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(54) **METHOD FOR THE ABSOLUTE CALIBRATION OF THE LOCATION AND ORIENTATION OF LARGE-FORMAT DETECTORS USING LASER RADAR**

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H04N 17/00	(2006.01)
H04N 5/225	(2006.01)

(52) **U.S. Cl.**
CPC ***G01T 7/005*** (2013.01); ***G01M 11/00*** (2013.01); ***G01S 17/88*** (2013.01); ***H04N 5/2253*** (2013.01); ***H04N 17/002*** (2013.01)

(58) **Field of Classification Search**
CPC G01T 7/005; G01S 17/88; G01S 7/497; G01S 7/4972
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

7,064,817 B1 *	6/2006	Schmitt	....	G01S 7/4972 356/139.01
2009/0086199 A1 *	4/2009	Troy	....	G01C 1/04 356/251

* cited by examiner

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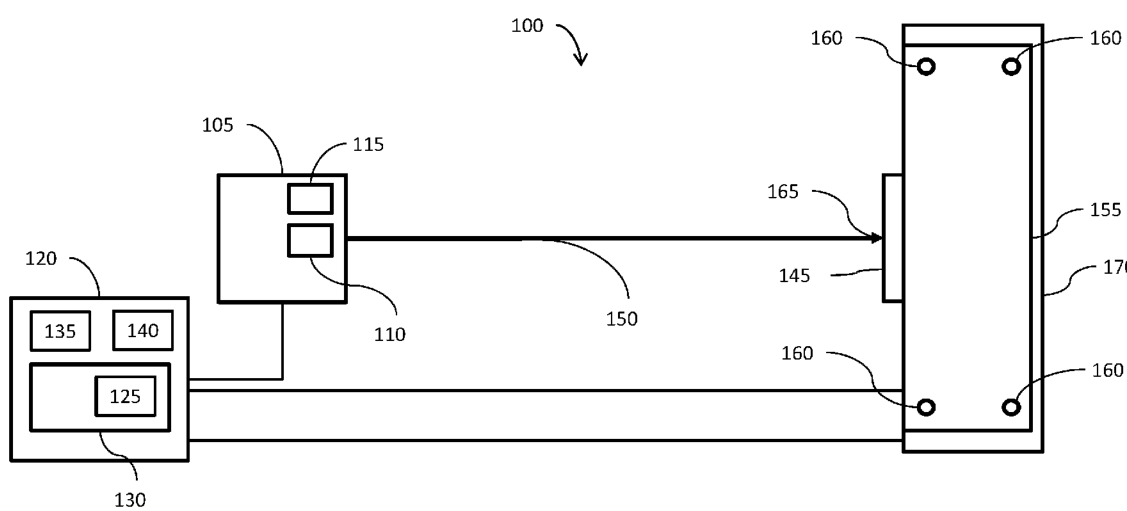
(57) **ABSTRACT**

A method of mapping pixel locations of a detector array includes measuring a location on the detector array, initiating a frame readout of the detector array, measuring a location of one or more metrology targets on the detector array, analyzing the frame readout to identify a pixel at the location on the detector array, and defining a location of the identified pixel with respect to the location of the one or more metrology targets. Subsequent measurement of the metrology targets alone by another metrology system allows one to infer the six degree of freedom alignment of the detector array in space.

16 Claims, 2 Drawing Sheets



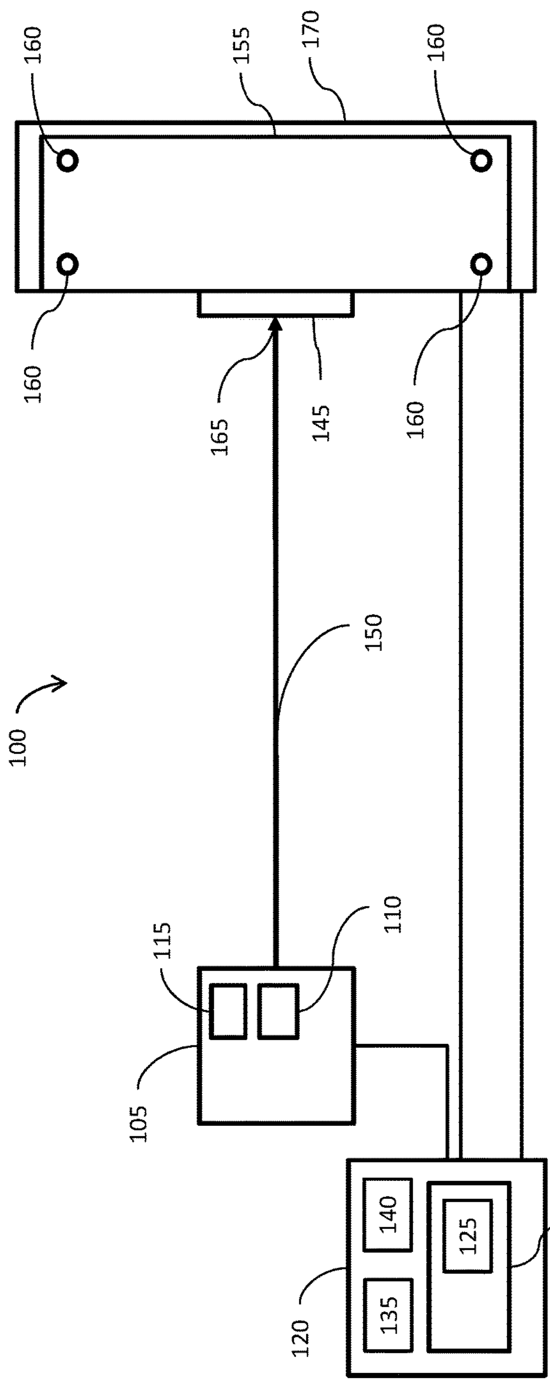

100
105
110
115
120
125
130
135
140
145
150
155
160
165
170

FIG. 1

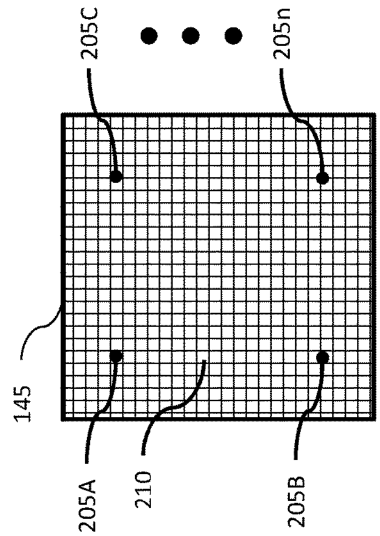

145
205A
205B
205C
205n
210

FIG. 2

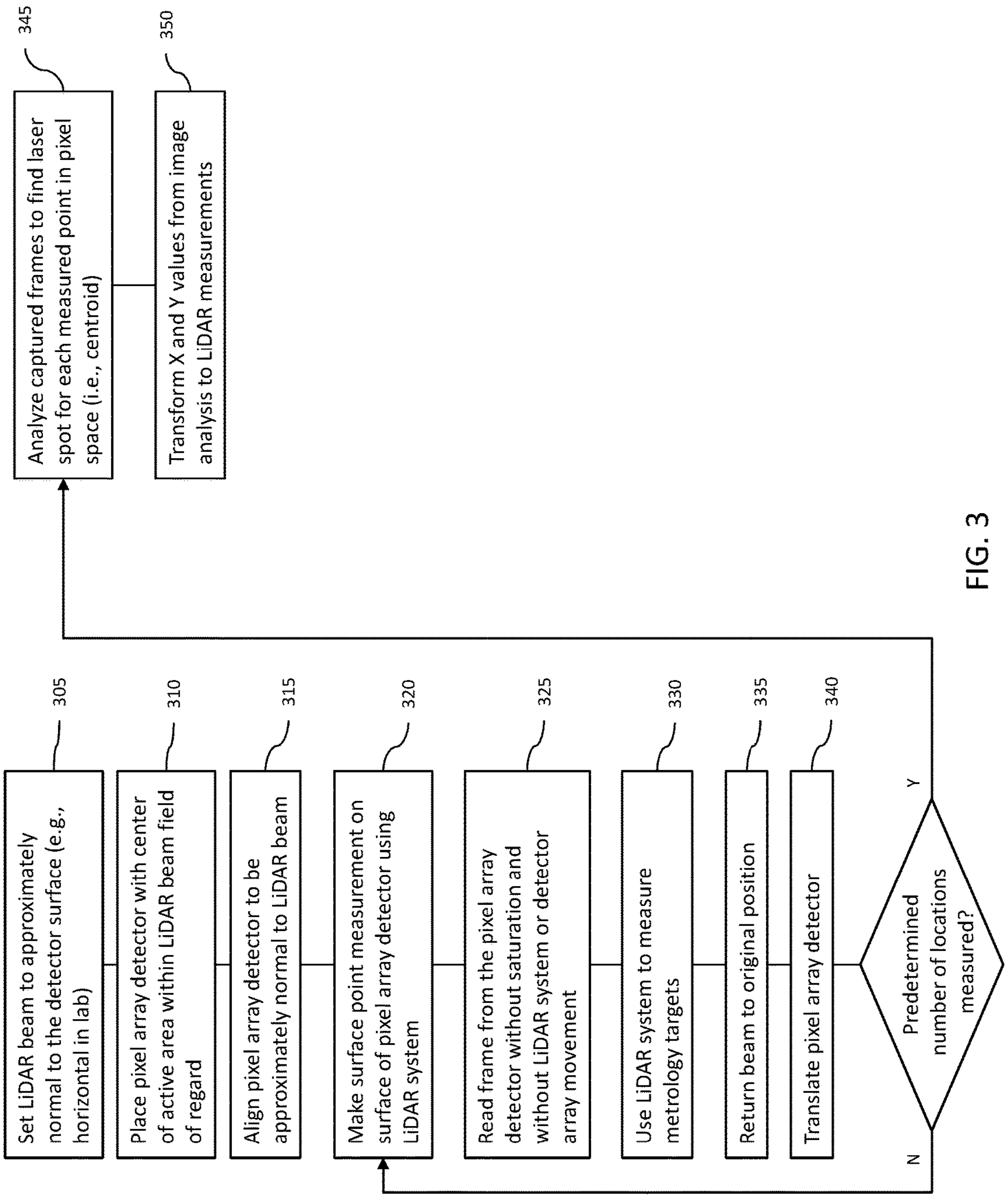

Set LiDAR beam to approximately normal to the detector surface (e.g., horizontal in lab)
305
Place pixel array detector with center of active area within LiDAR beam field of regard
310
Align pixel array detector to be approximately normal to LiDAR beam
315
Make surface point measurement on surface of pixel array detector using LiDAR system
320
Read frame from the pixel array detector without saturation and without LiDAR system or detector array movement
325
Use LiDAR system to measure metrology targets
330
Return beam to original position
335
Translate pixel array detector
340
Predetermined number of locations measured?
Y
N
Analyze captured frames to find laser spot for each measured point in pixel space (i.e., centroid)
345
Transform X and Y values from image analysis to LiDAR measurements
350

FIG. 3

METHOD FOR THE ABSOLUTE CALIBRATION OF THE LOCATION AND ORIENTATION OF LARGE-FORMAT DETECTORS USING LASER RADAR

ORIGIN OF THE INVENTION

Invention by Government Employee(s) Only

The invention described herein was made by one or more employees of the United States Government, and may be manufactured and used by or for the Government for governmental purposes without the payment of any royalties thereon or therefor.

BACKGROUND

The disclosed embodiments generally relate to mapping detector pixel locations, and to aligning a detector accurately in an optical system such that a projected image is in plane with pixels of the detector (i.e., aligned in focus, tip/tilt, and boresight/field space).

Optical imaging systems are required to produce images with adequate resolution located on a range of pixels in a large format, active pixel array detector, The construction of optical systems thus requires accurate alignment of the active area of the detector in multiple degrees of freedom, depending on the sensitivity of optical image quality to detector orientation. This must be accomplished in a non-contact manner, because detectors are highly sensitive. A three dimensional, optical metrology sensor, such as a laser radar or Light Detection and Ranging (LiDAR) system, produces target location information in three dimensions and supplies its own illumination independent of external lighting sources or the optical system under construction. If the detector can image the LiDAR beam, then non-contact metrology of the detector's surface is possible. The ability to locate a particular pixel in a large format, active pixel array detector would be beneficial. Furthermore, having an ability to accurately align a large format active pixel array detector into an optical system such that locations of particular pixels or ranges of pixels may be established in a working coordinate system of the optical system would be advantageous.

SUMMARY

A method has been developed to directly measure and map the physical location and orientation of large format detector active pixel arrays in a given coordinate system in six degrees of freedom in a non-contact manner. This method can be used to aid in the optical alignment of various systems and instruments in both terrestrial and extraterrestrial applications, for example, in the aerospace and other industries. In particular, the method may be used for pupil alignment reference measurements made on various sensors, and sensors comprising large format detector active pixel arrays at the focus of an optical system. The non-contact technique involves using a LiDAR system to measure the physical location and orientation of detector pixels on a large format detector with respect to an array of metrology targets attached to the detector bench or housing. Subsequent measurement of the metrology targets alone by another metrology system allows one to infer the six degree of freedom alignment of the detector array during construction. This information can be used to align a detector in an optical system or interpolate image data from the detector and correlate image features with physical locations in real space.

This technique was developed during metrology testing of the Fine Guidance Sensor engineering test unit for the James Webb Space Telescope (JWST) project. One of the objectives of the metrology test was to directly measure the image location of the Fine Guidance Sensor's pupil alignment target in the telescope's coordinate system. To accomplish this, a large format detector was placed at the nominal location of the JWST telescope's exit pupil location, as defined in the coordinate system. This technique solved two technical challenges. The first was to place a detector accurately such that the telescope pupil image is in plane with the detector pixels. The second was that, once the detector alignment is accomplished, to establish the location of key features (which correspond to a unique pixel or range of pixels on the detector) in the image in the working coordinate system.

In at least one aspect of the disclosed embodiments, a method of mapping pixel locations of a detector array includes measuring a location on the detector array with a laser radar system, initiating a frame readout of the detector array, measuring, using the laser radar system to measure the location of one or more metrology targets on the detector array, analyzing the frame readout to identify a pixel at the location on the detector array measured by the laser radar system, and defining a location of the identified pixel with respect to the location of the one or more metrology targets.

The method may include translating the detector array and repeating the elements of the method for a plurality of locations on the detector array. Alternatively or in addition, the method may include re-pointing the LiDAR beam to another location on the detector array and subsequent detector readout to establish a pattern of multiple "spots" between repeat measurements of the external metrology targets.

The method may include storing a plurality of locations of identified pixels with respect to the location of the one or more metrology targets in a table.

Measuring a location on the detector array may include positioning the detector array approximately normal to a measurement beam emitted by the laser radar system, and using the laser radar system to record X, Y, and Z coordinates of the location on the detector.

Analyzing the frame readout to identify a pixel at the location on the detector array may include reading an output of each pixel in the frame readout and identifying a pixel at a center of a measurement beam emitted by the laser radar system. Various fitting or centroid algorithms may be used to find the center pixel or sub-pixel location of the LiDAR spot.

In at least one other aspect of the disclosed embodiments, an apparatus for mapping pixel locations of a detector array includes a laser radar system operable to measure a location on the detector array and operable to measure a location of one or more metrology targets on the detector array, and a computer operable to perform a frame readout of the detector array, analyze the frame readout to identify a pixel at the location on the detector array measured by the laser radar system, and define a location of the identified pixel with respect to the location of the one or more metrology targets.

The apparatus may include a stage for translating the detector array, and the laser radar system and computer may be operable to cause the stage to move the detector array to a plurality of positions, measure a location on the detector array while the detector array is at each of the plurality of positions, perform a frame readout of the detector array while each location on the detector array is being measured, measure a location of one or more metrology targets on the detector array, analyze each frame readout to identify a pixel at the location on the detector array measured by the laser radar system, and define a location of each identified pixel with respect to the location of the one or more metrology targets.

The apparatus may include a table in a memory of the computer, and the table may store a plurality of locations of identified pixels with respect to the location of the one or more metrology targets.

The computer may cause the stage to position the detector array normal to a measurement beam emitted by the laser radar system, and the laser radar system may measure a location on the detector array by recording X, Y, and Z coordinates of the location on the detector array.

The computer may analyze the frame readout to identify a pixel at the location on the detector array by reading an output of each pixel in the frame readout and identifying a pixel at a center of a measurement beam emitted by the laser radar system using a centroid or fitting routine.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing aspects and other features of the embodiments are explained in the following description, taken in connection with the accompanying drawings, wherein:

FIG. **1** illustrates an exemplary detector characterization system according to the disclosed embodiments;

FIG. **2** shows a front view of a pixel array detector according to the disclosed embodiments; and

FIG. **3** shows an exemplary measurement and analysis process according to the disclosed embodiments.

DETAILED DESCRIPTION

FIG. **1** illustrates one embodiment of an exemplary detector characterization system **100** in which aspects of the disclosed embodiments can be applied. Although the disclosed embodiments will be described with reference to the embodiments shown in the drawings and described below, it should be understood that these could be embodied in many alternate forms. In addition, any suitable size, shape or type of elements or materials could be used.

The disclosed embodiments are directed to obtaining detector pixel location knowledge in 6 degrees of freedom. This knowledge can be applied to results derived from image analysis. The X, Y pixel value results for image analysis can be transformed into a three dimensional coordinate system. Using laser radar (i.e., focused LiDAR), the detector pixels may be physically mapped and then related to external metrology targets on the detector housing. The detector can next be aligned into a system, such as an optical instrument, using the metrology targets. For the purposes of the disclosed embodiments, the terms laser radar and LiDAR are used interchangeably.

The system **100** may also include a LiDAR system **105** with a laser **110** for illumination and a LiDAR detector array **115** for measuring return intensity and range. The laser **110** may produce ultraviolet, visible, or near infrared light with a beam divergence selected to illuminate a desired scene. For example, a near infrared laser may be used having a 20 degree or any suitable beam divergence. The laser beam divergence and gain may be adjustable in order to obtain a desired field of view, return intensity and range. The LiDAR detector array **115** may comprise, for example, a 256×256 PIN diode array or any detector array appropriate for use in a LiDAR system. The LiDAR detector array **115** may also have an adjustable gain and field of view in order to optimize the return intensity and range detection. The LiDAR system **105** generally provides output data in the form of range data in terms of X, Y, and Z values.

In at least one aspect of the disclosed embodiments, the detector characterization system **100** includes at least one computer **120** under the control of one or more programs in the form of computer readable program code **125** stored on at least one computer readable medium **130**. The computer readable program code **125** stored on the at least one computer readable medium **130** may be implemented for carrying out and executing the operations of the detector characterization system **100** described herein. The computer readable medium **130** may be a memory of the computer **120**. It should be understood that the computer readable medium **130** may store one or more operations for controlling the LiDAR system **105**, for reading pixels, groups of pixels and full frames of a large format pixel array detector **145**, for determining the locations of pixels of the large format pixel array detector **145**, for determining the locations of metrology targets, for processing frames read from the pixel array detector **145**, for storing pixel locations, metrology target locations, frames and any other data, for processing the data and mapping pixel locations, and for any other suitable processes for implementing the disclosed embodiments and techniques. Computer **120** may also include a microprocessor **135** for executing the computer readable program code **125** stored on the at least one computer readable medium **130**. In at least one aspect, computer **120** may include one or more input or output devices, generally referred to as a user interface **140** which may operate to allow input to the computer **120** or to provide output from the computer **120**.

The LiDAR system **105** emits a measurement beam **150** directed to the large format pixel array detector **145**. The large format pixel array detector **145** may be mounted on or within a detector housing **155**. The housing **155** may include a number of metrology targets **160**. The metrology targets **160** may be specular spheres, spherically mounted retro-reflectors, or any other suitable metrology targets, permanently or temporarily mounted to the detector housing **155**. The large format pixel array detector **145** and the detector housing **155** may be mounted on an actuator stage **170** capable of single or multi-axis movement under control of the computer **120**. In at least one embodiment, the stage **170** may operate to translate the pixel array detector **145** in a direction perpendicular to the measurement beam **150**.

Using the LiDAR system **105**, pixels of the large format pixel array detector **145** are physically mapped and then related to the metrology targets **160** on the detector housing **155**. A relationship is then established among the pixel locations and the metrology targets **160**, enabling the pixel array detector **145** to be aligned into another system, such as an optical instrument.

FIG. **2** shows a front view of the pixel array detector **145**. To accomplish the mapping, a measurement process and an analysis process may be initiated. The measurement process may be initiated by pointing and focusing the LiDAR system **105** on a location, for example, location **205**A on the pixel array detector's active area **210**. A surface point measurement of the location **205**A may be made with the LiDAR system **105**, while a full frame readout of the pixel array detector **145** may be captured. The surface point measurement may record the X, Y, Z coordinates of the exemplary location **205**A on the pixel array detector surface as measured by the LiDAR system **105**. The LiDAR system **105** may then be used to measure the location of one or more of the metrology targets **160**. The surface point measurement, the full frame readout of the pixel array detector, and the metrology target location measurements, made with respect to the exemplary location **205**A, may be stored for further processing. The measurement process may be repeated for more of locations **205**B-**205***n*.

Once the measurement process is complete, the analysis process may include an image analysis of each full frame readout to identify a pixel at each exemplary location **205**A-**205***n* in terms of X, Y values of the pixel array detector **145**. Each X, Y pixel array detector location may be mapped to the corresponding LiDAR system X, Y, Z coordinates with respect to the metrology target locations. Thus, using the map, the location of each identified pixel may be defined with respect to the metrology target locations. The locations of remaining pixels that are not measured directly may be interpolated using the locations of the measured pixels, because the pixel pitch is tightly controlled during the pixel array detector's manufacturing processes. Once the pixel mapping is complete, the pose of each pixel and the pose of the pixel array detector **145** itself can be established in space using the metrology targets **160** on the detector housing **155**.

Alternately, the analysis process may be combined with the measurement process such that after each surface point measurement, full frame readout of the pixel array detector **145**, and related metrology target location measurements, for a particular pixel location **205**A-**205***n*, the corresponding X, Y pixel array detector location may be mapped to the corresponding LiDAR system X, Y, Z coordinates with respect to the metrology target locations, and incorporated into a table. Thus, in the table, the location of each identified pixel may be defined with respect to the metrology target locations. This process may be repeated until each X, Y pixel array detector location is mapped to the corresponding LiDAR system X, Y, Z coordinates with respect to the metrology target locations.

The measurement and analysis process may generally be described in more detail as follows with respect to FIGS. **1** through **3**. As shown in block **305**, the LiDAR measurement beam **150** may be set to an elevation angle of approximately 90 degrees which may place the measurement beam **150** approximately horizontal to a ground or floor surface. The pixel array detector **145** may then be placed such that the measurement beam **150** at 90 degrees strikes an approximate center **165** of the pixel array detector **145**, as displayed in block **310**. The stage **170** under control of the computer **120** may be used to adjust the position of the pixel array detector **145**. Referring to block **315**, the pixel array detector **145** may be aligned so that it is normal to the 90 degree measurement beam **150**. For example, the LiDAR system **105** may be used to measure a number of points on the surface of the pixel array detector **145** in polar coordinates and the pixel array detector position may be adjusted until the distance or radial polar coordinate of all the points is the same.

Using the LiDAR system **105**, a surface point measurement may be made on the surface of the pixel array detector **145**, for example at location **205**A, as presented in block **320**. Without moving the LiDAR system **105** or pixel array detector **145**, a frame may be read out from the pixel array detector **145** with an exposure time set such that the pixel location **205**A on which the LiDAR is focused is not saturated, as shown in block **325**. The LiDAR system **105** may then measure the detector housing metrology targets **160**, as displayed in block **330** using, for example, a tooling ball mode of measurement. Referring to block **335**, the measurement beam **150** may be returned to its original horizontal position. The pixel array detector **145** may then be translated, by the stage **170** under control of the computer **120**, so that the measurement beam **150** strikes a different location of the pixel array detector **145**, for example, location **205**B, as displayed in block **340**. This process may be repeated until at least a predetermined number of pixel locations, for example, three to five, or as another example, locations **205**B-**205***n*, are measured on the pixel array detector **145**, as presented in block **345**.

The computer **120** may be utilized to perform image analysis on the captured frames to find a center of the measurement beam **150** for each measured point in pixel space in terms of X, Y coordinates on the pixel array detector **145**, as shown in block **345**. The X, Y coordinates on the pixel array detector **145** from the image analysis may be correlated with the LiDAR system X, Y, Z measurements, as shown in block **350**, via a best-fit process, which links the detector X, Y location values to the LiDAR system X, Y, Z measured values for the pixel location and the metrology targets **160**. As mentioned above, the locations of remaining pixels that are not measured directly may be interpolated using the locations of the measured pixels, because the pixel pitch is tightly controlled during the pixel array detector's manufacturing processes. Once the measurement and analysis process is complete, the pose of each pixel and the pose of the pixel array detector **145** itself can be established in space using the metrology targets **160** on the detector housing **155**.

This technique is unique in that it provides a non-contact method for the mapping of pixels on the pixel array detector **145**. The non-contact nature of this technique is advantageous, especially when the arrays are sensitive to low-force contact and electrostatic discharge. This technique may also be faster than measuring a detector using a coordinate measuring machine. This technique uses the laser radar and the detector's readout to locate the actual active pixel itself. In addition to large format pixel detectors, the disclosed structures and techniques may easily be extended to CMOS arrays, IR-sensitive detectors, and other detector technologies.

Using the structures and techniques disclosed herein, detector alignment can be precisely achieved, for example, to a level of tens of microns of absolute uncertainty in a mechanical coordinate system. The disclosed structures and techniques may be used in a wide range of applications involving detectors. For example, they may be implemented in the assembly and alignment verification of large focal plane arrays for telescopes or instruments with very large field of view requirements, such as imaging systems for commercial imagery satellites. Other exemplary applications may include the location and calibration in an absolute, mechanical coordinate system of the optical focus and other optical alignment indicators for an as-built optical system (e.g., pupil). The disclosed structures and techniques may also be utilized to improve field stop alignment and knowledge for telescope systems, for camera construction, and for the construction of medical instruments that use detectors, such as medical imaging scanners.

It is noted that the embodiments described herein can be used individually or in any combination thereof. It should be understood that the foregoing description is only illustrative of the embodiments. Various alternatives and modifications can be devised by those skilled in the art without departing from the embodiments. Accordingly, the present embodiments are intended to embrace all such alternatives, modifications and variances that fall within the scope of the appended claims.

The invention claimed is:

1. A method of mapping pixel locations of a detector array comprising:
measuring a location on the detector array;
initiating a frame readout of the detector array;
measuring a location of one or more metrology targets on the detector array;
analyzing the frame readout to identify a pixel at the location on the detector array measured by the laser radar system; and
defining a location of the identified pixel with respect to the location of the one or more metrology targets.

2. The method of claim **1**, further comprising translating the detector array and repeating the elements of claim **1** for a plurality of locations on the detector array.

3. The method of claim **2**, comprising storing a plurality of locations of identified pixels with respect to the location of the one or more metrology targets in a table.

4. The method of claim **3**, comprising interpolating locations of unmeasured pixels from the locations of the identified pixels and a pixel pitch of the detector array.

5. The method of claim **1**, comprising measuring the location on the detector array and a location of the one or more metrology targets in a non-contact manner.

6. The method of claim **5**, comprising measuring the location on the detector array and a location of the one or more metrology targets with a laser radar system.

7. The method of claim **1**, wherein measuring a location on the detector array comprises positioning the detector array normal to a measurement beam emitted by the laser radar system, and using the laser radar system to record X, Y, and Z coordinates of the location on the detector.

8. The method of claim **1**, wherein analyzing the frame readout to identify a pixel at the location on the detector array comprises reading an output of each pixel in the frame readout and identifying a pixel at a center of a measurement beam emitted by the laser radar system.

9. An apparatus for mapping pixel locations of a detector array comprising:
a measurement system operable to measure a location on the detector array and operable to measure a location of one or more metrology targets on the detector array; and
a computer operable to:
perform a frame readout of the detector array;
analyze the frame readout to identify a pixel at the location on the detector array measured by the measurement system; and
define a location of the identified pixel with respect to the location of the one or more metrology targets.

10. The apparatus of claim **9**, comprising a stage for translating the detector array, wherein the measurement system and computer are operable to:
cause the stage to move the detector array to a plurality of positions;
measure a location on the detector array while the detector array is at each of the plurality of positions;
perform a frame readout of the detector array while each location on the detector array is being measured;
measure a location of one or more metrology targets on the detector array;
analyze each frame readout to identify a pixel at the location on the detector array measured by the measurement system; and
define a location of each identified pixel with respect to the location of the one or more metrology targets.

11. The apparatus of claim **10**, comprising a table in a memory of the computer, the table storing a plurality of locations of identified pixels with respect to the location of the one or more metrology targets.

12. The apparatus of claim **11**, wherein the computer is operable to interpolate locations of unmeasured pixels from the locations of the identified pixels and a pixel pitch of the detector array.

13. The apparatus of claim method of claim **9**, wherein the measurement system is a non-contact measurement system.

14. The apparatus of claim **13**, wherein the measurement system is a laser radar system.

15. The apparatus of claim **14**, wherein the computer is operable cause the stage to position the detector array normal to a measurement beam emitted by the laser radar system, and the laser radar system is operable measure a location on the detector array by recording X, Y, and Z coordinates of the location on the detector array.

16. The apparatus of claim **14**, wherein the computer is operable to analyze the frame readout to identify a pixel at the location on the detector array by reading an output of each pixel in the frame readout and identifying a pixel at a center of a measurement beam emitted by the laser radar system.

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