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Wilson et al.

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(54) **COMPUTED TOMOGRAPHY IMAGING SPECTROMETER (CTIS) WITH 2D REFLECTIVE GRATING FOR ULTRAVIOLET TO LONG-WAVE INFRARED DETECTION ESPECIALLY USEFUL FOR SURVEYING TRANSIENT EVENTS**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 238 days.

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(51) **Int. Cl.**[7] **G01J 3/18**; G01J 3/28; G02B 5/18

(52) **U.S. Cl.** **356/328**; 359/571; 359/572

(58) **Field of Search** 306/328, 51; 359/569, 359/570–572

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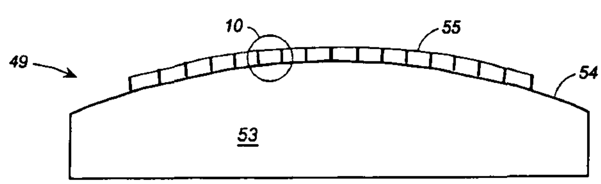
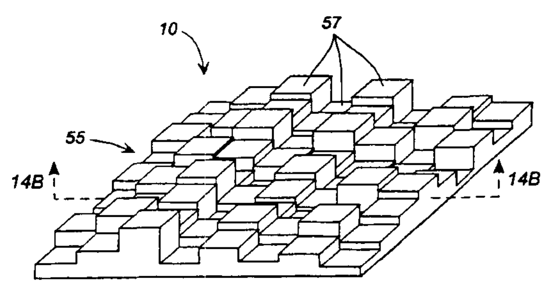
(57) **ABSTRACT**

The optical system of this invention is an unique type of imaging spectrometer, i.e. an instrument that can determine the spectra of all points in a two-dimensional scene. The general type of imaging spectrometer under which this invention falls has been termed a computed-tomography imaging spectrometer (CTIS). CTIS's have the ability to perform spectral imaging of scenes containing rapidly moving objects or evolving features, hereafter referred to as transient scenes. This invention, a reflective CTIS with an unique two-dimensional reflective grating, can operate in any wavelength band from the ultraviolet through long-wave infrared. Although this spectrometer is especially useful for rapidly occurring events it is also useful for investigation of some slow moving phenomena as in the life sciences.

38 Claims, 11 Drawing Sheets





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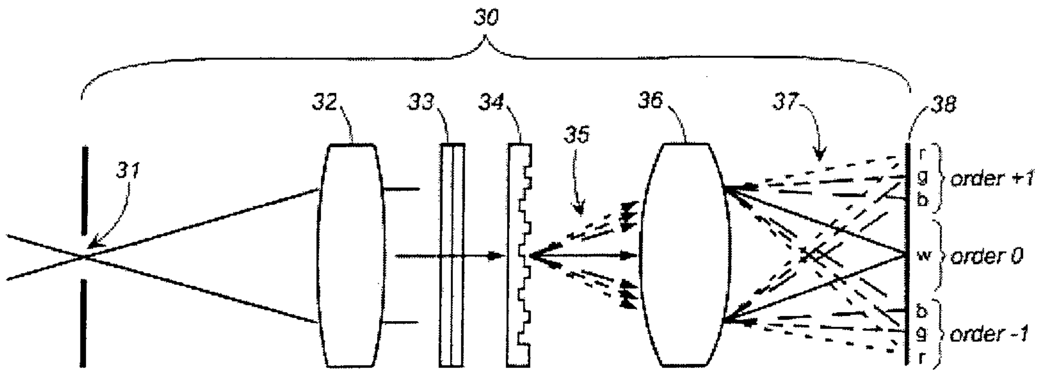
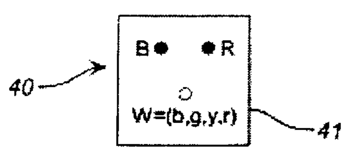


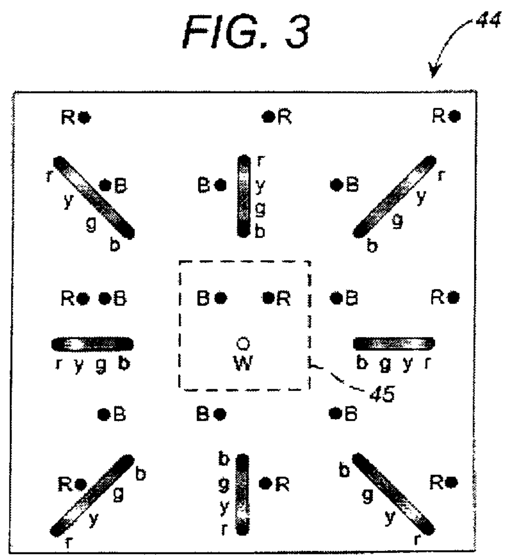
FIG. 1 (Prior Art)

FIG. 2



Object Scene
Three spots:
Red (R), Blue (B),
White (W) composed of
blue (b), green (g),
yellow (y), red (r)

FIG. 3



Detector Image

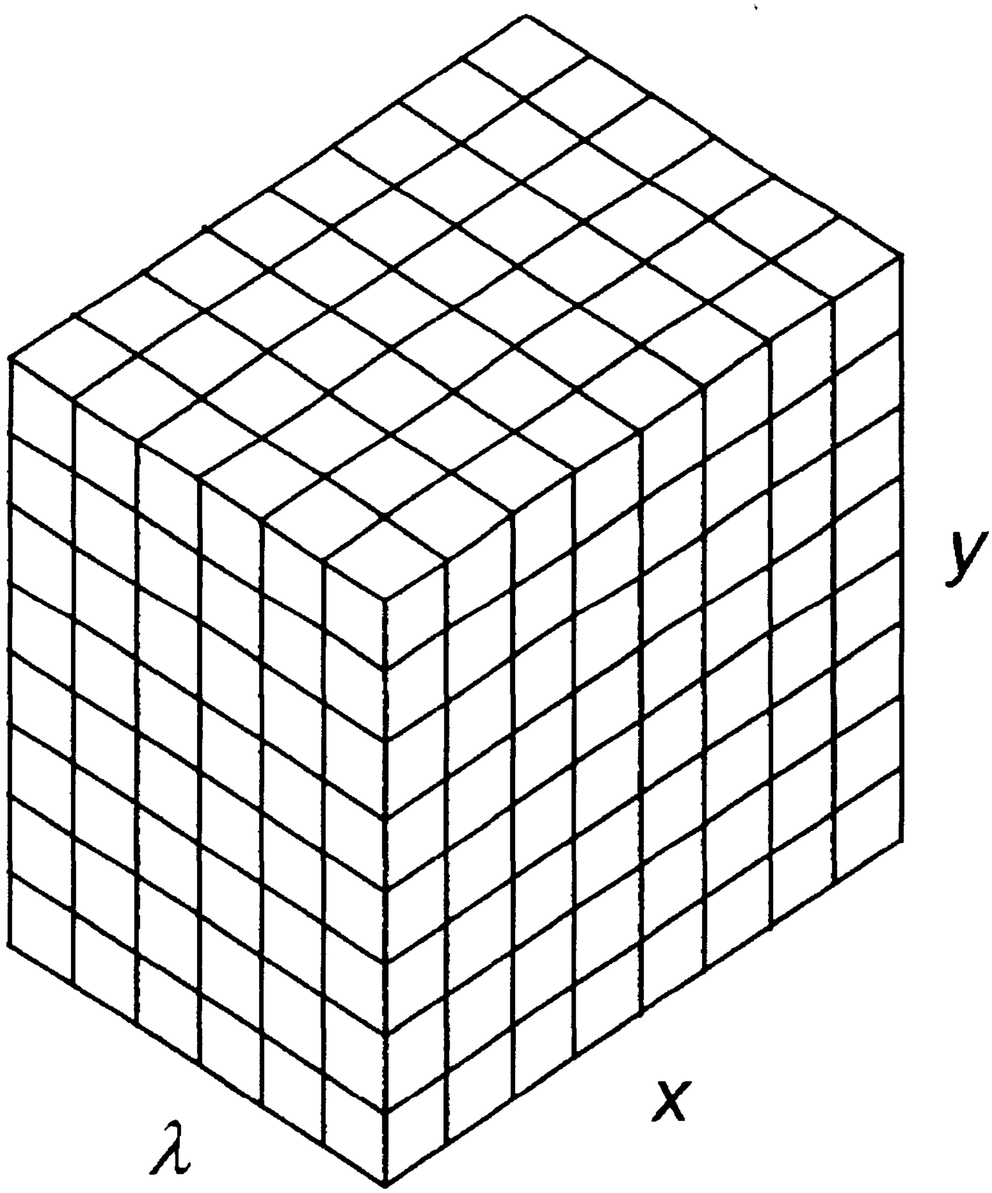
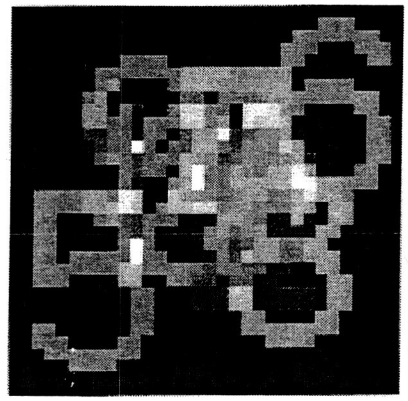


FIG. 4

FIG. 5



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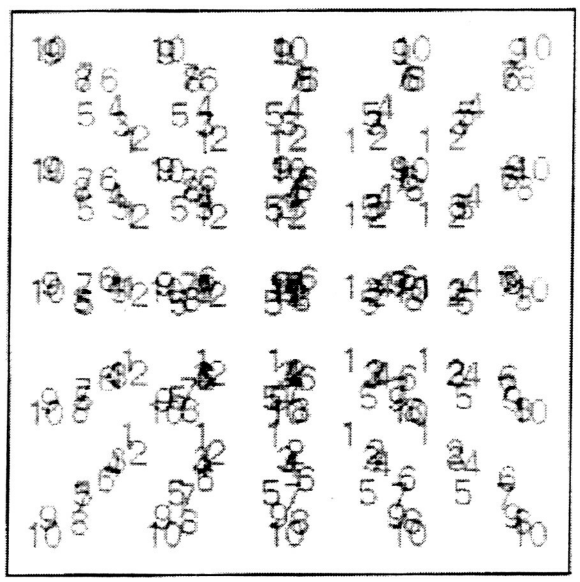
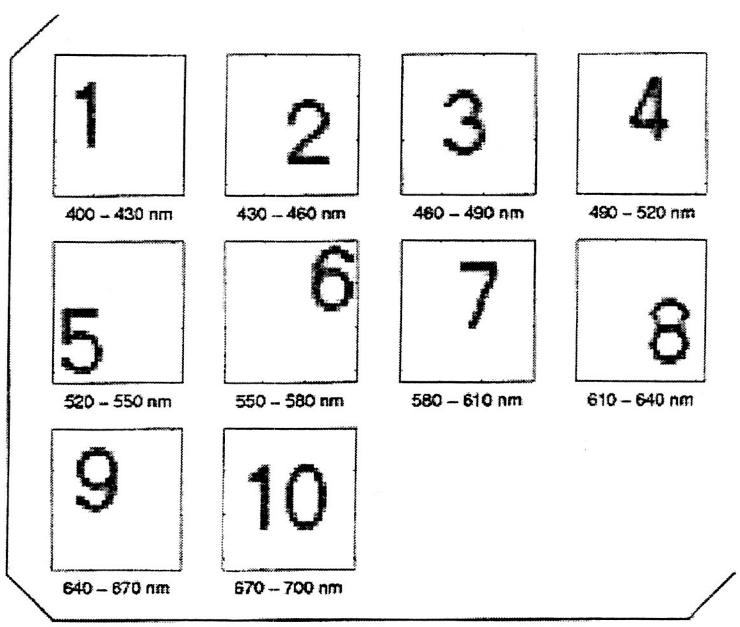


FIG. 7



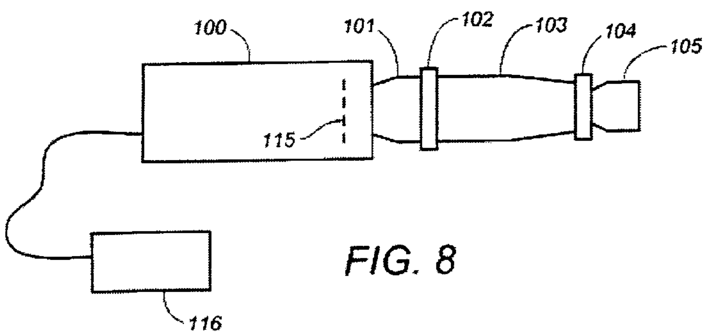


FIG. 8

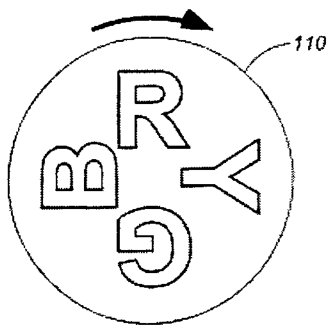


FIG. 9

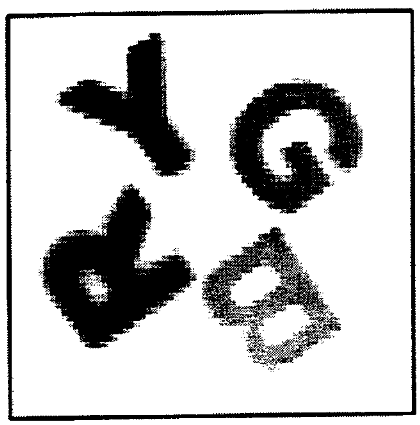
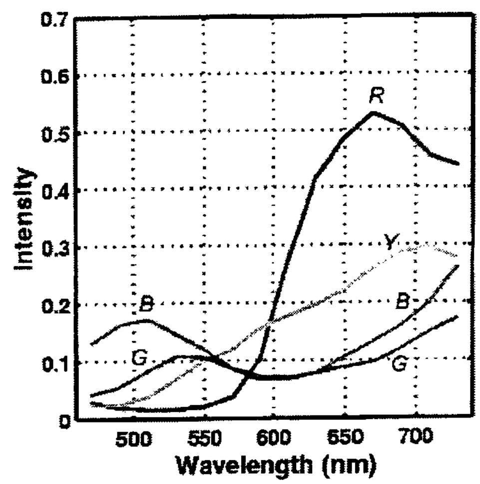


FIG. 10



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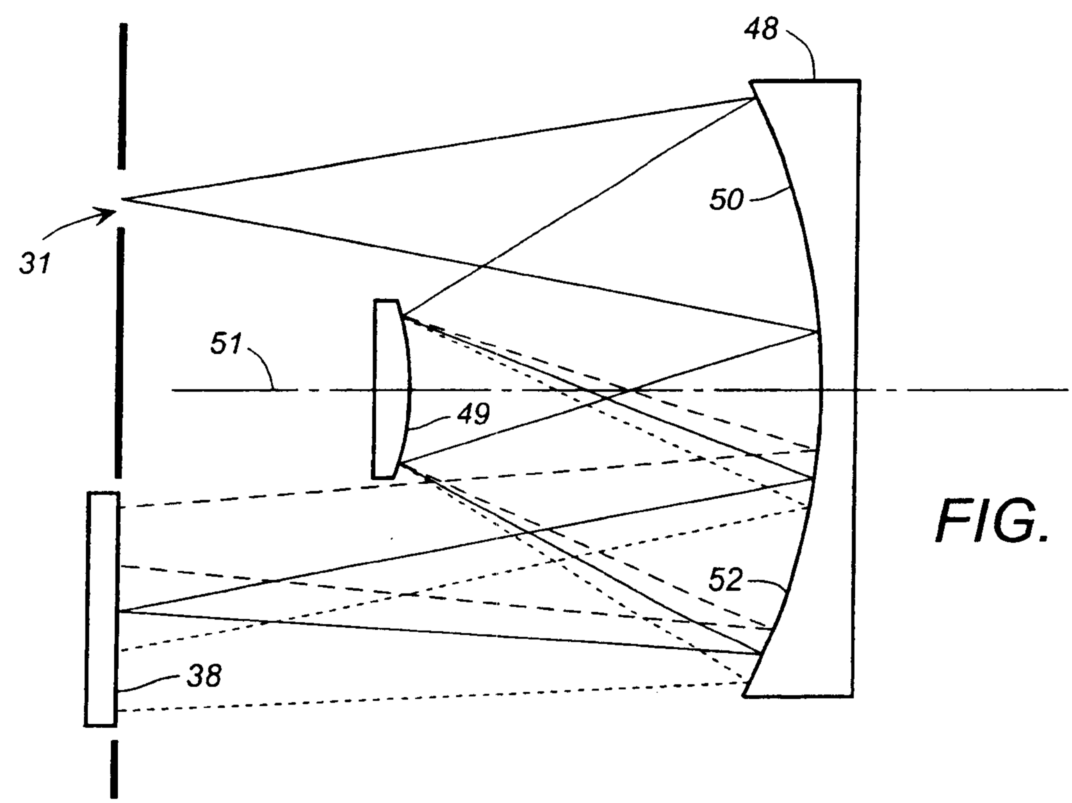

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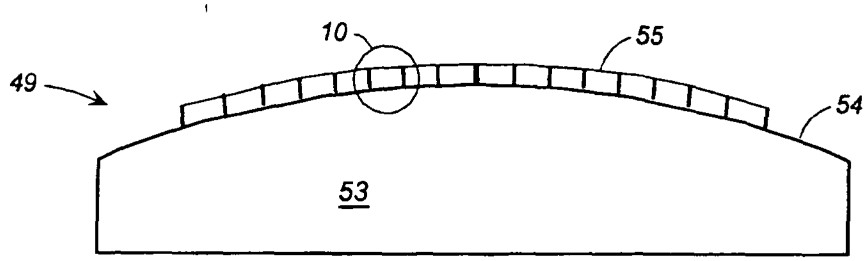

FIG. 13

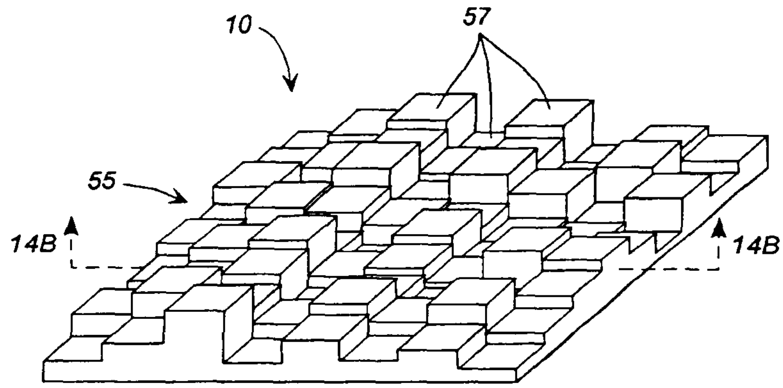

FIG. 14A

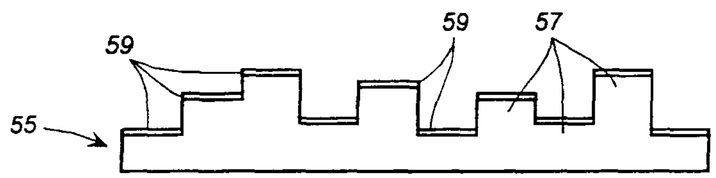

FIG. 14B

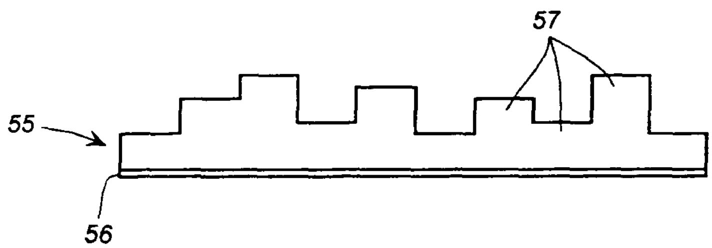

FIG. 14C

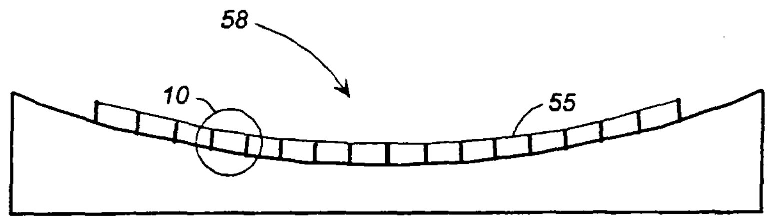

FIG. 14D

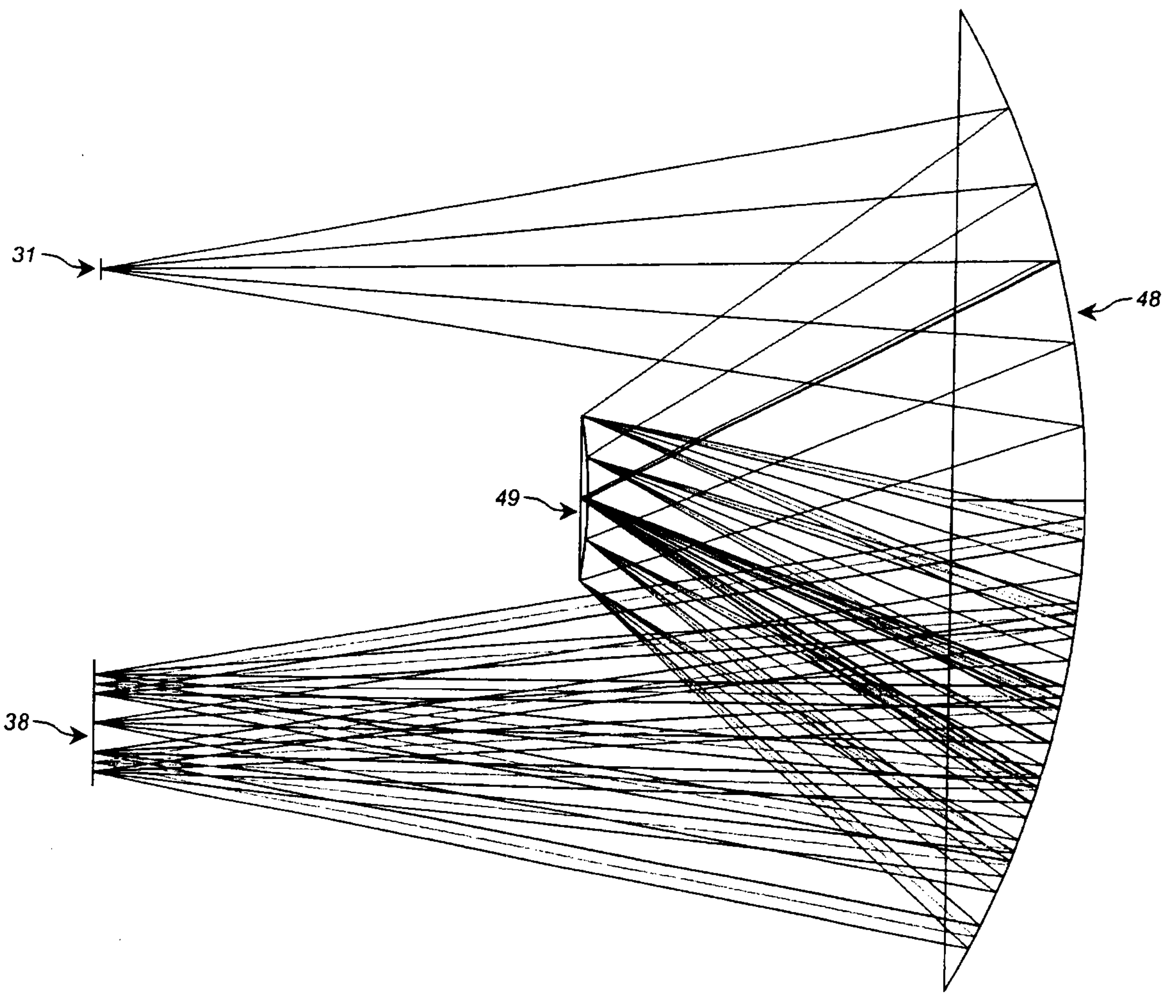

FIG. 15

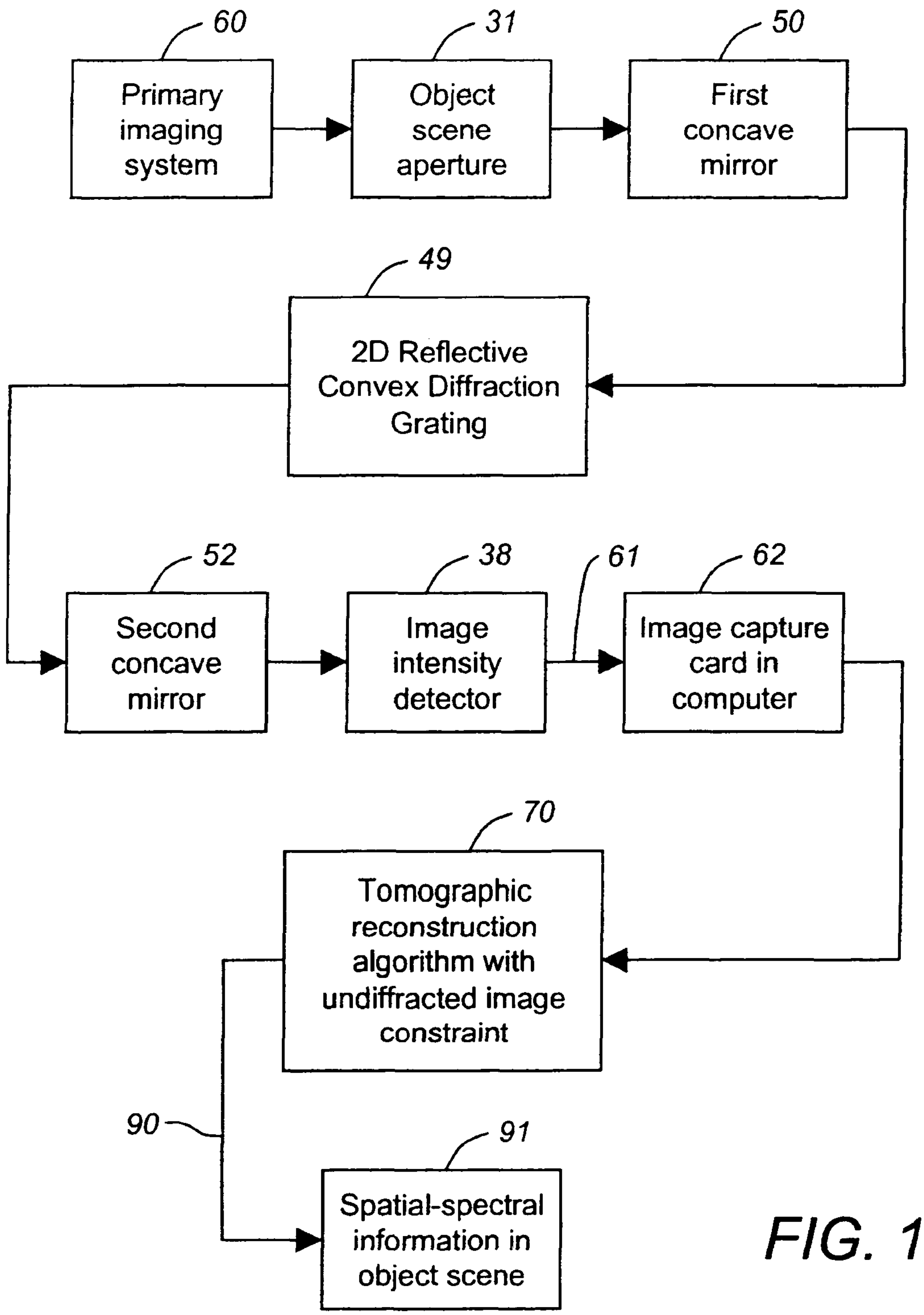
60
Primary imaging system
31
Object scene aperture
50
First concave mirror
49
2D Reflective Convex Diffraction Grating
52
Second concave mirror
38
Image intensity detector
61
62
Image capture card in computer
70
Tomographic reconstruction algorithm with undiffracted image constraint
90
91
Spatial-spectral information in object scene

FIG. 16

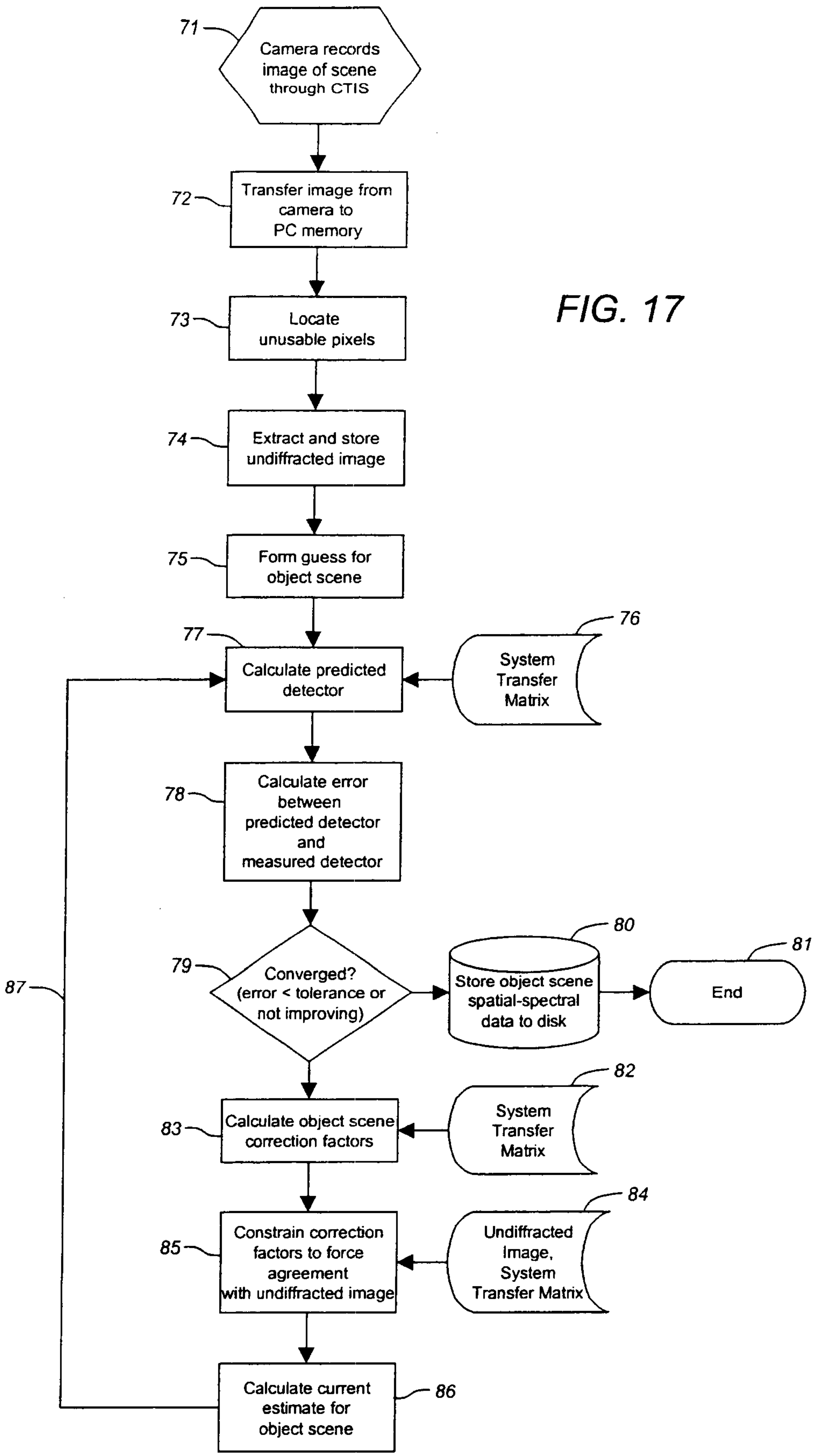
71
Camera records image of scene through CTIS
72
Transfer image from camera to PC memory
73
Locate unusable pixels
74
Extract and store undiffracted image
75
Form guess for object scene
76
System Transfer Matrix
77
Calculate predicted detector
78
Calculate error between predicted detector and measured detector
79
Converged? (error < tolerance or not improving)
80
Store object scene spatial-spectral data to disk
81
End
82
System Transfer Matrix
83
Calculate object scene correction factors
84
Undiffracted Image, System Transfer Matrix
85
Constrain correction factors to force agreement with undiffracted image
86
Calculate current estimate for object scene
87

FIG. 17

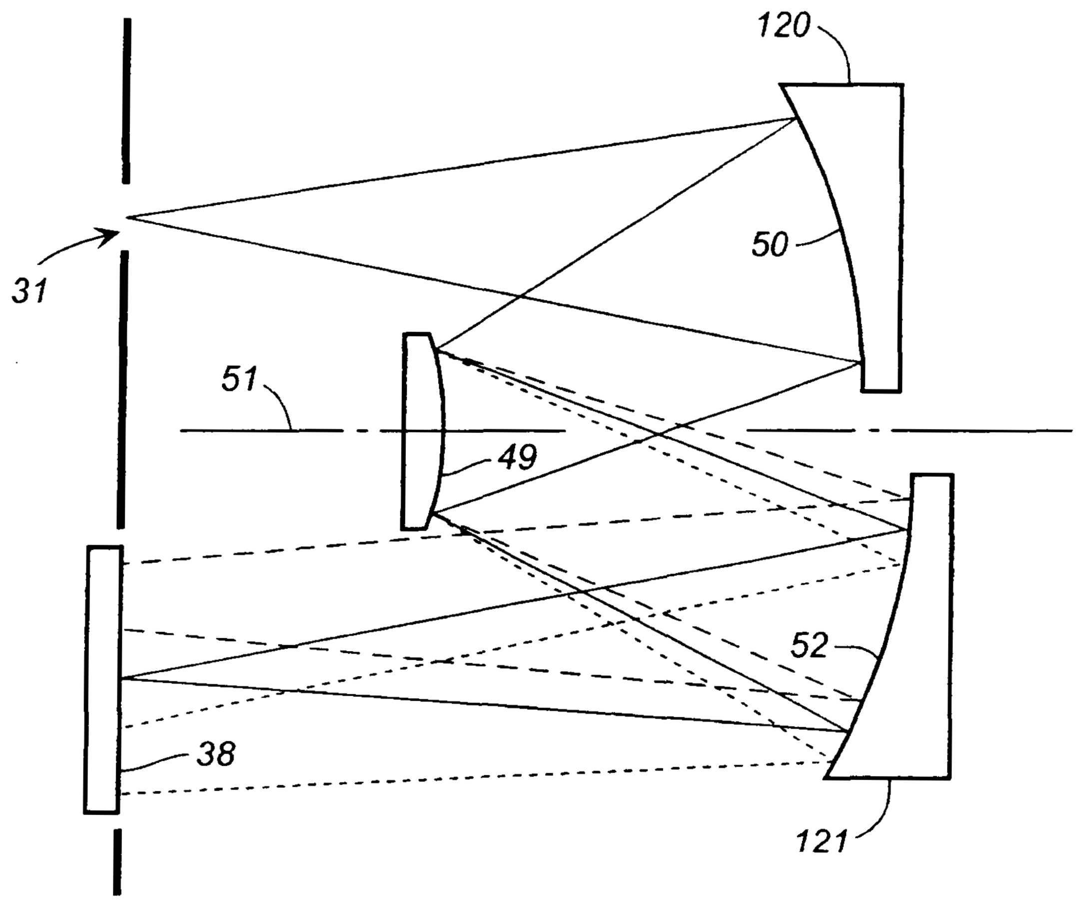

FIG. 18

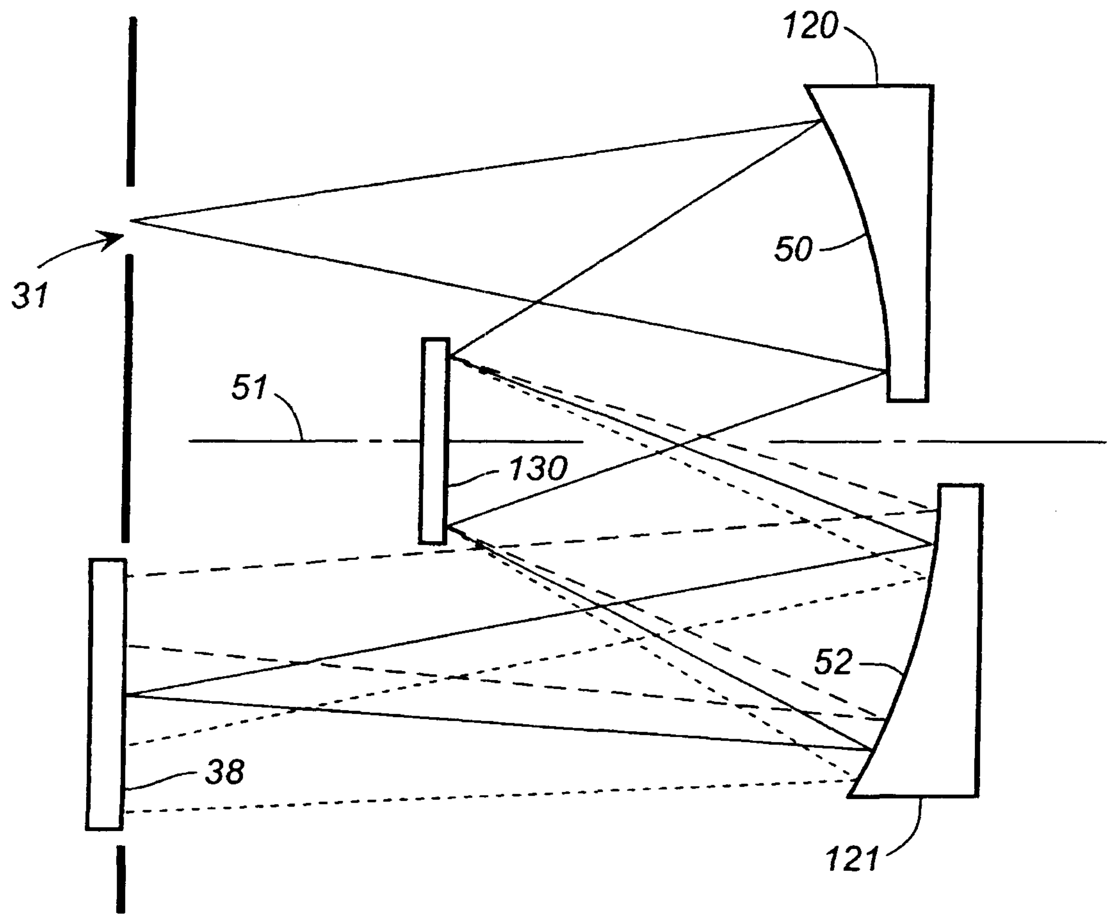

FIG. 19

the bottom of pixels **57**. In all embodiments diffraction occurs as a result of the phase shift due to the varying heights of pixels **57**. Pixel heights are determined by:

(a) Designing the phase profile of the grating to efficiently disperse light into the desired orders. This can be accomplished by, for example, the iterative Fourier transform algorithm {6, 7}.

(b) Converting the phases into pixel heights.

i. For the embodiment with reflective coating on top of the pixels, depth=(phase/(2*pi))*(lambda/2), where lambda is the design wavelength and depth is the maximum pixel height–pixel height.

ii. For the embodiment with reflective coating on the bottom of the pixels, height=(phase/(2*pi))*(lambda/(n_{EBR}−n_{air}))/2, where n_{EBR} is the refractive index of the electron beam resist and n_{air} is the refractive index of the grating cover material, most likely air.

In one embodiment of this invention, the 2D reflective diffraction grating **58** is concave as shown in FIG. **14D**. The reflective surface can be on the top or bottom of the cells as described with regard to FIGS. **14B** and **14C**. This particular grating can be used, for example, in a spectrometer not having a primary and tertiary mirror surface as shown in FIGS. **12**, **18** and **19**, in which the spectra enter aperture **31** and incident directly on the concave reflective grating **58** which diffracts the spectra and focuses the image directly on focal plane array detector **38**.

In this invention the 2D reflective convex diffraction grating is a computer-generated hologram grating. In one embodiment, the computer-generated hologram grating is on a convex substrate instead of a one-dimensional blazed grating. To determine if a reflective CTIS is feasible, we designed a system for the wavelength range of 6–10 microns.

In one embodiment of this invention, the 2D reflective convex grating is formed by a process comprising:

(a) providing a substrate having a desired curvature,

(b) forming pixels on the convex surface of the substrate by

(1) spin-coating electron beam resist on the convex surface,

(2) performing analog direct-write electron-beam lithography to expose the resist in a pattern proportional to the desired depth of the pixel pattern,

(3) etching away the resist with an effective developer in proportion to the e-beam dose, and leaving a surface relief profile with the desired pixel pattern, and

(c) depositing a thin layer of about 0.05 microns, of a reflective surface, such as aluminum.

FIG. **15**, which is similar to FIG. **12**, but with several diffraction orders of this invention illustrated with a ray-trace diagram of the system's optics. Table I lists some of the specifications of this particular system. Due to the large diffraction-limited spot size of the infrared radiation, the spatial resolution was reduced to about 60×60 pixels. However, the performance was near diffraction limited and demonstrated that the Offner form will work well for CTIS systems.

TABLE I

Example Reflective CTIS Specifications

Wavelength range	6–10 microns
f-number	3
Object scene aperture	2 mm × 2 mm
Detector	QWIP, 512 × 512, 25 micron square pixels
Spatial resolution	80 × 80 QWIP pixels, about 60 × 60 pixels due to IR diffraction
Spectral resolution	<0.5 microns (>8 spectral bands)
Length × Width	100 mm × 100 mm

where QWIP stands for quantum well infrared photodetector {11}.

An overview of our improved CTIS process of this invention is shown in FIG. **16** where radiation from a primary imaging system **60** is incident upon an object scene aperture **31** and transmitted through to a first concave mirror **50**. Radiation is reflected from mirror **50** to 2D reflective convex diffraction grating **49** whereupon it is further reflected to second concave mirror **52** which reflects the radiation to image intensity detector **38**. A radiation associated signal **61** is then transmitted from detector **38** to an image capture card **62** in the computer whereupon the signal is processed by a tomographic reconstruction algorithm, which, in one embodiment, includes reconstructing the image scene with our undiffracted image constraint process at **70**. After a predetermined number of iterations a data stream **90** is produced of spatial-spectral information from the object scene at **91**.

An example of a specific algorithm which conforms with tomographic reconstruction algorithm **70** of FIG. **16** is illustrated in FIG. **17**. In this embodiment, a camera first records a CTIS-dispersed image of scene at **71**; thereafter, the image is transferred from the camera to computer memory at **72**; thereafter, indices of undesirable pixels, which may be saturated or physically bad, are removed from the image at **73**; thereafter, the undiffracted image is extracted and stored separately whereupon image processing to remove noise is performed at **74**; and thereafter, an initial estimate is made for the scene S which equals the undiffracted image times unity spectrum at **75**.

From this point, a system transfer matrix H at **76** is multiplied by a scene S thereby producing a calculated predicted detector image at **77**. Then an error between the predicted detector image, D_p, and the measured detector image, D_m, is calculated ignoring bad pixels at **78**. Thereafter, a convergence check is made to determine if the error is less than a predetermined tolerance and, based on the convergence check, a decision is made at **79** to either

(i) accept the result and save the scene at **80** and end the iteration at **81**, or

(ii) not accept the convergence and iterate the scene again.

If it is decided by the algorithm at **79** that another iteration is required, then the system transfer matrix **82** is used in Eq. (2) to calculate a plurality of correction factors at **83** for each scene voxel that will improve agreement between the predicted detector image and the measured detector image.

The plurality of correction factors are then constrained so that the undiffracted image of the predicted detector at **84** and the measured detector will exactly agree thereby producing a new undiffracted image constraint correction at **85**. Thereafter, at **86** a new scene is calculated by multiplying the old scene by the correction factors at **85** thereby producing a signal **87** associated with the calculated current estimate for the object scene. Signal **87** is then sent to operation at **77** and the process is reiterated until the decision at 79 accepts the convergence and saves it at 80 and ends the iteration at 81. In another embodiment of this invention, the operations at 83 and 85 are combined.

Returning now to the reflective optical components, for ultraviolet and visible designs, diffraction is not the limiting factor. Imaging aberrations may limit the performance. In still another embodiment for such wavelengths, the large mirror is split into primary and tertiary mirrors that are optimized separately, as shown in a second embodiment of this invention illustrated in FIG. 18. In FIG. 18 the first concave mirror surface 50 of primary mirror 120 is non-abutting with the second concave mirror surface 52 of tertiary mirror 121.

In still other embodiments of this invention it is not necessary to use the Offner form, for example, a traditional three-mirror configuration with a two-dimensional flat reflective diffraction grating 130 can be used for large f-number systems as shown in FIG. 19.

In the following examples, the useful portion of the spectrum may be the ultraviolet (UV), visible, or the infrared (IR), so the reflective CTIS configuration has advantages over a transmissive CTIS.

EXAMPLE I

The reflective CTIS of this invention is used to perform remote sensing of the earth or other planetary bodies in a fast fly-by. Each CTIS frame is tomographically reconstructed to determine spectra from objects on the ground of such bodies to determine their composition.

For transient events occurring on such bodies, such as eruptions, impacts, explosions, etc., the reflective CTIS of this invention determines the spectra of such transient events even though the precise location is not known in advance. Thus, as long as such event occurs within the reflective CTIS field of view, the spectra are determined.

The advantages of the reflective CTIS of this invention over the prior art transmissive CTIS in this example are that much of the useful remote sensing science occurs in the ultraviolet and infrared portions of the spectrum and the transmissive CTIS would be difficult to design for those spectral regions due to a lack of proper materials. Also, the reflective CTIS will be lighter and hence more amenable to carrying aboard a flying platform.

Further advantages of using our undiffracted image constraint process for reconstructing the image scenes are that the spectra reconstructed by the instrument will be more accurate.

EXAMPLE II

The reflective CTIS of this invention is used to perform spectral imaging of rocket plumes. Our reflective CTIS records an entire movie of frames and then tomographically reconstructs the scene using our undiffracted image constraint process with CTIS. The resulting spatial-spectral movie enables comparison of measured spectra to predicted spectra. Such spectra are useful for identifying rockets from a long range for missile defense, and/or for studying burn chemistry.

The advantages of the reflective CTIS of this invention over the prior art transmissive CTIS in this example are that much of the interesting rocket plume science occurs in the ultraviolet and infrared portions of the spectrum and the transmissive CTIS would be difficult to design for those spectral regions due to a lack of proper materials.

The further advantages of using our undiffracted image constraint process for reconstructing the image scenes are that the spectra reconstructed by the instrument will be more accurate.

EXAMPLE III

The reflective CTIS of this invention is used to perform battlefield surveillance by continuously recording images of the battlefield scene. When an event occurs, the frames of interest are tomographically reconstructed using our undiffracted image constraint process with CTIS thereby yielding the spectra of the region of interest. Such spectra help to determine friend or foe, and/or if there is a chemical/biological threat associated with the event.

The advantages of the reflective CTIS of this invention over the prior art transmissive CTIS in this example are that ultraviolet and infrared battlefield spectral signatures are more useful than visible, and the transmissive CTIS is difficult to design for the infrared spectral regions. An infrared transmissive CTIS would be large and heavy.

The further advantages of using our undiffracted image constraint process for reconstructing the image scenes are that the spectra reconstructed by the instrument will be more accurate.

EXAMPLE IV

The reflective CTIS of this invention is used to record movies of biological active samples. Based on the reconstructed spatial-spectral data, metabolic/chemical processes can be identified. Movies of such events are used to increase the understanding of how the reactions initiate and progress. Such understanding enables formulation of improved drug treatments programs.

An advantage of the reflective CTIS of this invention over the prior art transmissive CTIS in this example is that of much the useful biological spectral information occurs in the ultraviolet and infrared. The transmissive CTIS would be difficult to design for those spectral regions due to a lack of proper materials.

The further advantages of using our undiffracted image constraint process for reconstructing the image scenes are that the spectra reconstructed by the instrument will be more accurate.

EXAMPLE V

The reflective CTIS of this invention is used to perform spatial-spectral imaging of human tissue during internal or external diagnostic procedures using our undiffracted image constraint process with CTIS. Spectra from such diagnostic procedures are used to identify spatial regions of abnormal tissue.

Since a live body is moving during such procedures even though the patient is resting, scanning imaging spectrometers produce corrupt data.

An advantage of the reflective CTIS of this invention over the prior art transmissive CTIS in this example is that of much the useful biological spectral information occurs in the ultraviolet and infrared. The transmissive CTIS would be difficult to design for those spectral regions due to a lack of proper materials.

The further advantages of using our undiffracted image constraint process for reconstructing the image scenes are that the spectra reconstructed by the instrument will be more accurate.

While the preferred embodiments of the present invention have been described, various changes and modifications may be made thereto without departing from the spirit of the invention and the scope of the appended claims. The present disclosure and embodiments of this invention described herein are for purposes of illustration and example and modifications and improvements may be made thereto without departing from the spirit of the invention or from the scope of the claims. The claims, therefore, are to be accorded a range of equivalents commensurate in scope with the advances made over the art.

What is claimed is:

1. A two-dimensional reflective diffraction grating effective for spectrally dispersing incident radiation thereon in a two-dimensional array, the grating having a plurality of cells comprising a plurality of pixels having a fixed periodicity, and a reflective surface on each pixel.

2. The grating of claim **1**, wherein the pixels are asymmetric.

3. The grating of claim **1**, wherein the grating is convex.

4. The grating of claim **1**, wherein the grating is flat.

5. The grating of claim **1**, wherein the grating is concave.

6. The grating of claim **1**, wherein the reflective surface is an outer surface of the pixels.

7. The grating of claim **1**, wherein in each of the cells the pixels therein are abutted.

8. The grating of claim **1**, wherein the pixels are square shaped.

9. The grating of claim **1**, wherein the cells of the grating are abutted.

10. The grating of claim **1**, further comprising a substrate having an outer surface for supporting the plurality of pixels.

11. The grating of claim **10**, wherein the reflective surface is between the outer surface of the substrate and the plurality of pixels.

12. The grating of claim **10**, wherein the outer surface of the substrate is convex.

13. The grating of claim **12**, wherein the convex outer surface of the substrate has a fixed curvature.

14. The grating of claim **13**, wherein the fixed curvature is spherical.

15. The grating of claim **1**, wherein the grating is electron-beam fabricated.

16. The grating of claim **1**, wherein the grating is a computer- generated hologram.

17. A reflective imaging spectrometer for detecting ultraviolet, visible and infrared spectra comprising:

a two-dimensional reflective diffraction grating effective for spectrally dispersing incident radiation thereon in a two-dimensional array, the grating having a plurality of cells comprising a plurality of pixels having a fixed periodicity, each pixel having a reflective surface;

a two-dimensional object scene aperture for receiving two-dimensional object scene radiation and for framing a two-dimensional object scene;

a first concave mirror positioned for reflecting the object scene radiation transmitted through the object scene aperture to the grating;

a second concave mirror positioned for reflecting radiation reflected and spectrally dispersed from the grating to an image focal plane; and

detector means positioned at the image focal plane for receiving and recording spectrally dispersed object scene radiation reflected from the second concave mirror in a two dimensional array of spectrally dispersed images.

18. The spectrometer of claim **17**, wherein the detector means has an integrate time effective for freezing action in the two-dimensional object scene thereby enabling the recording of a transient event in the two-dimensional object scene without requiring scanning thereof.

19. The spectrometer of claim **17**, wherein the detector means comprises:

a focal plane array detector positioned at the image focal plane for receiving and recording the spectrally dispersed object scene radiation; and

electronically linked to the detector, first means comprising high-speed computed-tomography reconstruction algorithm operable for reconstructing the spectra of each point in the object scene.

20. The spectrometer of claim **19**, wherein the focal plane array detector and the first means are operable for imaging rapidly evolving transient events in the two-dimensional object scene.

21. The spectrometer of claim **19**, further comprising second means associated with the first means for reconstructing the object scene with undiffracted image constraint comprising:

(a) calculating a predicted undiffracted image based on a current estimate of the object scene; thereafter

(b) calculating a new set of scaling factors for the object scene that force the predicted undiffracted image to equal a measured undiffracted image; and thereafter

(c) uniformly scaling the entire object scene so that a total number of photons in a predicted detector image remains constant from iteration to iteration.

22. The spectrometer of claim **19**, wherein the recording of the spectra occurs in a time span of from about one second to about 20 seconds for each frame of a movie taken of the two- dimensional object scene thereby enabling real time transient event spectral imaging.

23. The spectrometer of claim **17**, wherein the grating, and the first and the second concave mirrors are concentrically oriented.

24. The spectrometer of claim **17**, wherein the first concave mirror has a first curvature and the second concave mirror has a second curvature which is different than the first curvature.

25. The spectrometer of claim **17**, wherein the aperture is approximately rectangular.

26. The spectrometer of claim **17**, wherein the aperture has a geometric shape which in combination with the grating enables the entire two-dimensional object scene to approximately fill a field of view of the detector means.

27. The spectrometer of claim **17**, wherein the two dimensional array of the spectrally dispersed images produced has no chromatic imaging aberration.

28. The spectrometer of claim **17**, wherein a portion of the object scene radiation incident upon the aperture is received by the detector means at all times.

29. The spectrometer of claim **28**, wherein the portion of the object scene radiation is at least about 50% of the radiation incident upon the aperture.

30. The spectrometer of claim **28**, wherein the portion of the object scene radiation is at least about 70% of the radiation incident upon the aperture.

31. The spectrometer of claim **17**, further comprising an unitary primary mirror assembly which spans a grating axis of the grating and comprises the first and the second concave mirrors.

32. The spectrometer of claim **17**, wherein the grating is convex.

33. A process for separating spectrally and spatially ultraviolet, visible and infrared spectra from an object scene comprising:

(a) spectrally dispersing object scene spectra in a two-dimensional array with a two-dimensional diffraction grating effective for spectrally dispersing incident radiation thereon in a two-dimensional array, the grating having a plurality of cells comprising a plurality of pixels having a fixed periodicity;

(b) receiving and recording the spectrally dispersed object scene spectra from the grating with an effective focal plane array detector positioned at an image focal plane;

(c) electronically linking to the detector, first means comprising high-speed computed-tomography reconstruction algorithm;

(d) associating with the first means, second means for reconstructing the object scene with undiffracted image constraint comprising:

(i) calculating a predicted undiffracted image based on a current estimate of the object scene, thereafter

(ii) calculating a new set of scaling factors for the object scene that force the predicted undiffracted image to equal a measured undiffracted image, and thereafter

(iii) uniformly scaling the entire object scene so that a total number of photons in a predicted detector image remains constant from iteration to iteration; and

thereafter

(e) producing a reconstructed spectral and spatial object scene.

34. The process of claim **33**, wherein the grating is transmissive.

35. The process of claim **33**, wherein the grating is reflective.

36. The process of claim **35**, wherein the grating is flat.

37. The process of claim **35**, wherein the grating is convex.

38. The process of claim **35**, wherein the grating is concave.

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