A long-wave infrared hyperspectral sensor device employs a combination of an interferometer with an uncooled microbolometer array camera to produce hyperspectral images without the use of bulky, power-hungry motorized components, making it suitable for UAV vehicles, small mobile platforms, or in extraterrestrial environments. The sensor device can provide signal-to-noise ratios near 200 for ambient temperature scenes with 33 wavenumber resolution at a frame rate of 50 Hz, with higher results indicated by ongoing component improvements.
UNCOOLED LONG-WAVE INFRARED HYPERSONAL IMAGING

The subject matter herein was developed in part under research contracts provided by the U.S. Government, National Aeronautics and Space Administration (NASA), Planetary Instrument Definition and Development Program, Contract Nos. NAGS-10794 and NAGS-12970. The U.S. Government retains certain rights in the invention.

TECHNICAL FIELD

This invention generally relates to long-wave infrared (LWIR) hyperspectral imaging at moderate spectral resolution (~10 cm⁻¹).
light is incident on a beamsplitter 11 that splits the beam into a wavelength component that is reflected (RC) by the beamsplitter surface and directed by side mirrors 12 toward the camera lens, and another wavelength component that is transmitted (TC) through the beamsplitter surface and directed by side mirrors 12 toward the camera lens. As a result, the reflected and transmitted components are of different spectral wavelengths and separated spatially where they impact the microbolometer detector array. This produces an image with hyperspectral separation that can differentiate between spectral components of light received from the source subject.

In a test embodiment, the instrument employs a Sagnac interferometer that provides the wavefront division required for interferometry. Like a version of an imaging Michelson, the scene is imaged through the interferometer producing a two dimensional image upon which the interference pattern is superimposed. The interference pattern is spatially imposed on the scene rather than temporally. In order to build up a true three dimensional spectral data set, the scene is then scanned by the microbolometer across the interferometer pattern, in the same sense as a pushbroom imaging spectrometer. The microbolometer obtains this effect by exposure across the elements of its IR detector array. This allows the microbolometer to be used as an uncooled camera component avoiding excess volume, weight, heat, and power demand that would be unacceptable in the intended environments of use, such as military UAV surveillance vehicles, small mobile platforms, and extraterrestrial environments.

The Sagnac box configuration has the benefit of a slightly larger available field of view (10 degrees) versus other configurations. The scene is viewed through the interferometer by the camera, thus the interferometer must be large enough to accept both the clear aperture and field of view of the camera to optimize performance.

In FIG. 2, the assembled instrument consisted of the microbolometer camera (top of photograph), interferometer (middle), and a scan mechanism (lower unit). An Indigo Merlin microbolometer camera was used. Two versions of the instrument were implemented, one with a 25 mm lens that has a field of view much larger than the interferometer can accept, but has an unobstructed clear aperture, and the second with a 100 mm focal length lens that has a field of view smaller than the interferometer limit, but a much larger clear aperture. The former case limits the spectral resolution and the latter case limits the sensitivity.

FIG. 3 illustrates a first imaging demonstration in which a line of stone tiles was set up to provide an input light signal to the instrument. The stone tiles included tiles of carbonates, granites and one painted panel. Interferograms were collected, assembled into an image and transformed into spectra forming an image cube. FIG. 4A shows a single band of the test image at 11 microns (with 2 mrad resolution from image plane interferometer, and an Indigo Merlin microbolometer array camera with a 320x244 element array was used as the detector. The camera was equipped with a 50 mm f/1.4 IR lens and viewed the scene through the interferometer with field of view of 18x14 degrees. The measured sensitivity of the camera used in this experiment was 95 mK with the lens described. The geometry of Sagnac interferometers limits the field of view of the system to about 7 degrees so the image is substantially vignette. The vignette portion of the array was excluded from analysis leaving 120x177 pixels active. The optics of the Sagnac are 50 mm gold mirrors and a 50 mm zinc selenide beamsplitter so the central portion of the image is not vignette and uses the full f-number of the lens. The system viewed a motorized
mirror to provide the necessary scanning from a stationary position. A flat plate blackbody calibrator with adjustable temperature was used for calibration.

Using this instrument, data was collected both of an urban scene, and blackbody calibration sources. FIG. 7 shows a photograph of the scene to be imaged, which includes the Hawaii landmark Diamond Head and portions of urban and suburban Honolulu near the University of Hawaii Campus. A typical frame from the data collected is shown in FIG. 8, where the interference fringes superimposed by the Sagnac interferometer on the scene are evident. The data cube was constructed via the method published by Horton et al., by scanning the image across the scene slowly enough that the scan has advanced one pixel or less between each frame acquired at 50 Hz. See, Horton, Richard F., Conger, C. A., Pellegrino, L. S., “High endetude Imaging Fourier Transform Spectrometer: initial results”, Proc. SPIE Vol. 3118, p. 380–390, Imaging Spectrometry III, Michael R. Descour, Sylvia S. Shen, editors, 1997.

In this case, the scan rate advanced the image 1/4 pixel during a frame time of 20 ms. Each column of the array corresponds to a different optical path difference. As the scene is scanned, the images are obtained by each column in the fashion of a line scanner, as shown in FIG. 9. The images obtained by each column are registered to produce an image cube consisting of interferograms. A typical interferogram extracted from the data cube is shown in FIG. 10. Prior to registration, each image was corrected for gain and offset using images of the blackbody at two temperatures observed with the path difference adjusted to zero to provide a uniform unmodulated field.

To produce calibrated spectra, each interferogram was fit with a parabola and the fit subtracted to zero-mean the data. Then the interferograms were phase corrected using the method published by Mertz. See, Mertz, L., “Transformations in Optics”, Wiley, N.Y., 1965. The interferograms were then transformed to the spectral domain, as shown in FIG. 11. This process was also applied to interference images of the blackbody source at two temperatures to construct gain and offset calibration spectra. These data were used to calibrate the spectral images to radiance, and to correct spatially varying modulation of the interferometer. FIG. 12 shows a single band extracted from the data. The occasional horizontal lines running through the image are due to defective pixels that corrupted individual interferograms.

The wavelengths were calibrated only approximately. The peak response of the system was assumed to be 10 microns. This spectral channel was set to 1000 wavenumbers and the wavelength derived from this and the zero frequency. The spectral resolution determined by the cutoff frequency divided by half the interferometer samples was 33 wavenumbers, or about 300 nm.

The signal noise ratio achieved in this test was obtained at sufficient spectral resolution and rate (50 Hz frame rate) to be useful for some applications such as mine detection. However, significant improvements over this performance almost certainly can be demonstrated. First, literature reports of sensitivities for microbolometer arrays almost 10 times that of the camera used here would dramatically improve the values obtained in these tests. See, Murphy, Daniel F., Ray, Michael, Wyles, Richard, Ashbrook, James F., Lum, Nancy A., Wyles, Jessica, Hewitt, C., Kennedy, Adam, Van Lue, David, Anderson, John S., Bradley, Daryl, Chin, Richard, Kostrzewa, Thomas, “High-sensitivity 25-micron microbolometer FPAs”, Proc. SPIE Vol. 4721, p. 99–110. Infrared Detectors and Focal Plane Arrays VII, Eustace L. Dermenjak, Robert E. Sampson, editors, 2002; and Howard, Philip E., Clarke, John E., Parrish, William J., Woolaway, James T., “Advanced high performance 320x240 VOx microbolometer uncooled IR focal plane”, Proc. SPIE Vol. 3698, p. 131–136. Infrared Technology and Applications XXV, Bjorn F. Andresen, Marija Strojnik Scholl, editors, 1999. The optics used in the tests was f/1.4, but somewhat faster optics are available and would also provide some gains.

A larger interferometer would allow the entire array to be used, more than doubling the spectral resolution with no penalty in SNR. A Mach-Zender interferometer has a shorter path and would allow a more compact design while preserving field of view and f-number. Further, the Mach-Zender does not discard half the light, so a root 2 gain results from the use of that interferometer. The combination of a higher sensitivity (but existing) array and perhaps faster optics (f/1) and a Mach-Zender dual focal plane design should bring performance in the range of SNR=1000, with spectral resolutions near 10 wavenumbers, while still obtaining data at 50 Hz, acceptable for airborne hyperspectral imaging. See, Horton, Richard F., “Optical design for a high-endetude imaging Fourier-transform spectrometer,” Proc. SPIE Vol. 2819, p. 300–315, Imaging Spectrometry II, Michael R. Descour, Jonathan M. Mooney, editors, 1996. This performance would be achieved without the need for cryogenic cooling. However, the Sagnac interferometer is simpler to align and to maintain alignment.

In summary, a microbolometer imaging camera using an uncooled infrared detector array can be effectively used with an “image plane” interferometer to produce usable spectral imaging. The results can be applied to imaging Michelson interferometers as well, as the signal and noise advantages of imaging Michelson interferometers are equivalent to the “image plane” interferometer. The results indicated that the signal to noise ratios obtained are high and consistent with prediction. System design issues need to be optimized for an operational system, including matching the field of view and clear aperture to the fast optics desired, correcting for optical distortions that give rise to spectral artifacts, and compensating for motion of objects in the scene during data collection. These systems issues can be resolved by employing other known techniques such as wedge or step filter spectrometers, AOTF spectrometers, and imaging Michelson interferometers. Commercial microbolometer cameras have sufficient sensitivity so that the type of interferometric hyperspectral imaging obtained herein can be an appropriate application. Improved sensitivity as indicated in ongoing research could result in uncooled hyperspectral imagers competitive with some cooled systems.

It is understood that many modifications and variations may be devised given the above description of the principles of the invention. It is intended that all such modifications
5. A method according to claim 1, wherein the interferometer is a box type interferometer with no moving parts and having an aperture facing toward an input light source which receives input light incident on a beamsplitter and reflected and transmitted components from the beamsplitter are combined on a two-dimensional image plane, and the camera is an uncooled microbolometer camera with thermal IR detector array used with the interferometer to obtain usable hyperspectral IR imaging with acceptable to high signal-to-noise ratio (SNR).

6. A method according to claim 5, wherein said interferometer and microbolometer camera are configured for hyperspectral imaging in the 8–14 micron region of thermal infrared or long-wave infrared (LWIR).

7. A method according to claim 5, wherein said interferometer and microbolometer camera are configured for use on UAV vehicles, small mobile platforms, or in extraterrestrial environments.

8. A method according to claim 5, wherein said interferometer and microbolometer camera are configured to provide signal-to-noise ratios near 200 for ambient temperature scenes with 33 wavenumber resolution at a frame rate of 50 Hz.

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