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A NEW MICHELSON SPECTROPHOTOMETER SYSTEM

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RESUMEN

Un nuevo espectrofotómetro Michelson, que ópticamente es muy sencillo, ha sido desarrollado tomando en cuenta todos los problemas de procesamiento. Los datos obtenidos con el telescopio se registran analógicamente; pero todo el trabajo posterior es realizado por computadoras. Los programas necesarios están funcionando a la perfección.

Los primeros resultados obtenidos con este espectrofotómetro Michelson se han publicado como la primera parte de un Atlas Estelar. El intervalo de longitud de onda va de 4000Å a 10000Å. Sin embargo, se pueden observar longitudes de onda más largas, simplemente sustituyendo el detector de Silicio usado para el Atlas, por otro más adecuado.

ABSTRACT

A new and optically very simple Michelson Fourier Transform Spectrophotometer has been developed. The development includes full consideration of the data processing problems and their solutions. The raw data are recorded in analog form at the telescope, but all succeding work is done by computers; all the necessary software has been written and is in successful operation.

The first results from this new Michelson spectrophotometer been published as *An Atlas of Stellar Spectra, I.* The wavelength coverage of this *Atlas* is from 4000Å to 10000Å, but longer wavelengths may be observed merely by substituting an appropriate detector for the Silicon photodiode used for the *Atlas.*

Key Words: ASTRONOMICAL TECHNIQUES — FOURIER SPECTROSCOPY.

I. INTRODUCTION

It was approximately ten years ago that I started a project using a rapid-scanning Michelson interferometer to obtain infrared stellar spectra. The first instrument which I used was the one shown in the picture on page 46 of Lawrence Mertz's (1965) book *Transformations in Optics*. Dr. Mertz was kind enough to lend us his personal instrument, which was used to produce, among other things, the first high-altitude infrared spectra of Venus (Kuiper and Forbes 1967).

Shortly thereafter, we purchased from Block Engineering Co. an improved version of Mertz's design, which included a separate reference interferometer and a nearly-monochromatic helium reference lamp. This interferometer was used to obtain additional spectral from a high-flying aircraft (Kuiper *et al.* 1968) and to obtain spectra of 8 cm^{-1} resolution of 32 stars (Johnson and Méndez 1970; Johnson *et al.* 1968). During this time, the data reductions were all perfomed by IBM 1130 computer programs provided by Block Engineering Co. A description of the design of the interferometer and the reduction programs is provided in Mertz's book 1965).

About five years ago we acquired a Block Engineering Co. Model 296 interferometer. This instrument is an improvement over its predecessor in several respects: 1) the maximum resolution was increased to 0.5 cm^{-1} (1.0 cm mirror motion); 2) a feedback servo-loop around the reference interferometer (cf., Mertz 1965, page 47) was added, greatly increasing the linearity and stability of the mirror motion; 3) a HeNe laser was used as the monochromatic reference source; and 4) the diameter of the optics was doubled so that a beam diameter of 2 inches could be accommodated. This basic interferometer was incorporated into an instrument which, in one form, was used to obtain the solar spectrum from 1 to 5 μm from an altitude of 14 km (Johnson *et al.* 1973*a*) and, in a two-beam, two detector form, to obtain infrared spectra having 0.5 cm^{-1} resolution for a number of bright stars (Johnson, *et al.* 1972, 1973).

The rapid-scanning interferometer was first proposed by Lawrence Mertz and in my work I have been largely following in Mertz's footsteps. I believe that his rapid-scanning technique is the best procedure for use in astronomical Fourier-Transform spectroscopy over the spectral range from the visual to the intermediate infrared (0.4 μm to 6 μm). Provided the fringe frequencies are sufficiently high (greater than 500 Hz) this procedure essentially eliminates all problems caused by stellar scintillation and seeing, as well as the effects caused by guiding errors and thin clouds.

The third instrument which I constructed and used (Johnson 1973*a*) used both two input beams (for sky cancellation) and two detectors (in order to use the maximum amount of light). The instrument also used colimated light in the interferometer cube. This design results in an optically and mechanically complicated device which takes considerable time and effort to align (and is easy to mis-align) and which requires many mirrors to reflect the light into its several paths. My fourth design, the one described here, is very much simpler and is much nearer to Mertz's original recommendations.

II. ADVANTAGES AND DISADVANTAGES OF FOURIER-TRANSFORM SYSTEMS

There have been many discussions printed regarding the relative advantages and disadvantages of Fourier-Transform Systems compared with other systems. It was Fellgett (1951) who first pointed out that the signal-multiplexing property of a Michelson interferometer allowed such an instrument a considerable advantage (the "Fellgett Advantage") over a conventional monochromator in the case where detector noise limits the performance. The most recent such comparison I have seen is that of Tai and Harwit (1976) who compared Fourier and Hadamard transform spectrometers. I believe however, that the discussions of Meaburn (1973, 1975) are the most rigorous and most nearly represent the true state of affairs.

The results of these comparisons may be summarized as follows:

1. In the detector-noise-limited case (i.e., when the noise level is constant, independent of signal intensity), the FTS exhibits the "Fellgett Advantage". This means that the FTS is superior in this case to a scanning monochromator using the same detector by a factor of $\sqrt{N/2}$, where N is the number of spectral elements observed. This comparison assumes that the light comes from a point source. If the light source is extended, the FTS has a considerable further advantage over the scanner.

2. In the radiation-noise-limited case (i.e., when the detector dark noise is small compared with the radiation-induced detector noise), the FTS does not exhibit the Fellgett advantage and the FTS and a scanning monochromator have essentially the same signal-to-noise ratio when the same detector is used on each. Again, this comparison assumes that the light comes from a point source; the FTS has a considerable advantage over the scanner for an extended source (Meaburn 1975).

3. In all cases, simple comparisons of a FTS with a multi-element detector having N detectors operating simultaneously result in considerable disadvantages for the FTS for large N. These simple comparisons, however, ignore the practical fact that the limit on N due to the limited number of independent detectors available in arrays is much smaller than the limit on N due to limitations on FTS path difference, and many multiple exposures are necessary with a multi-element detector array to duplicate the large number of spectral elements and spectral range available with the FTS.

The one fatal flaw in most of these comparison of the FTS with scanners of multi-element array is the fact that only one of the essential attribute

—the signal-to-noise ratio for faint objects— is considered. In actual practice the FTS has other important attributes which make it the system of choice for many astronomical spectroscopic applications. A FTS has the following important advantages (other than signal-to-noise ratio) over a single-channel spectrum scanner:

i) The FTS has an automatic laser-based wavelength calibration for each spectral element. No additional exposure time is needed for wavelength calibration.

ii) A rapid-scanning FTS provides true *simultaneous* measures at all wavelegenths. If the fringe frequencies for all frequencies (wavelengths) of interest are made greater than 500 Hz, the FTS will be free from any significant or noticeable effects of seeing, scintillations, guiding or clouds (other than the spectral absorbance of the clouds). No spurious spectral features will be introduced by these omnipresent observational problems. Furthermore, any variation of the stellar spectrum during the observation will be observed simultaneously in all wavelengths.

iii) Provided the sampling and data-processing are done correctly (this point is discussed in detail in section IV) the instrumental line profile of a FTS is rectangular with a flat top with no significant interference with or from other spectral elements. The instrumental diffraction pattern from the entrance slit of a spectrograph prohibits such an instrumental line profile for a scanner or multielement detector unless the detector width is large compared with the diffraction pattern —a situation which results in a considerable loss of efficiency in light usage.

iv) A FTS has no problems with grating "ghosts" or overlapping grating orders. It can cover as wide a spectral range simultaneously as the detector and beam-splitter permit; this can be as much as 3:1 or more.

v) A FTS has no scattered-light problem. This is not to say that there is no scattered light in a FTS —all practical optical surfaces scatter some light— but that the scattered light which reaches the detector cannot produce modulation of the detector output at a frequency other than that of the light-frequency, and therefore will not appear elsewhere in the spectrum.

vi) The multiplexing (Fellgett) advantage of a FTS makes it possible to choose detectors on the basis of high quantum efficiency, rather than low dark noise. This means that high-efficiency detectors, such as Si detectors,, can be used instead of photomultipliers. A factor of 10 increase in quantum efficiency results in a reduction of observing time of a factor of 10, surely not a negligible factor.

While a FTS cannot be said to be a simple instrument, I believe that I can show one way to make an FTS that is sufficiently simple to align and to operate that it can be used in general observatory service. This instrument is described in the next section of this paper.

III. INSTRUMENTATION

The instrument is basically a simple, rapid-scanning Michelson interferometer. A schematic drawing of the optics is shown in Figure 1. There is only one detector, which is placed in the telescope focal plane, with the telescope beam passing through the interferometer to reach the focus. Thus, the interferometer is operated in the convergent f/45 beam of the telescope, and the entire instrument contains no optics other than the beam-splitter and the two mirrors of he interferometer. This design assures that the light losses are minimized. There is only one adjustable optical component —the interferometer mirror opposite the detector— and it is easily adjusted by eye, using a diffuse mercury 5461Å source.

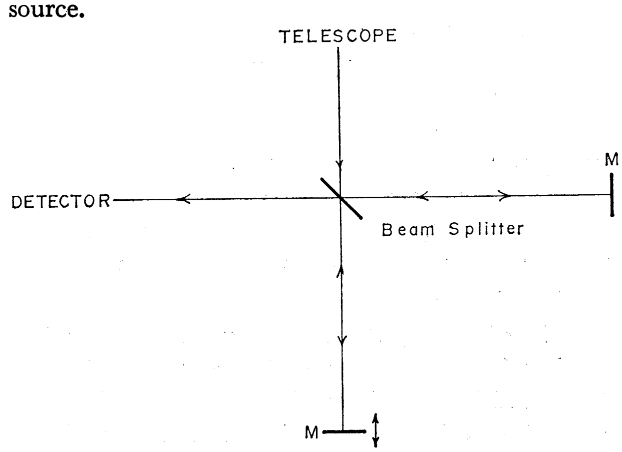

FIG. 1. The schematic diagram of the optics of the new Michelson Fourier Transform spectrophotometer.

In a sense, this new design represents a retrogression from the previous two-beam, two detector design (Johnson 1973). It does, in fact, return to the simple, compact design advocated by Mertz (1965). The lack of collimation of the beam limits the maximum path-difference and, hence, the resolution that can be used; the use of a single detector ignores the second interferometer output and rejects 50% of the light; the use of only one of the two inputs to the interferometer precludes optical sky cancellation within the instrument. The previous instrument (Johnson 1973) possessed all of these features nevertheless, after the experience gained from use of that instrument, the present much simpler instrument was designed and built. The reasons for this decision are:

1. The 1973 instrument had many critical optical adjustments and required much time and effort to align; the new instrument is simple to align (one optical component only) and retains its adjustment over long periods of time.

2. Although the 1973 instrument had optics to collimate the light, the fact that both inputs and both outputs were used meant that it did not actually work with parallel light. A glance at Figure 1 shows the reason —the second output beam (which the new instrument does not use) is reflected exactly back along the beam from the telescope. For an interferometer with plane mirrors it is necessary to send the telescope beam into the interferometer at an angle, so that the return beam can be separated and sent to the detector. In actual fact, the angle between the input and output beams in the 1973 instrument was approximately 0.4 degree, corresponding to a focal ratio of 140; even so, we were able to obtain spectra having a resolution of 0.5 cm^{-1}. Thus, it is possible to obtain a resolution of 1-2 cm^{-1} using the f/45 beam of the 90-inch Steward Observatory telescope; or 4-6 cm^{-1} with an f/15 beam. The observations with the new instrument confirm these conclusions.

It is, of course, the very large "through-put" of an interferometer system (Mertz 1965, Meaburn 1975) which makes it possible to obtain such resolution without beam-collimation. Incidentally, Mertz (1965) has shown that "no diffraction limited monochromator can accommodate all of the light from a large telescope. Either the monochromator or the telescope must be used at only a small fraction of its capability".

3. The measured eficiency of the 1973 instrument, which had two detectors, was measured to be 22%. Thus, in spite of the fact that both outputs were used (and, therefore all the light was collected) the losses in the many mirrors needed to separate and to collimate the two input and output beams caused a loss of more than three-fourths of the radiation. Since the simple one-detector instrument shown in Figure 1 theoretically has an efficiency of 50% (one beam) it was chosen. The measured efficiency is actually approximately 40% —almost double than that of the two-detector instrument.

4. Lastly, it was decided not to use optical sky subtraction, again because it increases greatly the complexity of the instrument. Sky measures are not necessary for bright stars and for very faint stars increase the observing time by a factor of two. The higher efficiency of the single-detector single-beam instrument (40% versus 22%) more than compensates for the average time lost in measuring the sky. If it becomes important to make simultaneous sky measures, this can be accomplished with the present instrument (40W versus 22%) more than compen immediately adjacent to the other one. This second detector observes the sky and its interferogram would be recorded separately on a multiple channel analog recorder, transformed to a spectrum and then used to correct the stellar spectrum for sky contamination.

The quartz beam-splitter was coated with a layer of ZnSe one-quarter wavelength thick at 4500Å this combination produced a beam-splitter whose transmission stays between 40% and 60% over the entire range from 4800Å to 2.5 μm, and which has no measurable absorption (reflection plus transmission equals unity). The efficiency of the beam splitter drops rapidly for shorter wavelengths; it and a Schott GG13 filter limit the optical band to wavelengths longer than 4000Å, and the efficiency is high only for wavelengths longer than 4800Å.

The interferometer mirrors were coated with evaporated silver upon which was deposited a special low-reflection film. The mirror reflectivity has remained higher than 96% for several years.

Because of its high quantum efficiency and low dark current an EG + G UV100B photodiode was chosen as the detector for the 4000Å to 10000Å range. The quantum efficiency of the detector is approximately 50% at 4000Å and 80% at 9000Å; it remains good to 10000Å but falls rapidly nearly to zero at 11000Å.

Since a Si detector is a photodiode and has no internal amplification, as does a photomultiplier, it is necessary to use a very low noise, very high input impedance amplifier. The general design of the preamplifier follows the precepts established by Johnson (1948), with high-frequency compensation following the second recomendation there. Of course, modern solid state components are used instead of the vacuum-tube components discussed in 1948, and the input transistor is placed in the refrigerated chamber along with the detector and load resistor. The measured NEP of the detector-amplifier combination is approximately $1.6 \times 10^{-16} \mathrm{w/Hz}^{1/2}$. The noise is entirely from the detector, which has a resistance of approximately 10^{12} ohms. The amplifier noise is about 1/4 that of the detector. The circuit diagram of the preamplifier and 3000 Hz sharp cut-off band-limiting filter is shown in Figure 2. From this preamplifier the signal is sent without further conditioning to the analog magnetic tape recorder.

Several years ago, for the reasons explained by Johnson *et al.* (1973), I decided to use only analog recording techniques for recording data from an FTS. Briefly summarized, the advantages of analog recording with later digitization and reduction are:

i) The analog recording method is much simpler and, hence, has much higher reliability than digital systems.

ii) The analog tapes can be replayed to the digital analyzer so that the reductions can be redone, or a new method of reduction can be tried with the same raw-observational data.

iii) The density of data recording by analog techniques is much greater than present digital techniques. One 14-inch reel of analog tape is sufficient for more than six hours of data recording.

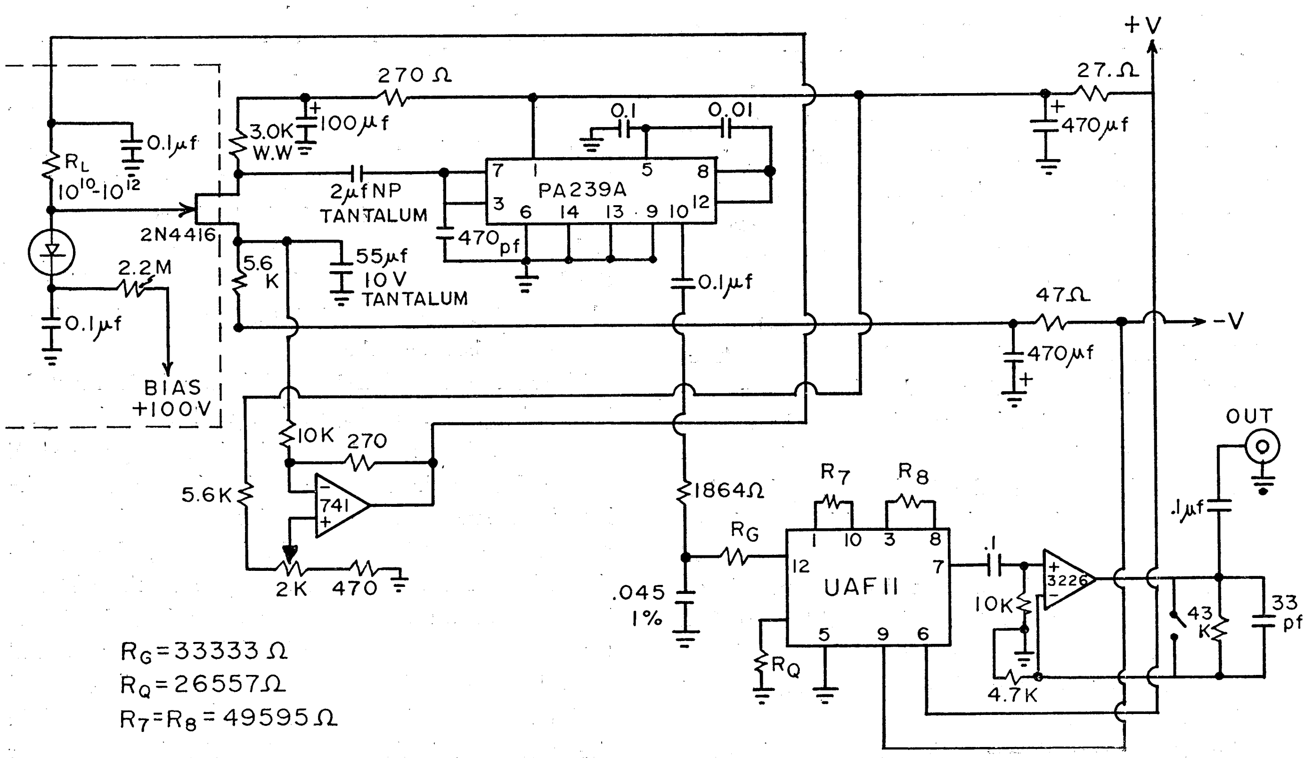

FIG. 2. The schematic diagram of the electronics of the detector and preamplifier.

The entire system, then, consists of the interferometer and detector-cold box, which is attached to the telescope; the interferometer control electronics and monitor oscilloscope; and the analog magnetic tape recorder. The entire system is isolated from power line fluctuations or interference by a motor-generator and highly-regulated power supplies.

IV. DATA PROCESSING AND ANALYSIS

The reduction of the analog-recorded data from the telescope at the observatory proceeds in several stages:

1. Digitization and co-adding of the interferograms.
2. Fourier transformation to produce the observed spectra.
3. Correction for atmospheric extinction and absorption.
4. Correction to the standard photometric system.
5. Analysis of the spectra.

The full details of the first two steps have been worked out and are presented here. Approximate atmospheric extinction corrections and corrections to a standard photometric system for the November, 1975, observations have been computed and were applied to the data in *An Atlas of Stellar Spectra. I.*, and in our paper on shell-stars (Johnson, Wisniewski and Fäy 1977). More accurate corrections will be derived at a later time when more data are available. Analyses of the spectra are proceeding; this is being done almost entirely by computer operation directly upon the data files (spectra).

The observational and data reduction procedures were chosen after careful consideration of the properties of discrete Fourier transforms (Champeney 1973). The calculation of a discrete Fourier transform is carried out on the basic assumption that the interferogram is infinitely repetitive, at intervals of 2N, where N is the number of discrete and independent frequencies output by the transform. The number 2N comes from the well-known fact that it is necessary to obtain a minimum of two samples per cycle of the highest frequency present in the interferogram.

The assumption that the interferogram is repetitive was rejected by Mertz (1965) as a "wild assumption", and his example has apparently been followed by almost all practioners of Fourier Transform Spectroscopy. Nevertheless, the physical fact is that the interferograms from a rapid-scanning interferometer are indeed repetitive —in my FTS work no observation has ever been based upon less than 100 interferograms, and some observations have contained more than 10000 interferograms. Thus, the repetitive nature of the observational data is a fact of the observational procedure. It is irrelevant that we do co-add the individual interferograms and then assume that the observation consists of a series of identical interferograms; if we wanted to spend the computer time, we could in principle transform the entire observation without first co-adding; the final result would be the same.

This recognition changes drastically the concept of instrumental profile as expounded by Mertz (1965) and others. Thus the transformed spectrum is *not* convolved with the transform of a "window" whose length is equal to the length of the interferogram but, instead, is convolved with the transform of a window whose length is at least as long as 100 interferograms placed end-to-end. As a consequence, the sin x/x instrumental profile has a width *less than one per cent* of the distance between the output points from the Fourier transform. Far from being a "wild assumption", the assumption that the interferogram is infinitely repetitive is in actual fact only a short extrapolation from the physical observational procedure. Therefore, each of the N spectral points from the Fourier transform of a interferogram of 2N samples is independent of all the others and there is no interaction between them.

There are additional conditions which must be imposed upon the observation and reduction procedures. It is essential that the interferogram shall not be longer than the repetition interval; i.e., the interferograms must be 2N points, long, with the repetition every 2N points. Furthermore, the resolution of the spectrum must be equal to the distance between the output spectral points; i.e., the interferogram mut start as path difference = zero and extend to a path difference corresponding to N cycles of the highest frequency to be contained in the spectrum. This means that the interferometer must be operated in the "single-sided" mode; but this is the mode of choice anyway because it provides the highest spectral resolution from a given distance of mirror motion. These conditions listed in this paragraph are necessary to insure that the output data points are statistically independent. When they are met, the sin x/x funcion associated with the unavoidable observational truncation (do not confuse this with apodization, below, which is a voluntary action) has exactly the correct width so that each output point falls exactly on the zero crossing of the sin x/x function associated with every other point.

The interferograms must be band-limited, so that only frequencies lower than the reference laser frequency are present. This band-limiting may be optical or audio frequency, but optical band-limiting has the advantages of providing much sharper frequency cut-off and reducing the detector noise by removing unwanted radiation from the detector. Also, the phase shifts introduced by optical band-limiting are independent of variations in the speed of the moving mirror. The disadvantage of optical band-limiting is that no optical filter has 100% transmission in its pass-band.

The interferometer described here has its electronics so arranged that four equally-spaced sample points are taken of the signal interferogram for each cycle of the interferogram of the HeNe reference laser; the speed of the moving mirror is such that 6000 samples are taken per second, and the audio-frequency of 3000 Hz corresponds to a wavelength of 3164Å (one-half of 6328Å). The optical band-limiting is produced by a combination of the beam-splitter characteristics and a GG-13 filter, with a cut-off at approximately 4000Å. In order to minimize audio-frequency noise, a sharp cut-off A. F. filter is placed at 3000Hz; the highest frequency in the interferogram, however, is approximately 2300 Hz corresponding to 4000Å. The 700 Hz margin between the two cut-off frequencies is provided so that the rapid phase-shifts introduced by the A. F. filter near its cut-off frequency do not fall within the band occupied by the observed spectrum.

The combination of optical and audio-frequency bandlimiting eliminates the "alias" frequencies and, at the same time, causes the discrete output points of the Fourier transform to represent the integrals over the input spectrum $\pm\frac{1}{2}$ resolution element. The output spectrum is, therefore, a histogram, not the continuous smoothed type of spectrogram produced by a spectrum scanner. Although all of the information available from the interferograms is presented in a histogram-type spectral plot, such a diagram appears very rough compared with the output of a spectrum scanner. One should resist all pressures to smooth the spectrum, however, because any smoothing degrades the spectrum, reducing its resolution and may add spurious additional spectrum "features" (Norton and Beer 1976).

The phase correction of the spectra follows the precepts outlined by Mertz (1965). This procedure appears to be entirely satisfactory for all stars or objects which have primarily an absorption line spectrum superposed upon a continuum. Only if the spectrum contains an extremely strong emission line does this procedures appear to fail— and then only in the immediate vicinity of the emission line. A phase correction procedure for emission line objects is being developed.

The phase-correction procedure requires that a low-resolution, symmetrical interferogram be Fourier-transformed to obtain the phase spectrum. It is then necessary that the interferogram which is to be transformed into the high-resolution stellar spectrum be multiplied by a short ramp centered on path-difference zero, and exactly the same width as the low-resolution interferogram used for the phase spectrum. The resolution of the phase spectrum should be no higher than is necessary to resolve the *instrumental* phase spectrum. For the interferometer system discussed here, the optimum width of the phase interferogram is 200 points.

Since the ramp by which the main interferogram is multiplied extends 100 points on both sides of path-difference zero, it is necessary to begin the transformed region of the main interferogram 100 points to the left of zero path-difference— in contradiction with the requirement (above) that the interferogram begin at zero. However, 100 points is small compared with the total of 16384 points in the entire interferogram and the error introduced has been observed to be negligible.

The observed interferogram beings about 250 points to the left of zero path-difference but, after

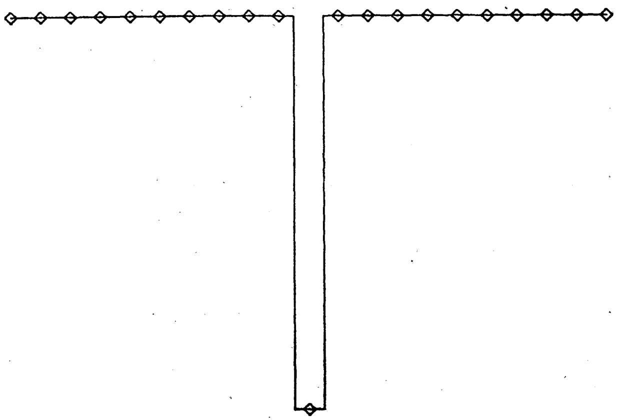

FIG. 3. An illustration of a spectrum from a Fourier Transform spectrometer.

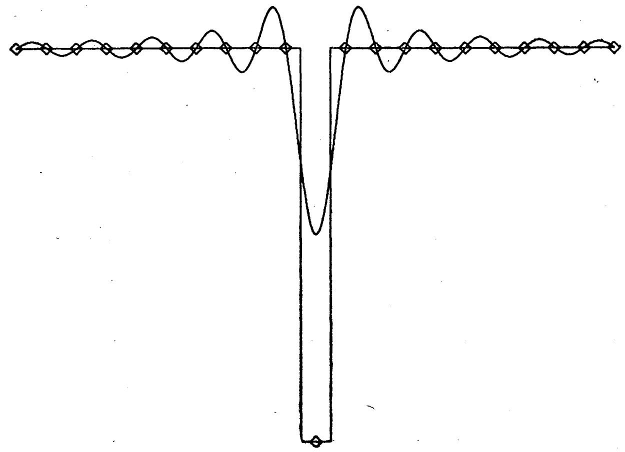

FIG. 4. The spectrum of Figure 3 interpolated with the sin x/x function.

the position of zero path-difference has been determined by the computer the interferogram is "pushed left"; i.e., the transformed region starts 100 points to the left of zero. The observed interferograms contain an extra 512 points (16384 + 512 = 16896), to provide "push-space" at the other end of the interferogram. The entire transformed region is filled with data; no zero-words have been appended to either end of the interferogram. Any extra observed points, not needed when the interferogram is "pushed left", are discarded; the transformed region is 2N (16384) points long.

The type of spectrum from a FTS system is illustrated by Figure 3. The diamond represents the data output from the transform (intensity increases upward while the frequency increases left-to-right). A single resolution element contains a strong absorption line, or lines, wholly contained within that element. There is no interaction between this element and any of the others.

It is common practice among practitioners of Fourier-transform spectroscopy to add another 2N numbers, all zero, to the interferogram. This addition has the effect of interpolating one point between each of the discrete outputs of the transform. It also has the effect of destroying the repetitive nature of the data and of multiplying the interferogram by a short window the length of the interferogram; as a result, it convolves the output spectrum with a sin x/x function. If one carries out this convolution to the point where there are a large number of interpolated points, the result is tha shown in Figure 4. Along with the over-shoots and undershoots of the sin x/x function, a considerable amount of smearing of the spectrum has occurred; much of the energy originally concentrated in the single spectral element of Figure 3 has been distributed throughout the spectrum, lowering the resolution, reducing the depth of the absorption line, and introducing spurious additional features.

In an effort to reduce the spurious features (not present in the original spectrum) introduced by the act of interpolation, it is common practice to "apodize" the interferogram by multiplying it by a function which is unity at path difference = zero and decreases linearly to zero at the maximum path difference. This is called "triangular apodization".

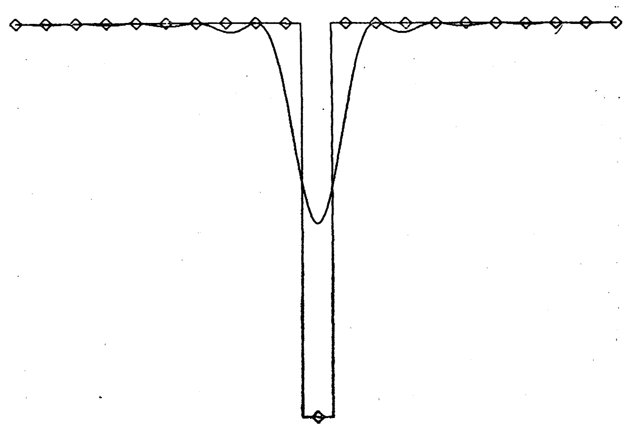

FIG. 5. The spectrum of Figure 3 interpolated with the $(\sin x/x)^2$ function.

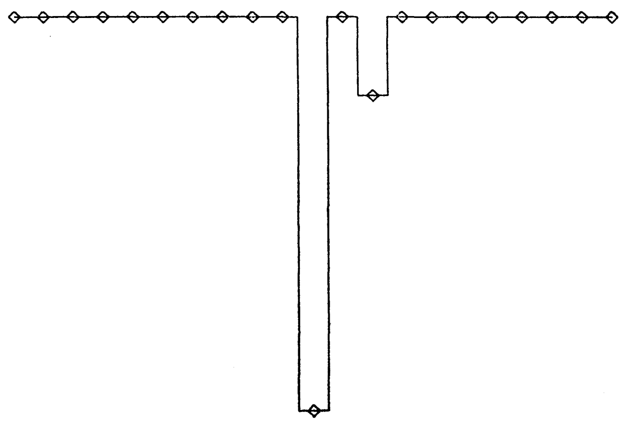

FIG. 6. A spectrum, consisting of one narrow strong absorption feature and one narrow weak absorption feature, from a Fourier Transform Spectrometer.

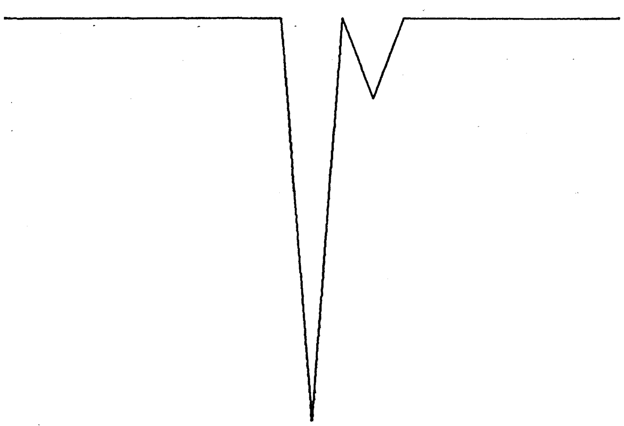

FIG. 7. The spectrum of Figure 6 interpolated with straight lines between points.

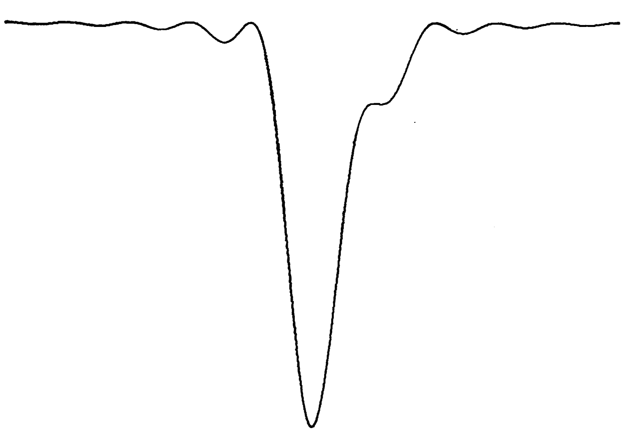

FIG. 8. The spectrum of Figure 6 after "triangular" apodization of the interferogram and interpolation with the resultant (sin x/x)^2 function.

The result of apodization and interpolation by this function is shown in Figure 5; the spurious added features have indeed been reduced in amplitude, but the resolution of the spectrum also has been lowered even further. Other, better, apodizing function which do less damage to the spectrum have been proposed by Norton and Beer (1976).

It has been claimed that apodization allows small features adjacent to strong ones to be better resolved and seen more clearly (Treffers *et al*, 1976). Let us see if this is true. Take the spectrum shown in Figure 6, which has two absorption features, one large and one small, clearly resolved in the uninterpolated output of the FTS. Merely interpolating with straight lines produces Figure 7, which demonstrates that even straight-line interpolation has a small smearing effect, although the two absorption features remain clearly resolved.

Now, what happens when we use the "triangular" apodizing function, and interpolate the spectrum with the resultant (sin x/x)^2 function? This result is shown in Figure 8. Not only is the smearing of the spectrum so great that the clearly resolved small feature of Figure 6 and 7 becomes only a bump on the side of the large feature, but a small feature, *not present in the original FTS output*, has been introduced on the left side of the large feature.

The spectrum has been smoothed to resemble the output of a scanning monochromator (and in fact, the (sinx/x)^2 instrumental profile is that produced by a diffraction limited monochromator), but at the cost of a large reduction in resolution and the introduction of spurious, non-existent spectral features. It seems clear to me that, while the spectra of Figures 6 and 7 present a more angular, rougher appearance, the loss of information which is caused by the production of the smooth spectrum of Figure 8 is intolerable.

The only question which remains is: do the actual stellar spectra observed and reduced according to the precepts above exhibit the sharp-cornered appearance and lack of over-shoots and under-shoots to be expected if the theory is correct. More explicitly, since no apodization has been performed, is there any evidence of the existence of sin x/x curves for very sharp stellar lines? As examples demonstrating that all is well, compare Figure 9, a mag-

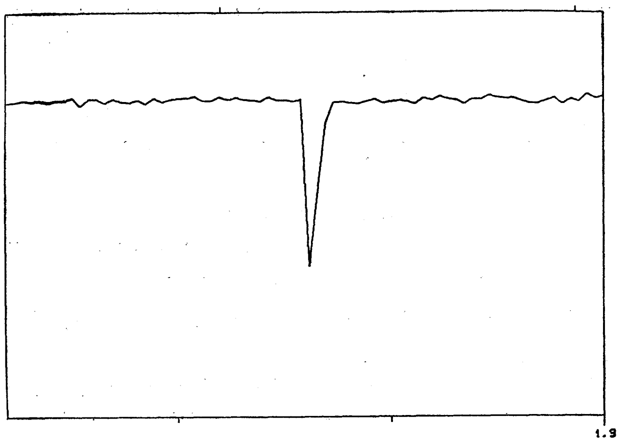

FIG. 9. The narrow infrared 7774Å oxygen line in the spectrum of α Cygni. The lower scale is frequency in cm^{-1}.

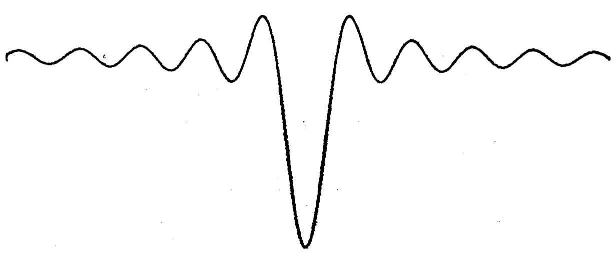

FIG. 10. The sin x/x function, for comparison with Figure 9.

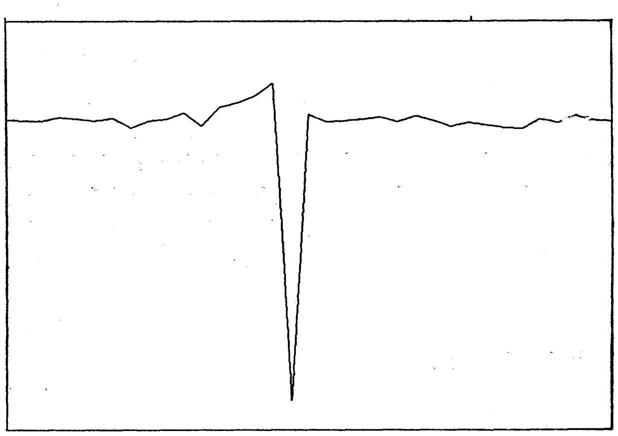

FIG. 11. The nebular Hα emission line from the spectrum of θ^1C Orionis.

nified portion of the α Cyg spectrum showing a sharp infrared oxygen line, with Figure 10, the smooth sin x/x curve which many practitioners of FTS would expect to find. There is no trace

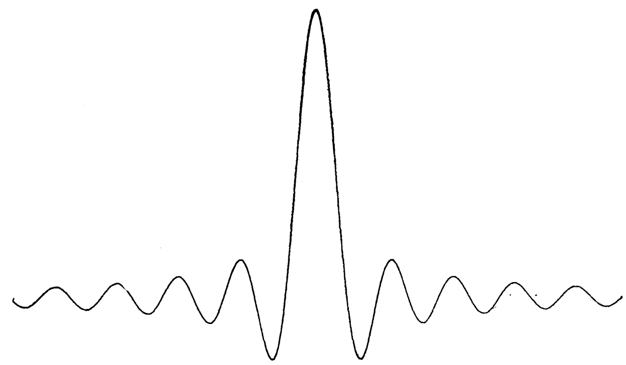

FIG. 12. The sin x/x function for comparison with Figure 11.

of the sin x/x curve, and the corners of the line where it joins the continuum are fully as sharp as in the Figure 7. The same comments may be made about the Hα emission line in θ^1 Ori A, and its comparison sin x/x curve, in Figures 11 and 12. The very sharp nebular Hα emission line is entirely contained within one resolution element (2.5Å wide); while it exhibits a slight P Cyg profile, the Hα emission line in θ^1 Ori A has the required sharp corners at the continuum and lacks any trace of sin x/x contamination. Many other examples from these and other stellar spectra could have been exhibited, but these two are sufficient to make the point. (Because of the minor programming error present when the spectra of the *Atlas of Stellar Spectra, I.*, (Johnson 1977) were plotted, small spurious ringing

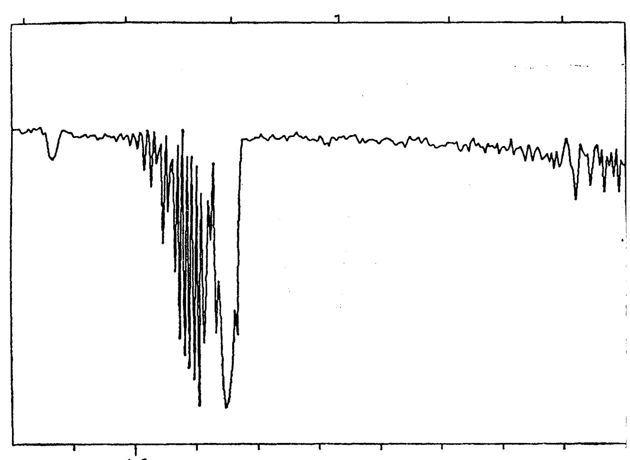

FIG. 13. The region of the atmospheric A-band in α Aql. The spectrum in the uninterpolated output of the Fourier Transform System.

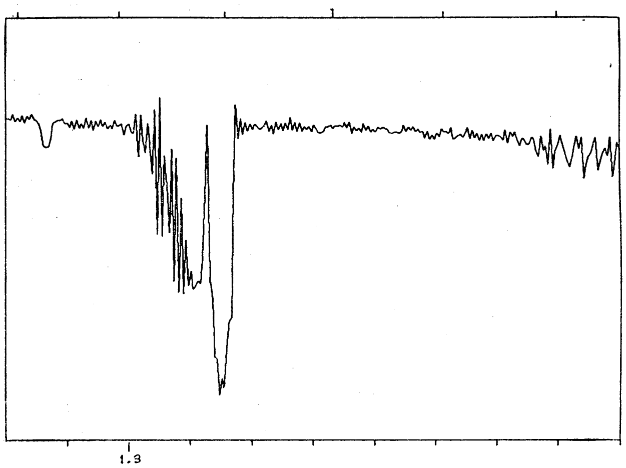

FIG. 14. The region of the atmospheric A-band in α Aql. The spectrum has been interpolated using the sin x/x function.

effects occur next to some strong lines. All such spurious effects were removed by correction of the programming error).

The final demonstration of the effects of interpolation and apodization is shown in Figures 13 and 14. Figures 13 shows the region of the atmospheric A-band in α Aql; the right-hand corner of the A band is sharp and square with no evidence of ringing. On the other hand Figure 14, which was reduced with sin x/x interpolation, has very noticeable ringing at this corner and additional peculiar noise throughout the figure caused by the partially resolved rotational bands between 1.30 and 1.31 μm^{-1}. Notice also the reduced resolution of these rotational bands when the spectrum is interpolated. The use of triangular apodization would reduce the ringing and added noise (however, not to zero), but would reduce the resolution even further. I conclude that the observation and data reduction procedures derived here are correct and that the FTS output data points are indeed independent of each other, except for the wanted correlation introduced by the stellar spectrum itself.

V. DATA ANALYSIS

The writing of computer programs for the analysis of the data from the new Michelson Fourier Transform System has barely been started. The first program which was developed was a BASIC-language program which computes the equivalent widths and effective wave-lengths of selected spectral features. This program requires an oscilloscopic display under the control of the computer. It is an interactive program which allows the astronomer to display any desired portion of the spectrum under analysis (using the computer-contained data file), and to draw in the computer a line representing the continuum. When the computer has drawn a continuum line which the astronomer considers to be satisfactory (based upon the oscilloscopic display), he tells the computer to calculate the equivalent width and effective wavelength (center of gravity) of the line or feature. The results are stored in a computer file for print-out when the astronomer desires. The equivalent widths and wavelegenths of the lines in *An Atlas of Stellar Spectra, I.*, (Johnson 1977) were computed using this program, as were those given in the paper on the Shell Stars (Johnson, Wisniewski, and Fäy 1977).

In the early stages of development is a computer program which will search a spectrum such as that of α Cyg, detect all significant spectral features, and measure their wavelengths and equivalent widths. Only by such completely computerized analysis will it be possible to provide really significant analysis of these new spectra. Perhaps it will be possible to program the computer to compare its measured stellar wavelengths with a file containing the known lines from the various elements. Then, the computer could even identify many lines and features.

Other analysis programs are possible. Preliminary tests suggest that it should be possible to measure radial velocity variations of spectroscopic binary stars by cross-correlating several independent spectra of the same star. The accuracy should be in the neighborhood of $\pm$1-2 km/sec for stars such as α Cyg, which has many narrow lines, even for spectra of the resolution of the *Atlas* (Johnson 1977).

VI. SUMMARY

This paper has been concerned with the techniques of Fourier Transform Spectroscopy and contains mainly a discussion of the instrument and the observation and reduction procedures by which the spectra in the *Atlas of Stellar Spectra, I.*, were obtained. Only the sections concerning atmospheric extinction and transformations to a standard system are incomplete. This incompleteness was unavoidable at this time because we had data from only three nights of observation reduced to the proper stage. Many more data are in the process of reduction and these sections will be revised when it becomes possible.

We have shown that the observations should be taken in a specific manner and that, if the observations and reductions are done correctly, the output of an FTS consists of a set of statistically independent data points, and that the resultant spectra are actually histograms. The spectra may accurately be described as multi-color photometry (4000 colors) using square, flat-topped filters which have no significant tails. In this respect these spectra differ *fundamentally* from those produced by spectrum scanners, or by spectrographs using multi-element detectors.

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