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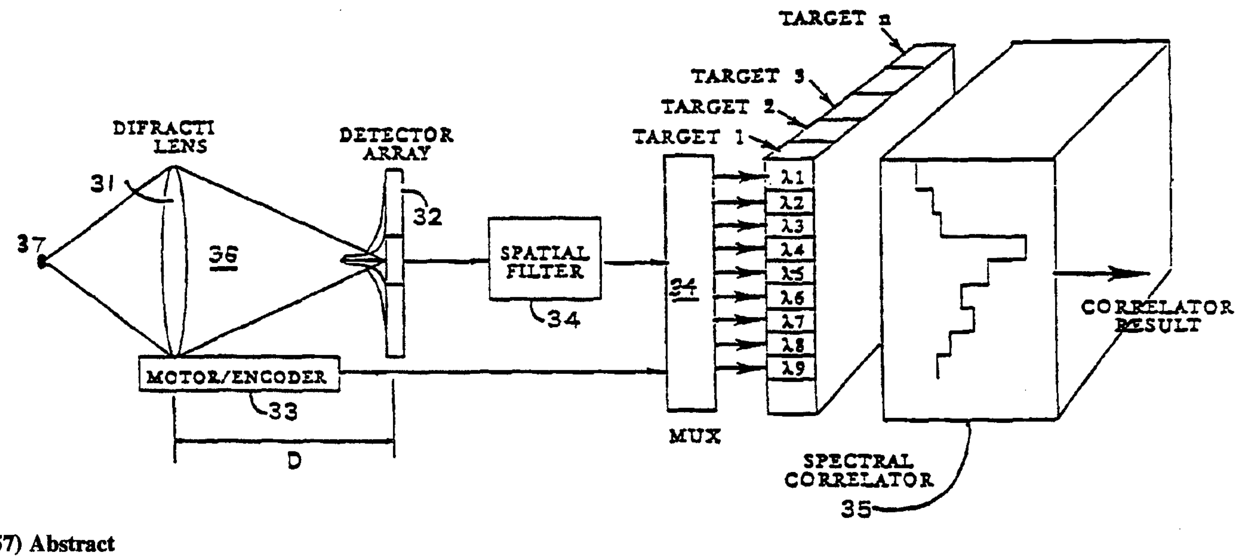
(54) Title: IMAGE MULTISPECTRAL SENSING



(57) Abstract

A spectrophotometer useful for spectral analysis of light emanating from one or more targets (37) within an image. The apparatus comprises a diffractive lens (13) having an optical axis, a planar array of photodetector elements (pixel's) (32), a means for changing the distance between the photodetector array (32) and the diffractive lens (31) along the optical axis and a signal processor (34). If either the array (32) or lens (31) is moved along the optical axis, different wavelengths of light from each target within the image come into or out of focus on particular photodetector elements in the plane of array (32) generating sequential images corresponding to different wavelenghts. By tracking each pixel's output in the array as a function of lens position relative to the array, the spectral composition of each target within the image is generated.

IMAGE MULTISPECTRAL SENSING

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention is directed toward the field of spectral signature sensors useful for target recognition and more particularly, the invention provides a method and an apparatus for performing spectral recordation of images for the purpose of identification, matching or storage.

2. Prior Art

Spectrophotometers (color meters) are widely used in the area of target recognition. The principle of recognition is that different targets reflect, emit or absorb light differently. Alternatively, different targets represent independent light sources, each target having an observable spectra which is particular to that target. Baird, in U.S. Patent 3,343,448 describes a spectroscopic apparatus useful for analyzing the emission spectrum of an object positioned along the optical axis of a reflecting zone plate. Baird's apparatus has means for excitation of a sample located along the optical axis of the apparatus. The sample, once excited, emits light having a characteristic sample-specific spectrum which is gathered and collimated by a reflecting lens and brought to focus on the reflecting zone plate. The reflecting zone plate is analogous to a diffraction grating in which dispersion of reflected light occurs along the optic axis. The emission spectrum by the sample is reflected from the zone plate and brought to focus on a photodetector, which also lies along the optic axis and which is capable of motion with respect to the reflecting zone plate. The various colors comprising the emission spectrum are brought to focus at different points along the optic axis, depending upon the color. Thus, the position of the translating detector with respect to the reflecting zone plate together with the signal out of the photodetector provides a measure of the emission spectrum of the sample.

One difficulty with employing the Baird-type of apparatus to target recognition, in general, is that to avoid light loss the target must lie along the optic axis defined by the reflective zone plate and concave mirror. More particularly, since the Baird apparatus utilizes reflective optical elements, the source or target must lie between the reflecting mirror and the reflecting zone plate. Such an optical construction is not operable for analyzing the spectrum of light emanating from a remote object or target or a group of such targets within a field of interest.

A color signature sensor for analyzing the spectrum of light reflected from the surface of a remote object is described in U.S. Patent 4,954,972 to Sullivan. This apparatus employs a lamp to irradiate the object and a pick up fiber optic to conduct the light reflected from the object to a diffraction grating. The diffraction grating receives the light from the fiber optic and disperses it, bringing it to focus on a substantially linear detector array. The detector array comprises individual photosensitive pixels which are sampled and analyzed to reconstruct the spectral image of the object.

Image multi-spectral sensing (IMSS) differs from the foregoing devices in that it records the spectrum of individual targets within an image or scene. It is capable of simultaneously recording the spectrum of many different points or targets within an image or a field of view. It is desirable to have an apparatus which is compact and is suitable for simultaneously analyzing the spectral composition of light emanating from one or more targets within an image.

SUMMARY OF THE INVENTION

In view of the foregoing limitations of prior art spectral sensors, it is an object of this invention to provide a spectrophotometric apparatus for measuring the spectral composition of infrared, visible or ultraviolet light emanating from remote targets within a field of view.

It is yet another object of this invention to provide a spectrophotometric apparatus which is capable of simultaneously discerning the spectral composition of light emanating from multiple objects (targets) within an image.

It is still another object of this invention to provide a spectrophotometric apparatus which is capable of measuring the reflection, absorption or emission spectrum from a remote target that is relatively light, compact and portable.

It is another object of this invention to provide a spectrophotometric apparatus which can compare the characteristic spectrum of light (color signature) emanating from unknown target objects with the color signature of known objects to enable target recognition.

These and other aspects of the invention will soon become apparent as we turn to a description of the preferred embodiment.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 demonstrates how the dispersion of light from a target by a transmissive Fresnel lens brings different colors to focus at different points along the optic axis.

Figures 2(a) and 2(b) illustrate the spectral resolution of image multispectral sensing with respect to wavelength and background.

Figure 3 is a schematic diagram of the IMSS spectrophotometer of the present invention.

Figure 4 is a computer simulation of the output image of the various pixels in the detector array from an actual scene comprising two point-like targets.

Figure 5 is a computer simulation of one spectral line output from a generalized image with two targets.

Figure 6 shows the variation in light output from a single pixel in the photodetector array as a function of the distance of the diffractive lens (or mirror) from the photodetector array.

Figure 7 demonstrates the application of image multispectral sensing (IMSS) to target recognition.

Figure 8 shows contour lines giving the fraction of the total light intensity which falls within small circles (v) centered on the optical axis for various distances (u) between the lens and the focal plane.

DESCRIPTION OF THE PREFERRED EMBODIMENT

A graphic illustration of the theory behind IMSS is shown in Figures 1 and 2. Consider light from a target 10 as it is focused on a n x n pixel photodetector array 12 by a diffractive lens or mirror 11. At long ranges the target 10 appears as an unresolved point which subtends a single pixel 16 at the photodetector array 12. At shorter ranges, the target 10 resolves and covers multiple pixels. The diffractive lens in the image multispectral sensing (IMSS) apparatus of the present invention has the property that one wavelength band is in focus at a time in the plane of the photodetector array for a particular focal length. Wavelengths of a narrow spectral band from a target at infinity are focused on a single pixel 16, while all other wavelengths are smeared into a multiple pixel blur with a gradual graded structure as shown in Figure 2(b). By changing the focal length, a different wavelength, if present, comes into focus on the photodetector array. Since the only finely focused objects in the field of view are those with a spectral signature at the wavelength corresponding to the current lens/focal plane spacing, by modulating or stepping the lens/focal plane spacing and recording the image for each value of the lens/focal plane spacing, sequential spectral images are made.

Returning to Figure 1, two spectral bands, λ_1 (red) represented by the solid line, and λ_2 (blue) represented by the dotted line, are used for illustrative purposes. The solid state photodetector array 12 having a total area A consisting of n by n elements or pixels 16 with a center-to-center detector element spacing of x is shown. The clear aperture diameter of the diffractive lens 11 is D_A and is shown near the far left of the figure. The focal length of the system when tuned for red light is f_r, and the total length of the system when tuned for blue light is f_b. Thus, $\Delta = f_b - f_r$ is the difference in focal length between the red and blue wavelengths The diffraction limited blurred diameter, which is the diameter of the red light in focus at half peak height, is d_0. It is important for the spatial filtering algorithm, that d_0 be smaller than the diameter of one pixel. When the optical path length is changed to the position of the focal length for the blue light, f_b, the blurred diameter of the red light becomes d_n, which is much larger than the diameter of one pixel. At this point, the blue light is in focus and the diffraction limited, blurred diameter of the blue light is d_b ($\sim d_o$), again smaller than one pixel. A pixel with a focused monochromatic spot will also detect broad band radiation, however, the majority of the signal will come from the focused spot.

If the diffractive lens 11 is moved in the direction of the optical axis OA, different wavelengths sequentially come into and out of focus on the photodetector array 12, generating sequential images at different wavelengths. The output of individual pixels 16 in the photodetector array 12 and the position of the lens with respect to the photo detector array which corresponds to the pixel output are stored in a signal processor 14. The signal processor 14 uses a spatial filtering algorithm to build up the in-focus image of each "frame" of data from the photodetector array. A "frame" corresponds to the photodetector array output for a single lens-photodetector array distance. The unfocused image will be subtracted out leaving substantially only the signal from the focused component of the image. By tracking the intensity of the individual pixels in the image synchronously with the frame rate of the photodetector array, the spectra or "color signature" of all objects in the image are generated. The background clutter will have a smoothly changing type spectrum, while individual targets within the image will have fine spectral signature and are thereby easily differentiated from the background clutter. The function of the n x n photosensitive elements 16 of the detector array 12 is to detect the spectrally filtered light from targets within an image. Only those pixels having an output very different from the output of neighboring pixels remain after passage through the signal processor 14. The processed signal from such pixels represent light received from either (a) a single target in the image if the target is small or (b) an edge of the target if the target is large. The rest of the image is ignored thus reducing the amount of data that is processed by the spectral correlator 15. The spectral correlator 15, compares the spectral signature of the image or targets within the image with a library of known target signatures for purposes of identification.

A fundamental property of diffractive lenses which serves as the basis for IMSS is that the focal length of a diffractive lens varies inversely with the illumination wavelength, i.e. $f(\lambda) = \lambda_0 f/\lambda$. A diffractive lens is more dispersive than any known glass lens and the dispersion has the opposite sign. Thus, if an image detector is located at a distance $f(\lambda_1)$ behind the lens, objects with emission wavelength λ_1 will be in sharp focus, whereas objects at other wavelengths will be significantly defocused. The defocused images from the other wavelength components can be subtracted out using image processing techniques described earlier. If the image detector is moved to a distance $f(\lambda_2)$ behind the lens, distant objects with emission wavelength λ_2 will be in sharp focus. Hence, by varying the distance between the diffractive lens and the detector, one can obtain the spectrum for each object contained within the field of view.

In Figures 2(a) and 2(b), we see the spectral resolution possible from the use of IMSS using the present invention. In Figure 2(a) the intensity is plotted as a function of position along the photo detector array for several different wavelengths from $\lambda 1$ to $\lambda 4$. As can be seen in Figures 2(a) and 2(b), $\lambda 1$ is in focus such that the majority of the radiation falls on a single pixel 21 of the photodetector array 12. Even though the primary wavelength λ1 is in focus, radiation from adjacent wavelength bands, λ2 - λ4, contribute to the total energy falling on a pixel. However, the focused light has a stronger signal in one pixel as compared to the neighboring pixels.

The spectral resolution of IMSS can be thought of as the ratio of the amount of in-band radiation to the amount of out-of- band radiation falling on a pixel. An analytic derivation of the spectral resolution can be found in diffraction theory (See, for example, E. Wolf, Proc. Roy.Soc. (A) 204,542(1975)). Figure 8 is a plot showing the contour lines of the radiant intensity in a scaled coordinate system of u and v where:

$$u=\frac{\pi}{2\lambda_0}\frac{\Delta}{f/\#_0^2} \quad (1)$$

$$v=\frac{\pi}{\lambda_o}\frac{r}{f/\#_0} \quad (2)$$

Both u and v are dimensionless parameters wherein u is related to a position along the optical axis through Δ and v is related to a position perpendicular to the optical axis through r. Δ is the actual translation along the optical axis to change the in-focus spectral band. f/# is the f-number of the lens. Solving equation (1) for Δ gives:

$$\Delta=\frac{2u}{\pi}\lambda_0 f/\#_0^2 \quad (3)$$

if u is equal to 2π then:

$$\Delta = 4\lambda_0 f/\#_0^2 \tag{4}$$

which is the equation for the geometric depth of focus. In equation (2) r is the radius of the blur circle containing x% of the in focus light. Solving equation (2) for r gives:

$$r = \frac{v}{\pi}\lambda_0 f/\#_0 \tag{5}$$

and if v is equal to 1.22π, then:

$$r = 1.22\lambda_0 f/\#_0 \tag{6}$$

which is the equation for the geometric diffraction limited blur circle radius.

The spectral resolution of the IMSS is a function of the incident wavelength, the focal length, the pixel size, the f-number and the ratio of the dimensionless parameters u and v. It is given by the following equation:

$$\Delta\lambda = \frac{pixel\,size\, f/\#_1\lambda_1}{f_2}\frac{u}{v} \tag{7}$$

The derivation of equation (7) is as follows:

by definition the fundamental equation for diffractive lens is:

$$f_1 = \frac{\lambda_2}{\lambda_1} f_2 \text{ and } f_2 = \frac{\lambda_0}{\lambda_2} f_0 \tag{8}$$

Referring to Figure 1

$$\Delta = f_2 - f_1 = f_0\lambda_0\frac{\lambda_1 - \lambda_2}{\lambda_1\lambda_2} \tag{9}$$

$$\Delta\lambda = \lambda_1 - \lambda_2 \; \textit{and therefore}, \quad \Delta = \frac{f_0 \lambda_0 \Delta\lambda}{\lambda_1 \lambda_2} \tag{10}$$

from equation (3)

$$\Delta = \frac{2u}{\pi} \lambda_0 \, f/\#_0^2 \tag{11}$$

substituting from equation (5) for v

$$\Delta = 2r \, f/\#_0 \frac{u}{v} \tag{12}$$

let 2r equal pixel size; then

$$\Delta = \textit{pixel size} \; f/\#_0 \frac{u}{v} \tag{13}$$

equating (10) and (13)

$$\frac{\lambda_0 f_0 \Delta\lambda}{\lambda_0 \lambda_1} = \textit{pixel size} \; f/\#_0 \frac{u}{v}$$

$$\Delta\lambda = \frac{\textit{pixel size} \; f/\#_1 \lambda_1 \lambda_2}{\lambda_0 f_0} \frac{u}{v} \tag{14}$$

let $\lambda_2 = \lambda_0$ then:

$$\Delta\lambda = \frac{\textit{pixel size} \; f/\#_0 \lambda_1}{f_0} \frac{u}{v}$$

Δ can be considered the depth of focus. Another way to define the spectral resulution of IMSS is

$$\Delta\lambda = \frac{\Delta\lambda_1}{f_0} \tag{15}$$

from equation 15 we see that the spectral resolution of the IMSS is directly proportional to the depth of focus and the wavelength of incident radiation and inversely proportional to the focal length.

The instantaneous field of view, IFOV is given by:

$$IFOV_0 = \frac{pixel\,size}{f_0} \tag{16}$$

Therefore, the spectral resolution can be written as:

$$\Delta\lambda = IFOV_0\, f/\#_0\, \lambda_1 \frac{u}{v} \tag{17}$$

The finest spectral resolution can be achieved by using small pixel sizes, i.e., small IFOV and long focal length lenses. The longer the focal length lens, i.e., the narrower the instantaneous field of view, the finer the spectral resolution of the IMSS system.

A schematic diagram of a preferred embodiment of the present invention is shown in Figure 3. The apparatus comprises a diffractive lens 31, a photodetector array 32, a motor with a position encoder 33, a signal processor 34 and a spectral correlator 35. Light 36 from a remote target 37 is focused by the diffractive lens or mirror 31 onto the photodetector array 32. The distance of the photodetector array 32 from the lens 31 is controlled by means of a stepper motor, piezoelectric translation device or other such translating means 33 as is appropriate for the wavelength range. The distance D is read by the signal processor 34 which simultaneously reads the output of each pixel (not shown) in the photodetector array 32. Thus, for every value of D, which corresponds to a focal distance for a particular color, different spectral components of L the image will be brought into focus on the photodetector array 32. The spectral components of targets 1 through n in the image are recorded for each value of D. Recordings for each position D comprise a single frame. In the example shown there is only a single target. The spectral components of the light L emanating from the target shown as $\lambda 1$ - $\lambda 9$ in Figure 3, may be compared with spectral components of known targets in a spectral correlation 35. The correlation 35 permits identification of the target 37.

As stated earlier the solid state sensor 22 is electronically scanned and the signal is processed to filter out all portions of the image that extend over more than one pixel. Therefore, at the position of f_r only in-focus objects (or edges) with spectral content of red light will pass through the filter and likewise at the position of f_b only in-focus objects with the spectral content of blue light will pass through the filter. A modulation of the focal length along with point and edge spatial filtering for each focal length will give spectral information for all in the field of view. There are several ways to vary the distance between the lens and the photodetector array. One possible approach is to use a piezoelectric driven mirror in the optical path. Velocities of 160 millimeters per second is practical with this approach. As mentioned earlier, stepper motors or pneumatic hydraulic devices can also be employed for changing the distance between the diffractive focusing element and the photodetector array.

In view of the foregoing, and in light of the objectives of the invention, it will be apparent to those skilled in the art that the subject matter of this invention is capable of variation in its detail, and I do not therefore desire to be limited to the specific embodiment selected for purposes of explanation of the invention. The foregoing has been merely a description of one embodiment of the imaging spectrophotometer. Instead, the scope of the applicant's invention can be determined by the claims appended hereto.

CLAIMS

What I claim is:

1. An apparatus for measuring the spectral composition of an image comprising:

(a) a diffractive focusing element for dispersing spectral components of an image into a volume having an area A and a length L;

(b) a photodetector array having an area substantially equal to A; and

(c) means for measuring portions of said image that are focused upon said photodetector array; and

(d) means for changing the relative position of said diffractive lens with respect to said photo detector array in the direction of L;

(e) means for measuring the relative position of said diffractive lens and said photodetector array; said spectral composition of said image being determined by combining the images for each position along L.

2. The apparatus of claim, wherein said diffractive focusing element is a diffractive lens.

3. The apparatus of claim, wherein said diffractive focusing element is a diffractive mirror.

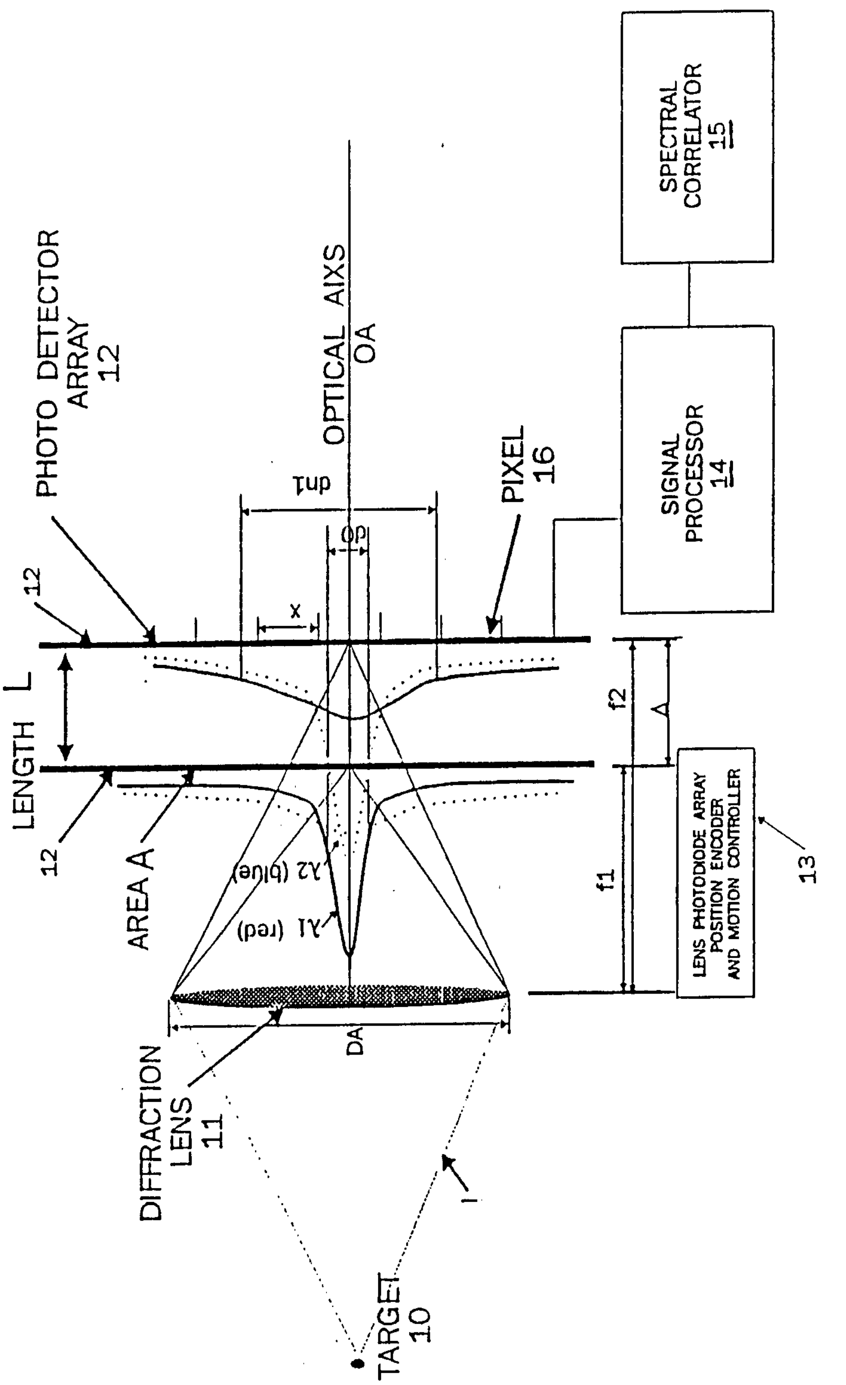


Fig. 1

SUBSTITUTE SHEET (RULE 26)

Fig. 2A (Top view of Fig. 2)

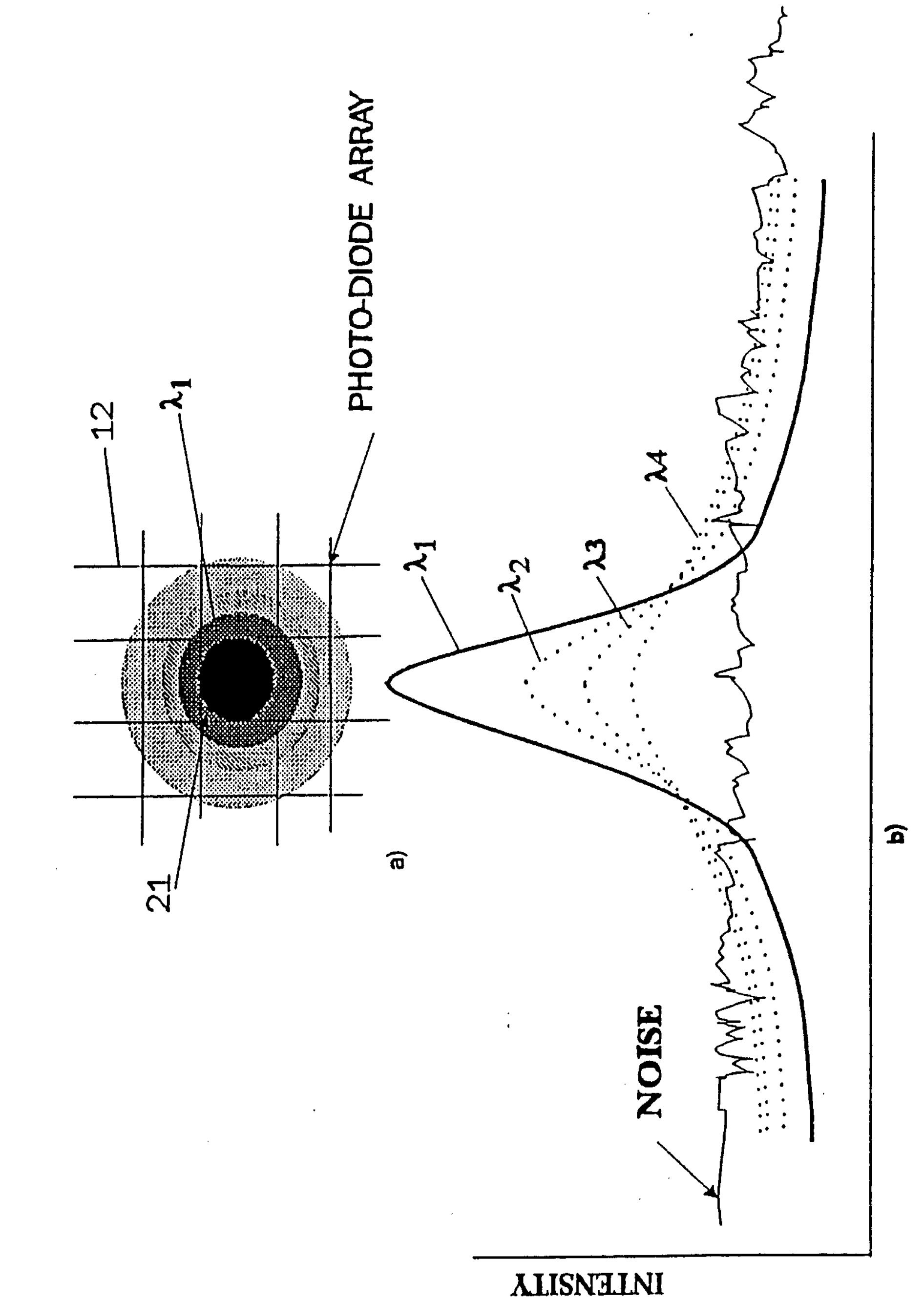


Fig. 2

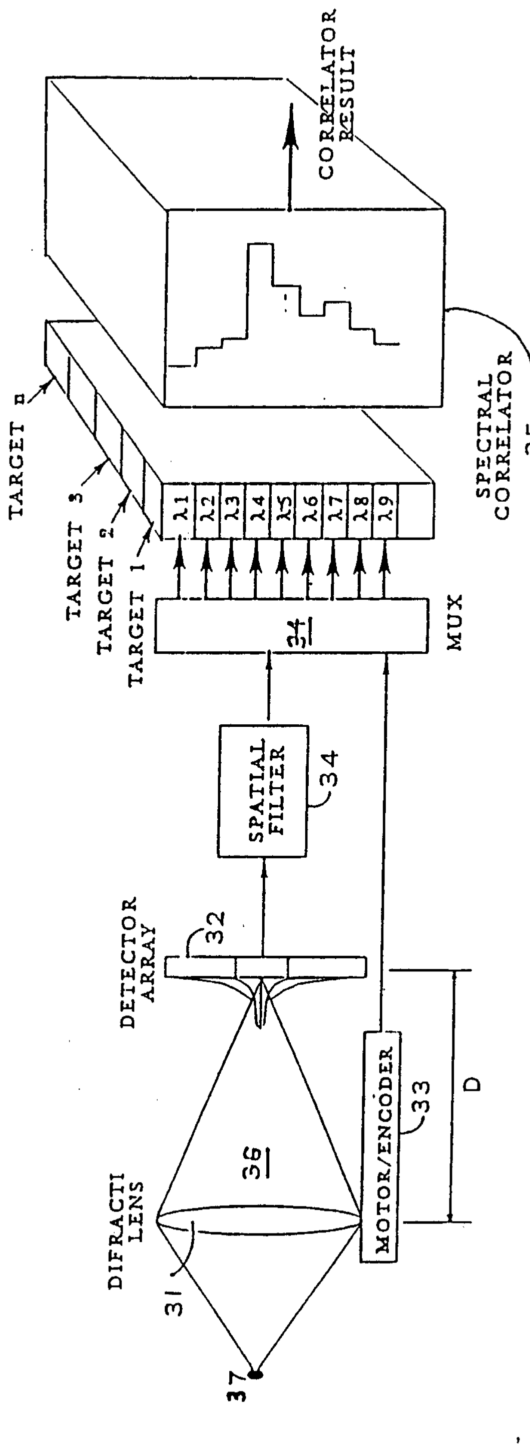


Fig. 3

SUBSTITUTE SHEET (RULE 26)

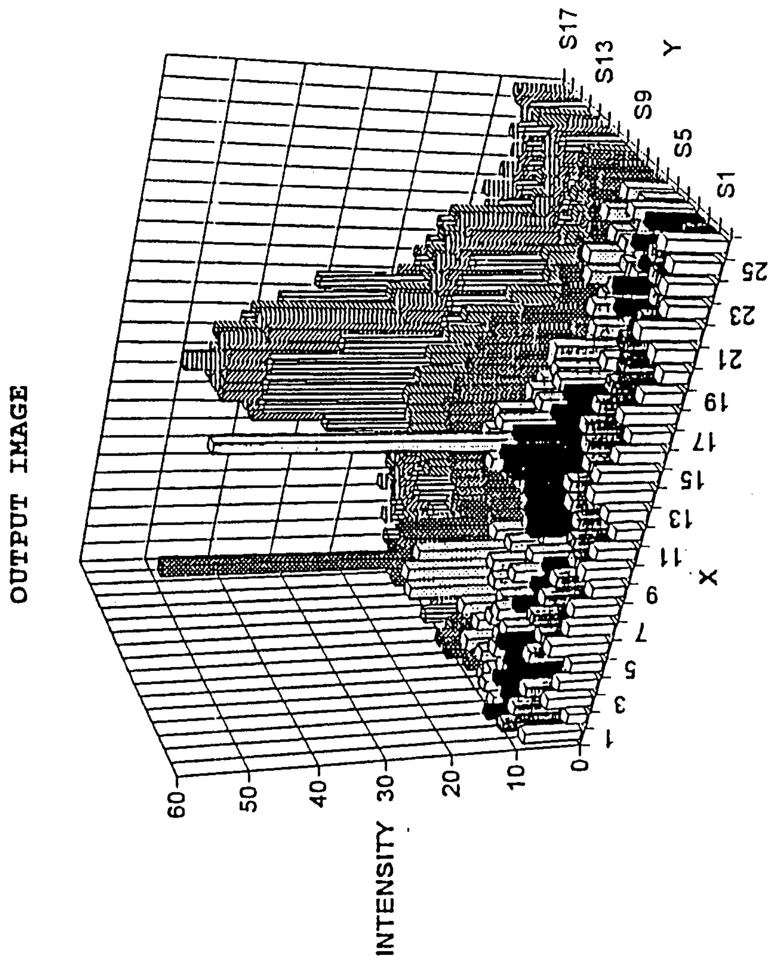
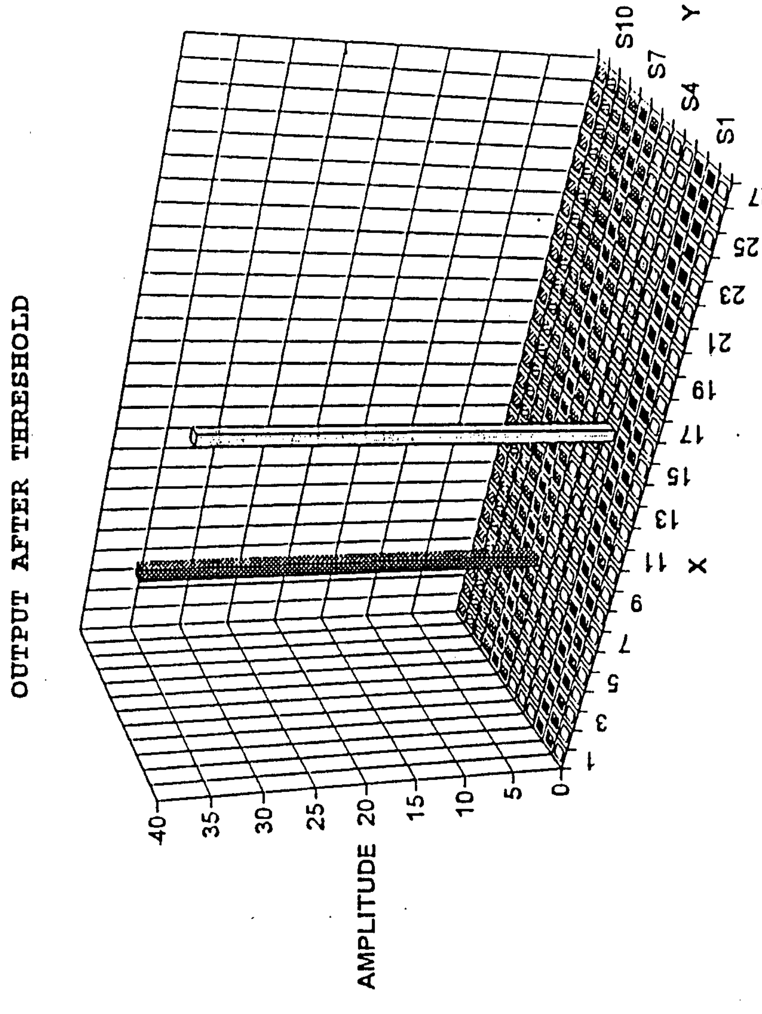

OUTPUT IMAGE
INTENSITY
0
10
20
30
40
50
60
1
3
5
7
9
11
13
15
17
19
21
23
25
X
S1
S5
S9
S13
S17
Y

Fig. 4


OUTPUT AFTER THRESHOLD
AMPLITUDE
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35
30
25
20
15
10
5
0
1
3
5
7
9
11
13
15
17
19
21
23
25
27
X
S1
S4
S7
S10
Y

Fig. 5

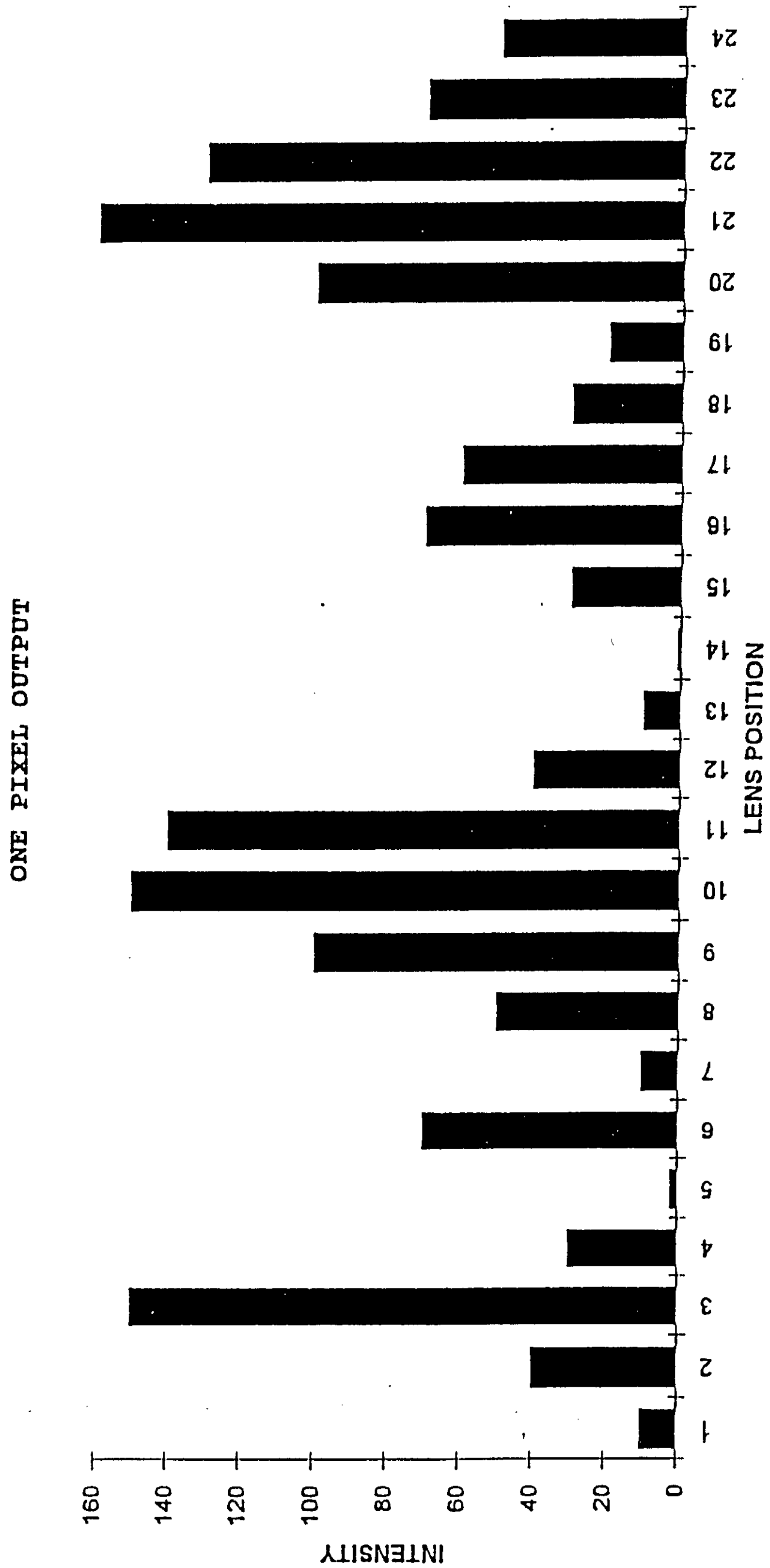

ONE PIXEL OUTPUT
INTENSITY
0 20 40 60 80 100 120 140 160
LENS POSITION
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

Fig. 6

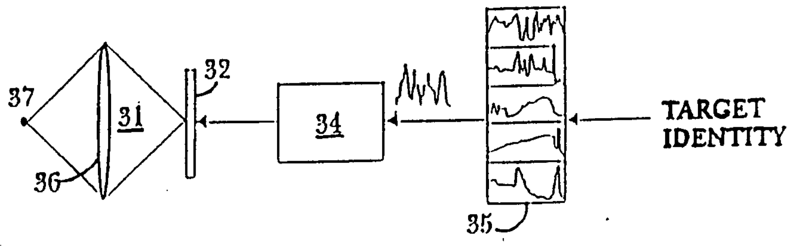
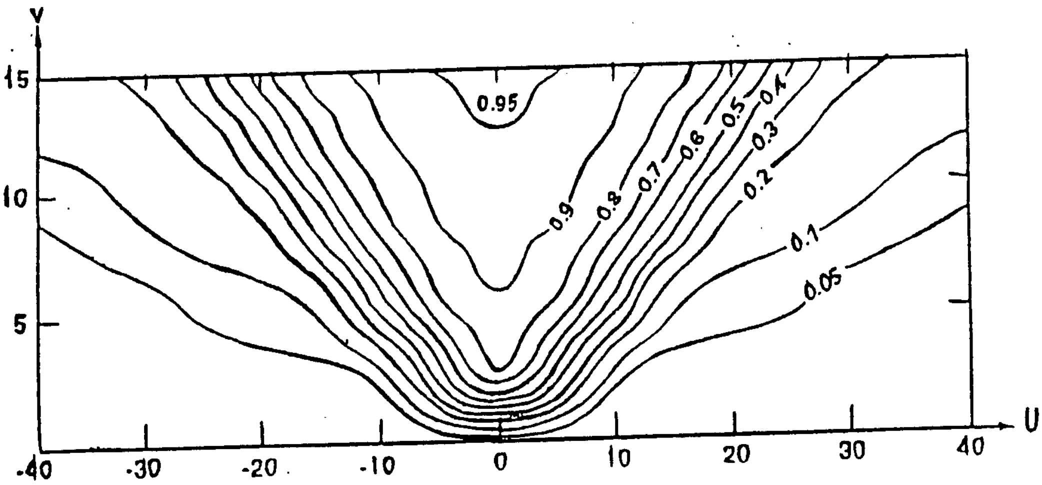

37
31
32
34
TARGET
IDENTITY
36
35

Fig. 7


V
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0.95
0.9
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0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.05
-40
-30
-20
-10
0
10
20
30
40
U

Fig. 8

INTERNATIONAL SEARCH REPORT

International Application No.
PCT/US93/12584

A. CLASSIFICATION OF SUBJECT MATTER

IPC(5) : IPC (5) GO1J 3/28
US CL : 356/ 326,328, 300,330-334; 250/226
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 356/ 326,328, 300,330-334; 250/226

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US, A, 4,742,222(Retfalvy et al) 03 May 1988,see entire document	1-2
Y	US, A, 4,705,396(Bergstom) 10 November 1987, see entire document	1-2
Y	American Chemical Society, 1983,Denton et al, "Charged-Injected and Charge-coupIded Devices in Practical Chemical Analysis, see entire document	1-2

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be part of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
04 March 1994	14 MAR 1994

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	For VINCENT P. MCGRAW
Facsimile No. NOT APPLICABLE	Telephone No. (703) 308-4801

Form PCT/ISA/210 (second sheet)(July 1992)★

INTERNATIONAL SEARCH REPORT

International Application No.
PCT/US93/12584

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This international report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.: 3
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

Please See Extra Sheet.

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest.

☐ No protest accompanied the payment of additional search fees.

BOX I. OBSERVATIONS WHERE CLAIMS WERE FOUND UNSEARCHABLE
2. Where no meaningful search could be carried out, specifically:

The disclosure refers to the diffraction focusing element to be a lens or mirror. It is not clear how a mirror can be acting as a diffraction focusing element since a mirror acts to reflect or direct spectral components of light to a point and not diffract the light in any way. The specification is silent as to how the mirror acts like a diffractive focal lens.