A HIGH PRECISION FOURIER SPECTROMETER FOR THE VISIBLE

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1. INTRODUCTION

The idea is commonly held that the Fourier spectrometer is a marvelous instrument with many advantages for use in the infrared (where detector noise is usually dominant), but that it is worthless in the visible (where photon noise dominates) because one of those advantages -- the multiplex advantage -- has been lost. My own conversion to Fourier methods did not occur until I attended the Aspen International Conference on Fourier Spectroscopy in March of 1970. The papers presented there made it clear that for many applications this instrument comes closer to the ideal than any other form of spectrometer now in use. As a solar physicist, I was especially interested in high resolution, high precision applications, where the usual alternatives are high-angle grating spectrometers or Fabry-Perot interferometers. Consider, then, the following advantages, all of which apply even in the visible:

i) High throughput. The Fourier spectrometer, like the Fabry-Perot interferometer, has an axis of symmetry, so that the entrance aperture is a hole rather than a slit. For extended sources, this generally confers a throughput advantage of 30 to 4001. For stars, the main advantage over grating spectrometers is the elimination of the image slicer and thus a small gain (around two) in efficiency.

ii) High optical efficiency. Using a dielectric beamsplitter, the optical efficiency approaches that of the mirrors used in the foreoptics and interferometer arms. A grating instrument of comparable precision must generally be double passed, requiring two reflections from the grating and thus a loss of a factor of two to ten, depending on the proximity of the blaze. Further losses occur in the predisperser needed to separate orders. The elements required to restrict the spectral range for a Fabry-Perot are similarly lossy.

iii) High wavelength accuracy. As demonstrated by Pinard2), the Fourier spectrometer yields wavelengths of superior quality. A whole spectrum can be observed on an internally consistent wavelength scale of "interferometric" accuracy, tied directly to a single reproducible standard.

iv) Adjustable free spectral range. By proper choice of sampling interval, used where necessary with heterodyning or aliasing techniques, the free spectral range of the Fourier spectrometer may be fitted to the problem at hand, from the study of an individual emission line to the whole broad absorption spectrum of a star. For a general-purpose
instrument, this is a major advantage over the Fabry-Perot.

v) Two-dimensional, stigmatic imaging. When combined with array detectors, this property allows us to use the high throughput to observe many small spatial elements simultaneously.

vi) Finally, there are at least two situations in which a kind of multiplex advantage exists even in the visible. The first of these is exemplified by laboratory emission spectra, where the average intensity is much lower than the typical peak intensity. Since the empty regions contribute no noise, a multiplex advantage is realized. The second situation arises when the total signal level is raised by multiplexing to such a level that the photon noise is greater than the noise in typical silicon diode detectors, so that such detectors can be used in place of photomultiplier tubes. The gain in quantum efficiency over even the best developmental tubes (not yet commercially available) is roughly 2 at 6000 Å, 3 at 8000 Å, 8 at 9000 Å, 10 at 10000 Å, and 100 at 11000 Å.

These points are discussed in greater detail in an excellent review article by Connes.

2. DESIGN SPECIFICATIONS

Taken altogether, the theoretical advantages are obviously very impressive, and we soon decided to try to build such an instrument. The design was strongly influenced by the fact the prime applications will be to solar problems, which dictated the following specifications:

i) Photometric accuracy of 0.1% or better.

ii) Resolution greater than $3 \times 10^8$ for solar lines; maximum path difference of 50 cm for terrestrial oxygen lines. Up to $10^6$ samples.

iii) Scan time to be as short as possible to take advantage of short periods of good seeing and to minimize the effect of varying terrestrial absorption. Design goal to be 100 seconds for a full $10^6$ point interferogram; this may be reduced to something like one second for array scans with very restricted spectral range.

iv) Spectral range should extend at least down to 3800 Å.

v) For maximum flexibility and observing efficiency, the sampling interval should be adjustable in small increments.

3. THE RESULTING SPECTROMETER DESIGN

When taken in combination, these specifications pose some interesting technical problems. Unfortunately, the speed requirement alone rules out the possibility of taking advantage of Connes' elegant solutions to some of
CATSEYE and CASTING-Precision Ways, Linear Motor

Fig. 1

FOURIER SPECTROMETER - Stellar Mode (unmagnified)

Fig. 3

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Fig. 2
those problems. The implied sample rate of the order of 10 kHz clearly indicates a continuous scan system. It should perhaps be mentioned here that continuous scan techniques seem to have a reputation for low efficiency which is completely unwarranted. The analysis of Sakai\textsuperscript{4)}, for example, shows only that it is poor practice to combine poor speed regulation (10\%) with primitive filters (simple RC circuits). However, neither of these conditions is basic to the method, and with proper design there should be a negligible loss of efficiency.

Once we accept the necessity for continuous scanning, it becomes obvious that inertial mass in the moving element can be an asset rather than a liability.

The final design of the moving carriage is shown in Fig. 1. The retroreflector used is a conventional cat's eye, mounted in a massive carriage. This carriage is supported and guided by plane hydrostatic bearings and driven by a pair of linear DC motors. There are no tubes or wires connected to the moving carriage; the only physical contact is through the oil film.

All information about the position and velocity of the carriage will be obtained from a system similar to the one shown in Fig. 2. This design is not yet final, so the diagram should be considered only as an illustration of possible techniques. The heart of the system is a Zeeman He-Ne laser which produces two beams of opposite circular polarization, physically coincident but separated in optical frequency by about 1.8 mHz. This beat frequency is used as a carrier on which the distance information is impressed as follows: the two polarized beams are separated after the beamsplitter, each arm of the interferometer being sampled by a single polarization. The beam returning from the moving mirror has been shifted in frequency by the usual Doppler effect, and when it is recombined with the beam from the stationary mirror, the beat frequency will be found to have shifted by one Hz/fringe/second. The unshifted beat frequency, which serves as the local oscillator in this heterodyne system, is obtained by mixing a portion of the two beams before they enter the interferometer. Now, all the power of frequency multiplication and mixing techniques can be used to modify the apparent fringe spacing. Figure 2 shows one way of deriving a sampling frequency which is N/12 times the frequency of the He-Ne fringes, where N is an integer between 3 and 50. This will allow us to work as high as 30,000 cm\textsuperscript{-1} in steps of about 600 cm\textsuperscript{-1}.

An optical diagram of the spectrometer as it is now being constructed is shown in Fig. 3. Both the foreoptics and the interferometer arms have been folded to keep the instrument compact. Several problems were eliminated and the resolution doubled by making both arms identical, including oil bearings and drives. In use, the carriages will be driven equally in opposite directions, so that the center of mass remains fixed. Since each carriage can travel well over 25 cm, the total path difference for the two
exceeds one meter, which should provide ample resolution. Several alternate arrangements of the foreoptics (not shown) have also been provided. The most important of these are an input at the opposite end of the spectrometer (where laboratory sources may be set up without interfering with the astronomical work), and an alternate output giving a magnified image for use on solar problems where the energy density in the image may be considerable.

In order to isolate the interferometer from its environment several steps have been taken. First, the whole interferometer is mounted on a massive granite slab 30 cm x 183 cm x 120 cm. This slab is mounted on four pneumatic supports which provide isolation from mechanical vibrations in the floor. Finally, this whole assembly is mounted in a vacuum tank to suppress all acoustic and microthermal disturbances. Operation in vacuum also has the advantage that vacuum wavenumbers are observed directly, thus removing another source of uncertainty in wavelength determinations.

4. DATA HANDLING

Since each scan is so short, there will be many situations in which repeated scans must be added to achieve the desired signal-to-noise ratio. In addition, the decision has been made to record two-sided interferograms, since this is the only way of ensuring that all frequency components have the same mean epoch; phase correction is also simpler and more accurate. These requirements obviously imply the existence of considerable mass storage. Fortunately, at the same time that these problems were being considered, other plans for computers at Kitt Peak were under review, so that it was possible to obtain a far more powerful and versatile computer system (Fig. 4) than would have been possible for this project alone. The Fourier spectrometer will now have priority access to a large disk as well as the considerable computing power of a Datacraft 6024/3 which will be used for a partial real-time reduction of the interferogram. Access to these devices is through a Varian 620f which acts as a buffer and controller.

Also shown on Fig. 4 is another critical component in the data chain -- an auto-ranging analog-digital converter designed by Richard Aikens of this laboratory. Pre-conversion gain is automatically selected in steps of 2 from 1 to 128 depending on the size of the input signal. This is followed by a 14-bit plus sign converter. The overall combination is capable of sampling at 10 kHz, so our goal of one million points in 100 seconds seems feasible.

5. CONCLUSION

The Fourier spectrometer described above is expected to give an information flow 100 - 4000 times greater than the double-pass grating
Fig. 4 Data Handling System

spectrometer now in use at the McMath Solar Telescope. For many of our problems, the improvement is roughly the ratio between an hour and a working year. We hope to have the instrument operating by the summer of 1973, but as in most projects of this complexity, the schedule will probably slip a little.

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REFERENCES


DISCUSSION

RING: I am glad you pointed out the possibility of two-dimensional imaging through an interferometer. If this is combined with a two-dimensional photon event counter we will be able to have interference spectra of several hundred points at once.

BRAULT: I agree.