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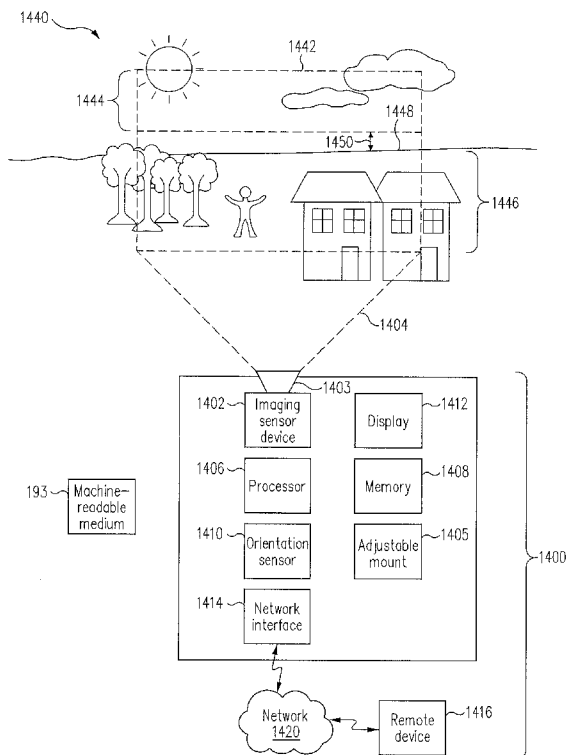


FIG. 14

(57) Abstract: Various techniques are provided for systems and methods to process images to reduce consumption of an available output dynamic range by the sky in images. For example, according to one or more embodiments of the disclosure, a region or area in images that may correspond to the sky may be identified based on the location of the horizon in the images. A distribution of irradiance levels in the identified sky region may be analyzed to determine a dynamic range attributable to the sky region. A transfer function that compresses the dynamic range attributable to the sky region may be generated and applied so that the sky in the images may be suppressed, thereby advantageously preserving more dynamic range for terrestrial objects and other objects of interest in the images.



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SYSTEMS AND METHODS OF SUPPRESSING SKY REGIONS IN IMAGES

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CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Patent Application No.
10 61/745,440 filed December 21, 2012 and entitled "SYSTEMS AND METHODS OF
SUPPRESSING SKY REGIONS IN IMAGES" which is hereby incorporated by reference in
its entirety.

This application is a continuation-in-part of U.S. Patent Application No. 14/101,245
filed December 9, 2013 and entitled "LOW POWER AND SMALL FORM FACTOR
15 INFRARED IMAGING" which is hereby incorporated by reference in its entirety.

This application is a continuation-in-part of U.S. Patent Application No. 14/099,818
filed December 6, 2013 and entitled "NON-UNIFORMITY CORRECTION TECHNIQUES
FOR INFRARED IMAGING DEVICES" which is hereby incorporated by reference in its
entirety.

20 This application is a continuation-in-part of U.S. Patent Application No. 14/101,258
filed December 9, 2013 and entitled "INFRARED CAMERA SYSTEM ARCHITECTURES"
which is hereby incorporated by reference in its entirety.

This application claims the benefit of U.S. Provisional Patent Application No.
61/748,018 filed December 31, 2012 and entitled "COMPACT MULTI-SPECTRUM
25 IMAGING WITH FUSION" which is hereby incorporated by reference in its entirety.

This application claims the benefit of U.S. Provisional Patent Application No.
61/792,582 filed March 15, 2013 and entitled "TIME SPACED INFRARED IMAGE
ENHANCEMENT" which is hereby incorporated by reference in its entirety.

This application claims the benefit of U.S. Provisional Patent Application No. 61/793,952 filed March 15, 2013 and entitled "INFRARED IMAGING ENHANCEMENT WITH FUSION" which is hereby incorporated by reference in its entirety.

5 This application claims the benefit of U.S. Provisional Patent Application No. 61/746,069 filed December 26, 2012 and entitled "TIME SPACED INFRARED IMAGE ENHANCEMENT" which is hereby incorporated by reference in its entirety.

This application claims the benefit of U.S. Provisional Patent Application No. 61/746,074 filed December 26, 2012 and entitled "INFRARED IMAGING ENHANCEMENT WITH FUSION" which is hereby incorporated by reference in its
10 entirety.

TECHNICAL FIELD

One or more embodiments of the invention relate generally to imaging systems and methods, and more particularly, for example, to systems and methods for processing images to optimize dynamic ranges in images.

15 BACKGROUND

In many imaging applications (e.g., surveillance camera applications, thermal imaging applications, and/or other applications of cameras and imaging systems), a user may be more interested in observing terrestrial phenomenon and/or objects such as roads, people, cars, buildings, while less interested in the atmosphere or objects above ground (e.g., birds, planes,
20 clouds, treetops, and/or other objects). However, for images (e.g., still images and/or video frames) captured by conventional imaging systems, the sky, if present, often consumes a large portion of the available dynamic range. This may make it harder for a user to discern or identify objects of interest in the captured images.

While there are conventional dynamic range compression algorithms or automatic
25 gain control (AGC) methods that adjust image dynamic ranges, such conventional methods cannot reliably suppress the sky (e.g., reduce the consumption of the available dynamic range by the sky) in images. Those conventional methods fail, for example, because the sky captured in images is often non-uniform (e.g., may contain a large amount of scene

information) and/or often exhibits different properties depending on atmospheric conditions, the climate, the sun angle, and/or other conditions.

SUMMARY

Various techniques are provided for systems and methods to process images to reduce consumption of an available output dynamic range by the sky in images. For example, according to one or more embodiments of the disclosure, a region or area in images that may correspond to the sky may be identified based on the location of the horizon in the images. A distribution of irradiance levels in the identified sky region may be analyzed to determine a dynamic range attributable to the sky region. A transfer function that compresses the dynamic range attributable to the sky region may be generated and applied so that the sky in the images may be suppressed, thereby advantageously preserving more dynamic range for terrestrial objects and other objects of interest in the images.

In one embodiment, a system includes a memory adapted to store an image of a scene including a sky region and a ground region; and a processor adapted to communicate with the memory, the processor adapted to identify the sky region in the image, analyze a distribution of pixel levels associated with the sky region in the image, determine a dynamic range attributable to the sky region based on the distribution of the pixel levels, generate a transfer function that compresses the dynamic range attributable to the sky region, and apply the transfer function to at least a portion of the image.

In another embodiment, a method includes receiving an image of a scene including a sky region and a ground region; identifying the sky region in the image; analyzing a distribution of pixel levels associated with the sky region in the image; determining a dynamic range attributable to the sky region based on the distribution of the pixel levels; generating a transfer function that compresses the dynamic range attributable to the sky region; and applying the transfer function to at least a portion of the image.

The scope of the invention is defined by the claims, which are incorporated into this section by reference. A more complete understanding of embodiments of the invention will be afforded to those skilled in the art, as well as a realization of additional advantages thereof, by a consideration of the following detailed description of one or more embodiments. Reference will be made to the appended sheets of drawings that will first be described briefly.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 illustrates an infrared imaging module configured to be implemented in a host device in accordance with an embodiment of the disclosure.

5 Fig. 2 illustrates an assembled infrared imaging module in accordance with an embodiment of the disclosure.

Fig. 3 illustrates an exploded view of an infrared imaging module juxtaposed over a socket in accordance with an embodiment of the disclosure.

Fig. 4 illustrates a block diagram of an infrared sensor assembly including an array of infrared sensors in accordance with an embodiment of the disclosure.

10 Fig. 5 illustrates a flow diagram of various operations to determine non-uniformity correction (NUC) terms in accordance with an embodiment of the disclosure.

Fig. 6 illustrates differences between neighboring pixels in accordance with an embodiment of the disclosure.

15 Fig. 7 illustrates a flat field correction technique in accordance with an embodiment of the disclosure.

Fig. 8 illustrates various image processing techniques of Fig. 5 and other operations applied in an image processing pipeline in accordance with an embodiment of the disclosure.

Fig. 9 illustrates a temporal noise reduction process in accordance with an embodiment of the disclosure.

20 Fig. 10 illustrates particular implementation details of several processes of the image processing pipeline of Fig. 8 in accordance with an embodiment of the disclosure.

Fig. 11 illustrates spatially correlated fixed pattern noise (FPN) in a neighborhood of pixels in accordance with an embodiment of the disclosure.

25 Fig. 12 illustrates a block diagram of another implementation of an infrared sensor assembly including an array of infrared sensors and a low-dropout regulator in accordance with an embodiment of the disclosure.

Fig. 13 illustrates a circuit diagram of a portion of the infrared sensor assembly of Fig. 12 in accordance with an embodiment of the disclosure.

Fig. 14 illustrates a block diagram of an imaging system, such as an infrared camera, to capture and/or process images in accordance with an embodiment of the disclosure.

5 Fig. 15 illustrates a flowchart of a process to suppress the sky in images in accordance with an embodiment of the disclosure.

Figs. 16A–16C illustrate various example histograms of infrared irradiance levels in sky regions of images in accordance with various embodiment of the disclosure.

10 Fig. 17A illustrates an example gamma curve implementing a transfer function to compress a dynamic range attributable to a sky region in images, in accordance with an embodiment of the disclosure.

Fig. 17B illustrates an example piece-wise linear function implementing a transfer function to compress a dynamic range attributable to a sky region in images, in accordance with another embodiment of the disclosure.

15 Fig. 18A illustrates another example of a gamma curve implementing a transfer function to compress a dynamic range attributable to a sky region in images, in accordance with another embodiment of the disclosure.

20 Fig. 18B illustrates another example of a piece-wise linear function implementing a transfer function to compress a dynamic range attributable to a sky region in images, in accordance with another embodiment of the disclosure.

Fig. 19 illustrates another example of a piece-wise linear function implementing a transfer function to compress a dynamic range attributable to a sky region in images, in accordance with another embodiment of the disclosure.

25 Fig. 20A illustrates an example screenshot of a thermal image prior to applying a transfer function to compress a dynamic range attributable to a sky region, in accordance with an embodiment of the disclosure.

Fig. 20B illustrates an example screenshot of a processed thermal image obtained by applying, to the thermal image of Fig. 20A, a transfer function to compress a dynamic range attributable to a sky region, in accordance with an embodiment of the disclosure.

Embodiments of the invention and their advantages are best understood by referring
5 to the detailed description that follows. It should be appreciated that like reference numerals are used to identify like elements illustrated in one or more of the figures.

DETAILED DESCRIPTION

Fig. 1 illustrates an infrared imaging module 100 (e.g., an infrared camera or an infrared imaging device) configured to be implemented in a host device 102 in accordance
10 with an embodiment of the disclosure. Infrared imaging module 100 may be implemented, for one or more embodiments, with a small form factor and in accordance with wafer level packaging techniques or other packaging techniques.

In one embodiment, infrared imaging module 100 may be configured to be implemented in a small portable host device 102, such as a mobile telephone, a tablet
15 computing device, a laptop computing device, a personal digital assistant, a visible light camera, a music player, or any other appropriate mobile device. In this regard, infrared imaging module 100 may be used to provide infrared imaging features to host device 102. For example, infrared imaging module 100 may be configured to capture, process, and/or otherwise manage infrared images and provide such infrared images to host device 102 for
20 use in any desired fashion (e.g., for further processing, to store in memory, to display, to use by various applications running on host device 102, to export to other devices, or other uses).

In various embodiments, infrared imaging module 100 may be configured to operate at low voltage levels and over a wide temperature range. For example, in one embodiment, infrared imaging module 100 may operate using a power supply of approximately 2.4 volts,
25 2.5 volts, 2.8 volts, or lower voltages, and operate over a temperature range of approximately -20 degrees C to approximately +60 degrees C (e.g., providing a suitable dynamic range and performance over an environmental temperature range of approximately 80 degrees C). In one embodiment, by operating infrared imaging module 100 at low voltage levels, infrared imaging module 100 may experience reduced amounts of self heating in comparison with

other types of infrared imaging devices. As a result, infrared imaging module 100 may be operated with reduced measures to compensate for such self heating.

As shown in Fig. 1, host device 102 may include a socket 104, a shutter 105, motion sensors 194, a processor 195, a memory 196, a display 197, and/or other components 198.

5 Socket 104 may be configured to receive infrared imaging module 100 as identified by arrow 101. In this regard, Fig. 2 illustrates infrared imaging module 100 assembled in socket 104 in accordance with an embodiment of the disclosure.

Motion sensors 194 may be implemented by one or more accelerometers, gyroscopes, or other appropriate devices that may be used to detect movement of host device 102.

10 Motion sensors 194 may be monitored by and provide information to processing module 160 or processor 195 to detect motion. In various embodiments, motion sensors 194 may be implemented as part of host device 102 (as shown in Fig. 1), infrared imaging module 100, or other devices attached to or otherwise interfaced with host device 102.

Processor 195 may be implemented as any appropriate processing device (e.g., logic
15 device, microcontroller, processor, application specific integrated circuit (ASIC), or other device) that may be used by host device 102 to execute appropriate instructions, such as software instructions provided in memory 196. Display 197 may be used to display captured and/or processed infrared images and/or other images, data, and information. Other components 198 may be used to implement any features of host device 102 as may be desired
20 for various applications (e.g., clocks, temperature sensors, a visible light camera, or other components). In addition, a machine readable medium 193 may be provided for storing non-transitory instructions for loading into memory 196 and execution by processor 195.

In various embodiments, infrared imaging module 100 and socket 104 may be implemented for mass production to facilitate high volume applications, such as for
25 implementation in mobile telephones or other devices (e.g., requiring small form factors). In one embodiment, the combination of infrared imaging module 100 and socket 104 may exhibit overall dimensions of approximately 8.5 mm by 8.5 mm by 5.9 mm while infrared imaging module 100 is installed in socket 104.

Fig. 3 illustrates an exploded view of infrared imaging module 100 juxtaposed over
30 socket 104 in accordance with an embodiment of the disclosure. Infrared imaging module

100 may include a lens barrel 110, a housing 120, an infrared sensor assembly 128, a circuit board 170, a base 150, and a processing module 160.

Lens barrel 110 may at least partially enclose an optical element 180 (e.g., a lens) which is partially visible in Fig. 3 through an aperture 112 in lens barrel 110. Lens barrel 110
5 may include a substantially cylindrical extension 114 which may be used to interface lens barrel 110 with an aperture 122 in housing 120.

Infrared sensor assembly 128 may be implemented, for example, with a cap 130 (e.g., a lid) mounted on a substrate 140. Infrared sensor assembly 128 may include a plurality of infrared sensors 132 (e.g., infrared detectors) implemented in an array or other fashion on
10 substrate 140 and covered by cap 130. For example, in one embodiment, infrared sensor assembly 128 may be implemented as a focal plane array (FPA). Such a focal plane array may be implemented, for example, as a vacuum package assembly (e.g., sealed by cap 130 and substrate 140). In one embodiment, infrared sensor assembly 128 may be implemented as a wafer level package (e.g., infrared sensor assembly 128 may be singulated from a set of
15 vacuum package assemblies provided on a wafer). In one embodiment, infrared sensor assembly 128 may be implemented to operate using a power supply of approximately 2.4 volts, 2.5 volts, 2.8 volts, or similar voltages.

Infrared sensors 132 may be configured to detect infrared radiation (e.g., infrared energy) from a target scene including, for example, mid wave infrared wave bands (MWIR),
20 long wave infrared wave bands (LWIR), and/or other thermal imaging bands as may be desired in particular implementations. In one embodiment, infrared sensor assembly 128 may be provided in accordance with wafer level packaging techniques.

Infrared sensors 132 may be implemented, for example, as microbolometers or other types of thermal imaging infrared sensors arranged in any desired array pattern to provide a
25 plurality of pixels. In one embodiment, infrared sensors 132 may be implemented as vanadium oxide (VOx) detectors with a 17 μm pixel pitch. In various embodiments, arrays of approximately 32 by 32 infrared sensors 132, approximately 64 by 64 infrared sensors 132, approximately 80 by 64 infrared sensors 132, or other array sizes may be used.

Substrate 140 may include various circuitry including, for example, a read out
30 integrated circuit (ROIC) with dimensions less than approximately 5.5 mm by 5.5 mm in one

embodiment. Substrate 140 may also include bond pads 142 that may be used to contact complementary connections positioned on inside surfaces of housing 120 when infrared imaging module 100 is assembled as shown in Fig. 3. In one embodiment, the ROIC may be implemented with low-dropout regulators (LDO) to perform voltage regulation to reduce power supply noise introduced to infrared sensor assembly 128 and thus provide an improved power supply rejection ratio (PSRR). Moreover, by implementing the LDO with the ROIC (e.g., within a wafer level package), less die area may be consumed and fewer discrete die (or chips) are needed.

Fig. 4 illustrates a block diagram of infrared sensor assembly 128 including an array of infrared sensors 132 in accordance with an embodiment of the disclosure. In the illustrated embodiment, infrared sensors 132 are provided as part of a unit cell array of a ROIC 402. ROIC 402 includes bias generation and timing control circuitry 404, column amplifiers 405, a column multiplexer 406, a row multiplexer 408, and an output amplifier 410. Image frames (e.g., thermal images) captured by infrared sensors 132 may be provided by output amplifier 410 to processing module 160, processor 195, and/or any other appropriate components to perform various processing techniques described herein. Although an 8 by 8 array is shown in Fig. 4, any desired array configuration may be used in other embodiments. Further descriptions of ROICs and infrared sensors (e.g., microbolometer circuits) may be found in U.S. Patent No. 6,028,309 issued February 22, 2000, which is incorporated herein by reference in its entirety.

Infrared sensor assembly 128 may capture images (e.g., image frames) and provide such images from its ROIC at various rates. Processing module 160 may be used to perform appropriate processing of captured infrared images and may be implemented in accordance with any appropriate architecture. In one embodiment, processing module 160 may be implemented as an ASIC. In this regard, such an ASIC may be configured to perform image processing with high performance and/or high efficiency. In another embodiment, processing module 160 may be implemented with a general purpose central processing unit (CPU) which may be configured to execute appropriate software instructions to perform image processing, coordinate and perform image processing with various image processing blocks, coordinate interfacing between processing module 160 and host device 102, and/or other operations. In yet another embodiment, processing module 160 may be implemented with a field programmable gate array (FPGA). Processing module 160 may be implemented with other

types of processing and/or logic circuits in other embodiments as would be understood by one skilled in the art.

In these and other embodiments, processing module 160 may also be implemented with other components where appropriate, such as, volatile memory, non-volatile memory, and/or one or more interfaces (e.g., infrared detector interfaces, inter-integrated circuit (I2C) interfaces, mobile industry processor interfaces (MIPI), joint test action group (JTAG) interfaces (e.g., IEEE 1149.1 standard test access port and boundary-scan architecture), and/or other interfaces).

In some embodiments, infrared imaging module 100 may further include one or more actuators 199 which may be used to adjust the focus of infrared image frames captured by infrared sensor assembly 128. For example, actuators 199 may be used to move optical element 180, infrared sensors 132, and/or other components relative to each other to selectively focus and defocus infrared image frames in accordance with techniques described herein. Actuators 199 may be implemented in accordance with any type of motion-inducing apparatus or mechanism, and may be positioned at any location within or external to infrared imaging module 100 as appropriate for different applications.

When infrared imaging module 100 is assembled, housing 120 may substantially enclose infrared sensor assembly 128, base 150, and processing module 160. Housing 120 may facilitate connection of various components of infrared imaging module 100. For example, in one embodiment, housing 120 may provide electrical connections 126 to connect various components as further described.

Electrical connections 126 (e.g., conductive electrical paths, traces, or other types of connections) may be electrically connected with bond pads 142 when infrared imaging module 100 is assembled. In various embodiments, electrical connections 126 may be embedded in housing 120, provided on inside surfaces of housing 120, and/or otherwise provided by housing 120. Electrical connections 126 may terminate in connections 124 protruding from the bottom surface of housing 120 as shown in Fig. 3. Connections 124 may connect with circuit board 170 when infrared imaging module 100 is assembled (e.g., housing 120 may rest atop circuit board 170 in various embodiments). Processing module 160 may be electrically connected with circuit board 170 through appropriate electrical connections. As a result, infrared sensor assembly 128 may be electrically connected with processing

module 160 through, for example, conductive electrical paths provided by: bond pads 142, complementary connections on inside surfaces of housing 120, electrical connections 126 of housing 120, connections 124, and circuit board 170. Advantageously, such an arrangement may be implemented without requiring wire bonds to be provided between infrared sensor
5 assembly 128 and processing module 160.

In various embodiments, electrical connections 126 in housing 120 may be made from any desired material (e.g., copper or any other appropriate conductive material). In one embodiment, electrical connections 126 may aid in dissipating heat from infrared imaging module 100.

10 Other connections may be used in other embodiments. For example, in one embodiment, sensor assembly 128 may be attached to processing module 160 through a ceramic board that connects to sensor assembly 128 by wire bonds and to processing module 160 by a ball grid array (BGA). In another embodiment, sensor assembly 128 may be mounted directly on a rigid flexible board and electrically connected with wire bonds, and
15 processing module 160 may be mounted and connected to the rigid flexible board with wire bonds or a BGA.

The various implementations of infrared imaging module 100 and host device 102 set forth herein are provided for purposes of example, rather than limitation. In this regard, any of the various techniques described herein may be applied to any infrared camera system,
20 infrared imager, or other device for performing infrared/thermal imaging.

Substrate 140 of infrared sensor assembly 128 may be mounted on base 150. In various embodiments, base 150 (e.g., a pedestal) may be made, for example, of copper formed by metal injection molding (MIM) and provided with a black oxide or nickel-coated finish. In various embodiments, base 150 may be made of any desired material, such as for
25 example zinc, aluminum, or magnesium, as desired for a given application and may be formed by any desired applicable process, such as for example aluminum casting, MIM, or zinc rapid casting, as may be desired for particular applications. In various embodiments, base 150 may be implemented to provide structural support, various circuit paths, thermal heat sink properties, and other features where appropriate. In one embodiment, base 150 may
30 be a multi-layer structure implemented at least in part using ceramic material.

In various embodiments, circuit board 170 may receive housing 120 and thus may physically support the various components of infrared imaging module 100. In various embodiments, circuit board 170 may be implemented as a printed circuit board (e.g., an FR4 circuit board or other types of circuit boards), a rigid or flexible interconnect (e.g., tape or other type of interconnects), a flexible circuit substrate, a flexible plastic substrate, or other appropriate structures. In various embodiments, base 150 may be implemented with the various features and attributes described for circuit board 170, and vice versa.

Socket 104 may include a cavity 106 configured to receive infrared imaging module 100 (e.g., as shown in the assembled view of Fig. 2). Infrared imaging module 100 and/or socket 104 may include appropriate tabs, arms, pins, fasteners, or any other appropriate engagement members which may be used to secure infrared imaging module 100 to or within socket 104 using friction, tension, adhesion, and/or any other appropriate manner. Socket 104 may include engagement members 107 that may engage surfaces 109 of housing 120 when infrared imaging module 100 is inserted into a cavity 106 of socket 104. Other types of engagement members may be used in other embodiments.

Infrared imaging module 100 may be electrically connected with socket 104 through appropriate electrical connections (e.g., contacts, pins, wires, or any other appropriate connections). For example, socket 104 may include electrical connections 108 which may contact corresponding electrical connections of infrared imaging module 100 (e.g., interconnect pads, contacts, or other electrical connections on side or bottom surfaces of circuit board 170, bond pads 142 or other electrical connections on base 150, or other connections). Electrical connections 108 may be made from any desired material (e.g., copper or any other appropriate conductive material). In one embodiment, electrical connections 108 may be mechanically biased to press against electrical connections of infrared imaging module 100 when infrared imaging module 100 is inserted into cavity 106 of socket 104. In one embodiment, electrical connections 108 may at least partially secure infrared imaging module 100 in socket 104. Other types of electrical connections may be used in other embodiments.

Socket 104 may be electrically connected with host device 102 through similar types of electrical connections. For example, in one embodiment, host device 102 may include electrical connections (e.g., soldered connections, snap-in connections, or other connections)

that connect with electrical connections 108 passing through apertures 190. In various embodiments, such electrical connections may be made to the sides and/or bottom of socket 104.

Various components of infrared imaging module 100 may be implemented with flip
5 chip technology which may be used to mount components directly to circuit boards without the additional clearances typically needed for wire bond connections. Flip chip connections may be used, as an example, to reduce the overall size of infrared imaging module 100 for use in compact small form factor applications. For example, in one embodiment, processing module 160 may be mounted to circuit board 170 using flip chip connections. For example,
10 infrared imaging module 100 may be implemented with such flip chip configurations.

In various embodiments, infrared imaging module 100 and/or associated components may be implemented in accordance with various techniques (e.g., wafer level packaging techniques) as set forth in U.S. Patent Application No. 12/844,124 filed July 27, 2010, and U.S. Provisional Patent Application No. 61/469,651 filed March 30, 2011, which are
15 incorporated herein by reference in their entirety. Furthermore, in accordance with one or more embodiments, infrared imaging module 100 and/or associated components may be implemented, calibrated, tested, and/or used in accordance with various techniques, such as for example as set forth in U.S. Patent No. 7,470,902 issued December 30, 2008, U.S. Patent No. 6,028,309 issued February 22, 2000, U.S. Patent No. 6,812,465 issued November 2,
20 2004, U.S. Patent No. 7,034,301 issued April 25, 2006, U.S. Patent No. 7,679,048 issued March 16, 2010, U.S. Patent No. 7,470,904 issued December 30, 2008, U.S. Patent Application No. 12/202,880 filed September 2, 2008, and U.S. Patent Application No. 12/202,896 filed September 2, 2008, which are incorporated herein by reference in their entirety.

25 In some embodiments, host device 102 may include other components 198 such as a non-thermal camera (e.g., a visible light camera or other type of non-thermal imager). The non-thermal camera may be a small form factor imaging module or imaging device; and may, in some embodiments, be implemented in a manner similar to the various embodiments of infrared imaging module 100 disclosed herein, with one or more sensors and/or sensor arrays
30 responsive to radiation in non-thermal spectrums (e.g., radiation in visible light wavelengths, ultraviolet wavelengths, and/or other non-thermal wavelengths). For example, in some

embodiments, the non-thermal camera may be implemented with a charge-coupled device (CCD) sensor, an electron multiplying CCD (EMCCD) sensor, a complementary metal-oxide-semiconductor (CMOS) sensor, a scientific CMOS (sCMOS) sensor, or other filters and/or sensors.

5 In some embodiments, the non-thermal camera may be co-located with infrared imaging module 100 and oriented such that a field-of-view (FOV) of the non-thermal camera at least partially overlaps a FOV of infrared imaging module 100. In one example, infrared imaging module 100 and a non-thermal camera may be implemented as a dual sensor module sharing a common substrate according to various techniques described in U.S. Provisional
10 Patent Application No. 61/748,018 filed December 31, 2012, which is incorporated herein by reference.

For embodiments having such a non-thermal light camera, various components (e.g., processor 195, processing module 160, and/or other processing component) may be configured to superimpose, fuse, blend, or otherwise combine infrared images (e.g., including
15 thermal images) captured by infrared imaging module 100 and non-thermal images (e.g., including visible light images) captured by a non-thermal camera, whether captured at substantially the same time or different times (e.g., time-spaced over hours, days, daytime versus nighttime, and/or otherwise).

In some embodiments, thermal and non-thermal images may be processed to generate
20 combined images (e.g., one or more processes performed on such images in some embodiments). For example, scene-based NUC processing may be performed (as further described herein), true color processing may be performed, and/or high contrast processing may be performed.

Regarding true color processing, thermal images may be blended with non-thermal
25 images by, for example, blending a radiometric component of a thermal image with a corresponding component of a non-thermal image according to a blending parameter, which may be adjustable by a user and/or machine in some embodiments. For example, luminance or chrominance components of the thermal and non-thermal images may be combined according to the blending parameter. In one embodiment, such blending techniques may be
30 referred to as true color infrared imagery. For example, in daytime imaging, a blended image may comprise a non-thermal color image, which includes a luminance component and a

chrominance component, with its luminance value replaced by the luminance value from a thermal image. The use of the luminance data from the thermal image causes the intensity of the true non-thermal color image to brighten or dim based on the temperature of the object. As such, these blending techniques provide thermal imaging for daytime or visible light
5 images.

Regarding high contrast processing, high spatial frequency content may be obtained from one or more of the thermal and non-thermal images (e.g., by performing high pass filtering, difference imaging, and/or other techniques). A combined image may include a radiometric component of a thermal image and a blended component including infrared (e.g.,
10 thermal) characteristics of a scene blended with the high spatial frequency content, according to a blending parameter, which may be adjustable by a user and/or machine in some embodiments. In some embodiments, high spatial frequency content from non-thermal images may be blended with thermal images by superimposing the high spatial frequency content onto the thermal images, where the high spatial frequency content replaces or
15 overwrites those portions of the thermal images corresponding to where the high spatial frequency content exists. For example, the high spatial frequency content may include edges of objects depicted in images of a scene, but may not exist within the interior of such objects. In such embodiments, blended image data may simply include the high spatial frequency content, which may subsequently be encoded into one or more components of combined
20 images.

For example, a radiometric component of thermal image may be a chrominance component of the thermal image, and the high spatial frequency content may be derived from the luminance and/or chrominance components of a non-thermal image. In this embodiment, a combined image may include the radiometric component (e.g., the chrominance component
25 of the thermal image) encoded into a chrominance component of the combined image and the high spatial frequency content directly encoded (e.g., as blended image data but with no thermal image contribution) into a luminance component of the combined image. By doing so, a radiometric calibration of the radiometric component of the thermal image may be retained. In similar embodiments, blended image data may include the high spatial frequency
30 content added to a luminance component of the thermal images, and the resulting blended data encoded into a luminance component of resulting combined images.

For example, any of the techniques disclosed in the following applications may be used in various embodiments: U.S. Patent Application No. 12/477,828 filed June 3, 2009; U.S. Patent Application No. 12/766,739 filed April 23, 2010; U.S. Patent Application No. 13/105,765 filed May 11, 2011; U.S. Patent Application No. 13/437,645 filed April 2, 2012; 5 U.S. Provisional Patent Application No. 61/473,207 filed April 8, 2011; U.S. Provisional Patent Application No. 61/746,069 filed December 26, 2012; U.S. Provisional Patent Application No. 61/746,074 filed December 26, 2012; U.S. Provisional Patent Application No. 61/748,018 filed December 31, 2012; U.S. Provisional Patent Application No. 61/792,582 filed March 15, 2013; U.S. Provisional Patent Application No. 61/793,952 filed 10 March 15, 2013; and International Patent Application No. PCT/EP2011/056432 filed April 21, 2011, all of such applications are incorporated herein by reference in their entirety. Any of the techniques described herein, or described in other applications or patents referenced herein, may be applied to any of the various thermal devices, non-thermal devices, and uses described herein.

15 Referring again to Fig. 1, in various embodiments, host device 102 may include shutter 105. In this regard, shutter 105 may be selectively positioned over socket 104 (e.g., as identified by arrows 103) while infrared imaging module 100 is installed therein. In this regard, shutter 105 may be used, for example, to protect infrared imaging module 100 when not in use. Shutter 105 may also be used as a temperature reference as part of a calibration 20 process (e.g., a NUC process or other calibration processes) for infrared imaging module 100 as would be understood by one skilled in the art.

In various embodiments, shutter 105 may be made from various materials such as, for example, polymers, glass, aluminum (e.g., painted or anodized) or other materials. In various embodiments, shutter 105 may include one or more coatings to selectively filter 25 electromagnetic radiation and/or adjust various optical properties of shutter 105 (e.g., a uniform blackbody coating or a reflective gold coating).

In another embodiment, shutter 105 may be fixed in place to protect infrared imaging module 100 at all times. In this case, shutter 105 or a portion of shutter 105 may be made from appropriate materials (e.g., polymers or infrared transmitting materials such as silicon, 30 germanium, zinc selenide, or chalcogenide glasses) that do not substantially filter desired infrared wavelengths. In another embodiment, a shutter may be implemented as part of

infrared imaging module 100 (e.g., within or as part of a lens barrel or other components of infrared imaging module 100), as would be understood by one skilled in the art.

Alternatively, in another embodiment, a shutter (e.g., shutter 105 or other type of external or internal shutter) need not be provided, but rather a NUC process or other type of calibration may be performed using shutterless techniques. In another embodiment, a NUC process or other type of calibration using shutterless techniques may be performed in combination with shutter-based techniques.

Infrared imaging module 100 and host device 102 may be implemented in accordance with any of the various techniques set forth in U.S. Provisional Patent Application No. 61/495,873 filed June 10, 2011, U.S. Provisional Patent Application No. 61/495,879 filed June 10, 2011, and U.S. Provisional Patent Application No. 61/495,888 filed June 10, 2011, which are incorporated herein by reference in their entirety.

In various embodiments, the components of host device 102 and/or infrared imaging module 100 may be implemented as a local or distributed system with components in communication with each other over wired and/or wireless networks. Accordingly, the various operations identified in this disclosure may be performed by local and/or remote components as may be desired in particular implementations.

Fig. 5 illustrates a flow diagram of various operations to determine NUC terms in accordance with an embodiment of the disclosure. In some embodiments, the operations of Fig. 5 may be performed by processing module 160 or processor 195 (both also generally referred to as a processor) operating on image frames captured by infrared sensors 132.

In block 505, infrared sensors 132 begin capturing image frames of a scene. Typically, the scene will be the real world environment in which host device 102 is currently located. In this regard, shutter 105 (if optionally provided) may be opened to permit infrared imaging module to receive infrared radiation from the scene. Infrared sensors 132 may continue capturing image frames during all operations shown in Fig. 5. In this regard, the continuously captured image frames may be used for various operations as further discussed. In one embodiment, the captured image frames may be temporally filtered (e.g., in accordance with the process of block 826 further described herein with regard to Fig. 8) and be processed by other terms (e.g., factory gain terms 812, factory offset terms 816, previously

determined NUC terms 817, column FPN terms 820, and row FPN terms 824 as further described herein with regard to Fig. 8) before they are used in the operations shown in Fig. 5.

In block 510, a NUC process initiating event is detected. In one embodiment, the NUC process may be initiated in response to physical movement of host device 102. Such movement may be detected, for example, by motion sensors 194 which may be polled by a processor. In one example, a user may move host device 102 in a particular manner, such as by intentionally waving host device 102 back and forth in an “erase” or “swipe” movement. In this regard, the user may move host device 102 in accordance with a predetermined speed and direction (velocity), such as in an up and down, side to side, or other pattern to initiate the NUC process. In this example, the use of such movements may permit the user to intuitively operate host device 102 to simulate the “erasing” of noise in captured image frames.

In another example, a NUC process may be initiated by host device 102 if motion exceeding a threshold value is detected (e.g., motion greater than expected for ordinary use). It is contemplated that any desired type of spatial translation of host device 102 may be used to initiate the NUC process.

In yet another example, a NUC process may be initiated by host device 102 if a minimum time has elapsed since a previously performed NUC process. In a further example, a NUC process may be initiated by host device 102 if infrared imaging module 100 has experienced a minimum temperature change since a previously performed NUC process. In a still further example, a NUC process may be continuously initiated and repeated.

In block 515, after a NUC process initiating event is detected, it is determined whether the NUC process should actually be performed. In this regard, the NUC process may be selectively initiated based on whether one or more additional conditions are met. For example, in one embodiment, the NUC process may not be performed unless a minimum time has elapsed since a previously performed NUC process. In another embodiment, the NUC process may not be performed unless infrared imaging module 100 has experienced a minimum temperature change since a previously performed NUC process. Other criteria or conditions may be used in other embodiments. If appropriate criteria or conditions have been met, then the flow diagram continues to block 520. Otherwise, the flow diagram returns to block 505.

In the NUC process, blurred image frames may be used to determine NUC terms which may be applied to captured image frames to correct for FPN. As discussed, in one embodiment, the blurred image frames may be obtained by accumulating multiple image frames of a moving scene (e.g., captured while the scene and/or the thermal imager is in motion). In another embodiment, the blurred image frames may be obtained by defocusing an optical element or other component of the thermal imager.

Accordingly, in block 520 a choice of either approach is provided. If the motion-based approach is used, then the flow diagram continues to block 525. If the defocus-based approach is used, then the flow diagram continues to block 530.

Referring now to the motion-based approach, in block 525 motion is detected. For example, in one embodiment, motion may be detected based on the image frames captured by infrared sensors 132. In this regard, an appropriate motion detection process (e.g., an image registration process, a frame-to-frame difference calculation, or other appropriate process) may be applied to captured image frames to determine whether motion is present (e.g., whether static or moving image frames have been captured). For example, in one embodiment, it can be determined whether pixels or regions around the pixels of consecutive image frames have changed more than a user defined amount (e.g., a percentage and/or threshold value). If at least a given percentage of pixels have changed by at least the user defined amount, then motion will be detected with sufficient certainty to proceed to block 535.

In another embodiment, motion may be determined on a per pixel basis, wherein only pixels that exhibit significant changes are accumulated to provide the blurred image frame. For example, counters may be provided for each pixel and used to ensure that the same number of pixel values are accumulated for each pixel, or used to average the pixel values based on the number of pixel values actually accumulated for each pixel. Other types of image-based motion detection may be performed such as performing a Radon transform.

In another embodiment, motion may be detected based on data provided by motion sensors 194. In one embodiment, such motion detection may include detecting whether host device 102 is moving along a relatively straight trajectory through space. For example, if host device 102 is moving along a relatively straight trajectory, then it is possible that certain objects appearing in the imaged scene may not be sufficiently blurred (e.g., objects in the

scene that may be aligned with or moving substantially parallel to the straight trajectory). Thus, in such an embodiment, the motion detected by motion sensors 194 may be conditioned on host device 102 exhibiting, or not exhibiting, particular trajectories.

5 In yet another embodiment, both a motion detection process and motion sensors 194 may be used. Thus, using any of these various embodiments, a determination can be made as to whether or not each image frame was captured while at least a portion of the scene and host device 102 were in motion relative to each other (e.g., which may be caused by host device 102 moving relative to the scene, at least a portion of the scene moving relative to host device 102, or both).

10 It is expected that the image frames for which motion was detected may exhibit some secondary blurring of the captured scene (e.g., blurred thermal image data associated with the scene) due to the thermal time constants of infrared sensors 132 (e.g., microbolometer thermal time constants) interacting with the scene movement.

15 In block 535, image frames for which motion was detected are accumulated. For example, if motion is detected for a continuous series of image frames, then the image frames of the series may be accumulated. As another example, if motion is detected for only some image frames, then the non-moving image frames may be skipped and not included in the accumulation. Thus, a continuous or discontinuous set of image frames may be selected to be accumulated based on the detected motion.

20 In block 540, the accumulated image frames are averaged to provide a blurred image frame. Because the accumulated image frames were captured during motion, it is expected that actual scene information will vary between the image frames and thus cause the scene information to be further blurred in the resulting blurred image frame (block 545).

25 In contrast, FPN (e.g., caused by one or more components of infrared imaging module 100) will remain fixed over at least short periods of time and over at least limited changes in scene irradiance during motion. As a result, image frames captured in close proximity in time and space during motion will suffer from identical or at least very similar FPN. Thus, although scene information may change in consecutive image frames, the FPN will stay essentially constant. By averaging, multiple image frames captured during motion will blur

the scene information, but will not blur the FPN. As a result, FPN will remain more clearly defined in the blurred image frame provided in block 545 than the scene information.

In one embodiment, 32 or more image frames are accumulated and averaged in blocks 535 and 540. However, any desired number of image frames may be used in other
5 embodiments, but with generally decreasing correction accuracy as frame count is decreased.

Referring now to the defocus-based approach, in block 530, a defocus operation may be performed to intentionally defocus the image frames captured by infrared sensors 132. For example, in one embodiment, one or more actuators 199 may be used to adjust, move, or otherwise translate optical element 180, infrared sensor assembly 128, and/or other
10 components of infrared imaging module 100 to cause infrared sensors 132 to capture a blurred (e.g., unfocused) image frame of the scene. Other non-actuator based techniques are also contemplated for intentionally defocusing infrared image frames such as, for example, manual (e.g., user-initiated) defocusing.

Although the scene may appear blurred in the image frame, FPN (e.g., caused by one
15 or more components of infrared imaging module 100) will remain unaffected by the defocusing operation. As a result, a blurred image frame of the scene will be provided (block 545) with FPN remaining more clearly defined in the blurred image than the scene information.

In the above discussion, the defocus-based approach has been described with regard
20 to a single captured image frame. In another embodiment, the defocus-based approach may include accumulating multiple image frames while the infrared imaging module 100 has been defocused and averaging the defocused image frames to remove the effects of temporal noise and provide a blurred image frame in block 545.

Thus, it will be appreciated that a blurred image frame may be provided in block 545
25 by either the motion-based approach or the defocus-based approach. Because much of the scene information will be blurred by either motion, defocusing, or both, the blurred image frame may be effectively considered a low pass filtered version of the original captured image frames with respect to scene information.

In block 550, the blurred image frame is processed to determine updated row and
30 column FPN terms (e.g., if row and column FPN terms have not been previously determined

then the updated row and column FPN terms may be new row and column FPN terms in the first iteration of block 550). As used in this disclosure, the terms row and column may be used interchangeably depending on the orientation of infrared sensors 132 and/or other components of infrared imaging module 100.

5 In one embodiment, block 550 includes determining a spatial FPN correction term for each row of the blurred image frame (e.g., each row may have its own spatial FPN correction term), and also determining a spatial FPN correction term for each column of the blurred image frame (e.g., each column may have its own spatial FPN correction term). Such processing may be used to reduce the spatial and slowly varying (1/f) row and column FPN
10 inherent in thermal imagers caused by, for example, 1/f noise characteristics of amplifiers in ROIC 402 which may manifest as vertical and horizontal stripes in image frames.

 Advantageously, by determining spatial row and column FPN terms using the blurred image frame, there will be a reduced risk of vertical and horizontal objects in the actual imaged scene from being mistaken for row and column noise (e.g., real scene content will be
15 blurred while FPN remains unblurred).

 In one embodiment, row and column FPN terms may be determined by considering differences between neighboring pixels of the blurred image frame. For example, Fig. 6 illustrates differences between neighboring pixels in accordance with an embodiment of the disclosure. Specifically, in Fig. 6 a pixel 610 is compared to its 8 nearest horizontal
20 neighbors: d0-d3 on one side and d4-d7 on the other side. Differences between the neighbor pixels can be averaged to obtain an estimate of the offset error of the illustrated group of pixels. An offset error may be calculated for each pixel in a row or column and the average result may be used to correct the entire row or column.

 To prevent real scene data from being interpreted as noise, upper and lower threshold
25 values may be used (thPix and -thPix). Pixel values falling outside these threshold values (pixels d1 and d4 in this example) are not used to obtain the offset error. In addition, the maximum amount of row and column FPN correction may be limited by these threshold values.

Further techniques for performing spatial row and column FPN correction processing are set forth in U.S. Patent Application No. 12/396,340 filed March 2, 2009 which is incorporated herein by reference in its entirety.

Referring again to Fig. 5, the updated row and column FPN terms determined in block 550 are stored (block 552) and applied (block 555) to the blurred image frame provided in block 545. After these terms are applied, some of the spatial row and column FPN in the blurred image frame may be reduced. However, because such terms are applied generally to rows and columns, additional FPN may remain such as spatially uncorrelated FPN associated with pixel to pixel drift or other causes. Neighborhoods of spatially correlated FPN may also remain which may not be directly associated with individual rows and columns. Accordingly, further processing may be performed as discussed below to determine NUC terms.

In block 560, local contrast values (e.g., edges or absolute values of gradients between adjacent or small groups of pixels) in the blurred image frame are determined. If scene information in the blurred image frame includes contrasting areas that have not been significantly blurred (e.g., high contrast edges in the original scene data), then such features may be identified by a contrast determination process in block 560.

For example, local contrast values in the blurred image frame may be calculated, or any other desired type of edge detection process may be applied to identify certain pixels in the blurred image as being part of an area of local contrast. Pixels that are marked in this manner may be considered as containing excessive high spatial frequency scene information that would be interpreted as FPN (e.g., such regions may correspond to portions of the scene that have not been sufficiently blurred). As such, these pixels may be excluded from being used in the further determination of NUC terms. In one embodiment, such contrast detection processing may rely on a threshold that is higher than the expected contrast value associated with FPN (e.g., pixels exhibiting a contrast value higher than the threshold may be considered to be scene information, and those lower than the threshold may be considered to be exhibiting FPN).

In one embodiment, the contrast determination of block 560 may be performed on the blurred image frame after row and column FPN terms have been applied to the blurred image frame (e.g., as shown in Fig. 5). In another embodiment, block 560 may be performed prior

to block 550 to determine contrast before row and column FPN terms are determined (e.g., to prevent scene based contrast from contributing to the determination of such terms).

Following block 560, it is expected that any high spatial frequency content remaining in the blurred image frame may be generally attributed to spatially uncorrelated FPN. In this regard, following block 560, much of the other noise or actual desired scene based information has been removed or excluded from the blurred image frame due to: intentional blurring of the image frame (e.g., by motion or defocusing in blocks 520 through 545), application of row and column FPN terms (block 555), and contrast determination (block 560).

Thus, it can be expected that following block 560, any remaining high spatial frequency content (e.g., exhibited as areas of contrast or differences in the blurred image frame) may be attributed to spatially uncorrelated FPN. Accordingly, in block 565, the blurred image frame is high pass filtered. In one embodiment, this may include applying a high pass filter to extract the high spatial frequency content from the blurred image frame. In another embodiment, this may include applying a low pass filter to the blurred image frame and taking a difference between the low pass filtered image frame and the unfiltered blurred image frame to obtain the high spatial frequency content. In accordance with various embodiments of the present disclosure, a high pass filter may be implemented by calculating a mean difference between a sensor signal (e.g., a pixel value) and its neighbors.

In block 570, a flat field correction process is performed on the high pass filtered blurred image frame to determine updated NUC terms (e.g., if a NUC process has not previously been performed then the updated NUC terms may be new NUC terms in the first iteration of block 570).

For example, Fig. 7 illustrates a flat field correction technique 700 in accordance with an embodiment of the disclosure. In Fig. 7, a NUC term may be determined for each pixel 710 of the blurred image frame using the values of its neighboring pixels 712 to 726. For each pixel 710, several gradients may be determined based on the absolute difference between the values of various adjacent pixels. For example, absolute value differences may be determined between: pixels 712 and 714 (a left to right diagonal gradient), pixels 716 and 718 (a top to bottom vertical gradient), pixels 720 and 722 (a right to left diagonal gradient), and pixels 724 and 726 (a left to right horizontal gradient).

These absolute differences may be summed to provide a summed gradient for pixel 710. A weight value may be determined for pixel 710 that is inversely proportional to the summed gradient. This process may be performed for all pixels 710 of the blurred image frame until a weight value is provided for each pixel 710. For areas with low gradients (e.g., areas that are blurry or have low contrast), the weight value will be close to one. Conversely, for areas with high gradients, the weight value will be zero or close to zero. The update to the NUC term as estimated by the high pass filter is multiplied with the weight value.

In one embodiment, the risk of introducing scene information into the NUC terms can be further reduced by applying some amount of temporal damping to the NUC term determination process. For example, a temporal damping factor λ between 0 and 1 may be chosen such that the new NUC term (NUC_{NEW}) stored is a weighted average of the old NUC term (NUC_{OLD}) and the estimated updated NUC term (NUC_{UPDATE}). In one embodiment, this can be expressed as $NUC_{NEW} = \lambda \cdot NUC_{OLD} + (1-\lambda) \cdot (NUC_{OLD} + NUC_{UPDATE})$.

Although the determination of NUC terms has been described with regard to gradients, local contrast values may be used instead where appropriate. Other techniques may also be used such as, for example, standard deviation calculations. Other types flat field correction processes may be performed to determine NUC terms including, for example, various processes identified in U.S. Patent No. 6,028,309 issued February 22, 2000, U.S. Patent No. 6,812,465 issued November 2, 2004, and U.S. Patent Application No. 12/114,865 filed May 5, 2008, which are incorporated herein by reference in their entirety.

Referring again to Fig. 5, block 570 may include additional processing of the NUC terms. For example, in one embodiment, to preserve the scene signal mean, the sum of all NUC terms may be normalized to zero by subtracting the NUC term mean from each NUC term. Also in block 570, to avoid row and column noise from affecting the NUC terms, the mean value of each row and column may be subtracted from the NUC terms for each row and column. As a result, row and column FPN filters using the row and column FPN terms determined in block 550 may be better able to filter out row and column noise in further iterations (e.g., as further shown in Fig. 8) after the NUC terms are applied to captured images (e.g., in block 580 further discussed herein). In this regard, the row and column FPN filters may in general use more data to calculate the per row and per column offset coefficients (e.g., row and column FPN terms) and may thus provide a more robust

alternative for reducing spatially correlated FPN than the NUC terms which are based on high pass filtering to capture spatially uncorrelated noise.

In blocks 571-573, additional high pass filtering and further determinations of updated NUC terms may be optionally performed to remove spatially correlated FPN with lower spatial frequency than previously removed by row and column FPN terms. In this regard, some variability in infrared sensors 132 or other components of infrared imaging module 100 may result in spatially correlated FPN noise that cannot be easily modeled as row or column noise. Such spatially correlated FPN may include, for example, window defects on a sensor package or a cluster of infrared sensors 132 that respond differently to irradiance than neighboring infrared sensors 132. In one embodiment, such spatially correlated FPN may be mitigated with an offset correction. If the amount of such spatially correlated FPN is significant, then the noise may also be detectable in the blurred image frame. Since this type of noise may affect a neighborhood of pixels, a high pass filter with a small kernel may not detect the FPN in the neighborhood (e.g., all values used in high pass filter may be taken from the neighborhood of affected pixels and thus may be affected by the same offset error). For example, if the high pass filtering of block 565 is performed with a small kernel (e.g., considering only immediately adjacent pixels that fall within a neighborhood of pixels affected by spatially correlated FPN), then broadly distributed spatially correlated FPN may not be detected.

For example, Fig. 11 illustrates spatially correlated FPN in a neighborhood of pixels in accordance with an embodiment of the disclosure. As shown in a sample image frame 1100, a neighborhood of pixels 1110 may exhibit spatially correlated FPN that is not precisely correlated to individual rows and columns and is distributed over a neighborhood of several pixels (e.g., a neighborhood of approximately 4 by 4 pixels in this example). Sample image frame 1100 also includes a set of pixels 1120 exhibiting substantially uniform response that are not used in filtering calculations, and a set of pixels 1130 that are used to estimate a low pass value for the neighborhood of pixels 1110. In one embodiment, pixels 1130 may be a number of pixels divisible by two in order to facilitate efficient hardware or software calculations.

Referring again to Fig. 5, in blocks 571-573, additional high pass filtering and further determinations of updated NUC terms may be optionally performed to remove spatially

correlated FPN such as exhibited by pixels 1110. In block 571, the updated NUC terms determined in block 570 are applied to the blurred image frame. Thus, at this time, the blurred image frame will have been initially corrected for spatially correlated FPN (e.g., by application of the updated row and column FPN terms in block 555), and also initially
5 corrected for spatially uncorrelated FPN (e.g., by application of the updated NUC terms applied in block 571).

In block 572, a further high pass filter is applied with a larger kernel than was used in block 565, and further updated NUC terms may be determined in block 573. For example, to detect the spatially correlated FPN present in pixels 1110, the high pass filter applied in block
10 572 may include data from a sufficiently large enough neighborhood of pixels such that differences can be determined between unaffected pixels (e.g., pixels 1120) and affected pixels (e.g., pixels 1110). For example, a low pass filter with a large kernel can be used (e.g., an N by N kernel that is much greater than 3 by 3 pixels) and the results may be subtracted to perform appropriate high pass filtering.

In one embodiment, for computational efficiency, a sparse kernel may be used such that only a small number of neighboring pixels inside an N by N neighborhood are used. For any given high pass filter operation using distant neighbors (e.g., a large kernel), there is a risk of modeling actual (potentially blurred) scene information as spatially correlated FPN. Accordingly, in one embodiment, the temporal damping factor λ may be set close to 1 for
15 updated NUC terms determined in block 573.

In various embodiments, blocks 571-573 may be repeated (e.g., cascaded) to iteratively perform high pass filtering with increasing kernel sizes to provide further updated NUC terms further correct for spatially correlated FPN of desired neighborhood sizes. In one embodiment, the decision to perform such iterations may be determined by whether spatially
20 correlated FPN has actually been removed by the updated NUC terms of the previous performance of blocks 571-573.

After blocks 571-573 are finished, a decision is made regarding whether to apply the updated NUC terms to captured image frames (block 574). For example, if an average of the absolute value of the NUC terms for the entire image frame is less than a minimum threshold
30 value, or greater than a maximum threshold value, the NUC terms may be deemed spurious or unlikely to provide meaningful correction. Alternatively, thresholding criteria may be

applied to individual pixels to determine which pixels receive updated NUC terms. In one embodiment, the threshold values may correspond to differences between the newly calculated NUC terms and previously calculated NUC terms. In another embodiment, the threshold values may be independent of previously calculated NUC terms. Other tests may be applied (e.g., spatial correlation tests) to determine whether the NUC terms should be applied.

If the NUC terms are deemed spurious or unlikely to provide meaningful correction, then the flow diagram returns to block 505. Otherwise, the newly determined NUC terms are stored (block 575) to replace previous NUC terms (e.g., determined by a previously performed iteration of Fig. 5) and applied (block 580) to captured image frames.

Fig. 8 illustrates various image processing techniques of Fig. 5 and other operations applied in an image processing pipeline 800 in accordance with an embodiment of the disclosure. In this regard, pipeline 800 identifies various operations of Fig. 5 in the context of an overall iterative image processing scheme for correcting image frames provided by infrared imaging module 100. In some embodiments, pipeline 800 may be provided by processing module 160 or processor 195 (both also generally referred to as a processor) operating on image frames captured by infrared sensors 132.

Image frames captured by infrared sensors 132 may be provided to a frame averager 804 that integrates multiple image frames to provide image frames 802 with an improved signal to noise ratio. Frame averager 804 may be effectively provided by infrared sensors 132, ROIC 402, and other components of infrared sensor assembly 128 that are implemented to support high image capture rates. For example, in one embodiment, infrared sensor assembly 128 may capture infrared image frames at a frame rate of 240 Hz (e.g., 240 images per second). In this embodiment, such a high frame rate may be implemented, for example, by operating infrared sensor assembly 128 at relatively low voltages (e.g., compatible with mobile telephone voltages) and by using a relatively small array of infrared sensors 132 (e.g., an array of 64 by 64 infrared sensors in one embodiment).

In one embodiment, such infrared image frames may be provided from infrared sensor assembly 128 to processing module 160 at a high frame rate (e.g., 240 Hz or other frame rates). In another embodiment, infrared sensor assembly 128 may integrate over longer time periods, or multiple time periods, to provide integrated (e.g., averaged) infrared image frames

to processing module 160 at a lower frame rate (e.g., 30 Hz, 9 Hz, or other frame rates). Further information regarding implementations that may be used to provide high image capture rates may be found in U.S. Provisional Patent Application No. 61/495,879 filed June 10, 2011 which is incorporated herein by reference in its entirety.

5 Image frames 802 proceed through pipeline 800 where they are adjusted by various terms, temporally filtered, used to determine the various adjustment terms, and gain compensated.

 In blocks 810 and 814, factory gain terms 812 and factory offset terms 816 are applied to image frames 802 to compensate for gain and offset differences, respectively, between the
10 various infrared sensors 132 and/or other components of infrared imaging module 100 determined during manufacturing and testing.

 In block 580, NUC terms 817 are applied to image frames 802 to correct for FPN as discussed. In one embodiment, if NUC terms 817 have not yet been determined (e.g., before a NUC process has been initiated), then block 580 may not be performed or initialization
15 values may be used for NUC terms 817 that result in no alteration to the image data (e.g., offsets for every pixel would be equal to zero).

 In blocks 818 and 822, column FPN terms 820 and row FPN terms 824, respectively, are applied to image frames 802. Column FPN terms 820 and row FPN terms 824 may be determined in accordance with block 550 as discussed. In one embodiment, if the column
20 FPN terms 820 and row FPN terms 824 have not yet been determined (e.g., before a NUC process has been initiated), then blocks 818 and 822 may not be performed or initialization values may be used for the column FPN terms 820 and row FPN terms 824 that result in no alteration to the image data (e.g., offsets for every pixel would be equal to zero).

 In block 826, temporal filtering is performed on image frames 802 in accordance with
25 a temporal noise reduction (TNR) process. Fig. 9 illustrates a TNR process in accordance with an embodiment of the disclosure. In Fig. 9, a presently received image frame 802a and a previously temporally filtered image frame 802b are processed to determine a new temporally filtered image frame 802e. Image frames 802a and 802b include local neighborhoods of pixels 803a and 803b centered around pixels 805a and 805b, respectively. Neighborhoods
30 803a and 803b correspond to the same locations within image frames 802a and 802b and are

subsets of the total pixels in image frames 802a and 802b. In the illustrated embodiment, neighborhoods 803a and 803b include areas of 5 by 5 pixels. Other neighborhood sizes may be used in other embodiments.

5 Differences between corresponding pixels of neighborhoods 803a and 803b are determined and averaged to provide an averaged delta value 805c for the location corresponding to pixels 805a and 805b. Averaged delta value 805c may be used to determine weight values in block 807 to be applied to pixels 805a and 805b of image frames 802a and 802b.

10 In one embodiment, as shown in graph 809, the weight values determined in block 807 may be inversely proportional to averaged delta value 805c such that weight values drop rapidly towards zero when there are large differences between neighborhoods 803a and 803b. In this regard, large differences between neighborhoods 803a and 803b may indicate that changes have occurred within the scene (e.g., due to motion) and pixels 802a and 802b may be appropriately weighted, in one embodiment, to avoid introducing blur across frame-to-
15 frame scene changes. Other associations between weight values and averaged delta value 805c may be used in various embodiments.

The weight values determined in block 807 may be applied to pixels 805a and 805b to determine a value for corresponding pixel 805e of image frame 802e (block 811). In this regard, pixel 805e may have a value that is a weighted average (or other combination) of
20 pixels 805a and 805b, depending on averaged delta value 805c and the weight values determined in block 807.

For example, pixel 805e of temporally filtered image frame 802e may be a weighted sum of pixels 805a and 805b of image frames 802a and 802b. If the average difference between pixels 805a and 805b is due to noise, then it may be expected that the average
25 change between neighborhoods 805a and 805b will be close to zero (e.g., corresponding to the average of uncorrelated changes). Under such circumstances, it may be expected that the sum of the differences between neighborhoods 805a and 805b will be close to zero. In this case, pixel 805a of image frame 802a may both be appropriately weighted so as to contribute to the value of pixel 805e.

However, if the sum of such differences is not zero (e.g., even differing from zero by a small amount in one embodiment), then the changes may be interpreted as being attributed to motion instead of noise. Thus, motion may be detected based on the average change exhibited by neighborhoods 805a and 805b. Under these circumstances, pixel 805a of image frame 802a may be weighted heavily, while pixel 805b of image frame 802b may be weighted lightly.

Other embodiments are also contemplated. For example, although averaged delta value 805c has been described as being determined based on neighborhoods 805a and 805b, in other embodiments averaged delta value 805c may be determined based on any desired criteria (e.g., based on individual pixels or other types of groups of sets of pixels).

In the above embodiments, image frame 802a has been described as a presently received image frame and image frame 802b has been described as a previously temporally filtered image frame. In another embodiment, image frames 802a and 802b may be first and second image frames captured by infrared imaging module 100 that have not been temporally filtered.

Fig. 10 illustrates further implementation details in relation to the TNR process of block 826. As shown in Fig. 10, image frames 802a and 802b may be read into line buffers 1010a and 1010b, respectively, and image frame 802b (e.g., the previous image frame) may be stored in a frame buffer 1020 before being read into line buffer 1010b. In one embodiment, line buffers 1010a-b and frame buffer 1020 may be implemented by a block of random access memory (RAM) provided by any appropriate component of infrared imaging module 100 and/or host device 102.

Referring again to Fig. 8, image frame 802e may be passed to an automatic gain compensation block 828 for further processing to provide a result image frame 830 that may be used by host device 102 as desired.

Fig. 8 further illustrates various operations that may be performed to determine row and column FPN terms and NUC terms as discussed. In one embodiment, these operations may use image frames 802e as shown in Fig. 8. Because image frames 802e have already been temporally filtered, at least some temporal noise may be removed and thus will not

inadvertently affect the determination of row and column FPN terms 824 and 820 and NUC terms 817. In another embodiment, non-temporally filtered image frames 802 may be used.

In Fig. 8, blocks 510, 515, and 520 of Fig. 5 are collectively represented together. As discussed, a NUC process may be selectively initiated and performed in response to various NUC process initiating events and based on various criteria or conditions. As also discussed, the NUC process may be performed in accordance with a motion-based approach (blocks 525, 535, and 540) or a defocus-based approach (block 530) to provide a blurred image frame (block 545). Fig. 8 further illustrates various additional blocks 550, 552, 555, 560, 565, 570, 571, 572, 573, and 575 previously discussed with regard to Fig. 5.

As shown in Fig. 8, row and column FPN terms 824 and 820 and NUC terms 817 may be determined and applied in an iterative fashion such that updated terms are determined using image frames 802 to which previous terms have already been applied. As a result, the overall process of Fig. 8 may repeatedly update and apply such terms to continuously reduce the noise in image frames 830 to be used by host device 102.

Referring again to Fig. 10, further implementation details are illustrated for various blocks of Figs. 5 and 8 in relation to pipeline 800. For example, blocks 525, 535, and 540 are shown as operating at the normal frame rate of image frames 802 received by pipeline 800. In the embodiment shown in Fig. 10, the determination made in block 525 is represented as a decision diamond used to determine whether a given image frame 802 has sufficiently changed such that it may be considered an image frame that will enhance the blur if added to other image frames and is therefore accumulated (block 535 is represented by an arrow in this embodiment) and averaged (block 540).

Also in Fig. 10, the determination of column FPN terms 820 (block 550) is shown as operating at an update rate that in this example is 1/32 of the sensor frame rate (e.g., normal frame rate) due to the averaging performed in block 540. Other update rates may be used in other embodiments. Although only column FPN terms 820 are identified in Fig. 10, row FPN terms 824 may be implemented in a similar fashion at the reduced frame rate.

Fig. 10 also illustrates further implementation details in relation to the NUC determination process of block 570. In this regard, the blurred image frame may be read to a line buffer 1030 (e.g., implemented by a block of RAM provided by any appropriate

component of infrared imaging module 100 and/or host device 102). The flat field correction technique 700 of Fig. 7 may be performed on the blurred image frame.

In view of the present disclosure, it will be appreciated that techniques described herein may be used to remove various types of FPN (e.g., including very high amplitude FPN) such as spatially correlated row and column FPN and spatially uncorrelated FPN.

Other embodiments are also contemplated. For example, in one embodiment, the rate at which row and column FPN terms and/or NUC terms are updated can be inversely proportional to the estimated amount of blur in the blurred image frame and/or inversely proportional to the magnitude of local contrast values (e.g., determined in block 560).

In various embodiments, the described techniques may provide advantages over conventional shutter-based noise correction techniques. For example, by using a shutterless process, a shutter (e.g., such as shutter 105) need not be provided, thus permitting reductions in size, weight, cost, and mechanical complexity. Power and maximum voltage supplied to, or generated by, infrared imaging module 100 may also be reduced if a shutter does not need to be mechanically operated. Reliability will be improved by removing the shutter as a potential point of failure. A shutterless process also eliminates potential image interruption caused by the temporary blockage of the imaged scene by a shutter.

Also, by correcting for noise using intentionally blurred image frames captured from a real world scene (not a uniform scene provided by a shutter), noise correction may be performed on image frames that have irradiance levels similar to those of the actual scene desired to be imaged. This can improve the accuracy and effectiveness of noise correction terms determined in accordance with the various described techniques.

As discussed, in various embodiments, infrared imaging module 100 may be configured to operate at low voltage levels. In particular, infrared imaging module 100 may be implemented with circuitry configured to operate at low power and/or in accordance with other parameters that permit infrared imaging module 100 to be conveniently and effectively implemented in various types of host devices 102, such as mobile devices and other devices.

For example, Fig. 12 illustrates a block diagram of another implementation of infrared sensor assembly 128 including infrared sensors 132 and an LDO 1220 in accordance with an embodiment of the disclosure. As shown, Fig. 12 also illustrates various components 1202,

1204, 1205, 1206, 1208, and 1210 which may implemented in the same or similar manner as corresponding components previously described with regard to Fig. 4. Fig. 12 also illustrates bias correction circuitry 1212 which may be used to adjust one or more bias voltages provided to infrared sensors 132 (e.g., to compensate for temperature changes, self-heating, and/or other factors).

In some embodiments, LDO 1220 may be provided as part of infrared sensor assembly 128 (e.g., on the same chip and/or wafer level package as the ROIC). For example, LDO 1220 may be provided as part of an FPA with infrared sensor assembly 128. As discussed, such implementations may reduce power supply noise introduced to infrared sensor assembly 128 and thus provide an improved PSRR. In addition, by implementing the LDO with the ROIC, less die area may be consumed and fewer discrete die (or chips) are needed.

LDO 1220 receives an input voltage provided by a power source 1230 over a supply line 1232. LDO 1220 provides an output voltage to various components of infrared sensor assembly 128 over supply lines 1222. In this regard, LDO 1220 may provide substantially identical regulated output voltages to various components of infrared sensor assembly 128 in response to a single input voltage received from power source 1230, in accordance with various techniques described in, for example, U.S. Patent Application No. 14/101,245 filed December 9, 2013 incorporated herein by reference in its entirety.

For example, in some embodiments, power source 1230 may provide an input voltage in a range of approximately 2.8 volts to approximately 11 volts (e.g., approximately 2.8 volts in one embodiment), and LDO 1220 may provide an output voltage in a range of approximately 1.5 volts to approximately 2.8 volts (e.g., approximately 2.8, 2.5, 2.4, and/or lower voltages in various embodiments). In this regard, LDO 1220 may be used to provide a consistent regulated output voltage, regardless of whether power source 1230 is implemented with a conventional voltage range of approximately 9 volts to approximately 11 volts, or a low voltage such as approximately 2.8 volts. As such, although various voltage ranges are provided for the input and output voltages, it is contemplated that the output voltage of LDO 1220 will remain fixed despite changes in the input voltage.

The implementation of LDO 1220 as part of infrared sensor assembly 128 provides various advantages over conventional power implementations for FPAs. For example,

conventional FPAs typically rely on multiple power sources, each of which may be provided separately to the FPA, and separately distributed to the various components of the FPA. By regulating a single power source 1230 by LDO 1220, appropriate voltages may be separately provided (e.g., to reduce possible noise) to all components of infrared sensor assembly 128 with reduced complexity. The use of LDO 1220 also allows infrared sensor assembly 128 to operate in a consistent manner, even if the input voltage from power source 1230 changes (e.g., if the input voltage increases or decreases as a result of charging or discharging a battery or other type of device used for power source 1230).

The various components of infrared sensor assembly 128 shown in Fig. 12 may also be implemented to operate at lower voltages than conventional devices. For example, as discussed, LDO 1220 may be implemented to provide a low voltage (e.g., approximately 2.5 volts). This contrasts with the multiple higher voltages typically used to power conventional FPAs, such as: approximately 3.3 volts to approximately 5 volts used to power digital circuitry; approximately 3.3 volts used to power analog circuitry; and approximately 9 volts to approximately 11 volts used to power loads. Also, in some embodiments, the use of LDO 1220 may reduce or eliminate the need for a separate negative reference voltage to be provided to infrared sensor assembly 128.

Additional aspects of the low voltage operation of infrared sensor assembly 128 may be further understood with reference to Fig. 13. Fig. 13 illustrates a circuit diagram of a portion of infrared sensor assembly 128 of Fig. 12 in accordance with an embodiment of the disclosure. In particular, Fig. 13 illustrates additional components of bias correction circuitry 1212 (e.g., components 1326, 1330, 1332, 1334, 1336, 1338, and 1341) connected to LDO 1220 and infrared sensors 132. For example, bias correction circuitry 1212 may be used to compensate for temperature-dependent changes in bias voltages in accordance with an embodiment of the present disclosure. The operation of such additional components may be further understood with reference to similar components identified in U.S. Patent No. 7,679,048 issued March 16, 2010 which is hereby incorporated by reference in its entirety. Infrared sensor assembly 128 may also be implemented in accordance with the various components identified in U.S. Patent No. 6,812,465 issued November 2, 2004 which is hereby incorporated by reference in its entirety.

In various embodiments, some or all of the bias correction circuitry 1212 may be implemented on a global array basis as shown in Fig. 13 (e.g., used for all infrared sensors 132 collectively in an array). In other embodiments, some or all of the bias correction circuitry 1212 may be implemented on an individual sensor basis (e.g., entirely or partially duplicated for each infrared sensor 132). In some embodiments, bias correction circuitry 1212 and other components of Fig. 13 may be implemented as part of ROIC 1202.

As shown in Fig. 13, LDO 1220 provides a load voltage V_{load} to bias correction circuitry 1212 along one of supply lines 1222. As discussed, in some embodiments, V_{load} may be approximately 2.5 volts which contrasts with larger voltages of approximately 9 volts to approximately 11 volts that may be used as load voltages in conventional infrared imaging devices.

Based on V_{load} , bias correction circuitry 1212 provides a sensor bias voltage V_{bolo} at a node 1360. V_{bolo} may be distributed to one or more infrared sensors 132 through appropriate switching circuitry 1370 (e.g., represented by broken lines in Fig. 13). In some examples, switching circuitry 1370 may be implemented in accordance with appropriate components identified in U.S. Patent Nos. 6,812,465 and 7,679,048 previously referenced herein.

Each infrared sensor 132 includes a node 1350 which receives V_{bolo} through switching circuitry 1370, and another node 1352 which may be connected to ground, a substrate, and/or a negative reference voltage. In some embodiments, the voltage at node 1360 may be substantially the same as V_{bolo} provided at nodes 1350. In other embodiments, the voltage at node 1360 may be adjusted to compensate for possible voltage drops associated with switching circuitry 1370 and/or other factors.

V_{bolo} may be implemented with lower voltages than are typically used for conventional infrared sensor biasing. In one embodiment, V_{bolo} may be in a range of approximately 0.2 volts to approximately 0.7 volts. In another embodiment, V_{bolo} may be in a range of approximately 0.4 volts to approximately 0.6 volts. In another embodiment, V_{bolo} may be approximately 0.5 volts. In contrast, conventional infrared sensors typically use bias voltages of approximately 1 volt.

The use of a lower bias voltage for infrared sensors 132 in accordance with the present disclosure permits infrared sensor assembly 128 to exhibit significantly reduced power consumption in comparison with conventional infrared imaging devices. In particular, the power consumption of each infrared sensor 132 is reduced by the square of the bias
5 voltage. As a result, a reduction from, for example, 1.0 volt to 0.5 volts provides a significant reduction in power, especially when applied to many infrared sensors 132 in an infrared sensor array. This reduction in power may also result in reduced self-heating of infrared sensor assembly 128.

In accordance with additional embodiments of the present disclosure, various
10 techniques are provided for reducing the effects of noise in image frames provided by infrared imaging devices operating at low voltages. In this regard, when infrared sensor assembly 128 is operated with low voltages as described, noise, self-heating, and/or other phenomena may, if uncorrected, become more pronounced in image frames provided by infrared sensor assembly 128.

For example, referring to Fig. 13, when LDO 1220 maintains V_{load} at a low voltage in the manner described herein, V_{bolo} will also be maintained at its corresponding low voltage and the relative size of its output signals may be reduced. As a result, noise, self-heating, and/or other phenomena may have a greater effect on the smaller output signals read
15 out from infrared sensors 132, resulting in variations (e.g., errors) in the output signals. If uncorrected, these variations may be exhibited as noise in the image frames. Moreover, although low voltage operation may reduce the overall amount of certain phenomena (e.g., self-heating), the smaller output signals may permit the remaining error sources (e.g., residual self-heating) to have a disproportionate effect on the output signals during low voltage
20 operation.

To compensate for such phenomena, infrared sensor assembly 128, infrared imaging module 100, and/or host device 102 may be implemented with various array sizes, frame rates, and/or frame averaging techniques. For example, as discussed, a variety of different array sizes are contemplated for infrared sensors 132. In some embodiments, infrared sensors
25 132 may be implemented with array sizes ranging from 32 by 32 to 160 by 120 infrared sensors 132. Other example array sizes include 80 by 64, 80 by 60, 64 by 64, and 64 by 32. Any desired array size may be used.
30

Advantageously, when implemented with such relatively small array sizes, infrared sensor assembly 128 may provide image frames at relatively high frame rates without requiring significant changes to ROIC and related circuitry. For example, in some embodiments, frame rates may range from approximately 120 Hz to approximately 480 Hz.

5 In some embodiments, the array size and the frame rate may be scaled relative to each other (e.g., in an inversely proportional manner or otherwise) such that larger arrays are implemented with lower frame rates, and smaller arrays are implemented with higher frame rates. For example, in one embodiment, an array of 160 by 120 may provide a frame rate of approximately 120 Hz. In another embodiment, an array of 80 by 60 may provide a
10 correspondingly higher frame rate of approximately 240 Hz. Other frame rates are also contemplated.

By scaling the array size and the frame rate relative to each other, the particular readout timing of rows and/or columns of the FPA may remain consistent, regardless of the actual FPA size or frame rate. In one embodiment, the readout timing may be approximately
15 63 microseconds per row or column.

As previously discussed with regard to Fig. 8, the image frames captured by infrared sensors 132 may be provided to a frame averager 804 that integrates multiple image frames to provide image frames 802 (e.g., processed image frames) with a lower frame rate (e.g., approximately 30 Hz, approximately 60 Hz, or other frame rates) and with an improved
20 signal to noise ratio. In particular, by averaging the high frame rate image frames provided by a relatively small FPA, image noise attributable to low voltage operation may be effectively averaged out and/or substantially reduced in image frames 802. Accordingly, infrared sensor assembly 128 may be operated at relatively low voltages provided by LDO 1220 as discussed without experiencing additional noise and related side effects in the
25 resulting image frames 802 after processing by frame averager 804.

Other embodiments are also contemplated. For example, although a single array of infrared sensors 132 is illustrated, it is contemplated that multiple such arrays may be used together to provide higher resolution image frames (e.g., a scene may be imaged across multiple such arrays). Such arrays may be provided in multiple infrared sensor assemblies
30 128 and/or provided in the same infrared sensor assembly 128. Each such array may be operated at low voltages as described, and also may be provided with associated ROIC

circuitry such that each array may still be operated at a relatively high frame rate. The high frame rate image frames provided by such arrays may be averaged by shared or dedicated frame averagers 804 to reduce and/or eliminate noise associated with low voltage operation. As a result, high resolution infrared images may be obtained while still operating at low voltages.

In various embodiments, infrared sensor assembly 128 may be implemented with appropriate dimensions to permit infrared imaging module 100 to be used with a small form factor socket 104, such as a socket used for mobile devices. For example, in some embodiments, infrared sensor assembly 128 may be implemented with a chip size in a range of approximately 4.0 mm by approximately 4.0 mm to approximately 5.5 mm by approximately 5.5 mm (e.g., approximately 4.0 mm by approximately 5.5 mm in one example). Infrared sensor assembly 128 may be implemented with such sizes or other appropriate sizes to permit use with socket 104 implemented with various sizes such as: 8.5 mm by 8.5 mm, 8.5 mm by 5.9 mm, 6.0 mm by 6.0 mm, 5.5 mm by 5.5 mm, 4.5 mm by 4.5 mm, and/or other socket sizes such as, for example, those identified in Table 1 of U.S. Provisional Patent Application No. 61/495,873 previously filed June 10, 2011 incorporated herein by reference in its entirety.

Fig. 14 illustrates a block diagram of an imaging system 1400 (e.g., an infrared camera) to capture and/or process images (e.g., digital still images or video) in accordance with an embodiment of the disclosure. For example, various embodiments of imaging system 1400 may be adapted to perform various operations of a process to suppress the sky in images as further described herein. In various embodiments, imaging system 1400 may include an imaging sensor device 1402, a processor 1406, a memory 1408, an orientation sensor 1410, a display 1412, and/or a network interface 1414. In various embodiments, components of imaging system 1400 may be implemented in the same or similar manner as corresponding components of host device 102 of Fig. 1. Moreover, components of imaging system 1400 may be configured to perform various NUC processes described above.

In some embodiments, various components of imaging system 1400 may be distributed and in communication with one another over a network 1420. In this regard, network interface 1414 may be configured to facilitate wired and/or wireless communication among various components of imaging system 1400 over network 1420. In some

embodiments, at least a portion of imaging system 1400 may be implemented using appropriate components of a remote device 1416 (e.g., a conventional digital video recorder (DVR), imaging processing computer, network camera host device, and/or other device) in communication with various components of imaging system 1400 via network interface 1414 over network 1420. That is, for example, all or part of processor 1406, all or part of memory 1408, all or part of display 1412, and/or all or part of network interface 1414 may be implemented or replicated at remote device 1416. In one embodiment, for example, remote device 1416 (e.g., a network camera host device) may be adapted to receive images captured from a remotely located imaging sensor device 1402 (e.g., a surveillance camera) to perform various image processing operations on the received images to suppress the sky in images as further described herein. It will be appreciated that many other distributed implementations of imaging system 1400 are also possible, without departing from the scope and spirit of the disclosure.

In various embodiments, imaging sensor device 1402 may be adapted to capture images (e.g., digital still images or video frames) of a scene. In some embodiments, imaging sensor device 1402 may be implemented using infrared imaging module 100 (e.g., a thermal imager or infrared camera) including infrared sensor assembly 128 (e.g., a FPA) described above, or other appropriate infrared imaging devices suitable for capturing thermal images. Thus, in one embodiment, imaging sensor device 1402 may include LDO 1220 adapted to provide a regulated voltage to a FPA, and bias circuit 1212 adapted to provide a bias voltage to infrared sensors 132 of the FPA, as described above. In one or more embodiments, the thermal images captured at imaging sensor device 1402 may include pixels having pixel values that may be indicative of infrared irradiance levels associated with corresponding locations in the scene.

In other embodiments, imaging sensor device 1402 may alternatively or additionally be implemented using imaging sensor arrays or modules adapted to capture non-thermal (e.g., including electromagnetic radiation in visible wavelengths, near-infrared (NIR) wavelengths, shortwave infrared (SWIR) wavelengths, ultraviolet (UV) wavelengths, and/or other non-thermal wavelengths) images of a scene. In these embodiments, conventional charge-coupled device (CCD) sensors, complementary metal-oxide semiconductor (CMOS) sensors, electron multiplying CCD (EMCCD) sensors, scientific CMOS (sCMOS) sensor, or other sensors may be utilized to additionally or alternatively implement imaging sensor device 1402. In

one or more embodiments, the non-thermal images captured at imaging sensor device 1402 may be visible light images that include pixels having pixel values that may be indicative of irradiance levels of radiation in the visible light spectrum (e.g., luminance, brightness, or other quantity of visible light intensity).

5 In some embodiments, imaging sensor device 1402 may include an optical element 1403 (e.g., lenses, prisms, fiber optics, and/or other elements) adapted to collect, route, and/or focus visible light, infrared radiation, and/or radiation in other spectrum from the scene onto an imaging sensor array of imaging sensor device 1402. In various embodiments, optical element 1403 may also define a field-of-view (FOV) 1404 of imaging sensor device 1402.
10 For example, a portion of a scene 1440 that falls within FOV 1404 may be captured as an image 1442 by imaging sensor device 1402. In some embodiments, optical element 1403 may include an adjustable optical element such as zoom lens. Optical element 1403 according to such embodiments may be adjusted to alter FOV 1404 provided by optical element 1403. In one embodiment, optical element 1403 may include a position sensor (e.g.,
15 a position encoder, potentiometer, and/or other suitable components) adapted to provide feedback information relating to the adjustment of optical element 1403 (e.g., a focal length set on a zoom lens).

 In some embodiments, imaging sensor device 1402 may include both an infrared imaging module (e.g., a thermal imager) and a non-thermal imaging module (e.g., a visible
20 light camera) which may be implemented and used in accordance with any of the various techniques referenced herein. For example, the infrared and non-thermal imaging modules may be implemented as substantially co-located non-thermal cameras and oriented such that an FOV of a non-thermal camera at least partially overlaps an FOV of a corresponding infrared imaging module. In such embodiments, images and/or image data captured by such
25 devices may be superimposed, fused, blended, or otherwise combined (e.g., by processor 1406), as described herein. Imaging sensor device 1402 implementations having more than two imaging modules are also contemplated.

 In some embodiments, imaging sensor device 1402 may optionally be mounted or otherwise installed at a location using an adjustable mount 1405 so that imaging sensor
30 device 1402 may be panned or tilted to adjust FOV 1404 toward a desired direction. For example, adjustable mount 1405 may be adapted to fix or otherwise attach a housing that

encloses imaging sensor device 1402 and/or other components of imaging system 1400 to a suitable structure or location (e.g., a wall). In some embodiments, adjustable mount 1405 may include a position sensor (e.g., a position encoder, potentiometer, and/or other suitable components) adapted to detect a rotation, a translation, and/or other directional changes of
5 imaging sensor device 1402 relative to an installed position. In some embodiments, adjustable mount 1405 may include one or more drive mechanisms (e.g. actuators, motors, and/or other suitable devices) adapted to pan, tilt, or otherwise change an orientation of the attached imaging sensor device 1402 or imaging system 1400 in response to command signals (e.g., from remote device 1416).

10 The example scene 1440 shown in Fig. 14 may be of a landscape that includes the sky and the ground. Thus, for example, image 1442 captured of such a scene 1440 may include a sky region 1444 and a ground region 1446, which may be partitioned at an approximate location of a horizon 1448 in image 1442. In some embodiments, sky region 1444 may be identified as a region or area (e.g., a group of pixels) above horizon 1448 allowing for some
15 margin 1450, as further described herein. As may be appreciated, sky region 1444, ground region 1446, and the location of horizon 1448 in captured image 1442 may change if FOV 1404 of imaging sensor device 1402 is altered.

Processor 1406 may be implemented using any appropriate processing device as described with regard to processor 195 in Fig. 1. In some embodiments, at least some part or
20 some operations of processor 1406 described herein may be implemented as part of imaging sensor device 1402, for example, at processing module 160 described above in connection with Fig. 1. Processor 1406 may be adapted to interface and communicate with other components of camera system 1400 to perform operations and processes described herein.

In various embodiments, processor 1406 may be adapted to receive image 1442 of
25 scene 1444 captured by imaging sensor device 1402, and perform various imaging processing operations on the received image 1442 to suppress the sky in image 1442 as further described herein. In some embodiments, processor 1406 may be adapted to access the captured image 1442 stored in memory 1408 to receive the captured image 1442. In other embodiments, processor 1406 may be adapted to receive and store image 1442 in memory 1408. In some
30 embodiments, processor 1406 may be adapted to store a processed image in memory 1408

after performing various imaging processing operations on the received image 1442 as further described herein.

For embodiments of imaging system 1400 that have both an infrared imaging module and a non-thermal imaging module, processor 1406 may be configured to superimpose, fuse, blend, or otherwise combine infrared images (e.g., including thermal images) captured by the
5 infrared imaging module and non-thermal images (e.g., including visible light images) captured by the non-thermal imaging module to obtain enhanced infrared images having improved resolution and/or contrast, as discussed.

In various embodiments, processor 1406 may include various hardware and/or
10 software modules adapted to perform various imaging processing operations to suppress the sky in image 1442 further described herein. In some embodiments, all or part of the software modules may be machine-executable software instructions stored in a separate machine-readable medium 193 and downloaded or otherwise transferred from such machine-readable
15 medium 193 to imaging system 1400 (e.g., in memory 1408) for execution by processor 1406. For example, the machine-executable software instructions may be executed by processor 1406 to perform various operations of process 1500 described below. In some embodiments, processor 1406 may include hardware logic (e.g., implemented with circuits and other electronic components) configured to perform various operations of process 1500
20 described below. In some embodiments, some operations of process 1500 may be performed by hardware logic of processor 1406 while other operations of process 1500 may be performed by executing software instructions.

Memory 1408 may include one or more memory devices or electro-mechanical storage devices and associated logic (e.g., implemented in hardware, software, or a combination of both) for storing and accessing data and information in the one or more
25 memory or electro-mechanical storage devices. The one or more memory or electro-mechanical storage devices may include various types of volatile and non-volatile memories and storages, such as a hard disk drive, a flash memory, a RAM (Random Access Memory), an EEPROM (Electrically-Erasable Read-Only Memory), and other devices for storing digital information. In various embodiments, memory 1408 may be adapted to store and
30 access images (e.g., image 1442) captured by imaging sensor device 1402, received via network interface 1414, and/or otherwise acquired to be processed by imaging system 1400.

In some embodiments, processor 1406 may be adapted to execute software modules stored in memory 1408 so as to perform various operations described herein.

Orientation sensor 1410 may be fixed relative to imaging sensor device 1402 to detect an orientation of imaging sensor device 1402. For example, orientation sensor 1410 may be
5 attached to or otherwise installed on imaging sensor device 1402 or other suitable parts of imaging system 1400 to obtain a tilt, rotation, altitude, or other orientation measurements of imaging sensor device 1402 relative to a reference point (e.g., relative to the Earth's ground plane or the horizon). In various embodiments, orientation sensor 1410 may be implemented
10 using a gyroscope, accelerometer, inclinometer, altimeter, inertial measurement unit (IMU), and/or other suitable sensors. For example, using an orientation measurement obtained by orientation sensor 1410, processor 1406 may be adapted to calculate or otherwise determine an approximate location of horizon 1448 in image 1442.

In some embodiments, orientation sensor 1410 may further include a global positioning system (GPS) receiver and/or an electronic compass. The GPS receiver and/or
15 electronic compass may be implemented with an appropriate chipset or electronics module adapted for integration into small electronic devices to provide GPS receiver operations, electronic compass operations, or both. The GPS receiver and/or the electronic compass may be utilized to obtain geopositional information associated with imaging system 1400.

In some embodiments, imaging system 1400 may include display 1412, which may be
20 implemented as an image display device (e.g., a liquid crystal display (LCD)) or various other types of generally known video displays or monitors. In some embodiments, processor 1406 may be adapted to display image data (e.g., the captured image and/or processed image) and other information on display 1412. In this regard, display 1412 may include display
25 logic (e.g., hardware circuitry and/or software routines), which may be utilized by the processor 1406 to display image data and information. In some embodiments, display 1412 may additionally or alternatively be implemented at remote device 1416, and adapted to receive image data and information via network interface 1414 to display images to a user remote from imaging sensor device 1402 and/or processor 1406.

In some embodiments, imaging system 1400 may include network interface 1414,
30 which may be adapted to handle, manage, or otherwise facilitate wired and/or wireless communication between imaging system 1400 and an external device, as well as between

various components (e.g., including components implemented at remote device 1416) of imaging system 1400, over network 1420 and/or other connections. In this regard, network interface 1414 according to some embodiments may be adapted to communicate using various wireless and/or wired networking interfaces, protocols, and standards. In one
5 embodiment, network interface 1414 may include a wireless communication component (e.g., based on the IEEE 802.11 WiFi standards, the Bluetooth™ standard, the ZigBee™ standard, or other appropriate short range wireless communication standards), a wireless broadband component (e.g., based on WiMax technologies), mobile cellular component, a wireless satellite component, or other appropriate wireless communication components. In one
10 embodiment, network interface 1414 may be adapted to interface with a wired network via a wired communication component such as a power-line modem (e.g., supporting HomePlug™ standard), a Digital Subscriber Line (DSL) modem, a Public Switched Telephone Network (PSTN) modem, an Ethernet interface, a cable modem, and/or other appropriate components for wired communication. In one embodiment, network interface 1412 may be configured
15 for a proprietary wired communication protocols and interface, and/or for a proprietary wireless communication protocol and interface based on radio frequency (RF), microwave frequency (MWF), infrared frequency (IRF), and/or other appropriate wireless transmission technologies.

In some embodiments, network interface 1414 may be further adapted to support
20 various interfaces, protocols, and/or standards for surveillance cameras and systems, such as the Open Network Video Interface Forum (ONVIF) standard and/or others. Thus, for example, imaging system 1400 may control and/or receive image from other ONVIF-compliant external cameras via network interface 1414, transmit captured and/or processed images to an ONVIF-compliant central monitoring station, and/or receive commands and
25 configurations from an ONVIF-compliant computer.

As discussed above, various components of imaging system 1400 may be combined, replicated, and/or omitted, as desired for particular applications of imaging system 1400. In one example, processor 1406 may be combined with imaging sensor device 1402, memory 1408, display 1412, and/or network interface 1414. In another example, part of processor
30 1406 may be combined with or implemented at imaging sensor device 1402 with only certain operations of processor 1406 performed by circuitry (e.g., a processor, a microprocessor, a logic device, a microcontroller, etc.) within imaging sensor device 1402. In another example,

adjustable mount 1405 may be omitted in fixed-mount applications or portable camera applications of imaging system 1400. In another example, network interface 1414 and remote device 1416 may be omitted in a standalone camera application of imaging system 1400.

5 Fig. 15 illustrates a process 1500 to suppress the sky in images in accordance with an embodiment of the disclosure. For example, all or part of process 1500 may be performed using one or more embodiments of imaging system 1400 of Fig. 14 to suppress the sky in captured images (e.g., reduce consumption of an available output dynamic range by the sky in images) so that more dynamic range can be preserved for terrestrial objects and other
10 objects of interest in the captured images. Although process 1500 may be described below with respect to imaging system 1400 as an example, it should be appreciated that other imaging systems or camera systems (e.g., including visible-light cameras) may be suitably configured and utilized to perform all or part of process 1500.

 At block 1502, an image (e.g., a digital still image or frame of digital video) of a
15 scene may be captured using an imaging sensor device. The scene and hence the captured image, may include, for example, a portion of the sky and a portion of the ground. By way of example, image 1442 including sky region 1444 and ground region 1446 may be captured of scene 1440 using imaging sensor device 1402. In some embodiments, image 1442 may be a non-thermal image (e.g., a visible light image) of scene 1440 captured using imaging sensor
20 device 1402 implemented with a non-thermal imaging module (e.g., a visible-light camera having a CMOS-based or CCD-based sensor).

 In some embodiments, image 1442 may be a thermal image captured using imaging sensor device 1402 implemented with, for example, one or more embodiments of infrared imaging module 100 including infrared sensor assembly 128 (e.g., an FPA) described above.
25 In this regard, capturing the thermal image at block 1502 may, in some embodiments, involve performing NUC operations on the thermal image by obtaining NUC terms and applying them to the thermal image as described above with respect to Figs. 5–11 and elsewhere herein. In some embodiments, capturing the thermal image at block 1502 may involve regulating a voltage supplied to the FPA using LDO 1220 and/or biasing infrared sensors 132
30 of the FPA using bias circuit 1212 as described above with respect to Figs. 12 and 13.

In various embodiments, the captured image 1442 may be represented using, for example, a plurality of pixels each having a pixel value that may be indicative of (e.g., correlated with but not necessarily directly proportional to) an irradiance level (e.g., power of incident radiation) associated with a corresponding location in the scene, as conventionally
5 used in digital imaging. Optionally in some embodiments, the irradiance levels associated with the scene may be further translated into pixel values through various conventional automatic gain control (AGC) methods, conventional dynamic range compression algorithms, conventional exposure control methods, or other conventional methods to fit the range of the irradiance levels associated with the scene to the range of available pixel values.

10 Thus, for embodiments in which the captured image 1442 may be a thermal image of scene 1440, the pixel values may be indicative of irradiance levels of incident infrared radiation from corresponding locations in scene 1440, which in turn may be correlated with temperatures associated with the corresponding locations. For embodiments in which the captured image 1442 may be a visible-light image of scene 1440, the pixel values may be
15 indicative of irradiance levels (also referred to as intensity levels) of incident visible light from corresponding locations in scene 1440. For color visible-light images, there may be three or more channels (e.g., red, green, and blue channels or other suitable color channels) of pixel values according to one or more embodiments.

In some embodiments, both thermal images and non-thermal images may be captured
20 at block 1502, for example by embodiments of imaging sensor device 1402 implemented with both an infrared imaging module and a non-thermal imaging module.

If desired for particular applications of such embodiments, block 1502 may further include superimposing, fusing, blending, or otherwise combining thermal and non-thermal images to obtain enhanced thermal images as discussed. Such combined images may have
25 enhanced resolution and/or contrast while retaining at least some thermal information (e.g., radiometric temperature information) from the captured thermal images. In such embodiments, operations of process 1500 may be performed on or using the combined images where applicable. That is, the sky region in the combined images may be suppressed to further enhance the combined images.

30 Alternatively, the captured thermal images and non-thermal images may be combined after performing operations of process 1500 to suppress the sky region. For example, blocks

1504–1512 of process 1500 may be performed on or using the captured thermal images and/or the captured non-thermal images to suppress the sky region in either or both, which may then be combined to enhance resolution and/or contrast.

5 In some embodiments, various operations of block 1502 may be omitted from process 1500. For example, if image 1442 is a previously captured and/or stored image of scene 1440 that may be provided to imaging system 1400, operations of block 1502 may involve receiving (e.g., via network interface 1414) such image 1442 instead of capturing it. Thus, some embodiments of process 1500 may be utilized to perform various image processing operations on already captured images to suppress the sky in those images without capturing
10 the images using imaging sensor device 1402.

At block 1504, a region or area (e.g., a group of pixels) that may correspond to the sky in the captured image (e.g., including previously captured and stored image) may be identified. For example, sky region 1444 in the captured image 1442 may be identified. In various embodiments, operations at block 1504 to identify the sky region may include
15 determining a location of a horizon (e.g., horizon 1448) in the image. Based on the location of the horizon, the captured image may be segmented into a sky region (e.g., sky region 1444) above the horizon and a ground region (e.g., ground region 1446) on or below the horizon. In some embodiments, some margin (e.g., margin 1450) may be added above the horizon to identify a sky region, so as to reduce misclassification of terrestrial objects
20 extending above the horizon as belonging to the sky. In some embodiments, margin 1450 may be adaptably adjusted (e.g., based on an image analysis). In other embodiments, margin 1450 may be specified (e.g., by a user).

The location of the horizon in the captured image may be determined in various ways. In some embodiments, the location of the horizon in the image may be determined using
25 orientation sensor 1410 (e.g., including a gyroscope, inclinometer, altimeter, and/or other sensor to determine an orientation relative to the horizon or other reference point), which may be fixed relative to imaging sensor device 1410 and/or calibrated to detect and provide the relative position of the horizon in FOV 1404 of imaging sensor device 1402. For example, the location of the horizon in the image may be calculated or otherwise determined from one
30 or more tilt angles of imaging sensor device 1402 in relation to the ground plane of the Earth as detected by orientation sensor 1410.

In some embodiments, the location of the horizon in the captured image may be determined based on a baseline location of the horizon for a particular application of imaging sensor device 1402 or imaging system 1400. For example, in applications where imaging sensor device 1402 and/or imaging system 1400 may be mounted or otherwise installed at some location or mounting point (e.g., utilized as surveillance cameras, vehicle-mounted cameras, or boat-mounted cameras), the baseline location of the horizon with respect to the given installation location may be indicated or otherwise provided (e.g., as pixel coordinates inputted by a user).

In this regard, for fixed-mount applications where camera angles/positions do not substantially change after installation, the indicated baseline location may be utilized as the location of the horizon in the captured image, for example. In another example application, imaging sensor device 1402 and/or imaging system 1400 may be installed using adjustable mount 1405 (e.g., a pan-and-tilt mount) having a position encoder, potentiometer, or other suitable components adapted to provide position feedback information. Such position feedback information may include, for example, a rotation, a translation, and/or other directional changes of imaging sensor device 1402 and/or imaging system 1400 relative to the installed position. In such applications, the position feedback information may be utilized to calculate offsets or otherwise adjust for any change to the location of the horizon in the image relative to the baseline location.

Similarly, in another example application, imaging sensor device 1402 may include optical element 1403 (e.g., a zoom lens) that may be adjustable and include a position sensor (e.g., a position encoder, potentiometer, and/or other suitable components) adapted to provide feedback information relating to the adjustment of the optical element (e.g., a focal length set on a zoom lens). Such feedback information may be utilized to adjust for any change to the location of the horizon relative to the baseline location due to a change in FOV 1404 provided by optical element 1403.

In some embodiments, the location of the horizon in the captured image may be determined by performing image analysis operations to detect the horizon in the captured image. Various suitable algorithms may be utilized to detect the horizon in the captured image, according to one or more embodiments. For example, the image analysis operations may include edge detection algorithms and/or line detection algorithms (e.g., using Hough

transform or other suitable methods) suitably modified to detect one or more lines that likely correspond to the horizon in the captured image.

At block 1506, a distribution of irradiance levels in the identified sky region (e.g., sky region 1444) may be analyzed. For example, statistical properties may be analyzed of pixels
5 values (e.g., values indicative of irradiance levels) associated the sky region in the image. In a specific example according to some embodiments, a histogram of such pixel values may be obtained at block 1506. In some embodiments, such a histogram may be obtained by collecting and aggregating over multiple image frames, so as to construct a more accurate histogram of the irradiance levels associated with the sky region. For example, for
10 applications in which a large margin of error may be present in the identification of the sky region (e.g., due to a variability in the location of the horizon such as when used for vehicle-mounted or boat-mounted cameras), the number of samples (e.g., image frames) to be aggregated may be increased accordingly. Other statistical properties, such as the mean, the median, the standard deviation, and/or other properties may be additionally or alternatively
15 collected, according to some embodiments.

At block 1508, a dynamic range attributable to the sky region may be determined based on the analysis of the distribution of irradiance levels. In various embodiments, the dynamic range attributable to the sky region may be a range of irradiance levels that are dominant in or otherwise representative of the sky region, wherein such a range may be
20 identified through various operations of block 1508. Various operations of block 1508 may be better understood with reference to Figs. 16A–16C, which illustrate example histograms of infrared irradiance levels (e.g., represented by pixel values) in sky regions, in accordance with various embodiments of the disclosure. The example histograms of Figs. 16A–16C may be obtained, for example, according to one or more embodiments of the distribution analysis
25 operations at block 1506. Although block 1508 may be described below with respect to infrared irradiance levels in thermal images, it will be appreciated that various operations of block 1508 may be applicable to irradiance levels, luminance levels, or other qualities relating to intensities of pixels in visible light images.

In the example histogram of Fig. 16A, a range 1602A of infrared irradiance levels that
30 are dominant (e.g., frequently observed) in the sky region may be identified, according to various embodiments. In various embodiments, range 1602A may be determined at block

1508 using various statistical criteria or statistical grouping methods. For example, in some embodiments, a range of irradiance levels having a frequency of occurrence above an absolute threshold or a relative threshold (e.g., percentage of some reference value) may be selected as range 1602A. In some embodiments, a distribution of irradiance levels in the ground region may also be analyzed to determine range 1602A. For example, in some
5 embodiments, the absolute or relative threshold utilized in selecting range 1602A may be based at least in part on the frequency, the mean value of the frequency, the mean irradiance level, and/or other statistical properties of the irradiance level distribution in the ground region.

10 Range 1602A in the example histogram of Fig. 16A corresponds to lower infrared irradiance levels, which may indicate that the sky region is mostly colder than the ground region. Although in many situations the sky is mostly colder than the ground, there may be situations where the sky is mostly warmer than the ground. For example, an overcast sky in a cold winter climate may be warmer than the ground. Fig. 16B illustrates an example
15 histogram that may be obtained in a situation where the sky is warmer than the ground. In this example histogram, dominant infrared irradiance levels in the sky region (e.g., a range 1602B determined through one or more operations of block 1508 described above) may correspond to higher infrared irradiance levels. In this regard, for some embodiments it may also be determined at block 1508 whether the irradiance levels in the sky region are generally
20 lower or higher relative to those of the ground region (e.g., whether the sky region is generally colder or warmer in embodiments where thermal images are utilized). For example, in one embodiment, range 1602A or range 1602B may be compared against the distribution of irradiance levels in the ground region, and based on the comparison, a cold sky condition (dark sky condition if used for visible light images) or warm sky condition (bright
25 sky condition if used for visible light images) may be indicated. In some embodiments, the indication of a cold (dark) or warm (bright) sky condition may be utilized in generating appropriate transfer functions as further described herein.

 In some situations, more than one ranges of irradiance levels may be identified using various operations of block 1508 described above for various embodiments. In the example
30 histogram of Fig. 16C, two separate ranges 1602C and 1604C may be identified using various operations of block 1508 described above. For example, the irradiance levels in range 1602C may be attributable to clear portions of the sky, whereas the irradiance levels in range 1604C

may be attributable to patches of clouds, the sun, and/or other objects in the sky. Thus, in some embodiments, operations of block 1508 may include selecting only one or some of the identified ranges to be the dynamic range attributable to the sky region.

More specifically in some embodiments, only the lowest identified range (e.g., if in a cold sky condition) or the highest identified range (e.g., if in a warm sky condition) may be selected to be the dynamic range attributable to the sky region. In the example histogram of Fig. 16C, range 1602C is the lowest identified range (e.g., the range covering the lower irradiance levels), and thus range 1602C, but not range 1604C, may be selected as the dynamic range attributable to the sky region according to some embodiments. In other embodiments, one or more of the identified ranges may be selected based alternatively or additionally on other criteria, such as for example the total frequency count of the identified ranges (e.g., the range that has the highest total frequency may be selected), the corresponding frequency of irradiance levels in the ground region (e.g., the range that has the lowest total frequency of occurrence in the ground region may be selected), and/or other suitable criteria.

At block 1510, a transfer function may be generated that compresses (e.g., maps to a narrower range) the dynamic range attributable to the sky region. A transfer function, as would be understood by one skilled in the art, may be utilized to map input signals or levels to desired output signals or levels. For example, a transfer function may be utilized to map input pixel values (e.g., in the captured images) to output pixel values to generate a desired output image.

In various embodiments, the transfer function that may be generated at block 1510 may be adapted to map the dynamic range attributable to the sky region in the captured image to a narrower range in an output image. In some embodiments, the generated transfer function may be a nonlinear function adapted to map the dynamic range attributable to the sky region to a narrower output dynamic range. In one embodiment, the nonlinear transfer function may be a gamma curve (also referred to as a gamma transfer function) having an exponent gamma (γ). For example, a gamma curve may be expressed as a power function:

$$\text{Output} = \text{Input}^{\gamma} \quad (\text{Equation 1}),$$

wherein the exponent gamma (γ) may be chosen such that dynamic range attributable to the sky region may be mapped to a narrower output dynamic range. As may be appreciated, a gamma curve with same or similar characteristics may be expressed using an equation different from Equation 1. As it may also be appreciated from the present disclosure, various other nonlinear functions may also be suitable as the transfer function. Non-limiting examples of such nonlinear functions include sinusoidal functions such (e.g., a sine or cosine function), nonlinear polynomial functions, power functions, or other suitable nonlinear functions. In other embodiments, the generated transfer function may be a piece-wise linear function having two or more sections and adapted to map the dynamic range attributable to the sky region to a narrower output dynamic range.

The generation of the transfer function at block 1510 may be better understood with reference to Figs. 17A–19, which illustrate examples of various transfer functions that may be generated in accordance with various embodiments of the disclosure. In Figs. 17A–19, input levels and output levels are both normalized to one, and assigned to the x axis and the y axis respectively. Fig. 17A illustrates an example gamma curve 1700A generated as a transfer function to compress the dynamic range attributable to the sky region, in accordance with an embodiment of the disclosure. In this example, an input range 1704 may correspond to the dynamic range attributable to the sky region in the captured image, whereas an input range 1706 may correspond to the dynamic range attributable to the ground region and/or other objects in the captured image. Fig. 17A shows as an example input range 1704 covering lower input levels, which may indicate that the sky region may be colder (or darker if the captured image is a visible light image) than the ground region as discussed above.

In various embodiments, gamma curve 1700A may be generated with an exponent γ such that input range 1704 maps to an output range 1708A that is narrower than input range 1704. For example, in some embodiments, an exponent γ may be chosen such that input range 1704 maps at most to some predetermined percentage (e.g., about 20% in Fig. 17A) of the output dynamic range. In some embodiments, an exponent γ may be chosen such that the ratio of output range 1708A to input range 1704 does not exceed a predetermined ratio (e.g., a predetermined slope as represented by a line 1712). In these embodiments, an appropriate exponent γ may be obtained (e.g., calculated or otherwise derived) from a mapping selected according to an embodiment. An exponent γ that is larger than one may be obtained, if for

example gamma curve 1700A is to be generated for a cold (dark) sky condition such as shown in the example of Fig. 17A.

In Fig. 17A, for example, gamma curve 1700A generated according one or more embodiments may map input range 1704, which consumes about 60% of the input dynamic range, to output range 1708A that consumes only about 20% of the output dynamic range. Correspondingly, input range 1706 (e.g., the dynamic range attributable to the ground region and/or other objects in the captured image), which accounts for only about 40% of the input dynamic range, may be expanded to a range 1710A that can span about 80% of the output dynamic range. Thus, for example, gamma curve 1700A may beneficially expand the output dynamic range available for terrestrial objects and other objects of interest, so that terrestrial objects or other objects of interest may be more easily distinguished or recognized by a user viewing an output image generated by applying gamma curve 1700A to the captured image.

Fig. 17B illustrates an example piece-wise linear function 1700B generated as a transfer function to compress the dynamic range attributable to the sky region, in accordance with another embodiment of the disclosure. In various embodiments, piece-wise linear function 1700B may include a plurality of sections. For example, piece-wise linear function 1700B may include sections 1701 and 1702 as illustrated in Fig. 17B, wherein section 1701 may be adapted to map input range 1704 (e.g., the dynamic range attributable to the sky region) to a narrower output range 1708B, while section 1702 may be adapted to map input range 1706 (e.g., the dynamic range attributable to the ground region and/or other objects in the captured image) to an expanded output range 1710B.

As shown, section 1701 (e.g., the section mapping the dynamic range attributable to the sky region in the captured image) may be generated to compress the dynamic range attributable to the sky region, while section 1702 may be generated to reciprocally expand the dynamic range attributable to the ground region and/or other objects in the captured image, according to various embodiments. For example, in some embodiments, the slope of section 1701 may be chosen such that input range 1704 maps at most to some predetermined percentage (e.g., about 20% in Fig. 17B) of the output dynamic range. In some embodiments, the slope of section 1701 may be chosen so that it does not exceed a predetermined slope (e.g., the slope of line 1712). Thus, for example, piece-wise linear function 1700B generated according to one or more embodiments may compress input range

1704 (which spans about 60% of the input dynamic range) to output range 1708B that only consumes about 20% of the output dynamic range, while reciprocally expanding input range 1706 (which spans about 40% of the input dynamic range) to output range 1710B that can consume about 80% of the output dynamic range, as shown in the example of Fig. 17B.

5 Fig. 18A illustrates another example gamma curve 1800A generated as a transfer function to compress the dynamic range attributable to the sky region, in accordance with another embodiment of the disclosure. In this example, an input range 1804 (covering higher input levels) may correspond to the dynamic range attributable to the sky region in the captured image, whereas an input range 1806 may correspond to the dynamic range
10 attributable to the ground region and/or other objects in the captured image. Input range 1804 and 1806 may thus correspond to a warm sky condition (or a bright sky condition if used for visible light images). Accordingly, gamma curve 1800A in various embodiments may be generated to compress input range 1804 attributable to a warmer-than-ground sky region, whereas gamma curve 1700A of Fig. 17A described above may be generated to compress
15 input range 1704 attributable to a colder-than-ground sky region.

 In various embodiments, gamma curve 1800A may be generated with an exponent γ such that input range 1804 maps to an output range 1808A that is narrower than input range 1804, in a manner similar to generating gamma curve 1700A. However, because gamma curve 1800A may be generated to compress a warmer-than-ground sky region, the exponent γ
20 may be smaller than 1 so that the shape of gamma curve 1800A may be suitable for compressing an upper input range (e.g., input range 1804). In some embodiments, an exponent γ may be chosen such that input range 1804 maps at most to some predetermined percentage (e.g., about 20% in Fig. 18A) of the output dynamic range. In some
25 embodiments, an exponent γ may be chosen such that the ratio of output range 1808A to input range 1804 does not exceed a predetermined ratio (e.g., a predetermined slope as represented by a line 1812). In the illustrated example of Fig. 18A, gamma curve 1800A generated according to one or more embodiments may map input range 1804 (which spans about 60% of the input dynamic range) to output range 1808A that only consumes about 20%
30 of the output dynamic range, while reciprocally expanding input range 1806 (which spans about 40% of the input dynamic range) to output range 1810A that can consume about 80% of the output dynamic range.

Fig. 18B illustrates another piece-wise linear function 1800B generated as a transfer function to compress the dynamic range attributable to the sky region, in accordance with another embodiment of the disclosure. In various embodiments, piece-wise linear function 1800B may be suitable for compressing the dynamic range attributable to the sky region (e.g., input range 1804) in a warm sky condition, but otherwise generated in a similar manner as piece-wise linear function 1700B of Fig. 17B. For example, piece-wise linear function 1800B generated according to one or more embodiments may include a section 1801 that may compress input range 1804 (e.g., spanning about 60% of the input dynamic range) to output range 1808B (e.g., consuming about 20% of the output dynamic range), and also include a section 1802 that may reciprocally expand input range 1806 (e.g., spanning about 40% of the input dynamic range) to output range 1810B (e.g., expanded to about 80% of the output dynamic range), as shown in Fig. 18B. In various embodiments, to compress input range 1804, the slope of section 1801 may be limited at most to a predetermined slope (e.g., the slope of line 1812) and/or to a slope that maps input range 1804 to at most some predetermined percentage (e.g., about 20% in Fig. 18B) of the output dynamic range.

Fig. 19 illustrates another example piece-wise linear function 1900 generated as a transfer function to compress the dynamic range attributable to the sky region, in accordance with another embodiment of the disclosure. In various embodiments, piece-wise linear function 1900 may include sections 1901, 1902, and 1903, wherein section 1901 may be adapted to map input range 1904 (e.g., the dynamic range attributable to the sky region) to a narrower output range 1908. In various embodiments, sections 1902 and 1903 may be adapted to map input ranges 1906 and 1907, which together may correspond to a dynamic range attributable to the ground region and/or other objects in the captured image, to expanded output ranges 1910 and 1911 respectively.

That is, for example, the illustrated piece-wise linear function 1900 may be suitable for compressing the dynamic range attributable to the sky region (e.g., input range 1904) in situations where two separated input ranges (e.g., input ranges 1906 and 1907) may together correspond to the dynamic range attributable to the ground region, but may otherwise be generated in a similar manner as piece-wise linear function 1700B or 1800B. Thus, to compress input range 1904, the slope of section 1901 may be limited at most to a predetermined slope (e.g., the slope of line 1912) and/or to a slope that maps input range 1904 to at most some predetermined percentage (e.g., about 20% in Fig. 19) of the output

dynamic range, according to various embodiments. In this regard, although piece-wise linear functions 1700B, 1800B, 1900 having two or three sections are described above, piece-wise linear functions 1700B, 1800B, or 1900 may be appropriately modified to include any number of sections to accommodate various other patterns of input range distributions in accordance with the scope and spirit of the disclosure.

Turning now to block 1512 of process 1500, the generated transfer function may be applied to the captured image to produce a processed (e.g., sky-suppressed) image. For example, in various embodiments, pixel values of the pixels in the captured image may be mapped or otherwise converted to new pixel values in the processed image according to various embodiments of the transfer function generated at block 1510. As discussed, the application of the generated transfer function to the captured image may advantageously reduce consumption of an available output dynamic range by the sky in images, so that more dynamic range may be available for terrestrial objects and other objects of interest in the captured images.

An example application of a transfer function of one or more embodiments to a captured image is illustrated in Figs. 20A–20B in accordance with an embodiment of the disclosure. More specifically, Fig. 20A is an example screenshot of a captured thermal image and Fig. 20B is an example screenshot of a processed (e.g., sky-suppressed) thermal image converted or otherwise obtained from the captured image through application of a transfer function generated according to one or more embodiments. In the captured image of Fig. 20A, an object of interest 2002 (e.g., a person) may be difficult to identify or distinguish due to, for example, insufficient contrast between object of interest 2002 and other terrestrial objects or the ground. In the processed image of Fig. 20B, the consumption of the dynamic range by the sky region may be reduced while the dynamic range available to the ground and terrestrial objects (e.g., including object of interest 2002) may be correspondingly expanded, which may permit object of interest 2002 to more easily distinguished or identified.

Therefore, various embodiments of the methods and systems disclosed herein may advantageously suppress the sky in images (e.g., reduce consumption of an available output dynamic range by the sky in images) to preserve more dynamic range for terrestrial objects and other objects of interest in images, for example, by identifying a sky region in images, analyzing the irradiance distribution in the sky region, determining a dynamic range

attributable to the sky region, and generating and applying a transfer function that compresses the dynamic range attributable to the sky region in images. Thus, for example, various embodiments of the methods and systems disclosed herein may be included in or implemented as various devices and systems that capture and/or process still and/or video
5 images (e.g., including thermal images) to beneficially allow a user to more easily identify or recognize terrestrial objects in the images.

Where applicable, various embodiments provided by the present disclosure can be implemented using hardware, software, or combinations of hardware and software. Also where applicable, the various hardware components and/or software components set forth
10 herein can be combined into composite components comprising software, hardware, and/or both without departing from the spirit of the present disclosure. Where applicable, the various hardware components and/or software components set forth herein can be separated into sub-components comprising software, hardware, or both without departing from the spirit of the present disclosure. In addition, where applicable, it is contemplated that software
15 components can be implemented as hardware components, and vice-versa.

Software in accordance with the present disclosure, such as non-transitory instructions, program code, and/or data, can be stored on one or more non-transitory machine readable mediums. It is also contemplated that software identified herein can be implemented using one or more general purpose or specific purpose computers and/or
20 computer systems, networked and/or otherwise. Where applicable, the ordering of various steps described herein can be changed, combined into composite steps, and/or separated into sub-steps to provide features described herein.

Embodiments described above illustrate but do not limit the invention. It should also be understood that numerous modifications and variations are possible in accordance with the principles of the invention. Accordingly, the scope of the invention is defined only by the
25 following claims.

CLAIMS

What is claimed is:

1. A system comprising:

5 a memory adapted to store an image of a scene including a sky region and a ground region; and

a processor adapted to communicate with the memory, the processor adapted to:

identify the sky region in the image,

10 analyze a distribution of pixel levels associated with the sky region in the image,

determine a dynamic range attributable to the sky region based on the distribution of the pixel levels,

generate a transfer function that compresses the dynamic range attributable to the sky region, and

15 apply the transfer function to the image.

2. The system of claim 1, wherein

the transfer function is a nonlinear gamma curve; and

20 the processor is adapted to determine an exponent of the gamma curve such that the gamma curve compresses the dynamic range attributable to the sky region.

3. The system of claim 1, wherein

the transfer function is a piece-wise linear function having a plurality of line sections;
and

the processor is adapted to determine slopes of the line sections such that the piece-wise linear function compresses the dynamic range attributable to the sky region.

4 . The system of claim 1, wherein the processor is adapted to:

5 determine a location of a horizon in the image; and

identify the sky region in the image based on the location of the horizon.

5 . The system of claim 4, wherein the processor is adapted to analyze the image to detect the location of the horizon.

10

6 . The system of claim 1, further comprising an imaging sensor device adapted to capture the image of the scene and to provide the captured image to the memory and/or the processor.

15 7 . The system of claim 6, further comprising an orientation sensor adapted to detect an orientation of the imaging sensor device relative to a horizon, wherein the processor is adapted to:

determine a location of the horizon in the image based on the orientation; and

identify the sky region in the image based on the location of the horizon.

20

8 . The system of claim 6, wherein

the image is a thermal image of the scene; and

the imaging sensor device is a thermal imager comprising a focal plane array (FPA) of infrared sensors and adapted to capture the thermal image.

25

9. The system of claim 8, wherein the FPA comprises:

a low-dropout regulator (LDO) integrated with the FPA and adapted to provide a regulated voltage in response to an external supply voltage; and

a bias circuit adapted to provide a bias voltage to the infrared sensors in response to
5 the regulated voltage from the LDO.

10. The system of claim 8, wherein:

the thermal imager is adapted to capture an intentionally blurred image of the scene, the blurred image comprising noise introduced by the thermal imager; and

10 the processor is further adapted to:

use the blurred image to determine a plurality of non-uniformity correction (NUC) terms to reduce at least a portion of the noise, and

apply the NUC terms to the thermal image.

15 11. A method comprising:

receiving an image of a scene including a sky region and a ground region;

identifying the sky region in the image;

analyzing a distribution of pixel levels associated with the sky region in the image;

determining a dynamic range attributable to the sky region based on the distribution
20 of the pixel levels;

generating a transfer function that compresses the dynamic range attributable to the sky region; and

applying the transfer function to the image.

12. The method of claim 11, wherein:

the transfer function is a nonlinear gamma curve; and

the generating the transfer function comprises determining an exponent of the gamma curve such that the gamma curve compresses the dynamic range attributable to the sky region.

13. The method of claim 11, wherein

the transfer function is a piece-wise linear function having a plurality of line sections; and

the generating the transfer function comprises determining slopes of the line sections such that the piece-wise linear function compresses the dynamic range attributable to the sky region.

14. The method of claim 11, further comprising determining a location of a horizon in the image, wherein the sky region in the image is identified based on the location of the horizon.

15. The method of claim 14, wherein the determining the location of the horizon comprises analyzing the image to detect the horizon.

16. The method of claim 11, further comprising capturing the image of the scene using an imaging sensor device.

17. The method of claim 16, further comprising:

detecting an orientation of the imaging sensor device relative to a horizon using an orientation sensor fixed relative to the imaging sensor device;

determining a location of the horizon in the image based on the orientation, wherein the sky region in the image is identified based on the location of the horizon.

5

18. The method of claim 16, wherein

the imaging sensor device is a thermal imager comprising a focal plane array (FPA) of infrared sensors; and

10 capturing the image comprises capturing a thermal image of the scene using the thermal imager.

19. The method of claim 18, further comprising:

receiving an external supply voltage at the FPA;

15 providing a regulated voltage in response to the external supply voltage using a low-dropout regulator (LDO) integrated with the FPA; and

providing a bias voltage from a bias circuit of the FPA to the infrared sensors of the FPA, the bias voltage provided in response to the regulated voltage from the LDO.

20. The method of claim 18, further comprising:

20 capturing an intentionally blurred image of the scene, the blurred image comprising noise introduced by the thermal imager;

determining a plurality of non-uniformity correction (NUC) terms to reduce at least a portion of the noise, using the blurred image; and

applying the NUC terms to the thermal image.

1

1/19

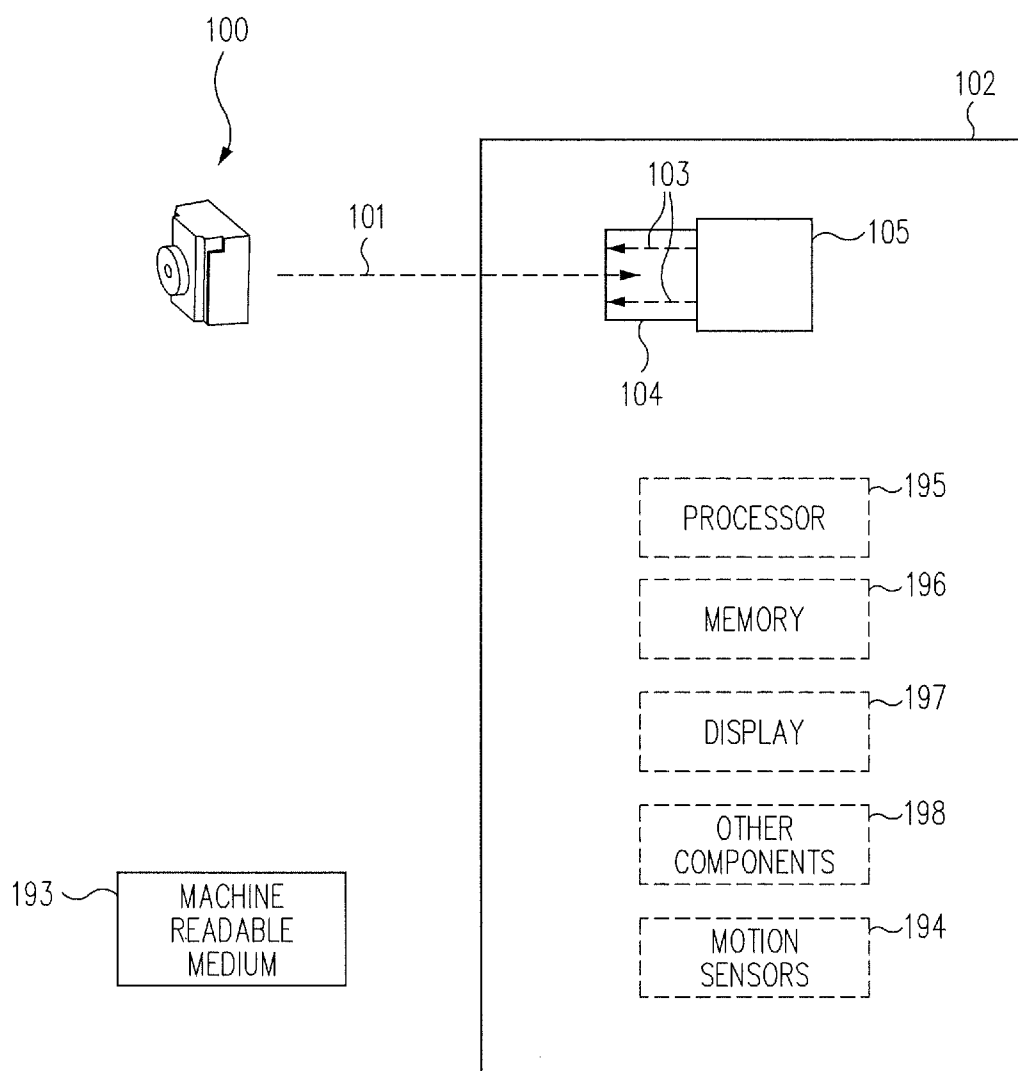


FIG. 1

2/19

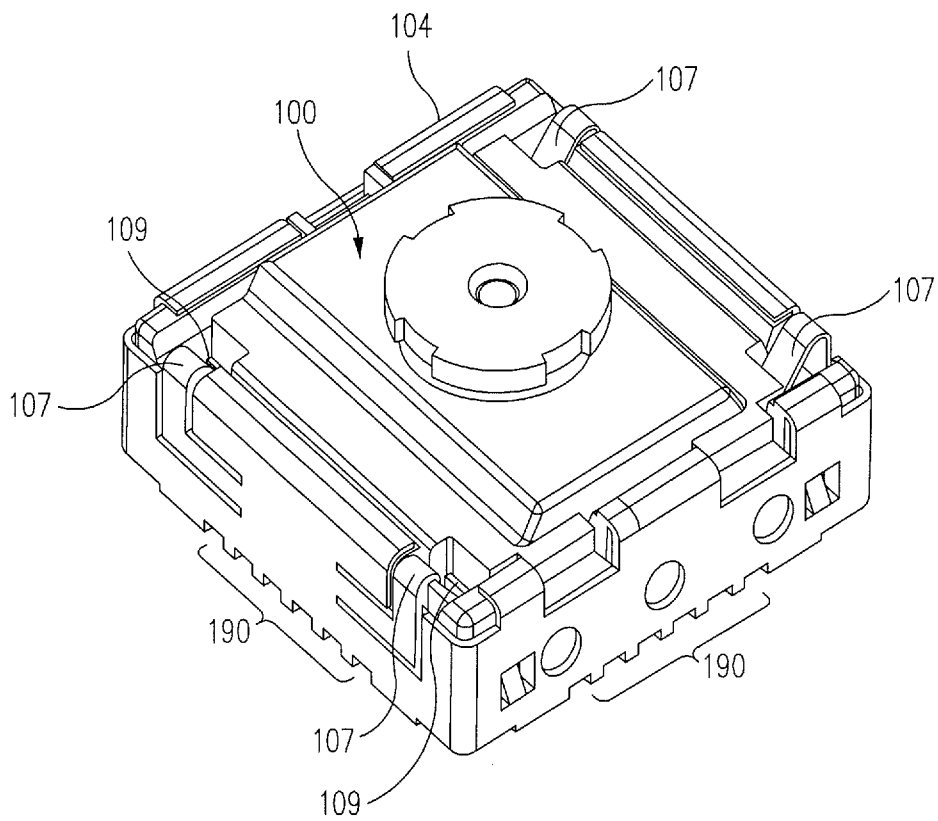


FIG. 2

3/19

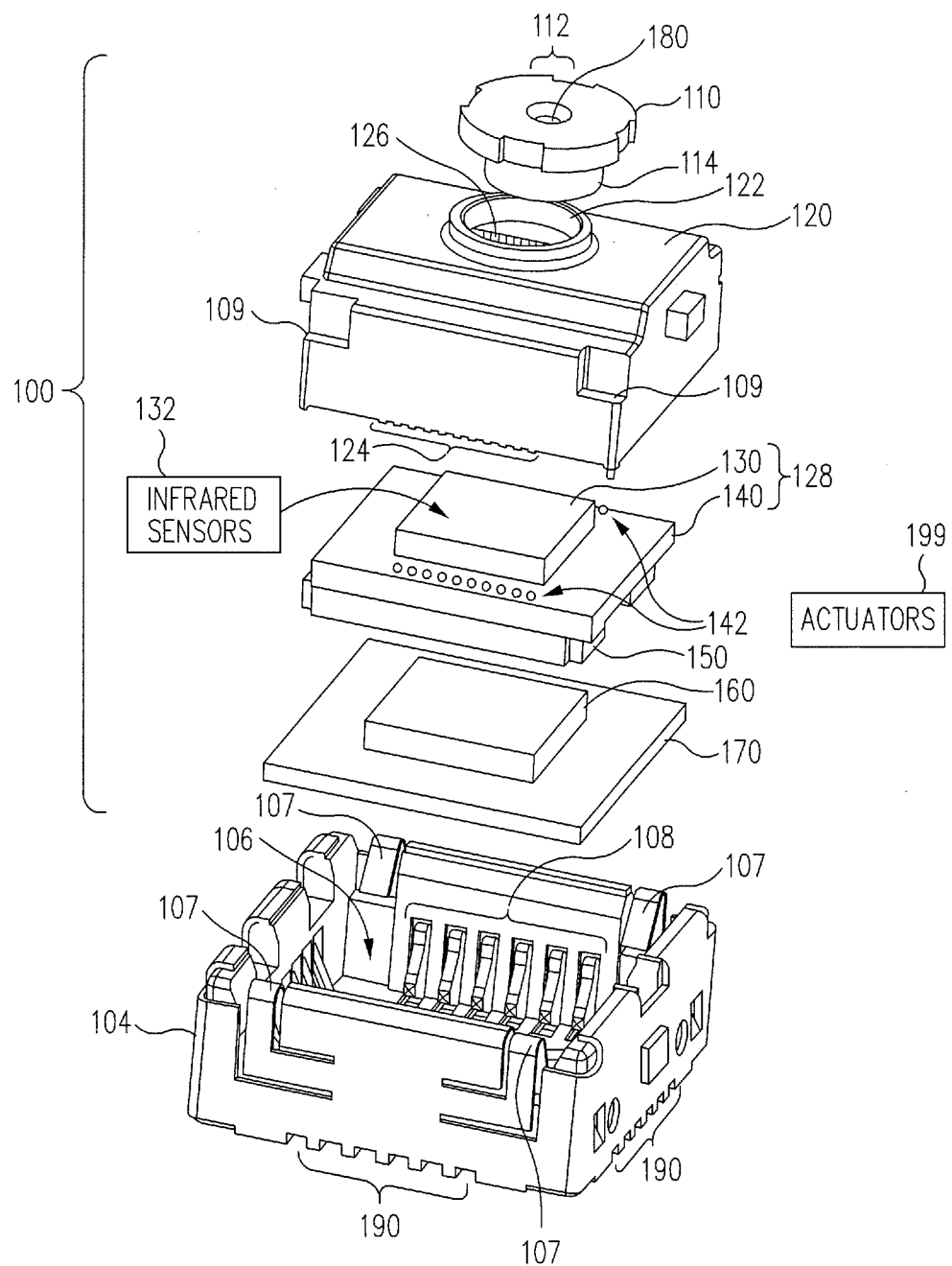


FIG. 3

4/19

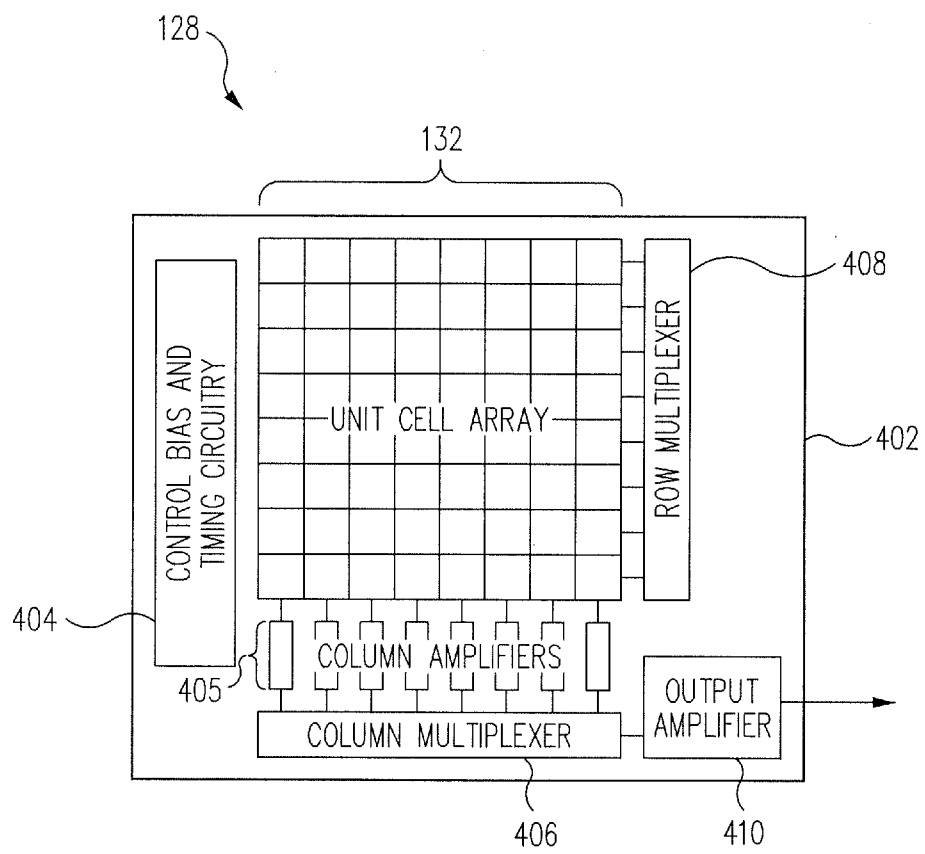


FIG. 4

5/19

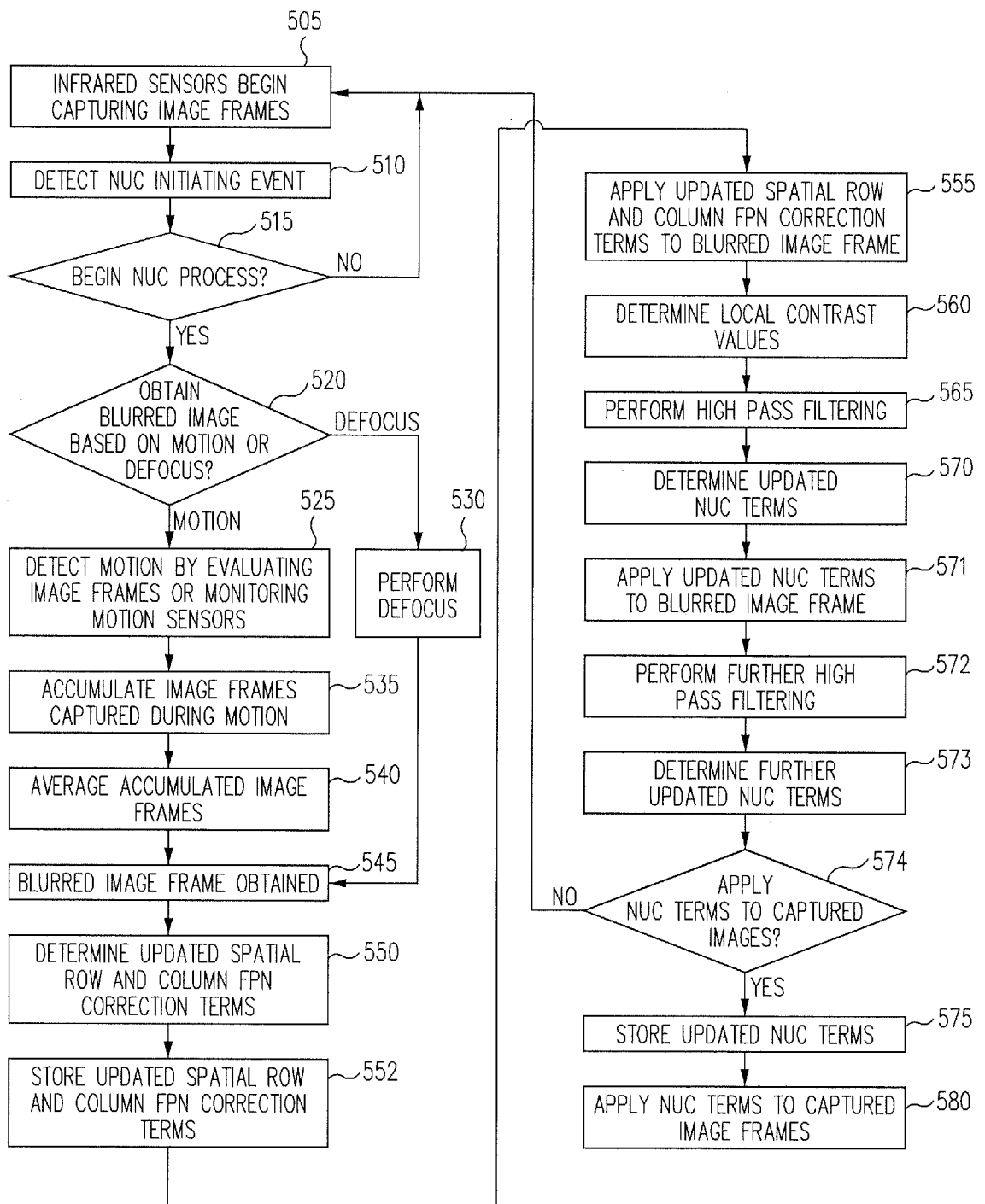


FIG. 5

6/19

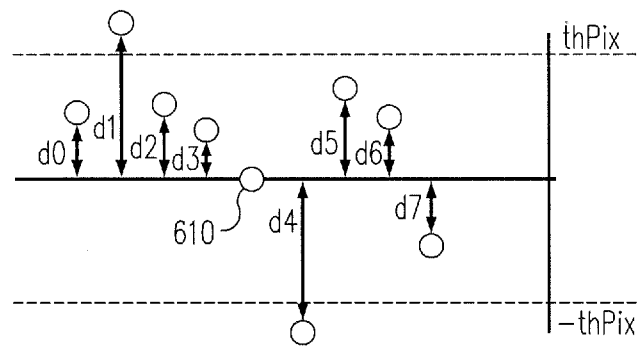


FIG. 6

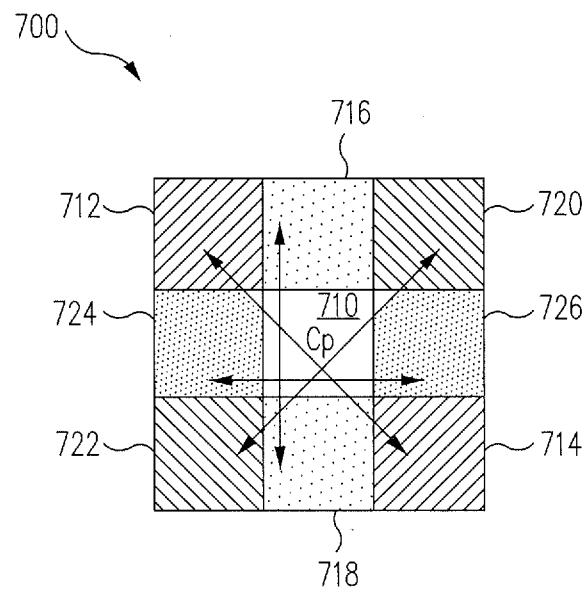


FIG. 7

7/19

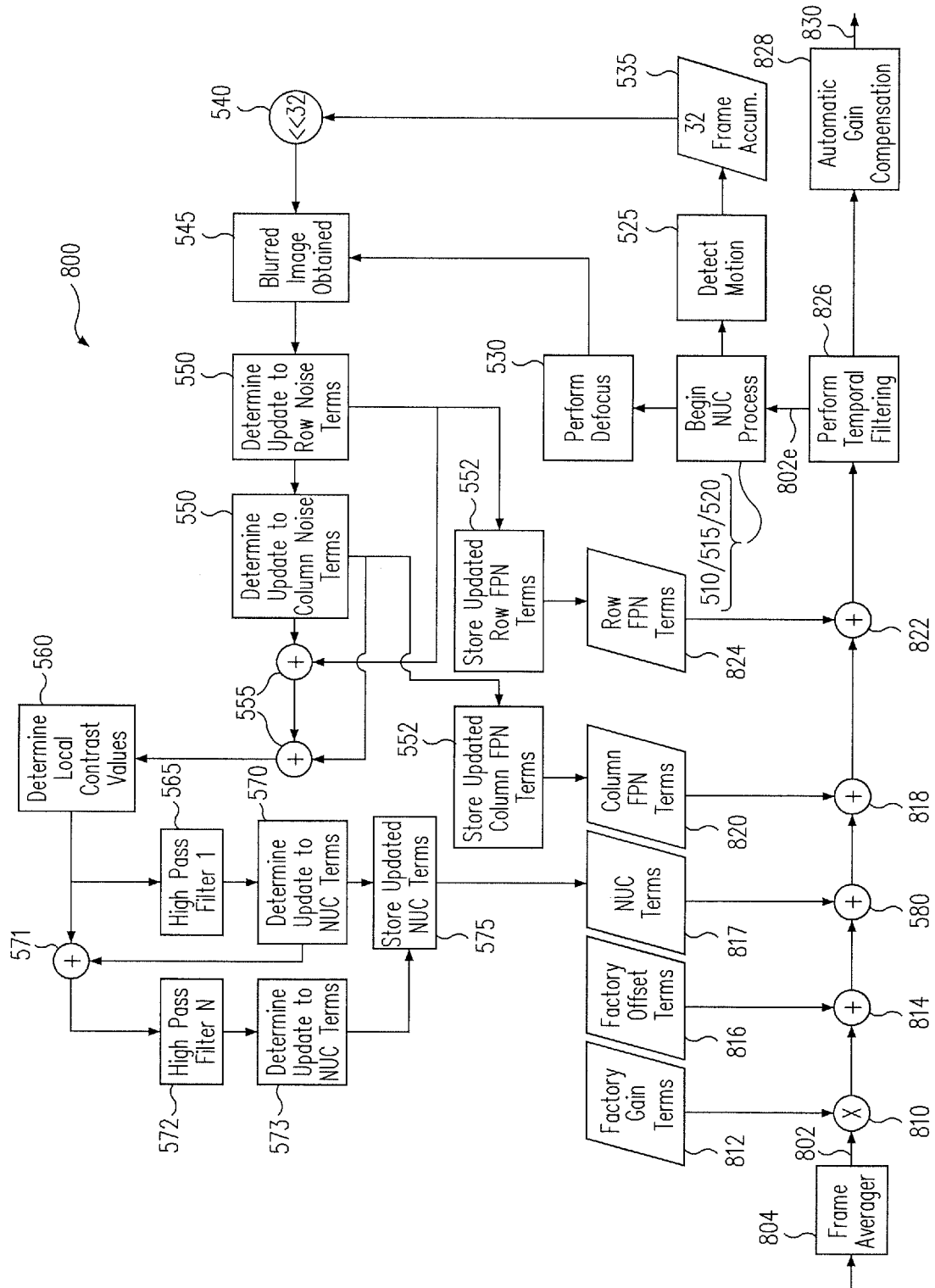


FIG. 8

8/19

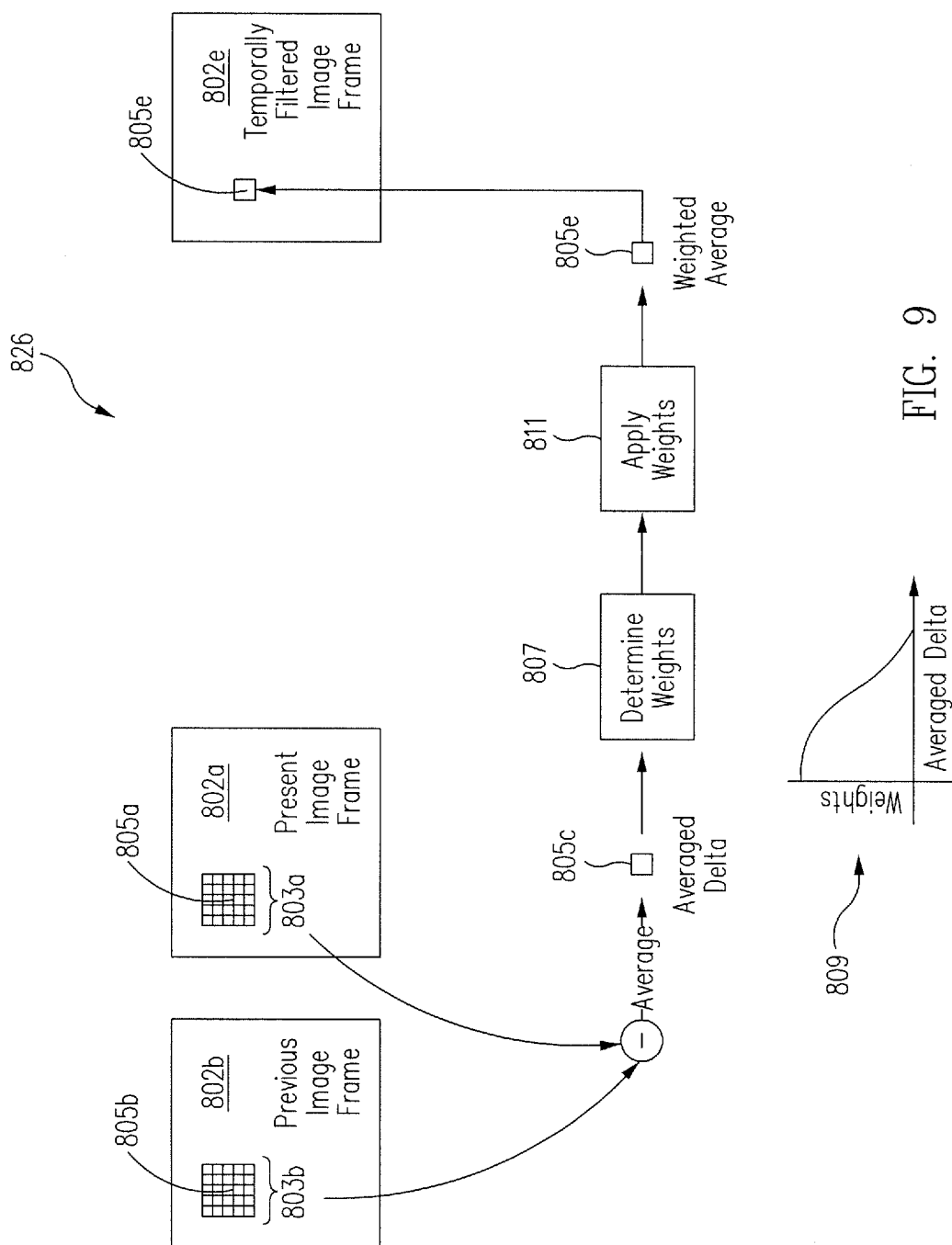


FIG. 9

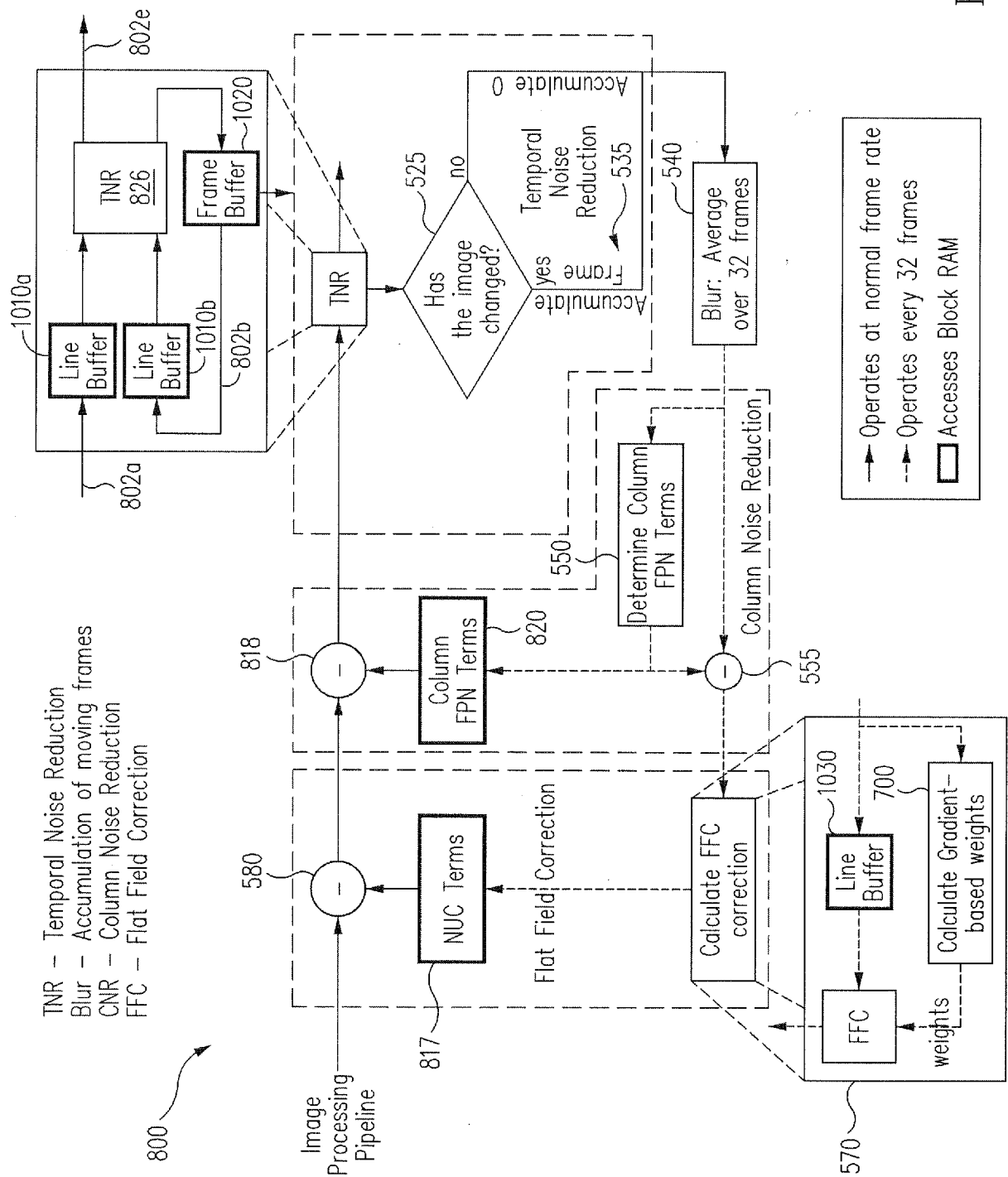


FIG. 10

10/19

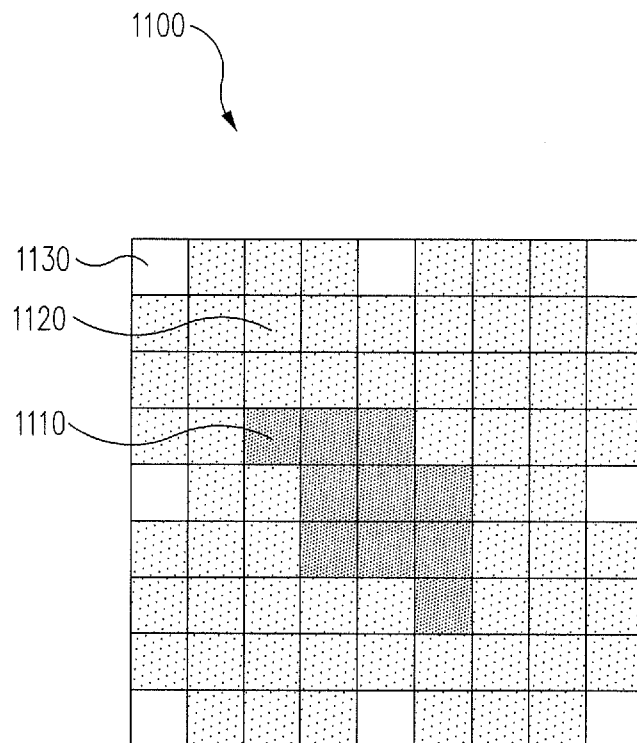


FIG. 11

11/19

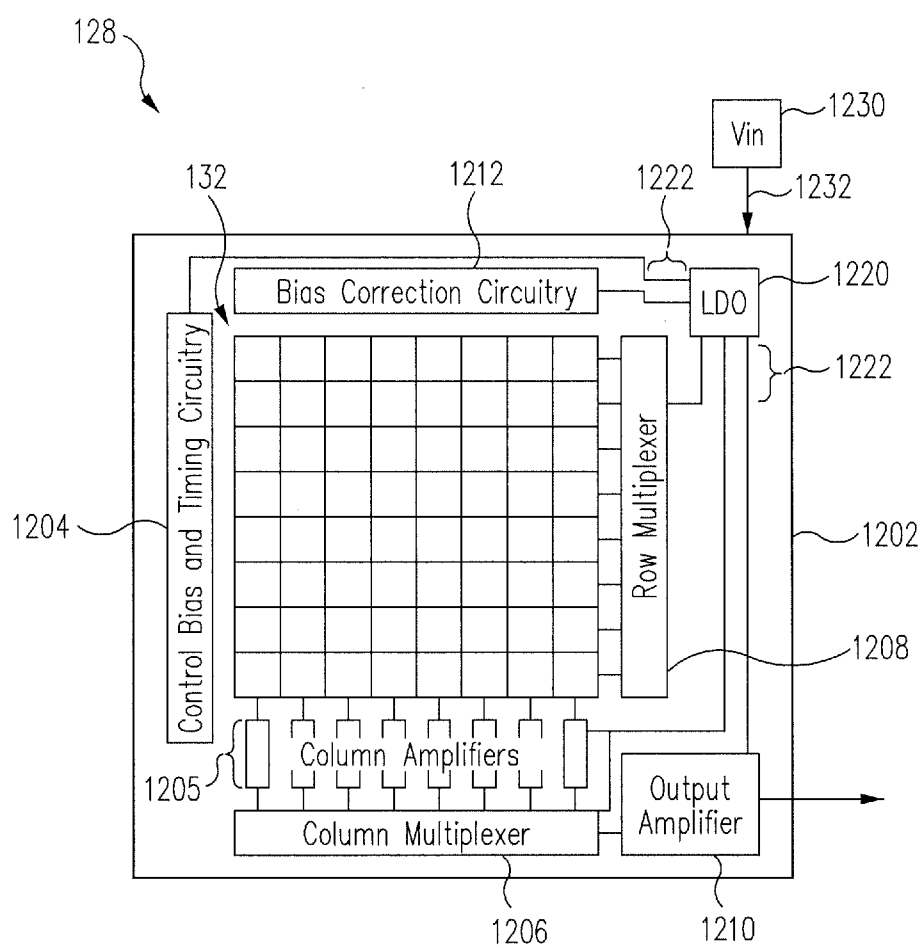


FIG. 12

12/19

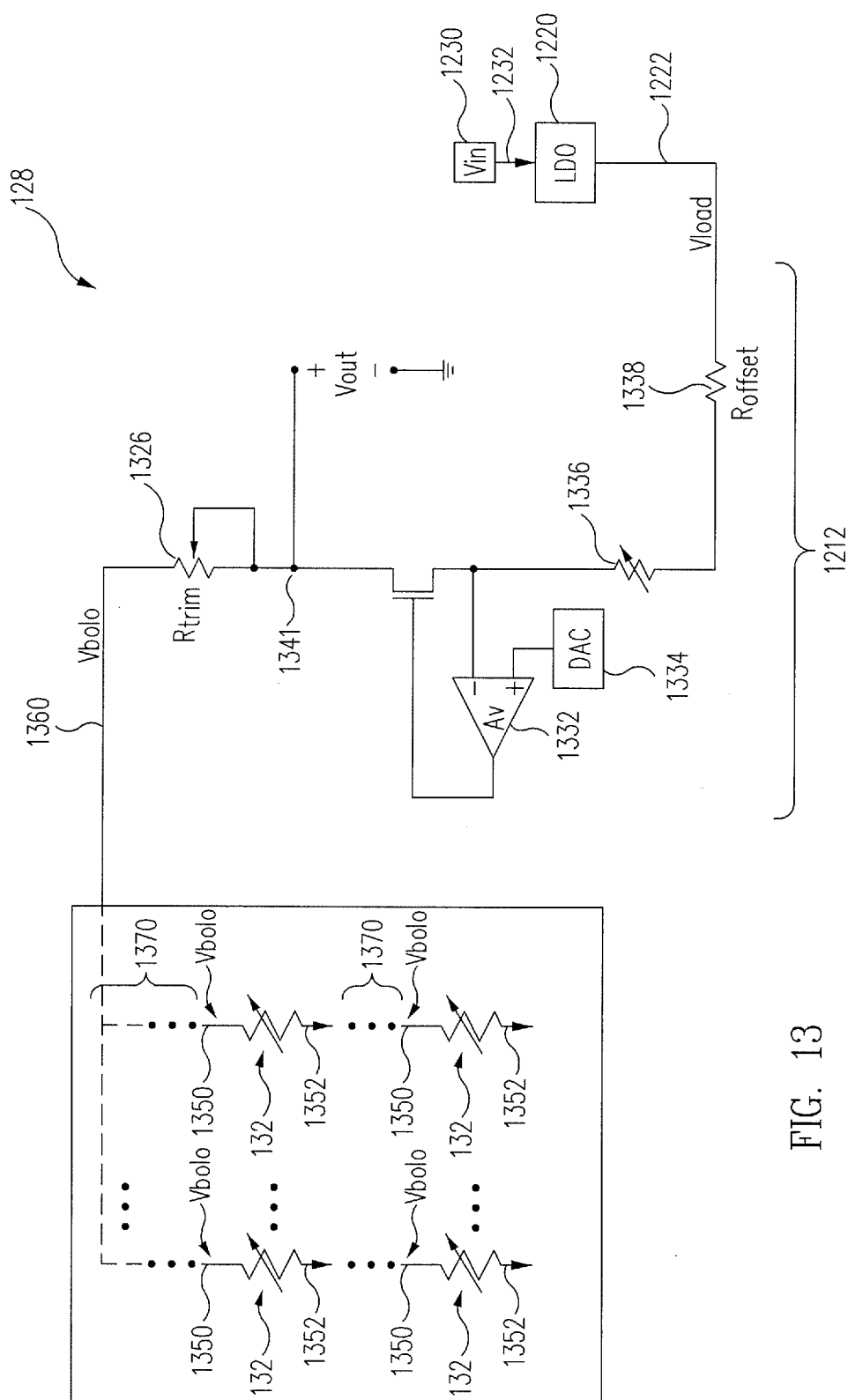


FIG. 13

13/19

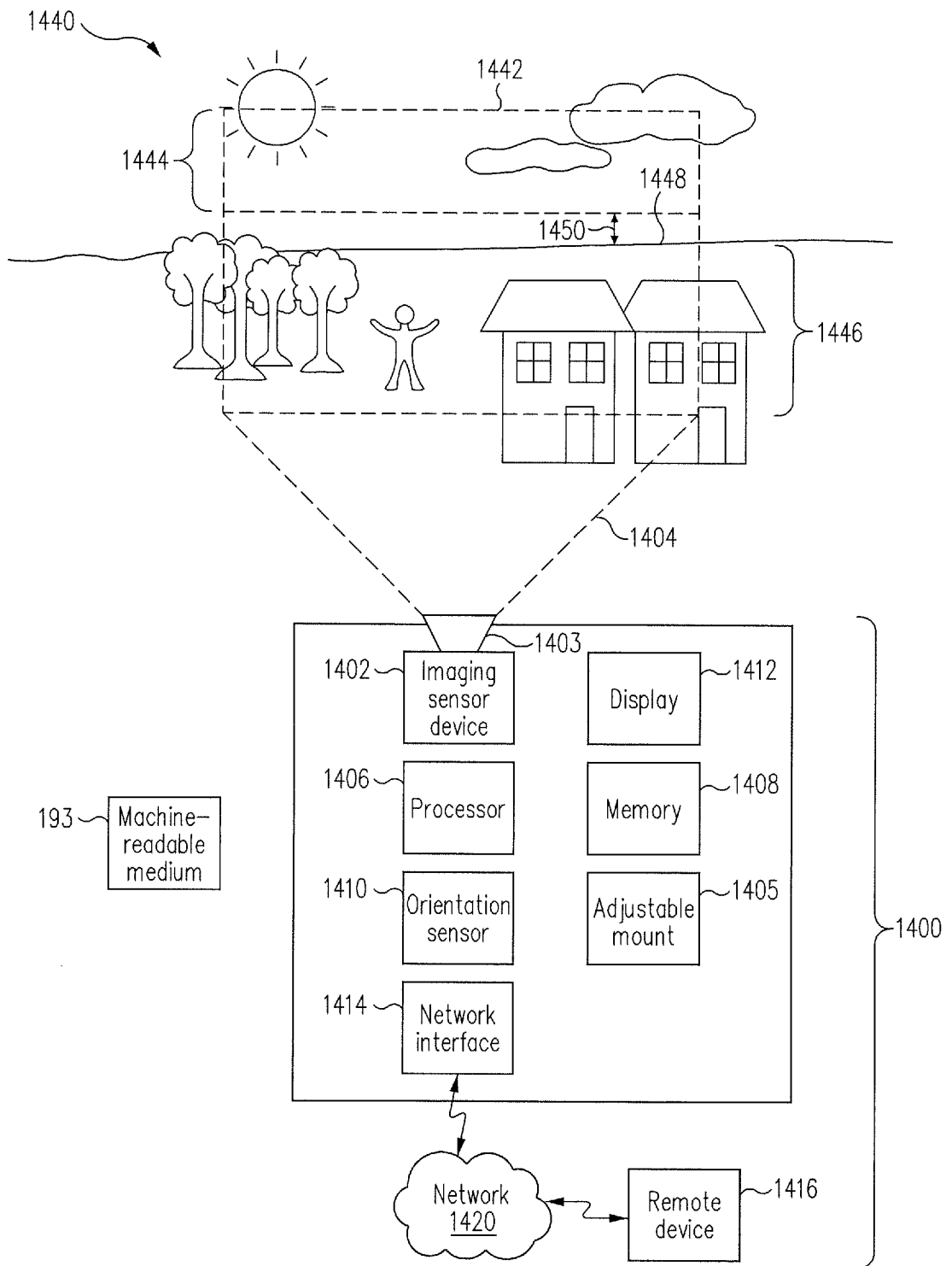


FIG. 14

14/19

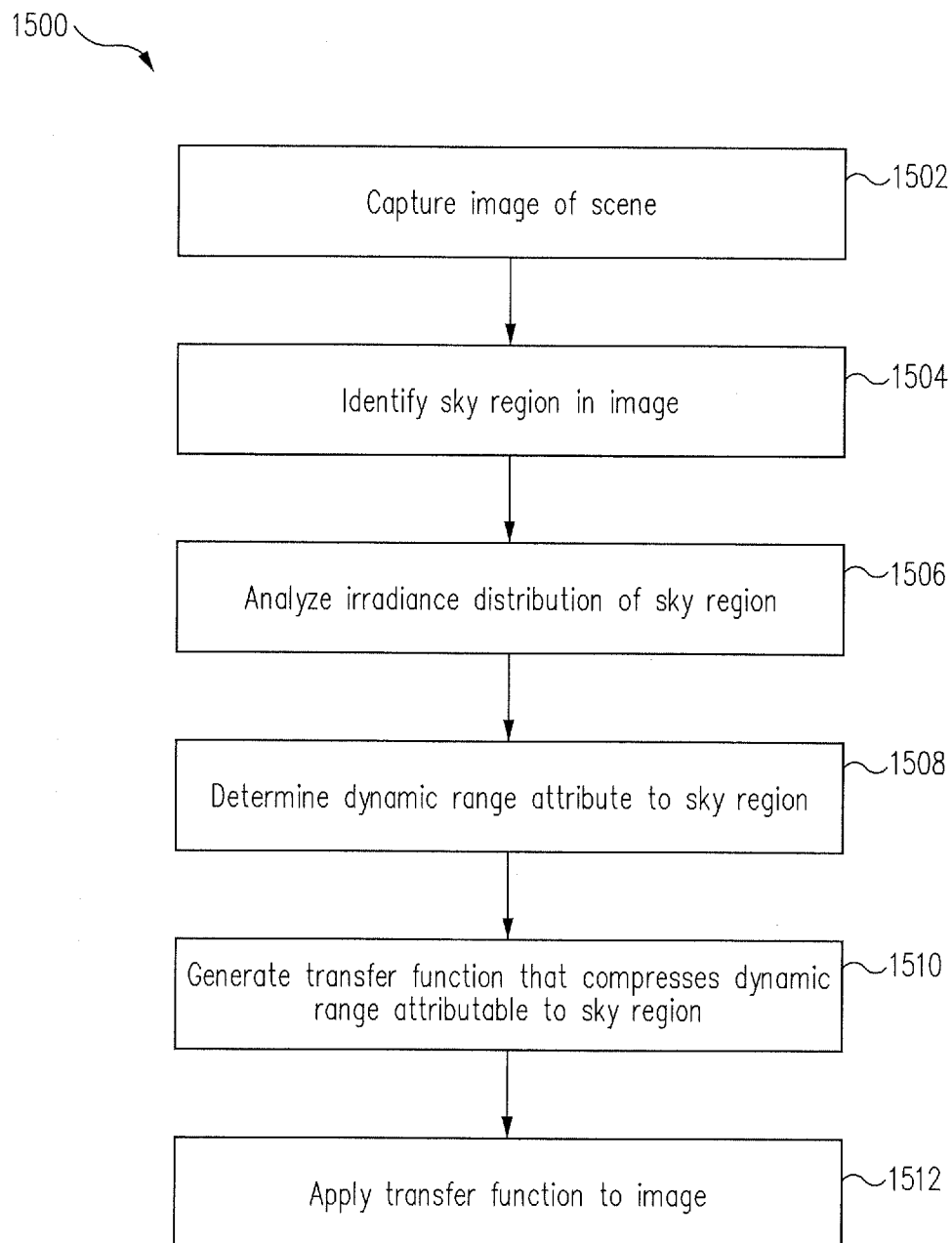
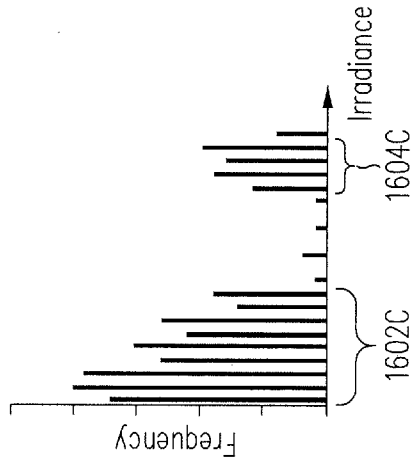
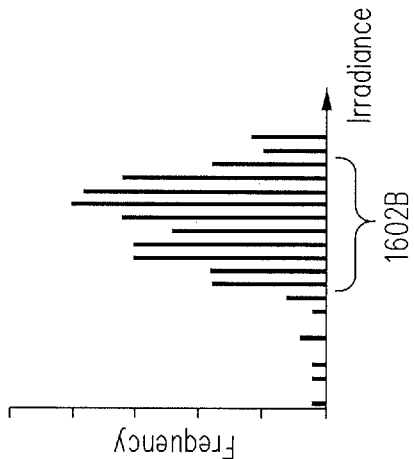


FIG. 15



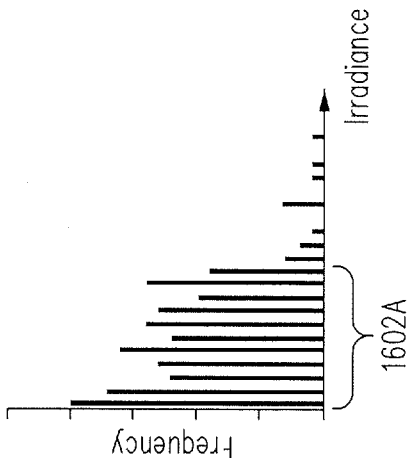
Sky (colder than ground)

FIG. 16C



Sky (warmer than ground)

FIG. 16B



Sky (colder than ground)

FIG. 16A

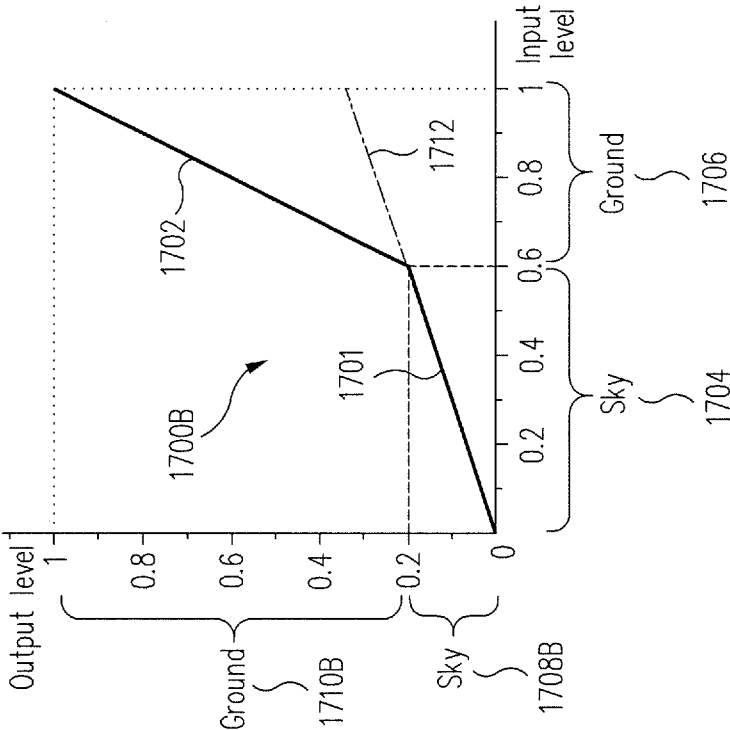


FIG. 17A

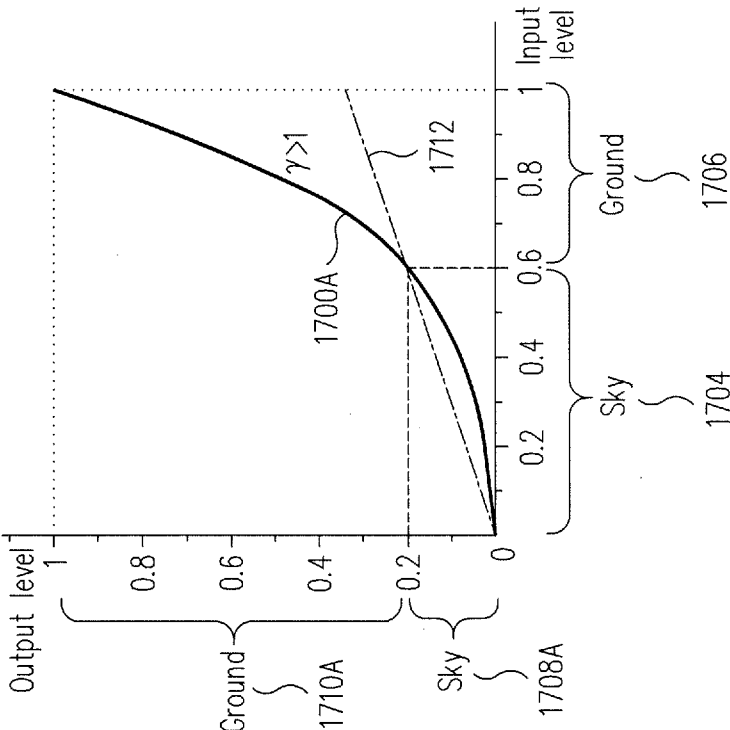


FIG. 17B

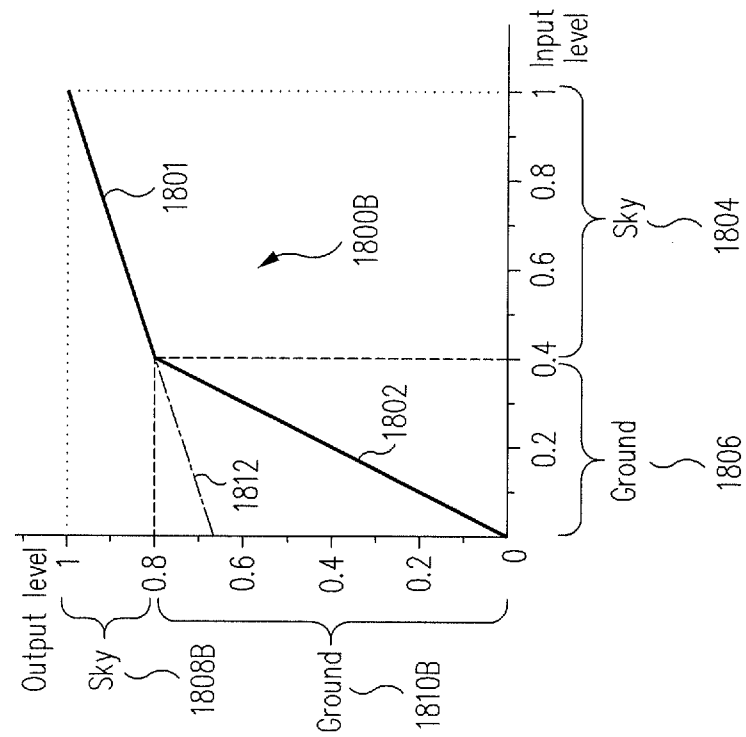


FIG. 18B

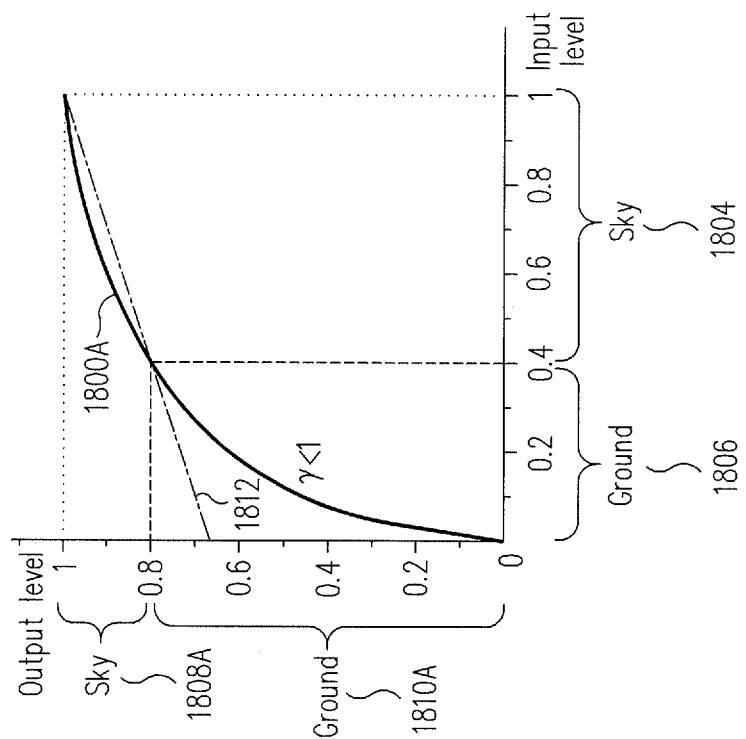


FIG. 18A

18/19

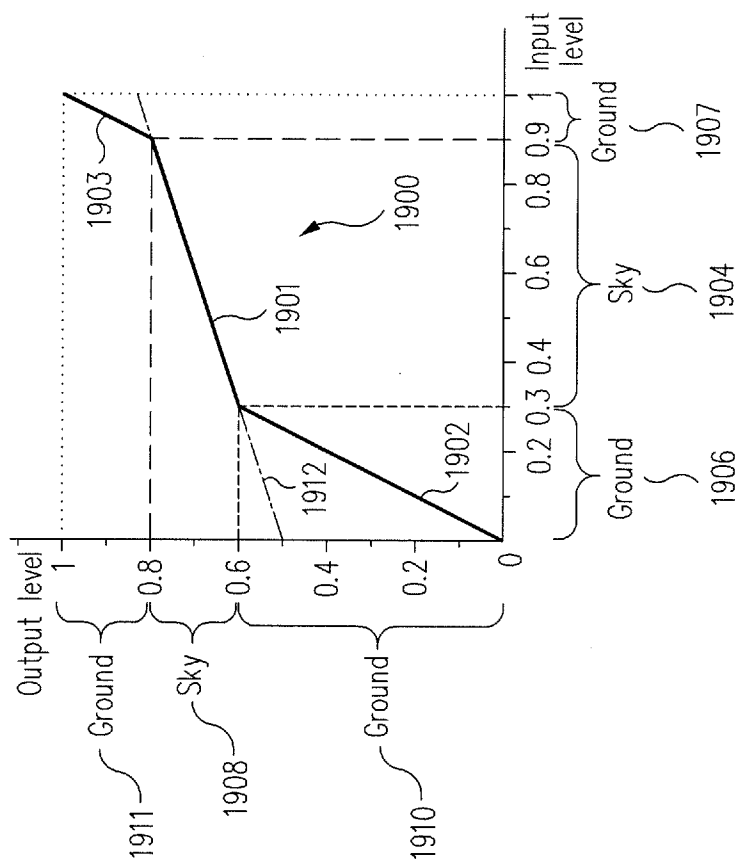


FIG. 19

19/19



FIG. 20A



FIG. 20B