A HIGH RESOLUTION FOURIER TRANSFORM SPECTROMETER FOR THE CASSEGRAIN FOCUS AT THE CFH TELESCOPE

Jean P. Maillard* and G. Michel°
*C.F.H.T. Corpn., Kamuela, Hawaii 96743, USA
°Meudon Observatory, France

ABSTRACT: A high resolution interferometer (60cm maximum path difference) for use from the visible region to 5μm has been designed and manufactured at Meudon Observatory to be part of the instrumentation of the Canada-France-Hawaii Telescope. The considerations which led to the choice of the interferometer being operated at the Cassegrain focus, and the design features which allow this to be achieved, are outlined.

INTRODUCTION

The spectrometer described here is a development of several generations of high resolution spectrometers built in France (Colloque CNRS, 1966; Guelachvili and Maillard, 1971; Connes and Michel, 1975). The goal was to build an instrument for a large and modern telescope located at a site far from large technical facilities. In addition, the instrument had to be usable by observers who would not necessarily be familiar with the techniques involved and it also had to be competitive with other instruments of the same class currently being used (Hall *et al.*, 1979; Davis *et al.*, 1980). This led us to adopt certain features of the previous interferometers and to develop some new designs. This paper does not set out to describe the basic properties of Fourier spectroscopy, but is intended to show the efforts which were made to realise the specified goals.

DESIGN CONSIDERATIONS

1. Spectral Range: The first definition of the project was an infrared, high resolution instrument to take advantage of the exceptional quality of the Mauna Kea site in this spectral range. Use of the Fourier method in the visible region was also taken into account. For very high resolution, grating spectrometers suffer dramatically from a lack of luminosity throughput and it is in this application that the Fourier technique becomes uniquely appropriate.

C. M. Humphries (ed.), Instrumentation for Astronomy with Large Optical Telescopes, 213–222.

2. Limit of Resolution: High resolution interferometers with 2m path-differences are now routinely in use in different French Laboratories (Maillard et al., 1976; Guelachvili, 1978; Gerstenkorn and Luc, 1976). This type of very high resolution is not normally required in astronomical spectroscopy and we therefore chose a resolution limit which corresponds to a Doppler velocity resolution of the order of 0.5km/sec. However, maximum luminosity of the instrument was required and considerable efforts were made to achieve this.

3. Choice of the Focus: The requirement for a large spectral coverage (visible to infrared) and high luminosity, led to discussion on the best choice of telescope focus at which to instal the instrument. Historically, low resolution fast scanning instruments have been frequently used at Cassegrain foci. They are compact and lightweight, due to the small path difference, and the mechanical tolerances are wide. On the other hand, the few astronomical high resolution interferometers that exist are restricted to operation at a coudé focus having a protected and stable environment. These are too massive and the optical tolerances too tight for use in any other way. However, maximum optical efficiency over a large spectral range could be achieved more easily at the Cassegrain focus than at the coudé focus.

The coudé train of the C.F.H. telescope was designed to allow easy interchange of the coudé mirrors to obtain optimum performance in each spectral range (UV, blue, red). But even with this arrangement, and with the best set of mirrors for the visible and infrared (using silver-coatings), the optical efficiency still does not exceed 55%. In addition, such a long coudé train presents a limited field of view (the unvignetted field does not exceed 30 arcsec for the optimum combination of mirrors). A larger field is needed to feed both entrances of the interferometer, a feature particularly useful in the infrared to subtract the thermal background.

The Cassegrain focus at the C.F.H. telescope presented the following advantages for an interferometer (as compared with the coudé focus): it improves the final efficiency by a factor of about 2 throughout the range 0.4 to 6μm; it gives a sufficiently large field of view; it offers all the facilities of the Cassegrain adaptor (finder eyepiece, TV camera, automatic guiding).

However, these advantages are balanced by some severe constraints: the need to maintain interferometric adjustments as the tilt changes, and the close temperature tolerances set by the shortest visible wavelength used. These considerations were incorporated into the design of the instrument built for the C.F.H. telescope. It may be noted that the only other instrument of comparable performance used at a Cassegrain focus is the one built at L.P.L. by Davis et al. (1980), adapted also from our previous instruments.

θ ″ R	1″	2″	5″	10″	20″
$1.5 \cdot 10^6$	1	0.8	▨	▨	▨
10^6	1.25	1.13	▨	▨	▨
$5 \cdot 10^5$	1.78	1.74	▨	▨	▨
10^5	3.8	3.8	3.8	1.44	▨
$5 \cdot 10^4$	5.6	5.6	5.6	4.7	▨
10^4	12.6	12.6	12.5	12.5	11.3

Table 1: Angular Tolerances Δi as a function of angular diameter of source (θ) and resolving power (R).

4. Interferometric Tolerances: The parameters which determine the interferometric tolerances are: the maximum path difference, the shortest wavelength required, and the field of view θ. The first two parameters define the maximum angular diameter of the source accepted. The angular misalignment (Δi) of the interferences can be calculated as a function of all these parameters. Table 1 gives values of Δi (in units of 10^{-4} radians) calculated as a function of θ and resolving power R. To obtain higher tolerances at very high resolution, observations eventually become limited to stellar objects.

5. Operation of the Instrument: Another concern was the desire to specify a versatile, easily usable instrument. The mechanical construction is therefore as stable as possible to minimize the necessity for optical adjustments. All adjustments which are controlled by the user can be made remotely, by micrometers. On the front panel of the electronics racks, only useful functions appear. Warning signals indicating malfunctions are also included. The instrument is permanently computer-controlled for spectrometer operation, data acquisition, and real-time data processing. All information about the state of the instrument is available on visual display.

INTERFEROMETER OPTICS

1. General Description: A simplified optical diagram of the instrument showing the general layout is given in Figure 1. The design is based upon the classical Michelson interferometer. Flat mirrors are replaced by two retroreflectors with primary mirrors (cat's eye). In this way the output beams on each side of the beam splitter can be received on two photoelectric detectors from one parallel input beam. The two outputs are conjugate with the two inputs, giving this system the capability of observing simultaneously the source and an equivalent area of sky. From a position where the optical path is equal in each arm (zero path difference) one of the cat's eyes can be moved on equal-length steps (step-by-step technique), up to a maximum distance of 30cm. A measurement of the signal received by the detectors, modulated by oscillation of the internal path difference, is recorded at each step. The instrument includes an auxiliary laser for alignment and a white light source which can be flipped into the input beams in place of the telescope.

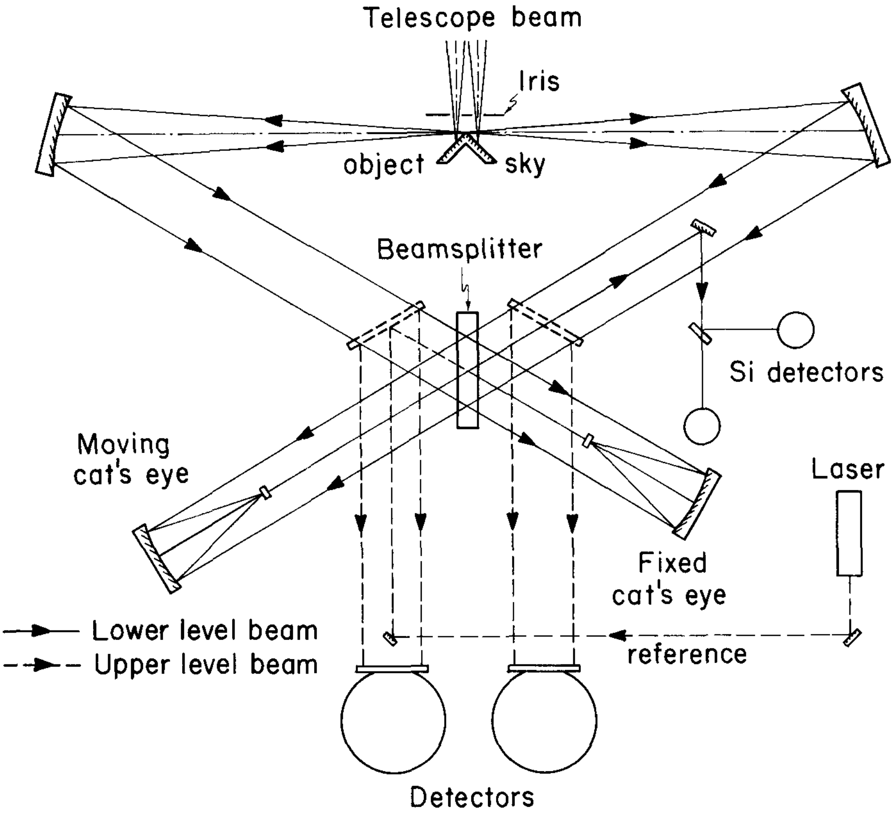


Figure 1: Simplified optical diagram of the interferometer.

All flatness tolerances for critical components in the interferometric arms were specified for $\lambda = 0.4\mu m$. The geometry of the cat's eyes were calculated to give residual aberrations at maximum resolution below the tolerances required at 0.4μm. The primary concave mirror of each cat's eye has a focal length of 400mm and a diameter of 80mm.

2. Beamsplitters: A minimum of three beamsplitters with different coatings are required for optimum instrument performance over the range 0.4-5.5μm. The following materials and coatings were chosen:

	Material	Range	Coating
(1)	Infrasil	0.4 - 1.0μm	multilayer
(2)	Infrasil	0.8 - 2.8μm	Si layer ($\lambda/4$ for 1.6μm)
(3)	CaF_2	2.5 - 5.5μm	Si layer ($\lambda/4$ for 3.8μm)

A novel feature of the instrument is the method of interchanging the beamsplitters without the need for further adjustment. Each beamsplitter is made of two rigorously flat, parallel ($\lambda/15$), plates of equal thickness. They are not mounted in the same vertical plane but offset to eliminate the lateral translation of the rays due to refraction through the plates at 6328A. To eliminate realignment of the interferometer when changing from one pair to the other, each plate is supported by three spacers of equal thickness, at 120^{o}, optically contacting the plate and a polished reference surface. The reference slab is made of low expansion glass and is drilled to permit the transmitted beams to pass through. The interchange is accomplished by a simple translation of the block. The optical polishing work was performed at the optical shop of the Institute of Optics in Paris.

MECHANICAL SPECIFICATIONS

Table 1 determines the tolerances on the mechanical features of the critical elements:

1. Optical Bench: An optical bench supports all the optical pieces. For maximum travel of the carriage, the maximum flexure of the extremities of the bench when tilted from horizontal (zenith oberservation) to vertical must be less than 30μm. The static flexure of the bench (made of aluminum casting (1790x700x12mm) with reinforcing ribs) loaded to simulate the cat's eyes was found to be 10μm.

2. Cat's Eyes: The moving cat's eye is mounted on a high quality ball bearing slide with a maximum play of 6μm for the entire track. The other one is supported by flexural pivots which provide an axis of rotation without any play. The support itself is of aluminum casting.

3. Linkage: The interferometer is hung on the flat bottom of the Cassegrain adaptor by a ring centred and fixed by 21 screws. The optical bench is tightly attached to the ring by 4 bars, 450mm long. The whole instrument is protected by a tank which can be evacuated to reduce the thermal instability. It is directly fixed at the ring with no connections to the optical bench, except by bellows. It can sag under its own weight without having any effect on the optical bench.

4. Thermal Stability: All critical optical components are made of low expansion coefficient material (CERVIT). In each cat's eye, a cylinder of fused silica keeps the distance between the primary and secondary mirror constant. For a change of temperature of 30°C the change of length is 6µm, inducing a variation of the wavefront of 6×10^{-2}µm. All sources of heating such as the power supply and the laser are located outside the tank.

5. Gravity Compensation: The change of attitude of the instrument at the Cassegrain focus also varies the load on the motors of the servo-controlled elements. To minimize the size of the power supplies and to increase the reliability of the servo-system, the load on these motors remains constant. Each cat's eye is equipped with a counter-weight moving in the opposite direction.

LASER REFERENCE CHANNEL

The method of producing interferometric signals from the reference laser uses the principle applied on the previous instruments. A thermally controlled double mode laser has been built by us and seems to provide the required stability simply. The two plane polarized modes of the laser are separated by a Glan-Thompson prism. The intensities of the two modes are compared. The variation of the difference of intensity of the modes is related to their drift. By heating the cavity more or less to change its length (so as to keep the difference constant) the modes can be stabilized with the required accuracy. By comparison with an iodine-stabilized laser, a long-term stability over 24h of 5×10^{-9} was obtained. The system has been tested at room temperature and -10°C, giving the same frequency (Millerioux, 1980).

DESCRIPTION OF THE SERVO-SYSTEM

1. Principle

The path difference needs to be closely controlled (within a few Angstroms) to operate the system in the visible region. The system we have built for the C.F.H.T. instrument is derived from a technique developed at the Aime COTTON Laboratory of C.N.R.S. (Connes and Michel, 1975).

One cat's eye has a fixed mean position but can oscillate around this by ±1mm. Its position is measured by a position transducer whose output voltage is fed to a DC motor through a servo loop which changes the position of the moving cat's eye. If we want to increment the path difference, an error voltage is fed to a loudspeaker coil which can rapidly translate the "fixed" cat's eye. As it starts moving, the position transducer departs from zero and the moving cat's eye moves until the position transducer is back to zero. Any friction encountered by the moving cat's eye will have no effect on the path difference since the fixed cat's eye will move keeping the path difference to the desired value until the voltage building up on the position transducer produces enough torque on the DC motor to overcome the friction. Fine adjustments for a large bandwidth servosystem are provided by small displacements of the individual segments of the cat's eyes which are mounted on piezoceramic stacks.

2. Servo-System Modes

Three operating modes are provided:

a) Velocity Mode: This mode is used for fast displacement of the moving cat's eye. The velocity information is given by a tachometer. Two servo loops keep the velocity to zero; the overall bandpass is 0 - 10 Hz. Offset voltages can be introduced by manual switches to move the carriage in either direction at a constant velocity of a few mm/sec. This mode is automatically set when the power is switched on.

b) Zero Path Difference Mode (ZPD): An approximate setting for zero path difference is obtained by a position transducer (ZPDT) which is mechanically adjusted so that its zero output is very close to the zero path difference condition. On activating this mode, when the moving cat's eye enters the ZPDT zone the ZPD mode is automatically switched in. This also is a double loop servo. The loop which includes the DC motor remains as in the Velocity Mode whilst the other loop works from the ZPDT output voltage operating the loudspeaker coil.

c) Fringe Mode: An Interferometric Error Signal, produced by comparing the interferometric signal with the programmed reference signal, is fed to the loudspeaker coil and piezo stacks through servo filters, providing phase correction and bandwidth separation. Frequencies 0 - 10 Hz are sent to the loudspeaker coil and 10 Hz - 1 KHz are fed to the ceramics. Another loop, similar to the two previous modes, operates the DC motor with a bandwidth 0 - 1 Hz. This mode can be selected only when the path difference is stabilized in the ZPD mode. The dynamic range of path difference control is equal to $32\lambda_R$ (or 20µm), where λ_R = reference wavelength. An emergency logic unit switches the system automatically to velocity mode in order to avoid permanent damage to the electronics or mechanics should this be necessary.

REMOTE SENSING

The occasionally hampered access to the Cassegrain focus and the compactness of the optical design forced us to develop remote sensing of some optical elements. All commands are made by hardware but from 2 possible locations: from the Cassegrain focus just out of the tank, or from the control room 70 metres away from the instrument. They are gathered on 2 identical front panels. Among the features commanded from these panels are:

- aperture of the 2 entrance iris diaphragms
- mechanical chopper
- auxiliary laser for alignment of the optics
- selection of the beamsplitter
- filters in the dewars
- gain of the preamplifiers

This automation is part of the effort to avoid any intervention by the users inside the instrument and to simplify its use.

INTERFEROMETER CONTROL AND DATA ACQUISITION SYSTEM

1. Hardware:

The control and data acquisition systems of the interferometer are shown in Figure 2. The HP21MX computer is responsible for on-line control of the equipment, and for retrieving and storing the interferograms on magnetic tape for off-line reduction. The interfacing between the spectrometer's electronic systems and the computer is made through

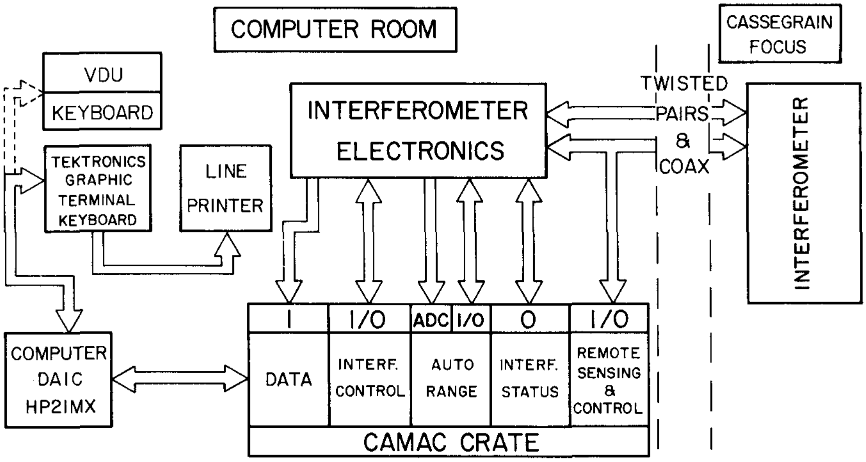


Figure 2. Block diagram of the interconnections at the Cassegrain focus to the computer through CAMAC modules.

different CAMAC modules which can be used for some other experiments in the observatory. The computer governs all digital operations involved in each function.

A new device is the automatic gain selection. The interferogram signal is delayed by 6msec by an analog delay line. During this time the input signal is converted by an A-D converter. The sample having the maximum absolute value is detected and the gain range is selected accordingly. This method solves perfectly the problem of selecting the required gain along a record.

2. Software:

All control operations of the interferometer and data acquisition are initiated through a key-board by control software. It has been largely adapted from the software developed by Davis (Davis et al., 1980).

Prior to starting data acquisition, the operator initially enters control directives at the keyboard in the course of a dialog to help him. The use of the computer gives powerful flexibility to select different modes of recording in an easy manner according to the nature of the source. For example: single scan or multiscan; symmetric scans with respect to ZPD; scan in forward or reverse direction; consecutive scans with toggling of the source. In addition, two real-time data processing options are offered on the graphic terminal: a record by record display of the interferogram or a spectrum display from an on-line Fourier transform. This last option is observationally time-consuming (7s at best for calculation and display of a portion of 256 samples).

PRELIMINARY RESULTS

The completed instrument was first tested in the Cassegrain mode on an auxiliary support in April 1980 to analyse the effects of the change of attitude. In order to estimate the performances up to large path differences, line profiles were produced by illuminating the interferometer with a part of the light of the reference laser. An example is given in Figure 3. Preliminary astronomical tests took

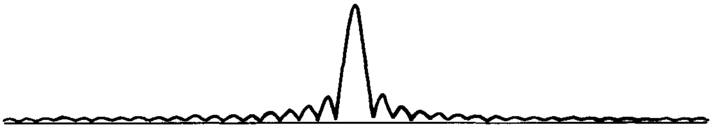
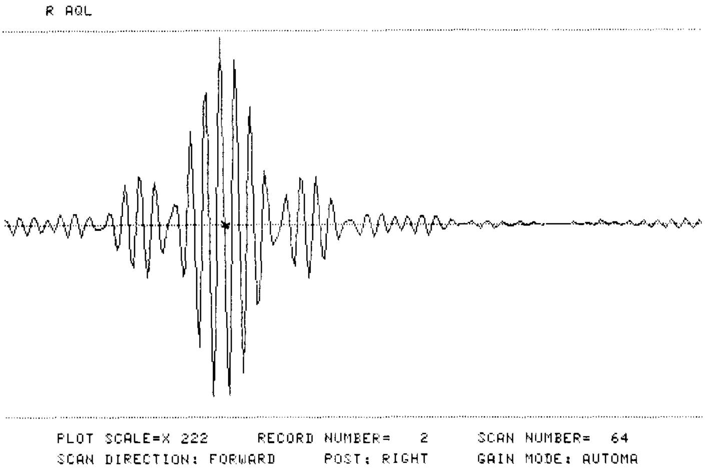


Figure 3. Real-time line profile of the stabilized 6328A laser line (Max. path difference 33.7cm).



```
R AQL

PLOT SCALE=X 222     RECORD NUMBER=   2     SCAN NUMBER=  64
SCAN DIRECTION: FORWARD     POST: RIGHT     GAIN MODE: AUTOMA
```

Figure 4. Real time graphics terminal display of the central part of a stellar interferogram (K filter).

place in May 1981 at the coudé focus (Figure 4).

The spectrometer which has been described is a part of the permanent instrumentation of the C.F.H. telescope. As such it was financed by the instrumentation budget of the telescope through an agreement between C.F.H.T. Corporation and C.N.R.S. represented by I.N.A.G., who contracted the whole project to the Observatoire de Paris - Meudon. The design of the spectrometer started in September 1977, and in June 1980 it was moved from France to the site in Hawaii. The final phase is planned for early 1982.

REFERENCES

Colloque CNRS, 1966: Methodes Nouvelles de Spectroscopie Instrumentale, published in Journal de Physique (1967) 28, Suppl. 3-4.

Connes, P. and Michel, G. 1975, Appl. Opt. 14, p. 2067.

Davis, D.S., Larson, M.P., Williams, M., Michel, G. and Connes, P. 1980, Appl. Opt. 19, p. 4138.

Gerstenkorn, S. and Luc, P. 1976, Nouv. Rev. Opt. 7, p. 149.

Guelachvili, G. and Maillard, J.P. 1971, Aspen International Conference on Spectroscopy, ed. G.A. Vanasse, A.T. Stair, D.J. Baker, AFCRL 71-0019, p. 151.

Guelachvili, G. 1978, Appl. Opt. 77, p. 1322.

Hall, D.N.B., Ridgway, S., Bill, E.A. and Yarborough, J.M. 1979, Instrumentation in Astronomy III, SPIE vol. 172, p. 121.

Maillard, J.P., Chauville, J. and Mantz, A.W. 1976, J. Mol. Spec. 63, p. 120.

Millerioux, Y. 1980, Thèse 3ième cycle, Université P. & M. Curie, Paris.