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(NASA-TM-X-73159) AN INVESTIGATION OF THE OPTIMIZATION OF PARAMETERS AFFECTING THE IMPLEMENTATION OF FOURIER TRANSFORM SPECTROSCOPY AT 2)-50. MICRON FROM THE C-141 AIRBORNE INFRARED OBSERVATORY (NASA) 18 p G3/89

N76-3;127
HC $3.50
Unclas
4799

NASA TECHNICAL MEMORANDUM

NASA TM X-73,159

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AN INVESTIGATION OF THE OPTIMIZATION OF PARAMETERS AFFECTING THE IMPLEMENTATION OF FOURIER TRANSFORM SPECTROSCOPY AT 20–500 μ FROM THE C-141 AIRBORNE INFRARED OBSERVATORY

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August 1976

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM X-73,159		

4. Title and Subtitle

AN INVESTIGATION OF THE OPTIMIZATION OF PARAMETERS AFFECTING THE IMPLEMENTATION OF FOURIER TRANSFORM SPECTROSCOPY AT 20-500 μ FROM THE C-141 AIRBORNE INFRARED OBSERVATORY

5. Report Date

6. Performing Organization Code

7. Author(s)

Rodger I. Thompson and Edwin F. Erickson

8. Performing Organization Report No.

A-6702

9. Performing Organization Name and Address

Steward Observatory, University of Arizona, Tucson, Arizona 85712
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10. Work Unit No.

352-02-03

11. Contract or Grant No.

12. Sponsoring Agency Name and Address

National Aeronautics and Space Administration
Washington, D. C. 20546

13. Type of Report and Period Covered

Technical Memorandum

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

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17. Key Words (Suggested by Author(s))	18. Distribution Statement
Infrared astronomy Fourier spectroscopy	Unlimited STAR Category – 89

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	16	$3.25

*For sale by the National Technical Information Service, Springfield, Virginia 22161

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Funds for the support of this study have been allocated by NASA-Ames Research Center, Moffett Field, California under Interchange NCA2-ORO40-504

Abstract

At the present time a program of 20-500 micron spectroscopy from the NASA flying C-141 infrared observatory is being carried out with a Michelson interferometer. It is the purpose of this report to study the parameters affecting the performance of the instrument and to recommend the optimal configuration for high performance on the C-141 aircraft. As each parameter is discussed the relative merits of the two modes of mirror motion (rapid scan or step and integrate) will be presented.

I. INTRODUCTION

At the present time a program of 20-500 micron spectroscopy from the NASA flying C-141 infrared observatory is being carried out with a Michelson interferometer. It is the purpose of this report to study the parameters affecting the performance of the instrument and to recommend the optimal configuration for high performance on the C-141 aircraft. As each parameter is discussed the relative merits of the two modes of mirror motion (rapid scan or step and integrate) will be presented. For those unfamiliar with the basic theory of Fourier transform spectroscopy, see Schnopper and Thompson "Fourier Spectrometers" in Methods of Experimental Physics Vol. 12 Part A, Carlton Ed. Academic Press Inc., 1974.

II. SIGNAL

Interferometers have in principle a large throughput advantage over dispersive systems such as grating spectrometers since they do not need narrow slits to achieve significant resolution. This feature is particularly important in the infrared spectral region for wavelengths greater than 20 μ as most of the bright astronomical sources are extended. In practice, however, even though a large solid angle can be accepted other parameters can reduce the signal strength. These include the choice of filters and windows, mirror reflection efficiency, beam splitter efficiency, chopping losses and unused outputs.

We will not attempt a discussion of filter and window materials here other than to state the obvious that they should have maximum transmission and the minimum of absorption. If possible all filters should be cold to reduce background emission. Beamsplitters currently present a severe limitation on the efficiency of interferometers in the 20-500 micron region. Stretched mylar is probably the best material available, however, it has a maximum transmission of 70% and a minimum reflectivity of 15% which results in an efficiency of 40% for the system relative to an ideal beam splitter. The high absorptivity of 15% for mylar also presents problems in terms of background emission which affects detector performance. A thorough search for improved beamsplitter materials should be made as a factor of at least 2.5 in efficiency can be gained in this area. The selected material should be dielectric and not conducting for reasons given in later sections.

Chopping losses, unusued outputs and mirror reflections are a function of the foreoptics used in the system. The simplest foreoptics configuration is shown in fig. 1. Incoming radiation enters the interferometer through one input and leaves through the opposite output where it falls on a detector. This is by far the simplest arrangement and therefore has the advantage of ease of alignment and a minimal number of mirror reflections. Serious loss of signal occurs in this configuration however. Half of the incoming light exits the interferometer through the original input and does not reach the detector. If the input is also chopped (alternated between source and sky), as is the standard practice in infrared photometry, then the signal is reduced by another factor of two which results in a net maximum efficiency of 25%. By an appropriate two input two output system this factor of four signal loss can be regained.

Figure 2 gives a sketch of a typical two input, two output foreoptic system. The input beams are slightly tilted to allow the output beams to pass over the small injection mirrors 1 and 2. These beams are then reflected onto separate detectors which eliminates the loss of one output beam. Chopping losses can be eliminated by chopping the source between the two injection mirrors rather than off the mirror. This system has numerous other advantages when used with a dielectric beam splitter which will be discussed in the following sections on noise. It should be noted here that with a dielectric beam splitter the modulated signals at the two detectors will be 180° out of phase.

III. NOISE

Multiplex spectrometers are susceptible to a wide range of noise problems due to their broad spectral acceptance of radiation. In the following section the effects of sky, background, detector, digitization, magnetic and microphonic noise will be studied as well as the effects of guiding errors and transmission changes.

Experience to date on the C-141 aircraft with foreoptics similar to figure 1 has shown that "sky" noise and variations in chopper performance are the dominant sources of noise. "Sky" noise is a little understood phenomenon in which a detector looking at the sky has an increase in its noise level over the usual background noise. The noise is most probably due to fluctuating sky emission due to local turbulence. Sky noise has dominated by factors between 3 and 10 over background noise under flight conditions. It is roughly proportional to $(P)^{\frac{1}{2}}$ where P is the power of the sky emission in the bandpass. This is only a rough estimate of the dependence, however, as an accurate measurement is precluded by the extreme variability of the phenomenon. The broad passband of the interferometer increases the effect of this noise over narrow band monochromatic spectrometers. There are two ways to reduce sky noise in Fourier transform spectroscopy. Since sky noise power falls off roughly inversely with the frequency the first way is to rapid scan the interferometer so that all signal frequencies are greater than the frequency at which sky noise dominates. A second method which can be used for step and integrate modes uses the properties of the foreoptics configuration of figure 2. This type of cancellation was first discussed by Mertz in conjunction with scintillation effects.

It may be easier to understand the sky noise cancellation if the interferometer is thought of as a variable transmission gate. For a single input the interferometer may for example put 80% of the power in one output and 20% in the opposite output.

For a different position of the moving mirror the ratio may change to 60% and 40% or 30% and 70%. For the other input of the interferometer the ratios are exactly reversed if the beam splitter is dielectric and would therefore be in the cases above 20% and 80%; 40% and 60%; and 70% and 30%. Let us consider the following example of an interferometer with inputs 1 and 2 and outputs onto detectors A and B. The source is chopped beteween inputs 1 and 2, and so there will be three positions sampled on the sky; the first centered on the source with flux S_C and also left and right of this position S_L and S_R. Below is a table of the flux from sky noise falling on the detector for each of the three interferometer mirror positions described above and for each of the two chop positions of source in input 1 and then in input 2.

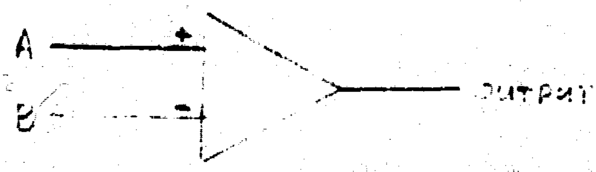
Table 1

Mirror Position	Chop Position	Flux on Detector A	Flux on Detector B
1	L	$(.8\ S_C + .2\ S_R)$	$(.2\ S_C + .8\ S_R)$
1	R	$(.8\ S_L + .2\ S_C)$	$(.2\ S_L + .8\ S_C)$
2	L	$(.6\ S_C + .4\ S_R)$	$(.4\ S_C + .6\ S_R)$
2	R	$(.6\ S_L + .4\ S_C)$	$(.4\ S_L + .6\ S_C)$
3	L	$(.3\ S_C + .7\ S_R)$	$(.7\ S_C + .3\ S_R)$
3	R	$(.3\ S_L + .7\ S_C)$	$(.7\ S_L + .3\ S_C)$

Chop Positions

Left (L) chop			Right (R) chop		
S_L	S_C	S_R	S_L	S_C	S_R
	Inputs			Inputs	
	1	2	1	2	

Now let the two detectors be connected in a difference circuit as shown below.



so that the output is A-B. Table 2 then gives the output for the positions shown in table 1.

Table 2

Mirror Position	Chop Position	Output
1	L	$.6\ S_C - .6\ S_R$
1	R	$.6\ S_L - .6\ S_C$
2	L	$.2\ S_C - .2\ S_R$
2	R	$.2\ S_L - .2\ S_C$
3	L	$-.4\ S_C + .4\ S_R$
3	R	$-.4\ S_L + .4\ S_C$

If the sky noise is correlated over the three sky positions ($S_L = S_C = S_R$) and the detectors have equal responsivity then the sky noise power at each chop position is trivially zero and complete elimination of sky nose is accomplished.

Now consider the case where the two detectors do not have equal responsivity but have responsivities R_A and R_B. For position one the output for the left and right chop positions are then [S_C (.8 R_A - .2R_B) + S_R (.8 R_B - .2 R_A)] for the left position and [S_L (.8 R_A - .2 R_B) - S_C (.8 R_B - .2 R_A)] for the right position. If the noise is completely correlated, $S_L = S_R \equiv S$, and the chopped signal is $0.6S_C(R_A + R_B) + S(R_B - R_A)$. In this case the chopped signal will contain sky noise at the chop frequency reduced by the difference between detector responsivities. This same calculation applies for all effects which may change the efficiency of the two outputs. If the noise is completely uncorrelated between the three positions then there will be simply a vector addition of the random phases of the radiation from each input and no reduction in sky noise will be accomplished. It is expected however that the noise will be correlated to a high degree over the three sky positions. Since the same analysis applies to rapid scanning which also has the high frequency advantage discussed earlier it is expected that rapid scanning techniques are better suited to reducing sky noise.

Background noise is a result of increased noise level in the detection system due to loading of the detectors with background radiation. In broadband applications such as interferometry the detectors are background limited in that the noise from background loading is greater than the intrinsic detector noise. Noise from background loading is roughly proportional to $(P_B)^{\frac{1}{2}}$ where P_B is the power of the background radiation on the detector.

At present there are two sources of background radiation which are major contributions to the detector loading. The first is emission from the mylar beam-splitter in the interferometer cube. In all systems the detectors must view the beamsplitter, therefore the only way to reduce the power is to cool the beam-splitter or find a material with lower absorbtivity in the passband being observed. A lower absorbtivity would be also desirable as mentioned in the first section to increase signal strength. Cooling the beamsplitter is a complicated engineering project which will not be discussed further here.

The effect of background emission from the sky can be calculated in the same manner as for sky noise. It should be noted that we are denoting the time varying component of the background as sky noise and the time (but not spatially) independent component as true background radiation. By replacing $S_{L,C,R}$ with $B_{L,C,R}$ in table 1 we can see the background loading on each detector. The first point to note is that if $B_L = B_C = B_R$ the total background load on each detector does not vary with mirror position. In this sense the modulated portion of the background is subtracted. The total power on the detectors which produces background noise has not been reduced however. Reduction of the modulated background signal has advantages for both the rapid scan and the step and integrate modes of operation. One of the main limitations of the rapid scan technique for high background applications is the large modulated background signal which is orders of magnitude larger than the signal from the object observed. This problem will be discussed more fully later but it is obvious that reduction in the modulation of the background signal is advantageous. In the step and integrate mode, large changes in the background loading due to modulation near the white light fringe produce large transient signals when the mirror is stepped. These transients must be allowed to die out before signal integration can begin. This produces a significant dead time which reduces the overall efficiency of the system. Reduction of the modulation will reduce the dead time.

Inspection of table 2 shows that linear background gradients or offsets are eliminated by this foreoptics and chopping configuration. As an example, consider a background flux B such that $B_L = B_C + \Delta$ and $B_r = B_C - \Delta$. The left chop position will have an output for mirror position 1 of $.6\ B_C - .6\ B_R = .6\ \Delta$ whereas the right chop position will have $.6\ B_L - .6\ B_C = .6\ \Delta$. Chopping between the left and right beams then will not produce an offset signal. Offsets should however be minimized by proper mirror adjustments if at all possible.

We shall next consider those sources of noise which are directly proportional to the signal such as chopper errors, tracking errors and transmission changes. These errors will affect rapid scan and step and integrate systems in very different ways. As most of these errors are low frequency they appear in rapid scanning systems simply as changes in total signal strength which change the efficiency of the system but do not add any noise to the spectrum. The situation is different however for step and integrate systems. In these systems significant changes in signal strength can occur during a single scan which will add noise by minimizing real modulation. In some interferograms recorded from the aircraft this type of noise seemed to dominate over sky noise. The source of this noise is thought to be changes in chopper performance but this is not certain. A most obvious solution for this type of noise is to remove its source. In the case of the chopper this is currently being accomplished by replacement with an improved chopper. Significant guiding errors can be eliminated by the use of the airplane tracking system.

There is another way of handling this type of error. Table 3 below gives the flux F from the source only for the three mirror positions used for tables 1 and 2.

Table 3

Mirror Position	Chop Position	Flux on Detector A	Flux on Detector B
1	L	.8 F	.2 F
1	R	.2 F	.8 F
2	L	.6 F	.4 F
2	R	.4 F	.6 F
3	L	.3 F	.7 F
3	R	.7 F	.3 F

From table 3 it is seen that the sum of the fluxes on detectors A and B is constant and equal to F. The sum can therefore be used to monitor the total flux into the system. Unfortunately this is a DC measurement which is subject to severe drift problems and cannot be done via lock-in techniques. An alternative is to chop off the source rather than to alternate between inputs. The chopped sum of the two detectors should then be constant and could be used as a reference. This method of course reduces the signal level by a factor of two.

A further complication of this technique occurs if the responsivities of the two detectors are not equal as is the case in actual practice. If x and y are the fractions of the output in each beam $(x + y = 1)$ and the detector responsivities, including output efficiency, are R_A and R_B, then in the left chop position the output $R_A x + R_B y$ and in the right chop position $R_A y + R_B x$ which leaves a chopped difference of $(R_A - R_B)\ (x - y)$. This difference is minimal in the region for the white light fringe since in that region $x \simeq y$. A similar analysis applies for chopping off the source where x and y equal the ratios of output fluxes at two different mirror positions.

IV. RAPID SCANNING VS. STEP AND INTEGRATE

Rapid scanning and step and integrate interferometers produce equivalent results under ideal laboratory conditions. Various noise, background, or environmental conditions can however weight the advantages toward one or the other of the systems. In partcular the high probability of nonconstant observing conditions and the existence of low frequency noise in astronomical, and particularly aircraft astronomical, observations gives an advantage to rapid scanning instruments.

In spectral regions with large background fluxes, however, rapid scanning techniques have a severe disadvantage. Often the background is on the order of $10^3 - 10^4$ times the signal strength of the source to be observed. A traditional rapid scanning instrument modulates both the background and the source at the same time. Another scan must be taken then with the source off or in the opposite input and the two interferograms subtracted to an accuracy of 10^{-6} to get 1% accuracy in the signal interferogram. At present it is not possible to record the signal this accurately or provide electronics linear to this accuracy. The sky subtraction techniques described above can reduce the problem by a factor of 10 to possibly 100 but still leaves a large problem.

Rapid scanning also presents another problem in that the detector used must be fast enough to respond to the high frequencies of rapid scanning. This means that photovoltaic rather than bolometric detectors must be used. Current photovoltaic detectors have NEP's a factor of 3 to 10 higher than bolometric detectors in the presence of high background levels such as are encountered in interferometric work.

Step and integrate systems on the other hand can use the proven method of chopping the source against the background which is used in photometric measurements. In this way only the source signal is recorded which reduces the dynamic range of the measurement techniques to reasonable levels. Although only the chopped signal is recorded all of the background radiation which passes through the interferometer is modulated by the mirror motion. In particular near the white light fringe the radiation falling on the detetor can change by almost 100% when the mirror is moved. These large changes in background radiation produce large transient signals which contain frequency components equal to the chopping frequency. Before accurate measurements can be made the transient signals must be allowed to die out which results in lost observing time--a low efficiency. Reduction in the background flux by cooling will help to some degree but will not eliminate the power on the detector from sky background radiation. Use of the two beam system described above however should greatly reduce the transient signals and result in a net gain in efficiency.

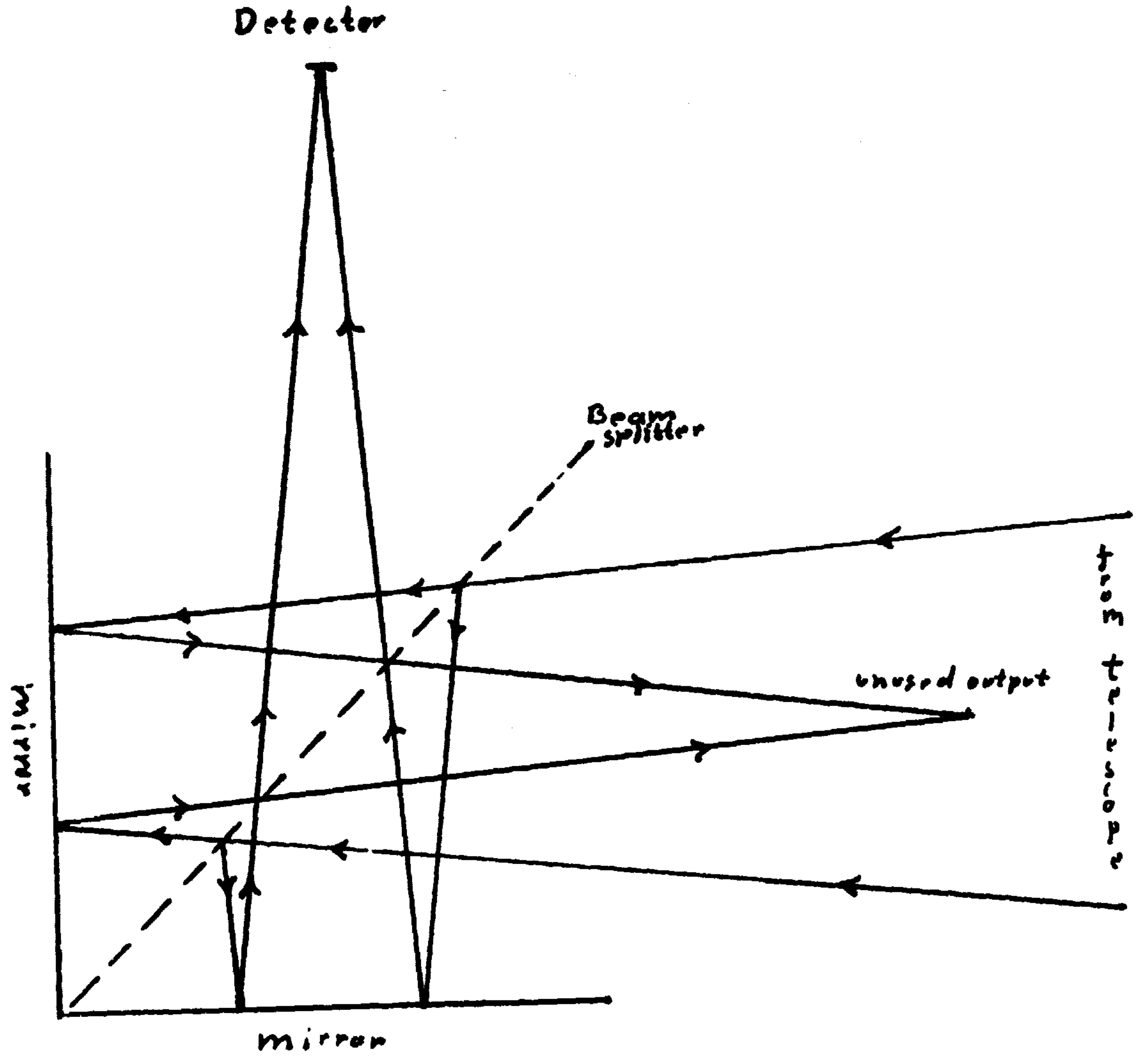
V. RECOMMENDED SYSTEMS

Independent of the drive system it is recommended that a two beam two detector foreoptics system similar to that shown in fig. 2 be adopted. This system offers the advantages of sky noise suppression, reduction of background modulation and increased efficiency. It has the disadvantage of increased complexity and difficulty of alignment. These disadvantages however are far outweighed by the improvement in performance.

An optimum drive system would be a rapid scanning system with ultra-fast chopping. This would involve a system with about a 10 kHz chop rate and all signals modulated at frequencies higher than 250 Hz. The chopped signal would be fed into a lock-in amplifier whose output would be the modulated signal. Present chopper and detector capabilities however cannot approach these frequencies.

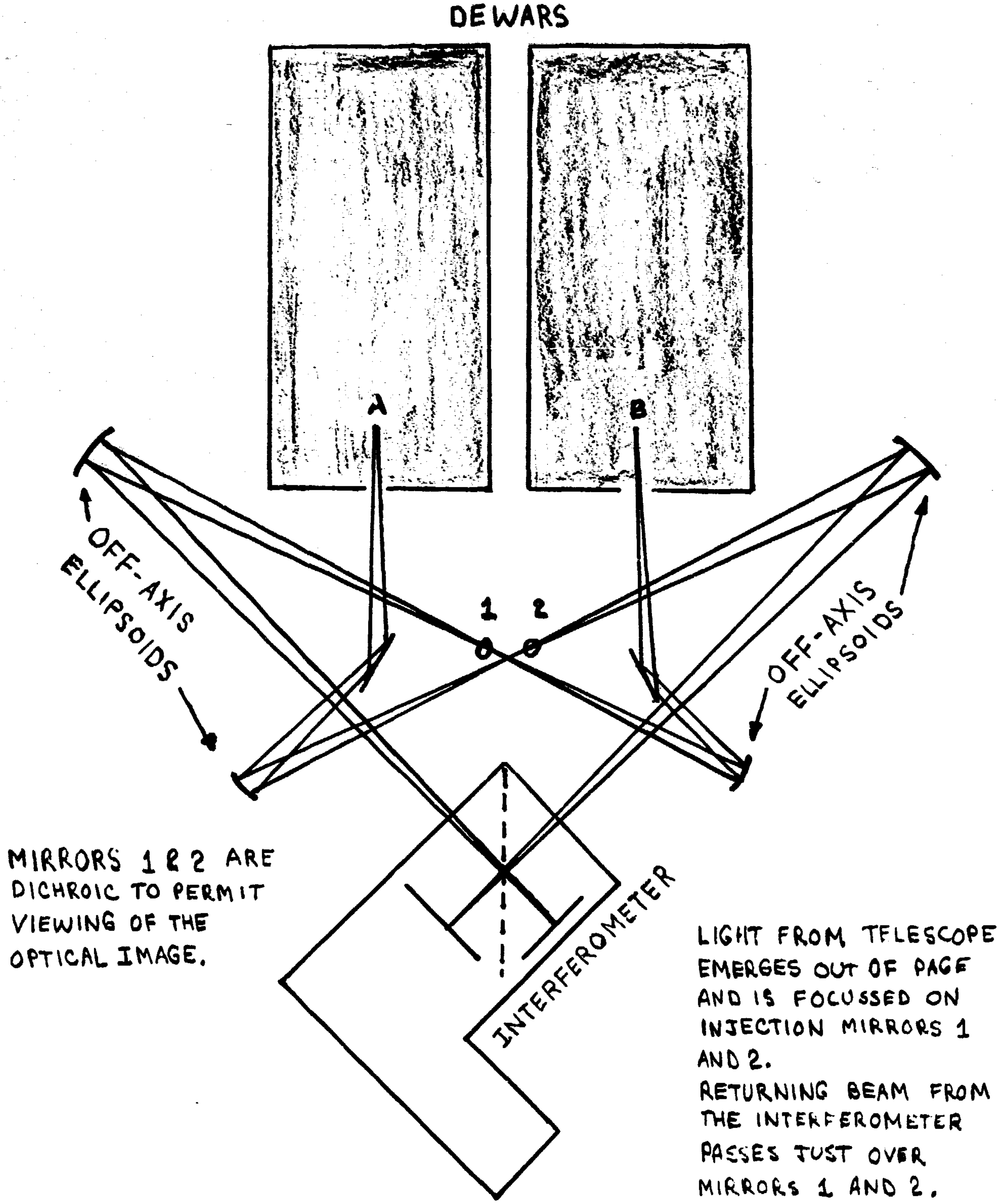
The best practical alternative is the step and integrate method used at the present time. As discussed earlier, this method reduces the dynamic range to a tractable value. The large transient problem can be handled by delaying integration until all transients have died out. This delay can be reduced, as is being done at the present time, when data are being taken at distances far from the white light fringe. The main conclusion, therefore, is that the greatest improvement can be obtained by concentrating on an improved two beam two detector fiberoptics system.

Fig 1



Detector
Beam splitter
from telescope
unused output
mirror
mirror

FIGURE 2



2 BEAM, 2 DETECTOR OPTICS, F/17

DRAWING IS 1/4 SCALE