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Ryland

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(54) **SYNTHETIC APERTURE RADAR (SAR) IMAGING SYSTEM**

(75) Inventor: **Robert Ryland**, Silver Spring, MD (US)

(73) Assignee: **Northrop Grumman Systems Corporation**, Falls Church, VA (US)

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G01S 13/90 (2006.01)

(52) **U.S. Cl.** ..... **342/25 A**; 342/25 F; 342/179

(58) **Field of Classification Search** ..... 342/25 R, 342/25 A–25 F, 179

See application file for complete search history.

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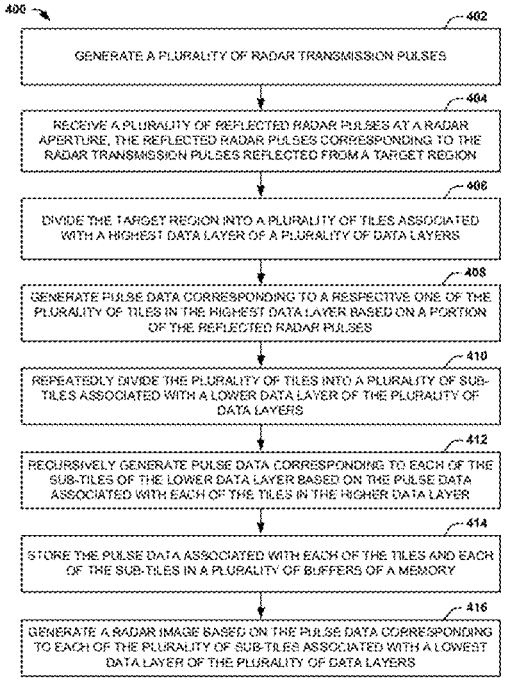
Primary Examiner — John B Sotomayor

(74) *Attorney, Agent, or Firm* — Tarolli, Sundheim, Covell & Tummino LLP

(57) **ABSTRACT**

One embodiment of the invention includes a synthetic aperture radar (SAR) system including a receiver configured to receive a plurality of reflected radar pulses corresponding to a plurality of radar transmission pulses having been reflected from a target region. A processing controller divides the target region into a plurality of tiles at a highest data layer and each of the plurality of tiles into a plurality of sub-tiles corresponding to one of a plurality of data layers and iteratively processes a portion of pulse data corresponding to a given tile associated with a higher data layer to generate pulse data corresponding to a given sub-tile in a lower data layer. An image processor is configured to generate a radar image of the target region based on the pulse data corresponding to each of the plurality of sub-tiles associated with a lowest data layer of the plurality of data layers.

20 Claims, 8 Drawing Sheets



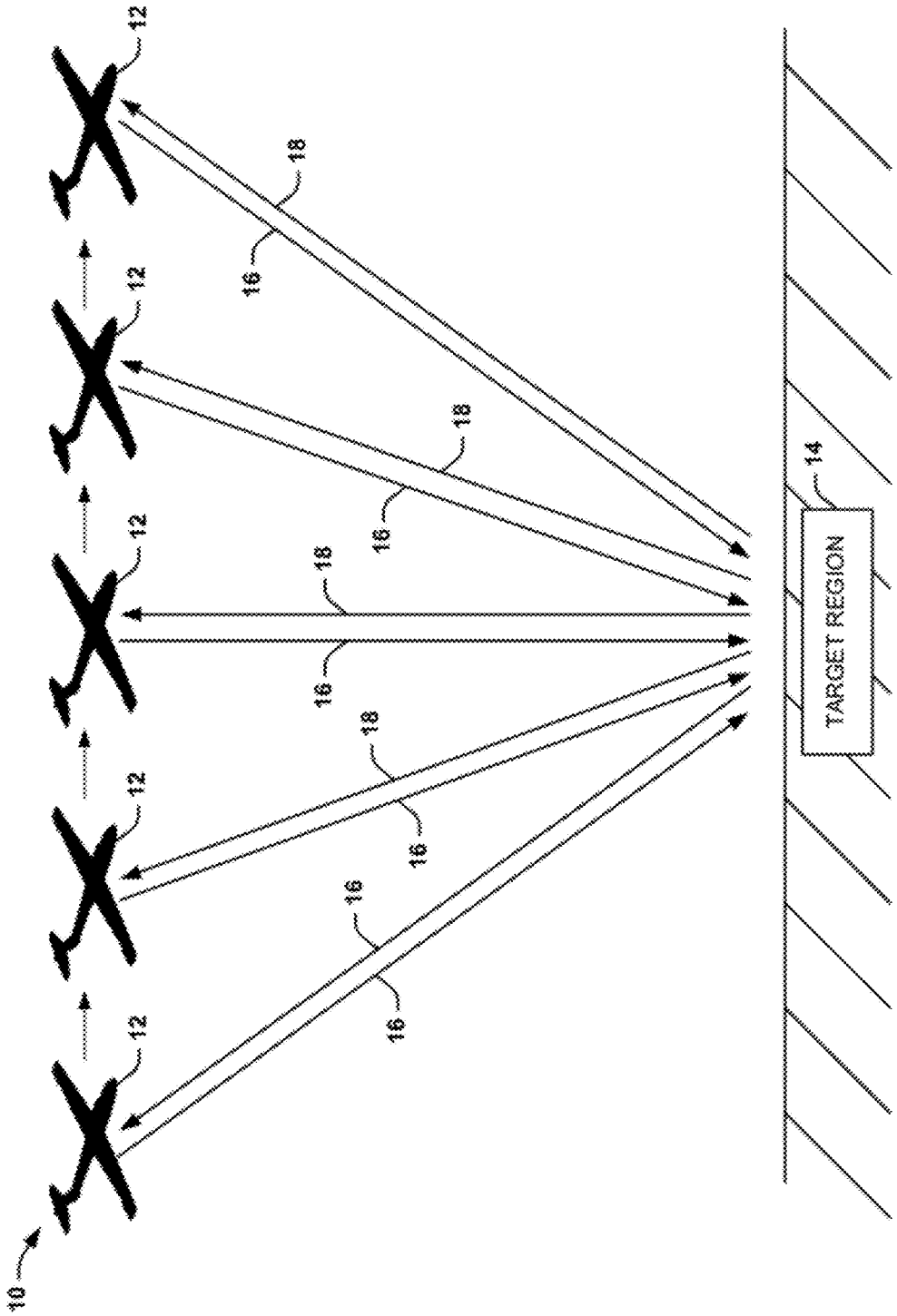


FIG. 1

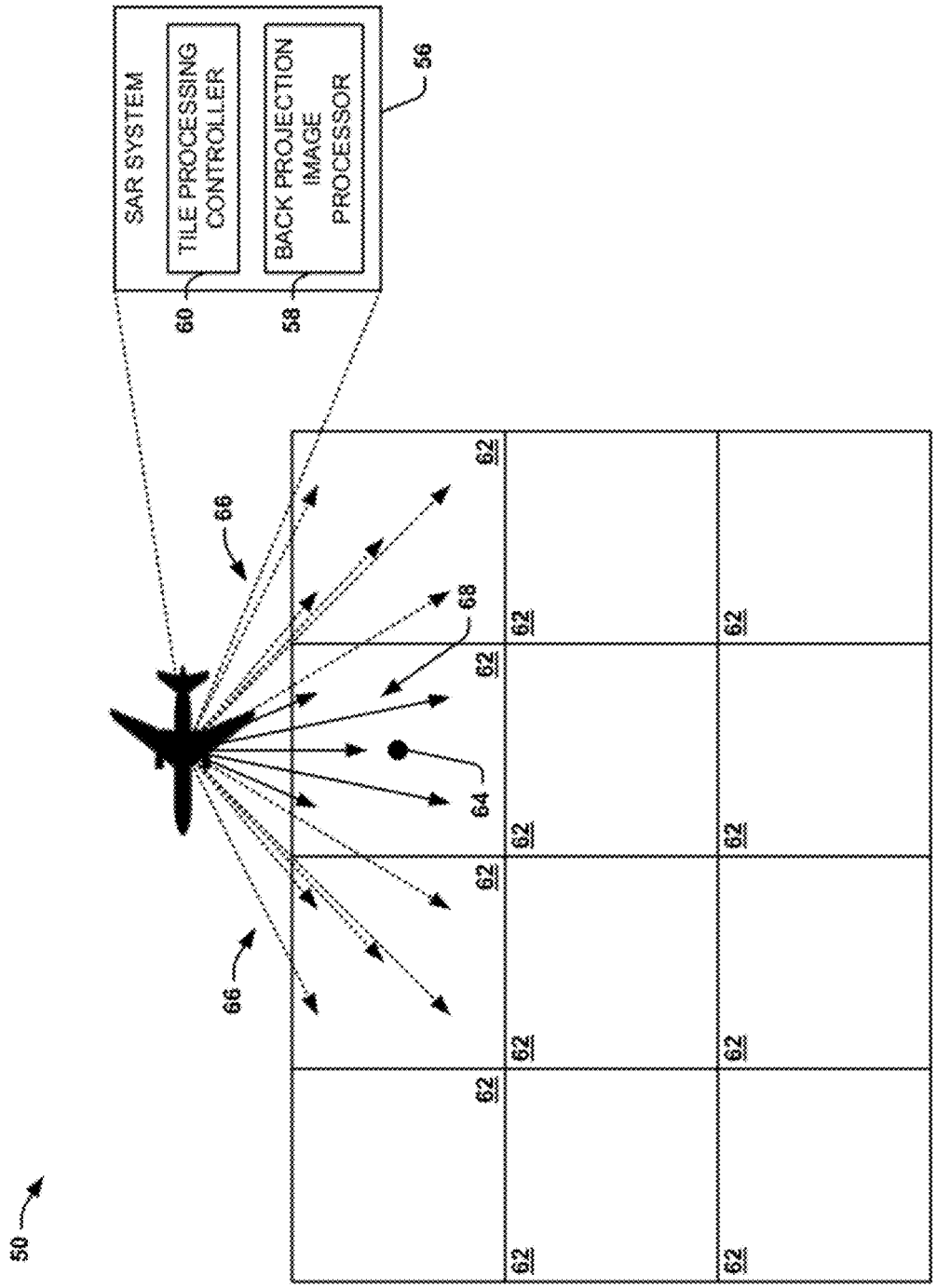

SAR SYSTEM
TILE PROCESSING CONTROLLER
BACK PROJECTION IMAGE PROCESSOR
56
60
58
62
64
66
68
50

FIG. 2

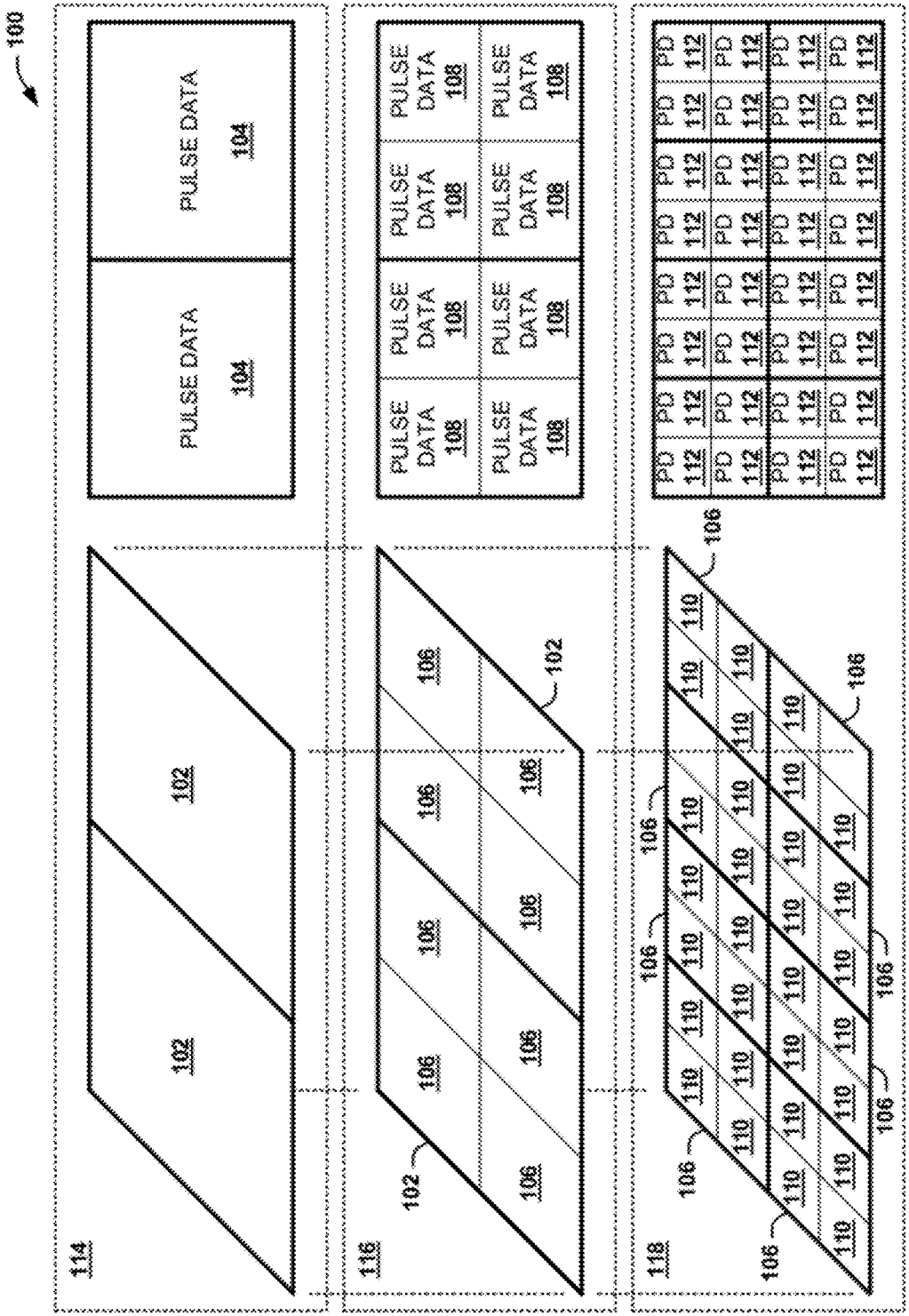


FIG. 3

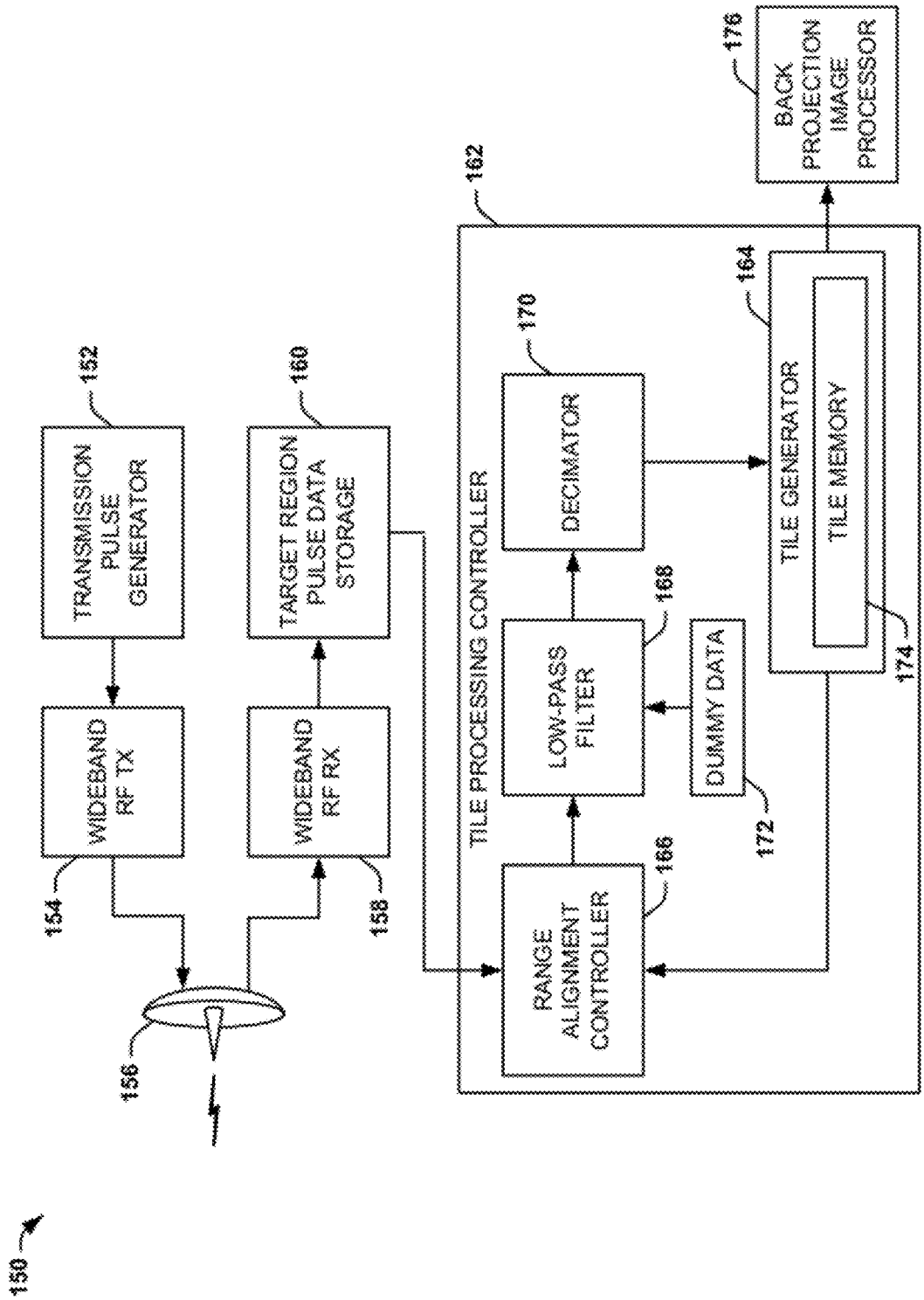

150
152
TRANSMISSION PULSE GENERATOR
154
WIDEBAND RF TX
156
158
WIDEBAND RF RX
160
TARGET REGION PULSE DATA STORAGE
162
TILE PROCESSING CONTROLLER
166
RANGE ALIGNMENT CONTROLLER
168
LOW-PASS FILTER
170
DECIMATOR
172
DUMMY DATA
164
TILE GENERATOR
174
TILE MEMORY
176
BACK PROJECTION IMAGE PROCESSOR

FIG. 4

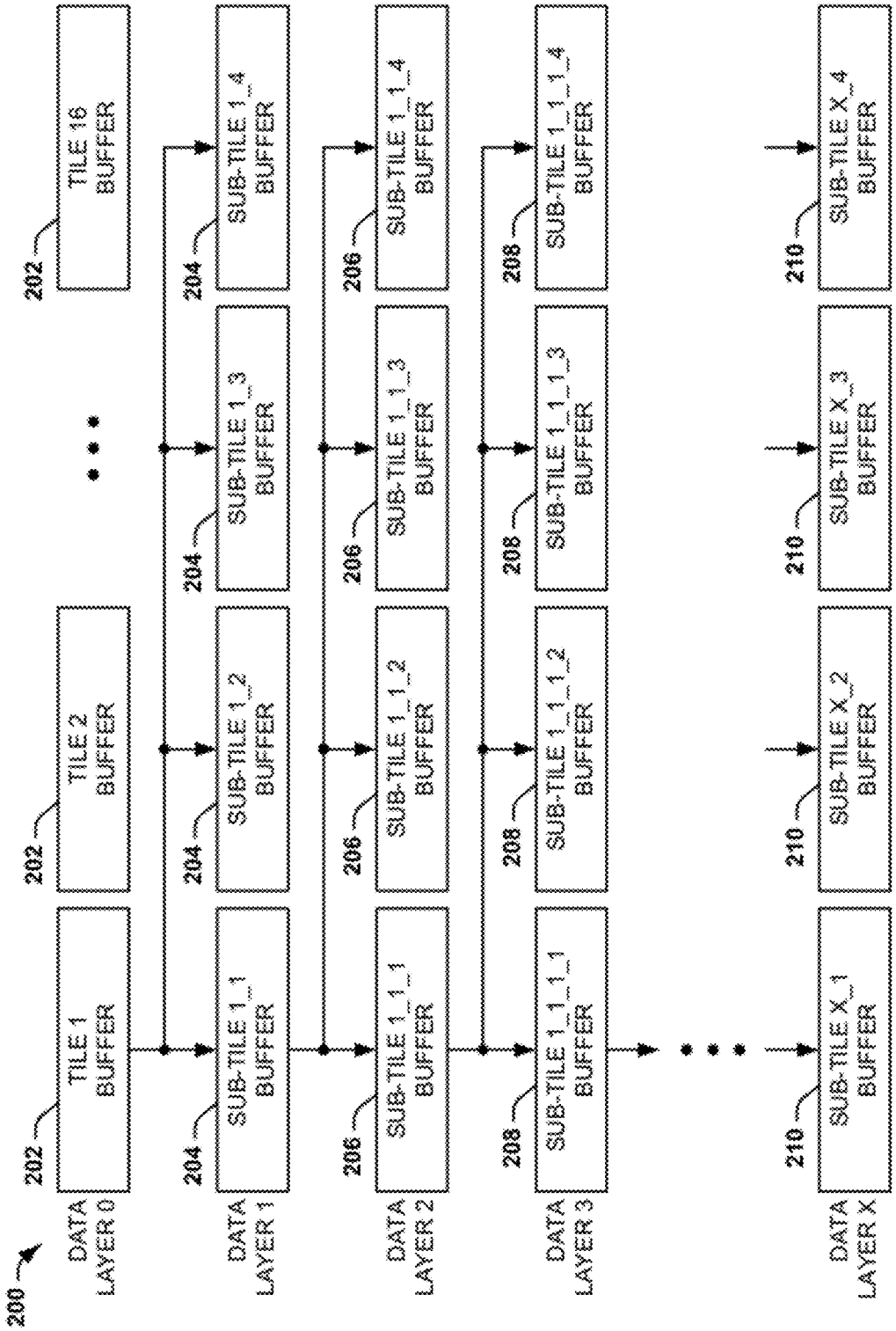

200
DATA LAYER 0
DATA LAYER 1
DATA LAYER 2
DATA LAYER 3
DATA LAYER X
202
TILE 1 BUFFER
TILE 2 BUFFER
TILE 16 BUFFER
204
SUB-TILE 1_1 BUFFER
SUB-TILE 1_2 BUFFER
SUB-TILE 1_3 BUFFER
SUB-TILE 1_4 BUFFER
206
SUB-TILE 1_1_1 BUFFER
SUB-TILE 1_1_2 BUFFER
SUB-TILE 1_1_3 BUFFER
SUB-TILE 1_1_4 BUFFER
208
SUB-TILE 1_1_1_1 BUFFER
SUB-TILE 1_1_1_2 BUFFER
SUB-TILE 1_1_1_3 BUFFER
SUB-TILE 1_1_1_4 BUFFER
210
SUB-TILE X_1 BUFFER
SUB-TILE X_2 BUFFER
SUB-TILE X_3 BUFFER
SUB-TILE X_4 BUFFER

FIG. 5

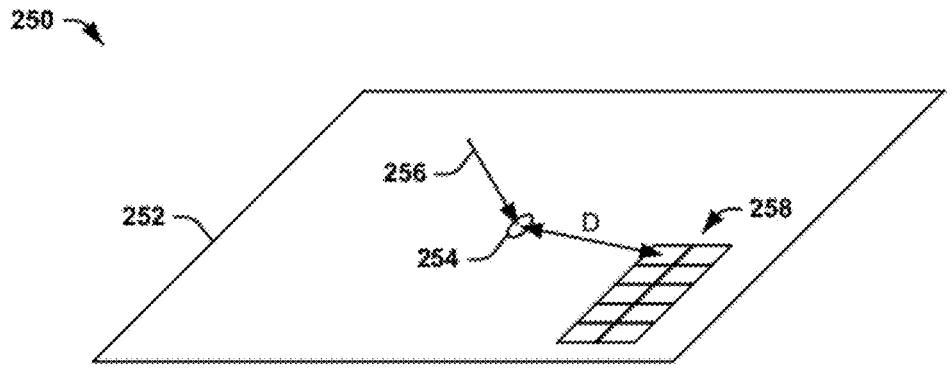

250
252
256
254
D
258

FIG. 6

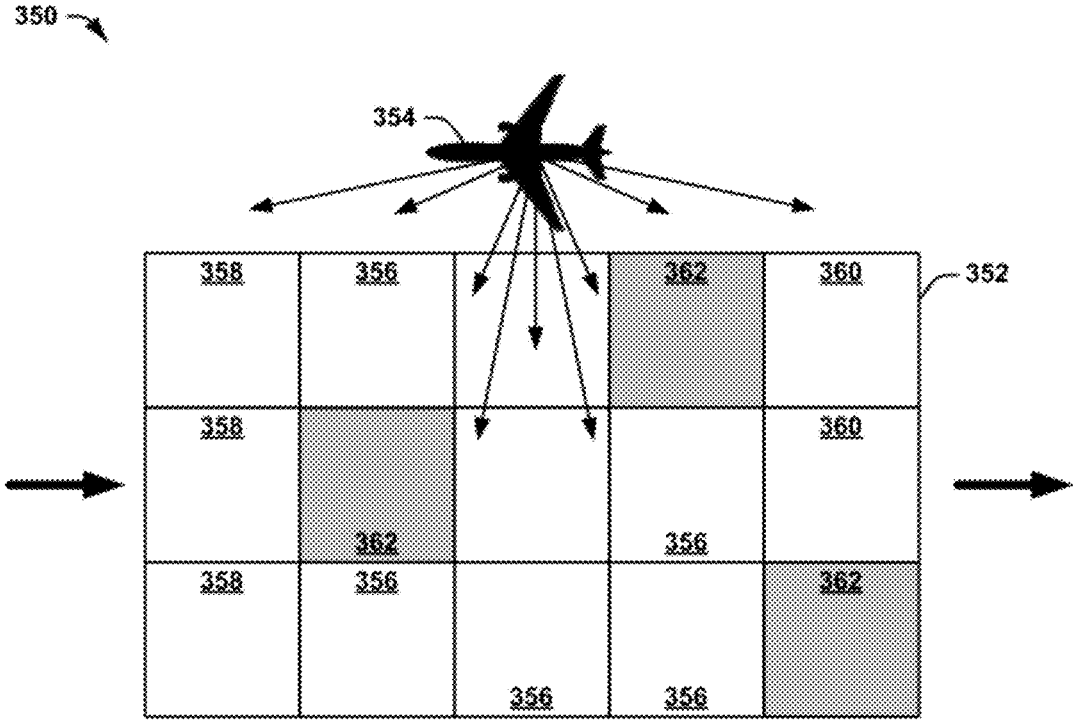

350
354
358
356
362
360
352
358
362
356
360
358
356
356
356
362

FIG. 8

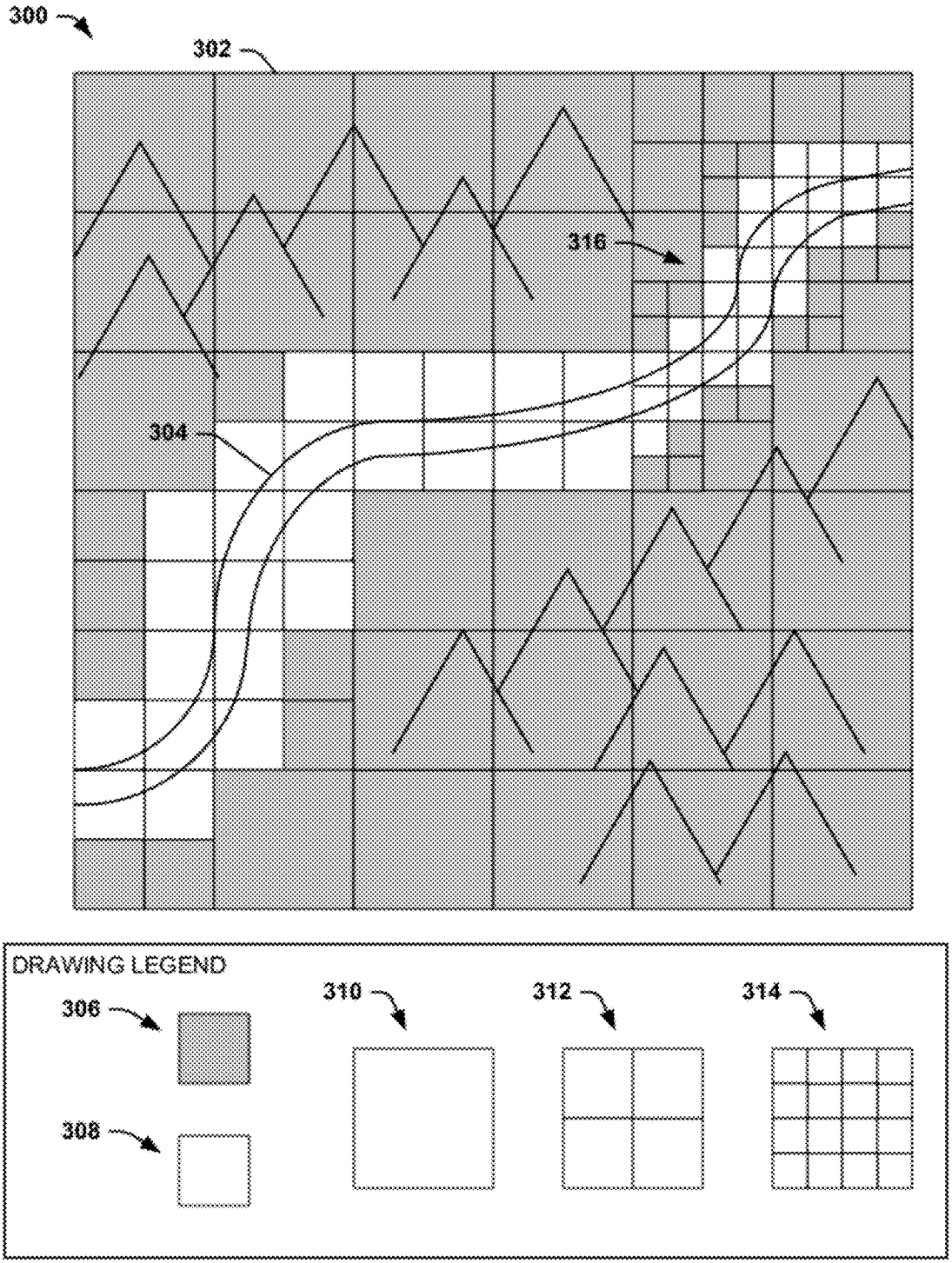


FIG. 7

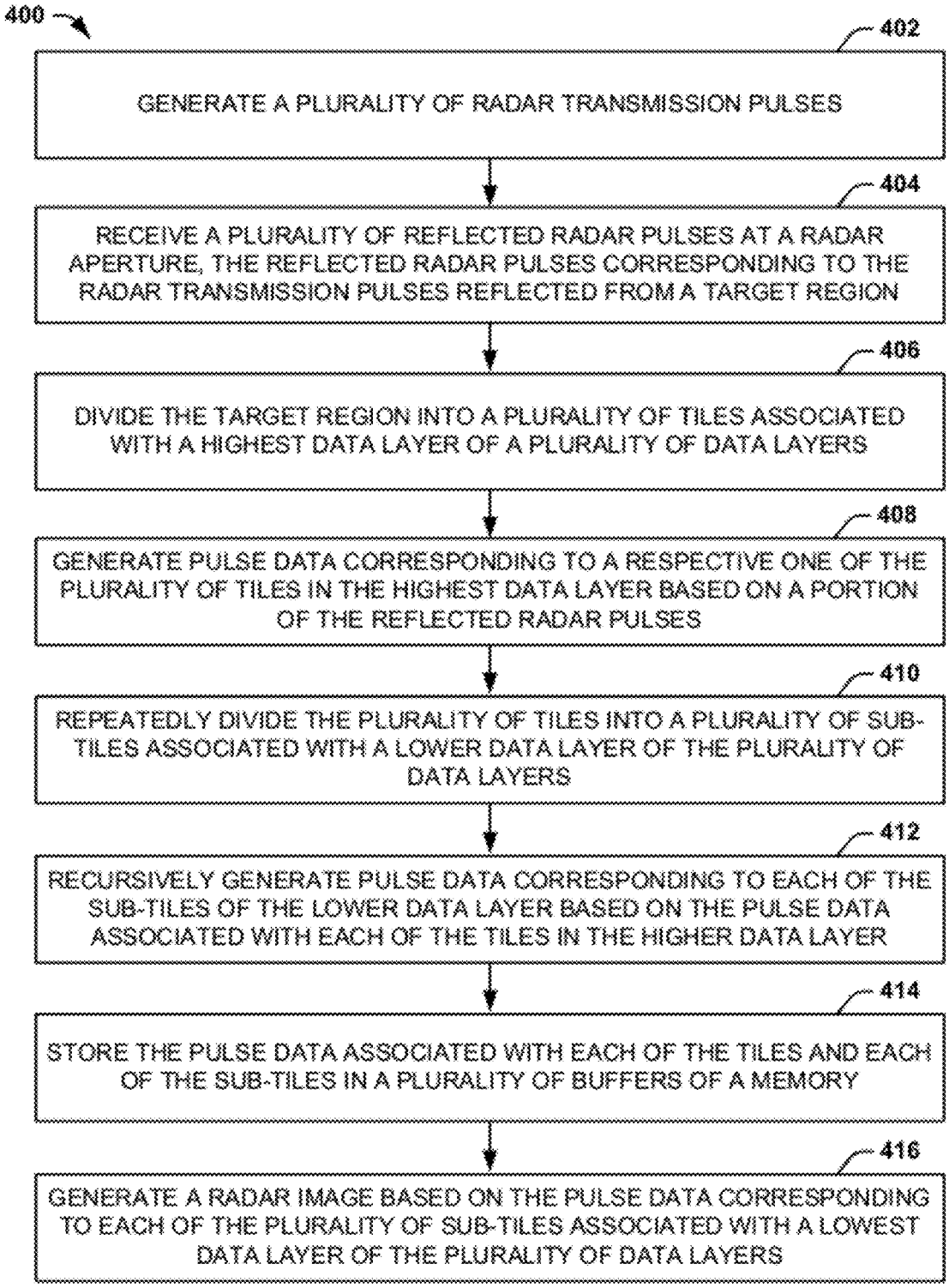

400
402
GENERATE A PLURALITY OF RADAR TRANSMISSION PULSES
404
RECEIVE A PLURALITY OF REFLECTED RADAR PULSES AT A RADAR APERTURE, THE REFLECTED RADAR PULSES CORRESPONDING TO THE RADAR TRANSMISSION PULSES REFLECTED FROM A TARGET REGION
406
DIVIDE THE TARGET REGION INTO A PLURALITY OF TILES ASSOCIATED WITH A HIGHEST DATA LAYER OF A PLURALITY OF DATA LAYERS
408
GENERATE PULSE DATA CORRESPONDING TO A RESPECTIVE ONE OF THE PLURALITY OF TILES IN THE HIGHEST DATA LAYER BASED ON A PORTION OF THE REFLECTED RADAR PULSES
410
REPEATEDLY DIVIDE THE PLURALITY OF TILES INTO A PLURALITY OF SUB-TILES ASSOCIATED WITH A LOWER DATA LAYER OF THE PLURALITY OF DATA LAYERS
412
RECURSIVELY GENERATE PULSE DATA CORRESPONDING TO EACH OF THE SUB-TILES OF THE LOWER DATA LAYER BASED ON THE PULSE DATA ASSOCIATED WITH EACH OF THE TILES IN THE HIGHER DATA LAYER
414
STORE THE PULSE DATA ASSOCIATED WITH EACH OF THE TILES AND EACH OF THE SUB-TILES IN A PLURALITY OF BUFFERS OF A MEMORY
416
GENERATE A RADAR IMAGE BASED ON THE PULSE DATA CORRESPONDING TO EACH OF THE PLURALITY OF SUB-TILES ASSOCIATED WITH A LOWEST DATA LAYER OF THE PLURALITY OF DATA LAYERS

FIG. 9

SYNTHETIC APERTURE RADAR (SAR) IMAGING SYSTEM

TECHNICAL FIELD

The present invention relates generally to radar systems, and specifically to a synthetic aperture radar (SAR) imaging system.

BACKGROUND

Since the early 20th century, experimentation has been conducted with radio waves as a means to detect distant targets of interest. Radar systems have developed from simple detection and ranging systems to essential systems on board aircraft and ships, and more recently to highly sophisticated space surveillance and imaging systems. Radar technology has followed, and in many cases driven, the advances in high-frequency electronic systems, digital processing, and computing. Most radar systems employ distinct but collocated transmitter and receiver electronics, as is explained in elementary radar systems textbooks. A modern aircraft or ship may have multiple radar systems of this type, for detecting and ranging airborne vehicles, marine vessels, and/or weather phenomena.

As radar technology has improved, radar based systems have been designed and implemented to provide critical imaging information regarding a target object or target area, particularly in scenarios where visible detection or visible images are not available or are not satisfactory. Signal parameters such as amplitude, time-delay, carrier-frequency, and modulation type are known to affect the performance of simple radar systems and advanced radar based imagery systems using synthetic aperture radar (SAR) techniques. In SAR systems, the motion of the platform hosting the radar transmitter is used to synthesize a much larger antenna aperture, consequently resulting in a higher resolution than is possible with the smaller physical aperture used in typical radar systems. The characteristics or parameters of radar signals that are reflected from a target object can be employed to provide imagery of the target. Because these images are generated from radio frequency (RF) waveforms as opposed to visible light, radar images can typically be obtained in poor weather or when the target is obscured by foliage, fog, or cloud cover.

In basic terms, SAR systems employ modulated pulse Doppler radar signals. Reflected signals from suitable radio-wave reflective targets can be processed to create a radar image that can often be distinct from an image obtained from a visible light based system. An SAR system typically uses the monostatic return from a target, which requires the radar receiver to be collocated, or nearly collocated, with the radar transmitter. As such, the SAR system can be located on a single platform in motion, such as an aircraft or orbiting satellite. In a bistatic or multistatic radar systems, the radar transmitter and the one or more radar receivers can be significantly separated in space, such that they can be located on separate and distinct platforms.

The performance of typical SAR systems can be characterized by examining an ambiguity function of the transmitted radar signal. The ambiguity function of the radar signal is related to the autocorrelation of the signal as a function of system parameters, time delay, and Doppler frequency shift. Ideally, the ambiguity function can be plotted as a narrow spike centered at the origin, with limited energy content along both the time and Doppler axis. Errors in interpreting the radar signal parameters in the pulsed radar signals, as

reflected from the target object or terrain, can result in artifacts and degraded resolution that can affect the processed radar image. Radar signals, including linear frequency modulated (FM) chirp pulse trains employed in SAR systems, may have limited bandwidth and time duration, such that the fundamental radar system performance can be compromised. The critical parameter of time-bandwidth product (TW) for a linear frequency modulated chirp is constrained by radar system design factors, such as ambiguous range, peak pulse power, and coherent bandwidth of the RF electronics. Accordingly, radar images may be generated without significant clarity or resolution.

SUMMARY

One embodiment of the invention includes a synthetic aperture radar (SAR) system. The system includes a radar transmitter configured to generate a plurality of radar transmission pulses and a radar receiver coupled to a radar aperture and configured to receive a plurality of reflected radar pulses corresponding to the plurality of radar transmission pulses having been reflected from a target region. The system also includes a processing controller configured to divide the target region into a plurality of tiles and to process a portion of the plurality of reflected radar pulses to generate pulse data corresponding to a respective one of the plurality of tiles in a highest data layer of a plurality of data layers. The processing controller also conducts a plurality of iterations, each corresponding to one of the plurality of data layers, of dividing each of the plurality of tiles into a plurality of sub-tiles corresponding to a lower data layer and to recursively process the pulse data associated with each of the plurality of tiles in a higher data layer to generate pulse data corresponding to each of the plurality of sub-tiles of the lower data layer. The system also includes an image processor configured to generate a radar image of the target region based on the pulse data corresponding to each of the plurality of sub-tiles associated with a lowest data layer of the plurality of data layers.

Another embodiment of the invention includes a method for imaging a target region based on SAR. The method includes generating a plurality of radar transmission pulses and receiving a plurality of reflected radar pulses at a radar aperture. The plurality of reflected radar pulses correspond to the plurality of radar transmission pulses having been reflected from the target region. The method also includes dividing the target region into a plurality of tiles associated with a highest data layer of a plurality of data layers and generating pulse data corresponding to a respective one of the plurality of tiles in the highest data layer based on a portion of the plurality of reflected radar pulses. The method also includes repeatedly dividing each of the plurality of tiles into a plurality of sub-tiles associated with a lower data layer of the plurality of data layers and generating pulse data corresponding to each of the plurality of sub-tiles of the lower data layer based on the pulse data associated with each of the plurality of tiles in a higher data layer of the plurality of data layers. The method also includes storing the pulse data associated with each of the plurality of tiles and each of the plurality of sub-tiles in each of the plurality of data layers in a plurality of buffers of a memory. The method further includes generating a radar image of the target region based on the pulse data corresponding to each of the plurality of sub-tiles associated with a lowest data layer of the plurality of data layers.

Another embodiment of the invention includes an SAR system. The system includes a radar transmitter configured to generate a plurality of radar transmission pulses and a radar receiver coupled to a radar aperture and configured to receive

a plurality of reflected radar pulses corresponding to the plurality of radar transmission pulses having been reflected from a target region. The system also includes a processing controller configured to divide the target region into a plurality of tiles, to range-align a portion of the plurality of reflected radar pulses to an approximate center of a given one of the plurality of tiles, to filter out components of the range-aligned pulses corresponding to tiles other than the given tile, and to decimate the filtered range-aligned pulses to generate pulse data corresponding to the given one of the plurality of tiles in a highest data layer of a plurality of data layers. The processing controller is further configured to conduct a plurality of iterations, each corresponding to one of the plurality of data layers, of dividing each of the plurality of tiles into a plurality of sub-tiles corresponding to a lower data layer, to range-align the pulse data associated with each of the plurality of tiles in a higher data layer to an approximate center of a given sub-tile, to filter out components of the range-aligned pulse data corresponding to sub-tiles other than the given sub-tile, and to decimate the filtered pulse data to generate pulse data corresponding to the given sub-tile in the lower data layer. The system further includes a back projection image processor configured to generate a radar image of the target region based on the pulse data corresponding to each of the plurality of sub-tiles associated with a lowest data layer of the plurality of data layers.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates an example of a synthetic aperture radar (SAR) imaging system in accordance with an aspect of the invention.

FIG. **2** illustrates another example of an SAR imaging system in accordance with an aspect of the invention.

FIG. **3** illustrates an example of a tile data structure in accordance with an aspect of the invention.

FIG. **4** illustrates an example of a schematic diagram of an SAR system in accordance with an aspect of the invention.

FIG. **5** illustrates an example of a tile memory system in accordance with an aspect of the invention.

FIG. **6** illustrates an example of a back-projection SAR distance calculation system in accordance with an aspect of the invention.

FIG. **7** illustrates an example of an image masking system in accordance with an aspect of the invention.

FIG. **8** illustrates an example of an SAR strip imaging system in accordance with an aspect of the invention.

FIG. **9** illustrates an example of a method for SAR imaging in accordance with an aspect of the invention.

DETAILED DESCRIPTION

The present invention relates generally to radar systems, and specifically to a synthetic aperture radar (SAR) imaging system. The SAR imaging system can be vehicle-based, such that an SAR transmitter and an SAR receiver can be located on a satellite or an aircraft. The radar transmitter can transmit radar transmission pulses, such as legacy linear frequency-modulated (FM) radar signals, to a target region to be imaged. A radar receiver that is coupled to a radar aperture can receive a plurality of reflected radar pulses corresponding to the plurality of radar transmission pulses having been reflected from a target region.

A tile processing controller can divide the target region into a plurality of tiles. The tile processing controller can include a range-aligner, a low-pass filter, and a decimator that can process the reflected radar pulses for each of the tiles, such that each of the tiles can have a set of pulse data corresponding to a processed portion of the reflected radar pulses in a highest data layer of a plurality of data layers. The tile processing controller can then iteratively divide each of the tiles into sub-tiles corresponding to one of a plurality of data layers, and can generate pulse data for each of the sub-tiles in a lower data layer based on the pulse data corresponding to the tile in a higher data layer. The iterative process can be repeated several times to generate pulse data for sub-tiles of sub-tiles, down to a lowest data layer. A back projection image processor can thus generate a radar image of the target region based on the pulse data of each of the sub-tiles in the lowest data layer.

It is to be understood that, as described and claimed herein, the terms "tile" and "sub-tile" are generally used interchangeably to refer to portions of the target region to be imaged with respect to the pulse data that is generated for the respective portions of the target region. A "sub-tile" may refer to a division of a "tile" in a next higher data layer, while that specific "tile" may be referred to as a "sub-tile" of yet another "tile" in an even next higher data layer. Thus, the term "tile" may refer to a portion of the target region in a higher data layer that may elsewhere be referred to as a "sub-tile". Similarly, the term "sub-tile" may refer to a portion of the target region in a lower data layer that may elsewhere be referred to as a "tile". Therefore, the terms "tile" and "sub-tile" are used to denote portions of the target region relative to each other. In addition, it is also to be understood that, as described and claimed herein, the data layers are referred to as "higher" and "highest" with respect to the larger and largest tiles of the target region, respectively, and that the data layers are referred to as "lower" and "lowest" with respect to the smaller and smallest sub-tiles of the target region, respectively, with the pulse data of the smallest sub-tiles in the lowest data layer being implemented for the SAR imaging.

FIG. **1** illustrates an example of a synthetic aperture radar (SAR) imaging system **10** in accordance with an aspect of the invention. The SAR imaging system **10** includes an aircraft **12**, demonstrated in the example of FIG. **1** as an airplane, flying past a target region **14** that is to be imaged. The target region **14** can include a variety of different landscapes.

The aircraft **12** can include an SAR system for imaging the target region. Specifically, the aircraft **12** can include an SAR transmitter that transmits radar transmission pulses **16** (e.g., linear frequency modulation (FM) chirps) to the target region and an SAR receiver that receives reflected radar pulses **18** corresponding to the radar transmission pulses **16** being reflected from the target region **14**. The radar transmission pulses **16** can be continuously transmitted from the aircraft **12** as it flies over the target region, thus simulating a much greater radar aperture based on the changing azimuth of the aircraft **12** relative to the target region, and thus the changing angle of the radar transmission pulses **16** and the reflected radar pulses **18**. It is to be understood that the radar transmission pulses **16** and the reflected radar pulses **18** are demonstrated simplistically, in that thousands of radar transmission pulses **16** (e.g., over 20,000) are transmitted and received as reflected radar pulses **18** as the aircraft **12** flies past the target region **14**.

As an example, the SAR system on board the aircraft **12** can implement back projection to image the target region. Specifically, for each of the reflected radar pulses **18**, the SAR system can calculate a range from the aperture of the SAR system to each pixel in the resultant image. The pulse return for the specific reflected radar pulse **18** can be interpolated at that range, and the radio frequency (RF) phase can be adjusted for that range. The data can then be summed into a resultant

radar image. Back projection SAR imaging can be implemented for arbitrary flight paths of the aircraft **12**, can project to digital terrain elevation data (DTED), and can typically yield the best and highest resolution images. However, back projection SAR imaging typically involves processing very large amounts of data, and thus image formation can be very slow, even with great processing capability.

FIG. **2** illustrates another example of an SAR imaging system **50** in accordance with an aspect of the invention. The SAR imaging system **50** includes an overhead view of an aircraft **52** flying over a target region **54**. Similar to as described above in the example of FIG. **1**, the aircraft **52** includes an SAR system **56** that emits radar transmission pulses and receives corresponding reflected radar pulses. The SAR system can include a back projection image processor **58**, similar to as described above in the example of FIG. **1**.

To significantly reduce the processing time of the generation of the radar image using back projection, the SAR system can include a tile processing controller **60** that is configured to divide the target region **54** into a plurality of tiles **62**. In the example of FIG. **2**, the tiles **62** are demonstrated as an array of sixteen square tiles corresponding to respective portions of the target region **54**. The SAR system can thus process the reflected radar pulses to generate sets of pulse data corresponding specifically to each of the tiles **62**. As an example, the tile processing controller **60** can range-align the reflected radar pulses to an approximate center point **64** of each of the tiles **62**. The SAR system can then implement a low-pass filter (LPF) to filter out reflected radar pulse components (i.e., radar scatterers) having frequencies that are Doppler-shifted, such as effectively corresponding to other portions (i.e., other tiles **62**) of the target region **54**. This is demonstrated in the example of FIG. **2** by the dashed lines **66** corresponding to reflected radar pulse components that are being filtered-out. Thus, the reflected radar pulse components that are filtered out are essentially removed from the image data corresponding to the respective tile **62** being processed. The filtered reflected radar pulses, indicated in the example of FIG. **2** by the solid lines **68**, are then decimated to reduce the corresponding pulse data for the respective tile **62**, such as by removing every other filtered reflected radar pulse. Accordingly, the pulse data associated with each of the tiles **62** is a set of data specific to the radar imaging of that respective portion of the target region **54**.

The pulse data that is generated for each of the tiles **62** corresponds to a broad data set for each of the respective portions of the target region **54**. However, as described above, back projection image processing achieves high resolution based on range calculations for each pulse to each pixel of the resultant image. Thus, the tile processing controller **60** is further configured to divide each of the tiles **62** of the target region **54** into a plurality of sub-tiles. The tile processing controller **60** can thus generate a separate set of pulse data for each of the sub-tiles based on the set of pulse data that was generated for the tile **62** that was divided into the respective sub-tiles.

FIG. **3** illustrates an example of a tile data structure **100** in accordance with an aspect of the invention. The tile data structure **100** can be implemented by the tile processing controller **60** in the example of FIG. **2**. Therefore, reference is to be made to the example of FIG. **2** in the following description of the example of FIG. **3**.

The tile data structure **100** demonstrates a pair of tiles **102** that can each correspond to one of the tiles **62** in the example of FIG. **2**. Specifically, the pair of tiles **102** can each represent specific portions of the target region **54**. The tile processing controller **60** generates a set of pulse data **104** associated with each of the respective tiles **102**, such as by range aligning and range-reducing the reflected radar pulses to a center point of each of the respective tiles **102**, filtering out components of the pulses, and decimating the filtered pulses. Thus, each of the sets of pulse data **104** corresponds to a broad set of image data associated with the respective portion of the target region **54** that is represented by the respective one of the tiles **102**. Although the tiles **102** are demonstrated as approximately square, it is to be understood that the pulse data **104** may not be representative of a completely square-shaped portion of the target region **54**, as demonstrated by the tiles **102**, and that the pulse data **104** for each of the tiles **102** could overlap with respect to the portions of the target region **54**.

The tile processing controller **60** is further configured to divide each of the tiles **102** into a plurality of sub-tiles **106**. The tile processing controller **60** can then generate a set of pulse data **108** associated with each of the respective sub-tiles **106** based on the pulse data **104** associated with each of the tiles **102**. Specifically, for each of the sub-tiles **106**, the tile processing controller **60** range-aligns and range-reduces the pulse data **104** corresponding to the tile **102** from which the respective sub-tile **106** is divided to a center point of the respective sub-tile **106**, filters out high-frequency components of the pulses of the pulse data **104**, and decimates the filtered pulses of the pulse data **104** to generate the pulse data **108**. Thus, each of the sets of pulse data **108** corresponds to a set of image data associated with the respective portion of the target region **54** that is represented by the respective one of the sub-tiles **106**, and which is narrower than the broader set of image data represented by the pulse data **104** from which the pulse data **108** is generated.

In the example of FIG. **3**, the tile processing controller **60** is yet further configured to divide each of the tiles **106** into a plurality of sub-tiles **110**. The tile processing controller **60** can then generate a set of pulse data **112**, demonstrated in the example of FIG. **3** as "PD", associated with each of the respective sub-tiles **110** based on the pulse data **108** associated with each of the tiles **106**. Specifically, for each of the sub-tiles **110**, the tile processing controller **60** range-aligns and range-reduces the pulse data **108** corresponding to the tile **106** from which the respective sub-tile **110** is divided to a center point of the respective sub-tile **110**, filters out high-frequency components of the pulses of the pulse data **108**, and decimates the filtered pulses of the pulse data **108** to generate the pulse data **112**. Thus, each of the sets of pulse data **112** corresponds to a set of image data associated with the respective portion of the target region **54** that is represented by the respective one of the sub-tiles **110**, and which is narrower than the broader set of image data represented by the pulse data **108** from which the pulse data **112** is generated.

Therefore, the example of FIG. **3** demonstrates that the tile processing controller **60** recursively generates pulse data in each of a plurality of data layers. Specifically, in the example of FIG. **3**, the tiles **102** and corresponding sets of pulse data **104** are demonstrated as occupying a highest data layer **114**, the tiles **106** and corresponding sets of pulse data **108** are demonstrated as occupying a lower data layer **116** relative to the highest data layer **116**, and the tiles **110** and corresponding sets of pulse data **112** are demonstrated as occupying a lowest data layer **118**. The tile processing controller **60** thus generates the pulse data in a recursive manner, such that the tile processing controller **60** implements pulse data from a next higher data layer corresponding to a given tile to generate pulse data for each of the sub-tiles associated with the given tile in a next lower data layer.

The tile processing controller **60** can continue to iteratively divide and sub-divide tiles and sub-tiles and generate sets of

pulse data in lower data layers from pulse data in a next higher data layer. Specifically, in the example of FIG. **3**, the tile processing controller **60** can further divide each of the tiles **110** into four sub-tiles, and can generate a set of pulse data for each of the four sub-tiles based on a corresponding set of pulse data **112**. Accordingly, the tile processing controller **60** can iteratively continue to divide tiles into sub-tiles and generate pulse data in lower data layers from higher data layers until the tile processing controller **60** generates a set of pulse data for each of the sub-tiles in a lowest data layer. The back projection image processor **58** can thus generate the radar image from the sets of pulse data in the lowest data layer. As described in greater detail below, the generation of the resultant radar image can be significantly faster than typical back projection radar imaging based on the tiling and sub-tiling and recursive generation of pulse data described herein.

It is to be understood that the SAR imaging system **50** and the tile data structure **100** are not intended to be limited to the examples of FIGS. **2** and **3**, respectively. As an example, the SAR system **56** is not limited to implementing back projection radar imaging, but could instead implement other types of SAR imaging, such as a polar format algorithm (PFA) or a range migration algorithm. As another example, the number of tiles in each of the data layers is not limited to that demonstrated in the examples of FIGS. **2** and **3**. Specifically, in the example of FIG. **2**, the highest data layer is not limited to the sixteen tiles **62**, but could have more or less tiles **62**. In addition, the tile processing controller **60** is not limited to dividing each tile into four sub-tiles, but could instead divide each tile into more or fewer sub-tiles with the corresponding filter and cutoff ratio. Therefore, the SAR imaging system **50** and the tile data structure **100** can be configured in a variety of ways.

FIG. **4** illustrates an example of a schematic diagram of an SAR system **150** in accordance with an aspect of the invention. The SAR system **150** can correspond to the SAR system **56** in the example of FIG. **2**. Therefore, reference is to be made to the examples of FIGS. **2** and **3** in the following description of the example of FIG. **4**.

The SAR system **150** includes a transmission pulse generator **152** that is configured to generate radar transmission pulses, such as the radar transmission pulses **16** in the example of FIG. **1**. As an example, the transmission pulse generator **152** can generate a baseband radar signal with a precisely controlled chirp rate, such that frequency can be monotonically increased or decreased along the length of the radar pulse, such as by linear FM techniques. The transmission pulses are provided to a wideband RF transmitter **154** that is configured to up-convert and/or modulate the radar transmission pulses for transmission. The radar transmission pulses are transmitted from an aperture **156** for transmission to the target region **54**.

The aperture **156** collects the energy of the reflected radar pulses, such as the reflected radar pulses **18** in the example of FIG. **1**. The reflected radar pulses are provided to a wideband RF receiver **158**. The wideband RF receiver **158** can be configured to down-convert the received reflected radar pulses to an intermediate frequency (IF). The data associated with the reflected radar pulses of the target region **54** are stored in a target region pulse data storage **160**. The target region pulse data storage **160** stores pulse data associated with substantially the entirety of the target region **54**. Specifically, the pulse data can be associated with all of the reflected radar pulses that are processed by the SAR system **150** to generate a resultant radar image of the target region.

The SAR system **150** includes a tile processing controller **162**. The tile processing controller **162** includes a tile generator **164**, a range-alignment controller **166**, a low-pass filter (LPF) **168**, and a decimator **170**. The tile generator **164** is configured to divide the target region **54** into the tiles **62**, similar to as described above in the examples of FIG. **2**. As an example, the tile generator **164** can designate approximate center points for the tiles **62** in the target region **54**. The pulse data associated with the reflected radar pulses is provided from the target region pulse data storage **160** to the range-alignment controller **166**. The range-alignment controller **166** thus range-aligns the reflected radar pulses to each of the approximate center points of each of the tiles **62** of the target region **54**. The range-alignment controller **166** then shifts a phase associated with each of the reflected radar pulses to simulate an approximate zero Doppler-shift at the approximate center point of the tile **62**.

In addition, the range-alignment controller **166** can range-reduce the range-aligned pulse data associated with reflected radar pulses to account for the range of the aircraft **52** to the associated tile **62**. As an example, the range-alignment can be performed by the range-alignment controller **166** in the Fourier domain. Thus, the range-alignment controller **166** can likewise range-reduce the range-aligned pulse data associated with reflected radar pulses in the Fourier domain by filtering and decimating the range-aligned pulse data to be specific to the range to the associated tile **62**. As another example, the range-reduction can be performed in the time domain, such that the range-alignment controller **166** can be configured to discard pulse data corresponding to return times that are outside of the range of the associated tile **62**. As described herein, the range-reduction operation can be performed as part of the range-alignment operation of the range-alignment controller **166**. However, it is to be understood that the range-reduction operation can be performed separately, such as by additional hardware.

The LPF **168** is configured to filter along the range-aligned and reduced reflected radar pulses to remove high-frequency components of the range-aligned pulses of the reflected radar pulse data that do not corresponding to the given tile **62**. The LPF **168** thus has a pass-band corresponding only to the given tile **62**. Specifically, radar scatterers that are Doppler-shifted, such as effectively corresponding to other tiles **62** of the target region **54**, are removed by the LPF **168**. As an example, the LPF **168** can be configured as a finite impulse response (FIR) filter having a plurality of taps, and can be implemented in a way that accounts for a group delay of the filter. The number of taps can be an odd number, for example, such that the group delay of the range-aligned pulses corresponds to an integer number of samples. As a result, it is not necessary for the tile processing controller **162** to interpolate the position of the aperture **156**.

The LPF **168** can include a pass-band having a frequency range from approximately zero to a first percentage of the Nyquist frequency. As an example, the first percentage of the Nyquist frequency can be greater than one quarter, such as approximately 30%, to substantially account for higher order effects in filtering the pulse data. The LPF can also include a transition-band between the pass-band and a stop-band. For example, the transition-band can occupy a range from approximately 30% to approximately 70% of the Nyquist frequency. The stop-band can thus occupy approximately 70% of the Nyquist frequency to the Nyquist frequency. Thus, the LPF **168** implements approximately equal pass-band and stop-band weighting, with a substantially broader transition-band.

The wide transition-band of the LPF **168** can substantially mitigate deleterious edge-effects associated with the filtering of the pulse data. Specifically, these deleterious edge-effects

can be completely removed by zero-padding the beginning and end of the data provided to the LPF **168**. Zero-padding along azimuth is accomplished by adding fictitious zero-filled pulses at the beginning and the end of the data. These fictitious pulses can have an associated antenna location; for this purpose it is sufficient to smoothly extrapolate the antenna path. The output of the LPF **168** can contain non-zero pulses outside of the physical aperture, but this can be an artifact of chopping the data, thus introducing sidelobes, and not an artifact of the filter itself. The zero-padding can thus allow the recursively tiled back projection image processing methodology described herein to produce a substantially similar output image as a traditional back projection image processor, but in a much more rapid manner.

The use of a wide transition band of the LPF **168** requires that the signal be oversampled for each individual top level tile. The initial oversampling can result from breaking the entirety of the image into a 4×4 array of top layer tiles so that each top layer tile contains Doppler frequencies less than one quarter of the Nyquist frequency after alignment. At each successive tiling stage, a given tile can be divided into 2×2 array of sub-tiles, each of the sub-tiles including approximately half the Doppler bandwidth and approximately half the range extent, such that after filtering and decimation a Doppler bandwidth of approximately 25% of Nyquist throughout is maintained through the tiling sequence. Other tiling strategies can be similarly implemented. For example, a 3×3 array of sub-tiles can be generated for each tile, with each sub-tile including a Doppler bandwidth approximately one third of Nyquist, thus allowing a LPF stage with a pass-band from zero to 0.33 Nyquist and a stop-band from 0.66 to Nyquist without initial oversampling. If the entirety of the image is significantly oversampled (e.g., has a Doppler bandwidth substantially below Nyquist), then the tiling sequence could use a smaller number of larger top layer tiles or the data could be filtered and decimated to reduce the degree of oversampling.

The decimator **170** is configured to remove a fraction of the filtered range-aligned pulse data. As an example, the decimator **170** can remove every other range-aligned pulse of the filtered pulse data that is output from the LPF **168**. As a result, the decimator **170** effectively reduces the size of the pulse data corresponding to the given tile **62** to a more processing manageable quantity while maintaining resultant image quality. The decimator **170** thus outputs the pulse data corresponding to the given tile, such as pulse data **104** in the example of FIG. **3**. The resultant pulse data for the tile **62** is saved within a buffer in a tile memory **174** in the tile generator **164**.

The tile processing controller **162** thus generates the pulse data for each of the tiles **62** in the highest data layer **114** via the range-alignment controller **166**, the LPF **168**, and the decimator **170** and stores the pulse data corresponding to each of the tiles **62** in separate buffers of the tile memory **174**. The tile generator **164** then divides each of the tiles **62** into sub-tiles, such as the sub-tiles **106** from the tiles **102** in the example of FIG. **3**. For each of the sub-tiles, tile generator **174** then provides the pulse data associated with the respective tile **62** from which the sub-tiles were divided to the range-alignment controller **166**. The tile processing controller **162** thus recursively generates a set of pulse-data for each of the sub-tiles in the next lower data layer based on the pulse data of the tile in the next higher data layer from which the sub-tile was divided. The tile processing controller **162** can continue to divide tiles into sub-tiles and recursively generate respective sets of pulse data over a number of iterations (e.g., six or more). As an example, the tile processing controller **162** can perform a number of tiling and pulse data generating iterations to divide the target region **54** having over 20,000 associated reflected radar pulses down to an array of 256×256 sub-tiles. Each of the sub-tiles can have approximately 64×64 pixels in the resultant image, for a total of approximately 16 k×16 k pixels in the resultant image, based on approximately 200 processed reflected radar pulses in the corresponding pulse data.

FIG. **5** illustrates an example of a tile memory system **200** in accordance with an aspect of the invention. The tile memory system **200** can correspond to the tile memory system **174** in the example of FIG. **4**. Thus, reference is to be made to the example of FIG. **4** in the following description of the example of FIG. **5**.

In the example of FIG. **5**, the tile memory system **200** includes a plurality of memory buffers **202** in a highest data layer, designated DATA LAYER **0**. The plurality of memory buffers **202** are each configured to store pulse data associated with a specific one of the tiles **52** in the example of FIG. **2**. Specifically, as demonstrated in the example of FIG. **5**, the memory system **200** includes sixteen of the memory buffers **202**, corresponding respectively to TILE **1** through TILE **16**. Thus, the tile processing controller **162** can store the generated pulse data for each of the tiles **62** in the respective one of the memory buffers **202**. As an example, the pulse data can correspond to data associated with a portion of the reflected radar pulses and/or other radar imaging data, such as phase history associated with the portion of the reflected radar pulses and an array of data associated with location of the aperture **156**.

The tile generator **164** can then divide each of the tiles **62** into a set of four sub-tiles. The memory system **200** includes a plurality of memory buffers **204** associated with a next lower data layer from DATA LAYER **0**, demonstrated in the example of FIG. **5** as DATA LAYER **1**. Specifically, the memory system **200** includes a set of four memory buffers **204** structured beneath each of the memory buffers **202** for a total of 64 of the memory buffers **204**. Thus, the memory buffers **204** are designated for SUB-TILE **1_1** through SUB-TILE **1_4**, such that the sub-tiles **204** associated with TILE **16** would be designated for SUB-TILE **16_1** through SUB-TILE **16_4**. Therefore, based on this structure pattern, the tile memory system **200** further includes a plurality of memory buffers **206** associated with a next lower data layer, DATA LAYER **2**, a plurality of memory buffers **208** associated with a next lower data layer, DATA LAYER **3**, and down a number of layers to a plurality of memory buffers **210** associated with a lowest data layer, DATA LAYER X, where X is an integer greater than 1. The memory buffers **210** are demonstrated as*__1 through*__4, where "*" denotes the tiles and sub-tiles from which the respective set of memory buffers **210** are structured. For example, for X=6, "*" can represent the memory buffer 1__1__1__1__1__1__1 in the next higher data layer, DATA LAYER **5**, beneath which the memory buffers **210** are structured based on each of the memory buffers demonstrated in the example of FIG. **5** being structured from the first, or "1", memory buffer in each of the data layers.

Each of the memory buffers **204**, **206**, **208**, and **210** stores pulse data that is generated by the tile processing controller based on the pulse data that is stored in the respective memory buffer in the next highest data layer beneath which it is structured. Specifically, the tile generator **164** accesses the pulse data from a respective one of the memory buffers in a given data layer for the tile processing controller **162** to generate sets of pulse data for the respective sub-tiles in the next lower data layer. Thus, the tile generator **164** thus stores the newly generated sets of pulse data into the respective memory buff-

ers structured beneath the accessed memory buffer in the next lower data layer within the tile memory system **200**. The memory buffers **210** thus store the pulse data associated with the smallest sub-tiles in the tiling process conducted by the tile generator **164**.

The memory buffers **202** through **210** of the tile memory system **200** can be very large to accommodate the large amounts of data that can represent a given set of pulse data for a given tile. Particularly, the memory buffers **202** can have the largest data capacity to accommodate the large amounts of pulse data associated with such a larger portion of the target region, with the memory buffers being increasingly smaller from one lower data layer to the next. However, the large amounts of pulse data can cause a memory buffer in a given one of the data layers to overflow. Thus, upon a given memory buffer corresponding to a respective tile in a data layer being full, the tile processing controller **162** can generate partial sets of pulse data for the respective sub-tiles in the next lower data layer at a given time. For example, if a given memory buffer **202** in the DATA LAYER **0** overflows, the tile processing controller **162** can begin generating sets of pulse data for the respective sub-tiles in DATA LAYER **1**, and thus storing the partial sets of pulse data in the respective memory buffers **204**. The pulse data in the given memory buffer **202** can then be overwritten by additional and/or the rest of the pulse data for the given tile in DATA LAYER **0**, after which the tile processing controller **162** can finish generating the sets of pulse data for the respective sub-tiles in DATA LAYER **1**, which is thus stored in the memory buffers **204**.

It is to be understood that the tile memory system **200** is not limited to the example of FIG. **5**. Specifically, the structure of the memory buffers **202** through **210** are demonstrated in the example of FIG. **5** as diagrammatically corresponding to the manner in which pulse data is generated for each of the sub-tiles that are divided from a respective tile in a next higher data layer. Thus, the memory buffers **202** through **210** can be configured in any of a variety of data structures within the tile memory system **200**.

Referring back to the example of FIG. **4**, the SAR system **150** further includes a back projection image processor **176**. The back projection image processor **176** is configured to access each of the memory buffers corresponding to the lowest data layer from the tile memory **174**, such as the memory buffers **210** in the example of FIG. **5**, to generate a radar image of the target region. Specifically, for each pulse of the pulse data corresponding to each of the sub-tiles in the lowest data layer, the back projection image processor **176** can calculate a range from the aperture **156** to each pixel in the given sub-tile. The pulse return for each specific pulse can be interpolated at that range, and the RF phase can be adjusted for that range. The resultant pulse data can then be summed into a resultant radar image. However, based on the iterative tiling and sub-tiling and the recursive generation of the pulse data based on pulse data of the tiles in the next higher data layer, the back projection image processor **176** can generate the resultant radar image very rapidly relative to typical back projection image processing.

By dividing the target region into the plurality of sub-tiles down to the lowest data layer, the back projection image processor **176** processes a greatly reduced number of pulses relative to typical back projection image processing. Specifically, in back projection image processing, the number of pulses that are implemented for image processing is proportional to the imaging area, such that the amount of processing for generating an image of a given area, such as a tile **62**, is proportional to N*X*Y, where N is a number of pulses and X and Y are the width and length of the resultant radar image in pixels. Thus, upon dividing a given tile into four sub-tiles, each approximately a quarter the size of the parent tile, the image associated with each of the sub-tiles is represented by (X/2)×(Y/2) pixels. Upon generating the pulse data for a given sub-tile based on the pulse data of the parent tile, the number of associated pulses in the pulse data for the sub-tile can be approximately half the number of pulses in the pulse data for the parent tile, thus approximately (N/2) pulses. Therefore, if the amount of processing for generating the image of a given tile is N*X*Y, then the amount of processing for generating the image of a the four sub-tiles corresponding to the given tile is 4*(N/2)*(X/2)*(Y/2), which simplifies to (N*X*Y)/2, minus the processing overhead required for dividing the sub-tiles and recursively generating the associated sets of pulse data. Therefore, the back projection image processing, as described herein, is approximately twice as fast for each data layer of the iterative tiling process, minus the processing overhead at each data layer, relative to a typical back projection imaging process. As a result, an image that would typically require ten or more hours to generate on a given computer could be generated in less than approximately three minutes based on the iterative tiling and recursive pulse data generation technique described herein.

Referring again to the example of FIG. **5**, the recursive tile generation of pulse data by the tile processing controller **162** and the storing of the pulse data in the memory buffers **202** through **210** can result in the memory buffers **202** through **210** overflowing in a cascade fashion. Specifically, the memory buffers in a lower data layer can thus overflow in response to an overflow of the respective memory buffer in the data layer above, such that the memory buffers in the lowest data layer can likewise overflow. Therefore, upon the memory buffer in the lowest data layer overflowing, the back projection image processor **176** can be configured to begin generating the radar image of the target region based on the pulse data in the memory buffers in the lowest data layer. The pulse data in the memory buffers in the lowest data layer can then be overwritten by additional and/or remaining pulse data that is generated for the sub-tiles in the lowest data layer. Accordingly, similar the tile processing controller **162** generating partial sets of pulse data from pulse data in overflowing memory buffers, the back projection image processor **176** can generate the radar image of the target region in a piece-meal fashion in response to an overflow of the memory buffers in the lowest data layer.

The generation of the pulse data down to a lowest data layer, such that each of the sub-tiles in the lowest data layer has a number of pulses in an associated set of pulse data that is specific to that respective sub-tile, allows for the implementation of additional efficient radar imaging techniques.

As one example, in a given collection period, the transmission pulse generator **152** can be configured to generate more than a sufficient number of radar transmission pulses to generate a given radar image. For example, whereas approximately 20,000 radar transmission pulses may be sufficient to generate a quality radar image of sufficient resolution, the transmission pulse generator **152** can be configured to generate approximately 40,000 or more radar transmission pulses. Thus, upon processing the reflected radar pulses and recursively generating the pulse data down to the sub-tiles of the lowest data layer, the pulse data associated with the sub-tiles of the lowest data layer could include a number of pulses that is greater than that which is necessary for the back projection image processor **176** to process the radar image (e.g., approximately 400 pulses instead of approximately 200 pulses). Therefore, the back projection image processor **176** can be configured to generate a plurality of separate radar

images of the target region **54** based on a respective plurality of unique subsets of the pulse data of each of the sub-tiles of the lowest data layer. Because the separate radar images are based on unique subsets of the pulse data of the sub-tiles of the lowest data layer, each of the separate radar images can be distinct images. The separate radar images can include an overlap in the pulse data in each of the unique subsets of the pulse data, such that the back projection image processor **176** can implement aperture weighting to simulate overlapped apertures. Thus, the back projection image processor can generate the separate radar images while maintaining side-lobe control and further avoiding edge effects.

As another example of efficient radar imaging techniques, the tile processing controller **162** can simulate spatially variant apertures based on the recursive generation and processing of the pulse data associated with separate portions of the target region **54**. Specifically, in processing the reflected radar pulses at the highest data layer, the tile processing controller **162** can be configured to increase a number of pulses corresponding to the pulse data for portions of the target region **54** that are further away from the radar aperture **156** relative to portions of the target region **54** that are closer to the radar aperture **156**. For example, the tile processing controller **162** can adjust the filtering and/or decimation characteristics of the LPF **168** and/or the decimator **170**, respectively, for each of the data layers from the highest data layer down to the lowest data layer. As a result, the back projection image processor **176** can generate the radar image in such a manner as to simulate a constant azimuth resolution across the radar image. Specifically, because the range and angular characteristics of the radar aperture **156** are applied at the level of the sub-tiles of the lowest data layer, the tile processing controller **162** can adjust the range and angular characteristics of the radar aperture **156** at the level of the sub-tiles of the lowest data layer.

Another example implementation of more efficient radar imaging techniques based on the tile generation procedures and recursive pulse data generation described herein is a more efficient range calculation. As described above, back projection radar imaging implements a calculation of the range from the aperture **156** to each pixel in the resultant radar image. The calculation of the range is a vector calculation in three-dimensional space, such that for a given aperture location $<X_A, Y_A, Z_A>$, and a given pixel location $<X_P, Y_P, Z_P>$, the range can be calculated as follows:

$$R=\sqrt{(X_A-X_P)^2+(Y_A-Y_P)^2+(Z_A-Z_P)^2} \quad \text{Equation 1}$$

The operation demonstrated by Equation 1 requires five additions, three multiplications, and a square-root for every pixel for each of the reflected radar pulses. The square-root operation alone can be very processing intensive. In addition, due to the extreme range of the radar aperture **156** relative to each of the pixels, the range calculation is typically performed at double precision (e.g., 8 bytes resolution instead of 4 bytes). Therefore, performing the range calculation using Equation 1 for every pixel for each of the reflected radar pulses can require a large amount of processing time.

FIG. **6** illustrates an example of a back-projection SAR distance calculation system **250** in accordance with an aspect of the invention. The SAR distance calculation system **250** can be implemented by the back projection image processor **174** to provide for an even more efficient manner of generating the radar image. Thus, reference is to be made to the example of FIG. **4** in the following description of the example of FIG. **6**.

The example of FIG. **6** demonstrates a sub-tile **252** corresponding to a given sub-tile associated with the lowest data layer, such that the pulse data associated with the sub-tile **252** is implemented by the back projection image processor **174** to generate the resultant radar image. For each of the range-aligned pulses of the pulse data associated with a given sub-tile, the back projection image processor **174** can implement a normal double-precision calculation to get Rc, the range from the aperture **156** to an approximate center point **254** of the sub-tile **252** using Equation 1. However, the back projection image processor **174** can then implement a low-order approximation to calculate dR, the difference between the range from the aperture **156** to a given pixel and Rc. The low-order approximation can thus be a single precision calculation based on the magnitude of D, the vector from the from the approximate center point **254** of the sub tile **252** to the individual pixel, being significantly less than the range Rc from the aperture **156** to the approximate center point **254**. Thus, the low-order approximation results in more rapid processing based on the series of single precision calculations, as opposed to double precision calculations.

A normalized look vector **256** (i.e., the vector from the center of the aperture **156** to the approximate center point **258** of the sub-tile **252**) of a given pulse of the pulse data corresponding to the sub-tile **252** is defined as L_N. A dot product between the normalized look vector and D is defined as dL, as follows:

$$dL=L_N \text{dot} \cdot D \quad \text{Equation 2}$$

Where: D is a vector from the approximate center point **254** to the given pixel **258**.

A first order approximation for the range from the aperture to the pixel can be expressed as:

1^{st} Order Approximation:

$$R \cong Rc+dL \quad \text{Equation 3}$$

A second order correction factor $d\rho^2$ can then be calculated based on the vector from the approximate center point **254** to the pixel D and dL as follows:

$$d\rho^2=|D|^2-dL^2 \quad \text{Equation 4}$$

The second order correction factor $d\rho^2$ can thus be used in a second or third order approximation to remove the square-root component of the range calculation R to the given pixel **258**, as follows:

2^{nd} Order Approximation:

$$R=Rc+dL+0.5*d\rho^2/Rc \quad \text{Equation 5}$$

3^{rd} Order Approximation:

$$R=R_C+dL+0.5*(1-dL/Rc)*(1+dL^2/Rc^2)*d\rho^2/Rc \quad \text{Equation 6}$$

The first, second, or third-order approximation of the range to each of the pixels **258** in a given sub-tile **252** for every pulse of the pulse data corresponding to the given sub-tile **252** is thus significantly faster based on Equations 2 through 6 than the calculation based on Equation 1. Specifically, the low-order approximations based on Equations 2 through 6 omit the use of a square-root, and are thus computationally faster in the back projection image processor **174**. Furthermore, because the range is calculated from the approximate center point **254** to each pixel **258** in a relatively small sub-tile **252**, double precision calculations are not necessary to achieve sufficient precision. Therefore, the calculations of Equations 2 through 6 can all be performed in single precision, thus further increasing the computational speed of the range calculation to each pixel **258** in the sub-tile **252**. The use of a low order approximation to the range is made possible due to the small size of the sub-tile relative to the range to the sub-tile. The selection of the first, second, or third order approximation can be based on the size of the sub-tile relative to the

range and the degree of precision required. In practice, these approximations could be used by first range aligning the pulse data corresponding to the lowest level sub-tile to the approximate center of the sub-tile, then performing the back-projection interpolation and phase correction based only on the difference between the range to the individual pixel and Rc, the range to the approximate center of the sub-tile.

It is to be understood that the above computations of the approximate range can accommodate back projection to digital terrain elevation data (DTED). The vector D from the approximate center of the sub-tile would simply include height component of each pixel due to the DTED, and the approximate tile centers used at each stage of tiling likewise include the height due to DTED.

Another implementation of additional efficient radar imaging techniques is demonstrated in the example of FIG. **7**. FIG. **7** illustrates an example of an image masking system **300** in accordance with an aspect of the invention. The image masking system **300** can be implemented in the SAR system **150** in the example of FIG. **4**. Therefore, reference is to be made to the example of FIG. **4** in the following description of the example of FIG. **7**.

The image masking system **300** is demonstrated as an overhead view of a target region **302** to be imaged. The target region **302** includes a river **304** that flows through the target region **302**. In the example of FIG. **7**, it may be necessary for the SAR system **150** to only image a portion of the target region **302** that includes the river **304**. Thus, it may not be important for the SAR system **150** to image the remaining portion of the target region **302**. Therefore, based on the tiling methodology and the recursive pulse data generation for the given data layers described herein, the portion of the target region **302** that includes the river **304** can be very quickly and efficiently imaged by the SAR system **150**.

In the example of FIG. **7**, the tile processing controller **162** can be configured to check a distance for a given tile in a given data layer from the given region to be imaged. As an example, the portion of the target region **302** can be designated based on a predetermined distance from the banks of the river **304**. Thus, the tile processing controller **162** can check to determine if a given tile in a given data layer is within the predetermined distance. If the given tile is not within the predetermined distance, the tile is masked from the resultant radar image, and is thus excluded from further processing. Therefore, the tile generator **164** does not generate a set of sub-tiles based on the given tile, and a set of pulse data is not generated for the given tile. Tiles that are masked from the radar image are demonstrated in the example of FIG. **7** as shaded tiles corresponding to a masked region **306**, while those that are to be included in the radar image are demonstrated in the example of FIG. **7** as a non-shaded region **308**.

The determination of whether a given tile is within the predetermined distance can be performed at any of the data layers, and can be programmable and/or variable. Specifically, the example of FIG. **7** demonstrates tiles in a first data layer **310**, tiles in a second data layer **312**, and tiles in a third data layer **314**. The tiles in the third data layer **314** occupying a next lower data layer of the tiles in the second data layer **312**, which occupy a next lower data layer of the tiles in the first data layer **310**. The tile processing controller **162**, upon dividing the target region **302** into the tiles of the first data layer **310**, can then determine if any portion of the tiles of the first data layer **310** are within the predetermined distance of the river **304**. If no portion of a given one of the tiles in the first data layer **310** is within the predetermined distance, then the tile processing controller **162** can mask the given one of the tiles in the first data layer **310**, thus further excluding the given tile from further processing. Those tiles of the first data layer **310** that are within the predetermined distance of the river **304** are processed further, such that the tile processing controller **162** generates a set of pulse data for those tiles of the first data layer **310** based on the pulse data of a tile in the next higher data layer or from the reflected radar pulses if the tiles in the first data layer **310** occupy the highest data layer.

Upon processing the pulse data of the tiles of the first data layer **310** that are within the predetermined distance of the river **304**, the tile processing controller **162** can divide those tiles into respective sub-tiles that occupy the second data layer **312**. The tile processing controller **162** can then check to determine if the respective sub-tiles in the second data layer **312** are within the predetermined distance **304**, and thus exclude the sub-tiles in the second data layer **312** that are outside of the predetermined distance **304** without generating pulse data for them. Thus, the masking of the tiles/sub-tiles can be performed at any data layer, including the sub-tiles of the lowest data layer. Specifically, in the example of FIG. **7**, a particular area of the river **304** is designated at **316** in which the tile processing controller **162** provides the selective tile masking at the third data layer **314**, as opposed to the higher data layers of the first and second data layers **310** and **312**. As an example, the tile processing controller **162** can perform the selective tile masking demonstrated in the example of FIG. **7** at higher data layers to provide a larger area of imaging of the selected portion of the target region **302**.

Thus, the example of FIG. **7** demonstrates a significantly more efficient radar imaging technique. Specifically, the image masking system **300** in the example of FIG. **7** substantially minimizes unnecessary processing by masking-out the portions of the target region **302** that are unnecessary for image formation. The small size of the sub-tiles at the lowest data layer can thus also substantially reduce the pixilation of the target region **302**. Furthermore, the image masking system **300** in the example of FIG. **7** is particularly well adapted to circle-mode collection of the reflected radar pulses with respect to the image formation.

Yet another implementation of additional efficient radar imaging techniques is demonstrated in the example of FIG. **8**. FIG. **8** illustrates an example of an SAR strip imaging system **350** in accordance with an aspect of the invention. The strip imaging system **350** can be implemented in the SAR system **150** in the example of FIG. **4**. Therefore, reference is to be made to the example of FIG. **4** in the following description of the example of FIG. **8**.

The strip imaging system **350** includes a target region **352** to be imaged as an aircraft **354** flies overhead. In the example of FIG. **8**, the aircraft **354** flies from right to left, and thus the target region **352** moves from left to right relative to the aircraft **354**. Thus, as the aircraft **354** flies over the target region **352**, the transmission pulse generator **152** can continuously generate the radar transmission pulses that are emitted from the radar aperture **156**. Thus, the tile processing controller **162** can divide the target region **352** into tiles **356**, which are further divided into sub-tiles for which pulse data is recursively generated, as described herein. Therefore, the back projection image processor **176** can be configured to generate a continuous strip radar image. Specifically, as the aircraft **354** moves to within a threshold distance of a new portion of the target region **352**, the tile processing controller **162** can generate a new set of tiles **358** with a corresponding set of pulse data. The recursive generation of pulse data for corresponding sub-tiles of the new tiles **358** can be performed by the tile processing controller **162** in parallel with the generation of further new sets of tiles toward which the aircraft **352** approaches.

To handle the large amounts of pulse data that can be required for generating the strip radar image, as the aircraft **354** moves beyond a threshold distance of already processed tiles **360**, the tile processing controller **162** can discard the pulse data associated with the already processed tiles **360**. As a result, the buffers of the tile memory **174** from which pulse data is discarded can be reused for pulse data associated with the new tiles **358**. The back projection image processor **176** can thus continue to store image data associated with the strip radar image as the strip radar image is being generated, thus ensuring that no portions of the strip radar image data are lost. In addition, in the example of FIG. **8**, the strip imaging system **350** can be configured to mask portions of the target region **352**, similar to as described above in the example of FIG. **7**. Specifically, in the example of FIG. **8**, as the aircraft **354** flies over portions of the target region **352**, certain tiles **362** can be selectively masked, such that pulse data is not generated for the selected tiles **362**. Accordingly, the strip imaging system **350** can generate the strip radar image of only the desired portions of the target region **352** as the aircraft **354** flies overhead.

In view of the foregoing structural and functional features described above, a methodology in accordance with various aspects of the present invention will be better appreciated with reference to FIG. **9**. While, for purposes of simplicity of explanation, the methodology of FIG. **9** is shown and described as executing serially, it is to be understood and appreciated that the present invention is not limited by the illustrated order, as some aspects could, in accordance with the present invention, occur in different orders and/or concurrently with other aspects from that shown and described herein. Moreover, not all illustrated features may be required to implement a methodology in accordance with an aspect of the present invention.

FIG. **9** illustrates an example of a method **400** for method for synthetic aperture radar (SAR) imaging. At **402**, a plurality of radar transmission pulses are generated. The radar transmission pulses can be generated by a transmission pulse generator and can be emitted by a radar aperture. At **404**, receiving a plurality of reflected radar pulses are received at a radar aperture, the plurality of reflected radar pulses corresponding to the plurality of radar transmission pulses having been reflected from a target region. The target region can be any of a variety of geographic areas, and can be a dynamic area, such that the resultant radar image is a strip radar image.

At **406**, the target region is divided into a plurality of tiles associated with a highest data layer of a plurality of data layers. The division of the target region into tiles can be performed by a tile generator within a tile processing controller, with each of the tiles having an associated approximate center point. At **408**, pulse data corresponding to a respective one of the plurality of tiles in the highest data layer is generated based on a portion of the plurality of reflected radar pulses. The tile processing controller can generate the pulse data as a set of the reflected radar pulses that are range-aligned to the approximate center point of the respective tile, low-pass filtered, then decimated to generate a set of processed pulses that are specific to the respective tile. At **410**, each of the plurality of tiles is repeated divided into a plurality of sub-tiles associated with a lower data layer of the plurality of data layers. The tile processing controller can iteratively divide each tile into a set of sub-tiles, and each sub-tile to a further set of sub-tiles from the highest data layer to a lowest data layer.

At **412**, pulse data corresponding to each of the plurality of sub-tiles of the lower data layer is recursively generated based on the pulse data associated with each of the plurality of tiles in a higher data layer of the plurality of data layers. Thus, the pulse data of a given tile in a given data layer is used to generate the pulse data of each of the sub-tiles from which the given tile is divided in the next lower data layer. Specifically, the pulse data of the given tile can be range-aligned to an approximate center point of each of the sub-tiles of the next lower data layer, and can then be low-pass filtered and decimated to generate the pulse data of the given sub-tile. At **414**, the pulse data associated with each of the plurality of tiles and each of the plurality of sub-tiles in each of the plurality of data layers can be stored in a plurality of buffers of a memory. Upon the buffers of a given data layer overflowing, the associated tile processing controller can generate partial sets of pulse data for the respective sub-tiles of the next lower data layer, such that the pulse data in the overflowing buffers can be overwritten. At **416**, a radar image of the target region is generated based on the pulse data corresponding to each of the plurality of sub-tiles associated with a lowest data layer of the plurality of data layers. The radar image can be generated as a back projection radar image.

What have been described above are examples of the present invention. It is, of course, not possible to describe every conceivable combination of components or methodologies for purposes of describing the present invention, but one of ordinary skill in the art will recognize that many further combinations and permutations of the present invention are possible. Accordingly, the present invention is intended to embrace all such alterations, modifications and variations that fall within the spirit and scope of the appended claims.

What is claimed is:

1. A synthetic aperture radar (SAR) system comprising:

a radar transmitter configured to generate a plurality of radar transmission pulses;

a radar receiver coupled to a radar aperture and configured to receive a plurality of reflected radar pulses corresponding to the plurality of radar transmission pulses having been reflected from a target region;

a processing controller configured to divide the target region into a plurality of tiles and to process a portion of the plurality of reflected radar pulses to generate pulse data corresponding to a respective one of the plurality of tiles in a highest data layer of a plurality of data layers, and to conduct a plurality of iterations, each corresponding to one of the plurality of data layers, of dividing each of the plurality of tiles into a plurality of sub-tiles corresponding to a lower data layer and to recursively process the pulse data associated with each of the plurality of tiles in a higher data layer to generate pulse data corresponding to each of the plurality of sub-tiles of the lower data layer; and

an image processor configured to generate a radar image of the target region based on the pulse data corresponding to each of the plurality of sub-tiles associated with a lowest data layer of the plurality of data layers.

2. The system of claim **1**, wherein the processing controller comprises:

a range alignment controller configured to range-align the pulse data corresponding to a given tile in a higher data layer to an approximate center of a given one of the plurality of sub-tiles of the lower data layer and to range-reduce the range-aligned pulse data;

a low-pass filter (LPF) configured to filter out high-frequency components of the range-aligned pulses of the pulse data corresponding to tiles other than the given tile; and

a decimator configured to remove a fraction of the filtered range-aligned pulses of the pulse data to generate the

pulse data corresponding to the given one of the plurality of sub-tiles of the lower data layer.

3. The system of claim 2, wherein the range alignment controller is configured to range-align the pulse data to the approximate center of the given one of the plurality of sub-tiles for each pulse of the pulse data and to shift a phase associated with each pulse of the pulse data to simulate zero Doppler-shift at the approximate center of the given one of the plurality of sub-tiles.

4. The system of claim 2, wherein the processing controller is configured to add at least one of dummy data and dummy pulses to the range-aligned pulse data, such that the LPF is configured to remove the at least one of the dummy data and dummy pulses to substantially mitigate deleterious edge-effects of the filtered pulse data.

5. The system of claim 2, wherein the LPF is configured as a finite impulse response (FIR) filter that is programmed to include a pass-band between 0 Hz and a first frequency, a stop-band between a second frequency and a Nyquist frequency associated with a frequency of the plurality of reflected radar pulses, and a transition-band between the first frequency and the second frequency, the transition-band being configured to filter oversampled pulse data corresponding to the plurality of sub-tiles in each of the plurality of data layers.

6. The system of claim 1, wherein the image processor is configured as a back-projection image processor configured to generate a range between the radar aperture and each of a plurality of portions of the target region corresponding to a pixel of the radar image, to interpolate a time of arrival of each of the plurality of reflected radar pulses to the radar aperture based on the range, and to adjust a phase associated with each of the plurality of reflected radar pulses at the range.

7. The system of claim 6, wherein the back projection image processor is configured to generate the range from a low-order approximation based on a range from the aperture to an approximate center of a given sub-tile associated with a lowest data layer of the plurality of data layers and a normalized vector associated with each pulse of the pulse data associated with each respective one of the plurality of sub-tiles in the lowest data layer at an approximate center of the respective one of the plurality of sub-tiles to each pixel in the respective one of the plurality of sub-tiles.

8. The system of claim 1, wherein the processing controller is programmed to selectively designate an area within the target region to be imaged, such that upon determining that the plurality of sub-tiles associated with a given one of the plurality of tiles of a higher data layer are outside of the designated area, the processing controller excludes the given one of the plurality of tiles with respect to processing the portion of the plurality of reflected radar pulses to generate the pulse data corresponding to the given one of the plurality of tiles.

9. The system of claim 1, wherein the image processor is further configured to generate a plurality of radar images of the target region based on a respective plurality of unique subsets of the pulse data corresponding to each of the plurality of sub-tiles associated with the lowest data layer of the plurality of data layers.

10. The system of claim 1, wherein the processing controller is further configured to increase a number of pulses corresponding to the pulse data at each of the plurality of data layers corresponding to a given one of the plurality of tiles having a first range from the radar aperture relative to a second one of the plurality of tiles having a second range from the radar aperture that is less than the first range.

11. The system of claim 1, wherein radar transmitter is configured to continuously generate the plurality of radar transmission pulses, and wherein the processing controller is further configured to discard the pulse data corresponding to each of the plurality of tiles in the highest data layer that move to beyond a first predetermined threshold distance and to process reflected radar pulses to generate pulse data corresponding to additional tiles and associated additional sub-tiles in the plurality of data layers that move to within a second threshold distance, the image processor adding image data associated with the additional tiles to the radar image of the target region based on the pulse data corresponding to each of the plurality of sub-tiles associated with the lowest data layer.

12. The system of claim 1, further comprising a memory system configured to store the pulse data associated with each of the plurality tiles in the highest data layer and each of the plurality of sub-tiles in each of the plurality of data layers in a plurality of buffers, and wherein, upon a first one of the plurality of buffers associated with a respective one of the plurality of tiles being full, the processing controller can be configured to begin generating the pulse data corresponding to each of the respective plurality of sub-tiles of the lower data layer based on the pulse data stored in the first one of the plurality of buffers, such that the pulse data stored in the first one of the plurality of buffers can be subsequently overwritten with remaining pulse data associated with the respective one of the plurality of tiles.

13. A method for synthetic aperture radar (SAR) imaging, the method comprising:

generating a plurality of radar transmission pulses;

receiving a plurality of reflected radar pulses at a radar aperture, the plurality of reflected radar pulses corresponding to the plurality of radar transmission pulses having been reflected from a target region;

dividing the target region into a plurality of tiles associated with a highest data layer of a plurality of data layers;

generating pulse data corresponding to a respective one of the plurality of tiles in the highest data layer based on a portion of the plurality of reflected radar pulses;

repeatedly dividing each of the plurality of tiles into a plurality of sub-tiles associated with a lower data layer of the plurality of data layers;

recursively generating pulse data corresponding to each of the plurality of sub-tiles of the lower data layer based on the pulse data associated with each of the plurality of tiles in a higher data layer of the plurality of data layers;

storing the pulse data associated with each of the plurality of tiles and each of the plurality of sub-tiles in each of the plurality of data layers in a plurality of buffers of a memory; and

generating a radar image of the target region based on the pulse data corresponding to each of the plurality of sub-tiles associated with a lowest data layer of the plurality of data layers.

14. The method of claim 13, wherein generating the pulse data comprises:

range-aligning the pulse data corresponding to a given tile in a higher data layer to an approximate center of a given one of the plurality of sub-tiles of the lower data layer;

range-reducing the range-aligned pulse data to the given one of the plurality of sub-tiles of the lower data layer;

filtering out components of the range-aligned and range-reduced pulses of the pulse data corresponding to tiles other than the given tile; and

decimating the filtered range-aligned pulses of the pulse data.

15. The method of claim 13, wherein generating the image comprises:

generating a range from a low-order approximation based on a range from the radar aperture to an approximate center of the respective one of the plurality of sub-tiles in the lowest data layer to each of a plurality of portions of the target region and a normalized vector associated with each pulse of the pulse data;

interpolating a time of arrival of each of the plurality of reflected radar pulses to the radar aperture based on the range; and

adjusting a phase associated with each of the plurality of reflected radar pulses at the range.

16. The method of claim 13, wherein generating the radar image comprises generating a plurality of radar images of the target region based on a respective plurality of unique subsets of the pulse data corresponding to each of the plurality of sub-tiles associated with the lowest data layer of the plurality of data layers.

17. A synthetic aperture radar (SAR) system comprising:

a radar transmitter configured to generate a plurality of radar transmission pulses;

a radar receiver coupled to a radar aperture and configured to receive a plurality of reflected radar pulses corresponding to the plurality of radar transmission pulses having been reflected from a target region;

a processing controller configured to divide the target region into a plurality of tiles, to range-align a portion of the plurality of reflected radar pulses to an approximate center of a given one of the plurality of tiles, to filter out components of the range-aligned pulses corresponding to tiles other than the given tile, and to decimate the filtered range-aligned pulses to generate pulse data corresponding to the given one of the plurality of tiles in a highest data layer of a plurality of data layers, the processing controller being further configured to conduct a plurality of iterations, each corresponding to one of the plurality of data layers, of dividing each of the plurality of tiles into a plurality of sub-tiles corresponding to a lower data layer, to range-align the pulse data associated with each of the plurality of tiles in a higher data layer to an approximate center of a given sub-tile, to filter out components of the range-aligned pulse data corresponding to sub-tiles other than the given sub-tile, and to decimate the filtered pulse data to generate pulse data corresponding to the given sub-tile in the lower data layer; and

a back projection image processor configured to generate a radar image of the target region based on the pulse data corresponding to each of the plurality of sub-tiles associated with a lowest data layer of the plurality of data layers.

18. The system of claim 17, wherein back projection image processor is configured to generate a range from a low-order approximation based on a range from the aperture to an approximate center of a given sub-tile associated with a lowest data layer of the plurality of data layers and a normalized vector associated with each pulse of the pulse data associated with each respective one of the plurality of sub-tiles in the lowest data layer at an approximate center of the respective one of the plurality of sub-tiles to each pixel in the respective one of the plurality of sub-tiles, to interpolate a time of arrival of each of the plurality of reflected radar pulses to the radar aperture based on the range, and to adjust a phase associated with each of the plurality of reflected radar pulses at the range.

19. The system of claim 17, wherein the processing controller is programmed to selectively designate an area within the target region to be imaged, such that upon determining that the plurality of sub-tiles associated with a given one of the plurality of tiles of a higher data layer are outside of the designated area, the processing controller excludes the given one of the plurality of tiles with respect to processing the portion of the plurality of reflected radar pulses to generate the pulse data corresponding to the given one of the plurality of tiles.

20. The system of claim 17, wherein the processing controller is further configured to increase a number of pulses corresponding to the pulse data at each of the plurality of data layers corresponding to a given one of the plurality of tiles having a first range from the radar aperture relative to a second one of the plurality of tiles having a second range from the radar aperture that is less than the first range.

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