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BACKGROUND SUPPRESSION IN DOUBLE-BEAM INTERFEROMETRY USING TAIL--ETC(U)
SEP 78 T F ZEHNPFENNIG, G A VANASSE F19628-77-C-0218
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AFGL-TR-78-0221, IP-271

(9) INSTRUMENTATION PAPERS

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LEVEL II

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Background Suppression in Double-Beam Interferometry Using Tailored Modulation Transfer Functions.

(10)

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(11)

18 Sep[redacted]78

(12) 19p.

(15) F19628-77-C-0218,
F19628-76-C-0198

(16) PROJECT 2310

(17) G1

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AIR FORCE SYSTEMS COMMAND, USAF

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This technical report has been reviewed and is approved *for publication.*

FOR THE COMMANDER

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Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AFGL-TR-78-0221

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle): BACKGROUND SUPPRESSION IN DOUBLE-BEAM INTERFEROMETRY USING TAILORED MODULATION TRANSFER FUNCTIONS

5. TYPE OF REPORT & PERIOD COVERED: Scientific. Interim.

6. PERFORMING ORG. REPORT NUMBER: IP No. 271

7. AUTHOR(s): T.F. Zehnpfennig*, G.A. Vanasse

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS: Air Force Geophysics Laboratory (OP), Hanscom AFB, Massachusetts 01731

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 61102F, 2310G101

11. CONTROLLING OFFICE NAME AND ADDRESS: Air Force Geophysics Laboratory (OP), Hanscom AFB, Massachusetts 01731

12. REPORT DATE: 18 September 1978

13. NUMBER OF PAGES: 18

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report): Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

*Visidyne Inc., Burlington, MA 01803

The research work leading to this report was partly supported under Air Force Contracts F19628-76-C-0198 and F19628-77-C-0218.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Double-beam
Interferometry
MTF

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An optical background suppression technique is described in which the lower spatial frequencies of a background field are effectively suppressed, thereby enhancing the detectability of point-like targets. The technique is particularly applicable for use in image-forming double-beam interferometers in which the individual detector elements are matched to the diffraction-limited resolution of the instrument. The technique utilizes pairs of optical systems whose modulation transfer functions are suitably matched and a number of these pairs are described.

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Summary

The advantages of the detection technique described here fall into two categories. First, there are certain advantages due to the fact that the instrument is an interferometer: the well-known throughput advantage; and the large free spectral range that permits target discrimination by means of spectral features that occur over broad regions of the spectrum. Then, there are the following additional advantages of the imaging dual beam interferometer having tailored modulation transfer functions:

(1) Background suppression can be obtained even when the detector size is matched to the system diffraction limit,

(2) Background suppression is done in real time at a largely optical level, reducing the requirements placed on the data processing electronic systems,

(3) The suppression is symmetrical, that is, it operates equally well in all directions in the focal plane,

(4) The output signals contain spectral, temporal, and positional information on targets,

(5) The technique can be used to detect both stationary and moving targets.

Preface

The authors wish to thank William Reidy, Orr Shepherd, and Saul Rappaport for their many helpful discussions, suggestions, and criticisms, as well as for certain calculations and measurements described in this report.

Contents

Illustrations

Background Suppression in Double - Beam Interferometry Using Tailored Modulation Transfer Functions

1. INTRODUCTION

The purpose of the technique described here is to enhance the detectability of point-like sources, or targets, in the presence of a nonuniform field of background radiation when using detection systems that are designed to operate at or near the diffraction limit. The technique allows both the spatial and spectral characteristics of the target to be exploited in order to aid the detection process while it suppresses in large part the contribution of the background to the observed signal. The optical system consists of an imaging dual-beam interferometer that has been configured to operate as a spatial filter by suitably tailoring the modulation transfer functions of the two main optical paths through the interferometer. In its role as a spatial filter, the dual beam interferometer preferentially suppresses the lower spatial frequencies found in the object. The detector is assumed to be of a multi-element focal plane array and a real image of the object is formed on the face of this array. The type of background suppression discussed here is particularly important in satellite detection of small targets against an earth background in the infrared region of the spectrum.

(Received for publication 15 September 1978)

2. DUAL BEAM INTERFEROMETERS

The technique of dual beam interferometry was first suggested by Fellgett[1] in 1957 and application of this technique to the problem of detecting point-like targets against a field of background clutter was first proposed by Vanasse, Murphy, and Cook[2] in 1976. Previous to this, dual beam interferometers in various forms had been used for laboratory and astrophysical measurements in which the spectra to be measured were superimposed on large background signals.

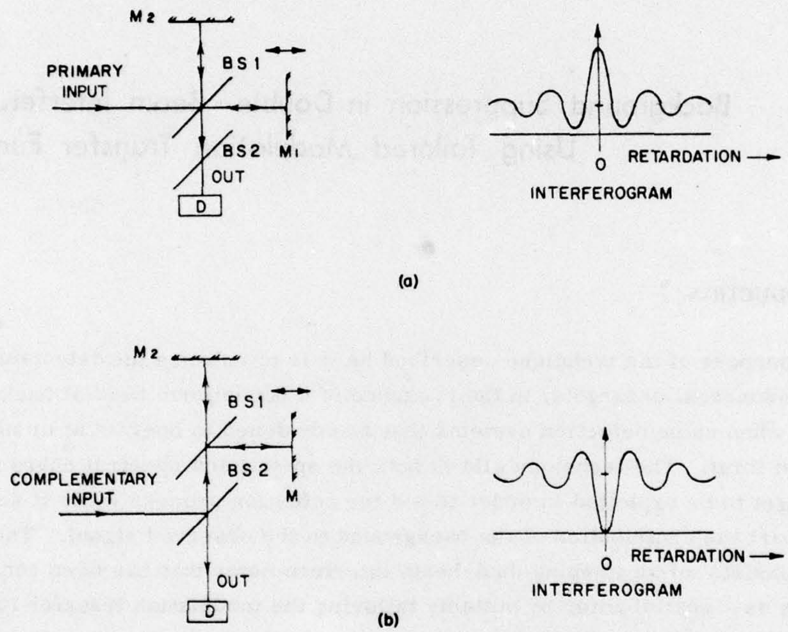

Figure 1. Basic Form of the Dual Beam Interferometer

Figure 1a illustrates the dual beam interferometer in its most basic form. In Figure 1a, the paths of radiation entering one of the dual inputs are traced through the system to the detector D. Let this input be called the primary input. Note that, whether the radiation is reflected from mirror M1 or mirror M2, it undergoes one reflection from dielectric beamsplitter BS1 and one transmission through BS1 before

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1. Fellgett, P. (1957) Les progres recents en spectoscopie interferentielle, Bellevue, Colloq. Int. C. Na. R. S. 53.
2. Vanasse, G.A., Murphy, R.E., and Cook, F.H. (1976) Appl. Opt. 15:290.

reaching the detector. When one of the mirrors M1 is then translated at a constant velocity as indicated, the detector will produce an interferogram of the source. Since the system as shown in Figure 1a is the basic Michelson interferometer, all wavelengths present will constructively interfere at the point of zero path length difference (or zero retardation), and thus, the interferogram will have a maximum at the center. In Figure 1b, rays from the second of the dual inputs are traced through the system. Let this input be called the complementary input. Note that the radiation initially approaches BS1 from the other side, and that it subsequently undergoes either two reflections from BS1 (the M1 path) or two transmissions through BS1 (the M2 path). Each of these reflections at 45° from the dielectric beamsplitter will produce a phase shift of $\pi/2$ in radiation travelling the M1 path, while radiation travelling the M2 path will experience no corresponding phase shifts. Thus, at zero retardation, the interference will be destructive and the interferogram for this input will have a minimum at the center, as shown. Further, it can be shown that, with both inputs viewing the same source and assuming that ideal optical components are used, the interferograms corresponding to the two inputs will be exactly complementary to each other, and if added, will produce a constant dc level for all values of retardation. Consider, however, the case where the sources for the two inputs are not identical. Let the field of view for one input contain only background radiation, while the field for the other input contains an identical background plus a target. Then, the signal at the detector due to the background radiation will be suppressed (that is, reduced to a dc level), and only the interferogram of the target will be observed. Thus, systems of this type should be potentially useful for detecting weak targets in the presence of background radiation.

Figure 2 shows a more highly developed version of the basic dual beam interferometer. The optical paths have been physically separated by replacing the plane mirrors M1 and M2 with roof reflectors (or cube-corner retroreflectors, or cat's eye retroreflectors). This permits the beamsplitter BS2 to be replaced with a plane mirror m, thereby eliminating a source of loss in the optical system. It also allows radiation which would normally be returned to the source to be intercepted by a second detector D', thereby increasing the signal. An additional advantage of a second detector is that it can be used to compensate for temporal fluctuations of the background. The detectors, as indicated in Figure 2, are mosaic detectors, and image forming lenses have been added in front of the detectors in order to emphasize that the system is intended to form a real image of the object.

In Figure 3, the optical paths have been laid out on two levels to achieve a more compact design, with the roof reflectors switching the rays from one level to the other.

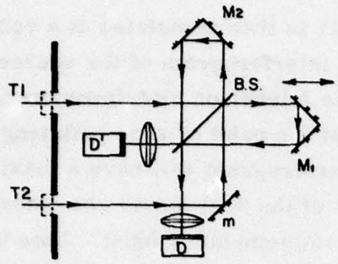


Figure 2. Dual Beam Interferometer With Separated Optical Paths

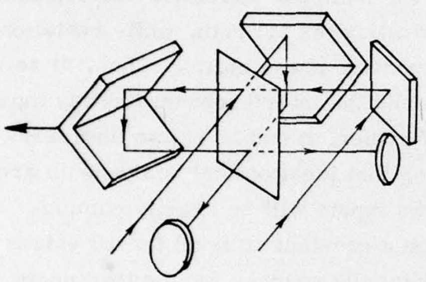
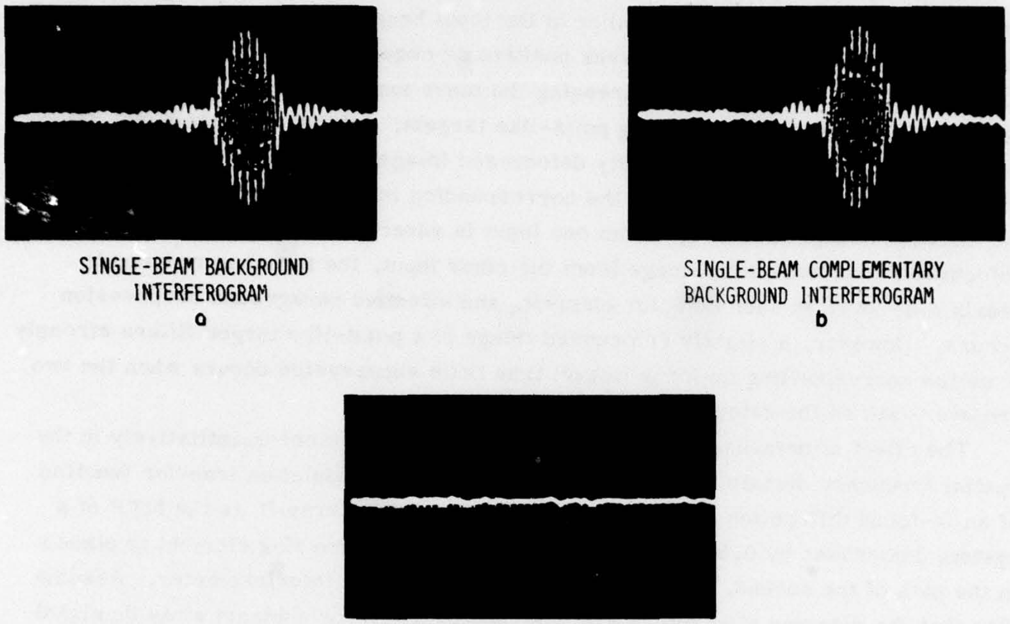


Figure 3. Compact Arrangement of Interferometer Components

The effectiveness with which a uniform background is suppressed in an actual system depends upon the tolerances of the beamsplitter coating and the accuracy and alignment of the various components in the system. Preliminary laboratory measurements have been made by Shepherd[3] using a dual-beam interferometer similar to that of Figure 2. The results are shown in Figure 4. The source in this case was an incandescent lamp whose spectral bandwidth was limited by a filter having a passband about 0.4 μm wide centered at 2.3 μm. Figure 4a shows the interferogram corresponding to primary input beam alone. Figure 4b is the interferogram from the complementary input alone. Figure 4c is the combined interferogram from both input beams, showing how nearly the resulting signal is reduced to a dc level. Let the suppression ratio be defined as the amplitude of the interferogram produced when the instrument is operating in the single beam mode vs the amplitude in the dual beam mode. Then, the suppression ratio demonstrated in Figure 4 is about 100 to 1.

3. Vanasse, G.A., Stair, A.T., Shepherd, O., and Reidy, W.P. (1977) Background Optical Suppression Scheme (BOSS), AFGL-TR-77-0135.

DOUBLE-BEAM INTERFEROMETER LABORATORY TEST RESULTS



SINGLE-BEAM BACKGROUND INTERFEROGRAM
a

SINGLE-BEAM COMPLEMENTARY BACKGROUND INTERFEROGRAM
b

DOUBLE-BEAM BACKGROUND INTERFEROGRAM
c

Figure 4. Laboratory Demonstration of Background Suppression

3. TAILORED MODULATION TRANSFER FUNCTIONS

Up this point, the background field has been considered to be uniform, so that background suppression could be obtained by use of displaced fields of view, as shown in Figure 5. Here, the image of the object area as seen through one input of the interferometer is displaced on the face of the detector array with respect to the image seen through the other input. Thus, the interferogram of a given target will appear on some detector element E, while the complementary interferogram of the same target will appear on some other element E'. No suppression of the target interferograms will occur. However, with a uniform background, each detector element will receive a complementary pair of interferograms from the background, thereby reducing the background signal to a dc level. The problem with this scheme is, of course, that the background cannot be considered to be uniform from point to point.

In a first attempt to deal with non-uniform backgrounds, deliberate introduction of a small amount of defocus into one of the input beams was considered. Referring again to Figure 2, images from either of the input beams can be slightly defocussed on the detector face by placing a weak positive or negative element at T1 or T2. This has the overall effect of suppressing the more smoothly varying regions of the background, while not suppressing point-like targets. Intuitively, this effect can be explained by realizing that a slightly defocussed image of a smoothly varying background does not differ much from the corresponding in-focus image. Thus, when the in-focus background image from one input is superimposed in coincidence on the defocussed complementary image from the other input, the signal is reduced to nearly a dc level on each detector element, and effective background suppression occurs. However, a slightly defocussed image of a point-like target differs strongly from the corresponding in-focus image; thus little suppression occurs when the two are over-lain on the detector face.

The effect of defocussing one input may be examined more quantitatively in the spatial frequency domain. Curve A of Figure 6 is the modulation transfer function of an in-focus diffraction limited optical system, while Curve B is the MTF of a system defocussed by 0.64 waves. Assume that the defocussing element is placed in the path of the second, or complementary, input to the interferometer. Assume also that the detector electronics are designed to ignore or subtract away dc signal levels. Then, with the in-focus image superimposed on the detector array along with the defocussed complementary image, the resulting system MTF is just Curve A minus Curve B, as shown. This shows that the system substantially suppresses the lower spatial frequencies in the background while leaving the higher spatial frequencies which characterize a target largely intact.

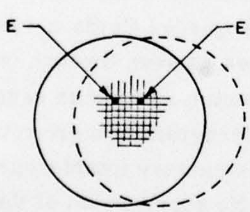


Figure 5. Displaced Fields of View

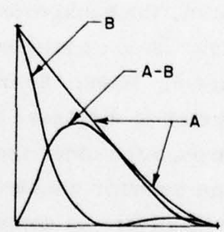


Figure 6. MTF's With One Input Defocussed

It was soon realized that defocussing was only one of many possible methods to alter the response of optical systems of this type, and that the two MTF's corresponding to the two input channels could be readily tailored to satisfy various system requirements. In addition to defocussing, some of the other techniques which can be used in altering MTF pairs are listed as follows:

(1) Introduction of controlled amounts of aberration such as spherical aberration into the system,

(2) Adjustment of the ratio of the diameters of the two entrance apertures of the system,

(3) Apodization of an entrance aperture with a central obstruction or with a filter whose transmittance varies with radius,

(4) Phase apodization of an entrance aperture by introducing phase-shifting annular rings or disks,

(5) Addition to an entrance aperture of some special optical component, such as a weak axicon,

(6) Controlled, small amplitude mechanical oscillation of an optical component in the system at a frequency high compared to the system time response.

The above techniques can be applied individually or in combination to one or both inputs of the dual beam interferometer to produce desired changes in the system MTF.

Figures 7 through 10 illustrate the tailoring of pairs of MTF's in some of the ways listed above, with the goal of suppressing, as completely as possible, the system response to all spatial frequencies below about one-fourth the cut-off frequency.

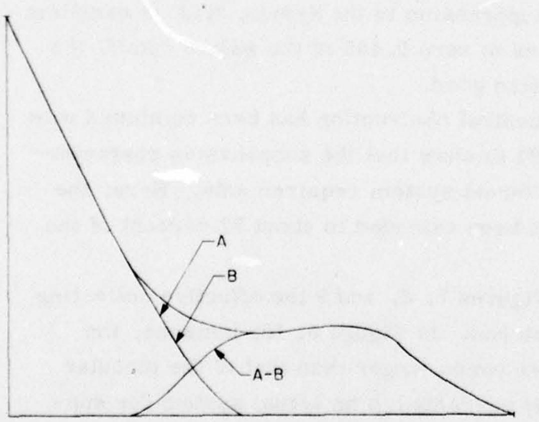


Figure 7. MTF Obstruction Ratio 0.52 (Curve A) Combined With MTF 0.45 Obstruction Ratio (Curve B)

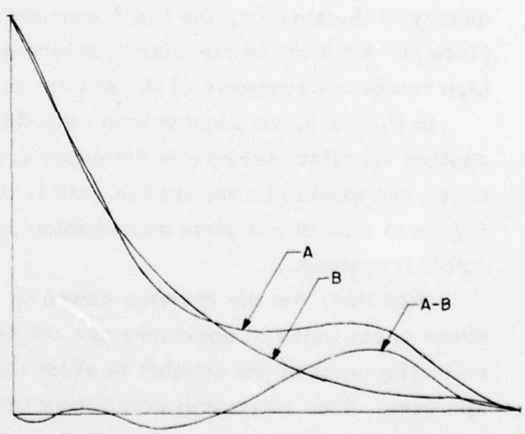


Figure 8. Aperture of 1.00 and Obstruction Ratio of 0.52 Combined With Circular Aperture of Diameter 0.465

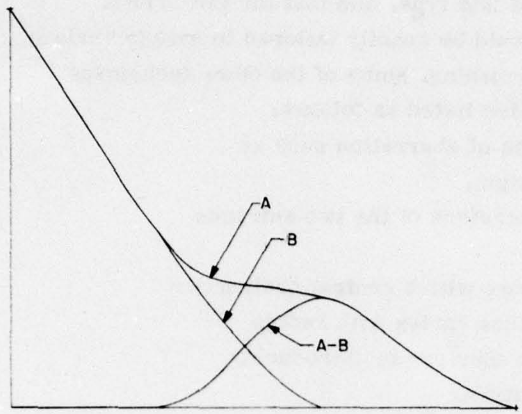


Figure 9. Annulus With Central Obstruction 0.28 Combined With Circular Aperture of Diameter 0.621

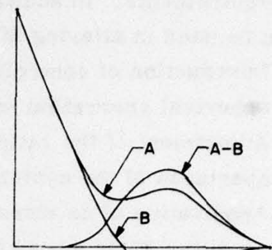


Figure 10. Curve A - Input Phase Apodized by 1/2 Wave; Curve B - MTF for Mechanically Wobbled Optical Component

In Figure 7, the MTF of an annular input aperture having a central obstruction ratio of 0.52 (Curve A) is combined with the MTF of an input of the same diameter having 0.45 waves of spherical aberration (Curve B). In the resulting System MTF (Curve A minus Curve B), the lower spatial frequencies are suppressed reasonably well. However, the response at the higher frequencies which would characterize a target is diminished substantially as well.

In Figure 8, an annulus with an aperture of 1.00 and an obstruction ratio of 0.52 has been combined with a circular aperture of diameter 0.465. Since the corresponding MTF's match almost perfectly out to one-quarter of the cut-off frequency of the annulus, the low frequency suppression in the System MTF is excellent. Since the MTF of the circular aperture goes to zero 0.465 of the way to cutoff, the high frequency response of the system is also good.

In Figure 9, an annulus with an 0.38 central obstruction has been combined with another circular aperture of diameter 0.621 to show that the suppression characteristics can readily be tailored to satisfy different system requirements. Here, the region of almost complete suppression has been extended to about 32 percent of the cutoff frequency.

Note that, for the systems shown in Figures 7, 8, and 9 the effective collecting areas of the pairs of apertures are not matched. In Figure 8, for instance, the collecting area of the annulus is about three times larger than that of the circular aperture. This mismatch would have to be corrected in an actual system for suppression to occur. One way to do this would be to enlarge the smaller aperture to the required area, and, at the same time divide it into three separate circular regions whose corresponding images add incoherently in the image plane. (The three images would add incoherently if, for instance, optical path length changes of different amounts were introduced in each of the three areas of the aperture.) Thus, the effective collecting area would be increased without changing the MTF. Another way would be to decrease transmittance of the annular without changing the MTF. Another way would be to decrease transmittance of the annular aperture of 0.33 with a neutral density filter. In a large-aperture system, however, this would be a wasteful way to use the polished area.

Figure 10 shows the MTF's for a system in which the effective collecting areas are very easily matched. Curve A corresponds to a phase apodized input in which the optical path length of the central 30 percent of the radius of the aperture has been changed (increased or decreased) by 1/2 wave. Curve B is the calculated MTF for an input in which one of the optical elements, such as a secondary mirror, is mechanically oscillated or wobbled so that the image points trace out small circles on the face of the detector array. In this case, the radii of the small circles is 74 percent of the radius of the first dark ring in the instantaneous or unoscillated Airy pattern. Curve B can be considered to be a time averaged MTF, which is what the system would see if the oscillations are rapid compared to the time response of the system. Also, Curve B has been slightly altered to improve the low spatial frequency match with Curve A by shifting the optical path length through the outer 2 percent of the radius of the aperture by 1/2 wave. The effective collecting areas of the two inputs are easily matched by making the two input apertures equal in diameter. Note that the system MTF, Curve A minus Curve B, produces effective suppression out to about 20 percent of cutoff, and that the system response to frequencies beyond 50 percent of the cutoff frequency is actually enhanced because Curve B has a reverse contrast characteristic in this region. In order to avoid the requirement for mechanical oscillations in this system, alternatives such as the use of a weak axicon or deflection by electro-optic means are being considered.

Signal-to-noise calculations on the system shown in Figure 10 have shown an improvement in signal-to-noise ratio by a factor of about 10 over an equivalent interferometer without background suppression, for a background with a 1/f frequency distribution.

4. FIELD OF VIEW

In discussions of interferometers of this type, the question of limitations on the field of view and the possible necessity of field widening frequently arises. However, as has been pointed out by Johnson[4] in connection with his Superthroughput

4. Johnson, N.J.E. (1977) Superthroughput in Michelson Interferometers, presented at the 1977 International Conference on Fourier Transform Infrared Spectroscopy, Columbia, South Carolina.

interferometer, the field of view of an interferometer need not be limited by the size of the central fringe on the face of the detector providing that the detector is a multi-element array in which the signals from the elements are processed separately. A detector element at the edge of the field of view will produce a valid interferogram of its region of the source even though the element may be many fringes from the central maximum as the retardation is increased, providing only that at maximum retardation the element is still small compared to the local fringe width. The scale of the interferogram does vary slowly with the field position θ of detector element but this can be corrected simply by applying a scale correction factor of $1/\cos\theta$ to the retardation scale of the interferogram. Field widening may, of course, still be used here, but the reasons are less compelling.