 dB. The 42 dB dynamic range was chosen because the analog tape recorder at Battelle has a 40 dB dynamic range.

The Battelle team studied data under two conditions:

1. Moderately stable conditions, early afternoon in which the data sampling was taken at an elevation of 58 meters.
2. Unstable conditions with the mean wind about 4.5 meters/sec. at an elevation of 4 meters.

The input to the program has fixed point data of 12-bit resolution which we call case A:

Case A □□□□□□□□□□□□ 66 dB dynamic range

Power spectra, cross spectra, coherency and phase were generated from data input A. These results are plotted at the dotted lines in Figures 7 through 12. Next, input B was generated by a bit masking routine:

Case B □□□□□□□□ set to zero 42 dB dynamic range

The results from this bit masking routine are shown as the solid line in Figures 7 and 8. Finally, Case C input was generated from:

Case C ☐☐☐☐☐☐☐ | set to zero | 30 dB dynamic range

These results are compared with the 66 dB input dynamic range in Figures 9 through 12.

The results of these experiments indicate that while 40 dB input dynamic range may be adequate, at least for these limited tests, 30 dB is clearly inadequate, particularly in the phase spectrum results. Battelle researchers have indicated to us that they seriously doubt the validity of analysis based on a 30 dB dynamic range input.

The total processing requirement for TOLCAT data is given in paragraph 4.3.

4.2.2 Spectrum Analysis Filter Parameters

4.2.2.1 Requirements

In Table I, Part IV, Analysis Parameters, the twelve users at FDL responded to quite a variety of desired response characteristics for the band-pass filters used in spectrum analysis. It will be shown that both optical and digital processing can implement all these characteristics with the aid of a small, general purpose digital computer controlling the data input/output structure of an optical processor or a digital FFT processor acting as a "computer peripheral."

The filter characteristics required for all users can be specified in terms of selectivity (the sidelobe response of the band-pass filter) and the spacing between the center frequency of the adjacent band-pass filters in the spectrum analysis. The spacing and associated selectivity requirements are summarized below:

1. Constant bandwidth spacing → selectivity = f^{-3} or f^{-1}

2. 1/3 octave spacing → a. selectivity = f^{-10}
   b. shape factor = 2.5
   c. shape factor = 2.0

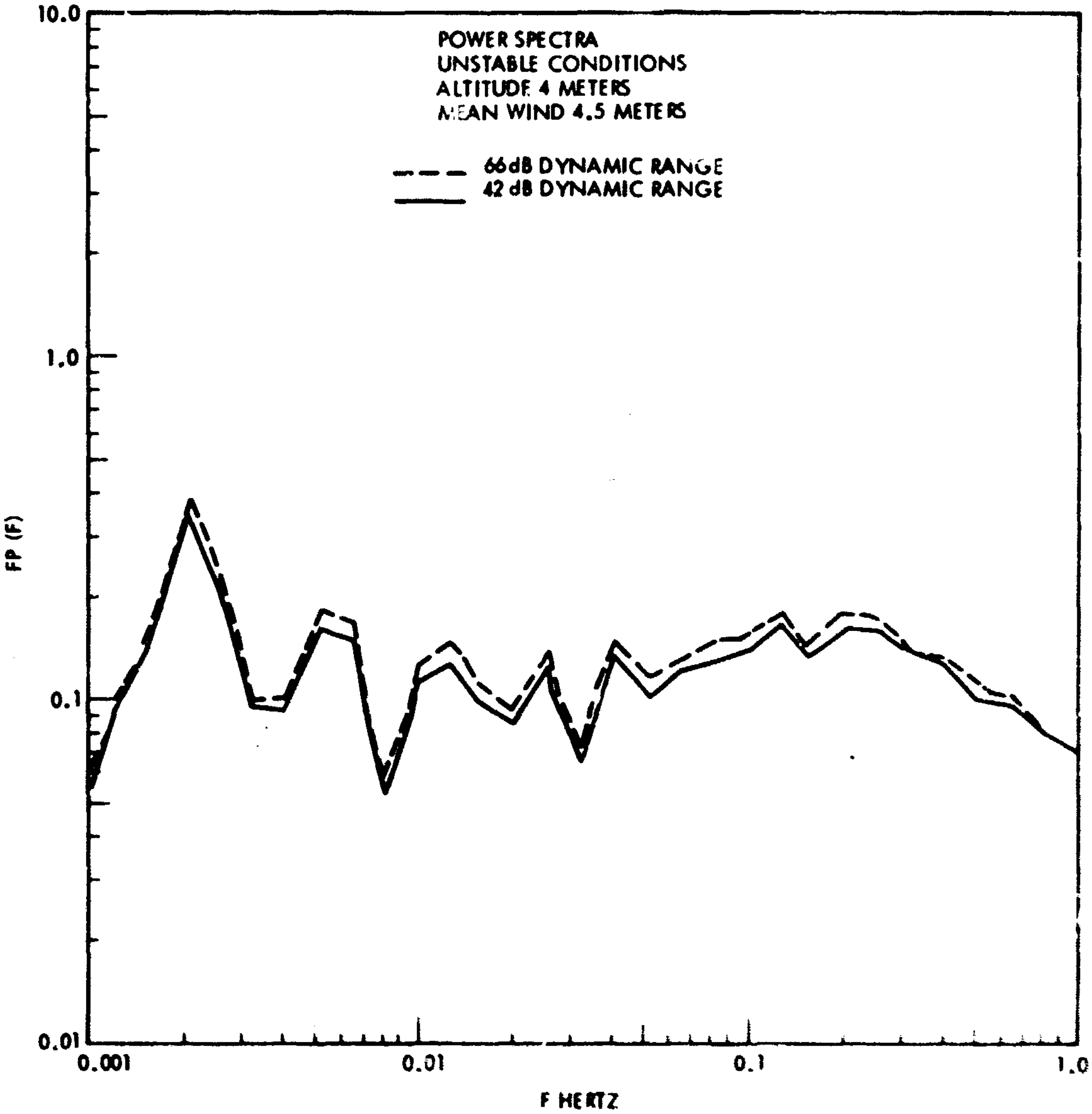


Figure 7. 40 dB Dynamic Range Test - Power Spectrum of Unstable TOLCAT Data

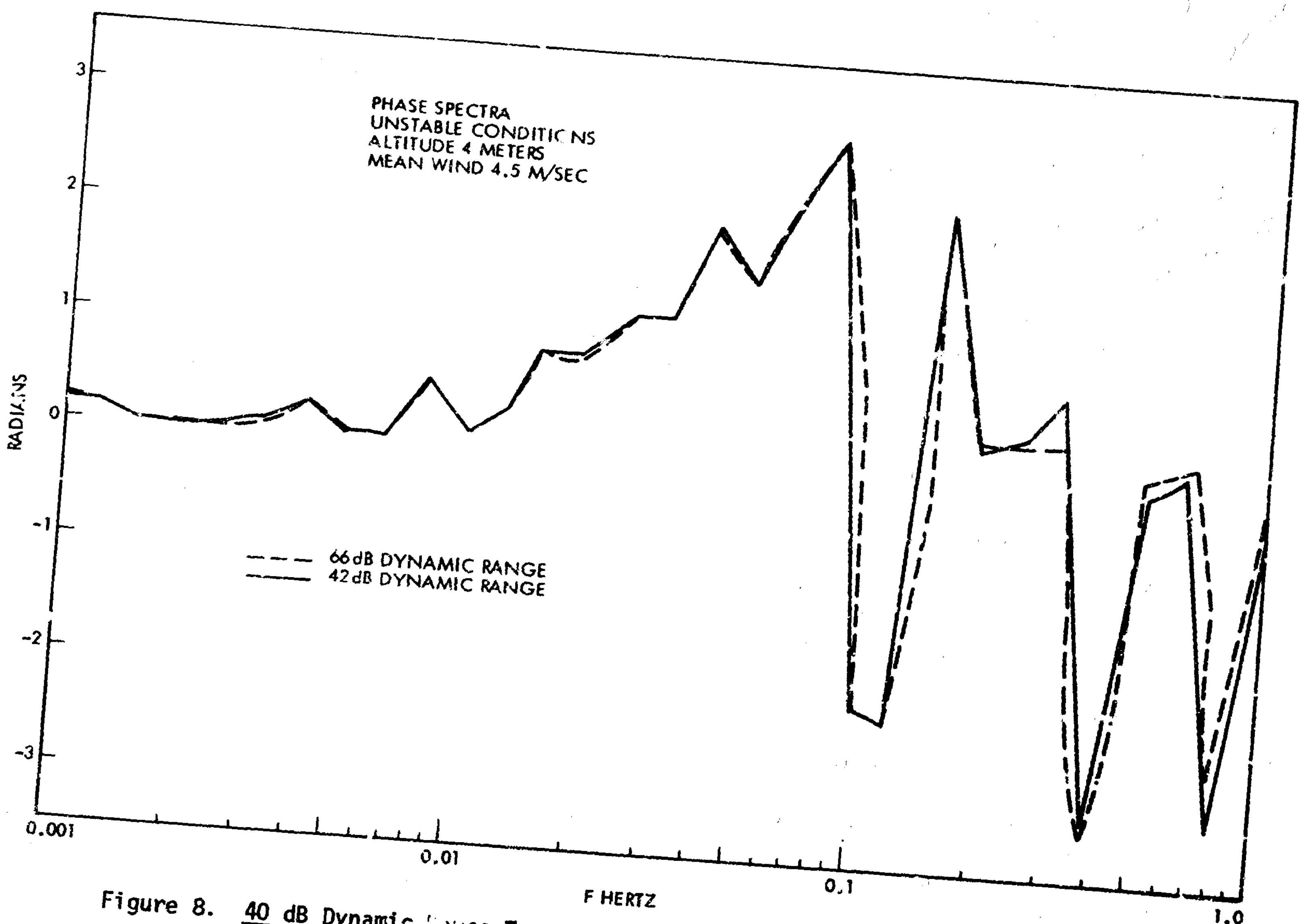


Figure 8. 40 dB Dynamic Range Test : Phase Spectrum of Unstable TOLCAT DATA

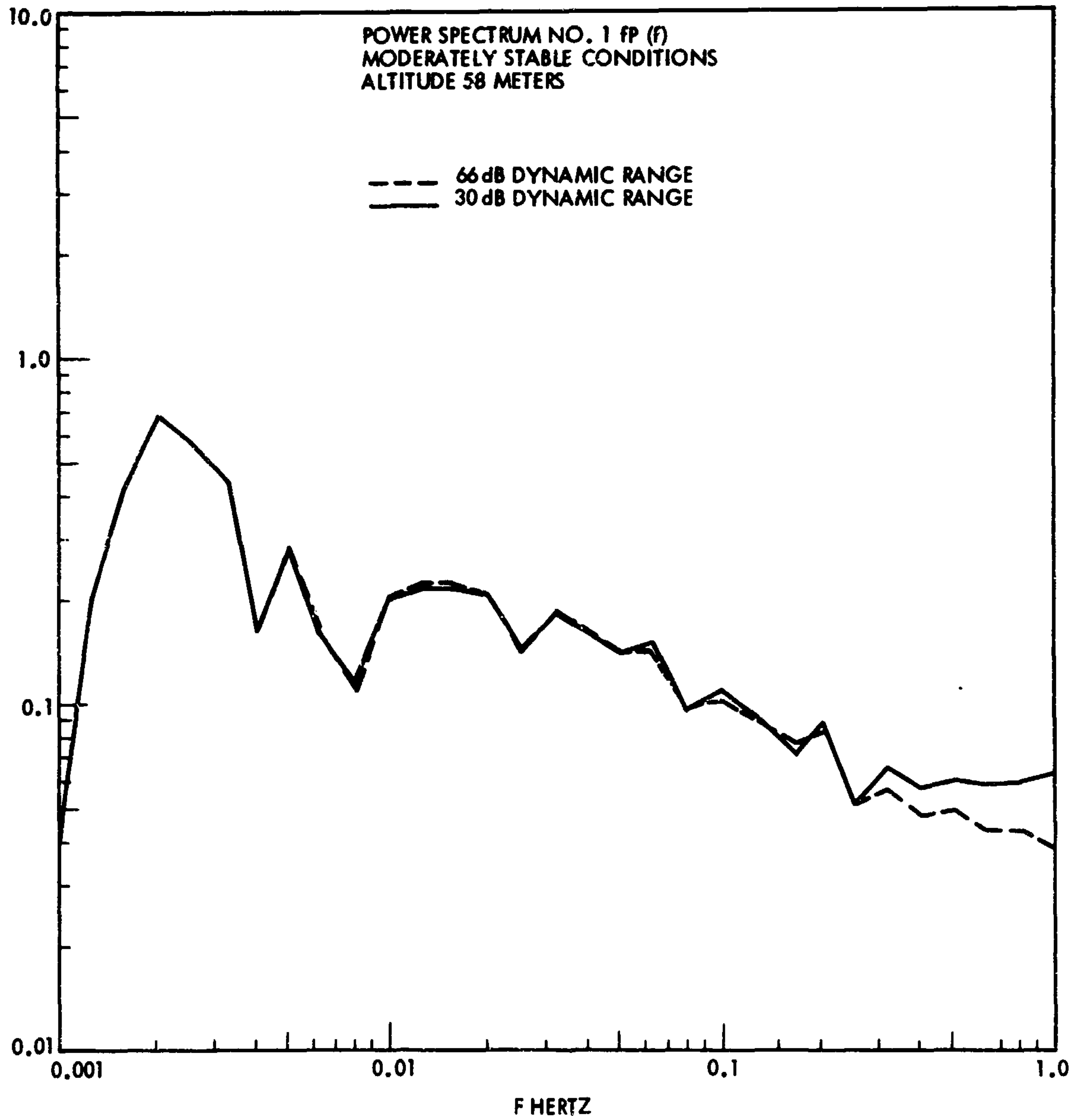


Figure 9. 30 dB Dynamic Range Test - Power Spectrum of Moderately Stable TOLCAT Data

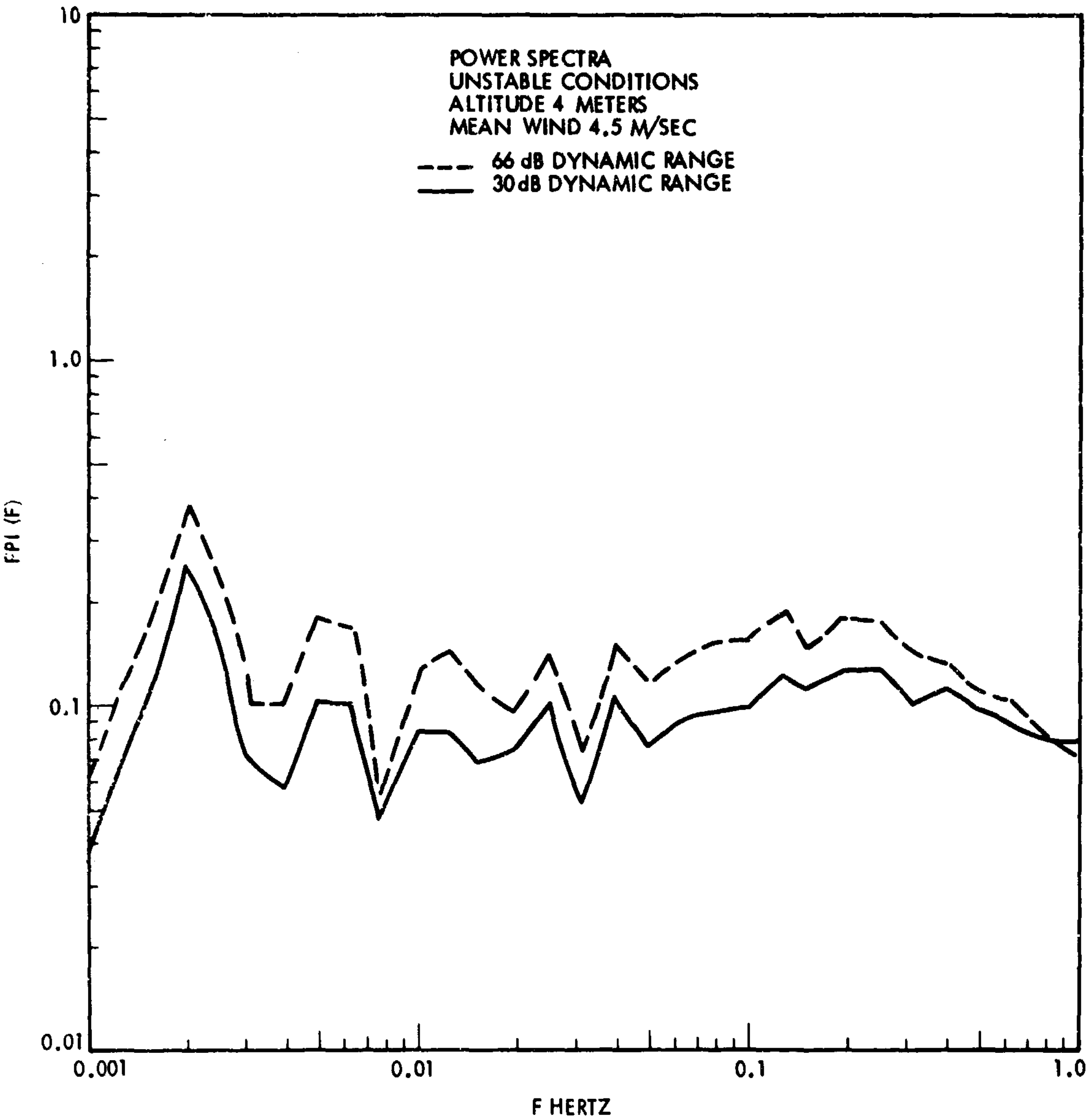


Figure 10. 30 dB Dynamic Range Test - Power Spectrum of Unstable TOLCAT Data

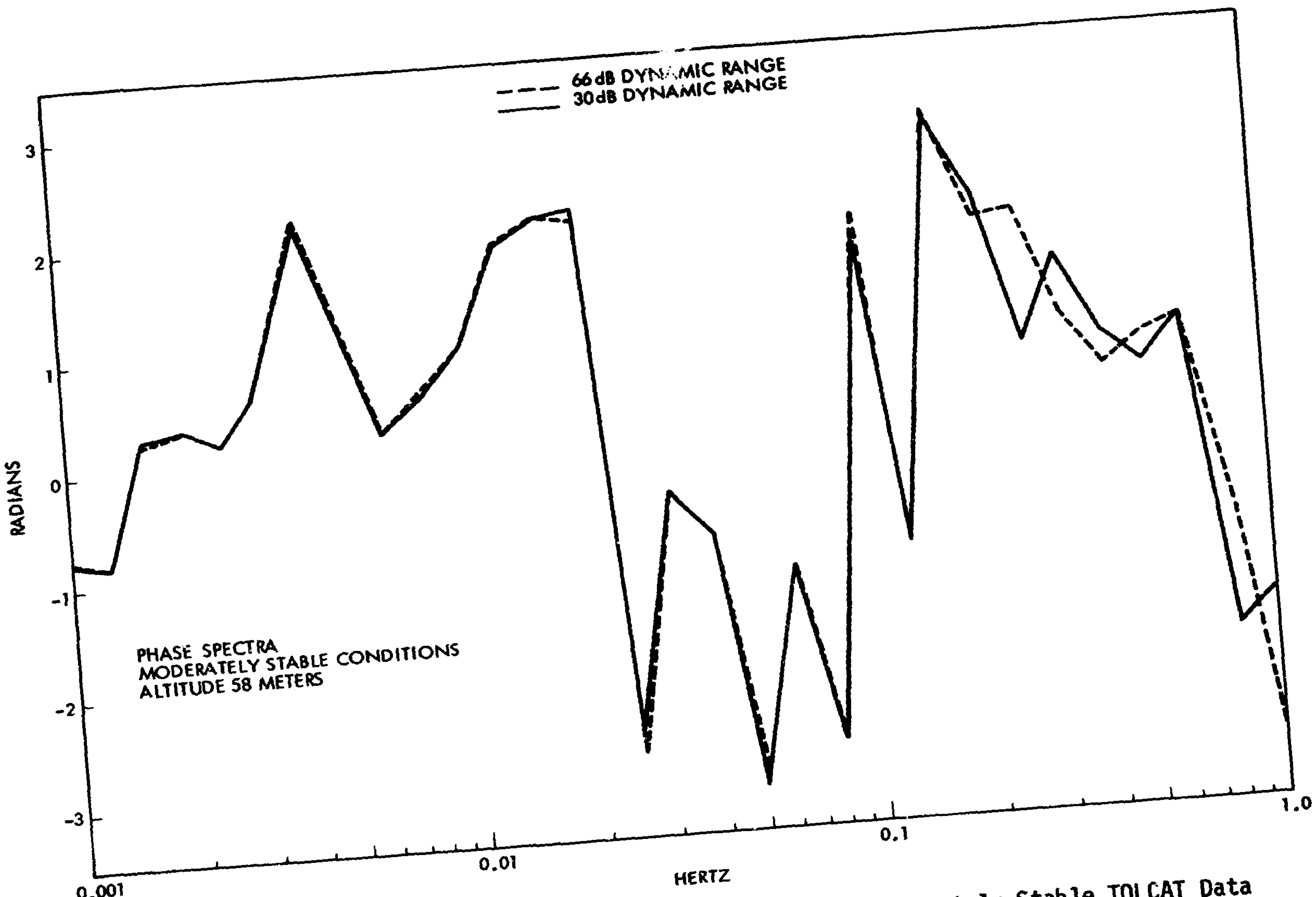


Figure 11. 30 dB Dynamic Range Test - Phase Spectrum of Moderately Stable TOLCAT Data

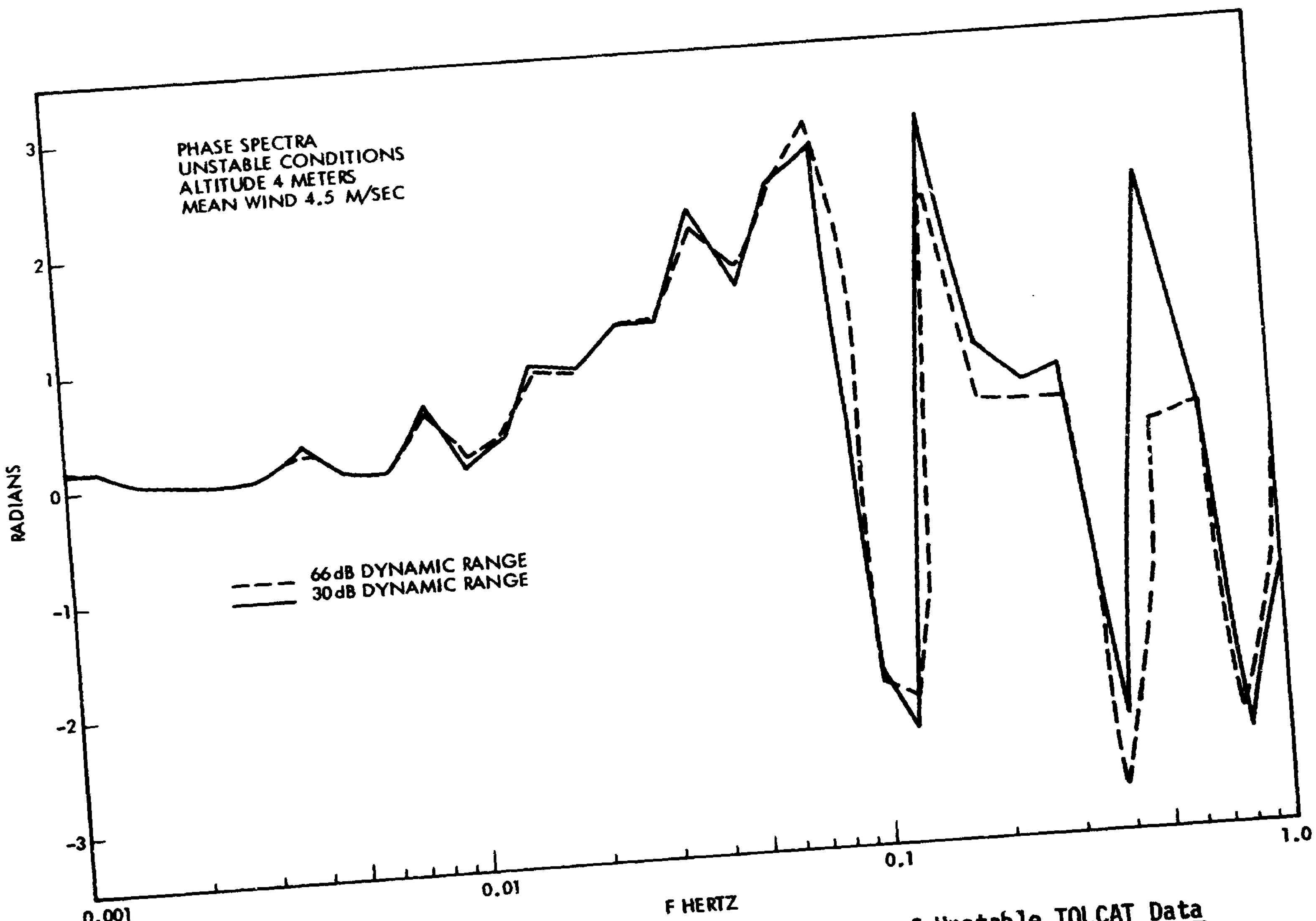


Figure 12. 30 dB Dynamic Range Test - Phase Spectrum of Unstable TOLCAT Data

These filter response characteristics can be economically realized by the weighted Fourier transform method obviating the need for the usual time consuming method of time-domain convolution with the filter impulse response.

4.2.2.2 Selectivity

The selectivity and bandwidth spacing required for TOLCAT processing is that which is usually preferred in an FFT or optical analysis. This filter is implemented by multiplying the input data x(t) (see step 3 of paragraph 5.2.1) by the Hanning window function.

$$\text{Hanning:} \quad \begin{aligned} a_H(t) &= 0.5 + 0.25 \cos \frac{2\pi t}{T} \qquad & |t| < T/2 \\ &= 0 & |t| > T/2 \end{aligned} \tag{3}$$

where T = NΔt for digital processing, and
= time in optical aperture for optical processing.
The FFT or optical processing with no window function gives a f^{-1} selectivity for

$$\text{Unshaded Window:} \quad \begin{aligned} a(t) &= 1 \qquad & |t| < T/2 \\ &= 0 & |t| > T/2 \end{aligned} \tag{4}$$

The unshaded Fourier transform, whether optically or digitally implemented, is not recommended because of the poor filter sidelobe response (see Figure 13).

The shape factor is defined as the ratio of the width of the response measured at the -60 dB points of the optically or digitally synthesized band-pass filter to the frequency width measured at the -3 dB point. Thus, the shape factor can only be defined for 60 dB or greater dynamic range systems - and therefore, digital or analog systems.

Figures 13, 14 and 15 illustrate the filter responses for the unshaded, Hanning and $(\text{Hanning})^2$ window functions. For the unshaded transform, the shape factor is not defined after 200 sidelobes, and for the Hanning window the shape factor is 9.5. Neither of these filters will give the desired shape factor available in some 1/3 octave analog spectrum analyzers.

However if the input data is multiplied by the $(\text{Hanning})^2$ window, i.e.,

$$a_{H^2}(t) = (0.5 + 0.25 \cos 2\pi t/T)^2, \quad |t| < T/2$$
$$= 0 \qquad\qquad , \quad |t| > T/2 \tag{5}$$

the shape factor is reduced to three. As the filter center frequencies are spaced every 1/T apart, a shape factor of 2.5 can be generated by averaging adjacent $(\text{Hanning})^2$ G_K values in pairs. Going one step further, a shape factor of 2 can be generated by averaging four adjacent a_{H2} spectral estimates together.

For systems of 40 dB dynamic range or less, shape factors cannot be defined at the -60 dB points. In these systems (optical and some fixed point FFT systems having 40 dB or less dynamic range), the Hamming window is preferable, since it minimizes the first and all subsequent sidelobes to be below -40 dB. This window is given by

$$a_{HM}(t) = 0.54 + 0.46 \cos 2\pi t/T \quad |t| < T/2$$
$$= 0 \qquad\qquad |t| > T/2 \tag{6}$$

The filter response for this system is shown in Figure 16.

4.2.2.3 Filter Spacing

The optical spectrum analyzer and the digital FFT spectrum analyzer each yeild a constant bandwidth spectrum analysis with filter selectivity determined by the particular window used in the transform. To generate the 1/3 octave spacing, one averages adjacent power spectral density estimates in logarithmic groups. This technique is presently used by Battelle Northwest in the TOLCAT data analysis. Also, the Cal Tech Jet Propulsion Laboratory determines the logarithmically grouped FFT spectral estimates (with the Hanning window) to perform a 1/3 octave analysis. JPL improves on this technique by isolating the low frequency end of the spectrum and sampling longer to obtain more spectral estimates per logarithmic grouping of low frequency spectral outputs (Reference 3). For JPL's case their input data is 10-5000 Hz, which is band-pass filtered into two regions: 10-200 Hz and 200-5000 Hz.

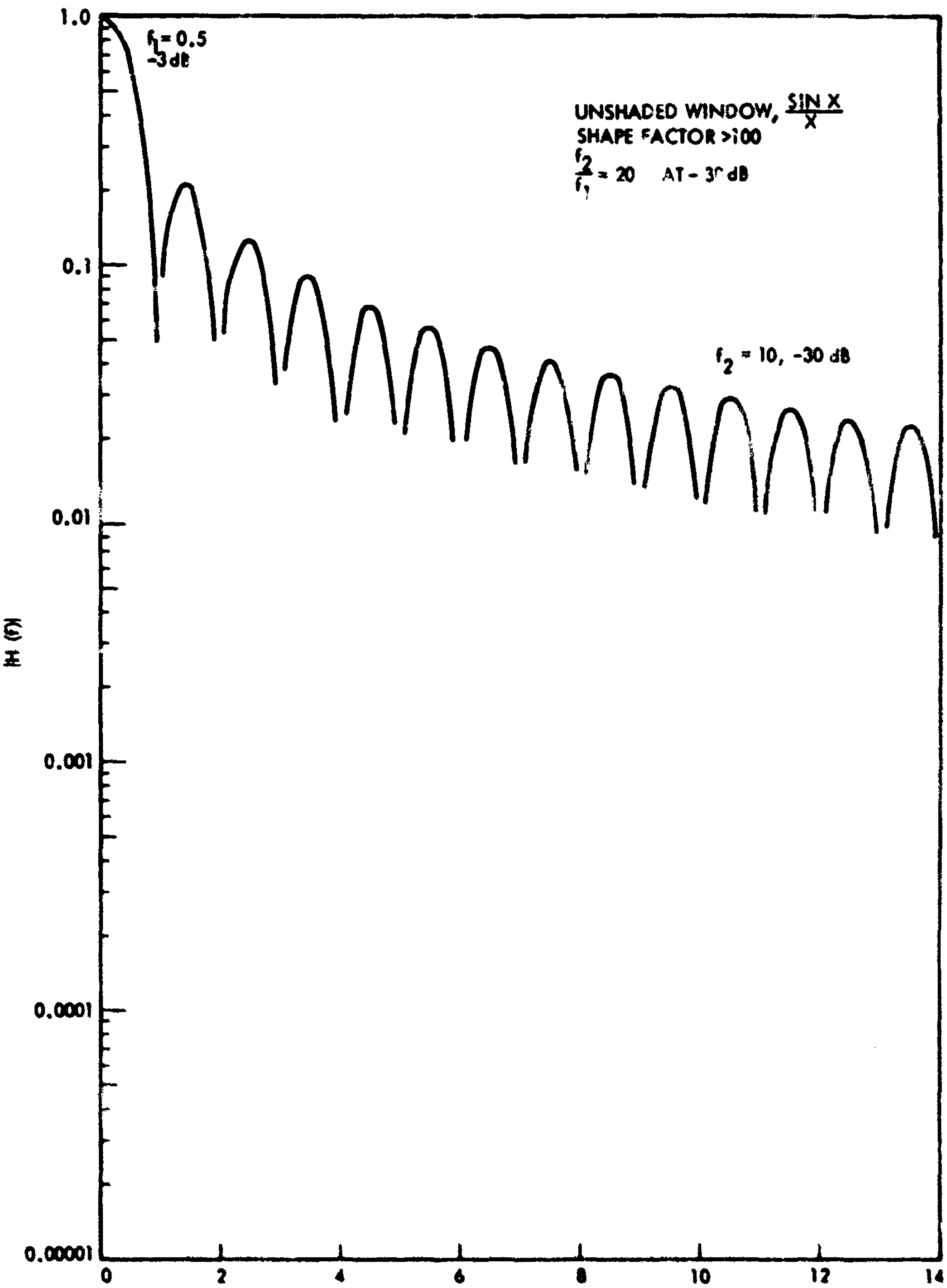


Figure 13. Filter Response for Unshaded Fourier Transform

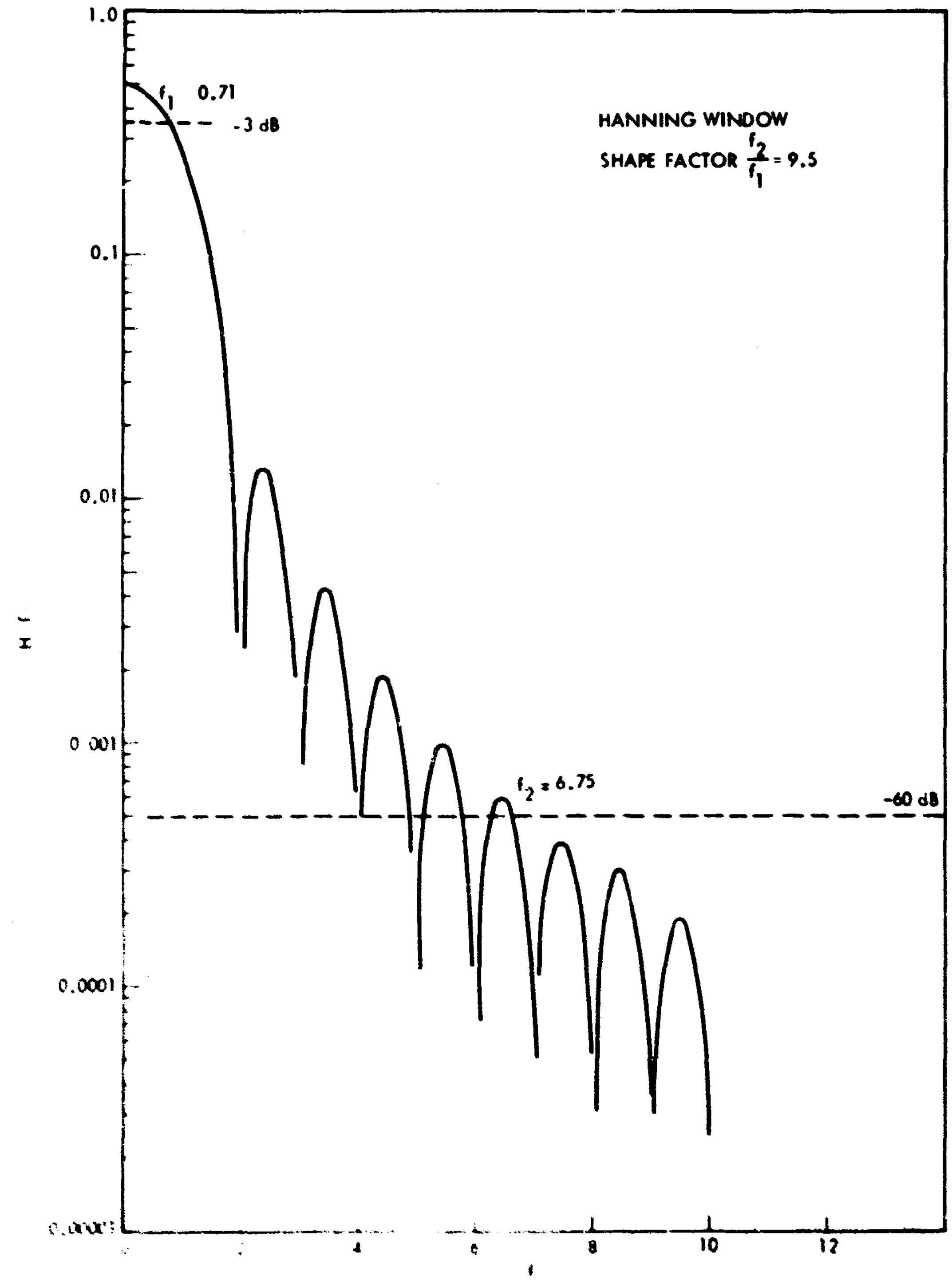


Figure 14. Filter Response for Fourier Transform with Hanning Window

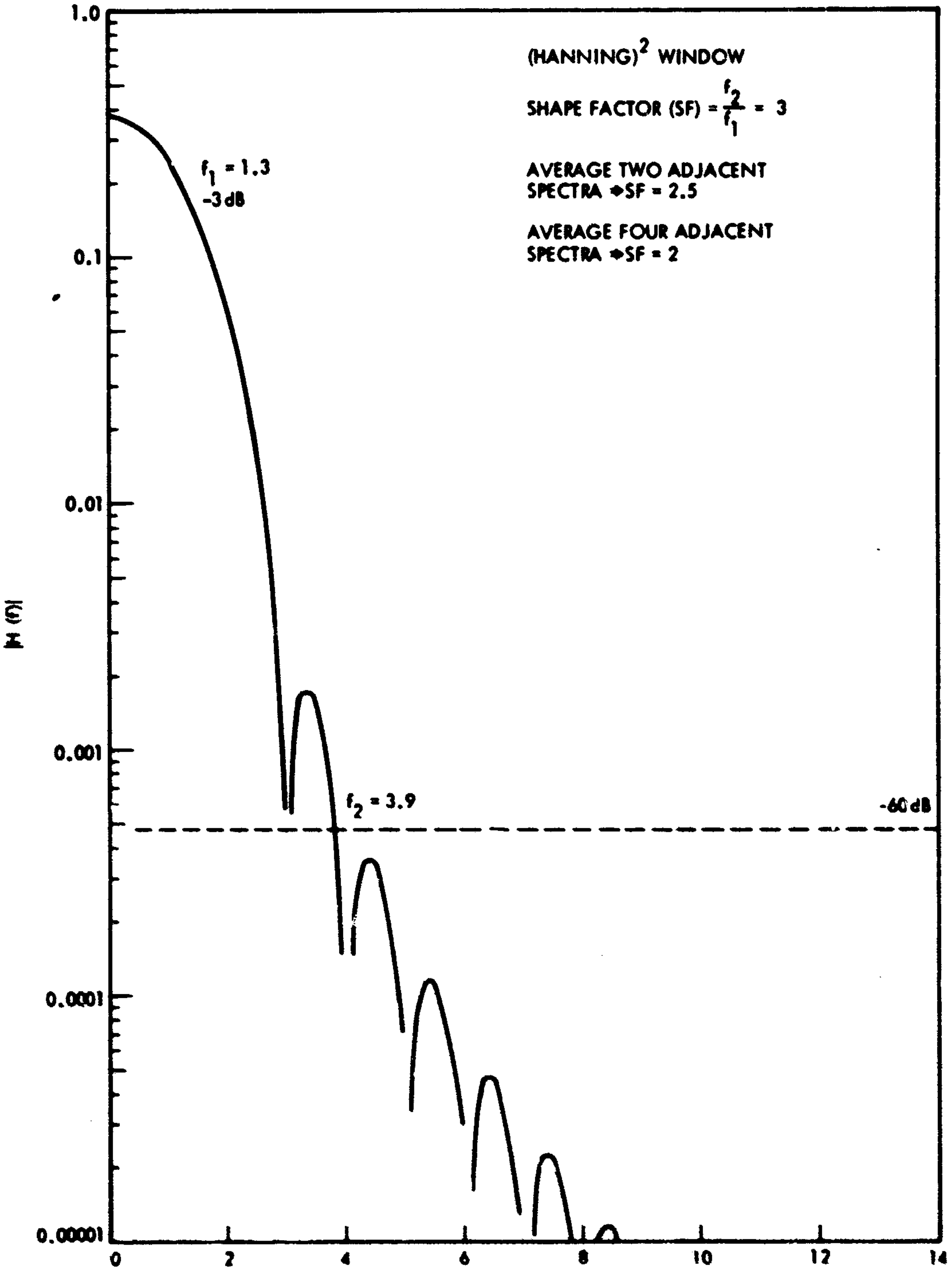


Figure 15. Filter Response for Fourier Transform with (Hanning)^2 Window

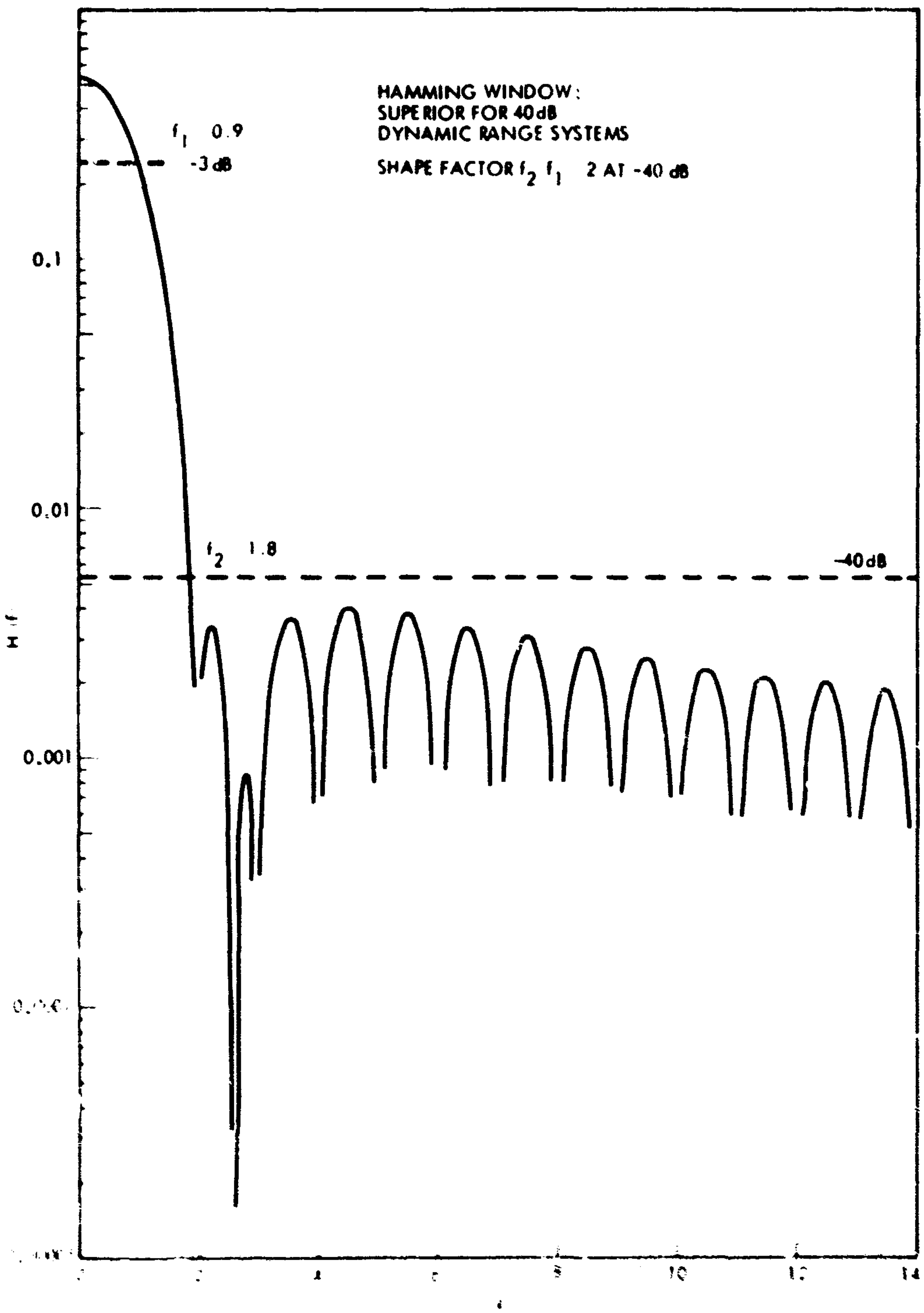


Figure 16. Filter Response for Fourier Transform with Hamming Window

The first band is sampled at 500 samples per second and the 5000 Hz data is sampled at 10,000 samples per second (with large aliasing errors, presumably). This technique was suggested to the Battelle research team for TOLCAT However, Battelle reported that it is not known whether the lower frequencies were stationary over a sufficient time duration to use this technique.

4.2.3 BT Product

The Time Bandwidth (BT) product requirements for the Laboratory are summarized in Table I. The BT product is a good indicator as to what kind of analysis is to be performed and what equipment would perhaps be best suited for the particular analysis.

4.2.3.1 Analog Processing

Once the system input bandwidth B is known or specified, the time T making up the BT product determines the resolution, Δf, of the band pass filter in the power spectral density (PSD) or cross power spectral density analyzer through the relation

$$\Delta f = 1/T \qquad (7)$$

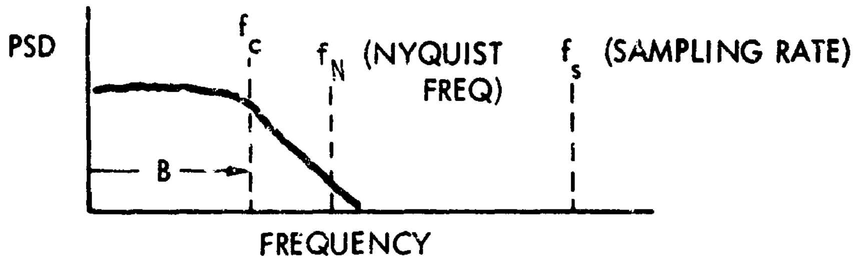
where Δf is the frequency width measured at the -3 dB response points of the band pass filter.

The above illustrates how one relates B, T and filter resolution in an analog PSD analyzer. These definitions carry over into the optical and digital domains as well.

4.2.3.2 Digital Processing

In the digital PSD analyzer, B is defined by that input frequency band in which all the appreciable spectral energy is contained.

The word "appreciable" is the key word in the above statement. In a system application, frequency content above f_c is usually attenuated by low-pass "aliasing" filters to guarantee a specified minimum error in the PSD due to a sampling of the analog data at a rate f_s prior to digital PSD analysis. The fact that the digital PSD analysis FFT algorithm "thinks" that the input $B = f_N$ (or one-half the sampling frequency) leads to an erroneous



conclusion that the time-bandwidth product is given by the product of f_N and the time interval T of digitization given by Equation (7). An example of this is the TOLCAT digital analysis presently underway. The effective sampling frequency is 2.5 samples/second and the time interval T is ≈55 minutes which yields BT ≅ 4000. In actuality BT is only 3500 since f_c = 1Hz, not 1.25 Hz.

4.2.3.3 Optical Processing

An optical processing system can perform two-dimensional Fourier transforms or many simultaneous one-dimensional transforms. The former case calls for the use of the two-dimensional integrating capability of a spherical transform lens. Optical engineers using these equipments usually speak of effective BT products as the product of the BT's for each dimension. That is a 10^6 BT product would actually represent a product of two BT = 1000 Fourier transforms, one for each degree of freedom (Reference 4).

For optical processing of CAT and vibration data in which many channels of correlation and spectrum analysis must be performed, the advantages of optical processing are best realized by the use of a cylindrical integrating transform lens. With this method many simultaneous channels of one-degree-of-freedom type processing are performed in parallel, thereby reducing the per channel cost of processing the data. In keeping with the BT definition in an analog or digital analyzer, the BT product in an optical system processing vibration data is only meaningful when speaking of the per channel BT product of the system.

The input bandwidth B is specified at the -3 dB response point in the MTF (Modulation Transfer Function) curve for the input system to the optical processor. The temporal frequency (cycles/sec.) of the actual data is recorded as spatial frequency in cycles/mm. The BT product of the system then is given by the product of the input frequency B at the input (cycles/mm), and T the spatial dimension (mm), corresponding to "time" in the optical transform aperture or "window."

4.2.3.4 Increased BT Product

A spherical lens Fourier analyzer coherently integrates N channels of one-dimensional transforms to yield a one channel analysis with a BT product equal to NBT. With a cylindrical lens, the same input yields N channels of PSD analyses each with a time-bandwidth product of BT (Reference 5). A digital analysis has the added flexibility in that it can coherently integrate any number of the N channels together to increase BT product (Reference 6).

To give an example, suppose one had N = 32 channels in a cylindrical-lens optical analyzer each with BT = 2000. A spherical lens would yield with the same input, a one-channel PSD analysis with BT = 64,000. A digital analyzer however, can perform both of these cases plus 16 channels with BT = 4000; 8 channels with BT = 8000; with no additional hardware.

4.3 TOLCAT Processing Requirement

The Optical Data Processing Study was directed towards FDTE's interest in the TOLCAT area. The detailed description of the problem and recommendations that follow resulted from inputs acquired from Dr. Charles E. Elderkin and Mr. David C. Powell of Battelle Northwest.

At the present time in the Battelle data processing of TOLCAT turbulence data, Fourier transform related functions represent a relatively small part of their requirements. Their processing is performed in two steps: data acquisition, and computation. The data acquisition, called Pass I, is shown in Figure 17. Here the data is digitized and converted to engineering units (velocities) prior to recording on digital magnetic tape.

Twelve channels of anemometer data and one channel of temperature information are recorded in the field at 1-7/8 ips and at the present time the tape is input to Pass I at the same speed. For a 3600 ft. reel of tape for instance, this is equal to over six hours of data acquisition per tape. Work is presently underway by Battelle to program the controlling computer in the data acquisition system to increase the input tape speed to cut down processing time.

Pass II of the Battelle analysis involves data preconditioning and analysis phases. The data preconditioning requirements are unique to TOLCAT as distinguished from all the processing requirements reported by AFFDL users. The twelve data channels on tape are actually four groups of x, y, and z coordinates, each group of which must be orthogonalized and rotated. In order, the three anemometer channels are made orthogonal, the mean wind in x and in y determined and the coordinate system is then rotated through an angle, θ:

$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix} \tag{8}$$

$$\theta = \tan^{-1}(\overline{y}/\overline{x})$$

An analog alternative to the present digital implementation of these data preconditioning functions was designed and presented to Battelle for their evaluation.* Their response was that analog methods yield an angle θ which varies from tower to tower upon which anemometers are fixed. This would of course introduce errors in the correlation function. Furthermore there is a need for archival store of the raw data for post

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* TRW letter to Battelle dated 13 February 1970.

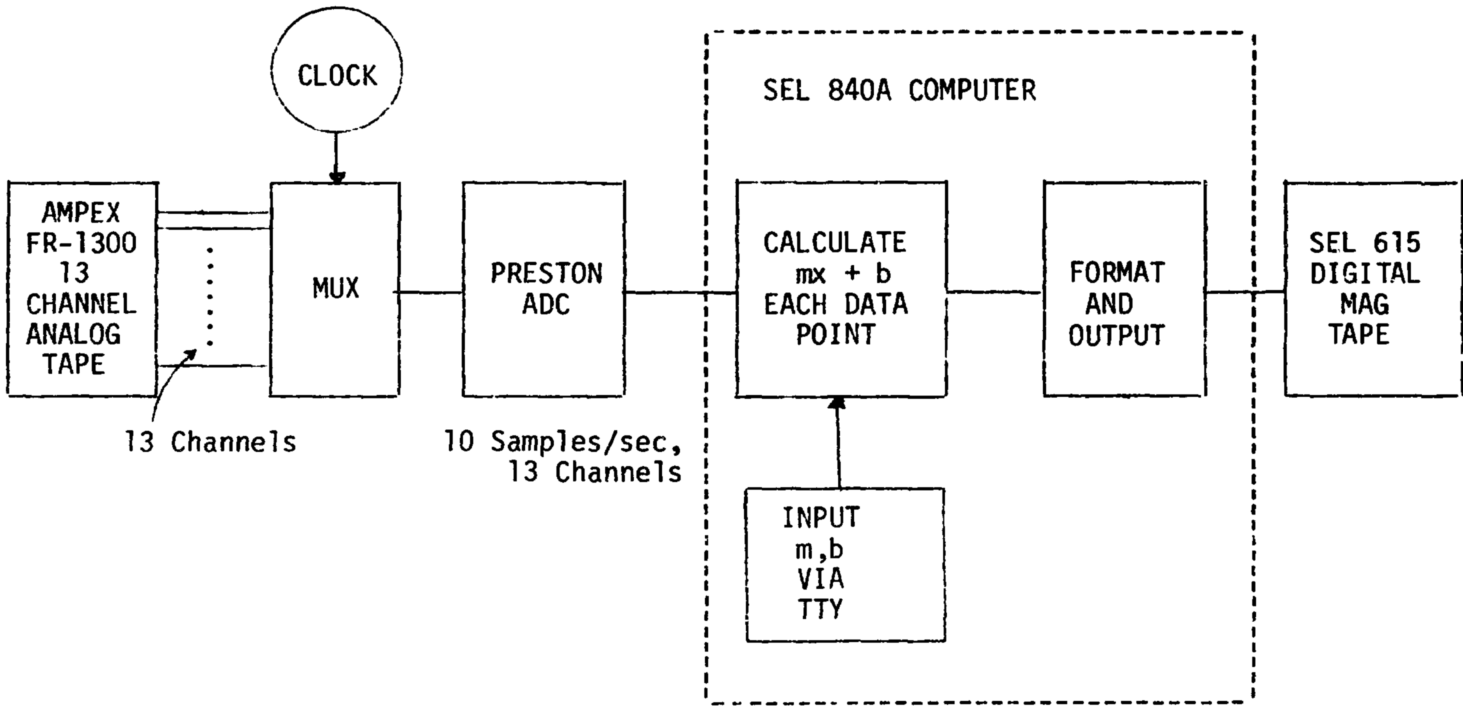

Figure 17. Present TOLCAT Data Reduction - Pass I

analysis interpretation. Investigation of special purpose FFT equipment to yield these coordinate transformations should be undertaken as it appears then that this computation must remain digital.

The analysis phase of Pass II of the TOLCAT data processing involved the standard statistical treatment of this data. A functional flow of this processing along with processing time required is shown in Figure 18.

Each channel x and y represents one hour of recorded data - the maximum interval under Battelle's stationary criteria. Notice that Pass I data acquisition required 10 minutes (2 channels effectively take up 1/6 of the hour required to acquire 12 channels) and Pass II processing requires less than one minute. It is seen from this that there is little use in improving the computational rate of the Fourier transform related processing (see shaded areas in Figure 18) until the 10:1 data acquisition to analysis ratio can be improved. Assuming that Pass I tape speed can be improved to increase the input rate to 60 ips, the result would be reduction by a factor of 32 in the data acquisition time. With this improvement there remains about 20 seconds (10 minutes ÷ 32) of Phase I vs one minute of Phase II processing. Phase II performance will have greater relative impact in this case.

Battelle Northwest future plans call for direct digitizing of the anemometer data in the field - literally eliminating the data acquisition Pass I. If this occurs then up to about 25% computer time savings in addition to processing convenience would be realized if one provided increased processing speed in the Fourier transform functions.

For optical processing to be of benefit to TOLCAT, the Fourier transforms related functions -- PSD, Cross-spectrum, Auto-Correlation, Cross-Correlation -- must be performed on line in the system, and with >40 dB dynamic range. Furthermore the Battelle research team indicates a preference toward digital analysis - because they have experience and confidence in these results. Any new technology should have obvious "order-of-magnitude" improvements, in performance or in cost to provide the motivation to abandon a proven methodology.

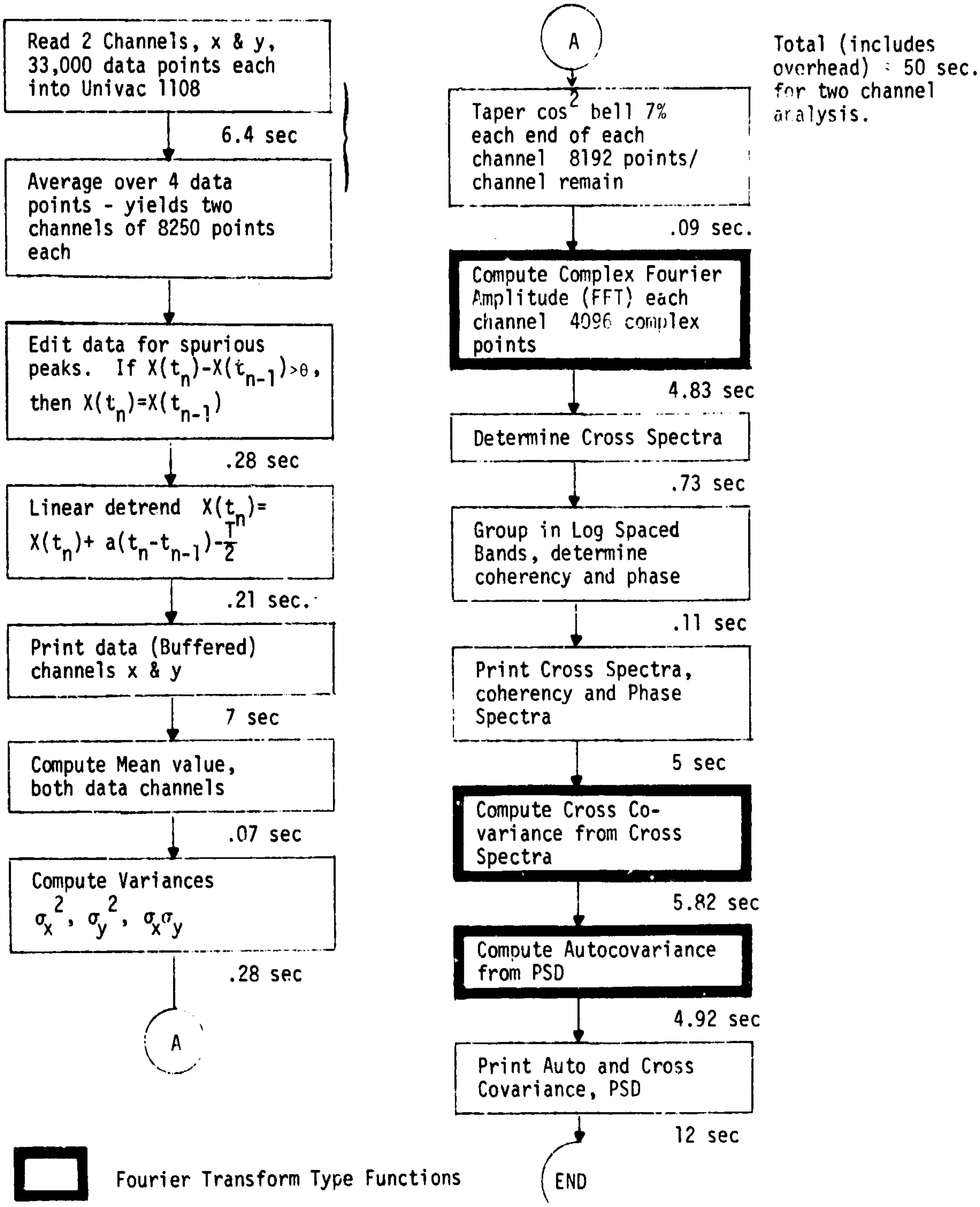

Figure 18. <u>Present TOLCAT Data Reduction - Pass II</u>

To present alternatives to Battelle researchers, a data system was designed to implement TOLCAT functions. Included were analog, digital and optical implementation options. Their impressions are that a FFT processor acting as a computer peripheral system was superior to optical processing.* As a by-product, amplitude probability density can be performed at no increase in processing time cost in this design. On the other hand due to the location of their installation, the Battelle people indicated a need for a system with high MTBF and low maintenance and mean time to repair. As the FFT systems are new equipments, little data concerning MTBF and MTTR are available.

Optical processing does not appear to be suited to the TOLCAT area. First of all, the dynamic range is inadequate - dynamic range tests suggested by TRW have been performed by Battelle on real data to verify this. Secondly TOLCAT data processing involves computations of functions which are not possible or are unsatisfactory in performance in more than just dynamic range. Digital FFT processing on the other hand lends itself well to low frequency data such as TOLCAT. A special purpose FFT processor acting as a peripheral to a small general purpose computer can substantially reduce cost over large scale general purpose computers for large volume processing. All digital processing will be very attractive once the digitization of the data is performed in the field.

To provide improved performance and reduced government expenditure, a study effort to determine the commercial vendor with the most cost/effective digital FFT system is recommended.

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* Battelle letter to TRW dated 11 March 1970.

V. METHODS OF IMPLEMENTATION OF AFFDL PROCESSING REQUIREMENTS

The following paragraphs describe the concepts used as a basis for performance and cost comparison of optical, digital, and analog implementation of the requirements identified in paragraph 4.1.

5.1 Optical Processing

5.1.1 Spectrum Analysis in Optical Processing

The technique of optical spectrum analysis arises from the property of a lens that, if an object is placed at the front focal plane*, the intensity distribution of the back focal plane is the Fourier transform of the intensity distribution of the object.

$$F(p,q) = \iint f(x,y)\, e^{-j(px + qy)} dx\, dy \qquad (9)$$

where p and q are spatial frequency variables described in Figure 19.

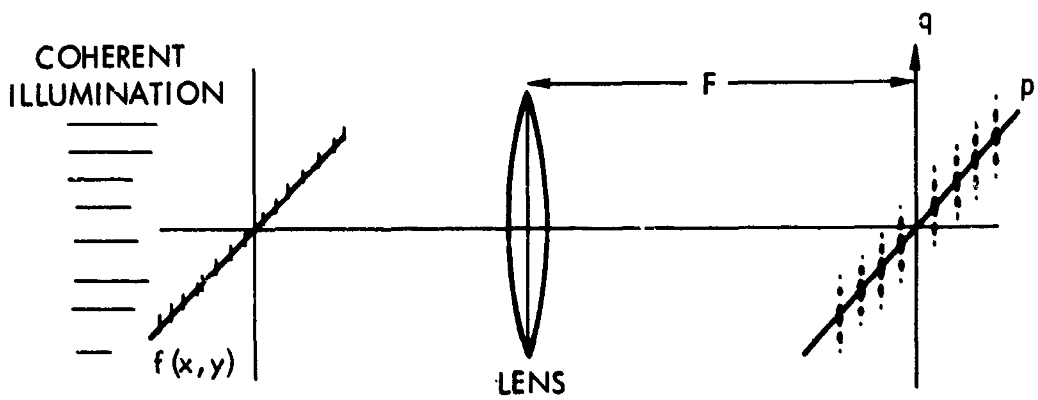

Figure 19. Fourier Transforming Properties of a Lens

* If phase information is not needed in the transform plane, the object may be placed close to the transform lens to maintain BT product.

The dual in the time domain to Equation (9) is:

$$F(\omega) = \int f(t)\, e^{-j\omega t} dt \tag{10}$$

which is exactly the spectrum analysis operation it is desired to perform. The major advantage to the optical technique is its two dimensional nature. This extra degree of freedom allows either two-dimensional analysis or many channels of one-dimensional analysis to be performed. Multichannel systems will be considered in this description.

The major components of a present day optical spectrum analyzer are the input system, optical transform system, and an output device. The entire optical data processing system depends, for its successful operation, on innovative design and development of the auxiliary input/output equipments. The optical subsystem is well developed; the lenses can be designed and built of the necessary high quality glass. Much work has been done on the auxiliary devices that could be called Input and Output Transducers. However to say that (for instance) photographic film serves as the Input Transducer to an optical processor implies that a sophisticated electro-optical device has converted the original signal(s) to transmission variations on the film. It is usually the case that a multichannel laser recorder for photographic film costs more than the optical subsystem (processor) itself. Similarly, after the optical subsystem has performed the desired operations on the input data, the results are available as a spatial array of light amplitude variations. To convert this to a useful form requires an Output Transducer. The output transducer could be diode arrays, mechanical scanners or Image Dissectors depending upon the application.

5.1.2 Frequency Response of Optically Synthesized Band-Pass Filters in Spectrum Analysis

The requirement for frequency selectivity under paragraph 4.2.2 can be implemented by placing a film or other partially transmissive medium in the optical aperture defining the Fourier transform time window T (see Figure 20). Since the optical processor is a limited dynamic range system we will use the Hamming function which gives a frequency response as shown in Figure 16. The Hamming aperture shading function can be implemented by use of film which has a transmission characteristic as shown in Figure 21 (see Equation 6).

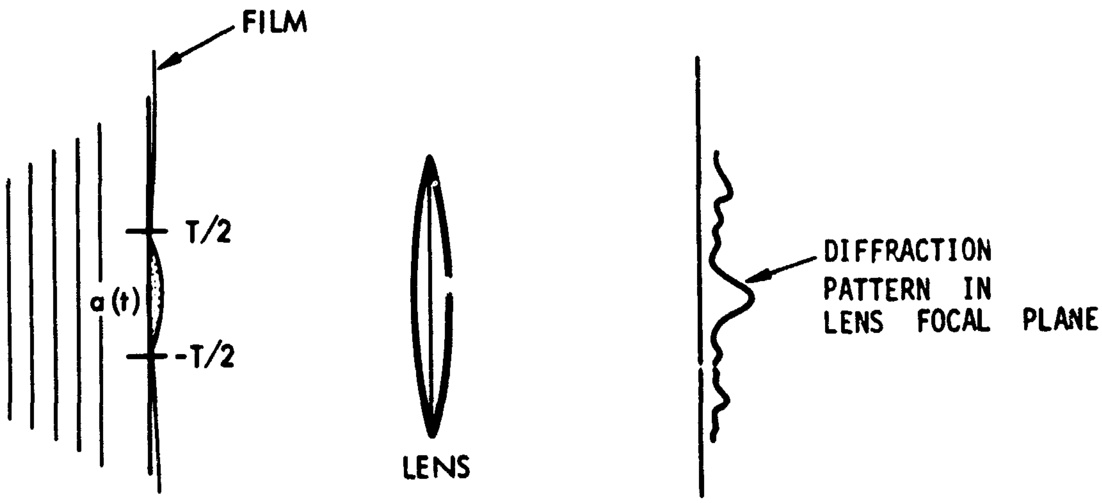

Figure 20. Optical Fourier Integrator with Aperture Shading

5.1.3 Input Transducer

5.1.3.1 Input Transducer Tradeoffs

The input transducer converts the input analog signals into a number of parallel channels of one-dimensional spatial modulations of a laser beam. This conversion can be accomplished by creating a signal mask on photographic film or photochromic material having transmission proportional to the spatial dimensions of each channel and then illuminating this mask with an unmodulated laser beam to create the proper input signal for the optical processor. Conversion can also be performed directly as with an acoustic delay line modulation or a CRT. Delay lines suffer high insertion losses, are limited to one-channel applications, and operate in the wrong frequency region (MHz) for this application. The disadvantages of a CRT are low light level output, resolution and non linear output.

For a signal mask, photochromic material offers potential advantages in high dynamic range (Reference 7). But there is a paucity of experimentation

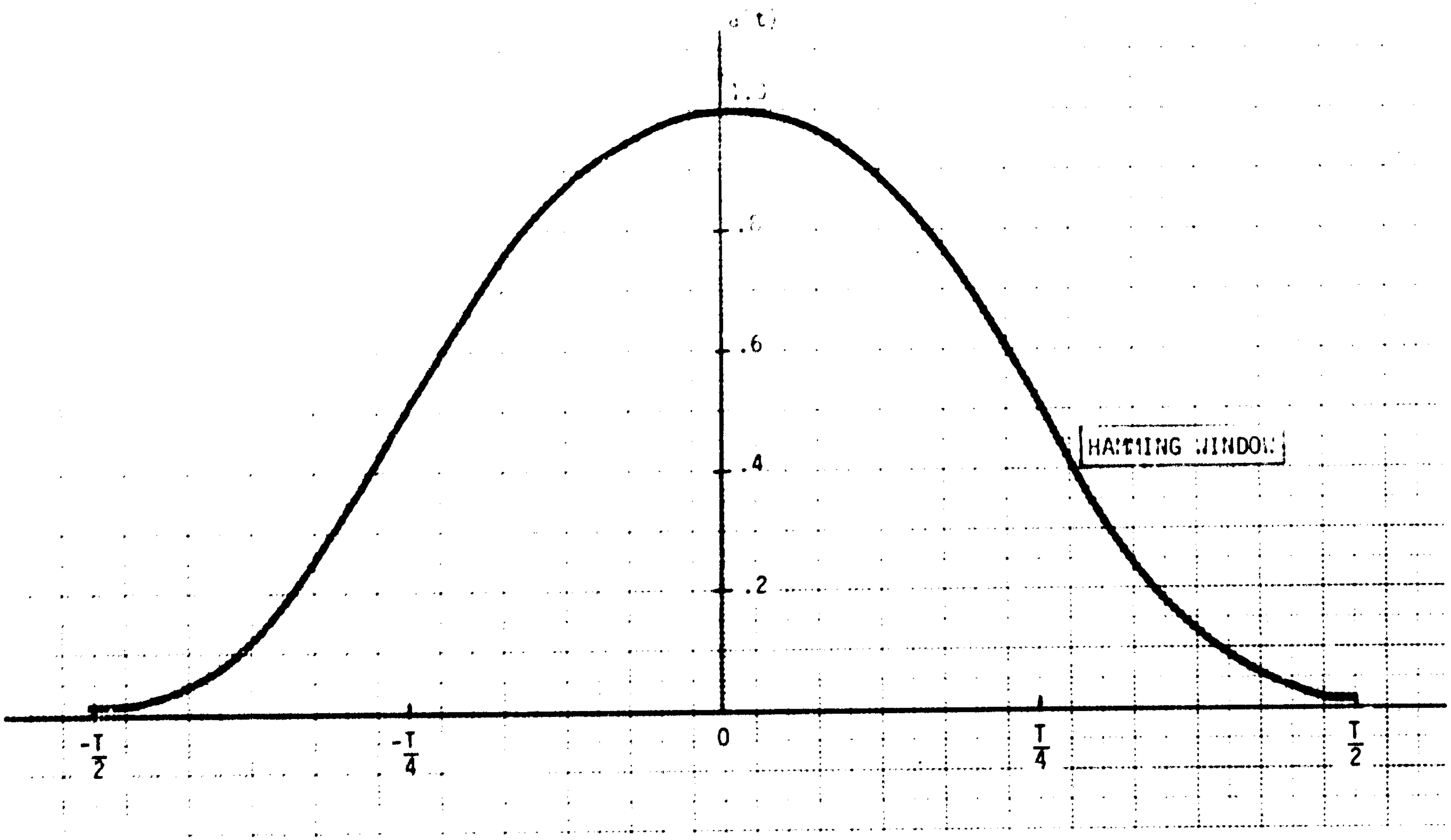

Figure 21. Hamming Time Window for Shaded Fourier Transform

concerning MTF data for an optical input light-modulator/photochromic system. In addition, improvements are needed in the removal of fatigue or S/N degradation as a function of the number of read/write/erase cycles (Reference 8). The potential of photochromic input media in optical processing still awaits development to be realized.

Thus we turn to photographic film for the signal mask medium. Optical processing studies at TRW indicate that the maximum dynamic range available on photographic film varies from 20 to 30 dB depending upon the film selected. This dynamic range limitation is generally agreed upon in industry; this fact is reflected in reports for AFFDL by Conductron and SEL (Reference 9).

Since the optical system is to process many one dimensional Fourier analyses (PSD) we chose the Synergistics PDR-5 Laser Recorder system as the basis for the input transducer to an optical spectrum analyzer. This recorder, described in the next paragraph, is designed to record 36 parallel analog signals on film with 30 dB dynamic range.

5.1.3.2 Synergistics PDR-5 Laser Recorder

The Synergistics PDR-5 is a 36-track laser film recorder capable of recording digital, analog and PCM signals on 8 mm wide microfilm. The system consists of excellent components (laser, multi-channel, modulator, diode array) and provides a long-overdue capability of multi-channel recording at high packing densities.

The PDR-5 is configured to record digital data as this mode circumvents several problems inherent in any analog film reocrder. These include non-linear film γ and modulator $\cos^2$ transfer functions, film stretch and cross talk from adjacent channels due to diffraction effects. These problems are present in all film recorders and must be dealt with if the machine is used to produce input film to an optical Fourier processor.

The machine is similar in operation to a magnetic tape recorder. Referring to Figure 22, a sensitized tape is transported at a uniform rate in front of the recording transducer where data is written on the tape. Playback duplicates this process except that data is read off at the transducer. The significant difference is the sensitive tape which is film and the recording transducer which modulates a light beam.

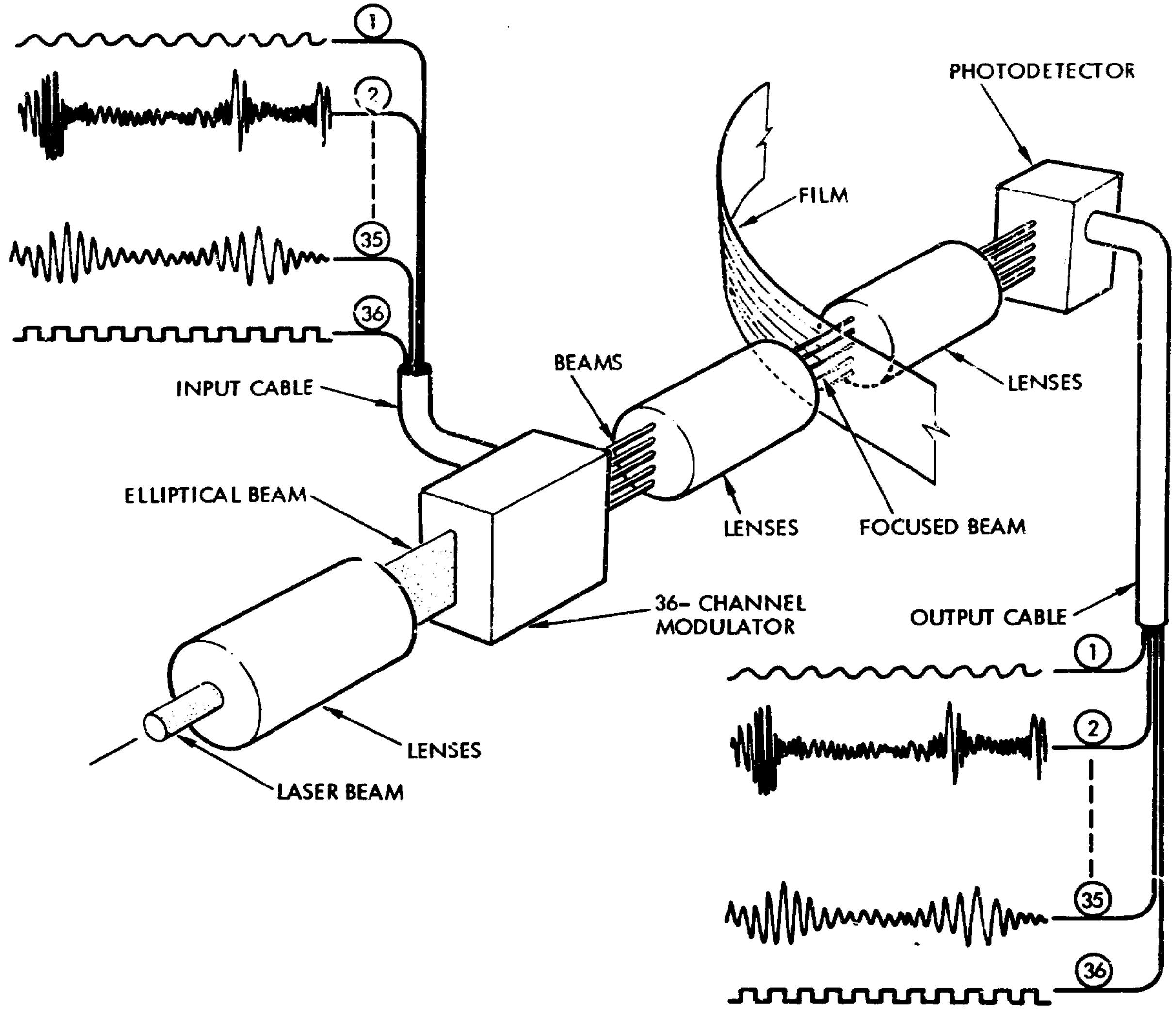

Figure 22. 36-channel Laser Recorder Schematic

The film transport utilizes a high inertia capstan-pinch roller drive for low wow and flutter and supply and takeup reels tensioned by torque motors. The electro-optic transducer consists of a continuous gas laser, cylindrical optics to form the beam to the desired shape, a 36-channel electro-optic modulator and a 36-channel solid-state photodetector. The output from the laser is a circular beam of light approximately 0.8 mm in diameter at the $1/e^2$ intensity points. The beam of light passes through an optical assembly, which reshapes the beam into an elliptical cross section that is less than one inch wide by 0.01 inch thick. This elliptical cross section beam is incident on an array of 36 modulator cells arranged side by side. The light emerging from this array of modulator cells is reshaped so that at the surface of the record the beam is approximately 0.24 inch in width across the film and approximately 0.0002 inch in thickness, measured longitudinally to the film.

Optics placed on the opposite side of the head from the laser expand the light which passes through the film to the same geometry as that on the modulator cell. This expanded beam is then incident on a 36-channel photodetector.

The film used in the recorder is commercially available microfilm Agfa 8E75 extensively used in holography work. The MTF of the input system measured at the film is shown in Figure 23. This, and the parametric curves generated in the following paragraph are used for the system design of an optical spectrum analyzer.

5.1.3.3 Input Parameters for Signal Mask Preparation

In this paragraph parametric design curves are developed to enable each of the system input applications required in paragraph 4.1 to be translated into the appropriate input format for optical spectrum analysis.

The initial consideration is to translate input frequency in Hz to film spatial frequency in c/mm (see Figure 24). The PDR-5 recorder film transports velocities are 1-7/8, 3-3/4, 7-1/2, 15 and 30 ips. Figure 24 shows the relation between the maximum frequency in Hz and the maximum spatial frequency on film with the film transport velocity as a parameter. Dotted lines on this figure apply to the TOLCAT area as described in paragraph 5.4.2.

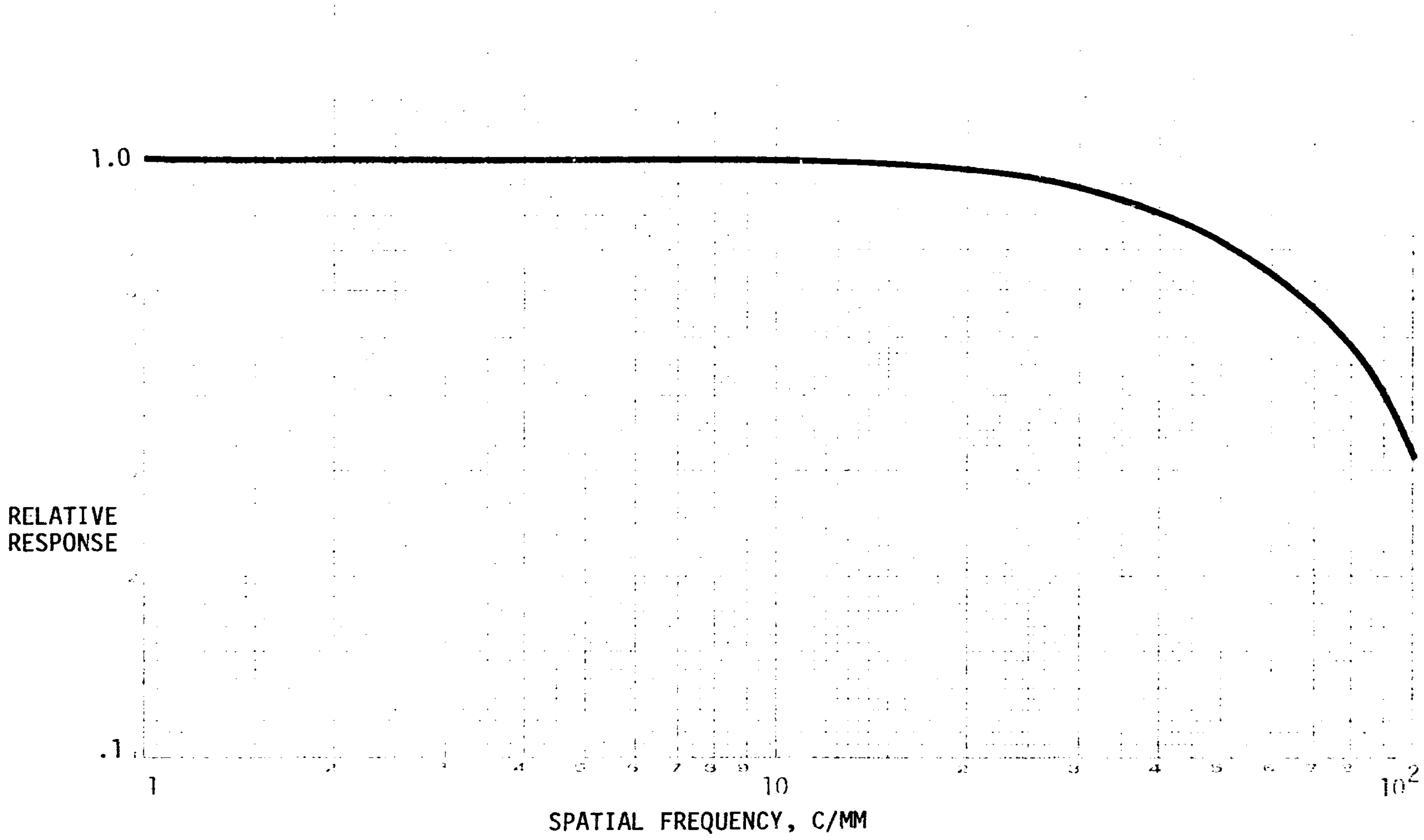

Figure 23. Laser Recorder Film MTF

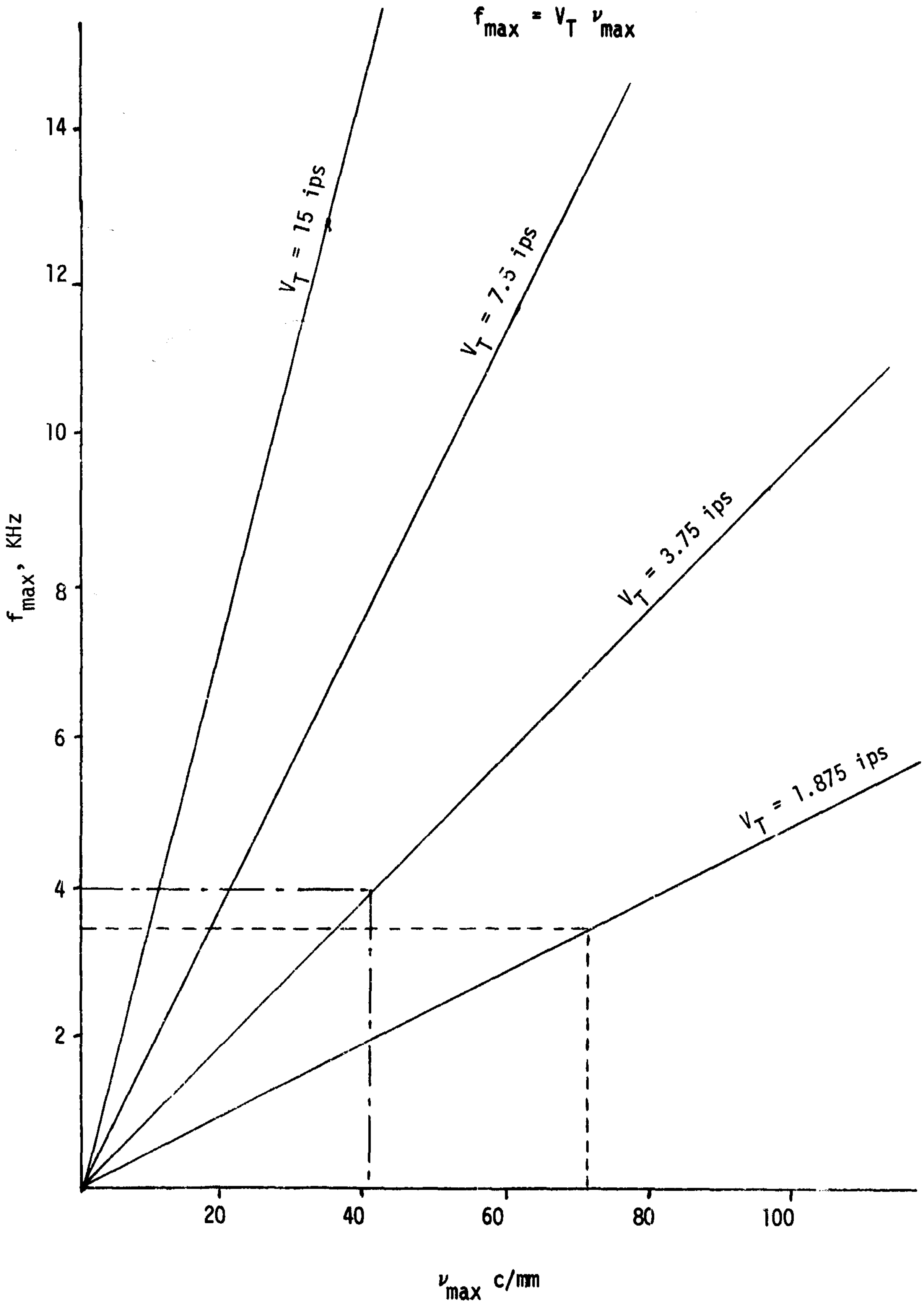

Figure 24. Relationship Between Film Recording Spatial Frequency/Input Data Frequency Laser Recorder System

Cost of an optical processor increases markedly with the diameter of the transform lens - particularly for a cylindrical lens system. Figure 25 illustrates the available BT product as a factor of lens diameter. The spatial frequency parameter ν_{max} has been determined from Figure 24. Notice the TOLCAT design is for a 2" lens system.

The third important consideration is processing loss due to sidelobe leakage from d.c. From the requirement in Figure 25 for a 50 mm diameter lens, we determine the focal length by setting $\lambda F = 0.5\ (mm)^2$. The first frequency resolution element is then sufficiently removed from the origin of the frequency transform plane.

5.1.4 Output Transducer

The square of the Fourier transform of each channel of input data appears in the focal plane of the transform lens. The light intensity along the x-axis is proportional to $|F.T.|^2$ and its spatial position is proportional to the original signal frequency. A readout device such as a linear array of Silicon detectors can be mechanically scanned across these spectra, and deliver to a multiplexer 32 analog signals, each representing the spectrum of one channel. The scan length is approximately 20 mm and contains 2000 resolution elements. The scan rate is 20 mm/sec with a flyback time of 1 sec. A new segment of input data is moved into the input plane once every 2 seconds. For optimum signal-to-noise at the output, the laser beam should be modulated (chopped) so that the detectors could operate in a region removed from their characteristic 1/f noise.

An alternative scheme which requires no moving parts would involve the use of an image dissector with appropriate scan circuitry and frame time compatible with the output plotter or computer storage.

5.1.5 Optical Cross Spectrum Analyzer

Cross spectrum analysis can be implemented by use of complex spatial filtering as described by Allen and Jones (Reference 10). However with optical alignment tolerances required, integration of this technique into a system which is to generate these data at high processing rates would require a considerable R&D effort.

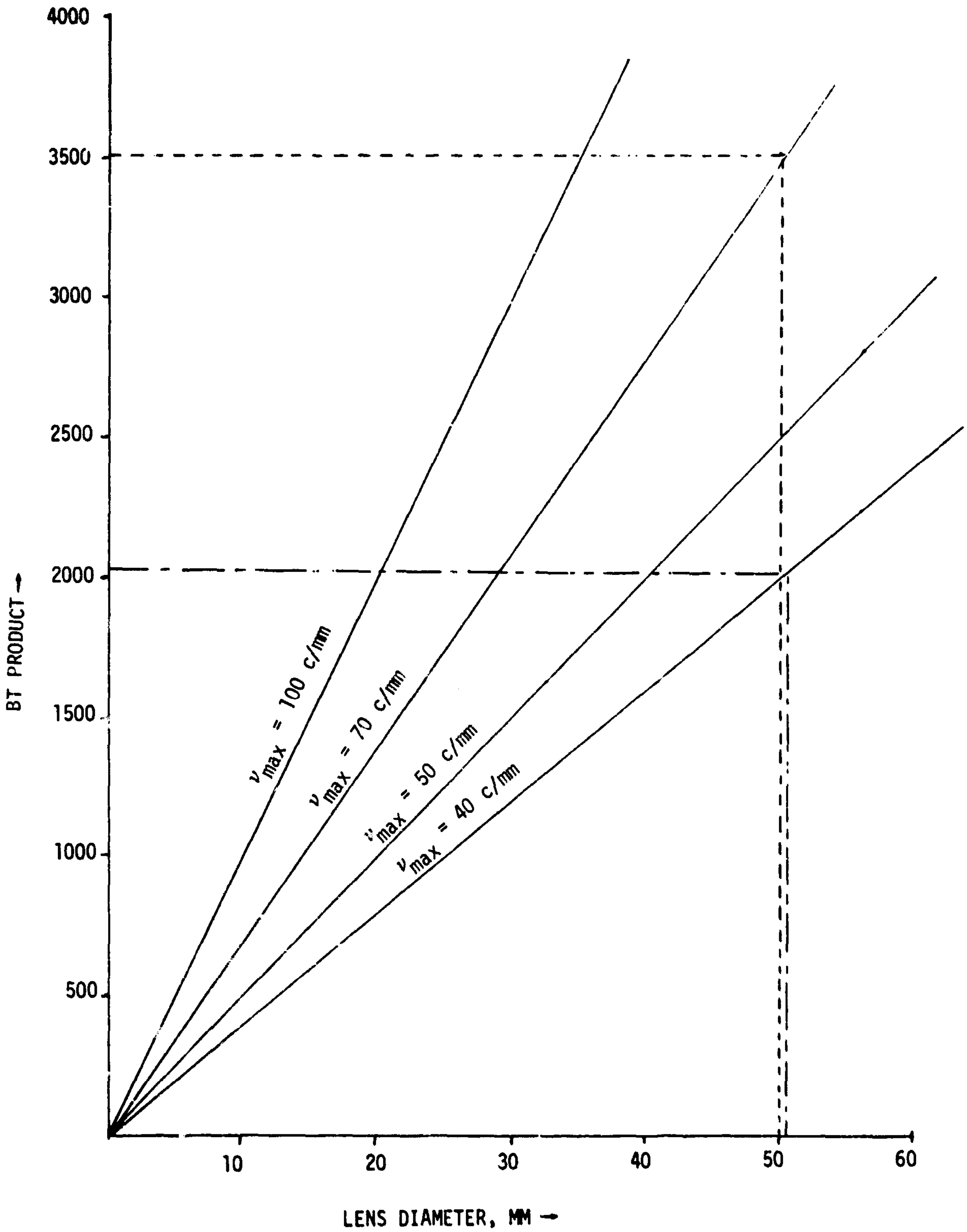

Figure 25. BT Product vs. Lens Diameter with Maximum Film Spatial Frequency as a Parameter

The optical diagram for accomplishing the cross-spectrum calculation is shown in Figure 26.

The collimated coherent light emerging from lens L_2 illuminates the film recording of x(t) + B(B = d.c. bias) which is placed in plane P_1 as close to the transforming lens L_3 as possible. The far field diffraction pattern is focused by the lens L_3 into the plane P_2. The diffraction pattern in P_2 represents the complex Fourier transform of the data $X(\omega)$. Multiplication of $X(\omega)$ by the complex spatial filter, $Y^*(\omega)$ present in the plane P_2 when detected yields the square of the amplitude of the cross spectrum.

The hologram $Y^*(\omega)$ is generated by interferometric means as shown in Figure 27. Here the collimated beam is divided into two parts by a beam splitter, the direct beam creating the Fourier transform at P_2 as before. The other beam is focused by lens L_R at plane P_R where a pinhole is used to remove unwanted noise and/or secondary reflections from the beamsplitter. Two mirrors are used to direct this beam to plane P_2.

The reference beam is incident to P_2 at angle α with respect to the signal beam. Provided that α is chosen properly, the square of the absolute value of $Y(\omega)$ recorded on film is proportional to $Y^*(\omega)\ e^{j\omega\alpha}$.

5.1.5.1 <u>Processing Rate Requirement</u>

Operationally, a system for generating cross spectrum would be a four stage process. The first two operations are to record the reference channels (y) on one film and the input signals (x) on a second film. The third stage of computational sequence would be to generate a series of holograms from the film containing the reference channels. The fourth stage would be to compute the product of $X(\omega)\ Y^*(\omega)$. It is desirable that signal masks and holograms would be generated in large quantities to set up for production type processing of the fourth stage.

To determine the processing rate required to be competitive with digital processing,* we take the case of a BT product of 1000. The time required to perform a 2000 point FFT (to get $Y^*(\omega)$) is approximately 56 msec. To obtain the product of $X(\omega)\ Y^*(\omega)$ would require 2 x 56 msec plus time for a 2000 point

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* Computational time estimates for TIME/DATA-90 Digital Fourier Transform Processor.

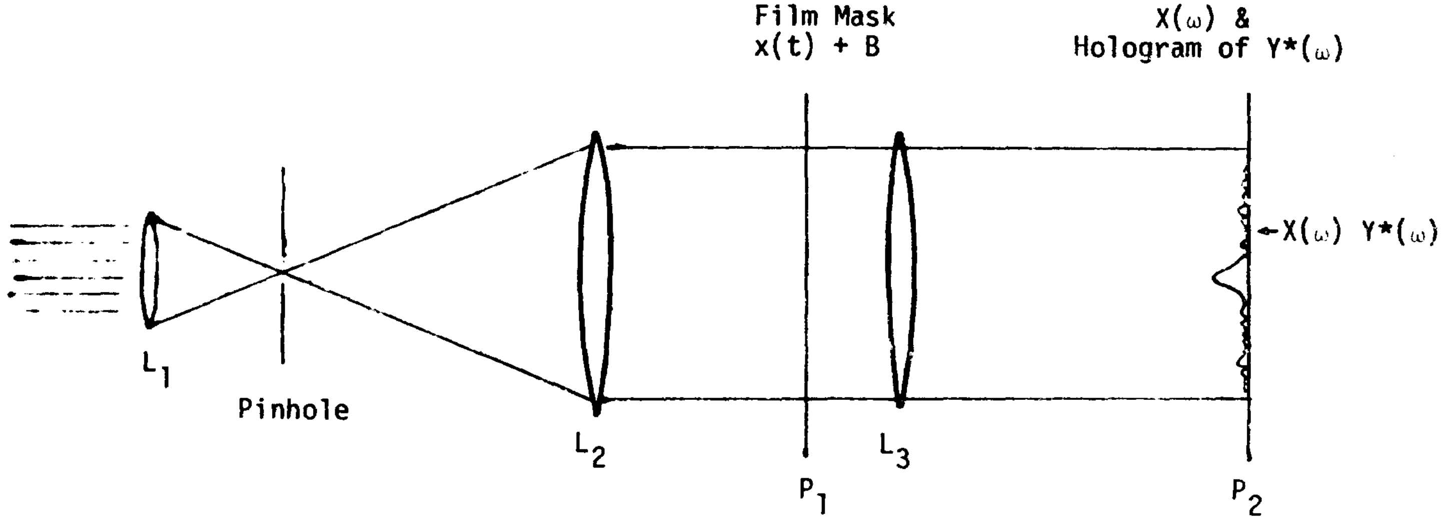


Figure 26. Optical Cross Spectrum Analyzer

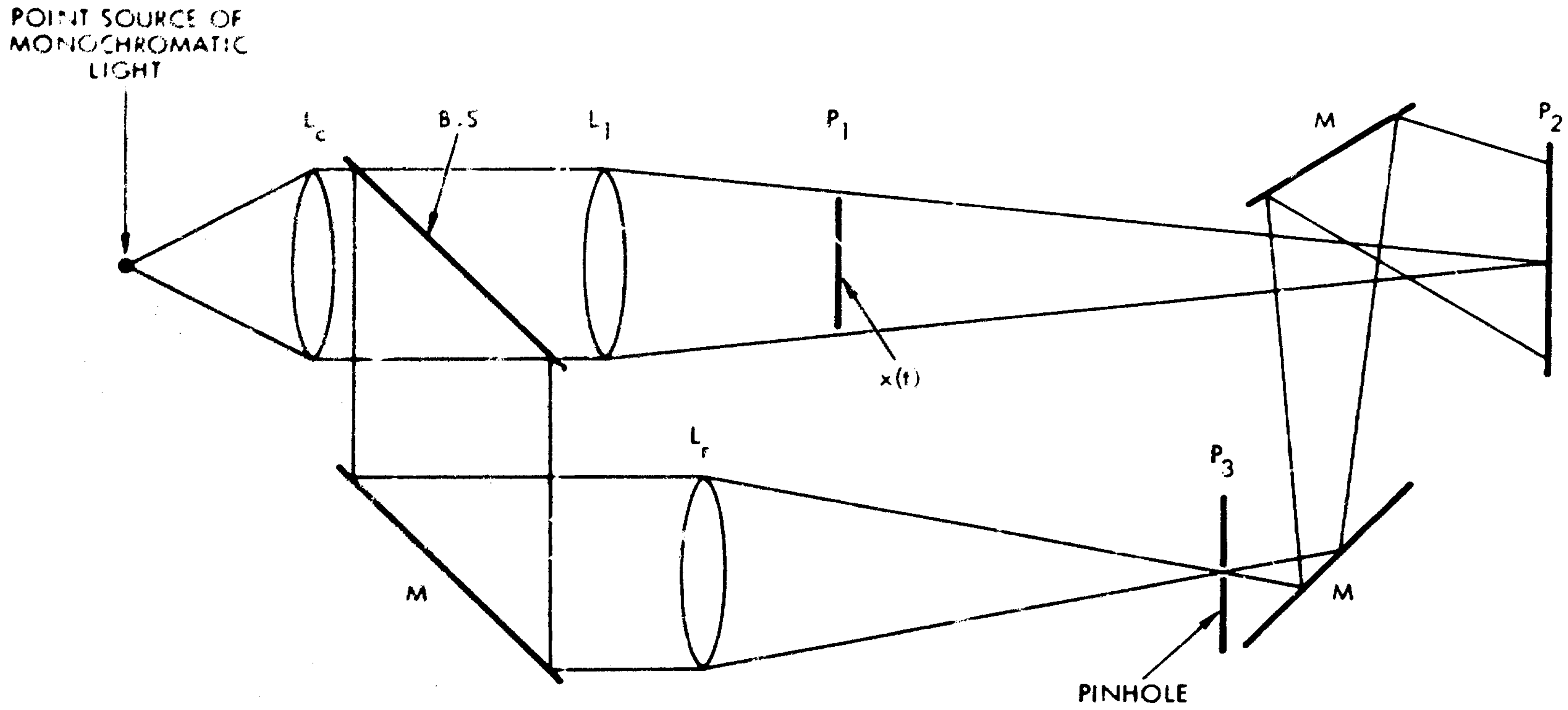


Figure 27. Interferometric Filter-Generator

complex multiply-add cycle. Thus, taking into account overhead for loading/unloading, a FFT processor could do all of this in about 0.25 seconds. Thus, the FFT processor can generate about 4 complex spectra per second with BT products of 1000.

Assuming an optical cross spectrum analyzer processing 16 simultaneous channels, new data must be present in the optical window of two inches at a rate of 2" per 4 seconds. This equates into a film transport velocity requirement of 0.5 inches per second.

However the frequency plane spatial filter must be positioned within a fraction of the diffraction limit of the input aperture. The signal-to-noise loss due to lateral displacement errors is calculated by Vander Lugt (Reference 11) as shown in Figure 28. For the optical system parameters described in paragraph 5.1.3.3, a lateral displacement error of greater than 5μ will cause S/N losses of 10 dB or more. The next paragraph discusses the feasibility of positioning the hologram film within 5μ at the processing rate required to be competitive with FFT digital processing.

5.1.5.2 Spatial Filter Positioning Tolerances For High Volume Processing of Cross Spectra

In order to produce the desired processing performance the photographic mask must be stepped 2" in a 4 second time period and then positioned with an accuracy better than 5μ. Two difficulties exist in accomplishing this goal:

- Extreme measures must be carried out in positioning the film drive; and
- Film stretching during processing and positioning must be very carefully controlled.

It is likely that the only feasible technique for rapid positioning with an accuracy of 5μ is utilization of a transmission encoded position signal on the edge of the film which would be picked up electro-optically and fed into a film drive control loop. Although fabrication difficulties make it an unlikely choice in practice, the mask of Figure 29 is conceptually representative of what would be required in the indicated control loop.

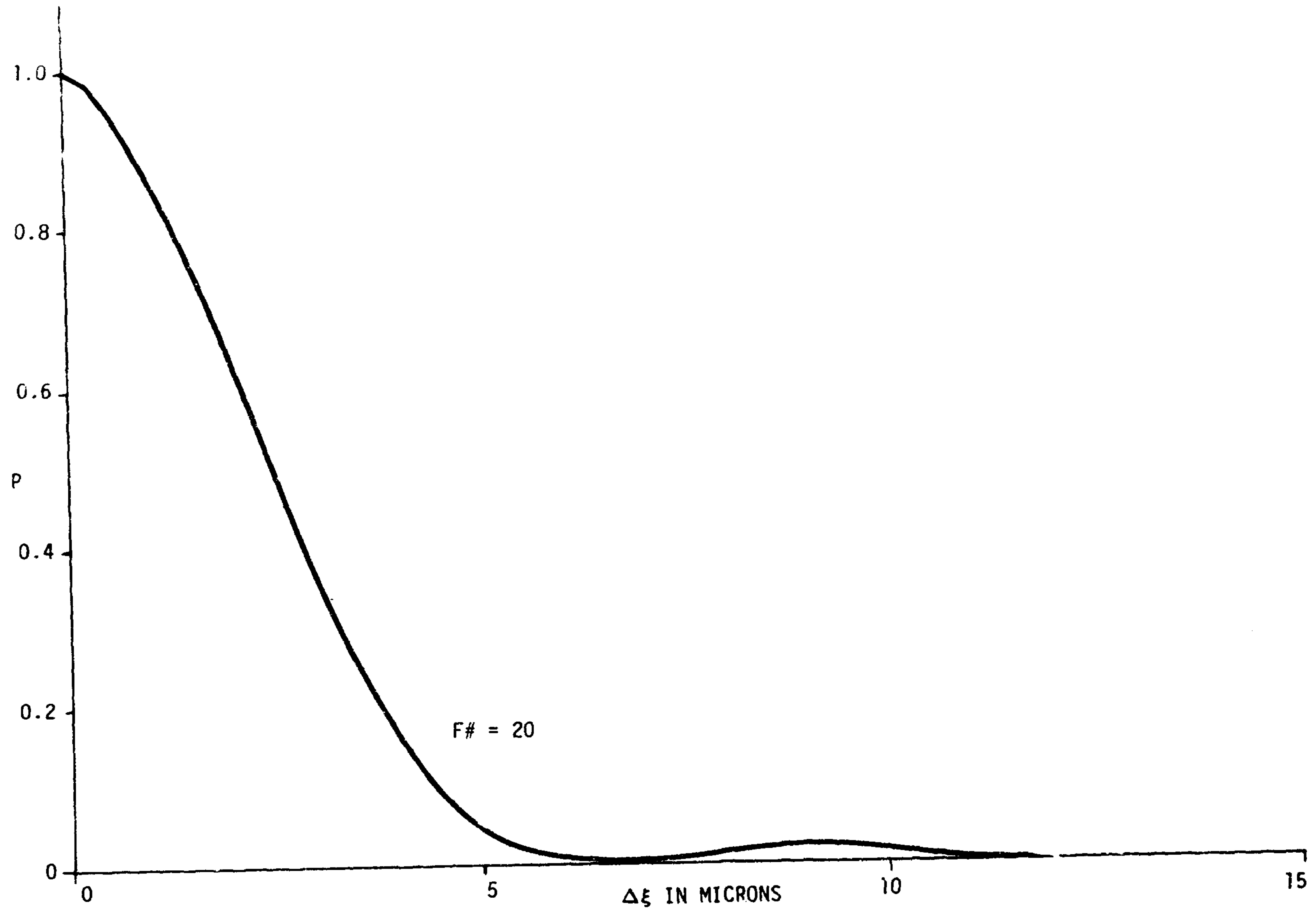


Figure 28. Power Loss in Output of Complex Filter for Lateral Displacement Error $\Delta\xi$

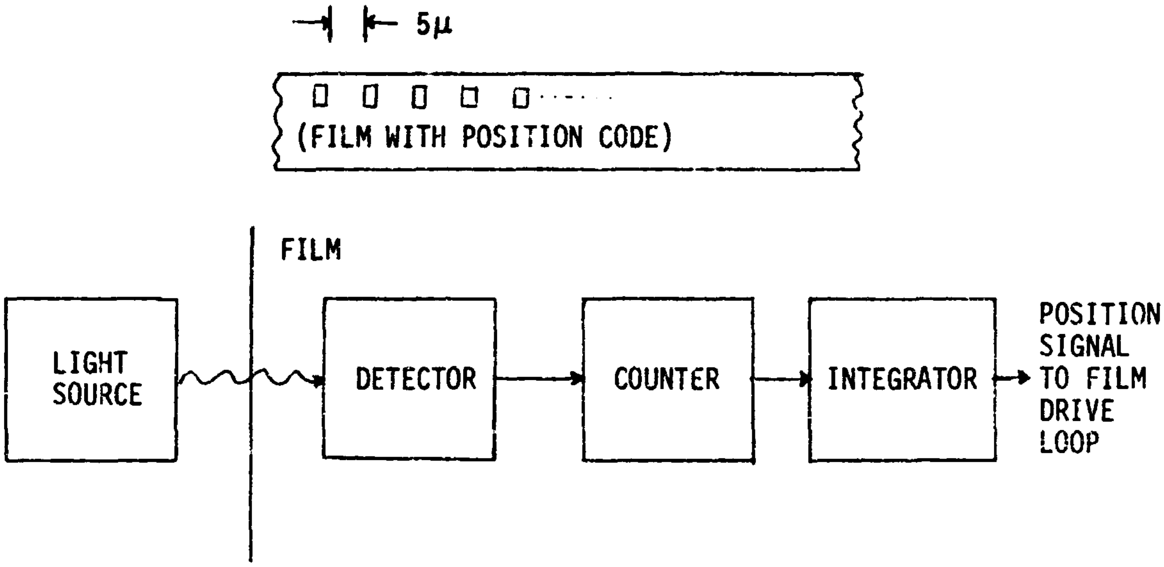


Figure 29. Position Indication Mask and Pickup Block Diagram

From both the position mask fabrication standpoint (required on each piece of production mask) and the control loop time constant standpoint, this concept would be difficult to implement. The required time constant of that control loop is approximated by:

$$\tau = \frac{\varepsilon}{V_T} \tag{11}$$

where

ε = allowable drive error, $<5\mu$

V_T = film transport velocity, 0.5"/sec or 12,700μ/sec

$\tau \leq \frac{5}{12,700}$

$T < 3.0 \times 10^{-4}$ sec

The task of implementing such control, although very difficult, is not impossible but the capability is not now available with off-the-shelf equipment, nor has the cost of supplying the film mask position marking been evaluated.

The film dimensional stability must be evaluated in terms of percentage stability as compared with presently available values. The required dimensional stability is:

$$k \leq \frac{5}{2 \text{ in} \times 25{,}400 \text{ /in}}$$

$$\leq 10^{-4}$$

$$k = 0.01\%$$

Without careful control of temperature and relative humidity before and after processing,irregularities considerably larger than this value occur in even the thickest base film (Reference 12). With $\pm$ 2% relative humidity control and $\pm$ 1°F temperature control, this level of dimensional stability can be approached with normal (<.004") and thick (.007") polyester base film.

In summary, the <5μ positioning and dimensional stability requirements impress a set of severe control problems which would require considerable R&D effort to obtain. Under the ground rules of this study, high volume cross-spectral density processing is not a likely candidate for use in AFFDL present applications.

5.1.5.3 Transfer Function

The transfer function is given by

$$H(\omega) = \frac{G_{xy}(\omega)}{G_x(\omega)} \tag{12}$$

The Allen and Jones article (paragraph 5.1.5) suggests a method adding more optics after the $X(\omega)Y^*(\omega)$ plane of Figure 26. However $G_x(\omega)^{-1}$ will have large values at frequencies where $G_x(\omega)$ tends toward zero (as it will in any physical system). The resulting signal-to-noise degradation can be avoided by transferring G_{xy} and G_x to a controlling digital computer in which operations (12) can be readily performed.

5.2 Digital Processing

5.2.1 Digital Power Spectral Density Analysis

The spectrum analysis functions can be generated with identical analysis parameters in the digital, optical, and analog domains. There are two established methods to digitally implement these functions. The first technique, the direct digital Fourier transform method (Reference 13), is performed in the following steps:

1. Electronically low-pass filter (corner frequency f_c) input analog signal(s) to attenuate frequencies above highest frequency of interest f_c.(See paragraph 4.2.3.2.)
2. Convert data with analog-to-digital sampling rate = $1/\Delta t$, where $1/\Delta t > 2 f_c$.
3. Accumulate N digitized data samples for T seconds, $T = N\Delta t$.
4. Perform digital Fourier Transform of length N and obtain the complex Fourier amplitude X(k).
5. Square X(k) to obtain N/2 power spectral density estimates.
6. Smooth ℓ spectral estimates G_K to obtain desired filter selectivity and bandwidth (this can also be performed by multiplying the digitized data by a time domain function prior to Fourier transform). This technique also reduces the statistical variability of the spectral estimate.
7. Repeat operations 2 through 5 above for M contiguous time records of T seconds duration.
8. Average M G_K values for $K = 0, 1, \ldots, (N/2)-1$ to reduct statistical variability of estimates by $\sqrt{M}$. This is valid only if data is stationary over MT seconds duration.

The computational time of the digital Fourier transform has been made manageable by the use of the Fast Fourier Transform (FFT) algorithm. Until the FFT breakthrough, the digital spectral estimation process was usually accomplished by the Blackman-Tukey method (Fourier transform of Equation 17).

The FFT algorithm computes N/2* complex Fourier coefficients X(k) of the input signal x(t) by

---

* N is usually (but not necessarily) a power of 2 ($N = 2^n$) because of the structure of the FFT algorithm.

$$X(k) = \sum_{n=0}^{N-1} X(n\Delta t) \quad e^{-jkn\Delta t/N} \qquad (13)$$

$$k = 0, 1, \ldots, (N/2-1)$$

where the $x(n\Delta t)$ are the N digitized samples of the analog signal $x(t)$ and the index k represents the location of the N/2 equally spaced synthesized band-pass filters throughout the frequency domain of the spectrum analysis being performed. The power spectral density is calculated by the relation

$$G_K = \frac{\Delta t}{N} |X(k)|^2 \qquad k = 0, 1, \ldots, (N/2)-1 \qquad (14)$$

An example of the above technique is given as an illustration. Suppose one wishes to perform the equivalent to an analog spectrum analysis on the input band 10-1000 Hz with a spectrum analysis filter resolution of 0.5 Hz (BT product = 2000). The band pass filter has a selectivity of -18 dB per octave. Each spectral estimate is averaged for 10 minutes.

To perform this analysis digitally, one first electronically low-pass filters the data with the filter corner frequency set at 1000 Hz. The selectivity of the low pass filter determines the allowed sampling rate within the rms aliasing specification desired in the analysis. Assume that a sampling rate of 4000 samples per second (sampling rate = $1/\Delta t$) is determined from this specification.

The frequency resolution desired in the analysis determines T by the relation that the filter width, Δf, measured at the -3 dB response points is given approximately by

$$\Delta f \approx 1/T \qquad ((7))$$

Therefore, Δf = 0.5 Hz requires that we digitize the analog signal $x(t)$ at a rate of 4000 samples/second for T = 2 seconds. Thus the "length" of the Fourier transform is N = 8000.*

To obtain the desired selectivity of -18 dB/octave for the digitally synthesized 0.5 Hz band-pass filters, we multiply the $x(n\Delta t)$ by the Hanning window as discussed in paragraph 4.2.2. The Hanning Function and other useful "window" functions in optical and digital analyses are found there.

* In practice, the sampling rate would be set to 4096 samples per second to yield N = 8192 = 2^{13}.

The new $x(n\Delta t)$ are now the input to the FFT algorithm, ultimately resulting in 4000 spectral estimates through the application of Equations 13 and 14. Not all 4000 G_K residing in the computer core memory are used however. (Some brochures describing FFT computer hardware give the misleading impression that one has significance in all these estimates - and the associated increase in BT product. But all N/2 power spectral density estimates have physical significance only where there is no spectral content in the data above the Nyquist frequency. "Brick wall" low pass aliasing filters of course do not exist.)

In fact we set up our analysis such that only the first 2000 spectral estimates have meaning, for the 2000 G_K values spaced in the band 0-1000 yield the correct result that the bandpass filters are spaced every 0.5 Hz, with a BT product of 2000.

5.2.2 Digital Cross-Power Spectral Density Analysis

To obtain the cross-power spectral density of analog signals $x(t)$ and $y(t)$ we perform operations 1 through 4 for input data $x(t)$ and $y(t)$, to obtain the complex Fourier Amplitudes $X(k)$ and $Y(k)$. On these data, perform the following to obtain the cross-power spectral density $G_{xy}(k)$.

$$G_{xy}(k) = \frac{\Delta t}{N} X^*(k)Y(k) \qquad k = 0, 1, \ldots, \frac{N}{2} - 1 \tag{15}$$

$$\triangleq C_{xy}(k) - jQ_{xy}(k)$$

where the real and imaginary points correspond to the Cospectrum and the Quadrature Spectrum. The phase spectra is given by

$$\phi_{xy}(k) = \tan^{-1} Q_{xy}/C_{xy} \tag{16}$$

Operations 6, 7, and 8 of the preceeding paragraph apply for statistical averaging and filter selectivity considerations.

5.2.3 Digital Cross Correlation

Operationally there are two methods to calculate the correlation function and depending upon the maximum correlation delay, each has its merits. The lagged-products method gives the autocorrelation R_{xx}

$$R_{xx}(\tau) = \frac{1}{N-\ell} \sum_{n=0}^{N-\ell} x_n \, x_{n+\ell} \qquad \ell = 0, 1, \ldots, m \tag{17}$$

where N is the accumulated number of samples representing T seconds of data and m represents the maximum time delay in the correlation $\tau = m\Delta t$.

The second method is recommended because it uses the identical equipment that is used to calculate PSD and cross-spectrum. To determine autocorrelation one merely performs the inverse Fourier transform of the power spectra (Equation 15) to obtain

$$R_{xx}(\tau) = \mathcal{F}^{-1}\left[\frac{\Delta t}{N} \; |X^*(k)X(k)|^2\right] \tag{18}$$

Replacing one of the x's by another input data signal y(t) yields the cross correlation function R_{xy}:

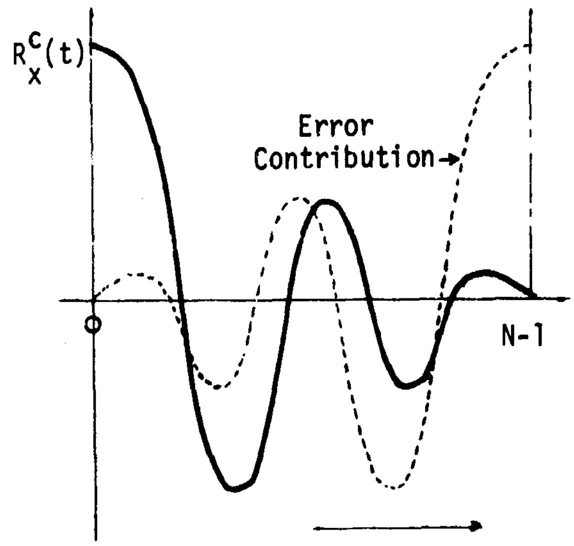
$$R_{xy}(\tau) = \mathcal{F}^{-1}\left[\frac{\Delta t}{N} \; |X^*(k)Y(k)|^2\right] \tag{19}$$

One way to avoid erroneous results is to add N zeros to the input data string of N digitized samples prior to the original FFT. This is to avoid computation of the circular correlation function

$$R^c_{xx}(\tau) = R_{xx}(\tau) + R_{xx}(T - \tau)$$

Examples (Reference 14) of $R^c_{xx}(\tau)$ and the true correlation function $R_{xx}(\tau)$ are shown in Figure 30.

A comparison of the computational speed of the two correlation methods are shown in Figure 31 (Reference 15). It is seen that the mean lagged products route (Equation 17) is more economical when the number of "lags" ℓ is a small fraction of the data sample N. For most cases however, the FFT is superior because one then can compute averages over M discrete time segments to produce a reliable spectrum (see step 8, paragraph 5.2.1).



Circular Correlation Function,
N Zeros Not Added (Superposition of Above Two Parts)

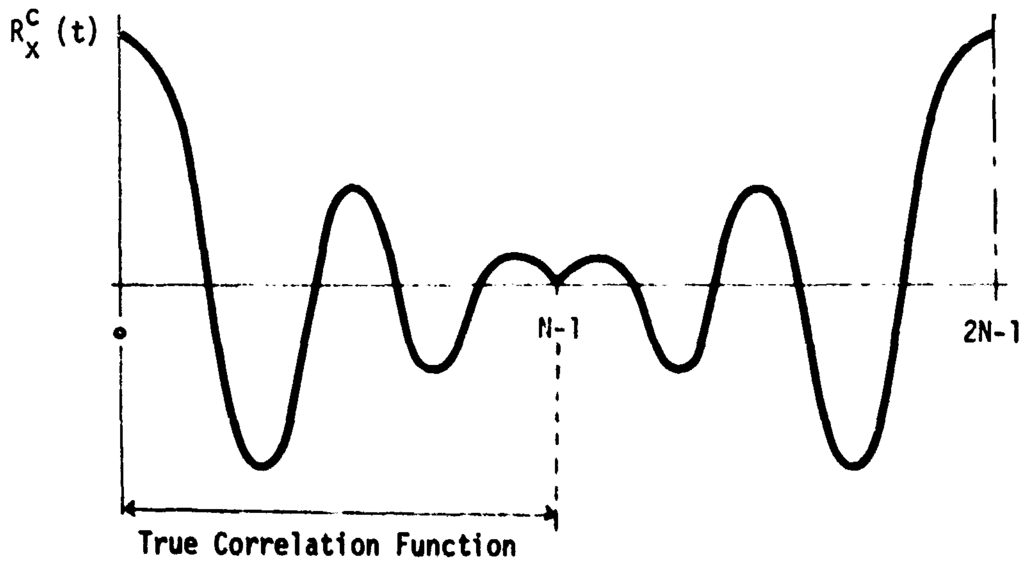


Figure 30. Calculation of True Correlation Function Via Fast Fourier Transform

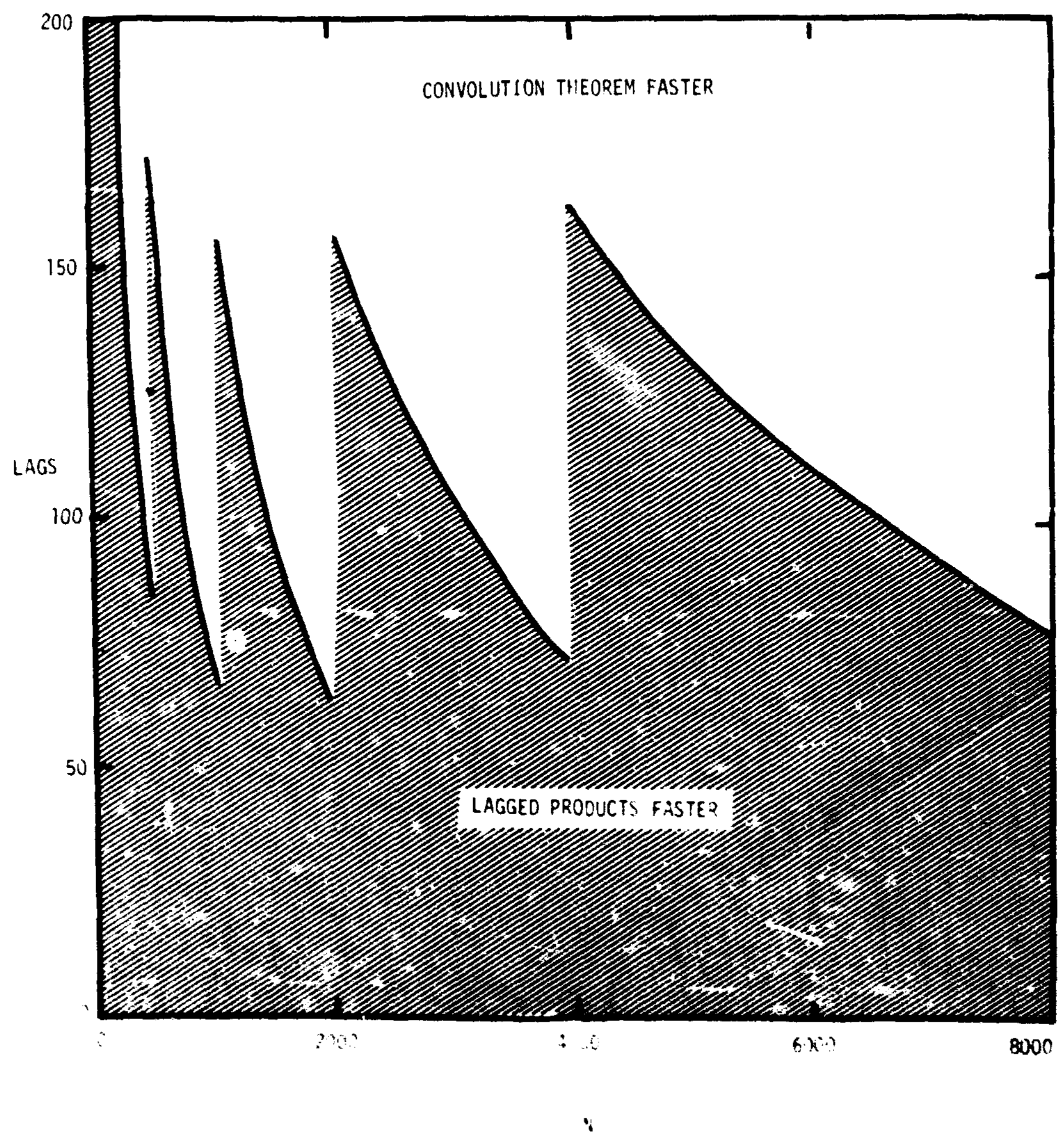


Figure 31. Region Where Correlation Via FFT is Faster Than Summing Lagged Products

Then, the inverse transform can be performed to produce the desired correlation.

5.2.4 The Fast Fourier "FFT Box"

As seen in paragraphs 5.2.1 through 5.2.3, all the initial analysis functions can be realized by computing complex spectral amplitude X(k). Optical processing computes $|X(k)|^2$, and therefore does not have this flexibility.

Industry has responded to the need for a special purpose FFT calculator to enable rapid processing of PSD, correlations and cross-spectra. Most of these FFT "Boxes" are computer attachments which relieve a general purpose computer of the burden of performing these operations. These FFT peripherals do a large portion of the computations -- sufficiently powerful to reduce the requirement for the general purpose computer controlling it to that of the small 16-bit computer available today in the \$10,000 - \$20,000 price range.

A survey of industry's capabilities in this field was taken last year and appears in the June 1969 issue of the IEEE Spectrum of Audio and Electro-acoustics. Cost and FFT sizing data are listed, along with developmental status.

The data in the IEEE article are supplied by the manufacturers and of course give a low cost impression. A study of these equipments acting in an analysis system tailored to AFFDL processing requirements would reflect the real value of these equipments.

5.3 Analog Processing

This paragraph describes the implementation of the PSD function by analog methods. A stationary random input signal x(t) has a power spectral density $G_x(f)$ which is given by

$$G_x(f) = \frac{1}{\Delta f\, T} \int_0^T x^2(t, f_0, \Delta f)\, dt$$

where $x(t, f_0\ \Delta f)$ is that portion of x(t) passed by a narrow band-pass filter. Most PSD analyzers perform the filtering operation by heterodyning the input data signal past a highly selective narrow band-pass filter with a fixed center frequency, f_0.

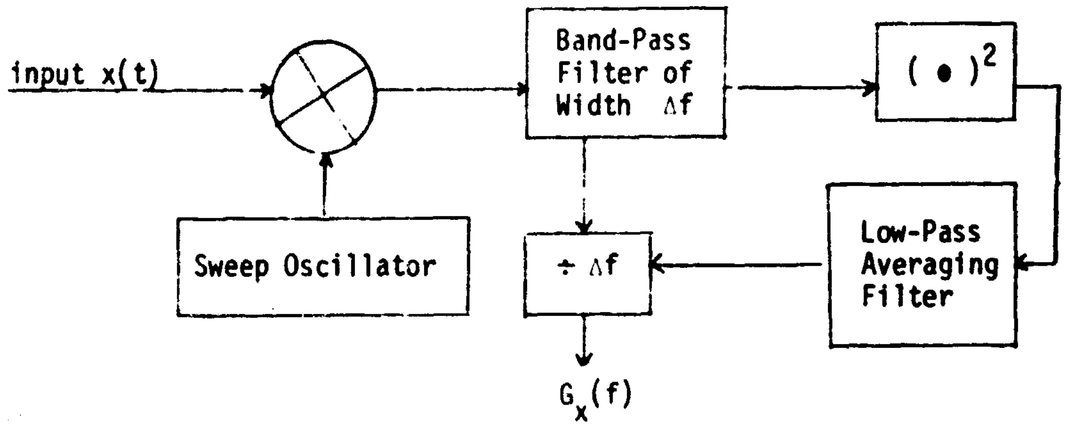


Figure 32. Analog PSD Analyzer

The time window T for the data input x(t) is on a tape loop which is continuously recirculated through the PSD analyzer. The sweep oscillator changes the effective center frequency of the bandpass filter. Each filter requires one tape loop pass through the analyzer. From this it is determined that a 1 Hz constant bandwidth analyzer would require 100 seconds to process a 100 Hz input frequency band. This would indicate that the analog type of spectrum analyzer described above is best suited for low volume processing where the advantage of low initial capital equipment expenditure is important in the overall processing cost.

It is seen in Section VI that the figure of merit for the cost effectiveness study is the need for high-volume high processing rate analysis in which the initial capital expenditure takes less significance. The analog processor is not cost effective in this case. For this reason, a hybrid "analog" processor, the Ubiquitous Spectrum Analyzer manufactured by Federal Scientific Corporation is used to give a more favorable cost comparison for the sweep heterodyne spectrum analysis method.

The Ubiquitous analyzer increases processing speed by the time compression technique (waveform acceleration, in Federal Scientific's terminology) mentioned in Reference 1. This spectrum analyzer is actually a digital/analog combination in which the data is first digitized, stored in memory, and converted into an analog signal in quite the same way as is done with data input to the optical spectrum analyzer as described in paragraph 5.4 below. The analog data is then superheterodyned to a crystal filter whose selectivity is -18 dB per octave. This gives a filter response similar to the Hanning window for optical and digital processing as shown in Figure 14. The Ubiquitous analyzer operates with a BT product of 500 which is nearly in accordance with the AFFDL requirements of Table I, paragraph 4.1. The analysis ranges available in the Ubiquitous spectrum analyzer are shown below.

Range	Analysis Range (Hz)	Bandwidth of Synthesized Filters (Hz)
A	0 - 10,000	20
B	0 - 5,000	10
C	0 - 1,000	2
D	0 - 500	1
E	0 - 100	.2

5.4 TOLCAT Spectrum Analysis Implementation

5.4.1 General

The system capability described in this paragraph is the result of a series of technical exchanges between TRW and the Battelle TOLCAT research group. Optical, digital, and analog designs were presented to Battelle for their review. For reasons stated in paragraph 4.3, a digital implementation for their processing requirements is preferred. However to provide a baseline for a cost tradeoff, optical implementation of a multi-channel spectrum analyzer most closely satisfying the TOLCAT requirements is described below.

5.4.2 TOLCAT Spectrum Analysis Requirements

The following analysis parameters are defined as the minimum requirement for TOLCAT spectrum analysis processing:

1. Input data format: 12 channels on Ampex FR-1300 analog tape recorder- future plans for direct digitization of data in field.

2. Input bandwidth: a) .001 - 1.0 Hz
b) >1.0 Hz

3. BT product: 2000-4000, with majority of computations run for BT = 3500

4. Dynamic range: 40 dB or greater

In addition, the optical spectrum analyzer must compute spectra (PSD) at a rate commensurate with the digital computation rate. The present digital method of computation at Battelle is by the UNIVAC 1108 digital computer. The 1108 can generate a power spectrum in about 2.5 seconds (see Figure 18). However, the new special purpose FFT computer peripherals can perform the same operation in about 0.25 second.

Therefore an optical processor should be able to compute at least four PSD analyses per second to be competitive with digital processing. As there are three decades per channel, a decade optical processor must perform 12 decade spectrum analyses per second. Therefore a spectrum analyzer using the Synergistics PDR-5 32 channel laser recorder (paragraph 5.1.3) designed to present new data every 2.5 seconds in the optical window of a spectrum analyzer is competitive in processing rate with FFT.

5.4.3 TOLCAT Input Frequency Band

From the preceeding paragraph, an optical spectrum analyzer must allow PSD to be calculated at a rate of 32 decades per 2.5 seconds. (This is somewhat faster than a special purpose FFT box acting as a peripheral to a general purpose computer.) The input data is recorded on the PDR-5 36 channel laser recorder described in paragraph 5.1.3. This input medium allows 32 decade frequency input bands to be processed simultaneously. Since the PDR-5 uses photographic film as the recording medium, the spectrum analysis dynamic range is limited to 30 dB.

The TOLCAT input frequency band of .001 - 1.0 Hz lends itself well for digital processing (Reference 16). Without frequency multiplication, this band is too low in frequency to be optically processed. However we have shown in paragraph 4.3 that the data must be digitized for orthogonalization and rotation of coordinates prior to spectrum analysis. This fact facilitates the required frequency multiplication for optical processing. For after orthogonalization, the digitized data can be output through Digital-to-Analog converter modules at a computer clock rate commensurate with the required frequency band for the optical spectrum analyzer.

The output rate through the digital-to-analog converter (DAC) modules can be selected by using the optical input transducer (film recording) parametric curves presented in paragraph 5.1.3. Figure 24 relates the output rate through the DAC's to the spatial frequency on film. An output rate of 3750 KHz can be recorded at a spatial frequency of 70 cycles/mm on the film used in the PDR-5. This spatial frequency is within the film spatial frequency bandwidth as shown in Figure 23.

With these input parameters we see from Figure 25 that the optical spectrum analyzer BT product is 3500 -- which fulfills the design goal for this parameter.

5.4.4 Optical Spectrum Analyzer

The optical spectrum analyzer is designed to operate in the system shown in Figure 33. This system meets the above design parameters with the following major components:

1. Small, general purpose digital computer such as the PDP-11. Computer acting as data acquisition system controllers such as the SEL 840A (at Battelle) or the ITI 4900 (at FDL) also fulfill the requirements. This kind of controlling computer is also needed for the FFT digital processing system.

2. Digital magnetic tape input, 60 KHz character rate.

3. Drum memory.

4. Digital-to-analog converters for 32 channels of analog data for recording on film.

5. Synergistics PDR-5 36 channel laser recorder and film developer (paragraph 5.1.3).

6. Optical processor (Fourier analyzer and output transducer as described in paragraphs 5.1.1 and 5.1.4).

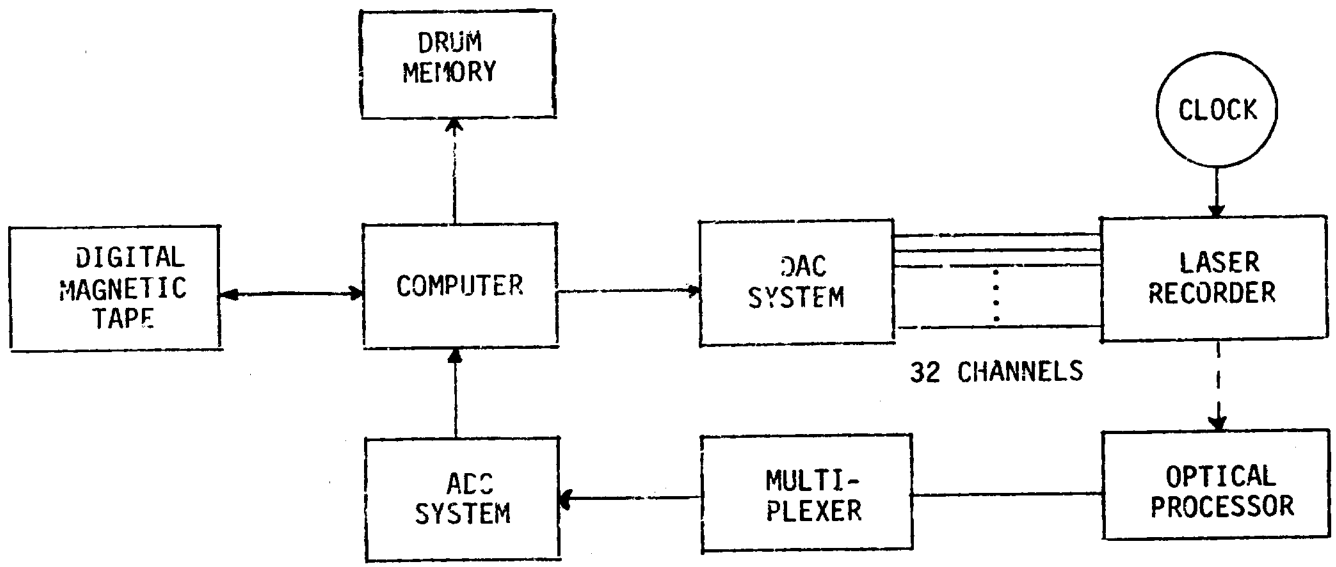


Figure 33. TOLCAT Optical Spectrum Analysis System

7. 32 channel - 64 KHz multiplexer system.

In the TOLCAT optical PSD system the data input is the digitized data which was acquired in Pass I TOLCAT processing, paragraph 4.3. The 32 channels of data are transferred to the 32 parallel tracks on the drum memory. Data preconditioning by the controlling computer is performed as prescribed under TOLCAT Pass II processing. The data are then ready for transfer to the laser recorder.

The data is presented as 32 analog signals to the 36 channel modulator of the PDR-5 Laser Recording system. One channel is used for timing information. The transfer rate through the computer I/O channel is given by

$$\text{Transfer rate} = 2.5 \times 3750 \times 32 = 300 \text{ KHz}$$

The factor 2.5 is present because the data is effectively sampled at 2.5 samples per cycle of the maximum frequency of interest. The 300 KHz transfer rate is feasible for the general purpose computer described above.

After the data is recorded and the film is processed, the optical processor performs the PSD analysis for 32 channels and the results are detected in the output transducer in either constant bandwidth or 1/3 octave spacings, depending on the system requirement. The ADC/multiplex system transfers the results back to the general purpose computer for display formatting.

In terms of cost per PSD analysis, this optical processor is roughly equal to cost for digital implementation for large volume processing of PSD analysis (see cost effectiveness study). However this optical equipment will not perform correlation or cross spectra and separate optical analyzers would have to be purchased in order to implement all functions required for TOLCAT. Since optical implementation of these other functions does not meet performance specifications, they are not considered for the cost analysis.

VI. COST EFFECTIVENESS ANALYSIS

6.1 Scope of Cost Analysis

The task of the cost effectiveness study is to provide cost tradeoff information for the implementation, using present-day technology, of the AFFDL computing functions in which optical processing has demonstrated the required performance characteristics.

The computing functions required were Power Spectral Density (PSD), Auto-Correlation, Cross-Correlation, Cross-Spectra, Transfer Functions, and Probability Density. None of these functions can be implemented by optical processing and meet all performance requirements. Optical PSD analyzers come nearest to meeting minimum requirements. Therefore to gain insight into relative costs of optical, digital and analog methods, this function is treated below.

The main competition to optical PSD analyzers is the Fast Fourier Transform (FFT) digital processor. Last year a special committee called the IEEE Workshop on Fast Fourier Transform Processing conducted a survey of industry to obtain relative performance and cost data from FFT manufacturers. Fifteen manufacturers filled in the questionnaire prepared by the workshop and these results appear in the June 1969 issue of the IEEE Transactions Survey article (Reference 17).

The cost figure of merit in the survey was high volume processing by Fourier Transform. The cost entries were reflected in a cost per analysis which assumes the following: the FFT hardware computes only FFT's for 8 hours every day, and its useful life is exactly 1200 days. This includes the prorated cost of any auxiliary equipment required (e.g., the general purpose computer when the FFT processor is a computer attachment).

The actual cost of course will vary with the system application, but under the above ground rules, the cost per analysis (BT = 1000) varies from .0033 cent to .01 cent. To compare this with the large scale digital computer, a Univac 1108 requires about 3.3 cents for the same analysis. Optical costs for these conditions are given in the following paragraph.

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6.2 Optical Spectrum Analyzer Cost Effectiveness

The purpose of this section is to present an estimate of the cost effectiveness of an optical spectrum analyzer on the basis of cost per 1000 point Fourier transform. The estimate is generated on the basis of 1200 days effective operating life and includes the original prorated cost of equipment plus operator. Maintenance and material are taken to be negligible. The first step is to generate the equipment cost estimate.

The elements of the analyzer and their estimated cost are summarized in Table II. The estimate of film recorder and spectrum analyzer costs are broken out in detail in Tables III and IV. The cost of the digital-analog unit and its power supply are based upon estimates supplied by Redcor Corp. and the output digitizer upon TRW computing equipment cost experience.

Table II.

Item	Cost
32 channel film recorder (including Synergistics PDR-5)	$109,000.
32 channel optical spectrum analyzer	92,400.
Digital-analog converter (Redcor)	8,000.
DACS Power supply	600.
TOTAL	$210,000.

The cost data of Table II is converted to a unit basis by prorating over 1200 days, assuming 8 hour operation per day.

$$K = \frac{210,000}{1200 \times 8}$$

$$K = \$21.9/\text{hour}$$

This figure must be adjusted to include operator salary, taken as $5.00 per hour and to account for an assumed duty cycle of 50% processing; 50% film mask generating. On this basis the adjusted cost is:

$$K' = \$53.8/\text{operating hour}$$

This figure can be converted to a standard reference value by noting that the spectrum analyzer is capable of 32 1000-point Fourier transforms per second, hence:

$$K = \frac{53.8 \times 100}{32 \times 3600}$$

$$K'' = .047¢/1000 \text{ pt. transform}$$

That is, the cost per 1000-point Fourier transform is $.047.

6.3 Cost Summary

The cost for power spectral density analysis can be reflected in two ways - total cost expenditure and cost per power spectral density analysis based on large volume processing.

	Univac 1108	FFT Digital Processor*	Optical Processor	Analog/Hybrid Processor**
Initial cost	$400 per hour	$85,000.	$210,000.	$24,000
Cost per analysis (based on BT=1000, 9600 hours of operation.)	$.033	$.0001	$.0005	$.002

* TIME/DATA proposal No. 21-2053, 26 February 1970.

** Based on TRW In/House Ubiquitous Spectrum Analyzer manufactured by Federal Scientific Corporation (see paragraph 5.3).

Table III. Film Recorder Cost Estimate

		Total
Engineering Labor		$ 7,000
Material:	32-channel Laser Recorder	84,750
	Handling. Technical Services, Travel	17,250
	TOTAL (Burdened)	$109,000

Table IV. Spectrum Analyzer Cost Estimate

	Total
Engineering Labor	$ 9,280
Shop, Technician	9,050
Material	61,500
Handling,Technical Services, Travel	12,600
TOTAL (Burdened)	$92,430

VII. CONCLUSIONS AND RECOMMENDATIONS

Optical processing of the Flight Dynamics Laboratory processing requirement studied in this report has been shown not to be cost effective when considered against digital processing of the same data. Digital implementation provides more than adequate dynamic range - a key performance deficiency in optical processing - and algorithms were developed to digitally (and optically, except for dynamic range) synthesize the wide variety of analysis parameters available in the various analog equipments at FDL. Analog/hybrid processing was shown to be inferior in the cost effectiveness comparison to both optical and digital processing.

The volume and rate of computation were shown to be important criteria for the method of implementation users at AFFDL might wish to consider. For low volume processing, the IBM 7094 or existing analog equipment can be efficently used at low cost. For the rapid processing of large quantities of data, purchase of a digital system with a special purpose Fast Fourier Transform (FFT) peripheral may result in reduction in government expenditure in the long term.

It could be said that the apparent "downfall" of optical processing as applied to FDL data started in 1965 with the appearance of the FFT algorithm. This reduces the number of machine instructions required to compute a digital Fourier transform. Next the integration of high speed microcircuit technology into commercially available logic modules made possible the development of a low cost special purpose "Black Box" hardwired to do the FFT algorithm. By 1969 at least twenty manufacturers were in the FFT market. At the time of this writing, digital processing has simply caught up with optical processing in the time/cost of computing one-dimensional Fourier transforms. Major advances in optical technology must be realized in the input/output devices in order to be competitive. Work in two-dimensional transforms which require subsequent inverse transforms such as image enhancement, is still most effeciently performed by an optical system, however.

With regard to recommendations concerning the "best" FFT equipment, suffice it to say that most of the twenty or more FFT manufacturers known to TRW have equipments that compute, for FDL purposes at least, at more or less the same rate. These equipments compute power spectra faster than it can be displayed and averaging techniques must be used to extract the information (see step #8, paragraph 5.2.1) in a manageable format. The key differences are cost, memory capacity, and flexibility. Memory capacity is important especially to the FDTE-sponsored TOLCAT processing which was treated at considerable length in the report. Flexibility of the computing system is also important because Fourier transforms are a small part of the TOLCAT data reduction problem and it is desirable that processing routines other than FFT can be implemented.

Representative of the digital FFT processing systems is that manufactured by TIME/DATA of Palo Alto, California. This equipment is competitive in price and 38 units have been sold, including systems to JPL, Lockheed, NASA Goddard, NASA-MSC and Holloman Air Force Base. These Government-owned equipments could be tested with AFFDL data prior to any financial committment by the Flight Dynamics Laboratory. Furthermore, some of the software paid for in these systems should be applicable in the processing areas described in this report.

The common limitation in all FFT manufacturers' equipment including TIME/DATA, is the maximum memory capacity of only 4096 words This will impact TOLCAT processing which has shown to require 8192 words. This limitation must be overcome by hardware modification or by use of the decimation-in-frequency algorithm described in Reference 6. The hardware modification is desirable if processing time is a major consideration.

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13. ABSTRACT

An optical data processing study was performed to determine the value of the use of present day coherent optical processing techniques on selected AFFDL data processing problems. Optical, digital and analog implementation of Power Spectral Density, Cross Spectrum, Auto and Cross Correlation, Transfer Function, and Filtering (Convolution) were considered for a wide variety of input data: from low frequency Clear Air Turbulence (cycles/hour) to high frequency acoustic data (10 KHz).

A sample problem supplied by AFFDL was analyzed by in-house optical, digital and analog computers to demonstrate the degree of computational equivalence. Next a study of twelve processing areas at Flight Dynamics Laboratory was performed to uncover promising areas for Optical Processing. Although most requirements could be met, all twelve users reported a dynamic range requirement 10 dB or more than that which is available in established optical processing technology. Areas in which optical processing shows advantages over digital processing, viz., two-dimensional Fourier transforms and high BT products were not desired nor within the current mission of the Laboratory.

Cost data for the three processing methods were generated. For large volume processing, the digital and optical implementations were found to be roughly equal and less than the cost of analog equipment for spectrum analysis. The digital method is found to be system cost effective in that once a special purpose Fast Fourier Transform (FFT) computer is purchased to generate power spectrum, the other functions can be calculated with negligible increase in cost.

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