HAL
open science

CONCLUSIONS ON MULTIPLEX METHODS

P. Fellgett

▶ **To cite this version:**

P. Fellgett. CONCLUSIONS ON MULTIPLEX METHODS. Journal de Physique Colloques, 1967, 28 (C2), pp.C2-165-C2-171. 10.1051/jphyscol:1967230 . jpa-00213208

HAL Id: jpa-00213208

https://hal.archives-ouvertes.fr/jpa-00213208

Submitted on 1 Jan 1967

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

CONCLUSIONS ON MULTIPLEX METHODS

P. FELLGETT

Department of Applied Physicals Science, University of Reading, England

Summary. — Developments in multiplex spectrometry are reviewed with particular reference to the results communicated at the present Conference. It is emphasised that the multiplex, interferometric and Fourier attributes are distinct, both logically and in a practical sense. The history of multiplex methods is outlined, and recent developments are discussed under the headings of applications, configurations and methods, performance, computation, commercial availability, technical developments and optical theory. It is concluded that in most respects multiplex methods are now capable of giving spectrometric performance as good as has yet been attained by any method. Solution of the initial technical problems has enabled the advantages of the basic simplicity of the multiplex interferometric method to be realised in practice.

Résumé. — Les développements récents de la spectrométrie multiplex sont passés en revue, en utilisant particulièrement les résultats présentés durant la conférence. Nous insistons sur le fait que les propriétés multiplex, Fourier et interférentielles sont distinctes à la fois logiquement et en pratique. L'histoire des méthodes multiplex est donnée et les développements récents discutés sous les rubriques : Applications, Méthodes et dispositifs, Résultats, Calculs, Réalisations commerciales, Développements techniques et Théorie optique. Nous concluons que dans la plupart des cas les méthodes multiplex sont capables de donner des résultats aussi bons que ceux obtenus par toute autre méthode. La solution des problèmes techniques a permis aux avantages dus à la simplicité fondamentale de la méthode multiplex interférentielle de donner des résultats pratiques.

1. **Introduction.** — In order to understand the present status of multiplex spectrometry, it will first be necessary to clarify the exact nature and scope of the multiplex method.

2. **Definitions and Historical.** — The frequent practical co-occurrence of multiplexing with the use of Fourier and interferometric methods provides some apparent justification for the assumption that these methods are identical. This view was expressed, for example, by one of the speakers who asserted, in effect, that a « Michelson » interferometer had the multiplex advantage.

In fact, of course, the multiplex, interferometric and Fourier attributes are distinct and independent. The use of an interferometer, or of Fourier methods, either alone or in combination, does not of itself guarantee multiplexing. Neither does the exclusion of either or both of these methods preclude the measurement from being multiplex. Multiplexing is always an attribute of the observation system as a whole, and is never guaranteed by the inclusion of a single element or any combination of elements such as interferometers or Fourier inverters. Multiplexing is specifically associated with orthogonal sets of functions, but it is not at all necessary that these should be the trigonometric functions as in Fourier spectrometry.

The fact that the multiplex, interferometric and Fourier attributes are independent, and can occur in all possible combinations, is illustrated in the logic diagram figure 1. The following example shows how each area of the diagram is occupied.

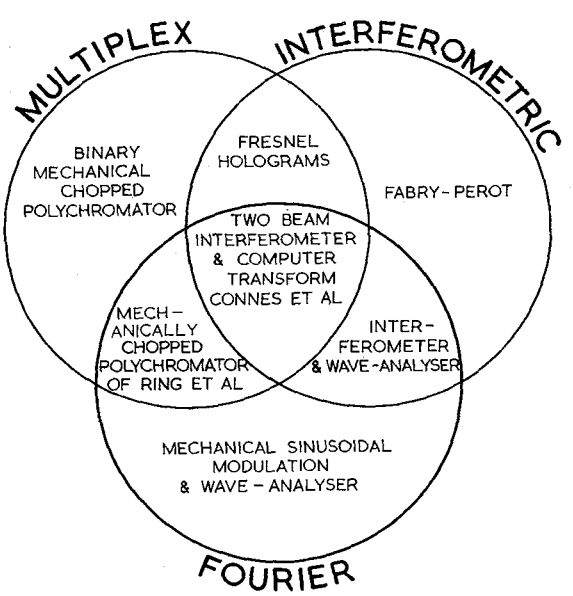

FIG. 1. — Logic diagram of multiplex, interferometric and Fourier methods of spectrometry.

Article published online by EDP Sciences and available at http://dx.doi.org/10.1051/jphyscol:1967230

(1) *Multiplex but not Interferometric or Fourier.*

A dispersing polychromator with orthogonal binary mechanical modulation of the resolved spectral elements realises this combination.

(2) *Multiplex and Interferometric but not Fourier.*

This combination can be achieved in principle using Fresnel functions, and hence probably occurs in some methods of holography. I do not know if anyone has actually demonstrated this possibility, though I would guess that the wide-ranging interest of Dr. Mertz may have led him into this region.

(3) *Interferometric but not Multiplex or Fourier.*

The classic example is the Fabry-Perot interferometer.

(4) *Multiplex and Fourier but not Interferometric.*

The dispersing polychromator with mechanical sinusoïdal modulation described by Ring et al. at this Colloquium comes into this category.

(5) *Multiplex, Interferometric and Fourier.*

The system described by the Connes et al. is one of the many which occupy this region of the diagram.

(6) *Interferometric and Fourier but not Multiplex.*

This result can be achieved (and this has actually happened inadvertently !) with a 2-beam interferometer feeding an ordinary scanning wave analyser.

(7) *Fourier but not Multiplex or Interferometric.*

This rather outré result (a phrase which I understand can be translated into French as « far out ») could be achieved by feeding the output of the Ring mechanically modulated polychromator to a scanning wave analyser.

It may help to clarify these questions further if we recall briefly when, and by whom, the various techniques of spectrometry were invented.

Fourier spectrometry was invented by Lord Rayleigh and Michelson [1, 2] around the years 1891-2. This work is too well known to merit further description here.

The *Interferometer* was invented by Michelson about a decade earlier [2]. Interference phenomena had of course been perfectly well known before Michelson's day. The distinctive feature of his experimental arrangement was that two interfering beams could be widely separated, and their path difference varied freely. He appears to have intended [3] the term « interferometer » to apply to an arrangement of this sort. Accordingly it is redundant, and to this extent incorrect, to use the term « Michelson interferometer » to refer to any such two-beam arrangement. The term « Michelson interferometer » can more properly be applied to the particular two-beam arrangement which he used, namely with two plane mirrors and plane splitting plate with separate compensator.

« Interferometric spectrometry » seems also to have been the invention of Michelson and Lord Rayleigh, but it did not come into prominence until the work of Fabry and Perot in around 1897 to 1899 [4], and of Lummer and Gehrcke in 1900 [5].

From these giants of the past, it is a long way (in every sense) to the invention of the multiplex method by Fellgett in 1949 [6]. The formulation of this principle arose from the realisation that the speed of working of an infra-red spectrometer was (in the relevant circumstances) limited by signal-to-noise rather than the bandwidth of the detector. Accordingly, the detector possessed spare channel capacity which could be used to remove the loss in signal-to-noise ratio encountered in a scanning spectrometer in which the spectral elements are examined one at a time.

I feel sure that Dr. Marcel J. E. Golay would permit me to quote from a letter which I received from him at that time [7] « It is certainly the first time, to my knowledge, that the S/N ratio advantages of the interferometric method have been pointed out. Michelson, under whom I took courses at the University of Chicago, developed his interferometer for the visible region, where there is no such advantage, basically, and he used to place emphasis on the accuracy advantages of his method. Also, he used to examine line spectra confined to a very narrow spectral region, for which he would determine the visibility curve, which was the Fourier transform of the spectrum referred to a carrier within the band observed. However, he treated the visibility as a scalar quantity, originally, although in his « Studies in Optics » he recognised the vectorial character of this quantity. Thus his method, which was based on visual observations, was limited to spectra which were symmetrical, or nearly symmetrical, about the carrier chosen. »

It is especially interesting that Dr. Golay had spotted, even at this early stage, the difficulty of realising a multiplex advantage in the visible region. Michelson of course did not formulate the multiplex principle, and in any case the multiplex advantage would have been negligible for the narrow spectral regions which he investigated. A further conclusive

reason why he could not have obtained a multiplex advantage is that he was not using a detector having the reciprocity between sensitivity and bandwidth upon which the method depends.

The technical recourses of Michelson's era enabled him to measure only the fringe visibility and not the complete interferogram. He was therefore not able to derive a spectrum by our present-day method of transforming the interferogram. Moreover, a search of the literature has failed to reveal any evidence that he ever took the Fourier transform even of the fringe intensity, though he clearly had the intention of doing so and constructed his well-known mechanical analogue device for this purpose. His actual procedure appears to have been to guess a spectral distribution, and then investigate its consistency with the observed fringe intensity.

The first reference I have found to the measurement of a genuine interferogram is that of Rubens and Hollnagel [8], and of Rubens and R. W. Wood [9], in 1910-11. These authors were concerned mainly with measuring the wavelength and distribution in reststrahlen, and they stress the luminosity advantage of the interferometric method by saying that no slit is required. They did not in fact take the Fourier transform of their interferogram, but like Michelson they guessed plausible spectral distributions, and then used semi-analytical methods to investigate the consistency of these distributions with the observed interferograms.

Here the matter seems to have rested for several decades. R. W. Wood, writing in 1934 [10], confirms that Michelson used only transforms of guessed intensity distributions. He says that the full « forward » numerical transformation would be « a much more difficult problem ». In referring to Michelson's harmonic analyser he does not say that it was ever successfully used. He concludes that the Fourier method is a difficult one, and has not been much used since Michelson's original work.

In 1950 I was able to demonstrate in the laboratory that the spectrum of a continuous source (a lamp affected by water-vapour absorption) could actually be obtained by Fourier transformation of an interferogram [6]. Rather to my surprise, this appears to be the first occasion on which a spectrum was obtained by a « forward » Fourier transformation of an interferogram. In order to recapture the climate of opinion at that time, it may be interesting to recall that it was regarded as self-evident that, although the method might work for discrete emission lines, all the information would be so jumbled up and smeared out that it would be irretrievably lost in the interferogram of a continuous source ! Moreover, my practical demonstration caused practically no modification of this opinion.

It is pertinent to mention, at this point, a development which does not come within the strict interpretation of the scope of our discussion, but which nevertheless had a decisive effect on subsequent developments. This is the study by Professor Jacquinot and his colleagues of the luminosity (American « throughput ») characteristics of spectrometric systems. Although the luminosity advantage of interferometric methods had been recognised much earlier, Professor Jacquinot was the first, so far as I am aware, to study this question systematically and to apply these studies effectively to the practical realisation of improved spectrometric methods. Professor Jacquinot also emphasised that the Fourier method of interferometric spectrometry combines this advantage with the advantage of wide spectral range, which is lacking in the classical interferometric method of Fabry and Perot. He and his associates have developed these Fourier interferometric methods (which in practice were usually multiplex as well) to a very high degree.

3. **The Development of Multiplex Methods.** — Multiplex spectrometry was conceived for the purpose of getting some kind of spectrum in circumstances where older methods were incapable of giving anything useful. In those days, we were well satisfied if we could achieve 30 resolved points. It is a measure of progress since that time that at the present Colloquium a resolution of 0.1 cm^{-1} and the ability to deal with 15 000 resolved points have each been called « limitations ».

The first person to use the multiplex method appears to have been Dr. Lawrence Mertz in 1951, using a polarisation method in the far infra-red.

The first high-grade spectra to be obtained by the multiplex interferometric method appear to be those by Mme Connes of the night sky in the region 6 000 to 1 040 cm^{-1} in 1959. A resolution of 1 000 was attained in a single observation, whereas using a grating spectrometer it had been necessary to take the mean of 10 spectra in order to obtain an effective resolution of 150. This improved resolution enabled the rotational structure to be clearly resolved for the first time.

Meanwhile Fellgett had pursued the original intention of obtaining infra-red spectra of stars, using a telescope of 1 metre aperture. By 1957 it had proved possible to push the sensitivity-limit to the 8th ma-

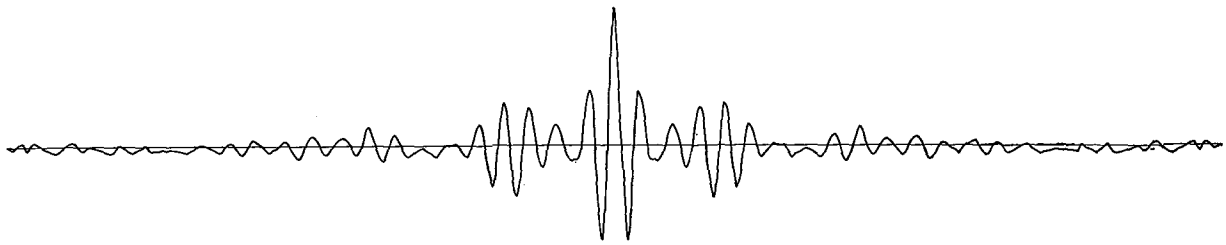

FIG. 2. — Interferogram of Jupiter recorded 13th june 1957 (36 inch reflector, Cambridge, run no. 1018).

gnitude, which was about the same as could be attained in direct photometry with the same telescope and detector (Since the spectrum yields more information, it is permissible to take a longer time for its observation than could be justified for straight photometry). Some illustrative results were presented at the previous Bellevue Conference in 1958, and it may be of some historical interest to show here, in figures 2 and 3, an interferogram obtained at this time on Jupiter

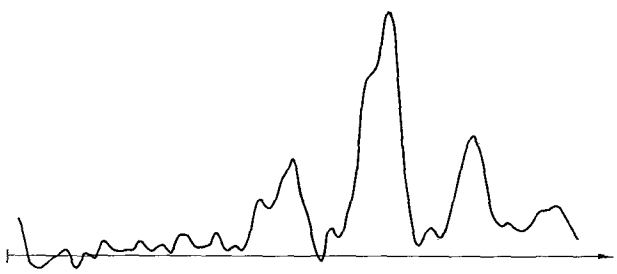

FIG. 3. — Fourier transform of interferogram shown in figure 2.

and the spectrum derived from it. This spectrum is of no scientific value because it was heavily affected by water-vapour absorption and because the path difference in the interferometer was not known with sufficient accuracy to exploit the resolution that the sensitivity would otherwise have permitted on Jupiter. This happened because the apparatus had been designed for much lower resolution on stars, and it resulted in the spectrum having a very poor resolution function. It was not therefore felt worthwhile to publish this spectrum at the time. Despite these limitations, the spectrum does show the tribolite structure appropriate to such a fossil, and may be compared with some of the spectra which have been presented at the present meeting. Similar results were obtained on Venus, which at these resolutions is an easy object even for a 36 inch telescope.

4. **The present Conference.** — It will be convenient to summarise the papers presented at the present Colloquium under several headings. The enumeration will not be exhaustive, and where no mention is made of a piece of work, which is perhaps on a topic less suited to inclusion in the necessarily brief form of a summarising discussion, there is no implication that this work is thereby of lesser importance.

4.1 DIVERSITY OF APPLICATIONS. An extraordinary variety of applications have been described. The work of Terrien and Michel is essentially « pure Michelson » but using techniques that Michelson could never have dreamed of. Beer has used a balloon-borne multiplex spectrometer for stratospheric solar studies. Gush and Buijs have studied the induced vibration spectrum of hydrogen, and Michel plasma emission. The work of Connes, Connes and Maillard has opened up a whole new realm of infra-red studies of planets. They have attained a resolution of 0.3 cm^{-1} in spectra of Jupiter, compared with a best previous resolution of 30 cm^{-1} using a larger telescope.

The range of wavelengths covered by the various studies which have been reported extends from near infra-red to sub-millimetre.

4.2 DIVERSITY OF CONFIGURATIONS AND METHODS. Here again an extraordinary variety is apparent. Connes and Pinard have developed the step-by-step method; Mertz uses rapid scan. Tinkham and Martin are so keen on multiplexing that they are even prepared to use a hundred virtual filters ; they are clearly well aware that the multiplex advantage is not obtained automatically by the use of an interferometric or Fourier method. Selby and Thorpe are using the mock interferometer, while Grainger, Ring and Stell are using a mechanical modulation method (but, for convenience, without the de-dispersion which I originally proposed).

The optical configurations are almost as numerous as the investigators. Gebbie, and Beer, have been successful with the Michelson configuration respectively in the laboratory and on a balloon. The work of Mme Connes on the night sky, already referred to, was also performed using this configuration. Delbouille and Mlle

Roland have joined me in preferring the cube-corner (*) configuration first described by Peck ; other methods of obtaining compensation against mechanical maladjustment are discussed later on. Klages has developed a new two-grating method which is particularly interesting because it appears possible, by its use, to convert an existing grating instrument for multiplex working.

4.3 New realms of performance. It is probably fair to say that the highest spectrometric resolutions now attainable are attainable by the multiplex interferometric method. Terrien and Pinard have reported the use of retardations of up to one metre, corresponding to 0.01 cm^{-1}.

Connes and al. have achieved an outstanding success in instrumental development by attaining an accuracy of resolution-function which far exceeds that which can be obtained by the figuring of optical surfaces or the ruling of gratings.

The combination of the above developments now makes multiplex interferometric spectrometry an outstanding method for precise measurements of wavelength.

It is of special interest that the sensitivity advantages of these methods have now been exploited to such an extent that field-compensation, in order to obtain still greater luminosity, has become of practical interest. Schemes for achieving this have been discussed by Connes and by Mertz.

4.4 Computational methods. Computational methods for Fourier transformation have now attained a high degree of sophistication. Connes and Connes have described how they identify the zero of path-difference with an accuracy of the order of 1 Å, calculate a basic spectrum and then interpolate to give a smooth function which, although redundant, is easier to interpret. The calculation of the basic spectrum employs Chebyshev recurrence, with careful control of rounding errors. Up to 15 000 points can now be transformed with reasonable economy.

Forman has reported an exciting new short-cut method which seems certain to revolutionise the computation of Fourier transforms.

From the consideration of computational methods, two topics emerge for special comment. The first concerns *interpolation methods*, and involves the need for an adequate guard-band so that the available points can be at finer intervals than is strictly necessary according to the sampling theorem. This is implicit both in the work of Connes and Connes, and in the paper presented by Filler.

Secondly, there is the need to *avoid restriction to symmetrical transforms*. Filler mentioned this, as did Mertz in his paper on the phase spectrum. It should be noted that phase is an integral part of the whole transform ; possibly this is more evident where de Moivre recurrence is used than for Chebyshev. Moreover, optical or electronic methods of « chirping » the interferogram by modifing the phases of its components have the potential advantage of reducing the dynamic range which is needed in the measurement, and are likely to be increasingly exploited in the future.

4.5 Special-purpose Fourier transforming machines. Special-purpose machines for Fourier transformation, working either on analogue principles or in a semi-digital manner, have been described by Ridyard ; Pritchard ; Edgar, Lawrensen and Ring ; and by Hoffman and Vanasse. Such machines can form an extremely valuable adjunct to an interferometric spectrometer, and make it into a complete spectrometric system all (so to speak) in one box. It is probably true, however, that they will meet increasing competition from general-purpose digital computers. A powerful reason for this is that the Fourier transformer is not of itself a complete system for interpreting interferograms (see the computational methods of Connes and Connes), and moreover the general-purpose computer can do far more to interpret the spectrum after it has been calculated. Digital computers are becoming increasingly competitive in price, weight, and reliability in most, but not by means all, circumstances. The impact of microminiaturisation is likely to accelerate this trend (*).

4.6 Commercial manufacture. Commercially manufactured multiplex interferometers have been described by Ridyard and by Pritchard. The availability of such instruments is very welcome, and brings to mind the time when commercially manufactured grating instruments for the infra-red first began to replace the home-made string and sealing wax devices that had mainly been used hitherto. It is a sign that the method has come of age.

4.7 Technical developments. A number of interesting technical developments have been described. Mertz has developed the rapid scan method and oscil-

(*) The designation « corner-cube » is incorrect. A door handle is a handle and not a door. A cube-corner is a corner and not a cube.

(*) It has been said that the ultimate in microminiaturisation is tobacco that counts, but it has been reported that some attempts to realise logic in this way have encountered a preference to fight rather than switch.

lating perturbation of the path difference has been used by the Connes. Connes and Pinard have, as already mentioned, made outstanding developments in the step-by-step method and in the associated servo techniques. Mlle Roland and Delbouille discuss several of the problems of interferometric spectrometry. James and Ring, and Lowestein and Engelsrath give attention to the extremely practical question of efficiency of beamsplitters.

New methods of *optical compensation* against mechanical adjustment have been described. Connes and al. use the cat's eye reflector, and Connes' non adjustable non maladjustable interferometer was described informally. Sakai and al. have a configuration using a doublesided mirror, and derived from the Mobius strip. Although each beam suffers nine reflections, and maladjustment does lead to errors of shear, the configuration has the advantage that the two interfering beams are completely matched for rotation and for polarisation.

4.8 THE NEED TO UNDERSTAND FOURIER TRANSFORMATION AND PHYSICAL OPTICS. The need for a clear understanding of the manipulative properties of Fourier transforms was brought out in the papers of Mertz, Filler, and Jaffe and Beer, and the paper of Hopkins also emphasised the need to relate this understanding to the phenomena of physical optics.

One may ask oneself how much of the discussion of these matters really involves textbook material which ought to be known to every student of the subject. How many of the topics, indeed, were already covered in Mme Connes' thesis ? There is an educational problem here, arising from the relative neglect of Fourier transforms and of physical optics in many Physics courses. It must be confessed that much of the material which ought to be in the textbooks is not so recorded, simply because there are no textbooks which treat Fourier transformation in the appropriate manner. Several participants at the Colloquium have drawn my attention to textbooks of Fourier practice which they recommend, but on the basis of past experience I shall examine these recommendations more hopefully than in the spirit of expecting to arrive.

5. **Conclusion.** — At the time of the previous Bellevue Conference, multiplex spectrometry was still in its infancy. With the results presented at the present Colloquium, it may be asked if there is any way in which the performance of multiplex methods can now be exceeded. In one form or another, they excel in precision of intensity (in many cases), in precision of resolution-function, in precision of wavelength, in luminosity, in possessing the multiplex signal-to-noise advantage, often in the total number of resolved points that are attainable, and in the ease with which parasitic radiation of widely different wavelengths can be separated.

It appears probable, moreover, that an outstanding advantage will eventually prove to be that proposed by Mertz, namely *simplicity*. If this assertion appears at first sight surprising, let us imagine that we have been doing interferometric multiplex spectrometry all our lives, and someone were to come along and propose the grating spectrometer for the first time. We should find that there were slits to cut off most of the light, only one element of the spectrum could be observed at one time, thousands of lines would have to be laid down on the grating with sub-wavelength accuracy, the resolution function would depend on the figure and phase shifts of the optical surfaces. Then there would be questions of overlapping orders, grating aberrations, blaze, etc. Would it really be surprising if such a proposal were rejected as too complicated ?

As a final word, I would like to suggest that it is no longer appropriate to accept the logical imprecision of the term « spectroscopy ». Ultra-violet, infra-red or microwave « spectroscopy » is a contradiction in terms ; unless, of course, it is taken to imply that we are using an oscilloscope. While it is possible to « scope » a visual spectrum, it is now many years since this was a common practice for scientific purposes ; visual spectra are nearly always graphed or metered.

The study of spectra has now attained the degree of scientific maturity which qualifies it to be called a Logos. It would accordingly be correct to call our subject « Spectrology ». The words « spectrometry » and « spectrography » remain available to indicate special branches of spectrology.

P. B. FELLGETT, May, 1966.

Bibliographie

[1] RAYLEIGH (Ld.), *Phil. Mag.*, (5), 1892, **34**, 407.

[2] MICHELSON (A.), *Amer. J. Sci.*, (3), 1881, **22**, 120. *Phil. Mag.*, (5), 1891, **31**, 256, 338. *Phil. Mag.*, (5), 1892, **34**, 280. « Light Waves and their Uses », Univ. of Chicago Press, 1903.

[3] MICHELSON (A.), « Studies in Optics », Phoenix Edition, Univ. of Chicago Press, 1962, p. 20.

[4] FABRY (C.) and PEROT (A.), *Ann. Chim. Phys.*, (7), 1897, **12**, 459. *Ann. Chim. Phys.*, (7), 1899, **16**, 115, 289, 331.

[5] LUMMER (O.), *Sitz. Berl. Acad.*, 1900, **24,** 504.
Verh. Deutzch. Phys. Gesel., 1901, **3,** 85.
LUMMER (O.) and GEHRCKE (E.), *Ann. Physik*, (4), 1903, **10,** 457.
[6] FELLGETT (P. B.), Doctoral Thesis, Univ. of Cambridge, 1951. Proceedings of Ohio State Symposium on Molecular Spectroscopy, 1952. *J. Physique Rad.*, 1958, **19,** pp. 187 and 237.
[7] GOLAY (M. J. E.), Letter dated 5 february 1949. See also *J. Opt. Soc. Amer.*, 1949, **39,** 437 ; Strong. J., Frederick Ives Medal address, *J. Opt. Soc. Amer.*, 1957, **47,** 354.
[8] RUBENS (H.) and HOLLNAGEL (H.), *Phil. Mag.*, (6), 1910, **19,** 761.
[9] RUBENS (H.) and WOOD (R. W.), *Phil. Mag.*, (6), 1911, **21,** 249.
[10] WOOD (R. W.), *Physical Optics*, McMillan Co., New York, 3rd edition, 1934, p. 303 ff.