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On-line Far-infrared Michelson Interferometry in a Time-shared Mode

Abstract: A method is described for implementing real-time far-infrared Fourier spectroscopy in a time-shared environment. The system makes use of the IBM 1800 TSX-based General Experimental Monitor (GEM) and reduces by at least an order of magnitude the time between experiment initiation and the display of useful spectral frequency and intensity information. The key feature of the system includes conversational mode operation with the incomplete data array. This feature enables one to review at any interval the Fourier transform of the partially acquired data without in any way disturbing the process of data collection. Procedures are illustrated also for performing signal averaging and several comparatively routine spectroscopic tasks.

Introduction

In recent years a good deal of interest in the use of Michelson interferometers has recurred.¹ This may be traced to two main factors. The first factor is the operational advantage these devices have over conventional spectrometers, in particular the multiplex advantage at longer wavelengths (≈ 20 to $1000\mu\text{m}$). Also, it is now possible with the aid of digital computers to perform the necessary Fourier transformations which produce the desired spectral frequency distribution. The problem of computation has been further simplified by the availability of the fast Fourier transform algorithm.²

The present work describes an interferometric system that operates in an on-line manner. Its major advantages are (1) computer control of the independent variable (mirror motion), which permits direct access to computer averaging of data; (2) direct access of output analog signals to computer storage on an uninterrupted time-shared basis; and (3) the ability with the software system to review locally the Fourier transform of the data as it is being accumulated, without disturbing the process of data accumulation.

Basis of the technique

Historically, spectroscopy in the far-infrared region has been a source of difficulty. This stems basically from the linear temperature dependence of the black-body frequency

spectrum in the low-frequency region and the fourth-power temperature dependence of the power emitted by black-body sources. Since most currently available far-infrared sources are operated at temperatures on the order of 1300°K the problem of filtering unwanted radiations becomes severe if one desires to study the spectral region $10\text{--}500\text{ cm}^{-1}$. The lack of suitable sharp-cutoff filters compounds this problem and generally limits severely the amount of radiant energy available for spectroscopic use in this region. This weak-source problem then places stringent requirements on the detection systems that must be used and historically has produced extremely low signal/noise ratios in the far-infrared region. Advances in detector technology, however, have relieved to an extent the problem of fast sensitive detection.³ The major advance in the development of far-infrared spectral techniques has been the realization that Michelson interferometry presents a conspicuous advantage in being able to channel greater energy at a given wavelength onto a given detector area. This advantage alleviates still further the problem of increasing signal/noise ratios.¹

Michelson interferometry involves the retrieval of the spectral frequency distribution $I(k)$ from a measured intensity flux function $I(x)$, a function of x (mirror position), by means of the following Fourier reciprocal relations,

$$I(x) = \int_{-\infty}^{+\infty} I(k) e^{2\pi i k x} dk \quad (1)$$

$$I(k) = \int_{-\infty}^{+\infty} I(x) e^{-2\pi i k x} dx. \quad (2)$$

The work reported was done by the authors at the IBM Research Laboratory, San Jose, Calif.

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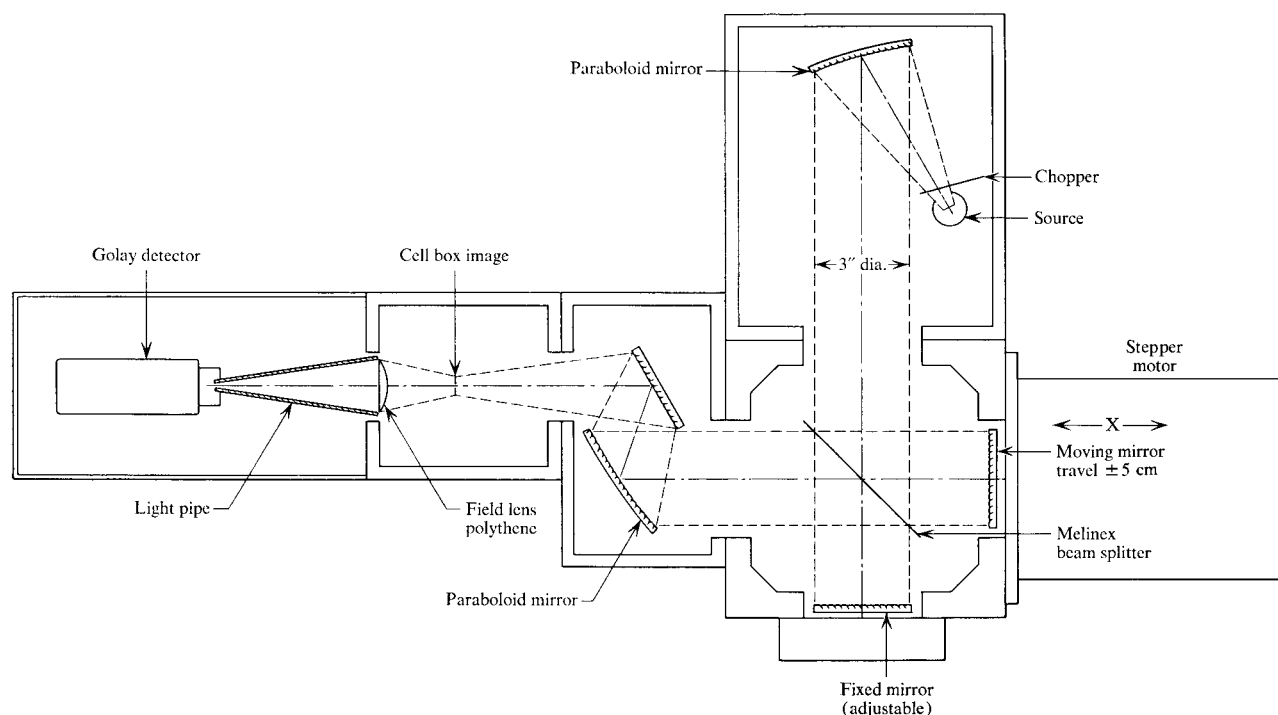


Figure 1 Ray diagram of Beckman (FS-720) two-beam interferometer.

The latter relation determines the desired spectral result and in practice involves evaluating the integral in Eq. (2) over some finite interval, say Δ . Figure 1 shows a ray diagram of the optical layout associated with two-beam Michelson interferometry. The moving mirror is stepped over a finite interval so that the problem of evaluating the integral Eq. (2) reduces to one of evaluating

$$I(k) = 2 \sum_{\Delta x=0}^{\Delta} I(x) \cos 2\pi k \Delta x. \quad (3)$$

Equation (3) assumes the interferogram is an even function. One commences sampling from a point of zero path difference for mirror-to-beam splitter distance over intervals Δx to a total path difference Δ . Recently a fast Fourier transform procedure² has become available which allows the evaluation of Eq. (3) in times proportional to $2N \log_2 N$ as opposed to (N^2) , where N data points represent the frequency with which the spectral flux function $I(x)$ is sampled. This is particularly important since in most instances an enormous data volume is generated in the course of performing the summation in Eq. (3).

A major inconvenience of most far-infrared interferometers that utilize digital computers available in a multi-user environment involves the hand carrying of unit records or paper tape to the site of the computer. A few systems are available which use dedicated computers simply

to synchronously step the moving mirror indicated in Fig. 1 and Fourier transform (by analog or digital means) the data on output paper tape or unit records. With cost and convenience in mind it seemed profitable to use a general purpose computer to pursue the possibility of *on-line* data acquisition, *on-line* computation of Fourier transforms, and further to introduce the possibility of dynamic review of the Fourier transforms of portions of the input flux function, $I(x)$, as it is acquired in computer storage. This latter point we emphasize, since frequently data acquisition may run over an extended period and spurious noise pulses necessitate having fast turn around abort-restart procedures. On-line procedures also make computer averaging a comparatively straightforward procedure. This has an enormous impact on the signal/noise problem still prevalent in far-infrared spectroscopy. It is also much faster to normalize source and sample spectra by using on-line procedures.

Michelson hardware

The hardware for this experiment can be classified into five units. They are the (1) vacuum system, (2) optics, (3) detection system, (4) motor control system, and (5) computer I/O and data processing interface. These five groups, with the exception of the vacuum system, are shown in their operational state in Fig. 2.

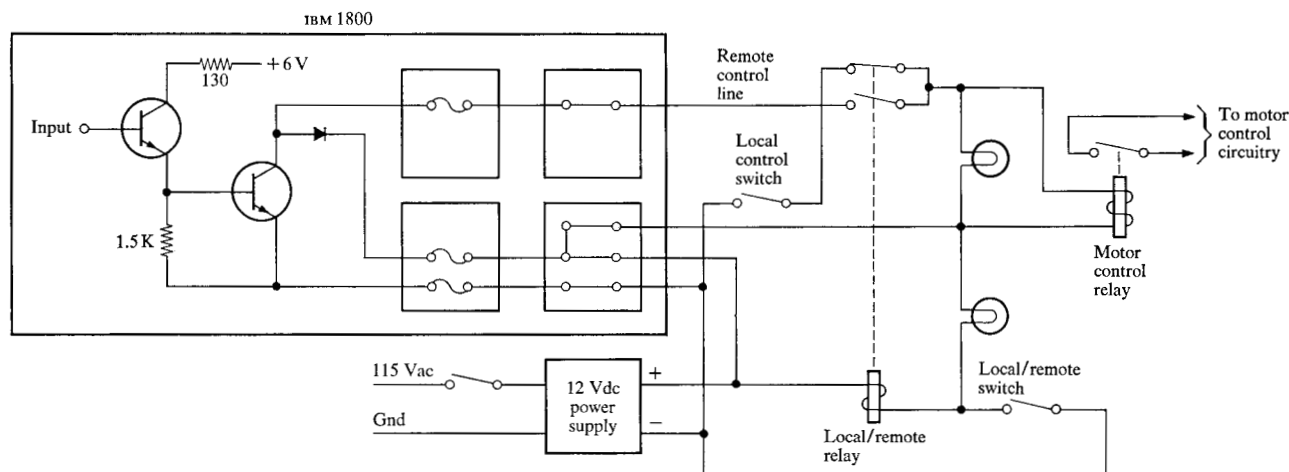


Figure 3 Typical hardware interface to IBM 1800 computer.

When the computer is ready to begin data acquisition a READ analog input address command is given. The computer services the request by returning a pulse of +12 V and 6 to 10 msec in duration over the contact-operate (111) line to an assigned bit number. This pulse then causes a mirror step by closing a relay in the motor control electronics package which generates 1, 2, 3, 4, 6, or 8 pulses, depending on the desired step length. The stepping motor is wired such that one 11.8 V (440 mA) pulse produces 1/200th of a revolution on the motor. After waiting a specified interval, the read-step-wait process is repeated until all of the data are collected. The waiting period may be varied from 0.5 to 32 sec with the present programming.

Figure 3 shows a typical circuit of the computer-input contact sense connections. When the local/remote switch is open, the interferometer is operated manually (i.e., locally). In the remote mode, the local control switches are replaced by the computer and the motor is controlled via the software.

In general, the wiring scheme is operated from a -18 Vdc power supply and the contact sense switches that place either +12 or -18 V on the computer terminals, which correspond to a logical 0 or +1 when the computer is issued a READ contact sense command. The complete panel control bank is shown diagrammatically in Fig. 4. These switches, combined with our analog input lines, control our input electronics to the computer.

The spectrophotometer, excluding the detector and mirror drive units, requires a 45 Vac supply to run the light chopper and a 5 Vdc Zener stabilized supply for the reference signal. The reference signal is generated by a phototransistor which focuses the light passing through the chopper blade, producing a symmetrical 5V square wave. The spectrophotometer is mounted on a heavy

table with leveling screws, with heavy rubber mounts between the FS-720 and the table top.

Software interface

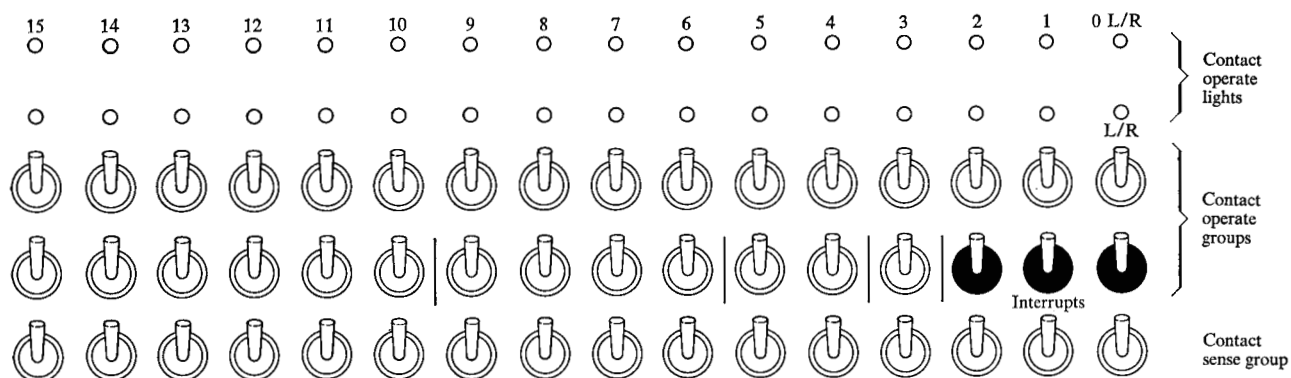
We will deal with the problem of computer interfacing primarily from the point of view of the software implementation of Fourier transform spectroscopy, since many of the hardware features of our system are common to others previously reported.⁶ We shall also follow as closely as possible the normal sequence of operations associated with performing a spectroscopic scan, that is, scan initialization, the commencement of data collection, the review of the Fourier transform of the incomplected data run, and computer averaging. Finally, there will be some discussion of various plotting and disk manipulation options.

• General features of the system

All incoming and outgoing digital communication with the computer is handled via contact-operate or voltage-sensing contact sense groups, all of 16-bit word size. Analog signals are transmitted over shielded conductors and reduced to ± 50 mV for the low level, floating inputs to the multiplexed analog-to-digital converter on the IBM 1800. The analog outputs are ± 10 V, high level, and single ended.

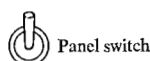
The entire process of data acquisition operates in the IBM 1800 TSX (time-shared executive) based GEM (general experimental monitor) system, the GEM portion of which was programmed by Gladney.⁷

Also, we have written a number of user-application programs. Interrupts generated in the laboratory call an interrupt program which simply queues a mainline core-load. The plotting routines are handled, however, with a lower priority.⁴ The mainline program channels control



No. cats	Burst length		Drive	Sample rate		No. data			1	Initialization
Month		Date			Run I. D.				2	Start data collection
									3	Review data
Block no.	End X	Start X	Var X					Scope 1627	4	Plot input
Block no.	End X	Start X	Var X	Over plot	Square apod	Tri apod	Norm plot	Scope 1627	5	Plot transform
		Block A		Block B			Operation		6	Block operations
									7	Unused

○ Panel light



Panel switch

Figure 4 Control panel for all operations. 16-bit word communication switches are indicated along with six functional tasks.

into any one of eight possible jobs such as initialization, data collection, plotting or termination. Typically one would seek the attention of the computer via an interrupt for initialization of the several interferometer run parameters. This program records the information on the appropriate area of the disk, rereads the information and returns the information to our storage oscilloscope in the laboratory for a validity check. This information appears in the form shown in Fig. 5. The operator then re-enters the queue via the interrupt routine with an option which then results in a call to the data collection program. This in turn calls the GEM subroutine INIO and a system-assigned computer software timer begins the data acquisition at a prescribed rate, i.e., analog signals are read as a function of mirror position. At this stage, the month, day and a run number are entered. The detailed hardware procedures associated with these read-analog signals have been discussed by other authors⁶ and have been dealt with briefly in the hardware section of the present paper.

If no further commands are sent to the computer, the GEM routines will complete the acquisition of data and will then queue an exit program which writes the complete

data array onto a designated disk file area for later Fourier transformation using appropriately modified library routines.

The data may be displayed via various subroutines that set up plotting options for the input interferogram or the transformed output. The optional devices for this display consist of local or remote storage oscilloscopes and a remote IBM 1627 plotter. Because of its fast writing speed we have most often used the local Tektronix 564A storage oscilloscope which is connected to the 1800 via two analog output lines through a tuned differential amplifier of unit gain simply to filter the incoming signals.

Conversational mode

A feature of the present experiment unique from several previously reported by this laboratory⁶ consists in our ability to "converse" with the partially completed data string. This is a particularly useful feature for Fourier spectroscopy since it is the Fourier transform of the data and *not* the actual data taken that is amenable to physical interpretation. This process of dynamic Fourier transformation is completely software implemented.

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NO. OF PTS.= 512

STEPPING TIME= 1000 MSEC.

DIRECTION= 1

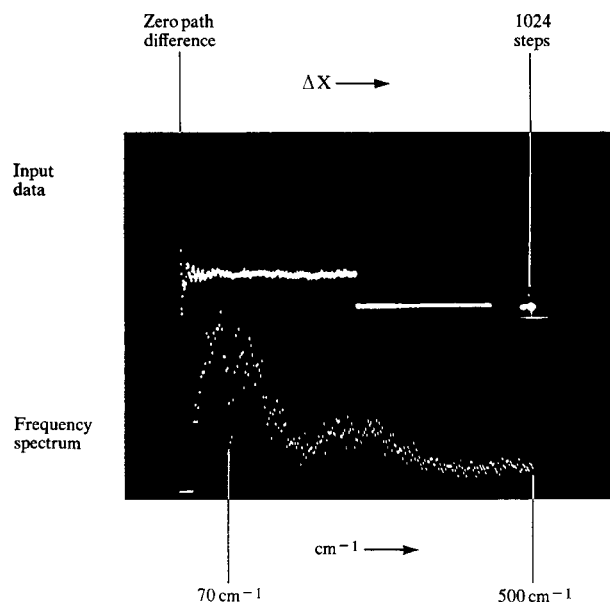
STEPPING LENGTH= 5.0 MICRONS

NO. OF CATS= 50

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Figure 5 Storage oscilloscope display of the initialization information. One bit is used to indicate forward (1) or reverse (0) mirror motion.

Figure 6 Conversational storage oscilloscope display. The upper portion of the display indicates the partially completed input interferogram, beginning of upper left with the zero maximum. The lower half on the display shows the Fourier-transformed output spectrum. The spectrum is a single scan of the source and a 50- μm thick urea nitrate crystal from 10 to 500 cm^{-1} at 281°K. The increment of path difference was 10 μm and resolution 1.0 cm^{-1} . The total run time was 10 minutes and the time consumed by this display is typically 30 sec to 1 min, depending on the number of data going into the transform program. This display is based on 910 points. The spectrum should be compared with Fig 8.



The procedure consists of signaling the computer via our interrupt program to another routine. This key routine enables us to monitor the number of cycles that the system-assigned timer has used and to retrieve all the data collected up to that point in time from filled and partly filled system-assigned buffer areas. This information is then written onto disk, and the routine proceeds to adjust the input array by means of the program so that the Fourier transform begins at zero path difference. Software timers are then assigned in order to plot both the completed portion of the input and the Fourier transform of that data on the upper and the lower portions, respectively, of the local storage oscilloscope. The form these data take appears in Fig. 6. For this case a single beam (somewhat noisy) spectrum of the source and a sample is shown in the lower half of the figure. One sharp filter line at 70 cm^{-1} is apparent from the half-completed scan. The half-completed data itself is shown in the upper portion of Fig. 6; it indicates a sharp maximum at zero path difference and a few oscillations immediately following this maximum. It should be emphasized that this entire process of data review proceeds to completion in 30 sec and does not interrupt data collection.

Other options

Computer-averaged transients (CATS) may also be performed on the present system. This process is implemented by a procedure in the termination routine. If CATING is called for in the initialization process the system queued exit coreload makes additional calls to the data collection program, adjusts each run by means of software to locate zero path, averages the data, and stores the last-run and averaged runs on different areas of disk. Data written onto disk may be manipulated independently by using a separate subroutine which assigns various task numbers (0-3) depending on the form this manipulation should take. One has the option of either simply writing on the storage oscilloscope the number of CATS completed, transferring arrays of data, normalizing spectral scans (sample/reference), or Fourier transforming input flux $[I(x)]$ arrays and storing them in assigned disk areas. As is true with most of our functional subroutines, this program has been left open for future additions.

We plot with several library routines which have different functional characteristics and are fully described elsewhere in other papers.⁷ As mentioned previously, we plot our data most frequently on a local storage oscilloscope or we may plot hard copy on a remote IBM 1627 Plotter.

Performance

The performance of the on-line interferometer system has met all specifications. We have on several occasions been noise limited solely by the Golay detector and the specifi-

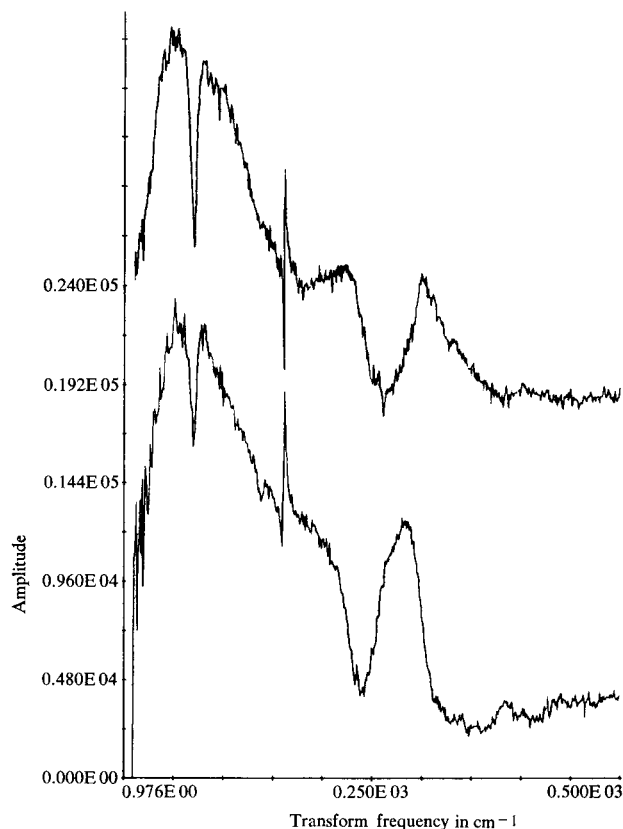


Figure 7 The far-infrared spectrum of chromium tribromide at 11°K (upper trace) and 281°K (lower trace). This is a single scan of a 20- μ m sample from 10 to 500 wave numbers at 1.2 cm^{-1} resolution.

cation for 150 ft analog lines from the IBM 1800. This has produced interferogram noise levels on the order of several tenths of a percent on our background scan. The analog lines themselves can be expected to add roughly two-tenths of a percent to our noise level. This amount is trivial compared to the noise figure of the Golay detector. The addition of a helium-cooled detection system¹ should reduce the detector noise by a factor of about 50.

The GEM system has enabled us to avoid delays exceeding one minute even operating on a time-shared basis and for several of the functional tasks. It should be emphasized that once data acquisition commences the process will then continue without any delay until the assigned timer expires at run completion or via the abort procedures. Because the sampling theorem relates increment of mirror motion, Δx , to scan frequency maximum, ν_{max} , (Ref. 8) in the form $\Delta x = 1/2\nu_{\text{max}}$, and theoretical resolution is simply the reciprocal of total path difference, there are easily established relations among the total points taken in a given scan and ν_{max} . We have routinely operated the present system within the theoretical limits imposed on resolution by scans over finite path difference.¹

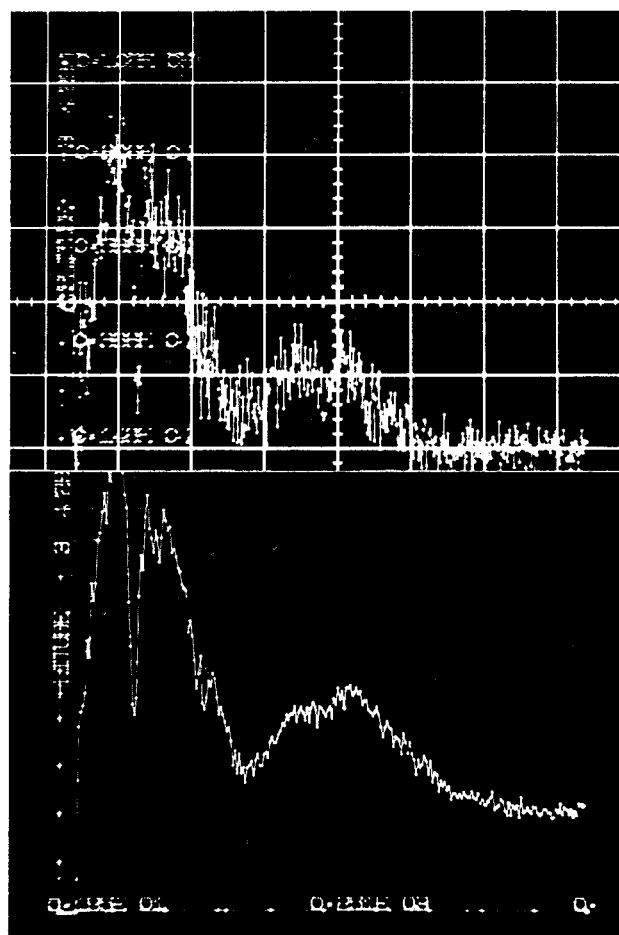


Figure 8 The effect of the computer averaging on the transmission (ordinate) vs frequency (0-500 cm^{-1}) far-infrared spectrum of urea nitrate (compare Fig. 6). The lower portion of the upper oscilloscope tracing should be compared with the lower oscilloscope tracing. Seven data runs are averaged in the lower trace. The entire averaging process required one hour. All conditions are otherwise the same as those specified in Fig. 6.

Two spectral scans are presented in Figs. 7 and 8. Figure 7 is a signal beam scan of CrBr_3 , the upper trace at 11.0°K and the lower trace at 281°K. These spectra were obtained on a sample of approximately 20 μm thickness at 1.2 cm^{-1} resolution. The feature at 70 cm^{-1} is a filter line, and the structure centered around 150, and 245 cm^{-1} regions are the site-split infrared active t_{1g} modes. The analysis of this spectrum has been presented elsewhere.⁹ Figure 8 is meant to give some indication of the advantages of computer averaging. The sample in this case is urea nitrate and the Fourier transformed spectra before and after seven averages are shown in the lower portion of the upper trace (compare Fig. 6), and in the lower trace, respectively.

Acknowledgments

It is a pleasure to acknowledge helpful conversations with several staff members of the San Jose Laboratory, in particular D. M. Hannon, H. M. Gladney, D. Clarke, T. Kuga, J. Duran, and K. Foster. D. Horne constructed the motor control-burst counter unit for which we are grateful. The storage scope was donated by the control group of this Laboratory. G. B. Street generously provided us with crystals of CrBr_3 . We should also like to acknowledge the continuing support and encouragement of J. D. Swalen.

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Received August 4, 1969