points out of the image plane which dramatically increases the number of observations. The analysis and/or reception steps 202-204 can be conducted using any form of time, frequency, or code-based gating to filter desired signals from unwanted signals. The gating could involve range gating. The gating can be conducted by fixed hardware on the satellites, or by mechanical, electrical analog, or digital filtering systems under the control of the software on the satellites.

[0016] Flow chart 200 also includes a step 205 of deriving a set of Earth observations using the data obtained in step 204. The step can be conducted by a terrestrial computer system after the data obtained in step 204 is transmitted to a ground station on Earth. The terrestrial computer system can be a server. The data from the constellation, all the way down to the primitive components of the sounding signals, can be stored in a data store that the server has access to. Alternatively, the data generated by the constellation can be stored by the constellation in a concentrated or distributed fashion. Alternatively or in combination, the data can be generated by the constellation at a single satellite or using a distributed computing approach. Specialized satellites in the constellation can be non-identical to the others and configured specifically for data storage or computation. The data obtained in step 204 can be shared between devices in the constellation to facilitate this analysis. Both the terrestrial or satellite-based analysis can be conducted in real time or using batch processing. The analysis can also utilize data regarding the position and identity of the satellites in the constellation during transmission and/or reception. In situations in which the satellites are in LEO, the position of the satellites can be determined by GNSS data obtained by the satellites during operation. The deriving can include scatterometry, altimetry, synthetic aperture radar (SAR), and interferometric derivations such as interferometric SAR (InSAR) derivations.

[0017] Flow chart 200 also includes a step 206 of setting or adjusting the spacing in the constellation. The relative positions of the satellites can be a set component of the mission or variable once the mission is in operation. The setting and adjusting of the spacing can be conducted relative to the direction of the constellation's orbit 241, as shown in illustration 240. The spacing can also be set or vary based on the requirements of the mission. Spacing can also be set or adjusted on an individual basis such that one or two satellites can change their position while the others maintain their relative positions with respect to the rest of the constellation. Movement along the direction of orbit 241 relative to the remainder of the

constellation can be referred to as axial movement. Movement perpendicular to the direction of orbit 241 relative to the remainder of the constellation can be referred to as lateral movement. The satellites can be designed to adjust their position along either direction.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] Figure 1 provides illustrations of the concepts involved with a constellation of satellites that both transmit and receive sounding signals with respect to the Earth's surface in accordance with approaches disclosed herein.

[0019] Figure 2 includes a flow chart of a set of methods for operating a symmetrical multistatic constellation of at least four satellites to generate a set of Earth observations in accordance with approaches disclosed herein.

[0020] Figure 3 provides illustrations of three types of cubesats that can be used in accordance with approaches disclosed herein.

[0021] Figure 4 provides an illustration of a fourth type of cubesat that can transform its configuration in orbit, and the different phases of that transformation, in accordance with approaches disclosed herein.

[0022] Figure 5 provides three aft-perspective orbit diagrams for a constellation of satellites with uneven lateral orbit tracks and even observation tracks along with a top-down orbit diagram for one of those constellations, all of which are in accordance with approaches disclosed herein.

[0023] Figure 6 provides a top-down orbit diagram for a constellation of satellites with uneven lateral orbit tracks and uneven axial spacing in accordance with approaches disclosed herein along with an illustration of a constellation in accordance with that diagram orbiting the Earth.

[0024] Figure 7 provides an illustration of how multiple forward scatter signals can provide useful information for scatterometry analysis and the derivation of related Earth observations in accordance with approaches disclosed herein.

[0025] Figure 8 provides two top-down orbit diagrams for a constellation of satellites with uneven lateral orbit tracks and uneven axial spacing in accordance with approaches disclosed herein.

[0026] Figure 9 provides an illustration of a constellation conducting multistatic delay Doppler observations in accordance with approaches disclosed herein.

separately. The multiple data streams from the various panels could then be re-combined in arbitrary ways to direct the full antenna gain to multiple targets after the fact. In another approach, transmission could be conducted at relatively high power from just one of the panels in an antenna to give wide coverage, while reception was conducted with multiple panels. Given antennas such as those disclosed in Fig. 3, the pattern of observation would then include a wider cone of transmitted signal coverage surrounding a narrow cone of full-gain receiving beam at nadir. The narrow receiving beam could then be redirected to any number of arbitrary points after the fact, so long as the received signals from all the panels were preserved in storage for analysis.

[0034] The sounding signals can be optimized for the particular composition of a given constellation and the types of observations that will be conducted in terms of frequency, structure, and strength. As stated previously, the fact that the constellation generates its own sounding signals provides the system with this level of flexibility as an advantage over systems that passively observe reflections from other sources. The sounding signals could be at a variety of frequencies. A given constellation may also be designed to produce sounding signals at variable frequencies or a variable frequency. The sounding signal may be based at 13.6 GHz and 5 GHz, and may have a lower band below 5 GHz such as 1.2-1.6 GHz or L-band signals. In the case of a 1.2-1.6 GHz band, the constellation would be primed to receive not only the sounding signals produced by the constellation itself, but also to receive and acquire reflected GNSS signals to obtain even more data. Although self-generated signals are preferred, if the constellation is already designed to receive signals at frequencies generated by other widely available sources of reflected radio signals, those signals could also be observed by the constellation and combined with the self-generated signals to produce additional data.

[0035] Various combinations of the above specifications for individual satellites could be applied to produce numerous benefits for the constellation. In a particular approach, type 0 and/or type 2 satellites could be configured with beam steering and the ability to transmit at two frequencies in order to receive both across-track and along-track returns where the different types of returns could be distinguished based on their frequencies. The antennas could be designed for this purpose to operate at two frequencies up to +/-45° along the wide beam axis without steering and +/-45° along the narrow beam axis with

than is possible with single-purpose systems. The constellation architecture introduces efficient concurrent and time-shared observations for various Earth observation missions.

[0038] The constellation can conduct altimetry measurements using standard approaches, but can also increase the performance of prior approaches through the generation of additional data. Absolute altimetry can be measured via signal delay measurement of monostatic returns or via bistatic and multistatic returns combined with location data for counterpart satellites. Relative altimetry measurements can be conducted using bistatic and multistatic returns.

[0039] Scatterometry can be measured by analyzing signal amplitude degradation from multiple angles. As the sounding pairs used to analyze signal amplitude degradation can be analyzed for delay at the same time as their amplitude is considered, relative altimetry and scatterometry information can emerge from a single observing system. In particular, in approaches in which the signals are PN-code modulated, a readily available PN-code signal analyzer can extract amplitude degradation and delay from a single pair of sounding signals automatically. For example, wind speed can be determined from the absolute amplitude of the returned signal in a sounding pair and wind direction can be obtained from an analysis of the variation of the absolute amplitude with the azimuth of the returned signal. Scatterometry can also be conducted by observing monostatic returns from off-nadir transmitted signals. Monostatic scatterometry observes backscatter of a signal transmitted directly at the Earth's surface obliquely. Returns are relatively weak as most energy scatters forward or in other directions. By comparison, the strength of the return signal and quality of data are greatly improved in the multistatic case. The use of multistatic sounding therefore greatly improves the capacity of the constellation to conduct accurate scatterometry.

[0040] SAR measurements can be conducted by directing beams from the satellites off nadir, lateral to the direction of orbit. The off-nadir angle could be anywhere from 10°-45°. A lateral SAR swath could then be observed by range-gating the returns by employing a series of delay windows. In a SAR measurement, rather than treating each return signal as a separate measurement, a series of return signals are captured and coherently combined to synthesize a larger aperture traced by the satellite's motion. In certain approaches, the coherently combined data can be analyzed in tandem with another set of coherently combined data to produce InSAR derivations. The processing and data storage

[0043] Fig. 5 illustrates three aft-perspective orbit diagrams for solutions to the question posed above in which n is equal to 4 satellites (500), 8 satellites (510), and 16 satellites (520) as derived using a flat earth model. Orbit diagram 515 is a top-down view of the 8-satellite case in which orbit tracks occupied by satellites are marked with rectangles 516 and orbit tracks for which a reflection point is generated, but no physical satellite is required are marked with circles 517. In the solution diagrams, circled dots 501 are satellite tracks and lone dots 502 are reflection point tracks. The upper numbers count the distinct reflection points while the lower numbers tell how many independent reflections occur at each point, assuming full mutual visibility. The 8-satellite case 510 yields 27 evenly spaced tracks (efficiency: 3.38). The 16-satellite case 520 yields 81 tracks (efficiency: 5.06). Furthermore, the lateral spacing of the satellites could be shifted if even track spacing was not required for a given application which would loosen the constraints of the optimization and increase the efficiency even more. The lateral spacing of the constellation could also be adjusted in flight if the observation needs of the constellation were to change during a given mission.

[0044] The satellites can be set in a straight line perpendicular to the direction of orbit, or at another angle relative to the direction of orbit. Such a configuration could be described as having a uniform axial spacing. The oblong antenna of the type 0 satellite provides an essentially elliptical beam well suited for this side-by-side arrangement. Orbit diagram 515 illustrates the satellites as rectangles 516 to illustrate how a type 0 or type 2 satellite could be oriented relative to the direction of orbit. If the long cell axis is in the direction of orbit as illustrated, the beam fans out to the sides toward the neighboring satellites. While the strongest bistatic returns can be acquired across-track, in both directions, in certain approaches each satellite can acquire both mono and bistatic returns along-track, some distance away from the lateral axis of the constellation. Just how far off the lateral axis observations can be made depends on the antenna characteristics and/or how the antenna is operated such as via physical movement and/or delay induced beam steering.

[0045] Another benefit of the redundancy afforded by constellations in accordance with some of the approaches disclosed herein is that the off-nadir angle can be limited by discarding redundant reflections. For example, in an East-West linear array in accordance with orbit diagram 520 and an observation track spacing at the equator of 11 km, capturing all possible reflections would require the two outermost cells to transmit and

receive at +/- 41° off nadir. However, redundant reflections allow the omission of the widest pairs and still provide adequate information concerning all 81 tracks. Therefore, adequate observation can be achieved by limiting the off-nadir angle for all cells to +/- 31°. Similar optimizations can be applied to other constellations with similar characteristics.

[0046] The satellites can also have a nonuniform axial spacing. The satellites can also be shifted axially during flight to shift between these configurations. Orbit diagram 600 is a top-down view of an 8-satellite constellation with nonuniform axial spacing in which orbit tracks occupied by satellites are marked with squares 601 and orbit tracks for which a reflection point is generated, but no physical satellite is required, are marked with circles 602. In particular, the specific points along the track at which the reflection point is generated are marked with a circle. Illustration 610 shows the flight pattern of that constellation in accordance with that orbit diagram as it orbits the Earth. The illustrated satellites are type 1 satellites with square antenna arrays using beam steering.

[0047] Certain benefits accrue to constellations in which the axial spacing is selected to generate reflection points such as reflection point 602. Reflection point 602 is of interest because multiple pairs of sounding signals strike that point from multiple perspectives. As illustrated, eight different sounding signals would impinge on reflection point 602 and generate eight forward scatter signals from four different perspectives and eight different directions. The result is highly useful information for scatterometry purposes. Furthermore, with beam steering, the cross-track soundings can all remain functional despite changes in the axial spacing. As illustrated, there are 27 distinct reflection points distributed in a two-dimensional pattern on equally spaced tracks. This allows instantaneous recovery of surface wind speed and direction at multiple points, while delivering undiminished altimetry on all 27 tracks.

[0048] Fig. 7 provides an illustration of how multiple forward scatter signals from the same look angle can provide useful information for scatterometry analysis and the derivation of related Earth observations. Fig. 7 includes a diagram 700 of a constellation of satellites from an aft-perspective. From the illustrated perspective, the satellites can be seen to have orbit tracks with even lateral spacing. However, the constellation can have nonuniform axial spacing such as the constellation discussed with reference to Fig. 6. As such, the sounding signals from the constellation of satellites impinging on a given reflection point can be conceptualized as forming the surface of a cone 705 with an

parallel, equally spaced tracks. This provides highly valuable information for a scatterometry determination as the same point is observed from nearly 360°. The broad distribution of azimuths provides more than enough information to determine Earth observations such as wind speed and direction at the shared reflection point instantaneously.

[0052] The spacing of the nonuniform axial spacing can be shifted in flight to change the location of the shared reflection point. After shifting the axial spacing, a second set of forward scatter signals can be reflected off this second shared reflection point. As the shared reflection point shifts laterally away from the center of the constellations, the number of satellites that can be configured to be located equidistant from the shared point begins to shrink. However, a sufficient number of forward scatter signals generated by satellites with a common look angle of a single point can generally still be obtained through an appreciable portion of the constellation's lateral extent with constellations having in excess of 8 satellites.

[0053] The axial spacing of the constellation can also be shifted to change the shared look angles from which multiple soundings are reflected. The process involves choosing a desired look angle, computing the required separation between two cells to achieve that angle for a bistatic reflection, drawing a circle of that diameter centered at a location (or latitude) of interest, laterally spacing the satellites so that as many of the orbit tracks are within the circle, and sliding the positions of the satellites along the tracks axially to put a sufficient number of satellites on the circle. The lateral spacing of the satellites can also be set as part of the mission or adjusted in flight to assure sufficient orbit tracks are within the circle.

[0054] The axial spacing of the constellation can also be shifted to obtain multiple shared look angles from which multiple soundings are reflected. In orbit diagram 810, a subset of satellites, such as 811, have been axially shifted to create another circle 812 centered around the shared reflection point 802 with a subset of 10 satellites falling on outer circle 803 and 6 satellites falling on inner circle 811. As such, when the constellation transmits sounding signals, a first subset of satellites in the constellation is equidistant from the reflection point according to a first distance, and a second subset of satellites in the set of satellites is equidistant from the reflection point according to a second distance. Even with this split in look angles, the mix of azimuths on each circle is sufficient to yield accurate

900 is made up of a series of concentric ellipses, and a set of hyperbolas centered about axis 904 extending out in either direction from that axis. The concentric ellipses define reflection points that can be isolated by one or the other satellites using range gating. They are elongated lateral to the direction of orbit. The center point corresponds with range gating at the specular reflection point midway between the satellites, with the delay of the range gating increasing with the major axis of the ellipse. The hyperbolas define reflection points that can be isolated using frequency shift gating. The observed Doppler shift is simply the sum of the one-way Doppler shifts from each satellite to the selected reflection point and is therefore zero at the specular reflection point. By using a combination of frequency and range gating reflection points, such as 905, can be isolated and observed using the illustrated signals without beam steering. As a result, a multi-correlator DDF method allows observations of many points concurrently fore and aft along the path of the midpoint to enhance the range of available observations for the constellation.

[0062] DDF can also be conducted by satellites that have nonuniform axial spacing, and indeed will operate with satellite constellations that are traveling in the same orbit track. The corresponding pattern for the case of two satellites in the same orbit track will be similar to view 900 except that the ellipses are elongated in the direction of orbit. The observed Doppler shift will be the sum or the one-way Doppler shifts from each satellite to the selected reflection point and will hence be zero at the mid-point as in even axial spacing case. For a constellation of satellites with 1 m nadir antennas transmitting a 6 cm wavelength from 600 km the satellite will see only about 1.7° off nadir with a round trip Doppler shift of about 7.55 kHz fore and aft. With a bistatic pair at 600 km separated by 3° along a single orbit track, the observed Doppler shift 1.7° fore and aft of the mid-point (as observed from each cell) is nearly the same: 7.35 kHz.

[0063] While the specification has been described in detail with respect to specific embodiments of the invention, it will be appreciated that those skilled in the art, upon attaining an understanding of the foregoing, may readily conceive of alterations to, variations of, and equivalents to these embodiments. Any of the method steps discussed above can be conducted by a processor operating with a computer-readable non-transitory medium storing instructions for those method steps. The computer-readable medium may be memory within a single satellite, distributed across a constellation of

WHAT IS CLAIMED IS:

1. A method for operating a symmetrical multistatic constellation of at least four satellites to generate a set of Earth observations comprising:

transmitting a set of at least four sounding signals from the constellation towards the Earth, wherein each satellite in the constellation individually generates at least one sounding signal in the set of sounding signals;

detecting a set of at least four forward scatter signals from the Earth using the constellation, wherein:

the signals in the set of forward scatter signals uniquely correspond with the signals in the set of sounding signals to form a set of sounding pairs; and

the signals in each sounding pair in the set of sounding pairs are transmitted and received by different satellites in the constellation;

analyzing, using a set of at least four signal analyzers, the set of at least four forward scatter signals to obtain a set of data, wherein each satellite in the constellation individually houses a signal analyzer in the set of at least four signal analyzers; and

deriving the set of Earth observations using the set of data.

2. The method of claim 1, wherein:

the set of data includes the phase, amplitude, delay, frequency and polarization of the set of forward scatter signals; and

the deriving includes scatterometry derivations and altimetry derivations.

3. The method of claim 1, wherein:

each satellite in the constellation individually generates at least two time-gated sounding signals in the set of sounding signals;

each satellite in the constellation includes an oscillator, whereby the constellation includes a set of oscillators;

the transmitting and detecting steps are conducted using the set of oscillators; and

the deriving includes synthetic aperture radar derivations.

4. The method of claim 1, wherein:

each satellite in the constellation individually generates at least two sets of time-gated sounding signals in the set of sounding signals;

each satellite in the constellation includes an oscillator, whereby the constellation includes a set of oscillators;

the transmitting and detecting steps are conducted using the set of oscillators; and

the deriving includes interferometric synthetic aperture radar derivations.

5. The method of claim 1, wherein:

each signal in the set of sounding signals is encoded using a unique PN code from a set of PN codes; and

the signal analyzers in the set of signal analyzers are PN-code signal analyzers.

6. The method of claim 1, further comprising:

detecting a set of at least four back scatter signals from the Earth using the constellation, wherein the signals in the set of back scatter signals uniquely correspond with the signals in the set of sounding signals to form a set of monostatic sounding pairs.

7. The method of claim 6, further comprising:

spacing the constellation using a nonuniform lateral spacing; and

reflecting the set of at least four forward scatter signals from the Earth at a set of reflection points on the Earth;

wherein the constellation includes a number of satellites;

wherein the set of sounding pairs has a set size equal to n squared where n is the number of satellites in the constellation;

wherein the set of reflection points is greater than twice the number of satellites; and

wherein the set of reflection points has a uniform lateral spacing.

8. The method of claim 1, wherein:

the transmitting of the set of at least four sounding signals targets a single shared reflection point on the Earth; and

the transmitting of the set of at least four sounding signals is conducted at a single time using a constellation of at least four oscillators located on the set of at least four satellites.

9. The method of claim 8, wherein:

when the constellation transmits the set of at least four sounding signals, each satellite in the constellation shares a look angle relative to the single shared reflection point with every satellite in the constellation.

10. The method of claim 1, further comprising:

spacing the constellation using a nonuniform axial spacing; and

reflecting the set of at least four forward scatter signals from the Earth at a single shared reflection point on the Earth;

wherein, when the constellation transmits the set of at least four sounding signals, each satellite in the constellation is equidistant from the single shared reflection point.

11. The method of claim 1, further comprising:

spacing the constellation using a nonuniform axial spacing; and

reflecting the set of at least four forward scatter signals from the Earth at a single shared reflection point on the Earth;

wherein, when the constellation transmits the set of at least four sounding signals, a first subset of satellites in the constellation is equidistant from the reflection point according to a first distance;

wherein, when the constellation transmits the set of at least four sounding signals, a second subset of satellites in the set of satellites is equidistant from the reflection point according to a second distance; and

wherein the first and second distances are not equal.

12. The method of claim 1, further comprising:

spacing the constellation using a nonuniform axial spacing;

reflecting the set of at least four forward scatter signals from the Earth at a first single shared reflection point on the Earth;

shifting the nonuniform axial spacing; and

reflecting a second set of at least four forward scatter signals from the Earth as a second single shared reflection point on the Earth;

wherein the first single shared reflection point and the second single shared reflection point are laterally shifted across the constellation.

13. The method of claim 1, wherein detecting the set of at least four forward scatter signals from the Earth using the constellation further comprises:

gating a time delay for the set of at least four forward scatter signals using a set of oscillators; and

gating a frequency shift for the set of at least four forward scatter signals;

wherein each satellite in the constellation includes an oscillator in the set of oscillators.

14. The method of claim 1, wherein the Earth Observations comprise:

relative topography, surface wind speed and direction, and absolute altitude.

15. A method for operating a constellation of at least four satellites to generate a set of Earth observations comprising:

transmitting a set of sounding signals from the constellation towards the Earth, wherein each satellite in the constellation individually generates at least one sounding signal in the set of sounding signals;

detecting a set of forward scatter signals from the Earth using the constellation, wherein:

the signals in the set of forward scatter signals uniquely correspond with the signals in the set of sounding signals to form a set of sounding pairs; and

the signals in each sounding pair in the set of sounding pairs are transmitted and received by different satellites in the constellation;

analyzing, using a set of signal analyzers, the set of forward scatter signals to obtain a set of data, wherein each satellite in the constellation individually houses a signal analyzer in the set of signal analyzers; and

deriving the set of Earth observations using the set of data;

wherein the analyzing step is conducted using a number of forward scatter signals equal to n(n-1) where n is the number of satellites in the constellation.

16. The method of claim 15, wherein:

the set of data includes the phase, amplitude, delay, frequency and polarization of the set of forward scatter signals; and

the deriving includes scatterometry derivations and altimetry derivations.

17. The method of claim 15, wherein:

each satellite in the constellation individually generates at least two sets of time-gated sounding signals in the set of sounding signals;

each satellite in the constellation includes an oscillator, whereby the constellation includes a set of oscillators;

the transmitting and detecting steps are conducted using the set of oscillators; and

the deriving includes interferometric synthetic aperture radar derivations.

18. The method of claim 15, wherein:

each signal in the set of sounding signals is encoded using a unique PN code from a set of PN codes; and

the signal analyzers in the set of signal analyzers are PN-code signal analyzers.

19. The method of claim 15, wherein:

the transmitting of the set of sounding signals targets a single shared reflection point on the Earth; and

the transmitting of the set of sounding signals is conducted at a single time using a set of at least four oscillators located on the constellation of at least four satellites.

wherein when the constellation transmits the set of sounding signals, each satellite in the constellation shares a look angle relative to the single shared reflection point with every satellite in the constellation.

20. The method of claim 15, further comprising:

spacing the constellation using a nonuniform axial spacing; and

reflecting the set of forward scatter signals from the Earth at a single shared reflection point on the Earth;

wherein, when the constellation transmits the set of sounding signals, each satellite in the constellation is equidistant from the single shared reflection point.

21. The method of claim 15, further comprising:

spacing the constellation using a nonuniform axial spacing; and

reflecting the set of forward scatter signals from the Earth at a single shared reflection point on the Earth;

wherein, when the constellation transmits the set of sounding signals, a first subset of satellites in the constellation is equidistant from the reflection point according to a first distance;

wherein, when the constellation transmits the set of sounding signals, a second subset of satellites in the set of satellites is equidistant from the reflection point according to a second distance; and

wherein the first and second distances are not equal.

22. The method of claim 15, further comprising:

spacing the constellation using a nonuniform axial spacing;

reflecting the set of forward scatter signals from the Earth at a first single shared reflection point on the Earth;

shifting the nonuniform axial spacing; and

reflecting a second set of forward scatter signals from the Earth as a second single shared reflection point on the Earth;

wherein the first single shared reflection point and the second single shared reflection point are laterally shifted across the constellation.

23. The method of claim 15, wherein detecting the set of at least four forward scatter signals from the Earth using the constellation further comprises:

gating a time delay for the set of forward scatter signals using a set of oscillators; and

gating a frequency shift for the set of forward scatter signals; and

wherein each satellite in the constellation includes an oscillator in the set of oscillators.

24. A method for operating a constellation of at least four satellites to generate a set of Earth observations comprising:

transmitting a set of at least four signals towards the Earth using the constellation;

receiving, after transmitting the set of at least four signals, a set of at least four reflected signals from the Earth using the constellation, wherein the set of at least four reflected signals are the set of at least four signals after having been reflected from the Earth;

analyzing, after receiving the set of at least four signals, and using a set of at least four signal analyzers, the set of at least four signals to generate a set of data, wherein each satellite in the constellation individually houses a signal analyzer in the set of at least four signal analyzers;

deriving the set of Earth observations using the set of data;

wherein each satellite receives a signal in the set of at least four signals from every other satellite in the constellation;

wherein the set of data includes the phase, amplitude, delay, frequency and polarization of the set of at least four signals; and

wherein the deriving includes scatterometry derivations and altimetry derivations.