WAMDII - Wide Angle Michelson Doppler Imaging Interferometer

Principal Investigator: G.G. Shepherd, York University, Toronto.

The instrument which we are proposing for Spacelab is a specialized type of optical Michelson interferometer working at sufficiently high resolution to measure line widths and Doppler shifts of naturally occurring atmospheric emissions. With its imaging capability, the WAMDII can potentially supply this information independently for each element of the 100 x 100 detector array. The field of view will be square, measuring 5 to 10° on a side. The objectives of the experiment are (1) to obtain vertical profiles of Atmospheric winds and temperatures as functions of latitude by observing near the limb, (2) to acquire exploratory wind and temperature data on smaller scale structures in airglow irregularities and in auroral forms and (3) to collaborate with other Spacelab experiments, such as barium cloud releases, in providing wind and temperature data.

A schematic view of WAMDII is shown in Fig. 1. It consists of a Michelson of the field-widened type followed by a camera lens and the 100 x 100 CCD photodiode array. An interference filter isolates the emission line being observed and the lens focuses an image of the emission on the CCD array. Thus the CCD camera takes a "picture" of the emission as viewed through the Michelson. The Michelson does not affect the imaging of the lens, but superimposes circular interference fringes, which also focus at the CCD array. The phase of the fringes depends upon the path difference between the two arms of the Michelson and the wavelength of the emission line. By choosing a sufficiently large path difference, even the tiny Doppler shifts caused by atmospheric winds can be made to produce a measurable phase shift in the interference fringes. Obviously the large Doppler shift due to spacecraft motion must be corrected for, and for this the look direction must be known within about 0.03 degrees.

Measurement of Doppler Shift and Temperature with a Michelson

The path difference of the interferometer is very nearly fixed; only enough motion of one reflector is provided to scan over a single fringe, in order to determine its phase. It is actually sufficient to measure three points on a fringe in order to determine its phase and amplitude. The mathematics assumes its simplest form when the points are separated by $\lambda/4$ in path difference. In figure 2, the I's are the three intensities

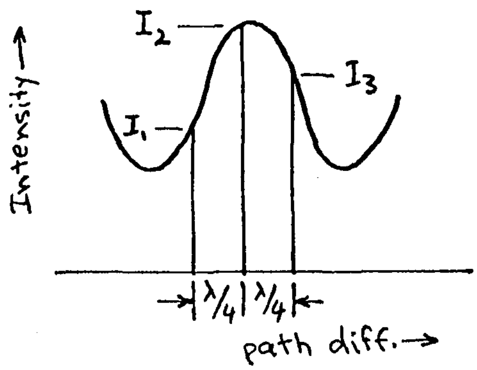


Fig. 2

measured at points on the fringe one-quarter wavelength apart. The phase, ϕ, is then given by

$$\phi = \tan^{-1} \frac{I_1 - I_3}{2I_2 - I_1 - I_3}, \qquad (1)$$

referenced to $\phi = 0$ at I_1. Thus one wind measurement by WAMDII requires that three "pictures" be taken, with the path difference stepped by $\lambda/4$ between successive exposures. Each exposure yields 10^4 intensities; a set of three exposures therefore yields 10^4 phase values, or Doppler shifts, for the one field of view.

The change in wavelength, $\Delta\lambda$, due to the Doppler shift is related to the relative velocity, v, of the emitting region by

$$v = \frac{\Delta\lambda}{\lambda_o} c,$$

where λ_o is the wavelength of the unshifted line and c is the velocity of light. In the interferometer, the wavelength shift $\Delta\lambda$ causes a phase shift of

$$\Delta\phi = 2\pi \frac{\Delta\lambda}{\lambda_o} \frac{D}{\lambda_o} = \frac{2\pi v D}{c\lambda_o}, \qquad (2)$$

where D is the path difference.

Wind velocity measurement is the primary objective of this experiment, but a secondary interest is the measurement of atmospheric temperature. This, too, can be derived from the three exposures described above without compromising the wind measurements. The fringe contrast, or visibility, V, is given by

$$V = \frac{2[I_2^2 + I_1I_3 - I_1I_2 - I_2I_3]^{1/2}}{I_1 + I_3} \qquad (3)$$

This is directly related to the Doppler temperature of the emitting gas through

$$V = \exp\ [-QTD^2] \qquad (4)$$

where T is the temperature

$$Q = 1.82 \times 10^{-12}\ (\sigma_o^2/M)\ \ K^{-1}\ cm^{-2}.$$

σ_o is the central freqneucy of the emission line in cm^{-1} and M is the mass of the atomic species in amu. This assumes a Gaussian line profile. In graphic terms, V is the ratio of the fringe amplitude to the average value. (see Hilliard and Shepherd, 1966).

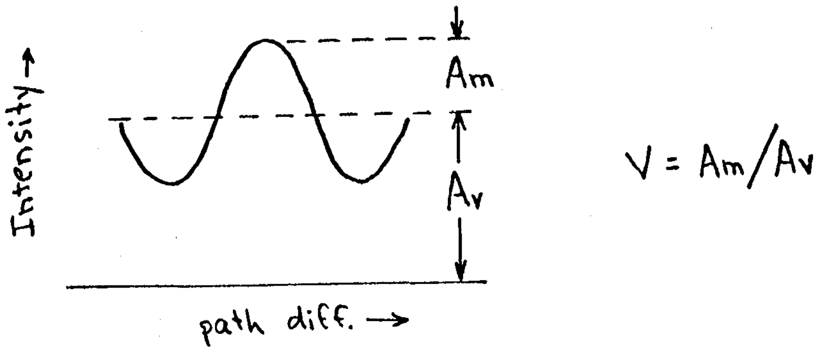


Fig. 3

Figure 4 is a schematic representation of a Gaussian emission line and its "interferogram" (Fourier transform) which would be produced by a scanning Michelson interferometer. The oscillations represent the individual fringes. The envelop causing the amplitude to decrease with path difference (described by equation (4)) is due to the finite width of the emission line. The broader the emission line, the more rapidly the fringe contrast decreases with path difference. Thus, for a given line width, an optimum path difference exists for finding the wind velocity through equation (2). Since several emissions will be observed, a compromise path difference will have to be used, probably in the range 5 to 10 cm. Or it may be possible to have two WAMDII units working at different path differences in the same instrument package, each dedicated to its own set of emissions. Some typical values for line width, visibility and phase shift are given in Table 1.

Figure 5 is another schematic illustrating an interferogram produced by two lines of equal width and intensity. A doublet, or even a more complicated multiplet can be used for the wind measurements if the path difference is chosen so that the fringes from the different components are nearly in phase with each other.

Field Widening

At the large resolving powers involved here ($\sim 10^5$), the fringes of a conventional Michelson are much too narrow to be useful. It is therefore necessary to use a technique called field widening, or field compensation, to enlarge the fringes to a useful size (Hilliard and Shepherd, 1966). The technique involves placing a refractive plate in one arm of the Michelson and adjusting the positions of the reflectors so that their virtual images are coincident. The resulting symmetry at the beamsplitter results in greatly enlarged interference fringes. In a well-compensated Michelson, the central fringe can be 15° in diameter, compared with 0.18° for a conventional instrument. Figure 6 illustrates the two configurations.

The degree of field widening is wavelength dependent. Because of dispersion in the refractive plate, the location of M_1 (Fig. 1) for maximum field compensation is different for each wavelength. But it is possible, using two plates of different refractivity and dispersion, one in each arm of the Michelson, to make the field widening achromatic enough to be useful over a wide range of the spectrum.

Instrument Description

The design of WAMDII is still evolving and many questions remain to be answered during the Project Definition Phase. Several aspects of the instrument are discussed below under separate headings.

(a) Optical System:

A beamsplitter will probably be a 5 cm cube of fused silica. The Michelson reflectors could be corner prisms or plane mirrors with active parallelism control. An achromatic field compensation system may be needed if the range of wavelengths desired is large. Alternatively, it may be necessary to move one of the reflectors to a different position for each wavelength in order to achieve optimum field compensation. The lens will be well corrected to provide a sharp image at the detector array, and will have an aperture ratio of about f/1. Pre-optics could be used to transform the field of view but this is not anticipated.

(b) Stepping Control:

In order to achieve accurate path difference steps of $\lambda/4$ between exposures, one of the reflectors must be moved in steps of $\lambda/8$, and this will be done under servo control using a reference emission line source. Collimated light from the reference lamp is passed through the Michelson in such a way that the field of view of the main detector is not obstructed. The emerging beam is sent to the reference detector and the signal is used to control the position of the reflector through a piezoelectric transducer (Fig. 7). The exact way in which this is done must still be determined, but one possibility is to use a system similar to the one described by Elsworth and James (1973), in which the emerging reference beam is polarized, the plane of polarization rotating 180° for each wavelength change in path difference. Stepping the reflector a given amount then corresponds to rotating the plane of polarization through a given angle, and the detection system must be designed to detect the angle of polarization.

The reference wavelength can be quite different from that of the line being measured by the main array channel. The filter in front of the array ensures that light from the reference lamp does not reach it.

Another interesting idea which has emerged recently is the possibility of building a completely solid Michelson with no moving parts. The small path difference steps could be provided by a Pockels cell after the beam has emerged from the interferometer. This has great advantages from the point of view of mechanical stability.

(c) Instrument Phase and Modulation Depth:

The reference lamp phase lock applies to only the reference path through the instrument, and cannot be used to characterize the phase over the field of view to the accuracy needed. Therefore a set of phase pictures will be taken of a reference-lamp-illuminated screen, at intervals of a few minutes, and the phase derived and stored for each picture element. The instrument does not yield 100% visibility in the fringes, even for an infinitesmally narrow line, because of imperfections in the optical surfaces and an imperfectly balanced beamsplitter. The instrumental component of the visibility response will be measured and stored in the same operation (the reference line width is finite but known), to be used in the determination of temperature as described by Hilliard and Shepherd (1966).

(d) Array Detector:

Present information suggests that a CCD array be used without an intensifier, which would yield only marginal improvement anyway. Figures available from the Galileo imaging team indicate that we may expect 30% quantum efficiency. The array would have to be cooled, probably to -60°C, to reduce dark current. A 100 x 100 array with 50μ pixels is possible with present technology. The array might even be somewhat larger than this.

(e)Sun and Horizon Baffles:

The WAMDII will be provided with a sunshade that will allow it to operate with the Spacelab in sunlight and the atmosphere in darkness.

There is also the possibility of horizon viewing with the ground sunlit, but this requires a more sophisticated baffle because the viewed limb and the lower atmosphere are very close together in angle. The problem is eased as the Spacelab altitude is lowered, and a solution is possible, provided the baffle can be made large enough.

(f) Direction Sensor:

The look direction for each exposure must ultimately be known within about 0.03°. Since this cannot be provided as the mission is presently configured, it will be necessary to determine the look direction independently. This can be done by observing the star field with a camera mounted parallel to WAMDII. The camera would use a similar array detector and would be exposed simultaneously with each WAMDII exposure. The actual pointing of the instrument during observations should be carried out within about ± 0.5° accuracy.

Sensitivity, Measurement Errors, etc.

The signal produced by a single element of the CCD array depends upon the area, A, of the element and the aperture ratio, f, of the camera lens. For one element, the area-solid angle product is

$$A\Omega = \frac{\pi}{4} f^2 A.$$

For a 50μ square pixel and f/1 lens, $A\Omega = 2 \times 10^{-5}$ cm^2 sr. With a transmission of 5%, a quantum efficiency of 0.3 and an emission intensity of 5 kR, a pixel produces 120 photoelectrons/s.

An intensity of a few kR is what would be expected for weak airglow viewed tangentially at the limb, or weak aurora viewed directly. It appears from an analysis of errors that the signal from a single pixel would have to be averaged for about 30 sec. to obtain a wind velocity with an error of 10-20 m/s. Individual exposures are likely to last about 1s, so the averaging could be done by adding together the signals from adjacent pixels corresponding to the same altitude. In this way the altitude information would not be lost.

The design proposed here uses a single array, whose simplicity has many advantages. Besides the technical factors, the wind and temperature equations (1) and (3) involve the ratios of intensity differences. This means that for a single detector the dark currents and calibration factors disappear through cancellation and need not even be determined.

References

Elsworth, Y. and James, J.F. 1973. J. Phys. E: Sci. Instrum. 6, 1134.

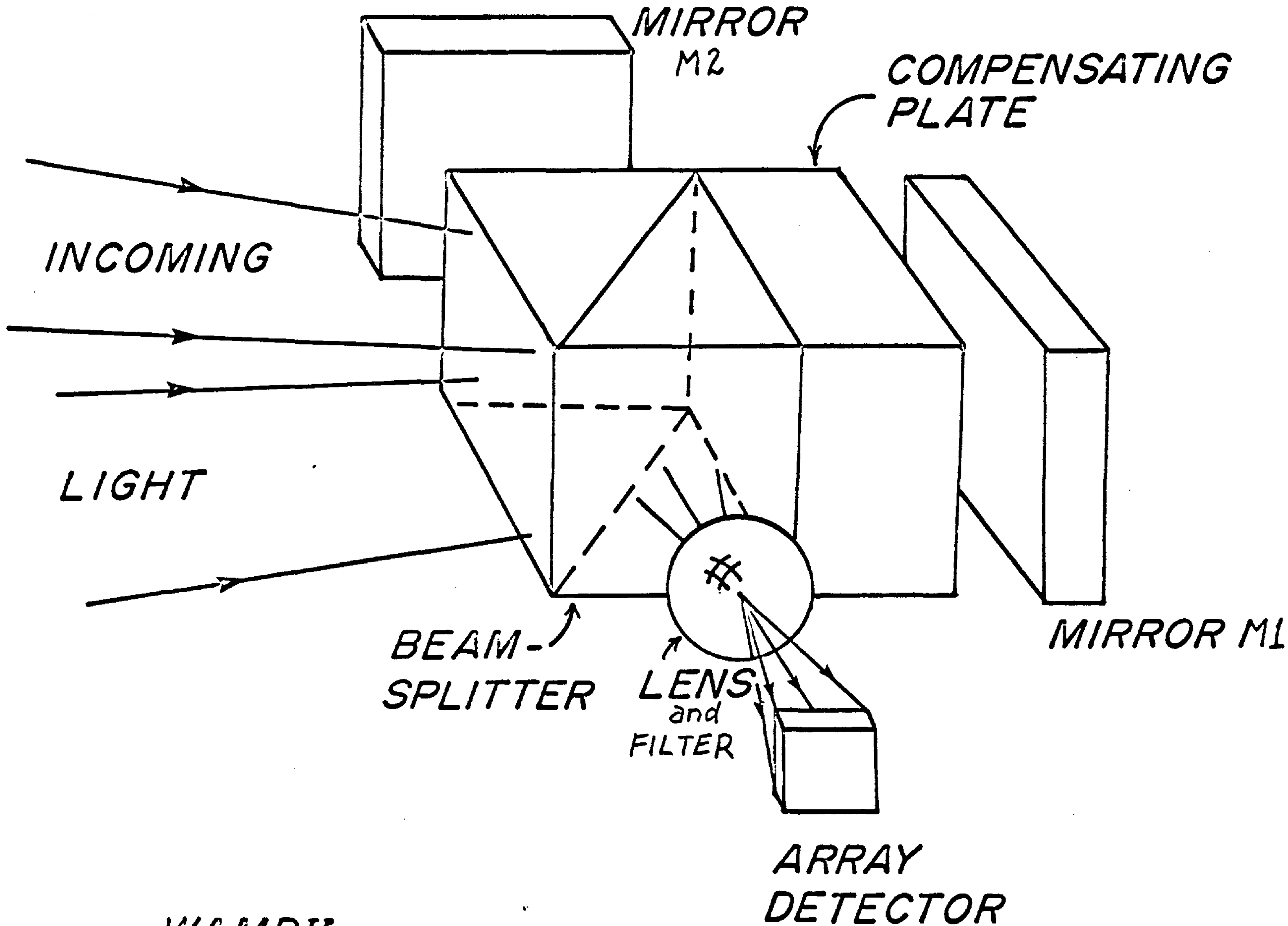
Hilliard, R.L. and Shepherd, G.G. 1966. J. Opt. Soc. Am. 56, 362.

<u>TABLE 1</u>

Emission	Temp. (K)	Line width (Å)	Visibility at path diff. of 6 cm
OI 6300	750	.031	0.46
	1000	.036	0.36
	1500	.044	0.21
OI 5577	150	.012	0.82
	200	.014	0.77
	300	.017	0.67

Velocity (m/s)	Approx. Doppler shift at 6000 Å	Phase shift at path diff. of 6 cm. (degrees)
10	0.0002	1.2
100	0.002	12
1000	0.02	120
7100	0.14	840

For each line width, there is an optimum path difference which gives greatest accuracy in the wind measurement. For example, for OI 6300 at T = 1000K it is 4.5 cm; for IO 5577 at T = 200 K it is 9.5 cm.



WAMDII

Figure 1

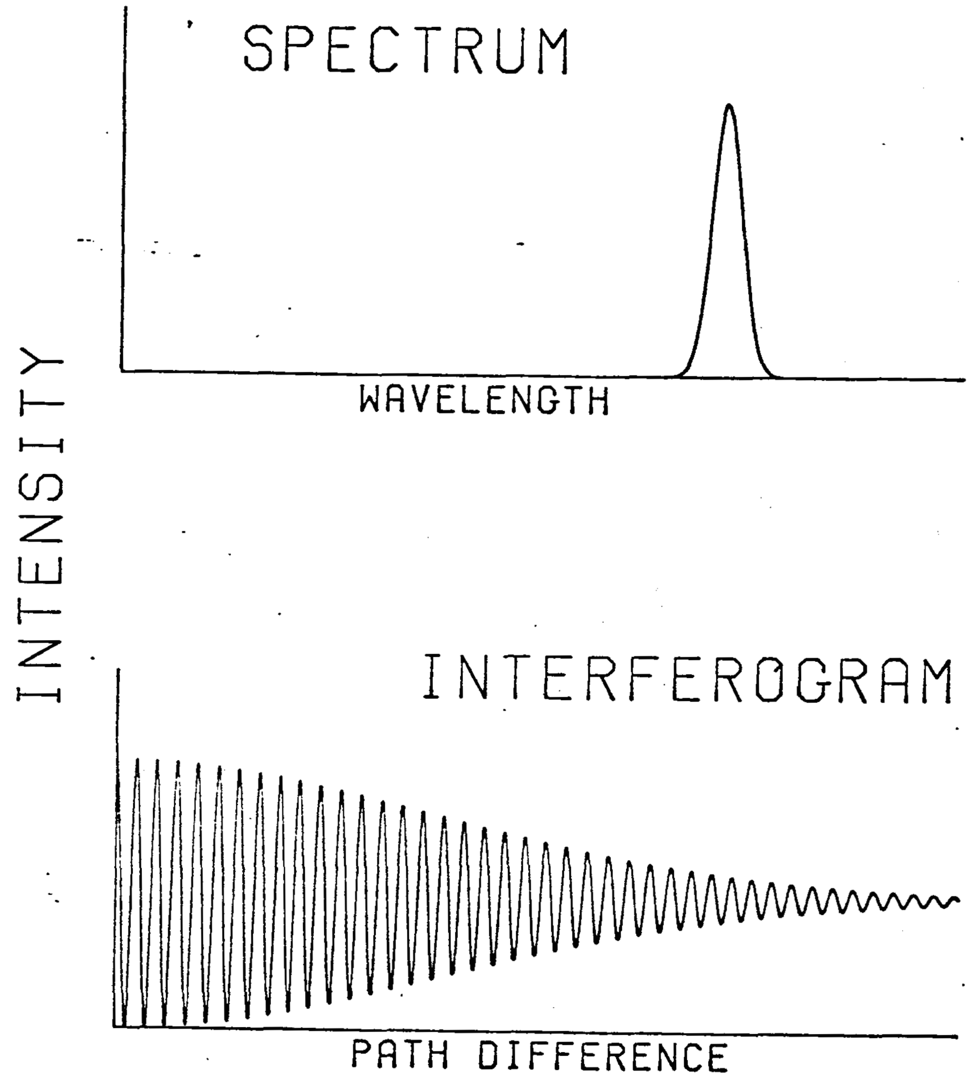

SPECTRUM
WAVELENGTH
INTENSITY
INTERFEROGRAM
PATH DIFFERENCE

Figure 4.

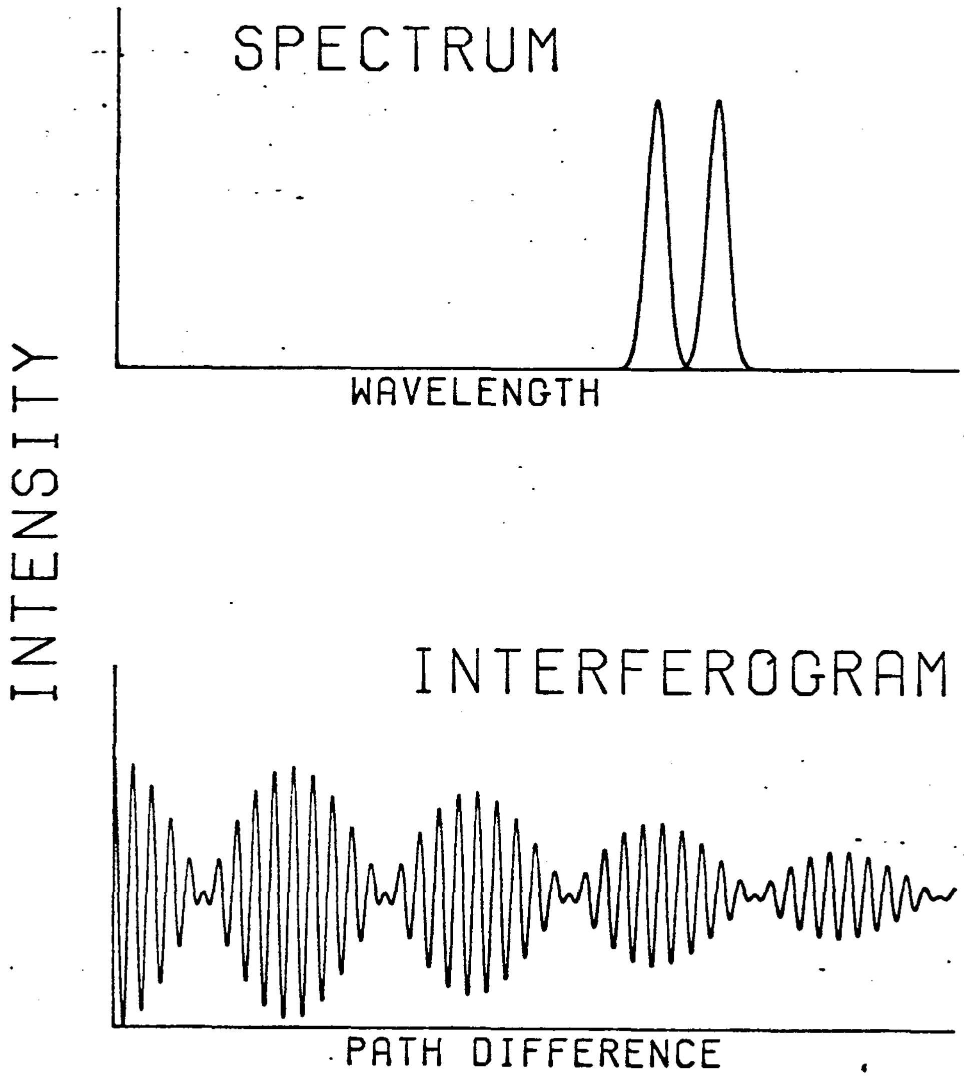

SPECTRUM
WAVELENGTH
INTENSITY
INTERFEROGRAM
PATH DIFFERENCE

Figure 5

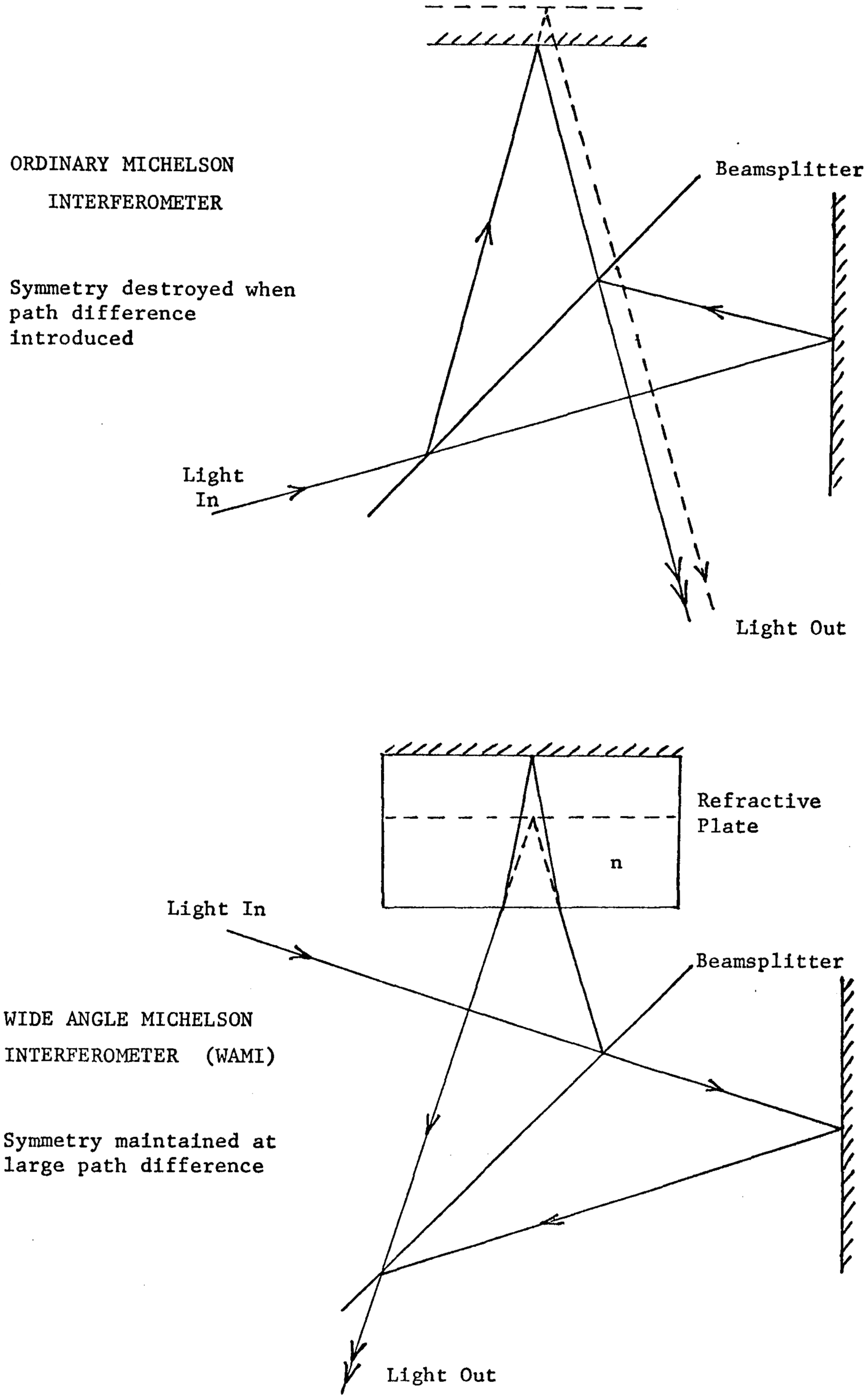
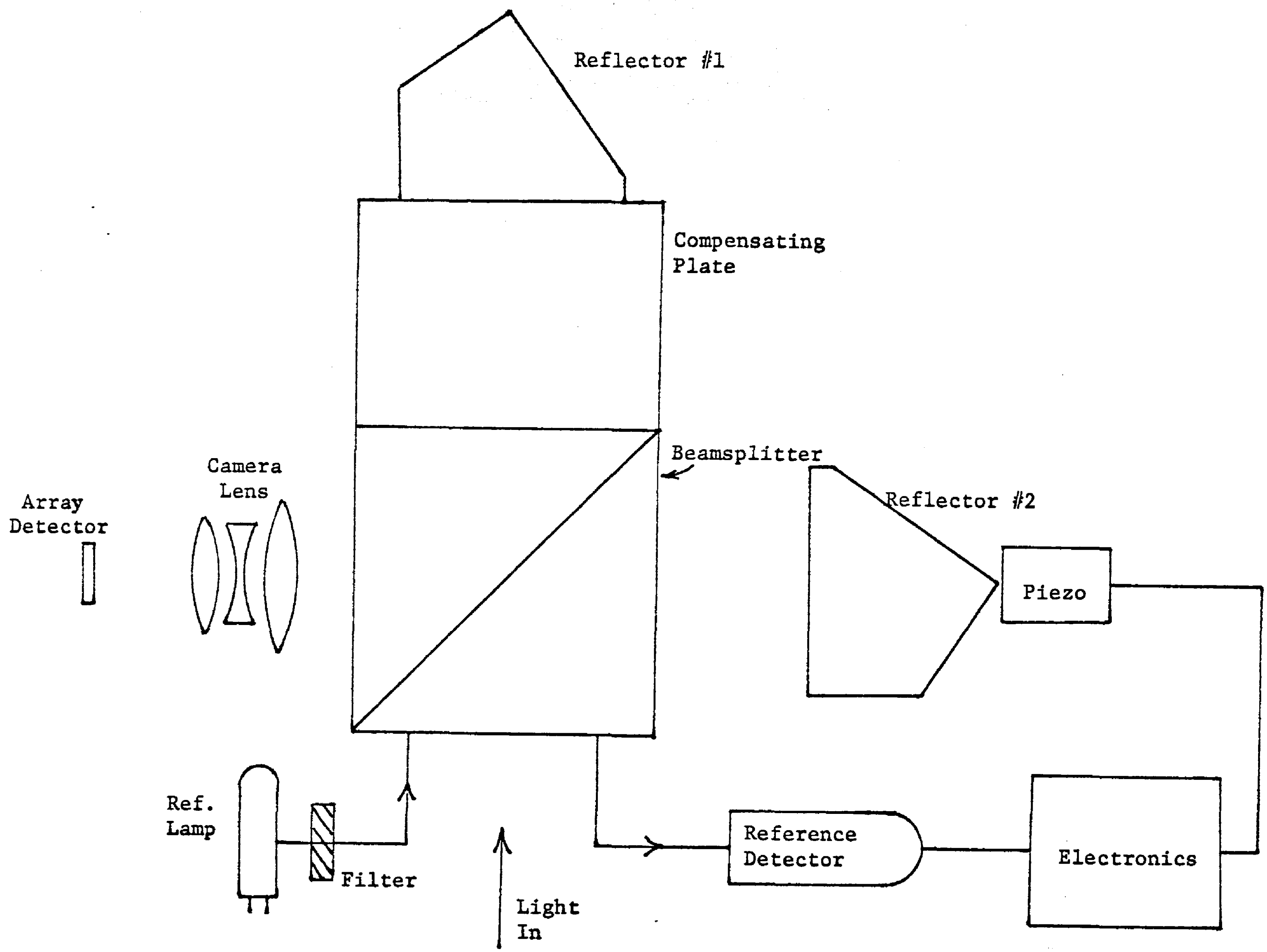

ORDINARY MICHELSON INTERFEROMETER
Symmetry destroyed when path difference introduced
Beamsplitter
Light In
Light Out
Refractive Plate
n
Light In
Beamsplitter
WIDE ANGLE MICHELSON INTERFEROMETER (WAMI)
Symmetry maintained at large path difference
Light Out

Figure 6



Schematic of Michelson
with Reference System

Figure 7