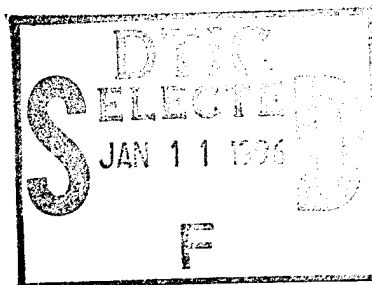


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# ATMOSPHERIC EMISSION AND ANALYSIS EXCEDE III SPECTRAL PROCESSING

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## FOREWORD

The Phillips Laboratory, Geophysics Directorate Environmental Effects Division PL/GPO has conducted a number of field experiments designed to collect information on the infrared characteristics of the earth-atmosphere backgrounds. The successful collection of the infrared background data constitutes the major effort in a field measurement program, however, it must be followed by an intensive activity to reduce the recorded data to a useful form in order to perform analysis and extract the scientific parameters which will characterize the background emissions. This scientific report describes the generation of a computer capability which greatly aids in the processing of data collected under the EXCEDE III program allowing for rapid generation and hands-on interaction with the high resolution spectra.

EXCEDE III was one of several PL/GPO field experiments which were designed to obtain infrared measurements of the atmosphere under the influence of perturbing energetic electrons. The EXCEDE III program utilized a rocket borne electron accelerator to inject a beam of energetic electrons into the atmosphere at altitudes extending over the 80 - 115 km regime. The electron induced radiation was observed by an number of sensors, all of which performed as intended, including a multi-channel, high resolution interferometer-spectrometer. The nature of the data collected by the interferometer-spectrometer is such that the data must be Fourier Transformed to obtain intensity spectra in the frequency (reciprocal wavelength) domain. Several additional computer manipulations of the data are also required to produce the intensity spectra in a useful form. Where the digital data base is very large, as with the EXCEDE III interferometer, it is highly desirable to have direct and interactive capability to perform many operations on the raw data and perform multiple analytical functions. In concert with the principal investigator for EXCEDE III software for a small personal computer has been developed which accomplishes this need.

This Scientific Report presents a brief introduction to the instrumentation flown on the EXCEDE III experiment with emphasis on the interferometer-spectrometer. The digital data obtained from the interferometer is discussed and the magnitude of the data base is presented. The mathematics required to process the interferograms and recover the spectra is reviewed. The computer software developed to provide a self-contained, personal-computer work-station to operate on the EXCEDE III interferograms is described in detail. Examples of the operations are provided. The complete computer code is provided in hard copy and an executable version has been installed at PL/GPO.

## ACKNOWLEDGEMENTS

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Thanks are due to all of the members of the EXCEDE III experiment team for their dedicated efforts in acquiring the data. A special note of thanks is due Alan Thurgood of Utah State University.

We are indebted to Dr. W.G.D. Frederick of BMDO/SN for his continued guidance, support and enthusiasm for this work.

## 1. INTRODUCTION

A major field measurement program was sponsored by the Defense Nuclear Agency in conjunction with the Strategic Defense Initiative Organization and carried out by the Phillips Laboratory, Geophysics Directorate, with support from several contractors. This program, EXCEDE III, was a follow-on to several earlier experiments which explored the phenomenology associated with the interaction of electrons with the atomic and molecular species in the earth's atmosphere [1]. The latest experiment in this series, EXCEDE III, was planned to extend the measurement data base using improved sensors and to utilize a more intense and stable means of exciting the earth's atmosphere. The experimental goal was to obtain detailed spectral and temporal measurements of emissions produced as a result of electrons impacting with the earth's atmospheric ambient species at altitudes above 80 km. The dose rate by the electron beam was much higher (by several orders of magnitude) than would be expected for auroral dosing in order to have sufficient signal levels from the relatively small excitation volume. This high dosing rate allowed investigation of excitation processes involving more than one excited state and extended the number of excitation processes that could be studied by the EXCEDE III experiment. The advantage of the EXCEDE III experiment was that the excitation conditions produced by the electron beam could be controlled in current, energy and time. Thus, the intensity of the radiation induced by the electrons could be referenced to the input dose and the radiative response of the atmosphere to perturbation by energetic electrons could be calibrated.

Considerable effort was expended in the development of a stable, high power, electron accelerator which could be carried aloft by a rocket. Similarly the optical sensors, covering particularly the infrared, but also the visible and the ultraviolet, were designed to match the expected EXCEDE III radiances. In addition, diagnostic packages were assembled to provide an accurate determination of the performance of the system and to define the exact conditions of the measurements. Two separate payloads were used so that the primary instruments could be far enough away from the beam to get a good aspect on the excited atmosphere. The field-of-view, FOV of the primary instruments intercepted the beam far enough from the accelerator module so that nearfield effects, collective effects, and contamination by degassants were all

minimal. The successful preparation and launch of the payload was the result of a very large effort on the part of many experts all working toward a common goal.

The remaining task associated with the EXCEDE III program, following its very productive flight, is the reduction, analysis and interpretation of the data obtained. As with the hardware implementation, scientists and engineers must concentrate on each individual instrument to extract all possible information which relates the emissive properties of the perturbed atmosphere relative to the excitation source. This report is concerned with the infrared emission measured by the Michelson interferometer used to obtain high resolution spectra of the excited atmosphere. Because of the unusual nature of this instrument, several computer intensive activities are required to process the data. In fact, the analysis needs have dictated that a special set of computer programs be developed to assist in the retrieval of the intensity spectra from the raw data. To this end interactive programming has been used to process the raw data on a standard personal computer.

This report briefly describes the interferometer spectrometer and electron beam flown on the EXCEDE III experiment. The fundamental physics related to the recovery of spectra from data taken by an interferometer is briefly described. The computer processing of the raw data is presented to establish the requirements which must be satisfied by the software. The details of the software programs are presented and examples of how to use the system are given. The ease of application and the simplicity of the instructions makes the system very useful for the analysis with immediate interactive control. Although the software is specifically orientated to the needs of the EXCEDE III data processing, the programs are sufficiently general so that they can easily be adapted to other experiments employing Michelson-type interferometers.

## **2. OVERVIEW OF THE EXCEDE III EXPERIMENT**

EXCEDE III was a rocket-borne experiment which was intended to obtain information on the radiative response of a small volume of air in the upper atmosphere to dosing by energetic electrons [2]. In general, the intent was to collect data on the radiative processes which are

produced as the high energy electrons impart their energy to the ambient atmospheric species. The principal interest was centered on the infrared emissions from 2.5 to 20  $\mu\text{m}$  and the ultraviolet/visible from 0.13 to 0.8  $\mu\text{m}$ . High resolution spectra of the infrared emission were required to establish the radiating species, intensities, production and loss sources, and altitude dependence. The visible and ultraviolet emissions were measured to assist in establishing the energy deposition, initial energy spatial distribution and to provide a reference for the determination of the energy efficiency for individual infrared radiating species.

The EXCEDE III payload was made up of two modules, the electron accelerator (electron gun) module and a second module which contained the majority of the optical sensors. The payload was separated from the booster rocket and the modules oriented and separated at a velocity of about 3 meters per second. The gun module was pointed so that the injected electron beam was up the earth's magnetic field lines and the sensor module pointed about 50 meters along the beam from the gun early in the experiment. Figure 1 illustrates the payload concept and geometries involved. The accelerator system consisted of two separate accelerator bays, each powered independently. The electron gun could be operated at 2.6, 2.1, and 1.5 kV so that if a restart was required it would do so at a lower voltage. The gun design was intended to produce an uncollimated beam of electrons at approximately 2.6 kV and 18 amps. At this level the electron dosing gave rise to a peak electron density approaching  $10^9$  per cubic centimeter which is several orders of magnitude larger than is found in an intense aurora. In addition to the electron gun, this module also carried a Circular Variable Filter spectrometer covering 2.5 - 22 $\mu\text{m}$ , film cameras, 6 photometers, a retarding potential analyzer and an electrostatic analyzer; all used to quantify the electron beam performance and the beam environment.

The sensor module contained three CVF spectrometers, ultraviolet and visible spectrometers, an oxygen sensor, two video cameras, an x-ray detector, a scanning photometer package (which swept over the beam) and a Michelson interferometer spectrometer. The three CVF spectrometers were oriented so that one pointed at the beam, one pointed 8 degrees into the afterglow and the third 20 degrees into the afterglow. This configuration of CVF's allows the time history of the emissions to be followed much in the same fashion as a laboratory flowing

afterglow experiment. The interferometer was pointed at the beam to observe the prompt radiating species with high spectral resolution.

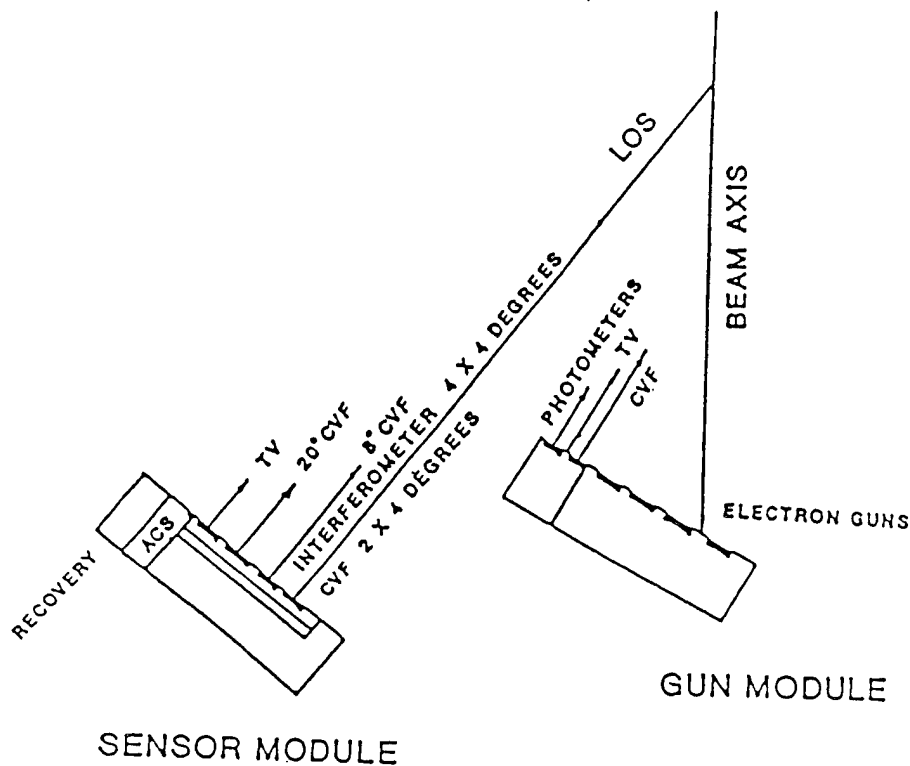


Figure 1. EXCEDE III Payload Showing the Sensor Module and Gun Module.

An Aries rocket carrying the EXCEDE III payload was launched from the White Sands Rocket Range at 01:00:59 MDT, April 27, 1990. The launch was from north to south in order to direct the trajectory parallel to the earth's magnetic field lines at one point on upleg. At this point, ( $t_0 + 141.7$  s) motion of the electron beam across the magnetic field lines is minimized and maximum dosing by the electron beam is achieved. Thereafter velocity of the accelerator and the beam across the field lines increases linearly according to the relation  $v_{\perp} = 4.57(t - 141.7)$  m/s. The payload was separated from the booster at 68 km and followed a ballistic trajectory reaching an apogee of 115 km. Following booster separation the sensor and gun modules were separated from each other at 82 km with a relative velocity of 3.17 m/s. The electron gun and all sensors operated in an outstanding fashion even exceeding expectation.

The first pulse by the electron gun occurred at 120.419 seconds after launch with an active period of 4.730 seconds followed by a beam off period of 2.370 seconds. The first two pulses were unstable but midway into the third pulse the beam became more stable and performed satisfactorily for the rest of the flight. Figure 2 shows the electron beam current relative to time after launch.

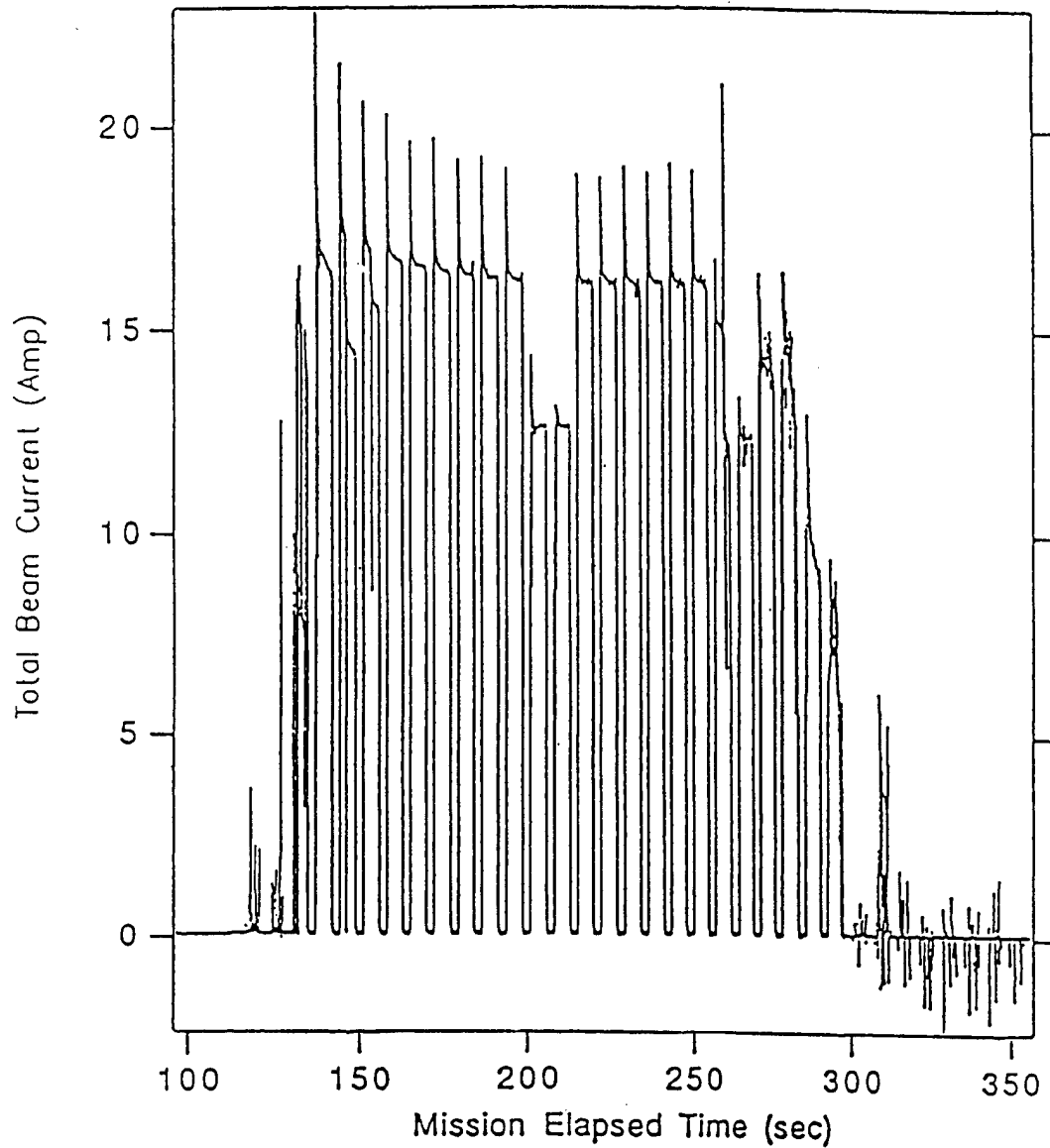


Figure 2. Pulsed Electron Gun Beam Current Versus Mission Elapse Time or Altitude.

The altitude of the payload and the timing for the triggering of the electron gun is respectively given by,

$$h = 115.0 + 0.004732(t - 195.0)^2 \quad \text{km} \quad (1)$$

$$t = 113.319 + 7.100 \times n \quad \text{relative to } t_0 \quad (2)$$

where  $t_0$  is 7:00:59 UT and  $n$  is the number of the gun pulse. As will be shown later the timing sequence is very important for the interferometer measurements. The stability and intensity of each beam pulse must be related to the emission spectrum being measured to give optical infrared efficiency determinations.

### 3. INTERFEROMETER DETAILS

Since this report is concerned with processing software for the data collected by the interferometer spectrometer flown on EXCEDE III, some detail on the make-up of the interferometer and its operation will be reviewed. The Michelson interferometer spectrometer was built by Utah State University [3]. Figure 3 shows the layout of the interferometer. For the EXCEDE III a dual optical cube design was utilized where separate fore optics brought the incident radiation into the individual optical cubes. The interferometer uses a porch swing type of motion to translate the two moving mirrors. Rotation by the torque motor about the pivot produces motion in the two mirrors in opposite directions. Each beamsplitter divides the radiation falling upon it so that half is transmitted through to its moving mirror and half is directed on to its fixed mirror. The radiation reflected from the fixed and moving mirror is recombined at the beamsplitter and directed onto a dichroic filter/beamsplitter (see Figure 4) which spectrally separates the radiation. The two beams emerging from the dichroic beamsplitter are directed to separate detectors and the signals (interferograms) recorded. Thus, the interferometer contains four channels with four separate detectors. The four spectral channels are spectrally isolated to the regions of 2.2 - 4.0, 4.0 - 7.5, 6.5 - 13.0, and 13.0 - 22.0  $\mu\text{m}$  respectively and designated as channels 1 - 4.

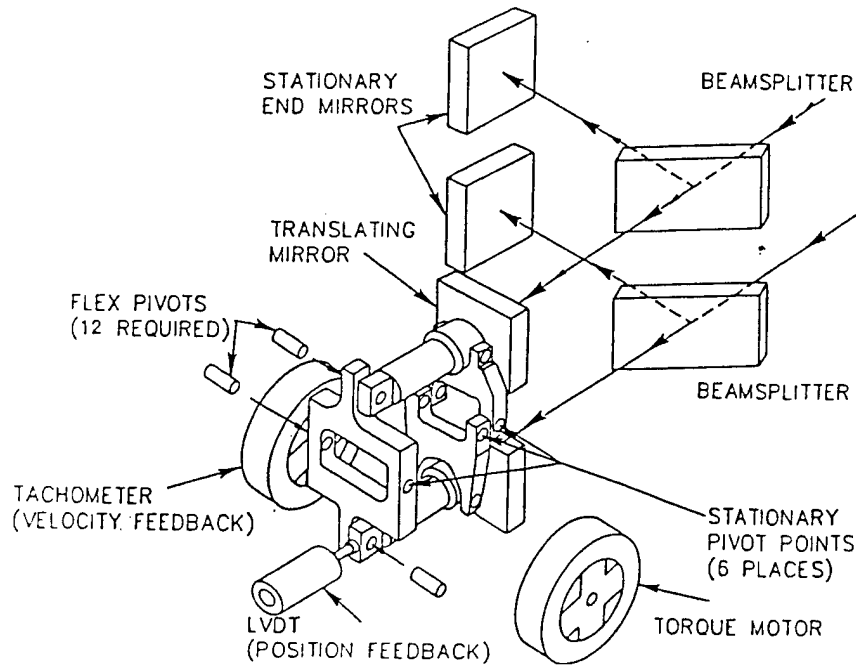


Figure 3. Schematic of the Interferometer Optics and Drive Mechanism.

The spectral channels with specific cut-on and cut-off wavelengths were chosen so that within any one channel only one major atmospheric radiator would be present and, in addition, cover less than one octave. This selection of band limits aids in the dynamic range requirements in a single channel and assists in suppressing nonlinear effects present in detectors and their electronics.

Figure 4 shows more detail of the optical paths in the interferometer and the connection of the moving mirrors. The optical distance traveled by the two beams differs by twice the differential distance between the beamsplitter and the respective mirrors. When the respective mirrors are both equidistant all the recombined radiation is in phase; this is referred to as zero optical path difference, ZOPD. As the optical path difference is varied by the movable mirror different frequencies of the radiation go in and out of phase giving rise to an interferogram. Essentially, an interferogram is the autocorrelation function of the incident radiation falling on the aperture of the interferometer.

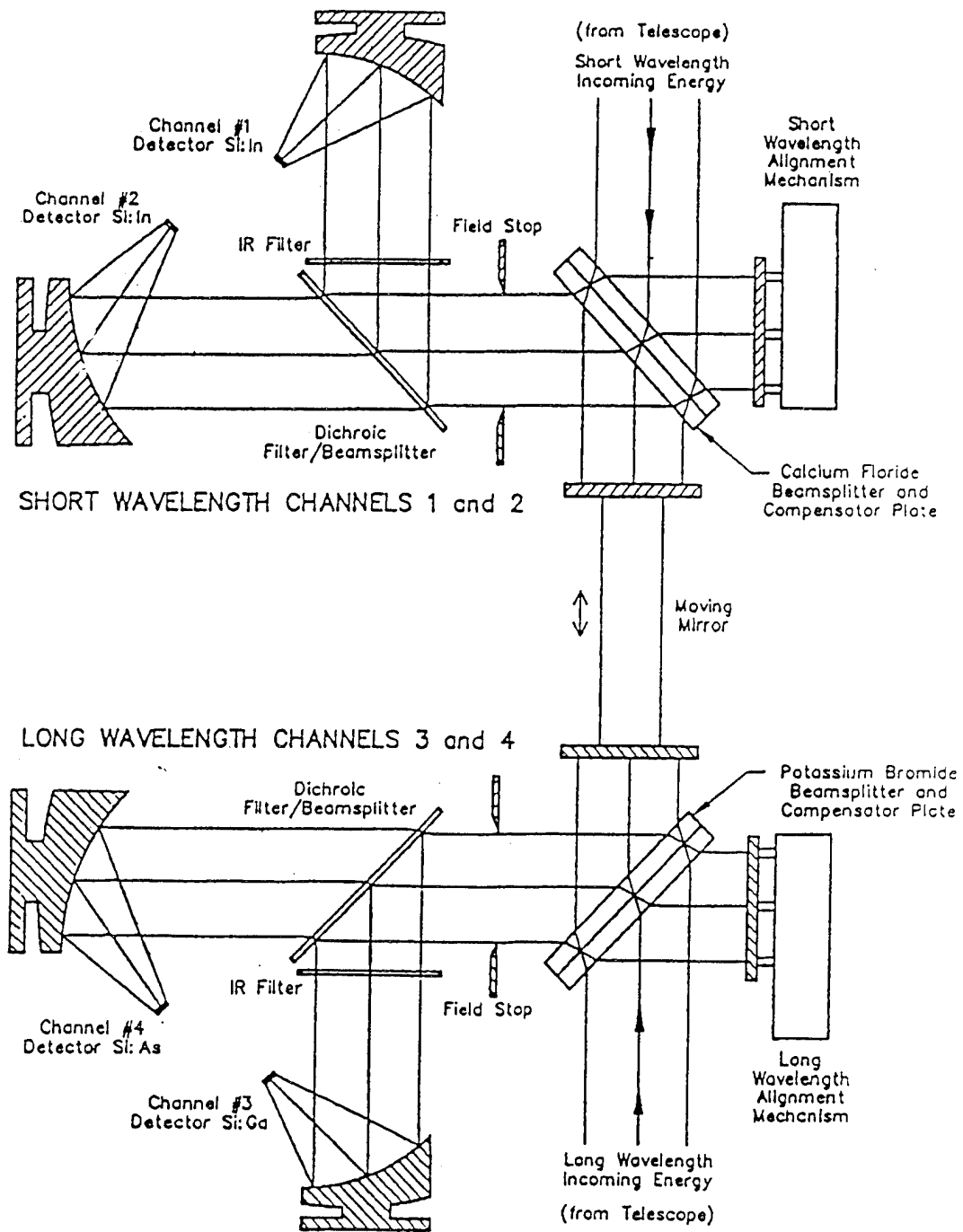


Figure 4. EXCEDE III Dual Optical Cube Interferometer Schematic Layout.

An interferogram obtained from an interferometer contains the multiplexed cosine encoded radiation of the source. It is highly desired that the source be constant over the time duration required to obtain the interferogram. Since the EXCEDE III electron gun was pulsed it was necessary to synchronize the mirror motion to the timing of the pulses. When the electron beam was initiated, the moving mirrors completed two full length scans. During the electron beam off condition the moving mirrors completed one full length scan and a short retrace so as to be in position for the next beam on pulse. Figure 5 gives the approximate timing sequence for the electron gun and a movable mirror.

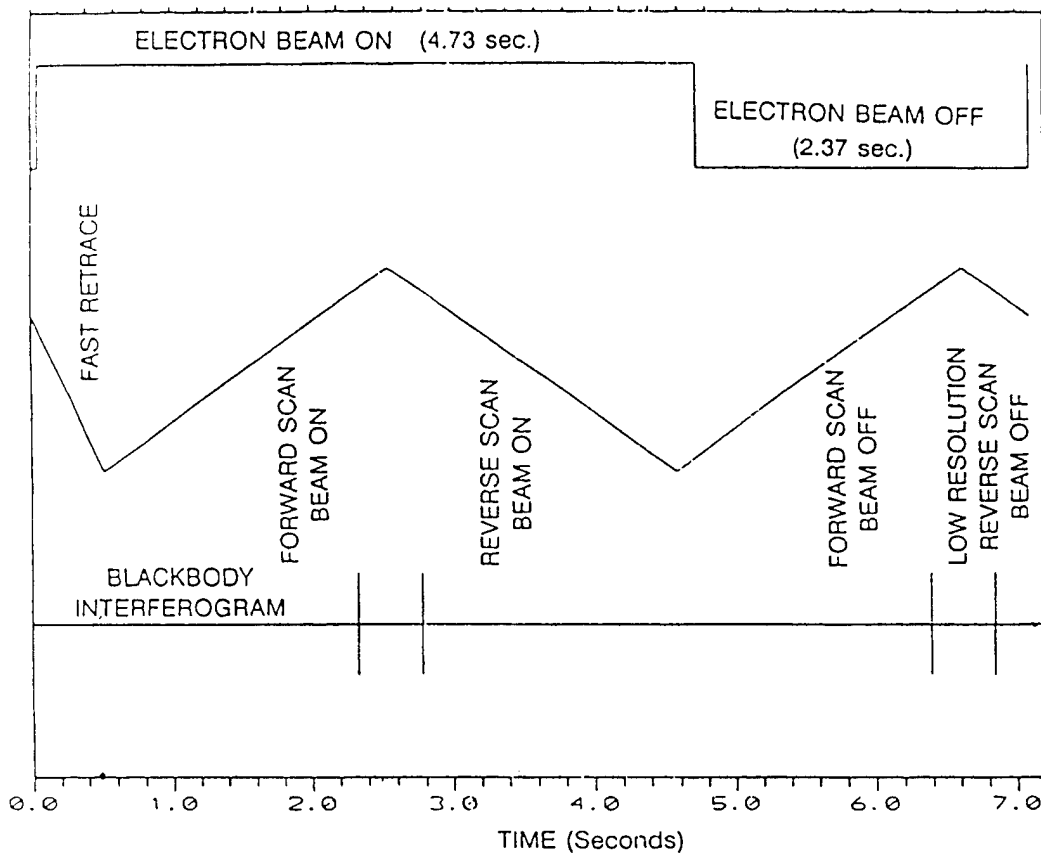


Figure 5. Timing of the Interferometer Scans Synchronized to the Electron Beam.

The moving mirrors were driven so that single sided interferograms were obtained. Ideally, an interferogram is symmetric about the ZOPD. Practical considerations forced the EXCEDE III system engineer to design for single sided interferograms by eliminating almost all of one side of the scan. Enough of the second side of the interferogram was obtained so that phase correction could be done and a full, symmetric interferogram could be created. The interferometer detectors produced an analog output interferogram as the mirrors are driven. The analog interferograms (channels 1 and 2) were converted to a digital data stream by digitally sampling the interferogram at the nulls of a reference channel of He-Ne laser radiation ( $15,798.0117 \text{ cm}^{-1}$ ). For channels 3 and 4 the sampling distance was twice that of channels 1 and 2 or half the sampling rate of channels 1 or 2. The interferogram data in all channels were over sampled to satisfy the Nyquist sampling theorem and eliminate aliasing. The salient specifications of the interferometer are included in Table 1.

Table 1. EXCEDE III Interferometer Spectrometer Specifications.

General Description:	Michelson interferometer with dual optical cubes and a common flex pivot drive system.
SPECTRAL RANGE:	2.2 $\mu\text{m}$ to 7.5 $\mu\text{m}$ and 7.0 $\mu\text{m}$ to 22 $\mu\text{m}$ .
SPECTRAL RESOLUTION:	2 $\text{cm}^{-1}$ apodized
FIELD OF VIEW:	4 degree full angle
SCAN RATE:	2 seconds/scan
SCAN MODE:	Single sided, bidirectional with fast retrace every other scan to synchronize with the electron gun pulse
OFF AXIS REJECTION:	Shaded primary mirror in telescope provides 7 orders of rejection
DETECTOR MATERIAL	Channels 1 & 2 -- Si:IN; Channel 3 -- Si:Ga; Channel 4 -- Si:As
CRYOGENIC DESIGN:	Liquid helium
DYNAMIC RANGE:	16 bit (65535) each data channel
DATA SAMPLING RATE:	4.74 KHz (from laser reference)
SENSITIVITY:	CH #1 2e-11 Watts/cm-2/Sr/cm-1 CH #2 5e-12 Watts/cm-2/Sr/cm-1 CH #3 6e-13 Watts/cm-2/Sr/cm-1 CH #4 3e-13 Watts/cm-2/Sr/cm-1

#### 4. INTERFEROMETER FIELD DATA

The interferogram signals from the interferometer detector electronics were passed through an on-board premodulation filter and then brought down over a telemetry link at 750 kbit per second in NRZ format. The telemetry data was recorded at several receiving sites. The data tapes recorded at the receiving stations were shipped to the Phillips Laboratory at Hanscom AFB, MA. At the laboratory the field tapes were decommutated and computer compatible digital tapes generated. During the course of the flight approximately 100 interferograms were collected from each channel. Channels 1 and 2 produced interferograms with about 9500 data points and channels 3 and 4 gave interferograms with about 5000 data points. The interferograms from channels 1 and 2 contained about 600 points beyond ZOPD and channels 3 and 4 contained about half that number. The interferograms are identified by channel and IRIG time at the beginning of each interferogram which in turn can be related to the electron gun performance and the altitude in the flight.

The raw interferograms on the digitized computer tapes contained relatively few interferograms which had not been contaminated by several unwanted sources. Figures 6a-d show rare examples of the interferograms from channels 1-4 which are free of signal contamination. The majority of the interferograms suffered from defects which could produce serious distortions in the recovered spectra. Figure 7a-d illustrates some of the defects which reside in the interferograms. In Figure 7, identifying letters correspond to various problems associated with an interferogram i.e.,

- T trend in the DC values
- Z DC requires subtraction ie., zero mean
- P effect of an external pulse (gun related)
- S spike often introduced by telemetry
- R periodic disturbance (also on other instruments)
- O offset followed by total drop-out

Some of the difficulties are easily corrected. Others where the disturbance is within the frequency band of the wanted signal require very special attention to restore. In many cases the

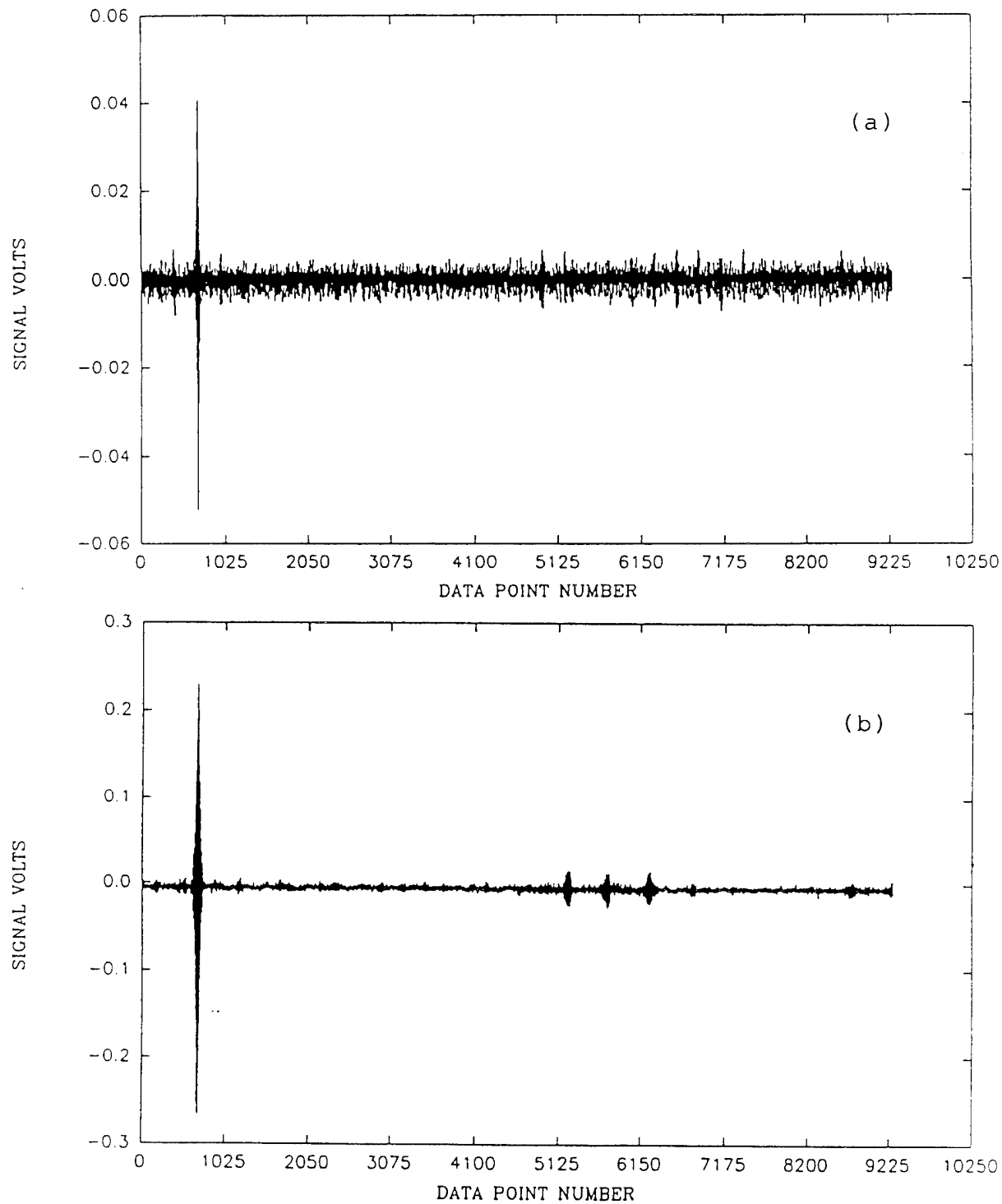


Figure 6 (a,b). Satisfactory Interferograms from Channels 1 and 2 Respectively.

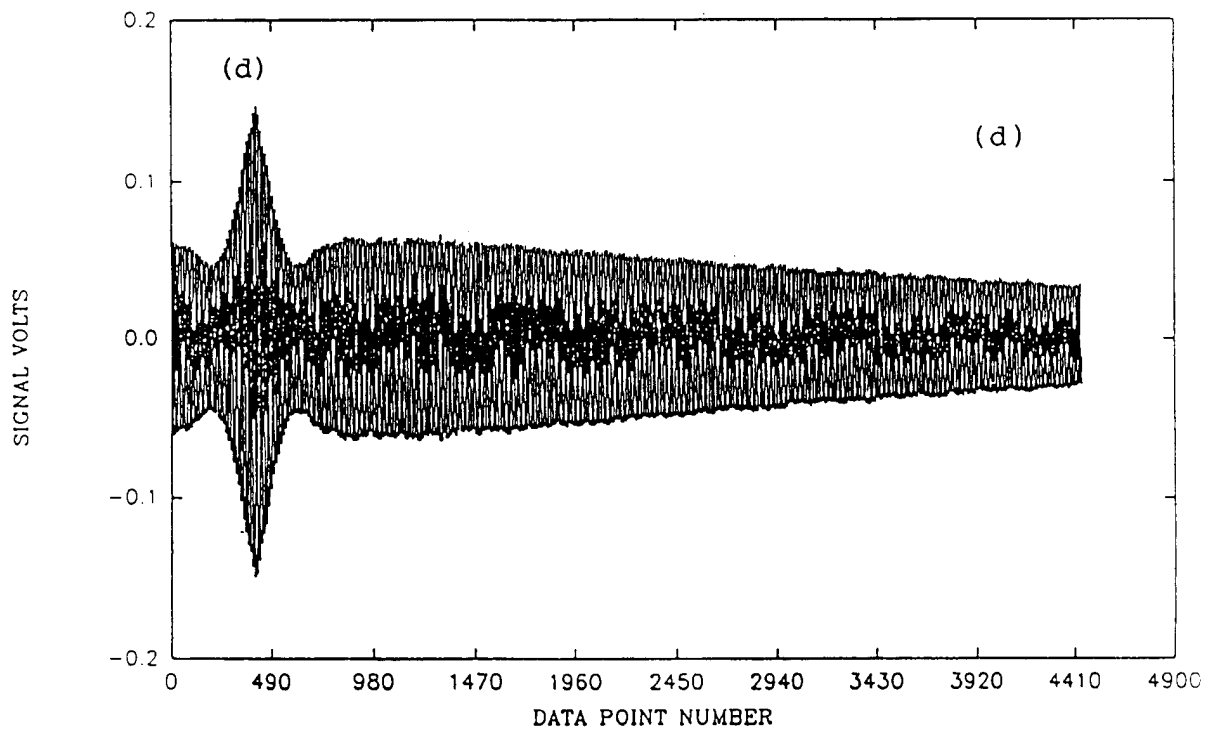
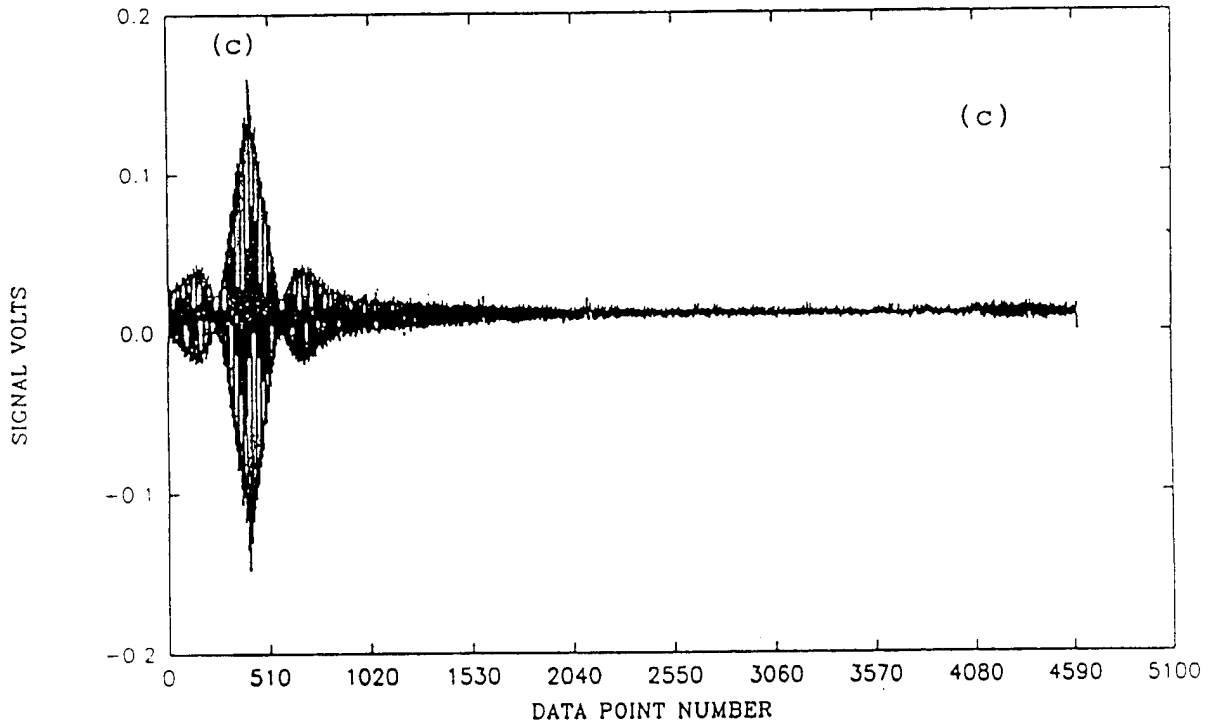


Figure 6 c,d. Satisfactory Interferograms from Channels 3 and 4 respectively.

EXCEDE III INTERFEROGRAMS  
ANOMOLIES REQUIRING CORRECTION

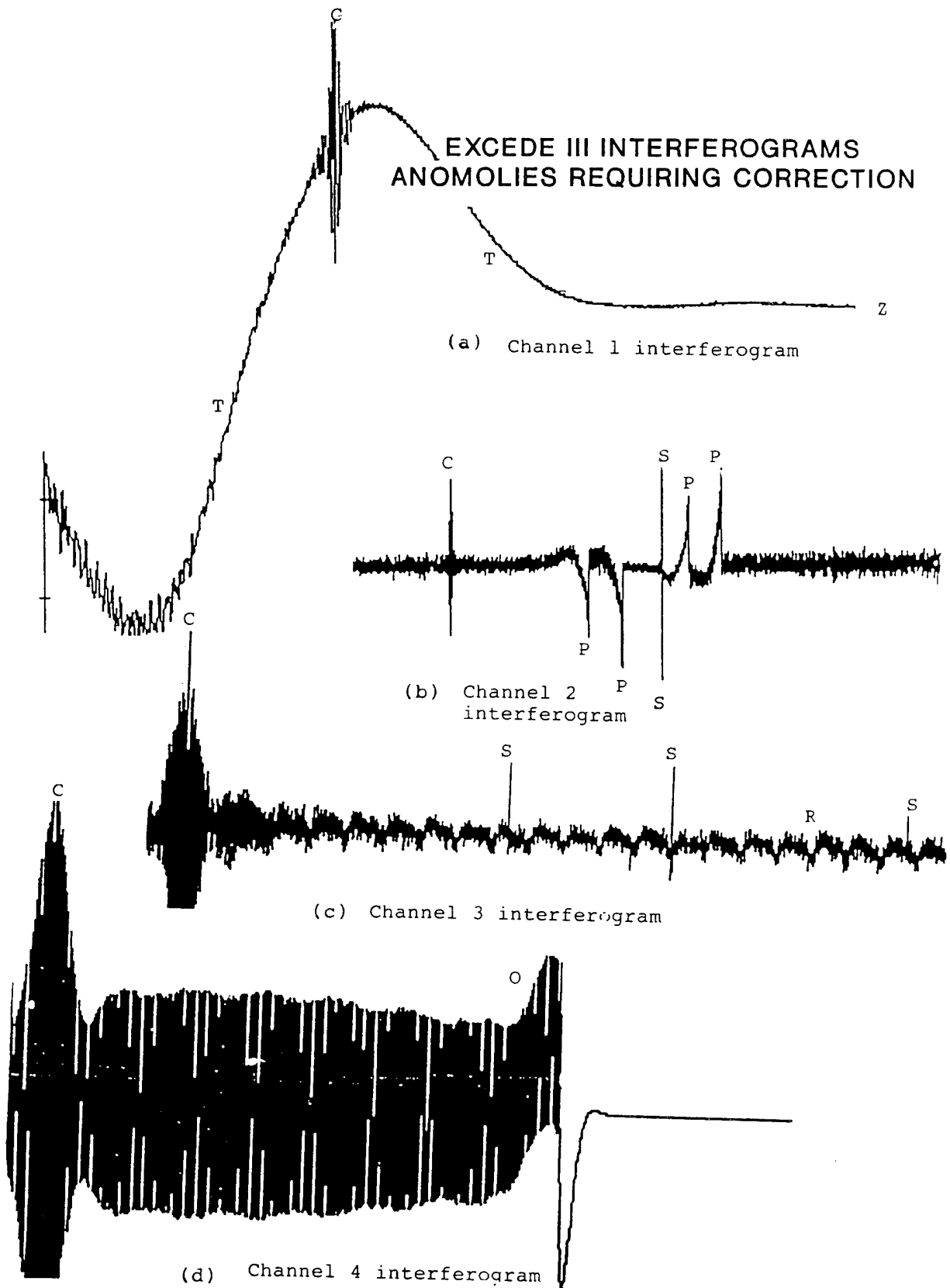


Figure 7 a-d. Interferograms Showing Several Defects Occurring in Channels 1-4  
Respectively.

interferograms were so distorted that the ZOPD was nearly indistinguishable, which made corrections even more difficult. Through the use of a number of labor intensive techniques requiring individual treatment of each interferogram, the interferogram database for the EXCEDE III experiment was generated. This database resides at the Phillips Laboratory and is available to interested investigators. However, they should be aware of the problems encountered with the raw data and the operations performed to bring it to its present form. This data base is the starting place to recover the spectra which can be obtained from the EXCEDE III interferograms. Within the data base the interferogram files are designated by channel and IRIG time, for example the interferograms of channel 1 are designated as 10504D.ASC, 10507D.ASC, 10509D.ASC, etc. indicating laser reference channel 1 beginning at IRIG time 7:05:04, Derived from the computer digital tape (including the special manipulations performed to eliminate the problems encountered with the raw data). The interferograms of channel 2 are similarly designated as 20504D.ASC, 20507D.ASC, and so on.

## 5. SPECTRAL RELATIONS AND THE INTERFEROGRAM

Monochromatic electromagnetic radiation consists of oscillating waves at a specific frequency  $f$  (or wavenumber  $\sigma$ , which is equal to  $1/\lambda$  with the wavelength  $\lambda$  in centimeters). Consider collimated, quasi-monochromatic radiation of spectral distribution  $B(\sigma)d\sigma$  which is divided in half by the beam-splitter of an interferometer (as in Figure 2) and fills the two optical arms (one arm being from the beamsplitter to the fixed mirror and the other arm from the beamsplitter to the movable mirror). If the interferometer arms are of equal length, say  $m\lambda$  where  $m$  is any integer, then an oscillating wave would 'fit' in both arms identically and upon recombination after being reflected from the mirrors would be reinforced or be in phase. This is the condition of ZOPD. If on the other hand one arm was shorter (or longer) by  $\lambda/4$  the radiation in that arm, after reflection, would have traveled less (or more) by the distance  $\lambda/2$  upon returning to the beamsplitter. For this condition waves from the two arms recombining at the beamsplitter are completely out of phase and nullify one another. For distances in between these two conditions the amplitude of the recombined waves take on intermediate values depending on their relative phase or alternatively the path difference  $x$  in the two arms. As the movable mirror is driven

the detector viewing the recombined waves responds to an intensity which goes through a maximum, decreases, reaches a null, and then increases in a sinusoidal manner. The representation of the signal can be written

$$D(x) = B(\sigma)[1 + \cos(2\pi\sigma x)]d\sigma. \quad (3)$$

The detector output or interferogram (after removing the DC level) is a cosine function. If the radiation is made up of more than a single frequency the signal is given by the integral of Eq. (3) over the range of frequencies i.e.,

$$D(x) = \int_0^{\sigma_{\max}} B(\sigma) [1 + \cos 2\pi\sigma x] d\sigma \quad (4)$$

Removal of the DC term from Eq. (4) gives the interferogram  $F(x)$ ,

$$F(x) = \int_0^{\sigma_{\max}} B(\sigma) \cos 2\pi\sigma x d\sigma = \operatorname{Re} \int_0^{\infty} B(\sigma) e^{i2\pi\sigma x} d\sigma \quad (5)$$

If  $B(\sigma)$  were an even function the spectral density distribution could be obtained by a cosine transformation.

$$B(\sigma) = \int_0^{\infty} F(x) \cos 2\pi\sigma x dx \quad (6)$$

Generally,  $B(\sigma)$  is not an even function so for mathematical convenience, negative frequencies are introduced although they have no corresponding physical reality. Any function can be written as the sum of its even and odd parts i.e.,  $B(\sigma)$  is the sum  $B_e(\sigma) + B_o(\sigma)$ . Further, the even and odd functions may be expressed as

$$B_e(\sigma) = \frac{1}{2} [B(\sigma) + B(-\sigma)], \quad B_o(\sigma) = \frac{1}{2} [B(\sigma) - B(-\sigma)] \quad (7)$$

$$F(x) = \int_{-\infty}^{\infty} B_e(\sigma) e^{i2\pi\sigma x} d\sigma + \int_{-\infty}^{\infty} B_o e^{i2\pi\sigma x} d\sigma \quad (8)$$

It is easily seen that the real interferogram becomes

$$F(x) = \int_{-\infty}^{\infty} B_e(\sigma) e^{i2\pi\sigma x} d\sigma = \int_{-\infty}^{\infty} B_e(\sigma) \cos 2\pi\sigma x d\sigma \quad (9)$$

In practice the interferogram is truncated by the limits of the movable mirror, over the maximum distance  $X$ . The truncation function  $T(x)$  is unity between  $-X$  and  $X$  and is zero elsewhere and the finite interferogram is

$$F(x) = \int_{-\infty}^{\infty} T(x) B_e(\sigma) e^{i2\pi\sigma x} d\sigma \quad (10)$$

and

$$B(\sigma) = \int_{-\infty}^{\infty} T(\sigma') F(\sigma - \sigma') d\sigma' = \tilde{T}(\sigma) * \tilde{F}(\sigma) \quad (11)$$

where  $*$  denotes convolution and  $T(\sigma)$  is  $2X\text{sinc}(2\sigma X)$  and the  $\tilde{\phantom{x}}$  indicates the Fourier transform.

For an ideal interferometer no phase distortion of the interferogram occurs and it is symmetric so that a cosine transform will recover the spectral density distribution. However, in most cases the interferometer optical components introduce a phase shift which is nonlinear

and frequency dependent. If the interferometer movable mirror is driven equi-distant from the ZOPD, from  $-X$  to  $X$ , the spectral density is the modulus of absolute value i.e.,

$$B(\sigma) = (C^2 + S^2)^{1/2} \quad (12)$$

where  $C$  and  $S$  are the cosine and sin transformations respectively.

In the EXCEDE III interferograms there was considerable phase distortion. The EXCEDE III interferometer was operated in a single sided mode where the optical path difference was scanned from the maximum optical path difference  $X$  through ZOPD to a small distance beyond ZOPD. For single-sided interferograms, the interferogram is represented by

$$F(x) = \int_{-\infty}^{\infty} B(\sigma) e^{i[2\pi\sigma x + p(\sigma)]} d\sigma \quad (13)$$

with the values of  $F(x)$  confined within  $-dX$  to  $X$ . The phase function can be obtained from a short double-sided interferogram. The Fourier transform of the interferogram extending from  $-dX$  to  $dX$  is

$$\int_{-\infty}^{\infty} B(\sigma) e^{ip(\sigma)} \text{sinc}[2dX(\sigma' - \sigma)] d\sigma \quad (14)$$

where  $B(\sigma)$  is an even function with the asymmetric nature being explicitly related to the phase function produced by the optical components of the interferometer. Due to the physical nature of the optical components, the expression  $e^{ip(\sigma)}$  varies very slowly compared to  $\text{sinc}(2X\sigma)$  and may be taken outside the integral,

$$e^{ip(\sigma)} \int_{-\infty}^{\infty} B(\sigma) \text{sinc}[\sigma X(\sigma' - \sigma)] d\sigma \quad (15)$$

The phase from a double-sided interferogram is simply the arctan of the imaginary part divided by the real part or

$$p(\sigma) = \frac{\int F(x) \sin(2\pi\sigma x) d\sigma}{\int F(x) \cos(2\pi\sigma x) d\sigma} = \arctan(S/C) \quad (16)$$

The phase function may be obtained from a single-sided interferogram by performing the sine and cosine transform over the very short optical path difference  $-dx$  to  $dx$ . Note that  $B(\sigma)$  is the Fourier transform of the measured interferogram modified by the apodization function

$$B(\sigma) = \text{Real } e^{[-ip(\sigma)]} B_u(\sigma) \quad (17)$$

An equivalent expression for  $B(\sigma)$  may be written as,

$$B(\sigma) = |B(\sigma)| e^{i\beta(\sigma)} \quad (18)$$

and the expression for the phase-corrected spectrum becomes,

$$B_c(\sigma) = |B_u(\sigma)| \text{Re } e^{[i\beta(\sigma) - p(\sigma)]} \quad (19)$$

or

$$B_c(\sigma) = |B_u(\sigma)| \cos[\beta(\sigma) - p(\sigma)] \quad (20)$$

which is the more familiar as the Mertz form [6].

A ramp function is used to calculate the phase corrected spectrum which consists of a linear, left ramp of short extent which passes through the chosen ZOPD with a magnitude of one half. The ramp extends equally on either side of the ZOPD with magnitude from zero to unity and then extends with a constant value of one to cover the full length of the interferogram. The ramp portion essentially multiplies the interferogram on either side of the ZOPD so as to eliminate counting the information about ZOPD twice. An apodizing function which has a value of one-half everywhere along the ramp function and abruptly becomes unity where the ramp first takes the value of one would also account for proper counting of information. However, the abrupt nature of this step function introduces unwanted effects in the instrument line shape and is therefore not acceptable. The ramp function described earlier is used in the programs which follow.

It should be noted that a more general phase function,  $\phi(\sigma)$  may contain both phase slip due to improper selection of the ZOPD in addition to the phase introduced due to the optical components of the interferometer. The phase for these two effects is given by

$$\phi(\sigma) = p(\sigma) + 2\pi\epsilon\sigma \quad (21)$$

where  $\epsilon$  is the displacement from the true ZOPD. The choice of an offset ZOPD is accommodated in the process of determining the phase function from the short, double-sided interferogram. If the chosen ZOPD is selected with a large displacement relative to the true ZOPD, distortion to the recovered spectrum can occur. For the EXCEDE III interferometer the mechanics producing the mirror turn around points were very reproducible and the ZOPD occurred within a few points of the same position for forward scans and similarly, but with a different position, for the reverse scans. Consequently, selection of the ZOPD was never very far from the true position and spectrum errors from this problem are easily avoided.

## **6. DESCRIPTION AND USE OF THE SOFTWARE**

Up to this point, it has been shown that the EXCEDE III data obtained from the

interferometer spectrometer contained many faults of various origins which were recorded on the field data tapes. These anomalies were preserved in converting the field tapes to computer compatible digital tapes. With considerable individual attention given to each interferogram a corrected version of each interferogram was generated. Digital files of all corrected interferograms are kept at PL/GPO. These data files easily fit into a modest personal computer. The material in this section deals with the capabilities which have been developed to investigate the spectral information which is contained in the corrected data files.

The directory of files (Fortran programs are given in Appendix A) for the software utility developed for use with the EXCEDE III interferometer data is :

```

Directory of C:\REM
.                <DIR>
..               <DIR>
FILTER   DAT      43
CAL1    ASC     24437
CAL2    ASC     15994
CAL3    ASC      9000
CAL4    ASC     4715
DATFILE DAT      27
COADD   EXE     228050
RANDY   EXE     405230

```

The right-hand column gives the bit count for the respective files. It is seen that the memory requirement for these programs is relatively small and can easily be accommodated by a personal computer. The function of each file is described briefly in the following:.

**FILTER.DAT:** This is an ASCII file used to set the cut-on and cut-off frequency (in wavenumbers) for each of the four spectral channels of the interferometer. The digital filter permits frequencies to be chosen to isolate a spectral region or may be used to help the signal to noise ratio by eliminating the noise outside the spectral region of interest. This file is shown in Table 2. These values for the filter band edges have been included with the delivery of the software to PL/GPO.

TABLE 2. Filter File

2650	4650
1330	2700
800	1430
465	830

The wavenumber values in the first row corresponds to the long wavelength upper band limit in column one and to the short wavelength band limit in column two for channel 1. Similarly, the rows two through four are the band limits for channels 2 through 4. The numerical values for this file can be modified with any standard editing routine.

CAL1.ASC: This is a calibration file for channel 1. The numerical values in the file are the factors required to convert the output voltages to engineering units. Interferograms are recorded in volts which may be Fourier transformed and then converted with the calibration factors to give the intensity in terms of the engineering units i.e., watts/cm<sup>2</sup> sr cm<sup>-1</sup>. The CAL files supplied with this software are based on the laboratory calibrations performed by Utah State University (USU) prior to the actual flight of EXCEDE III. It is known that the pre-flight calibrations are slightly inaccurate, however, they are currently the only calibration values available. It is anticipated that a better calibration will become available in the near future. Part of the advantage of this software package is that when a better calibration becomes available, it can be substituted directly into the Cal files. Figure 11 shows the calibration curve generated by USU for channel 1 which has been taken to produce CAL1.ASC. Similarly, CAL2.ASC, CAL3.ASC and CAL4.ASC are files for the conversion to engineering units for channels 2, 3 and 4. Figures 12 through 14 show the USU calibration curves for channels 2 through 4 respectively and have been delivered with the software package.

COADD.EXE: This is a routine which will add the interferogram values at a specific sampling point (optical path difference) for all sampling positions over the complete interferogram to the corresponding values of other selected interferograms. In this fashion, the numerical value in the coadded interferogram is the sum of the individual contributions at each

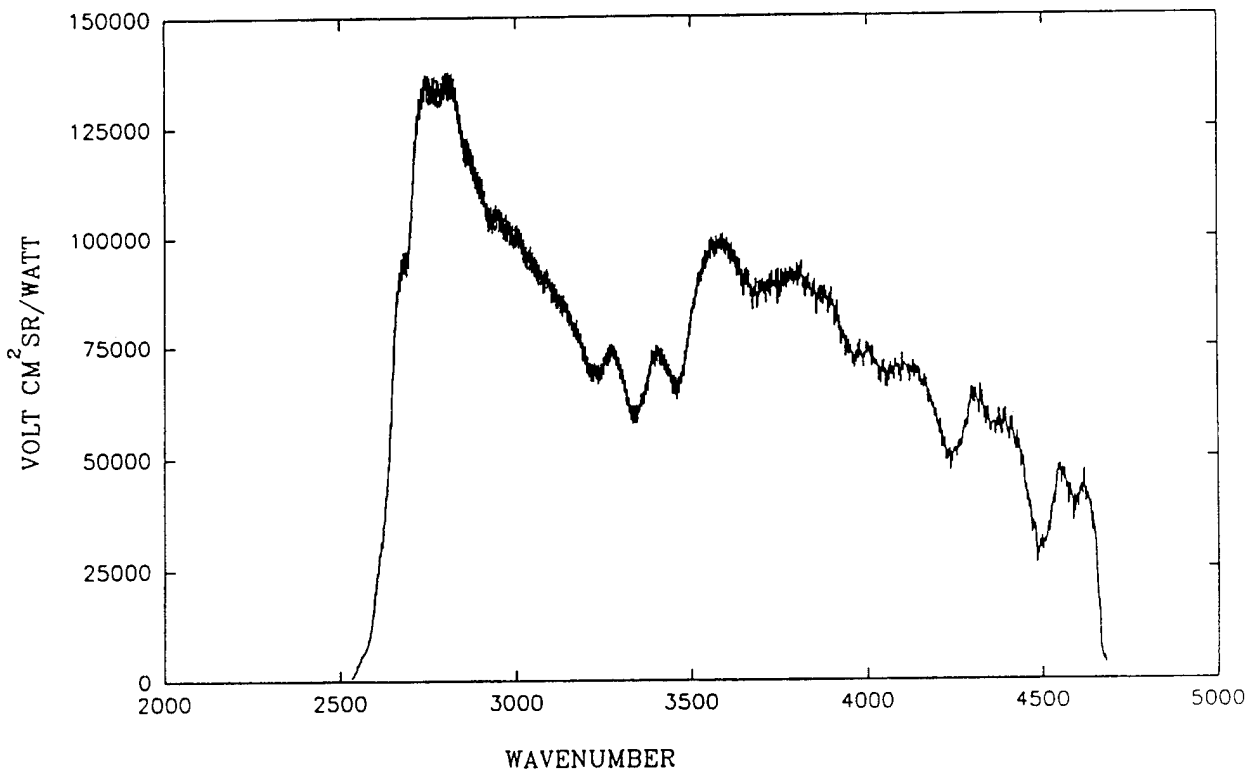


Figure 8. Spectral Response of Channel 1.

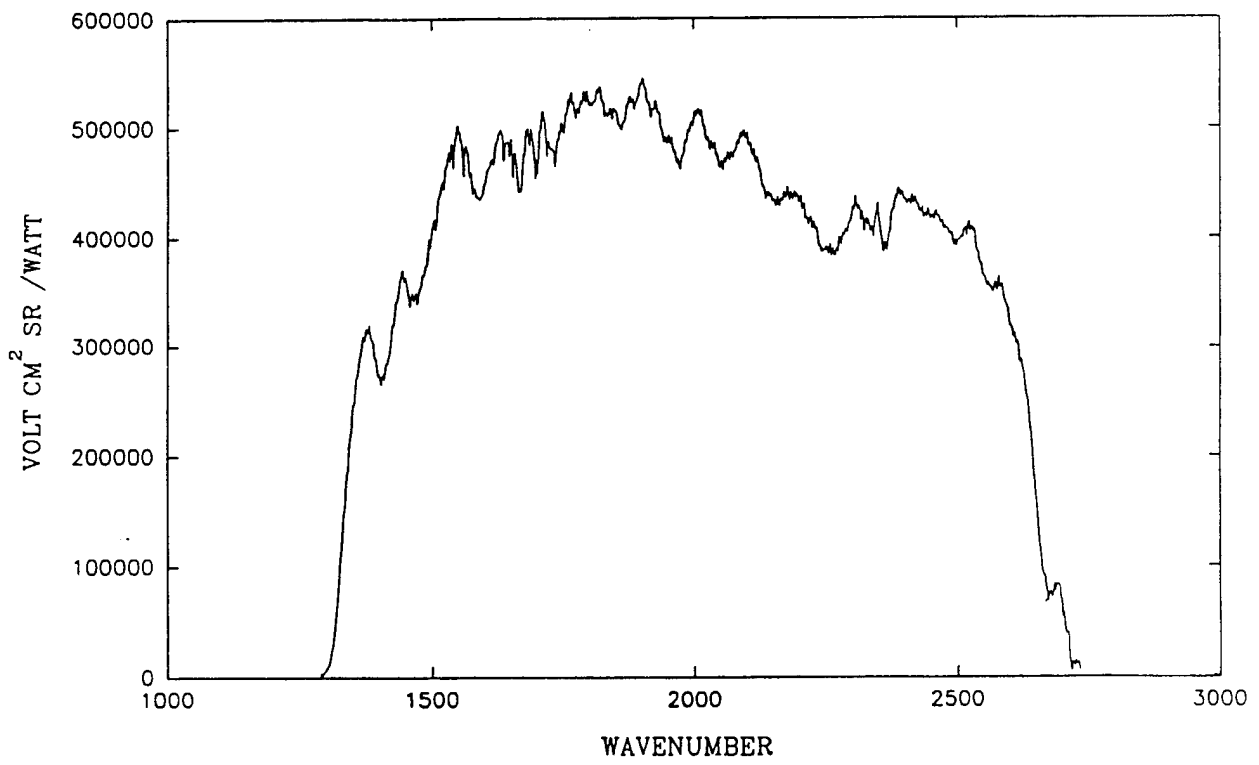


Figure 9. Spectral Response of Channel 2.

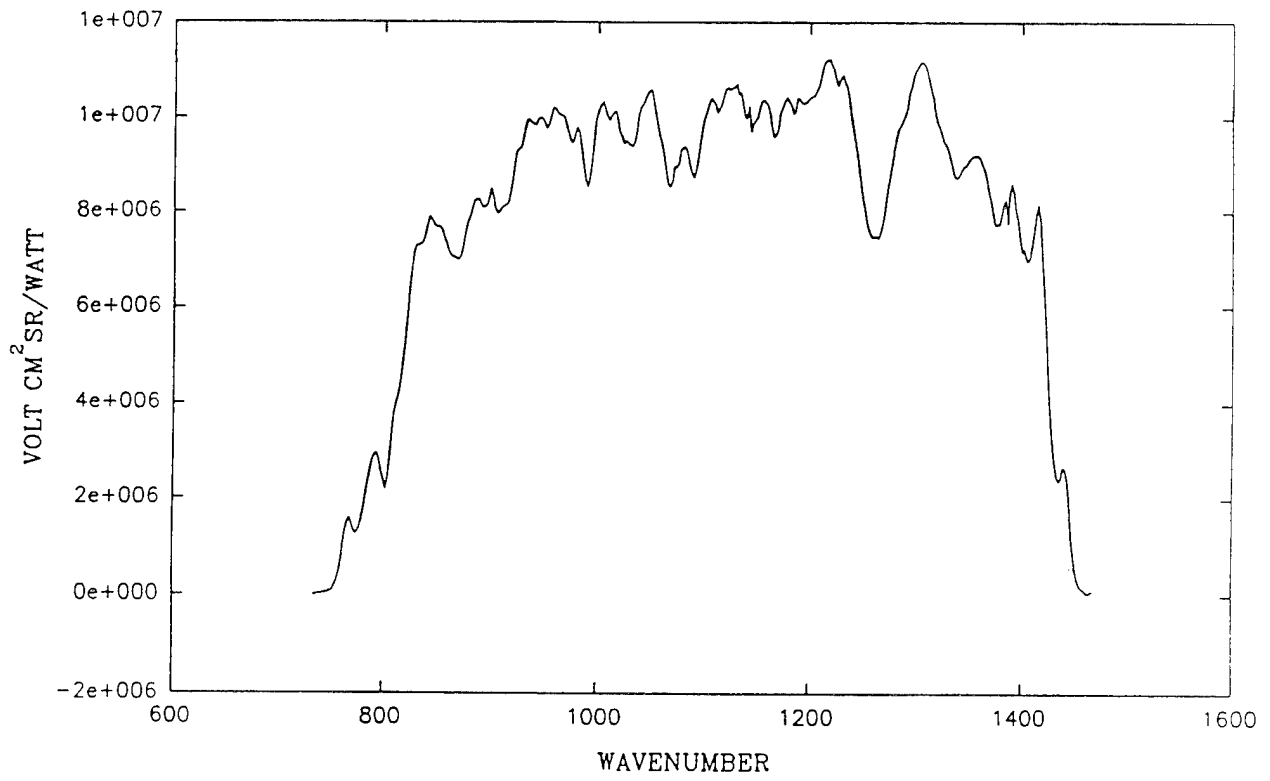


Figure 10. Spectral Response of Channel 3.

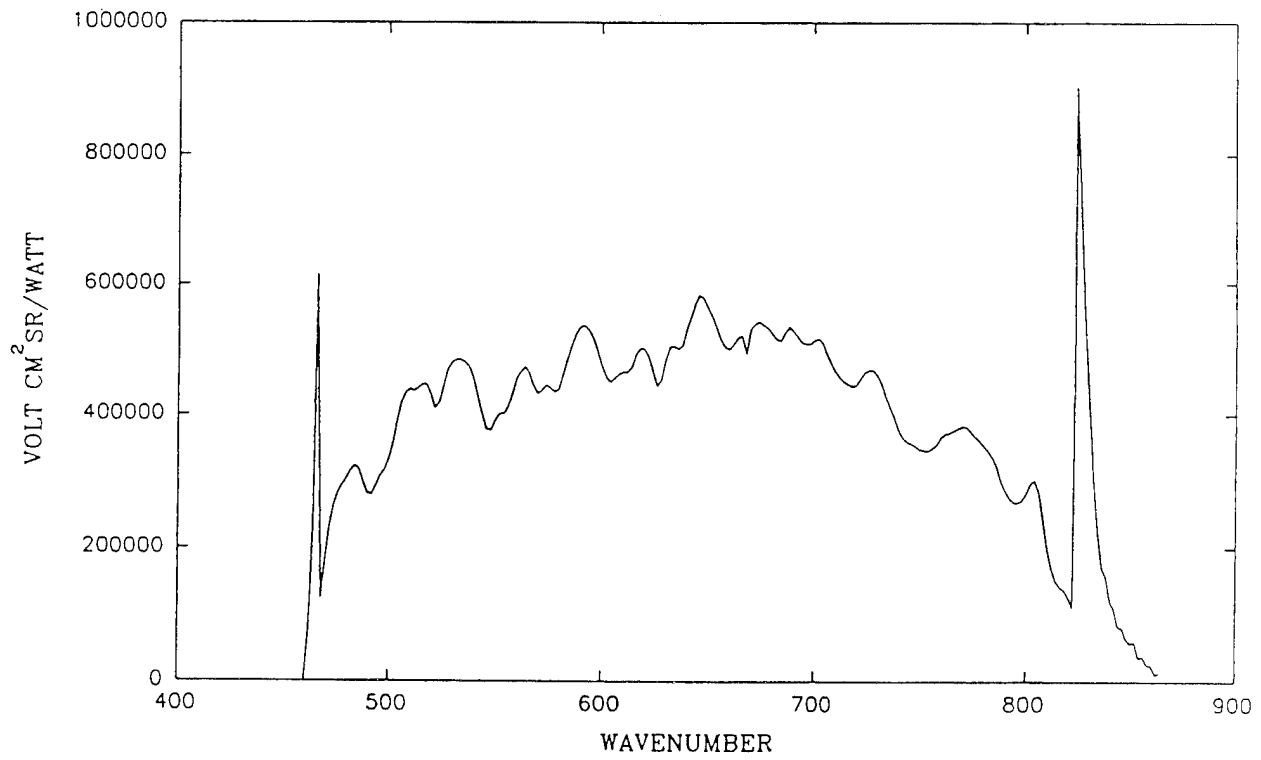


Figure 11. Spectral Response of Channel 4.

sample point for all the interferograms added. Obviously, the signal-to-noise ratio is improved through co-addition. It has been reported that there is a slight advantage in co-adding in the interferogram domain over co-addition in the spectral domain, so the former technique has been adopted in the softwares developed here. The Fortran code for co-adding interferograms is given in Appendix B.

**RANDY.EXE:** This is an executable file which performs the Fourier transformation of an interferogram file. The routine provides the user with the capability to perform 1) phase correction, 2) Fourier transform an interferogram, 3) get an uncalibrated or calibrated spectrum, 4) select an apodization function including Kaiser Bessel apodization with four values for alpha, and 5) select the number of points to be interpolated between transform output points. The spectral intensity files are produced as an ordered single column of intensity or two ordered columns of wavenumber and intensity.

### **SAMPLE CO-ADDITION AND PHASE CORRECTION**

By way of an illustration the procedure to perform co-addition will be demonstrated with the users input underlined and the computer screen response given. The illustration is for the co-addition of two interferograms but the extension to larger numbers of interferograms is obvious.

Before beginning the program, first select from the archived interferogram data files stored at GP/GPO the interferograms to be co-added. For example, select the interferograms; designated by the asterix i.e., files 20514D.ASC and 20516D.ASC.

20511D	ASC	204600
20513D	ASC	42680
20514D	ASC*	199100
20516D	ASC*	204600
20518D	ASC	204600
20520D	ASC	42680
20521D	ASC	204600
20524D	ASC	204600
20526D	ASC	204600

Load the selected interferogram files into the Directory REM.

Begin the co-add processes. Comments are denoted as {}

TYPE CD REM(CR) {(CR) denotes carriage return}

REM > RANDY (CR)

Input interferogram file name to read

20514D.ASC

Input channel # (1 - 4)

2

reading 20514D.ASC

9040 points read

{gives total no. of points in interferogram}

Interferogram file is 20514d.ing

{gives name to interferogram}

Input selection by number

\*\*\*\*\*

- \* 1 : phase correct \*
- \* 2 : get uncalibrated spectrum \*
- \* 3: get calibrated spectrum \*
- \* 4 : get new interferogram \*
- \* 5 : quit \*

\*\*\*\*\*

1

Phase corrected interferogram is 20514D.cor {Phase corrected file, indexed}

Phase corrected interferogram (1 col) is 20514D.cr1 {Phase corrected single column}

Input selection by number

\*\*\*\*\*

- \* 1 : phase correct \*
- \* 2 : get uncalibrated spectrum \*
- \* 3: get calibrated spectrum \*
- \* 4 : get new interferogram \*
- \* 5 : quit \*

\*\*\*\*\*

4

{select the second interferogram to be co-added}

Input interferogram file name to read  
20516D.ASC

Input channel # (1 - 4)  
2

reading 20516D.ASC  
9290 points read

Interferogram file is 20516D.ing

Input selection by number

\*\*\*\*\*

\* 1 : phase correct \*

\* 2 : get uncalibrated spectrum \*

\* 3 : get calibrated spectrum \*

\* 4 : get new interferogram \*

\* 5 : quit \*

\*\*\*\*\*

1

Phase corrected interferogram is 20516D.cor {name of phase corrected file, indexed}

Phase corrected interferogram (1 col) is 20516D.cr1 {single column of interferogram values}

Input selection by number

\*\*\*\*\*

\* 1 : phase correct \*

\* 2 : get uncalibrated spectrum \*

\* 3 : get caibrated spectrum \*

\* 4 : get new interferogram \*

\* 5 : quit \*

\*\*\*\*\*

5

Stop - Program terminated.

NOTE: The Directory of REM should look as indicated below with the phase corrected interferograms denoted by 20514D.cor and 20516D.cor. These are the phase corrected interferograms which will be used as the input files for use with the routine to co-add interferograms. Obviously, the program can be repeated to include as many interferograms for phase correction as is desired. The files ending with .ING, .CR1 are the truncated original interferogram and the phase corrected interferogram respectively and may be of use to some plotting routines. Otherwise these files may be discarded.

Directory of C:\REM

.		<DIR>
..		<DIR>
FILTER	DAT	43
CAL1	ASC	24437
CAL2	ASC	15994
CAL3	ASC	9000
CAL4	ASC	4715
DATFILE	DAT	27
20514D	ASC	199100
20516D	ASC	204600
20514D	ING	271200
20514D	COR	263550
20514D	CR1	158130
20516D	ING	278700
20516D	COR	271050
COADD	EXE	228050
20516D	CR1	162630
RANDY	EXE	405230

Figure 12a shows an interferogram, 20514D, taken from the anomalies corrected files and illustrates the distortion of the interferogram due to the optical components of the interferometer. After using the phase correction software program the interferogram is as shown in Figure 12b. If the phase corrected interferogram shows asymmetry after having been processed by the phase correction routine (for very distorted inteferograms) the processes may be repeated to give further correction. There is a small sacrifice to the total number of data points retained by repeated application of the phase correction process.

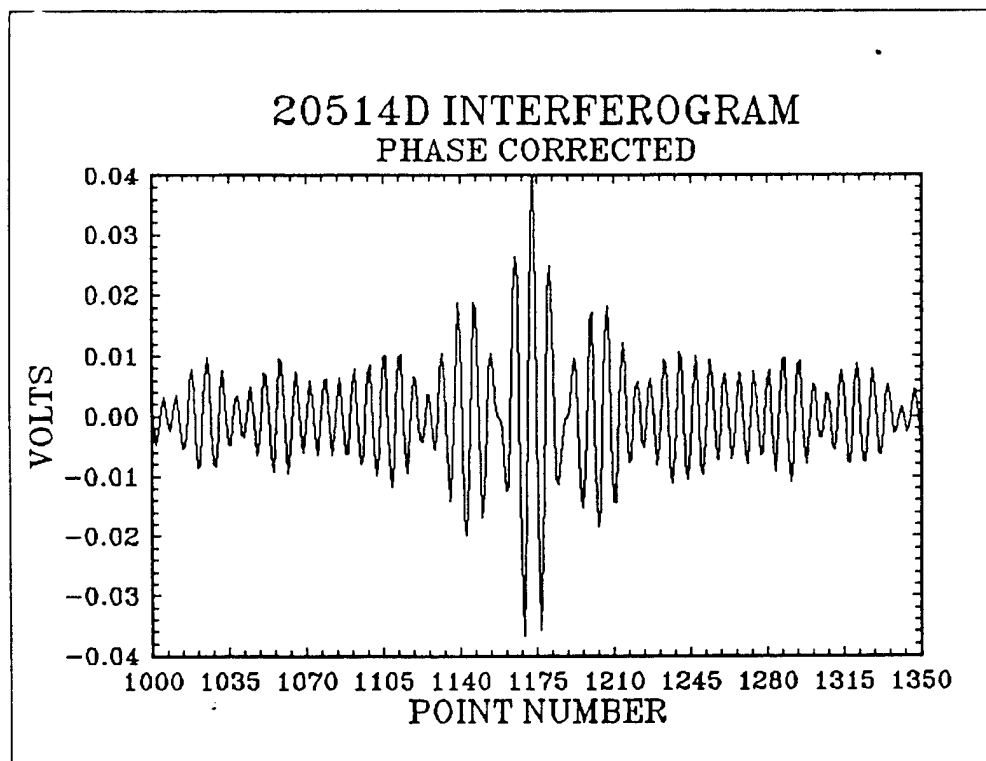
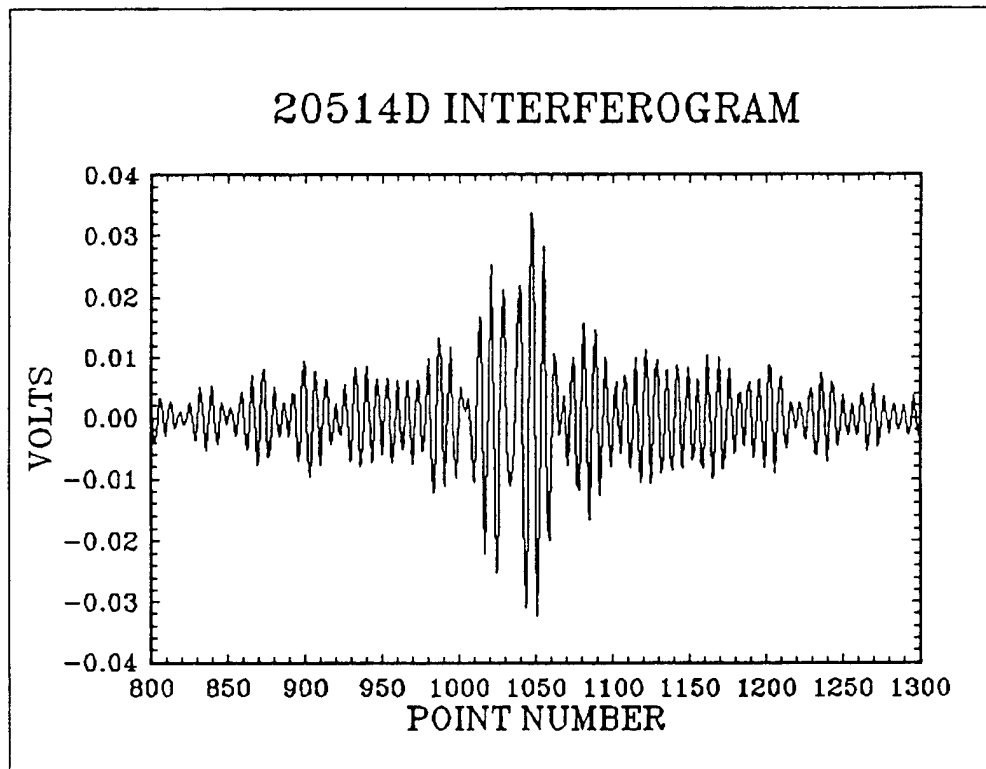


Figure 12. Interferogram a) Before Phase Correction and b) After Phase Correction

At this juncture it is necessary to create a file for the COADD routine which designates for the program which interferograms to co-add. Since we are co-adding the 20514 and 20516 files the required file, "DATFILE.DAT" consists of the simple ASCII file as follows:

```
DATFILE.DAT          27          {27 Bits}
                    2
                    20514D.cor
                    20516D.cor
```

(if more files were to be co-added the total number would be entered and the file names listed).

DATFILE.DAT must be in directory REM.

With DATFILE.DAT loaded into REM the co-addition routine can be implemented i.e.,

```
C:> CD REM (CR)
```

```
REM> COADD (CR)
```

```
Reading 20514D.cor
```

```
    919          920          7865      {7865 points after the center point at
                                         920 so that there are a total of 8785 points}
```

```
    8785 points read
```

```
reading 20516D.cor
```

```
    9035 points read
```

```
    568          569          8466
    568          569          8466          569      {Co-added interferogram
                                         of 8466 points beyond center with center point 569}
```

{When the interferograms are of unequal length the program essentially doubles the values of the longer interferogram where there are no values of the shorter interferogram as in the case above. The average of the value for the co-added interferograms is used.}

```
Writing coadded file OUT1.DAT      {Co-added interferogram as a single column}
```

```
Writing coadded file OUT2.ING      {Co-added interferogram as an indexed column}
```

```
Stop - Program terminated.
```

The file OUT1.DAT is the co-added interferogram made up from the average of files 20514D and 20516D. The co-added interferogram may be processed just as any other interferogram using the RANDY routines in REM.

NOTE: The Directory of REM should look as indicated in the following:

Directory of C:\REM

```

.                <DIR>
..               <DIR>
FILTER          DAT           43
CAL1            ASC          24437
CAL2            ASC          15994
CAL3            ASC           9000
CAL4            ASC           4715
DATFILE         DAT           27
20514D          ASC          199100
20516D          ASC          204600
OUT1            DAT          162630
20514D          COR          263550
OUT2            ING          271050
20516D          COR          271050
COADD           EXE          228050
RANDY           EXE          405230
```

## 8. SAMPLE SPECTRAL RECOVERY

The interferograms to be Fourier transformed must be placed in REM either from the co-add routine just given or by transferring the interferograms from the files at PL/GPO. The spectral recovery process will be illustrated using the co-added interferogram, OUT1.DAT from the previous example.

To execute the spectral recovery routines RANDY is used i.e.,

```
C: > CD REM(CR)
```

```
C:\REM > RANDY(CR)
```

```
Input interferogram file name to read      {phase corrected, coadded interferogram from
                                             the previous example}
```

```
out1.dat
```

Input channel # (1 - 4)

2

reading out1.dat  
9025 points read

Interferogram file is out1.ing

Input selection by number

\*\*\*\*\*

- \* 1 : phase correct \* {the uncalibrated spectrum does not apply
- \* 2 : get uncalibrated spectrum \* the USU engineering conversion,
- \* 3 : get calibrated spectrum \* this may be useful when the S/N
- \* 4 : get new interferogram \* of the calibration is poor}
- \* 5 : quit \*

\*\*\*\*\*

3

Choose apodization by number

\*\*\*\*\*

- \* 1 : Rectangular \* {3 types of apodization or spectral
- \* 2 : Triangular \* smoothing can be selected}
- \* 3: Kaiser Bessel \*

\*\*\*\*\*

1

Input factor to interpolate (1,2,4) {Output point per input point for the recovered spectrum can be obtained at factors of 2 and 4. The interpolation zero fills the interferogram to double or quadruple its length.}

2

Array size 65536  
Reading cal.file cal2.asc

Spectrum file is out1.spc {Spectral output two columns of wavenumber vs intensity}

Spectrum file (1 col) is out1.sc1 {Spectral output in an ordered single column}

Wavenumber file (1 col) is out1.wnc {Wavenumber corresponding to the intensity in  
out1.sp1]

{These spectral output files reside in REM}

{THIS COMPLETES THE RECOVERY OF THE SPECTRUM.}

{The process may be repeated with different selections for apodization or interpolation.  
For example, choosing the Kaiser Bessel apodization and interpolation by 4; we have}

Input selection by number

```
*****  
* 1 : phase correct *  
* 2 : get uncalibrated spectrum *  
* 3 : get calibrated spectrum *  
* 4 : get new interferogram *  
* 5 : quit *  
*****
```

3

Choose apodization by number

```
*****  
* 1 : Rectangular *  
* 2 : Triangular *  
* 3 : Kaiser Bessel *  
*****
```

Input alpha (0 - 3)

3

Input factor to interpolate (1,2,4)

4

Array size 131072  
Reading cal.file cal2.asc

Spectrum file is out1.spc

Spectrum file (1 col) is out1.sc1  
Wavenumber file (1 col) is out1.wnc

Input selection by number

```
*****  
* 1 : phase correct          *  
* 2 : get uncalibrated spectrum *  
* 3 : get calibrated spectrum *  
* 4 : get new interferogram  *  
* 5 : quit                   *  
*****
```

5

STOP PROGRAM TERMINATED

The three output files, i.e., out1.spc, out1.sc1 and out1.wnc are generated to make spectral plotting convenient depending on the input to plotting routines required. For example, out1.spc is easily plotted with the Sigma Plot programs. Out1.sc1 and out1.wnc are more convenient for the DaDISP programs. Both plotting programs are used at PL/GPO. Tables 3-5 show the typical out put from out1.spc, out1.sc1 and out1.wnc.

TABLE 3. Sample of the Output File OUT1.SPC

1330.161000	8.645130E-12
1330.281000	8.203711E-12
1330.402000	7.762762E-12
1330.522000	7.311606E-12
1330.643000	6.842475E-12
1330.763000	6.349588E-12
1330.884000	5.831322E-12
1331.005000	5.288738E-12
1331.125000	4.726105E-12
1331.246000	4.150521E-12
1331.366000	3.573100E-12
1331.487000	3.007161E-12
1331.607000	2.469104E-12

TABLE 4. Sample of the Output File OUT1.SC1

8.645130E-12  
8.203711E-12  
7.762762E-12  
7.311606E-12  
6.842475E-12  
6.349588E-12  
5.831322E-12  
5.288738E-12  
4.726105E-12  
4.150521E-12  
3.573100E-12  
3.007161E-12  
2.469104E-12  
1.976549E-12  
1.549820E-12  
1.209811E-12  
9.801906E-13  
8.784446E-13

TABLE 5. Sample of the Output File OUT1.WNC

1330.161000  
1330.281000  
1330.402000  
1330.522000  
1330.643000  
1330.763000  
1330.884000  
1331.005000  
1331.125000  
1331.246000  
1331.366000  
1331.487000  
1331.607000  
1331.728000  
1331.848000  
1331.969000  
1332.089000

The spectral plot of the data obtained from interferogram 20514D.ASC after using the software routines just described is shown in Figure 13.

20514D SPECTRUM  
PHASE CORRECTED

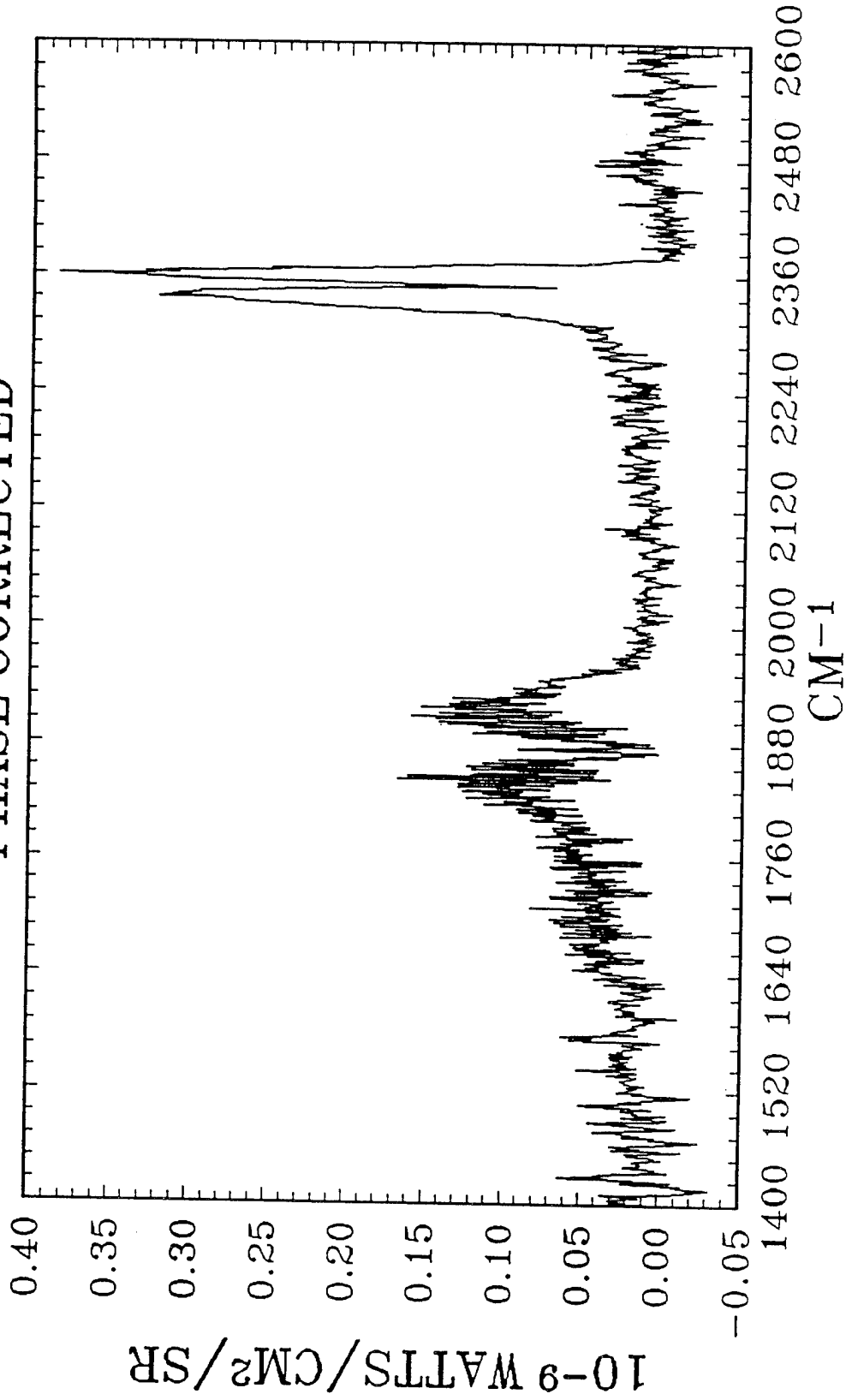


Figure 13. Recovered Spectrum of Electron Excited Air from the EXCEDE III Experiment.

## 9. SUMMARY AND CONCLUSIONS

The EXCEDE III rocket borne experiment succeeded in collecting a great deal of data on the response of the atmosphere to intense energetic electron bombardment. Interferometer data of the resulting emissions was collected over the altitudes of 80 to 115 km. Several other instruments on-board the sensor module collected additional data essential to the analysis of the emissions. The interferometer, its operation and the nature of the raw data, recorded as interferograms, was described briefly. The digital data (interferograms) require considerable processing in order to generate the final spectral product. The functions which must be performed on an interferogram were discussed. The goal of the effort reported here was to provide a simple desk top capability using a personal computer to perform all the necessary functions desired of a scientist wishing to investigate the EXCEDE III interferometer spectra.

A compact software package, delivered to PL/GPO has been developed which will perform the following; 1) phase correct interferograms, 2) co-add any number of interferograms, 3) Fourier transform a selected interferogram, 4) allow for Rectangular, Triangular or Kaiser Bessel ( $\alpha$  0-3) apodization, 5) interpolate output points in the recovered spectra using zero fill of factors of 2 and 4 in the interferogram which is then Fourier transformed, 5) permits pre-spectral filtering of the interferogram by setting filter band-pass edges, 6) provides spectral output files in different formats which are very useful for plotting programs, 7) is completely interactive with screen prompts. The software programs used in this package are provided in the appendices. An example of the capability showing the interaction between an operator and the computer is provided. A tutorial demonstrating the utility and ease of operation for this software has been given at GL/GPO.

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## **APPENDICES**

APPENDIX A: Fortran Program REM

APPENDIX B: Fortran Program Co-add

## APPENDIX A Fortran Program REM

```
$large : s
  dimension d(16384),dd(16384),w(2048),filt(4,2),cc(2048)
  complex s(32768)
  integer iwk(15)
  character*64 infile,outfile,calfile,tempfile
  character qq*1,dummy*1,ext*3
  logical exists
  pi=3.14159265
  nr=80
  icon1=0
  icon2=0
  icon3=0
  icon4=0
  icon5=0
  icon6=0
  ddx=-1.0
  fstart=0.0
  fend=8000.0
  inquire(file='debug.dat',exist=exists)
  if(.not.exists) goto 951
  open(unit=nr,file='debug.dat',status='old')
  rewind(nr)
  read(nr,*) icon1,icon2,icon3,icon4,icon5
  1,icon6
  if(icon6.gt.1) read(nr,*) ddx
959 close(nr)
  if(icon6.gt.1) icon6=1
951 continue
c***** start *****
  inquire(file='cal1.asc',exist=exists)
  if(.not.exists) then
    write(*,*)
    write(*,*) '***** Calibration file CAL1.ASC missing *****'
    goto 950
  endif
  inquire(file='cal2.asc',exist=exists)
  if(.not.exists) then
    write(*,*)
    write(*,*) '***** Calibration file CAL2.ASC missing *****'
    goto 950
  endif
  inquire(file='cal3.asc',exist=exists)
  if(.not.exists) then
    write(*,*)
    write(*,*) '***** Calibration file CAL3.ASC missing *****'
    goto 950
  endif
```

```

inquire(file='cal4.asc',exist=exists)
if(.not.exists) then
  write(*,*)
  write(*,*) '***** Calibration file CAL4.ASC missing *****'
  goto 950
endif
inquire(file='filter.dat',exist=exists)
if(.not.exists) then
  write(*,*)
  write(*,*) '***** Filter band file FILTER.DAT missing *****'
  goto 950
endif
open(unit=nr,file='filter.dat',status='old')
rewind(nr)
do 955 i=1,4
  read(nr,*,err=956,end=956) (filt(i,j),j=1,2)
955 continue
  goto 900
956 write(*,*)
  write(*,*) '***** Error reading filter band file FILTER.DAT *****'
  goto 950
c***** start of loop *****
900 continue
  write(*,*)
  write(*,*) 'Input interferogram file name to read'
  read(*,'(a64)') infile
  inquire(file=infile,exist=exists)
  if(.not.exists) then
    write(*,*)
    write(*,*) '***** File does not exist *****'
    goto 900
  endif
  outfile=infile
  write(*,*)
990 write(*,*) 'Input channel # (1-4)'
  read(*,*) ichan
  if(ichan.gt.4) goto 990
  if(ichan.le.0) goto 990
  if(ichan.eq.1) then
    fstart=filt(1,1)
    fend=filt(1,2)
    calfile='cal1.asc'
  elseif(ichan.eq.2) then
    fstart=filt(2,1)
    fend=filt(2,2)
    calfile='cal2.asc'
  elseif(ichan.eq.3) then
    fstart=filt(3,1)

```

```

    fend=filt(3,2)
    calfile='cal3.asc'
elseif(ichan.eq.4) then
    fstart=filt(4,1)
    fend=filt(4,2)
    calfile='cal4.asc'
endif
ilen=len(infile)
do 910 i=ilen,1,-1
    if(infile(i:i).eq.' ') goto 915
910 continue
915 ilen=i
    iread=0
    if(infile(ilen+1:ilen+1).eq.'C') infile(ilen+1:ilen+1)='c'
    if(infile(ilen+2:ilen+2).eq.'O') infile(ilen+2:ilen+2)='o'
    if(infile(ilen+3:ilen+3).eq.'R') infile(ilen+3:ilen+3)='r'
    if(infile(ilen+1:ilen+1).eq.'I') infile(ilen+1:ilen+1)='i'
    if(infile(ilen+2:ilen+2).eq.'N') infile(ilen+2:ilen+2)='n'
    if(infile(ilen+3:ilen+3).eq.'G') infile(ilen+3:ilen+3)='g'
    ext=infile(ilen+1:ilen+3)
    if(ext.eq.'cor'.or.ext.eq.'ing') iread=1
    write(*,*)
    write(*,*) 'reading ',infile
    open(unit=nr,file=infile,status='old')
    rewind(nr)
    if(iread.eq.1) goto 127
    do 125 i=1,10
        read(nr,'(a1)') dummy
125 continue
127 i=1
10 if(iread.eq.0) read(nr,*,err=10,end=15) d(i)
    if(iread.eq.1) read(nr,*,err=10,end=15) xi,d(i)
    i=i+1
    if(i.gt.16384) goto 15
    goto 10
15 close(nr)
    itotal=i-1
    write(*,*) itotal,' points read'
c    dx=6.328e-5
    dx=1.0/15798.0117
    if(ichan.ge.3) dx=dx*2
    if(ddx.gt.0.0) dx=ddx
    nw=90
c***** write interferogram *****
    outfile(ilen+1:ilen+3)='ing'
    open(unit=nw,file=outfile)
    rewind(nw)
    do 815 i=1,itotal

```

```

    write(nw,*) i,d(i)
815 continue
    close(nw)
    write(*,*)
    write(*,*) 'Interferogram file is ',outfile
920 continue
    write(*,*)
    write(*,*) '  Input selection by number'
    write(*,*)
    write(*,*) '*****'
    write(*,*) '* 1 : phase correct          *'
    write(*,*) '* 2 : get uncalibrated spectrum *'
    write(*,*) '* 3 : get calibrated spectrum  *'
    write(*,*) '* 4 : get new interferogram    *'
    write(*,*) '* 5 : quit                      *'
    write(*,*) '*****'
    write(*,*)
    read(*,*) isel
    if(icont6.eq.1.and.isel.eq.0) goto 930
    if(isel.le.0.or.isel.gt.5) then
        write(*,*) '***** Wrong selection, please select again *****'
        goto 920
    endif
    if(isel.eq.5) goto 950
    if(isel.eq.4) goto 900
    if(isel.ge.2) goto 940
930 continue
    do 870 i=1,itotal
        dd(i)=d(i)
870 continue
c***** get center portion *****
c    write(*,*) 'getting center piece'
    dp=0.0
    do 830 i=1,itotal
        if(dd(i).gt.dp) then
            dp=dd(i)
            icen=i
        endif
830 continue
c***** limit section to < 256 points *****
    if(icen.gt.128) then
        ishift=icen-128
        itot2=itotal-ishift
        do 840 i=1,itot2
            dd(i)=dd(i+ishift)
840 continue
        icen=icen-ishift
    endif

```

```

ileft=icen-1
istart=icen-ileft
iend=icen+ileft
c  write(*,*) istart,icen,iend,dp
   do 30 i=istart,iend
     dd(i+1-istart)=dd(i)
30  continue
   itot=iend-istart+1
   m=5
26  m=m+1
   nn=2**m
   n=nn/2
   if(nn.lt.itot) goto 26
c  write(*,*) 'array size is ',nn
   do 35 i=1,nn
     s(i)=0.0
35  continue
   df=1.0/nn/dx
   icen=ileft+1
   if(isel.eq.0) goto 935
   do 40 i=1,icen
     dd(i+icen)=dd(i+icen)*float(icen-i)/float(icen)
     dd(i)=dd(i)*float(i)/float(icen)
40  continue
   if(icont1.ne.1) goto 952
   outfile='ingram1.dat'
   open(unit=nw,file=outfile)
   rewind(nw)
   do 45 i=1,itot
     write(nw,*) i+istart-1,dd(i)
45  continue
   close(nw)
952 continue
   s(1)=dd(icen)
   do 50 i=1,icen-1
     s(i+1)=dd(i+icen)
     s(nn+i-icen+1)=dd(i)
50  continue
c  write(*,*) 'getting low res. phase, spectrum.'
   call reallft(s,m,iwk)
   if(icont2.ne.1) goto 953
   outfile='spect.dat'
   open(unit=nw,file=outfile)
   rewind(nw)
   do 60 i=1,n
     f=(i-1.0)*df
     if(f.lt.fstart.or.f.gt.fend) goto 60
     write(nw,*) f,cabs(s(i))

```

```

60 continue
  close(nw)
953 continue
  if(icont3.eq.1) then
    outfile='phase.dat'
    open(unit=nw,file=outfile)
    rewind(nw)
  endif
  con=180.0/pi
  do 70 i=1,n
    f=(i-1.0)*df
    dd(i)=0.0
    if(f.lt.fstart.or.f.gt.fend) goto 70
    if(real(s(i)).eq.0.0) then
      dd(i)=pi/2.0
    else
      dd(i)=atan2(aimag(s(i)),real(s(i)))
    endif
    if(icont3.eq.1) write(nw,*) f,dd(i)*con
  70 continue
  if(icont3.eq.1) close(nw)
935 continue
c  write(*,*) 'getting phase interferogram'
  s(1)=0.0
  z=-1.0
  do 80 i=2,n+1
    s(i)=0.0
    s(nn+2-i)=0.0
    f=(i-1.0)*df
    if(f.lt.fstart.or.f.gt.fend) goto 80
    if(isel.eq.0) then
      s(i)=1.0
      s(nn+2-i)=1.0
    else
      s(i)=cmplx(cos(dd(i)),z*sin(dd(i)))
      s(nn+2-i)=conjg(s(i))
    endif
  80 continue
  call hermfft(s,m,iwk)
  do 85 i=1,nn
    dd(i)=0.0
  85 continue
  do 90 i=1,icen
    dd(icen+i-1)=real(s(i))/nn
    if(i.eq.icen) goto 90
    dd(i)=real(s(nn+1-icen+i))/nn
  90 continue
  alpha=3.0

```

```

beta=pi*alpha
scale=beso(beta)
idelta=nn-icen-1
delta=float(idelta)
ipeak=icen
do 94 i=1,idelta
temp=(i-1.0)/delta
temp=sqrt(1.0-temp*temp)
apod=beso(beta*temp)/scale
dd(i+ipeak-1)=dd(i+ipeak-1)*apod
if(i.eq.1.or.i.gt.ipeak) goto 94
dd(ipeak+1-i)=dd(ipeak+1-i)*apod
94 continue
if(icont4.ne.1) goto 954
outfile='corr.dat'
open(unit=nw,file=outfile)
rewind(nw)
do 95 i=1,itot
write(nw,*) i,dd(i)
95 continue
close(nw)
954 continue
c write(*,*) 'phase correcting'
outfile=infile
outfile(ilen+1:ilen+3)='cor'
open(unit=nw,file=outfile)
rewind(nw)
do 110 i=1,itotal-itot
sum=0.0
do 120 j=1,itot
ij=i+j-1
if(ij.le.0) goto 120
if(ij.gt.itotal) goto 115
sum=sum+d(ij)*dd(j)
120 continue
115 write(nw,*) i,sum
110 continue
close(nw)
write(*,*)
write(*,*) 'Phase corrected interferogram is ',outfile
itotal=itotal-itot
infile=outfile
open(unit=nr,file=infile,status='old')
rewind(nr)
do 130 i=1,itotal
read(nr,*,end=135) j,d(i)
130 continue
135 itotal=j

```

```

close(nr)
goto 920
940 continue
write(*,*)
write(*,*) 'Choose apodization by number'
write(*,*)
write(*,*) '+++++'
write(*,*) '+ 0 : Rectangular +'
write(*,*) '+ 1 : Triangular +'
write(*,*) '+ 2 : Kaiser Bessel +'
write(*,*) '+++++'
write(*,*)
read(*,*) iapod
if(iapod.lt.0.or.iapod.gt.2) then
write(*,*) 'Wrong selection'
goto 940
endif
dp=0.0
do 150 i=1,itotal
if(d(i).gt.dp) then
dp=d(i)
ipeak=i
endif
150 continue
c write(*,*) ipeak,dp
do 155 i=1,itotal
dd(i)=d(i)
155 continue
c-----
c alpha=0.0
c call ksramp(ipeak,dd,itotal,alpha)
c call ksright(ipeak,dd,itotal,alpha)
c-----
delta=itotal-ipeak
idelta=itotal-ipeak
if(iapod.eq.1) then
do 210 i=1,idelta
dd(i+ipeak-1)=dd(i+ipeak-1)*(delta+1.0-i)/delta
if(i.ge.ipeak) goto 210
dd(ipeak-i)=dd(ipeak-i)*(delta-i)/delta
210 continue
elseif(iapod.eq.2) then
write(*,*) 'Input alpha (0-3)'
read(*,*) alpha
beta=pi*alpha
scale=beso(beta)
do 220 i=1,idelta
temp=(i-1.0)/delta

```

```

    temp=sqrt(1.0-temp*temp)
    apod=beso(beta*temp)/scale
    dd(i+ipeak-1)=dd(i+ipeak-1)*apod
    if(i.eq.1.or.i.gt.ipeak) goto 220
    dd(ipeak+1-i)=dd(ipeak+1-i)*apod
220 continue
    endif
222 write(*,*)
    write(*,*) 'Input factor to interpolate (1,2,4)'
    read(*,*) inter
    if(inter.lt.0) goto 222
    if(inter.eq.0) inter=1
    if(inter.eq.3) goto 222
    if(inter.gt.4) goto 222
    ilarge=0
    m=5
126 m=m+1
    nn=2**m
    n=nn/2
    if(m.gt.15) ilarge=ilarge+1
    if(n.lt.inter*idelta) goto 126
    df=1.0/nn/dx
128 continue
    jlarge=2**ilarge-1
    write(*,*) 'Array size ',nn
    if(m.gt.15) then
        m=15
        nn=2**m
        n=nn/2
        df=1.0/nn/dx
    endif
    do 160 i=1,nn
        s(i)=0.0
160 continue
    do 165 i=1,idelta
        s(i)=dd(i+ipeak-1)
        if(i.eq.1) goto 165
        s(nn+2-i)=s(i)
165 continue
    call realfft(s,m,iwk)
    tempfile='out0.dat'
    open(unit=nw,file=tempfile,form='unformatted')
    rewind(nw)
    do 820 i=1,n
        ans=real(s(i))
        f=(i-1.0)*df
        if(f.lt.fstart.or.f.gt.fend) goto 820
    write(nw) ans

```

```

820 continue
  close(nw)
  if(ilarge.ge.1) then
    do 600 kkk=1,jlarge
      do 810 i=1,nn
        s(i)=0.0
810  continue
      dpi=2.0*pi/float(nn)*float(kkk)/(jlarge+1.0)
      do 850 i=1,idelta
        ddpi=dpi*(i-1.0)
        s(i)=dd(i+ipeak-1)*cplx(cos(ddpi),sin(ddpi))
        if(i.eq.1) goto 850
        s(nn+2-i)=conjg(s(i))
850  continue
      call hermfft(s,m,iwk)
      write(qqq,'(i1)') kkk
      tempfile(4:4)=qqq
      open(unit=kkk,file=tempfile,form='unformatted')
      rewind(kkk)
      do 860 i=1,n
        ans=real(s(i))
        f=(i-1.0)*df
        if(f.lt.fstart.or.f.gt.fend) goto 860
        write(kkk) ans
860  continue
      close(kkk)
600  continue
      endif
      if(isel.eq.3) then
        nnr=50
        write(*,*) 'Reading cal. file ',calfile
        open(unit=nnr,file=calfile,status='old')
        rewind(nnr)
        i=1
        read(nnr,*)
        read(nnr,*)
c      read(nnr,*)
c      read(nnr,*)
180  read(nnr,*,end=185,err=180) w(i),cc(i)
        i=i+1
        goto 180
185  jtot=i-1
        close(nnr)
c      write(*,*) jtot,w(1),cc(1),w(jtot),cc(jtot)
      endif
      outfile=infile
      if(isel.eq.2) outfile(ilen+1:ilen+3)='spu'
      if(isel.eq.3) outfile(ilen+1:ilen+3)='spc'

```

```

tempfile='out0.dat'
open(unit=nr,file=tempfile,form='unformatted',status='old')
rewind(nr)
if(ilarge.ge.1) then
do 610 kkk=1,jlarge
write(qqq,'(i1)') kkk
tempfile(4:4)=qqq
open(unit=kkk,file=tempfile,form='unformatted',status='old')
rewind(kkk)
610 continue
endif
open(unit=nw,file=outfile)
rewind(nw)
nlarge=n
do 170 i=1,nlarge
f=(i-1.0)*df
cal=1.0
if(f.lt.fstart.or.f.gt.fend) goto 170
if(isel.eq.3) then
if(f.le.w(1).or.f.ge.w(jtot)) goto 197
do 190 j=1,jtot
if(w(j).gt.f) goto 195
190 continue
197 cal=0.0
goto 196
195 cal=(f-w(j-1))*(cc(j)-cc(j-1))/(w(j)-w(j-1))
cal=cal+cc(j-1)
cal=1.0/cal
196 continue
endif
read(nr) ans
write(nw,*) f,ans*dx*cal
if(ilarge.ge.1) then
do 620 kkk=1,jlarge
read(kkk) ans
fff=f+df*float(kkk)/(jlarge+1.0)
if(isel.eq.3) then
if(f.le.w(1).or.f.ge.w(jtot)) then
cal=0.0
else
cal=(fff-w(j-1))*(cc(j)-cc(j-1))/(w(j)-w(j-1))
cal=cal+cc(j-1)
cal=1.0/cal
endif
endif
write(nw,*) fff,ans*dx*cal
620 continue
endif

```

```

170 continue
    do 630 kkk=1,jlarge
        close(kkk)
630 continue
    close(nr)
    close(nw)
    write(*,*)
    write(*,*) 'Spectrum file is ',outfile
    goto 920
950 continue
    stop
    end

```

```

    subroutine ksramp(icent,b,len,alpha)
c***does 'left-ramp' portion of a Kaiser apodization
c***affects b(1) thru b(2*icent-1)
    real b(1)
    b(1)=b(1)*0.5
    if(icent.eq.1) return
    pi=3.14159265
    beta=pi*alpha
    relen=1.0/(len-icent)
    anorm=beso(beta)
    max=2*icent-1
    eta=2*(icent-1)
    temp=sqrt(1.0-(eta*relen/2.0)**2)
    temp=beso(beta*temp)/anorm
    slope=temp/eta
    do 10 k=1,max
        diff=k-icent
        temp=diff*relen
        temp=sqrt(1.0000001-temp*temp)
        apo=diff*slope+0.5*beso(beta*temp)/anorm
        b(k)=b(k)*apo
10 continue
    return
    end

```

```

c
    subroutine ksright(icent,b,len,alpha)
c***perform right-sided portion of Kaiser apodization
c***affects b(2*icent) thru b(len)
    real b(1)
    pi=3.14159265
    beta=pi*alpha
    relen=1.0/(len-icent)
    anorm=beso(beta)
    do 10 k=2*icent,len
        diff=k-icent

```

```

    temp=diff*relen
    temp=sqrt(1.0000001-temp*temp)
    apo=beso(beta*temp)/anorm
    b(k)=b(k)*apo
10 continue
    return
    end
c
function beso(x)
parameter(t=1.0e-8)
y=x/2.0
e=1.0
de=1.0
do 1 i=1,25
    de=de*y/i
    sde=de*de
    e=e+sde
    if(e*t-sde) 1,1,2
1 continue
2 beso=e
    return
    end

```

□

## APPENDIX B Fortran Program COADD

```
dimension d1(16384),d2(16384),d3(16384)
character*64 infile1,file2
nr=10
open(unit=nr,file='datfile.dat',status='old')
rewind(nr)
read(nr,*) itotal
read(nr,'(a64)') infile1
itotal=itotal-1
write(*,*) 'Reading ',infile1
call reader(infile1,d1,iii)
dp=0.0
ipeak1=1
do 10 i=1,iii
  if(d1(i).gt.dp) then
    dp=d1(i)
    ipeak1=i
  endif
10 continue
ileft1=ipeak1-1
iright1=iii-ipeak1
write(*,*) ileft1,ipeak1,iright1
write(*,*) iii,' points read'
do 20 i=1,itotal
  read(nr,'(a64)') file2
  write(*,*) 'reading ', file2
  call reader(file2,d2,jjj)
  write(*,*) jjj,' points read'
  dp=0.0
  ipeak2=1
  do 30 j=1, jjj
    if(d2(j).gt.dp) then
      dp=d2(j)
      ipeak2=j
    endif
30 continue
ileft2=ipeak2-1
iright2=jjj-ipeak2
write(*,*) ileft2,ipeak2,iright2
if(ileft2.lt.ileft1) ileft1=ileft2
if(iright2.lt.iright1) iright1=iright2
iii=iright1+1+ileft1
do 40 k=1,iii
  d3(k)=d1(ipeak1-ileft1+k-1)
40 continue
dp=0.0
do 50 k=1,iii
  d1(k)=d3(k)+d2(ipeak2-ileft1+k-1)
```

```

    if(d1(k).gt.dp) then
      dp=d1(k)
      ipeak=k
    endif
50 continue
    ipeak1=ileft1+1
    write(*,*) ileft1,ipeak1,iright1,ipeak
20 continue
    close(nr)
    nw=50
    write(*,*) 'Writing coadded file out1.dat'
    open(unit=nw,file='out1.dat')
    rewind(nw)
    do 60 i=1,iii
      write(nw,*) d1(i)/(itotal+1.0)
60 continue
    close(nw)
    write(*,*) 'Writing coadded file out2.ing'
    open(unit=nw,file='out2.ing')
    rewind(nw)
    do 70 i=1,iii
      write(nw,*) i,d1(i)/(itotal+1.0)
70 continue
    close(nw)
    stop
    end
    subroutine reader(infile1,d1,iii)
    dimension d1(1)
    character*64 infile1
    ilen=len(infile1)
    do 10 i=ilen,1,-1
      if(infile1(i:i).eq.'.') goto 15
10 continue
15 inum=0
    ilen=i
    if(infile(ilen+1:ilen+1).eq.'C') infile(ilen+1:ilen+1)='c'
    if(infile(ilen+2:ilen+2).eq.'O') infile(ilen+2:ilen+2)='o'
    if(infile(ilen+3:ilen+3).eq.'R') infile(ilen+3:ilen+3)='r'
    if(infile(ilen+1:ilen+1).eq.'T') infile(ilen+1:ilen+1)='i'
    if(infile(ilen+2:ilen+2).eq.'N') infile(ilen+2:ilen+2)='n'
    if(infile(ilen+3:ilen+3).eq.'G') infile(ilen+3:ilen+3)='g'
    if(infile(i+1:i+3).eq.'ing'.or.infile(i+1:i+3).eq.
l'cor') inum=1
    nrr=20
    open(unit=nrr,file=infile1,status='old')
    rewind(nrr)
    if(inum.eq.0) then
      do 30 i=1,10

```

```
    read(nrr,*)
30 continue
    endif
    i=1
20 if(inum.eq.0) then
    read(nrr,*,err=20,end=25) d1(i)
    else
    read(nrr,*,err=20,end=25) xj,d1(i)
    endif
    i=i+1
    if(i.gt.16384) goto 25
    goto 20
25 close(nrr)
    iii=i-1
    return
    end
```