R. J. Bell, Introductory Fourier Transform Spectroscopy (1972)

CHAPTER ONE

Fourier Transform Spectroscopy

INTRODUCTION

The subject of Fourier transform spectroscopy (FTS) is best introduced by discussing the merits and applications of Fourier transform spectrometers in terms of (1) general advantages over conventional instruments, (2) specific advantages and disadvantages, (3) the resolving power of two-beam interferometers, (4) quality factors, (5) spectral ranges, and (6) utilization in science and industry.

Some mention also needs to be made of the basic similarity of lamellar gratings and Michelson interferometers, the methods of judging interferometers, and the extension of spectral studies into the infrared and far-infrared regions through the ~~the~~ development of interferometry or Fourier transform spectroscopy.

A short article by P. Connes [1] that describes Fourier transform spectroscopy is recommended as supplementary reading. Dr. Pierre Connes and his wife, Dr. Janine Connes, are pioneers in the fields of infrared astronomy and interferometry.

GENERAL ADVANTAGES OF FOURIER TRANSFORM SPECTROMETERS

Basically, the advantages of Fourier transform spectrometers arise from two major concepts known as the Fellgett and Jacquinot advantages. These are discussed in more detail in the following chapter, but they are mentioned here because their physical aspects are easily understood if the reader has a cursory knowledge of spectroscopy.

An interferometer receives information from the entire range of a given spectrum during each time element of a scan, whereas a conventional grating spectrometer receives information from only the very narrow region which lies within the exit slit of the instrument. Thus, the interferometer receives information about the entire spectral range during an *entire* scan, while the grating instrument receives information only in a narrow band at a given time. This is a statement of the Fellgett or multiplex advantage.

The interferometer can have a large circular source at the input or entrance aperture of the instrument with no strong limitation on the resolution. Also, it can be operated with small *f*/numbers or with large solid angles at the source and detector. However, the resolution of a conventional grating-type spectrometer depends linearly on the instrument's slit width, and the detected power depends on the square of the area of equal slits. A grating-type spectrometer requires long and narrow slits which never can have the same area for the same resolving power as the interferometer. Also, for high resolution, a spectrometer requires large radii for the collimation mirrors, and this condition in turn necessitates large *f*/numbers or small solid angles. Quantitatively, the ability of interferometers to collect large amounts of energy at high resolution was expressed by Jacquinot as a throughput or *étendue* advantage of interferometers over spectrometers.

SPECIFIC ADVANTAGES AND DISADVANTAGES OF INTERFEROMETERS

Several additional advantages follow from the Fellgett and Jacquinot advantages and can be listed as follows:

1. Very large resolving power.
2. High wavenumber accuracy.
3. Vastly reduced stray or unwanted flux problems.
4. Fast scanning time, which increases the probability of successfully completing an experiment.
5. Large wavenumber range per scan.
6. Possibility of making weak-signal measurements at millimeter wavelengths.
7. Use of small images in sample compartments without requiring special measures.
8. Measurement in amplitude spectroscopy of complex reflection or transmission coefficients.

9. Low cost of basic optical equipment.
10. Smaller size and lower weight of interferometers than spectrometers.

The few disadvantages of interferometers are that they do require access to computer facilities, and computer costs do have to be considered as factors in their operation. They are also somewhat deficient because absolute magnitudes of flux are sometimes in error by a few per cent, and the interferograms (recorded signals versus interferometer arm displacement) sometimes cannot be visually interpreted, which makes it difficult for an operator to judge quickly whether or not an experiment is satisfactory.

The large resolving power of an interferometer is a result of the Fellgett and Jacquinot advantages and depends linearly on the relative arm displacement of the instrument's movable mirror. Relative mirror displacements of the order of 2 m can be attained with some interferometers. This displacement ability has made it possible to observe weak lines with resolving powers of the order of 10^5 or higher.

The high wavenumber accuracy and the problem of reduced stray light both result from the interference phenomena inherent in the instrument. Accurate movement of an interferometer's movable mirror carriage produces a precise change in the interference pattern which can be capitalized on with excellent wavenumber accuracy in the computed spectrum. Because the unwanted waves which reach the instrument's detector have a definite wavelength, they produce distinct interference patterns which, when transformed into spectra, are identifiable. It is not uncommon to obtain transmittance measurements which are reliable to as low as 0.3%.

Fast scan times (sometimes less than 1 sec), a large wavenumber range (sometimes as large as a decade from the minimum to maximum wave number), and a measurement capability in millimeter wavelengths even when the source is very weak are all gained through the Fellgett and Jacquinot advantages. The ability to use small images at the sample is also derived from the multiplex and *étendue* advantages.

Complex reflection or transmission coefficients can be measured directly in amplitude spectroscopy by placing the sample in one arm of the interferometer. The amplitude and phase angles of the complex reflection or transmission coefficients can be obtained without any special data manipulation, such as is required in a Kramers–Kronig analysis. Thus, complex indices of refraction can be noted experimentally. Also, it is possible to make accurate flux calculations even when the transmitted (reflected) flux is as low as 0.01%. Effects of different boundaries in a sample can also be separated.

Partly because interferometers are relatively simple instruments, their space requirement and weight are small. For example, the U.S. Nimbus III satellite carried a Michelson interferometer which weighed, with its power supply, 14.5 kg and required only 1 or 2 ft^3 of space. This instrument operated for several months in orbit around the earth and took 1% accurate radiometric data between 400 and 2000 cm^{-1}. In the Viking Project, one of the basic instruments in the probe will be an interferometer which will scan the surface of Mars. The optical systems of interferometers are frequently less expensive than those of spectrometers; however, the cost of high-speed data handling systems that are needed for the operation of interferometers can nullify these savings.

The disadvantages of interferometers are few, and these are rapidly being minimized. For instance, when transmittance or reflectance measurements are made, the results can be in error up to 5% of the absolute value. Fluctuations in the interferogram, or recorded signal versus the instrument's arm displacement, can produce this amount of error. If the error is random, repetition of the experiment can reduce the deviation. With some of the commercial instruments, which have scan times of less than 1 sec and computer controls, hundreds of repeated experiments can be performed in minutes and computer-averaged in the laboratory.

Often, a spectrum can be so complicated that the experimenter cannot immediately learn much from the interferogram. This problem can be solved with one of two methods. The low-cost method is through the experimenter's experience and in his knowing a few of the interferogram's signatures or tell-tale features which presage the particular spectral features sought. He can then apply Fourier analysis to a few simple cases, such as a Gaussian spectrum, and can make sliderule estimates of the experimental progress. The more expensive but more satisfying technique is to use real-time analyses or rapid computer calculations. If the experimenter has a minicomputer in his laboratory with a memory of 4000 or more words, he can compute the spectrum over the entire wavenumber range while the data are being recorded. In fact, as the interferometer's mirror carriage moves to larger displacements, he can observe the increase in resolving power, or if the experiment is especially long, he can watch the desired spectral features develop. If it is short, he can obtain the results of the entire scan almost instantly. In addition to the real-time analyses, he can wait until the end of the experiment and make on-line computer calculations of the spectrum in a very short time of seconds or minutes.

Large computers are used by most experimenters to transform the interferograms into spectra if the data points exceed 1024. If on-line computer time-sharing is available with suitable graphic and tabular data return, there is no problem, but if the data have to be recorded on paper tapes and converted to cards, there is usually a delay of one or two days. The computation time can be shortened considerably if the Cooley–Tukey algorithm is used. This

algorithm makes it possible to make rapid computations of Fourier transforms without approximations. For example, about 9 min are required to compute the spectrum from an interferogram of one million points (see Chapter 16). Nevertheless, many computerized plotters are slow and have large backlogs which introduce delays; this can be circumvented if minicomputers with plotters are used in the laboratory.

Although the costs of computation time vary considerably, a rule-of-thumb cost reference can be established on the basis that an IBM 360 model 50 computer can handle 256 data points for a sample and background scan and produce the ratio for less than $1 in about 20 sec, providing that the programmer uses the Cooley–Tukey algorithm. Minicomputers, with the necessary plotters and oscilloscopes, can be purchased for less than $25,000–$30,000, but they are versatile instruments and can be used to operate the interferometer, compare data, and average spectra. When they are not being used to transform interferograms, other research applications can be found for them. With judicious use, minicomputers can be used economically even in small research facilities.

TWO-BEAM INTERFEROMETERS, THE ULTIMATE IN SPECTROMETERS

Gebbie [2] suggests a direct comparison of spectral sorting techniques of various instruments (Table 1-1). The prism and grating spectrometers and the Fabry–Perot and two-beam interferometers are compared in terms of their ultimate resolving power.

The prism has the lowest resolution because its resolving power is limited by the size of the transparent prisms. The resolving power is the product of the length of the prism base b and the dispersion of the prism material $dn/d\lambda$. The best resolving powers that can be obtained with a prism-type instrument are of the order of only a few thousand.

The resolving power of the grating instrument depends on its slit width s, the focal length F of the collimating mirror in the monochromator section, and the angle of rotation θ of the grating away from the zero order. For good gratings, in the near-infrared, resolving powers of the order of 10^5 can be attained. This resolving power has a diffraction limited maximum of Nm, which is the product of the total number of grooves in the grating N and the grating order number m.

The Fabry–Perot interferometer used to be superior to the grating instrument in resolving power. However, large arm displacements used with

Dr. William H. Steel's book "Interferometry," Cambridge Univ. Press, New York, 1967 [9]. Steel's book contains many details about a number of different types of interferometers that are designed for a variety of experiments.

INTERFEROMETERS

Figure 2-1 is an optical diagram of the basic Michelson interferometer. There are a multitude of variations, but the different instruments are basically similar. In some variations, a part is omitted, such as the compensator, or a piece is added. In others, a considerable amount of study is required to determine whether or not an instrument is indeed an interferometer.

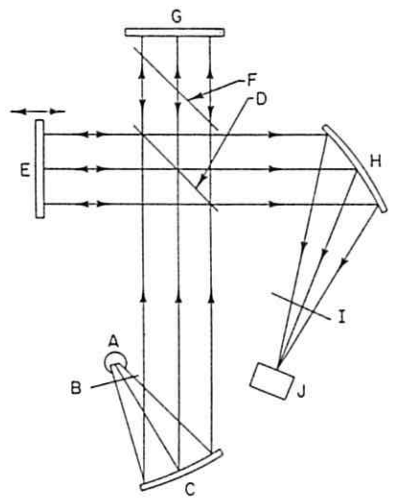

FIG. 2-1. Basic Michelson interferometer. A: Source. B: Chopper. C: Collimator. D: Beamsplitter. E: Movable mirror. F: Compensator. G: Fixed mirror. H: Focusing mirror. I: Spectral filters. J: Detector.

To understand the mechanics of the interferometer, one can start with the source, which is usually mated with a desired spectral region—mercury lamps for the far-infrared, glowers for the near-infrared, and a variety of lamps in the visible. A chopper is added to give an ac infrared flux which can be used with phase-sensitive detection and reference systems to eliminate background radiation and electronic fluctuations and drift. After the radiation beam is collimated by a mirror or lens, it is amplitude-divided at the beamsplitter. The thickness and coatings of the beamsplitter must be considered carefully (Chapter 9). One part of the radiation beam goes through a compensator plate to a fixed mirror, which reflects the beam back through the compensator plate. The beam then is reflected by a beamsplitter toward a focusing mirror. The other part of the radiation beam is reflected from the beamsplitter, goes to and returns from a movable mirror, is transmitted through the beamsplitter, and goes to the focusing mirror. The compensator plate is sometimes introduced to keep the optical paths in the two arms at approximately equal length including in the *beamsplitter material*. The focusing mirror merely focuses the recombined radiation beams on the detector. The spectral filters mainly eliminate the high-wavenumber flux, which is unwanted.

The various degrees of interference for different wavelengths are produced by an optical path difference in the two arms. The path difference is twice the carriage or arm displacement away from the balanced position. The balanced optical path position of the movable mirror is called the "origin," "white light position," or "grand maximum." The carriage can be moved to either side of the origin.

FUNDAMENTALS OF FOURIER TRANSFORM SPECTROSCOPY

Michelson realized that each wavelength in the interferometer produces its own characteristic interference pattern as the movable mirror is displaced. A monochromatic source yields a cosine variation in the flux of the combined beams at the detector. The period of the cosine function is uniquely determined by the wavelength and optical path difference for the radiation beams in the two arms. Each wavenumber band has its own characteristic cosine flux pattern with a particular magnitude. The recording of the detected signal versus optical path difference is the *interferogram*. For a source of many frequencies, the interferogram is the sum of the fluxes of each wavelength pattern. Fourier analysis, as outlined in Chapter 3, enables one to convert the interferogram into a spectrum, i.e., signal versus frequency. That is, Fourier analysis of the interferogram picks out the pattern for each frequency and determines the magnitude of the flux at that frequency, the Fourier coefficient.

JACQUINOT ADVANTAGE

The Jacquinot or throughput advantage (*étendue*) states that in a lossless optical system, the brightness of an object equals the brightness of the image; therefore, the flux throughput and brightness can be considered at any point in a lossless optical system. The validity of this concept can be illustrated with the following example:

First, consider a *point* source of radiant flux dF (with MKS units of watts) which is collected by an increment of area $d\mathscr{A}$ of an optical component (a mirror) at a distance r from the source. Assume that the normal to the mirror n is at an angle φ with respect to the central incident ray (Fig. 2-2).

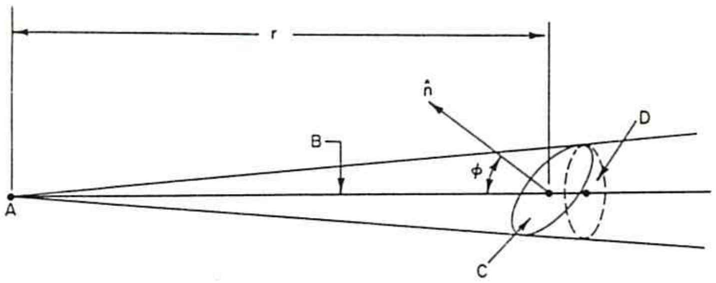

FIG. 2-2. Optical diagram of a point source and a collecting optical element. A: Point source. B: Optical axis. C: Optical element area $\equiv d\mathscr{A}$. D: Projected area $= \cos\varphi\, d\mathscr{A} \equiv dA$.

The flux striking the optical component is proportional to the projected area of the optical element and inversely proportional to the square of the distance from the source. Now, extend the source from a point to an area ds which is inclined at an angle θ between the source normal and the optical axis. The flux is emitted by the finite source which is inclined at an angle θ. The source is said to be a Lambert-law radiator when the flux is proportional to $\cos\theta\, ds$. Thus, the flux from a finite, inclined source striking an inclined optical element at distance r is

$$dF = B(\cos\theta\, ds)\,(\cos\varphi\, d\mathscr{A})/r^2. \tag{2-1}$$

The proportionality constant is the brightness B of the source, having MKS units of W m^{-2} ster^{-1}. Equation (2-1) applies to any general pair of optical elements.

By reassociating terms in Eq. (2-1), the solid angle subtended by the *source* can be defined as

$$d\Omega = (\cos\theta\, ds)/r^2 \tag{2-2}$$

and the projected area of the collimator is given by

$$dA = (\cos\varphi\, d\mathscr{A}). \tag{2-3}$$

The radiant flux is now given by

$$dF = B\, dA\, d\Omega. \tag{2-4}$$

If there is a series of optical elements with no losses between elements, the

same basic arguments which lead to Eq. (2-1) result in the following set of equations for the étendue E:

$$E \equiv (dF/B)_S = dA\, d\Omega = dA'\, d\Omega' = dA''\, d\Omega'' = \cdots = (dF/B)_D. \tag{2-5}$$

A good reference for Eq. (2-5) is F. A. Jenkins and H. E. White, "Fundamentals of Optics," 3rd ed. McGraw-Hill, New York (1957), p.111 [10]. In the reasoning used to obtain Eq. (2-5), the first optical element becomes the source for the second optical element, and so on. In Eq. (2-5), the subscript S refers to the source and the subscript D refers to the detector. If no flux is lost in the optical system, $B_S = B_D$.

For the interferometer, Jacquinot focused attention on the fact that $dA\, d\Omega$ is a constant for the instrument from the source to the detector. He pointed out that it is possible to use large values of $dA\, d\Omega$ in an interferometer and have high resolution which is virtually independent of dA and $d\Omega$. The product $dA\, d\Omega$ was called the "étendue" or "throughput."

If the power through the instrument is proportional to the étendue for sources of the same brightness B, then the étendue of grating spectrometers and interferometers can be compared. First, consider the étendue of the Michelson interferometer, E_M, as it is derived in Chapter 11, Field of View, of this book. The solid angle of the collimator mirror subtended by the source is

$$\Omega_M = \pi h^2/4F^2, \tag{2-6}$$

where h is the diameter of the circular source and F is the focal length of the collimator mirror. The resolving power of the Michelson interferometer R_M is given by

$$R_M \equiv \sigma/\delta\sigma = 8F^2/h^2; \tag{2-7}$$

therefore, the solid angle–resolving power product is given by

$$R_M\, \Omega_M = 2\pi. \tag{2-8}$$

The étendue of a Michelson interferometer, after combining Eqs. (2-5) and (2-8), is given by

$$E_M = A_M\, \Omega_M = 2\pi A_M/R_M \tag{2-9}$$

where A_M is the area of the collimator mirror and R_M is the resolving power of the interferometer. Note that the incremental parameters of Eq. (2-5) are replaced by their total values in obtaining Eq. (2-9).

For the grating spectrometer, the power through the instrument is limited by the area of the entrance slit. So the effective source area becomes the slit area, and the slit subtends the solid angle from the collimating mirror. With the slit in the focal plane of the collimator, the grating solid angle Ω_G becomes

$$\Omega_G = Wl'/F^2. \tag{2-10}$$

The slit width is W, the slit length is l', and F is the focal length of the collimator. The grating equation for a grating spectrometer system is

$$1/\lambda = \sigma = 1/(2md \cos\alpha \sin\theta) \tag{2-11}$$

where m is the order, d is the grating constant, α is the half-angle between incident and diffracted rays from the grating—entirely an instrument and not a grating parameter—and θ is the angle of rotation of the grating. By differentiation of Eq. (2-11), the resolving power can be found in terms of the increment of angle $\delta\theta$ through which the grating must be rotated to move a bandwidth $\delta\sigma$ across the equal exit slit. This small angle $\delta\theta$ is given by $W/2F$. So the resolving power R_G of a grating spectrometer is given by

$$R_G = (2F/W) \tan\theta. \tag{2-12}$$

Substituting W from Eq. (2-12) in Eq. (2-10) and using the definition of the étendue in Eq. (2-5) gives

$$E_G = A_G \Omega_G = (l'/F_G)(A_G/R_G)(2\tan\theta). \tag{2-13}$$

For grating instruments, the maximum efficiency is achieved when θ is near the blaze angle. With blaze angles of the order of 30° one has 2 tan θ of the order of unity. The grating spectrometer étendue becomes approximately

$$E_G \simeq (l'/F)(A_G/R_G). \tag{2-14}$$

Assuming the same area and focal length for the collimators and the same resolving power, the ratio of the interferometer and grating étendues becomes

$$E_M/E_G \simeq 2\pi(F/l'). \tag{2-15}$$

In the very best grating spectrometers, F/l' is never less than 30; therefore, E_M/E_G is of the order of 190 for the best grating instruments. That is, about 200 times more power can be put through the interferometer than through the best grating spectrometers. Also, the optical system can be mush smaller for the interferometer than for the grating spectrometer.

Jacquinot realized and wrote about the throughput advantage and other ideas in the following papers: P. Jacquinot and C. J. Dufour, *J. Rech. C.N.R.S.* **6**, 91 (1948) [11] and P. Jacquinot, *Rep. Prog. Phys.* **23**, 267 (1960) [12]. A clear statement of the étendue can be found in a book by A. Girard and P. Jacquinot on "Advanced Optical Techniques" (A.C.S. Van Hell, ed.), North Holland Publ., 1967, p. 71, 109 [13].

Jacquinot not only brought the throughput advantage to the attention of the scientific community, but he trained many fine students, such as Drs. Pierre and Janine Connes. Jacquinot deserves much credit for the revitalization and injection of major concepts into the field of Fourier transform spectroscopy. Later, he was made Director General of the Centre National de Recherche Scientifique.

FELLGETT ADVANTAGE

To study the multiplex or Fellgett advantage in quantitative terms, only a few basic ideas need be considered in addition to the physical description of the advantage that was given in Chapter 1. Fellgett, who was the first person to transform interferograms numerically, put forward his ideas shortly after Jacquinot stated the throughput advantage. The most comprehensive treatment of Fellgett's advantage appears in the dissertation which he submitted in 1951 to the faculty of Cambridge University in England. A more accessible article was published by P. Fellgett in *J. Phys. Radium*, Vol. 19, p. 187 (1958) [14].

The multiplex principle can be explained as follows: Suppose one is interested in measuring a broad spectrum between the wave numbers σ_1 and σ_2 with a resolution $\delta\sigma$. The number of spectral elements M in the broad band is then

$$M = (\sigma_2 - \sigma_1)/\delta\sigma \equiv (\Delta\sigma)/\delta\sigma. \tag{2-16}$$

If a grating or prism instrument is being used, each small band of width $\delta\sigma$ can be observed for a time T/M, where T is the total time required for a scan from σ_1 to σ_2. One can then say that the integrated signal received in a small band $\delta\sigma$ is proportional to T/M. If the noise is random and independent of the signal level, the signal noise should be proportional to $(T/M)^{1/2}$. Thus, for a grating instrument, the signal-to-noise ratio S/N would be

$$(S/N)_G \propto (T/M)^{1/2}. \tag{2-17}$$

The situation for the interferometer is different because it detects in the broad band $\sigma_2 - \sigma_1$ *all* small bands of resolution $\sigma\delta$ all the time. So the integrated signal in a small band $\delta\sigma$ is proportional to T. If the noise is random and independent of the signal level, the signal noise is proportional to $T^{1/2}$. Thus, for an interferometer, the signal-to-noise ratio would be

$$(S/N)_I \propto T^{1/2} \tag{2-18}$$

with the same proportionality constant as Eq. (2-17). Comparing Eqs. (2-17) and (2-18), the ratio of the $(S/N)_I$ for interferometers to the $(S/N)_G$ for gratings is

$$\frac{(S/N)_I}{(S/N)_G} = M^{1/2} \tag{2-19}$$

Since M is the number of spectral elements of width $\delta\sigma$ in the broad band $\sigma_2 - \sigma_1 = \Delta\sigma$, Eq. (2-19) predicts that the interferometer has a much higher signal-to-noise ratio than the grating or prism instruments. If $\sigma_2 - \sigma_1$ is of the order of the mean wave number σ, then by considering Eqs. (2-7) and (2-16), M is of the order of the resolving power R. Thus, if high resolving power is sought, say 10^4–10^6, the interferometer will have a better signal-to-noise ratio than the grating spectrometer by a factor of about $R^{1/2}$, or 10^2–10^3 for the hypothetical cases.

In deriving Eq. (2-19), it was assumed that the noise was independent of signal and, therefore, only depended on the measuring time. For the infrared region, the noise is usually detector noise, which is independent of signal. Hence, Eq. (2-19) is valid in infrared studies.

In the visible wavelength region, the detectors are much better than in the infrared, and individual photons can be detected. The noise is governed by the statistical fluctuations in the number of photons emitted by the source during a measurement period. Because the fluctuation in the number of photons is proportional to the total number of photons (random emission), the source illumination noise level is proportional to the square root of the source intensity.

For a grating instrument in which the photon noise dominates, if $I(\delta\sigma)$ is the intensity in the small band $\delta\sigma$, the signal recorded for the small band is proportional to $(T/M)I(\delta\sigma)$ and the noise is proportional to $[(T/M)I(\delta\sigma)]^{1/2}$. Thus, for grating instruments, the signal-to-noise ratio in the small band is

$$(S/N)_G \propto [(T/M)I(\delta\sigma)]^{1/2}. \tag{2-20}$$

A signal-to-noise ratio which is proportional to the square root of the source intensity is well known to spectroscopists who work in the visible wavelength range.

For interferometers with the noise proportional to the square root of the source intensity, the signal-to-noise ratio is entirely different than indicated by Eqs. (2-18) and (2-19). One still has the spectral signal *in a small band* proportional to $TI(\delta\sigma)$. At a particular position of the movable mirror in the interferometer, one can record a composite signal which has contributions from *all* wave numbers in the band from σ_1 to σ_2. This signal in the interferogram is proportional to $TMI(\delta\sigma)$ if all M small bands of width $\delta\sigma$ have the same intensity $I(\delta\sigma)$. The composite signal noise is then proportional to $[TMI(\delta\sigma)]^{1/2}$. In Fourier-transforming the composite recorded signal into a spectrum, the noise in the spectrum remains about the same as it was in the composite recorded signal. The computed noise $[TMI(\delta\sigma)]^{1/2}$ is the same for each small band but the signal in *a* band is $[TI(\delta\sigma)]$; so, for the interferometer, the signal-to-noise ratio *in the small band* is proportional to

$$(S/N)_I \propto [(T/M)I(\delta\sigma)]^{1/2}. \tag{2-21}$$

It is obvious that when the noise is proportional to the square root of the source intensity, there is no Fellgett advantage because Eqs. (2-20) and (2-21) are the same. Thus, in the visible wavelength range, where photon noise dominates, the Fellgett advantage is lost. However, the Jacquinot advantage is not affected; therefore, interferometers still have a large throughput advantage in the visible wavelength range.

STRONG'S GROUP

In the early 1950's, experimental efforts to make Fourier transform spectroscopy a reality were undertaken at Johns Hopkins University in Baltimore, Maryland, where Dr. John D. Strong had a group of outstanding investigators consisting of Drs. H. A. Gebbie, E. V. Loewenstein, and G. Vanasse. These four men† showed that the Fellgett and Jacquinot advantages could be actually achieved. They built instruments and obtained sample data which showed that excellent resolution could be obtained. Drs. Loewenstein and Vanasse worked with Dr. Strong for a few years and then joined the Air Force Cambridge Research Laboratories, where they established Fourier transform spectroscopy. Dr. Gebbie returned to the National Physics Laboratories at Teddington, England, and worked with Drs. J. E. Chamberlain, G. W. Chantry, and J. E. Gibbs. These four men developed Fourier transform spectroscopy with Michelson interferometers and interested such companies as Grubbs–Parsons in manufacturing some of their instruments. Dr. Gebbie is now with the National Bureau of Standards in Boulder, Colorado, where he is setting up a large, millimeter-wave telescope at Pike's Peak.

In addition to popularizing experimental Fourier transform spectroscopy, Dr. Strong's group developed the lamellar grating interferometer and published several articles concerning it. One article by G. A. Vanasse and J. D. Strong appeared as Appendix F, Application of Fourier Transforms in

† Dr. L. Wigglesworth was with the group for a while, and in an internal report, he applied Lord Rayleigh's concepts of apodization to Fourier transform spectroscopy. Apodization is described in Chapter 5.