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(54) **GPS SPOOFER DIRECTION FINDING AND GEOLOCATION**

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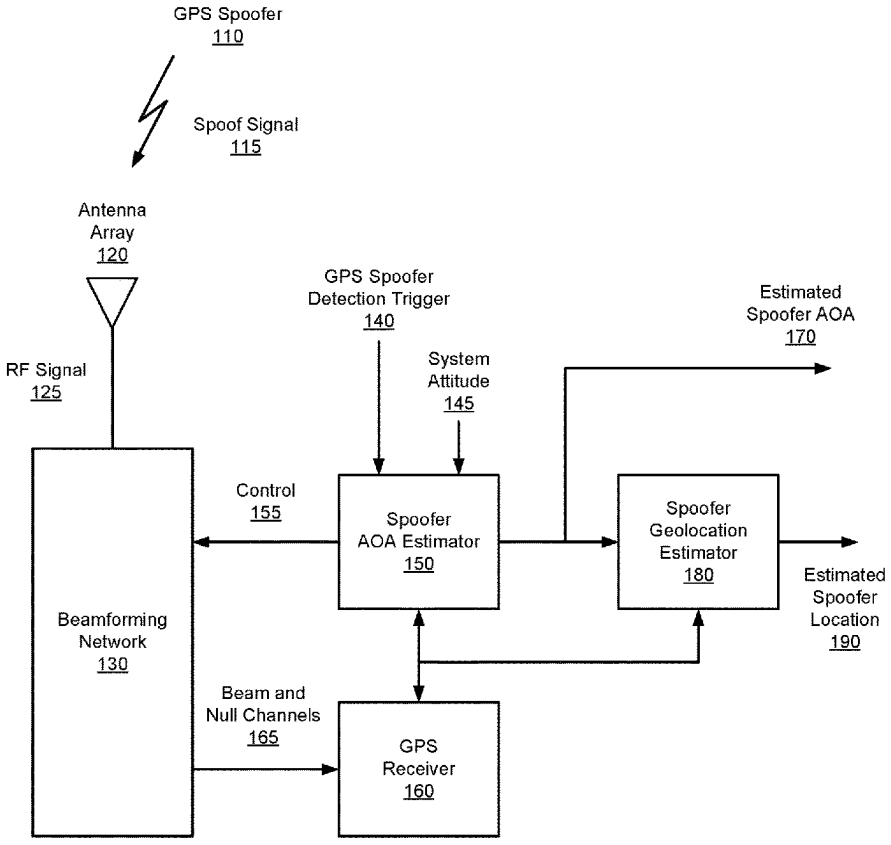
(57) **ABSTRACT**

Techniques for direction finding and geolocation of a GPS spoofer. A methodology implementing the techniques according to an embodiment includes steering a beam in a direction selected from a search constellation and measuring a first signal power received through the steered beam. The method also includes steering a null in the selected direction and measuring a second signal power received through the steered null. The method further includes calculating a difference between the first signal power and the second signal power and estimating an angle of arrival (AOA) of the GPS spoofer signal as the selected direction if the calculated difference exceeds a threshold power value. In some such examples, the method includes accumulating signals having four similar estimated AOAs, associated with unique pseudo-random noise codes, and employing a GPS receiver to calculate a candidate position of a source of the GPS spoofer signals based on the accumulated signals.

GPS Spoofer DF and Geolocation System
100



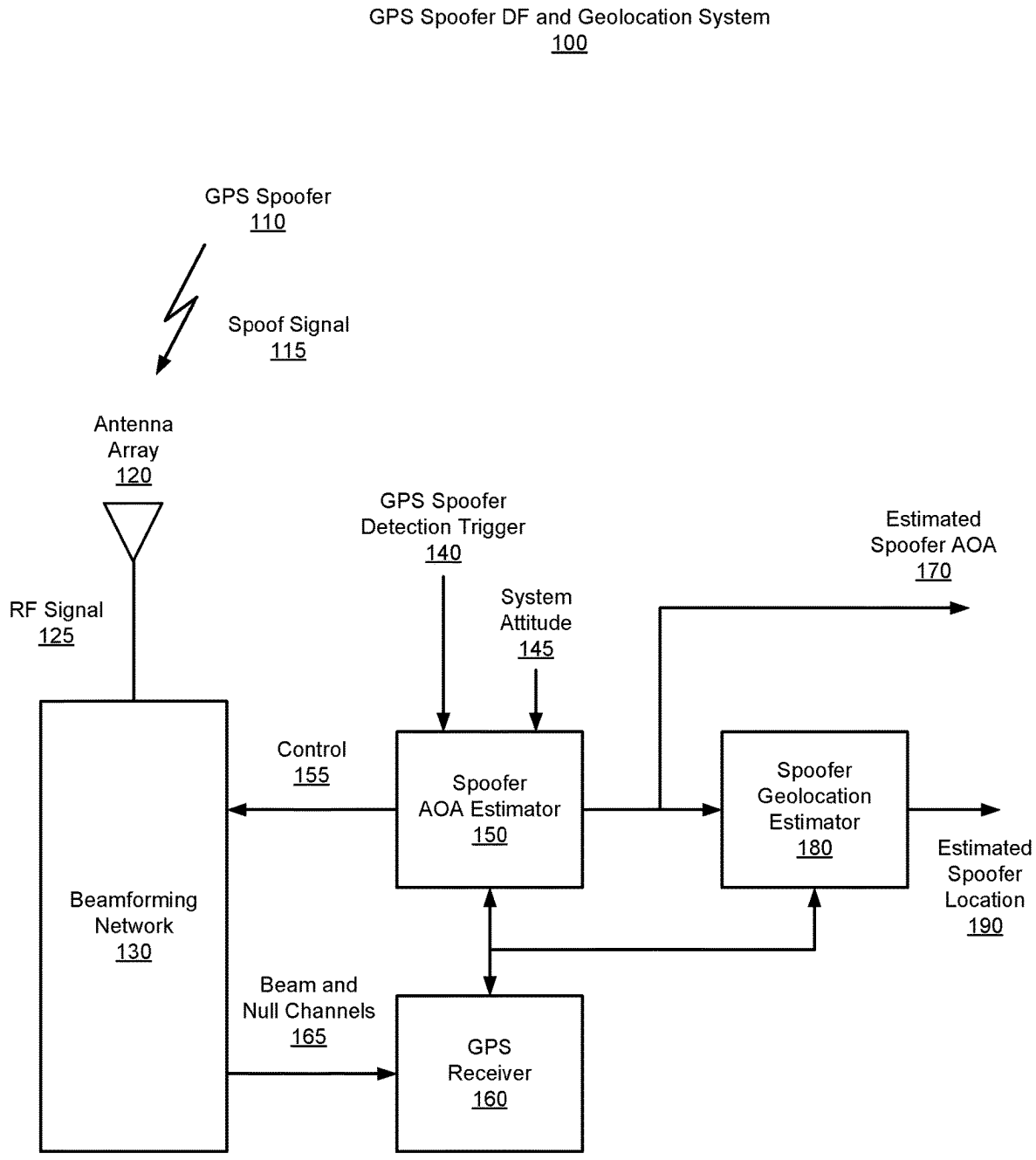

GPS Spoofer DF and Geolocation System
100
GPS Spoofer
110
Spoof Signal
115
Antenna
Array
120
RF Signal
125
GPS Spoofer
Detection Trigger
140
System
Attitude
145
Estimated
Spoofer AOA
170
Control
155
Spoofer
AOA Estimator
150
Spoofer
Geolocation
Estimator
180
Estimated
Spoofer
Location
190
Beamforming
Network
130
Beam and
Null Channels
165
GPS
Receiver
160

FIG. 1

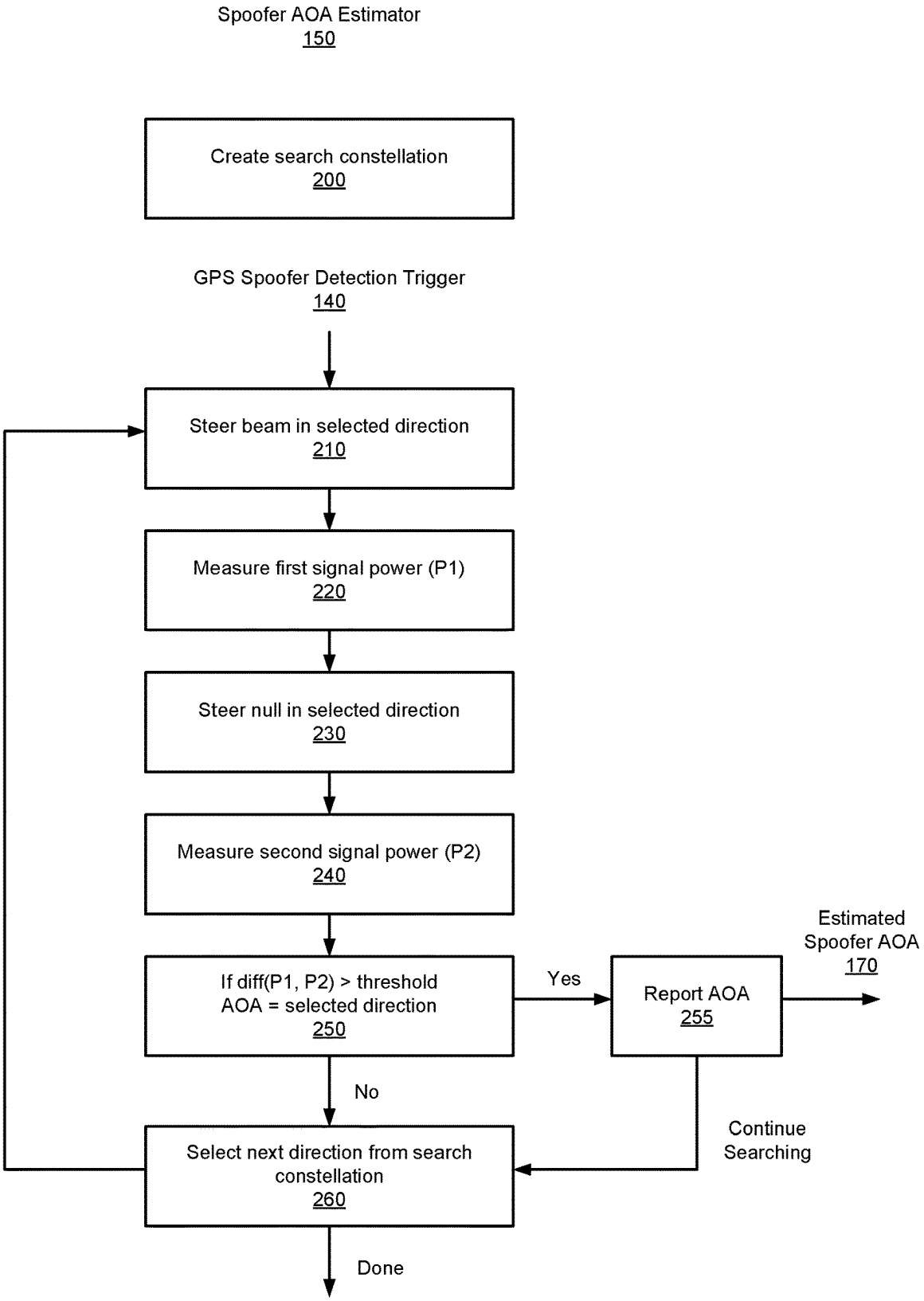

Spoofer AOA Estimator
150
Create search constellation
200
GPS Spoofer Detection Trigger
140
Steer beam in selected direction
210
Measure first signal power (P1)
220
Steer null in selected direction
230
Measure second signal power (P2)
240
If diff(P1, P2) > threshold
AOA = selected direction
250
Yes
Report AOA
255
Estimated
Spoofer AOA
170
No
Continue
Searching
Select next direction from search
constellation
260
Done

FIG. 2

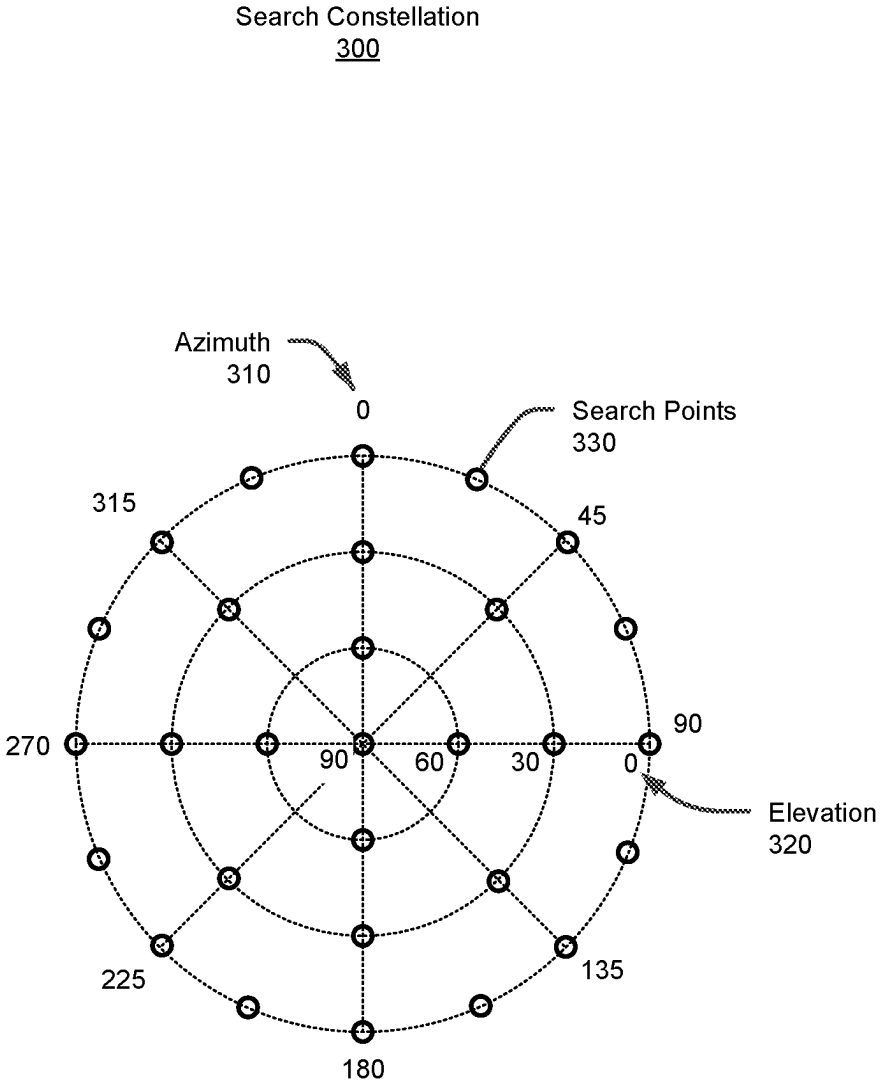

Search Constellation
300
Azimuth
310
0
Search Points
330
45
90
135
180
225
270
315
90
60
30
0
Elevation
320

FIG. 3

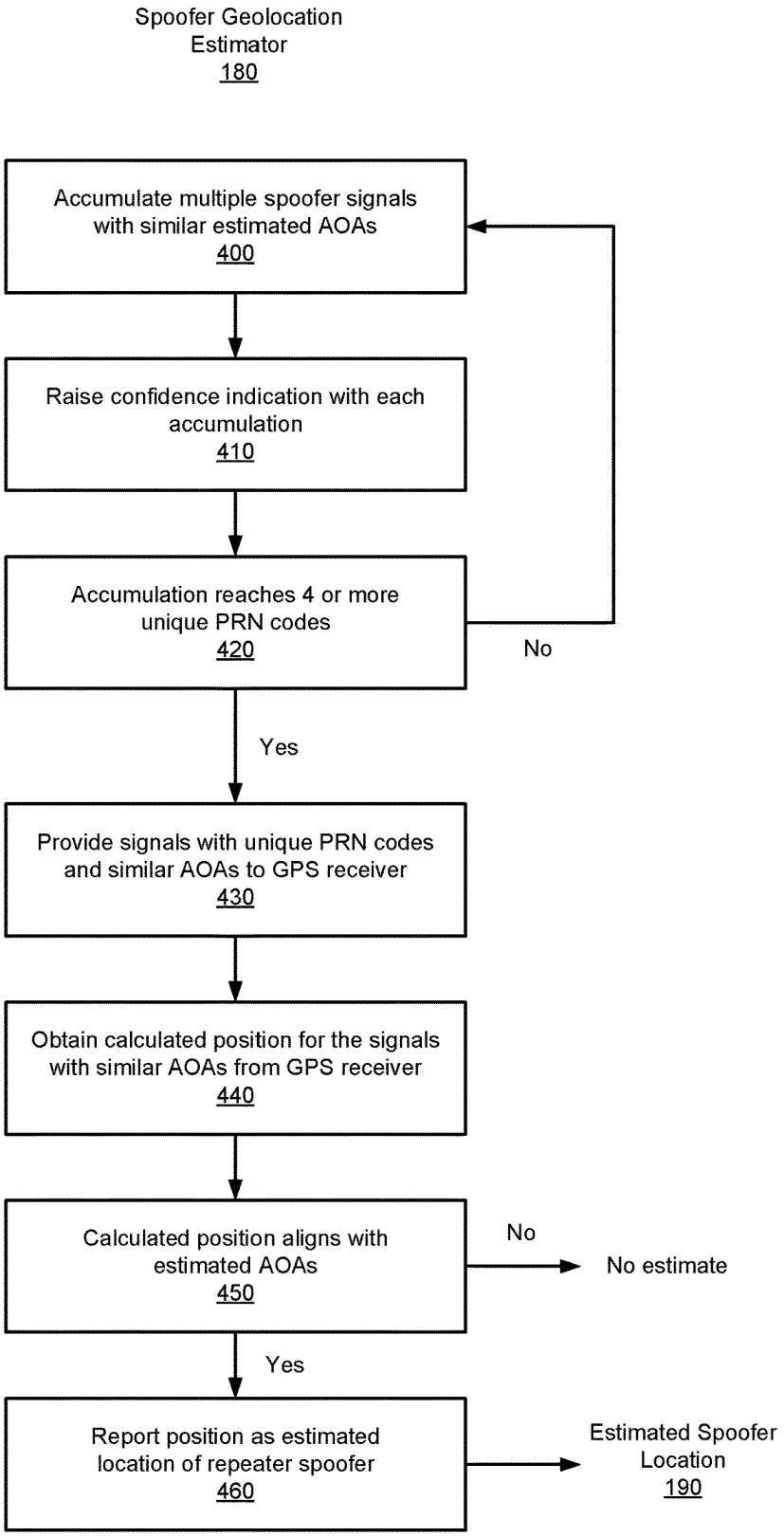

Spoofer Geolocation Estimator 180
Accumulate multiple spoofer signals with similar estimated AOAs 400
Raise confidence indication with each accumulation 410
Accumulation reaches 4 or more unique PRN codes 420
No
Yes
Provide signals with unique PRN codes and similar AOAs to GPS receiver 430
Obtain calculated position for the signals with similar AOAs from GPS receiver 440
Calculated position aligns with estimated AOAs 450
No
No estimate
Yes
Report position as estimated location of repeater spoofer 460
Estimated Spoofer Location 190

FIG. 4

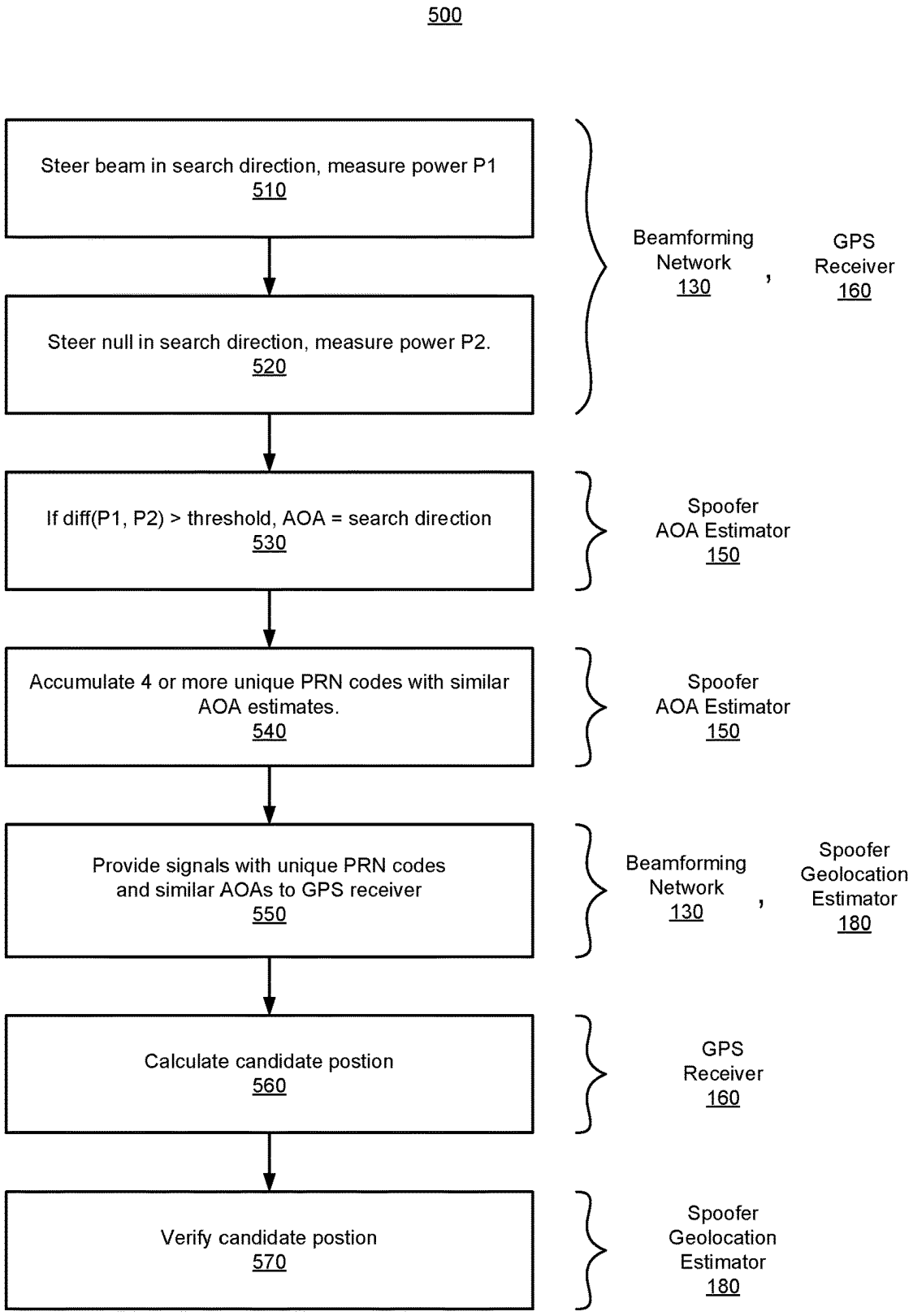

500
Steer beam in search direction, measure power P1
510
Steer null in search direction, measure power P2.
520
Beamforming Network 130 , GPS Receiver 160
If diff(P1, P2) > threshold, AOA = search direction
530
Spoofer AOA Estimator 150
Accumulate 4 or more unique PRN codes with similar AOA estimates.
540
Spoofer AOA Estimator 150
Provide signals with unique PRN codes and similar AOAs to GPS receiver
550
Beamforming Network 130 , Spoofer Geolocation Estimator 180
Calculate candidate postion
560
GPS Receiver 160
Verify candidate postion
570
Spoofer Geolocation Estimator 180

FIG. 5

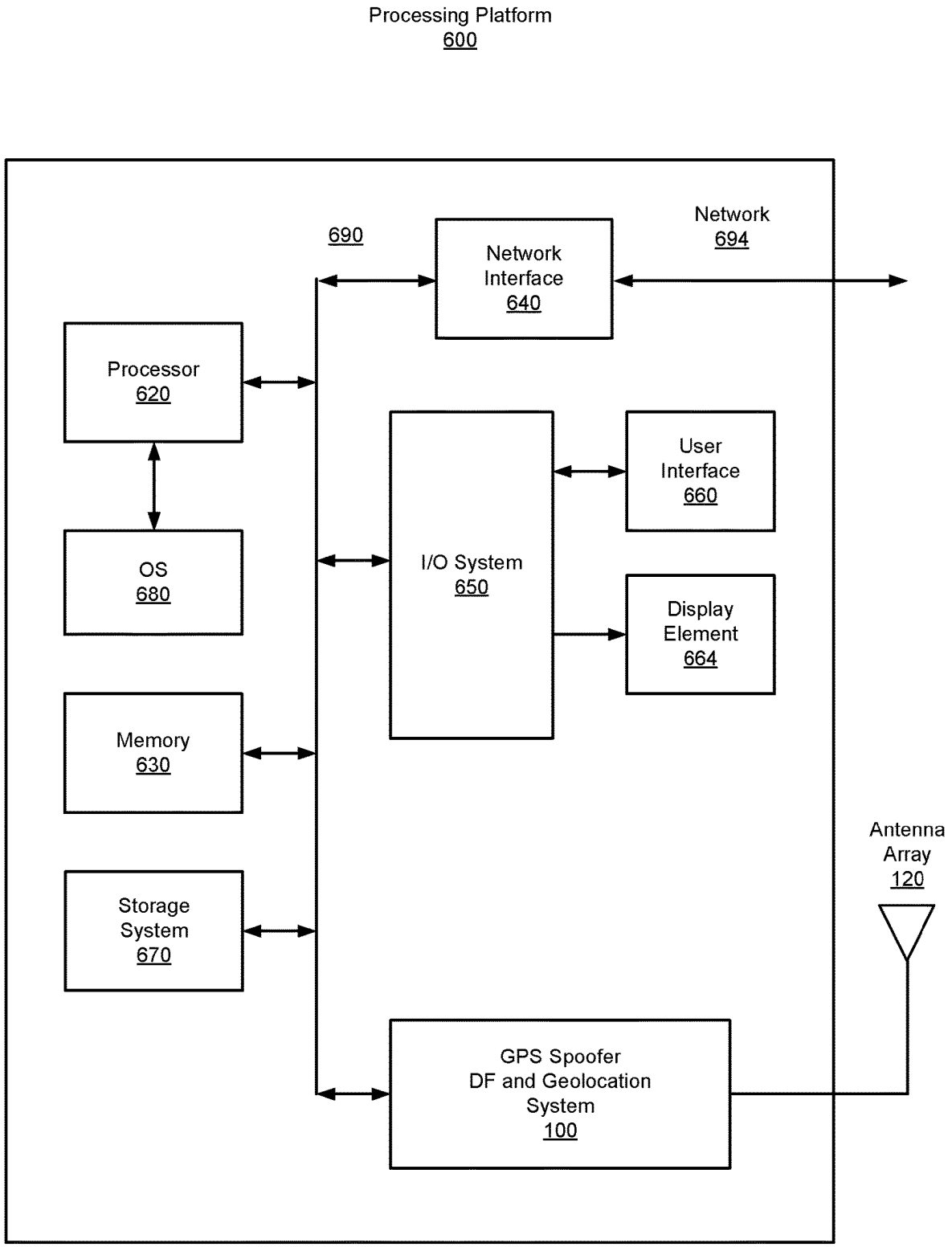

Processing Platform
600
690
Network Interface
640
Network
694
Processor
620
OS
680
I/O System
650
User Interface
660
Display Element
664
Memory
630
Storage System
670
Antenna Array
120
GPS Spoofer
DF and Geolocation
System
100

FIG. 6

GPS SPOOFER DIRECTION FINDING AND GEOLOCATION

FIELD OF DISCLOSURE

[0001] The present disclosure relates to electronic countermeasures, and more particularly, to a direction finding and geolocation system configured to locate a GPS spoofer.

BACKGROUND

[0002] GPS technology has been adopted into widespread use to provide location, timing, and navigation assistance for countless applications. Commercial aircraft, satellites, ships, trains, trucks, and vehicles use GPS for location and tracking. Many military applications depend on GPS, for example, to provide targeting of weapons systems and navigation functionality for aircraft, ships, ground vehicles, and ground troops. Unfortunately, GPS receivers can be spoofed by criminals, hackers, and adversaries. These parties may broadcast false GPS signals that mimic authentic GPS signals and introduce errors that render the GPS receiver ineffective. Such false GPS signals emanate from what is known as a GPS spoofer.

BRIEF DESCRIPTION OF THE DRAWINGS

[0003] FIG. **1** illustrates a GPS spoofer direction finding and geolocation system, in accordance with certain embodiments of the present disclosure.

[0004] FIG. **2** is a block diagram of the spoofer angle of arrival (AOA) estimator of the system of FIG. **1**, configured in accordance with certain embodiments of the present disclosure.

[0005] FIG. **3** illustrates a search constellation, in accordance with certain embodiments of the present disclosure.

[0006] FIG. **4** is a block diagram of the spoofer geolocation estimator of the system of FIG. **1**, configured in accordance with certain embodiments of the present disclosure.

[0007] FIG. **5** is a flowchart illustrating a methodology for direction finding and geolocation of a GPS spoofer, in accordance with an embodiment of the present disclosure.

[0008] FIG. **6** is a block diagram of a platform configured with the GPS spoofer direction finding and geolocation system of FIG. **1**, in accordance with certain embodiments of the present disclosure.

[0009] Although the following Detailed Description will proceed with reference being made to illustrative embodiments, many alternatives, modifications, and variations thereof will be apparent in light of this disclosure.

DETAILED DESCRIPTION

[0010] Techniques are provided herein for direction finding and geolocation of a GPS spoofer. As noted above, GPS receivers can be interfered with or otherwise spoofed by malicious actors that transmit fake signals which mimic an authentic GPS signal. Such spoofing can cause the GPS receiver to provide erroneous timing, position, and navigation information. While techniques exist to detect the presence of GPS spoofing signals, these techniques generally do not provide information that can be used to estimate an AOA or a location of the source of the spoofer signal. Additionally, techniques used to locate jammers rely on the fact that jamming signals are broadcast at relatively high power levels and these techniques are not suitable for GPS spoofer signals that are broadcast at relatively low power levels (e.g., frequently below the thermal noise floor).

[0011] To this end, techniques are provided to estimate an AOA of a GPS spoofing signal and, in some cases, estimate the geolocation of the source of the GPS spoofing signal. In an example, the AOA estimation technique steers an antenna beam and an antenna null to a number of directions selected from a search pattern or search constellation. If the spoofed signal is arriving from the selected search direction, a relatively significant difference in power is expected between the beamformed channel and the null formed channel. Additionally, if the source of the spoofed signal is a GPS constellation repeater spoofer (e.g., a system that rebroadcasts valid GPS signals received from GPS satellites), the spoofed signals can be used to locate the repeater spoofer, as will be explained in greater detail below.

[0012] A system to implement the disclosed techniques can be hosted on, or otherwise be incorporated into the electronic systems of an aircraft, UAV, munition, satellite, maritime vessel or ground vehicle, a navigation system, an anti-jamming system, a tracking ground station, a personal computer, workstation, laptop computer, tablet, touchpad, portable computer, handheld computer, cellular telephone, smartphone, embedded system, or any other platform where GPS spoofer direction finding is needed.

[0013] In accordance with an embodiment, an example methodology to implement these techniques includes steering a beam in a direction selected from a search constellation and measuring a first signal power received through the steered beam. The method also includes steering a null in the selected direction and measuring a second signal power received through the steered null. The method further includes calculating a difference between the first signal power and the second signal power and estimating an AOA of the GPS spoofer signal as being the selected direction if the calculated difference exceeds a threshold power value. GPS signals are modulated by Pseudo-Random Noise (PRN) codes that can serve to identify the satellite that transmits the signal. The method may further include accumulating four or more signals with unique PRN codes and similar estimated AOAs (e.g., differing by less than a threshold angular value). The method according to some such examples further includes employing a GPS receiver to calculate a candidate position of the source of the GPS spoofer signal based on the four or more unique PRN code signals with similar AOAs. The candidate position is determined to be the estimated position of the source of the GPS spoofer signal if the direction to the candidate position aligns with the estimated AOAs of the spoof signals. Once the spoofer position is determined, various measures can be taken to eliminate or mitigate the spoofer, and the spoofer position can be communicated to other systems to remediate further issues.

[0014] Although the techniques described herein are applied to GPS signals, they may also be applied to signals from other Global Navigation Satellite Systems (GNSS), such as, for example, the Galileo, GLONASS, BEIDOU, and QZSS systems.

[0015] It will be appreciated that the techniques described herein may provide information of strategic value (e.g., a direction, and in some cases, a location) of a GPS spoofer, compared to existing techniques that only detect the presence of spoofer signals. The techniques disclosed herein may further be implemented in hardware or software or a

combination thereof. Numerous embodiments and applications will be apparent in light of this disclosure.

System Architecture

[0016] FIG. **1** illustrates a GPS spoofer direction finding and geolocation system **100**, in accordance with certain embodiments of the present disclosure. The system is shown to include an antenna array **120**, a beamforming network **130**, a spoofer AOA estimator **150**, a spoofer geolocation estimator **180**, and a GPS receiver **160**.

[0017] The antenna array **120** (sometimes referred to as a controlled reception pattern antenna) is configured to receive radio frequency (RF) signals **125** from any number of sources which may include, for example, spoofer signals **115** broadcast by a GPS spoofer **110**.

[0018] The beamforming network **130** is configured to generate beamforming patterns (beams) and nullforming patterns (nulls) by adjusting the phases of the signals received by each of the antennas of the array **120**. A beam increases the gain of the antenna array in the direction of the beam while a null decreases the gain of the antenna array in the direction of the null. Beamforming network **130** may generate the beams and nulls in any desired directions (e.g., specified azimuth and elevation angles) based on control signals **155** received from other components of the system such as spoofer AOA estimator **150**, spoofer geolocation estimator **180**, and GPS receiver **160**, as will be explained below. Signals received through the beams and nulls are provided to the GPS receiver **160** over beam channels and null channels **165**.

[0019] The spoofer AOA estimator **150** is configured to generate an AOA estimate **170** of a GPS spoofing signal **115**. Operation of the spoofer AOA estimator is described in greater detail below, but at a high level, the spoofer AOA estimator is configured to estimate an AOA of a GPS spoofing signal by measuring the power difference between signals received through antenna beams and antenna nulls that are steered to the search directions. If the spoofing signal is arriving from the selected search direction, there will be a relatively large power difference between the beamformed channel and the null formed channel. If the spoofing signal is arriving from a different direction, however, the power difference will be smaller. Thus, if the power difference exceeds a threshold value, the spoofer signal is determined to arrive from that search direction. The threshold power value is application dependent and, in some embodiments, may be predetermined or otherwise provided by a user of the system. The threshold value may be selected based on operational requirements, such as probability of detection versus probability of false alarm, or other operational requirements.

[0020] The spoofer geolocation estimator **180** is configured to generate an estimated location **190** of the GPS spoofer **110** (e.g., the location of the source of the spoofer signal **115**), when the GPS spoofer **110** is a GPS constellation repeater spoofer. Operation of the spoofer geolocation estimator is described in greater detail below, but at a high level, the spoofer geolocation estimator is configured to identify four or more signals with unique (e.g., different) PRN codes and substantially similar estimated AOAs (provided by the spoofer AOA estimator **150**). GPS signals are modulated by PRN codes that can serve to identify the satellite that transmits the signal. Signals having different PRN codes and similar AOAs may originate from different satellites in a similar region of the sky, or they may be multiple spoofer signals. The GPS receiver **160** is employed to calculate a candidate position of the GPS spoofer. If the candidate position is in the direction of the previously estimated AOAs, confidence increases that a repeater spoofer is located in that direction and at the coordinates of the candidate position. If the candidate position is located in a different direction, it is more likely that a non-repeater spoofer exists in the previously estimated direction but at an unknown specific location.

[0021] FIG. **2** is a block diagram of the spoofer AOA estimator **150** of FIG. **1**, configured in accordance with certain embodiments of the present disclosure. The spoofer AOA estimator is shown to perform a number of operations.

[0022] At operation **200**, a search constellation is created to guide a search for the GPS spoofer **110**, over varying AOA directions. In some embodiments, the spatial search may proceed sequentially through the constellation, while in some other embodiments multiple points in the constellation may be searched in parallel as computational resources permit. FIG. **3** illustrates one such search constellation **300**, in accordance with certain embodiments of the present disclosure. The search constellation **300** is shown to include a number of search points **330** that are spatially distributed across azimuth angles **310** and elevation angles **320** which are visible to the antenna array **120**.

[0023] In some embodiments, the search points **330** are equally distributed across the hemisphere so that higher elevations (e.g., closer to 90 degrees) have fewer azimuth points than lower elevations, as shown in FIG. **3**. In some embodiments, the search points may be concentrated or restricted to points near the horizon (e.g., lower elevation angles) owing to the fact that GPS spoofers **110** are often ground based rather than in Earth orbit.

[0024] In some embodiments, search points in the direction of true GPS satellites may be omitted. Determination of the direction of true GPS satellites in antenna coordinates may be calculated based on provided information that includes the current time and position of the platform, a satellite constellation almanac, and antenna attitude (e.g., roll, pitch, and yaw) **145**. In some embodiments, this information may be provided by a navigation system of the platform, an almanac or ephemeris, or from other suitable sources. In some embodiments, the antenna attitude **145** may be provided directly to the GPS receiver **160**.

[0025] The process continues at operation **210**, in response to a trigger **140** provided by an external spoofer detection system. The trigger **140** signals that a GPS spoofer has been detected, but from an unknown direction and location. At operation **210**, a directional search commences by selecting an initial direction from the search constellation **300**. The beamforming network **130** is employed to steer a beam in the selected direction, for example using control signals **155**.

[0026] At operation **220**, a first signal power (P1) is measured for the signal received through the beam channel (e.g., one of the channels **165**).

[0027] At operation **230**, the beamforming network **130** is employed to steer a null in the selected direction, for example using control signals **155**. At operation **240**, a second signal power (P2) is measured for the signal received through the null channel (e.g., one of the channels **165**).

[0028] In some embodiments, operations **210** through **240** (e.g., steering the beam and the null, as well as performing

the power measurements), may be performed in parallel to reduce the possibility of time-dependent variations in received signal power.

[0029] At operation **250**, if the difference between P1 and P2 exceeds the power threshold value, then the currently selected direction is chosen as an estimated AOA **170** of the GPS spoofing signal **115**. At operation **255**, the estimated spoofer AOA **170** is reported to a user of the system, or a downstream application configured to act on that information.

[0030] At operation **260**, a next direction is selected from the search constellation **300** and the process iterates by looping back to operation **210** until all directions from the search constellation (or all directions of interest) have been processed. Any number of additional estimated spoofer AOAs **170** may be obtained at each iteration if the conditions described above are met (e.g., the difference between P1 and P2 exceeding the power threshold value). In some embodiments, the search may be halted once a valid spoofer AOA for a particular spoofed signal has been found, rather than processing all directions from the search constellation.

[0031] In some embodiments, the spoofer AOA estimator **150** may be implemented as one or more processors configured to execute software to perform the functions of blocks **200** through **260**.

[0032] FIG. **4** is a block diagram of the spoofer geolocation estimator **180** of FIG. **1**, configured in accordance with certain embodiments of the present disclosure. The spoofer geolocation estimator is shown to perform a number of operations.

[0033] At operation **400**, multiple spoofer signal AOAs, provided by the spoofer AOA estimator **150**, are accumulated. AOAs that are substantially similar (e.g., AOAs that differ by less than a threshold angular value) are grouped together.

[0034] At operation **410**, as the number of similar AOAs accumulate, confidence associated with the estimated spoofer direction increases. In some embodiments, a confidence indicator may be reported along with the estimated AOAs.

[0035] At operation **420**, the process iterates back to operation **400** until four or more unique PRN codes with similar AOAs have been accumulated.

[0036] At operation **430**, after four or more unique PRN codes with similar AOAs have been accumulated, those signals are provided to the GPS receiver **160**.

[0037] At operation **440**, a candidate position for the GPS spoofer **110** is obtained from the GPS receiver as a calculated navigation solution based on the provided signals with unique PRN codes and similar AOAs.

[0038] At operation **450**, if the direction to the candidate position aligns with the four or more estimated AOAs, then that candidate position is determined to be the estimated geolocation **190** of the GPS spoofer **110**. This will generally be true in the case of a GPS spoofer that is acting as a constellation repeater spoofer (e.g., a system that rebroadcasts valid GPS signals received from GPS satellites). In some embodiments, alignment is determined by calculating a direction from the platform to the candidate position, and if that direction matches the four estimated AOAs (e.g., differs from the AOAs by less than a second threshold angular value), the candidate position is considered to align with the four estimated AOAs. The first and second threshold angular values are application dependent and, in some embodiments, may be predetermined or otherwise provided by a user of the system, as described previously with respect to the threshold power value. These threshold angular values may be selected based on operational requirements, such as probability of detection versus probability of false alarm, or other operational requirements.

[0039] At operation **460**, if the direction to the candidate position aligns with the four or more estimated AOAs, the spoofer **110** is reported as a GPS constellation repeater spoofer and the estimated spoofer geolocation **190** is reported to a user of the system, or a downstream application configured to act on that information.

[0040] If, however, the direction to the candidate position does not align with the four or more estimated AOAs (e.g., the candidate position is in a different direction), then the spoofer **110** is reported as not being a GPS constellation repeater spoofer and a geolocation estimate is not possible using the disclosed techniques.

[0041] In some embodiments, the spoofer geolocation estimator **180** may be implemented as one or more processors configured to execute software to perform the functions of blocks **400** through **450**.

Methodology

[0042] FIG. **5** is a flowchart illustrating a methodology **500** for GPS spoofer direction finding and geolocation, in accordance with an embodiment of the present disclosure. As can be seen, example method **500** includes a number of phases and sub-processes, the sequence of which may vary from one embodiment to another. However, when considered in aggregate, these phases and sub-processes form a process for GPS spoofer direction finding and geolocation, in accordance with certain of the embodiments disclosed herein. These embodiments can be implemented, for example using the system architecture illustrated in FIGS. **1-4**, as described above. However other system architectures can be used in other embodiments, as will be apparent in light of this disclosure. To this end, the correlation of the various functions shown in FIG. **5** to the specific components illustrated in FIGS. **1**, **2**, and **4**, is not intended to imply any structural and/or use limitations. Rather other embodiments may include, for example, varying degrees of integration wherein multiple functionalities are effectively performed by one system. Numerous variations and alternative configurations will be apparent in light of this disclosure.

[0043] In one embodiment, method **500** commences, at operation **510**, by steering a beam in a direction selected from a search constellation and measuring a first signal power (P1) received through the steered beam. In some embodiments, the search constellation comprises a plurality of azimuth angles and elevation angles associated with a search region of interest. In some embodiments, the search region of interest excludes directions associated with known positions of GPS satellites. In some embodiments, the search region of interest is restricted to directions near the horizon, where GPS spoofers are more likely to be located.

[0044] At operation **520**, the method continues by steering a null in the direction selected from the search constellation and measuring a second signal power (P2) received through the steered null.

[0045] At operation **530**, a difference is calculated between P1 and P2 and, if the difference exceeds a threshold power value, the AOA of the GPS spoofer signal is estimated to be the selected direction.

[0046] At operation **540**, the process iterates over multiple PRN code signals and additional estimated AOAs are accumulated. In some embodiments, multiple points in the constellation may be searched in parallel as computational resources permit, rather than in a sequential iterative manner.

[0047] At operation **550**, after four or more unique PRN codes with substantially similar estimated AOAs (e.g., differ by less than a threshold angular value) have been accumulated, those signals are provided to a GPS receiver.

[0048] At operation **560**, the GPS receiver calculates a navigation solution, based on the four or more provided signals, to generate a candidate position of the source of the GPS spoofer signals.

[0049] At operation **570**, the candidate position is determined to be the estimated geolocation of the source of the GPS spoofer signals if the direction to the candidate position aligns with the estimated AOAs. In some embodiments, a direction to the candidate position is calculated and if that direction differs from the estimated AOAs by less than a second threshold angular value, the candidate position is considered to align with the estimated AOAs.

[0050] In some embodiments, additional operations may be performed, as previously described in connection with the system. For example, the process may be initiated or triggered by the detection of a GPS spoofer provided by another system.

[0051] In some embodiments, an approximate current time and position of the platform hosting the system, along with the attitude of the antenna array (e.g., roll, pitch, and yaw), may be provided to allow for the determination of directions in antenna coordinates.

Example System

[0052] FIG. **6** is a block diagram of a platform **600** for the GPS spoofer direction finding and geolocation system FIG. **1**, in accordance with certain embodiments of the present disclosure. In some embodiments, platform **600**, or portions thereof, may be hosted on, or otherwise be incorporated into an aircraft, the electronic systems of the aircraft, a ground vehicle, a ship, a ground station, a personal computer, workstation, laptop computer, tablet, touchpad, portable computer, handheld computer, cellular telephone, smartphone, embedded system, or any other suitable platform where direction finding and geolocation of GPS spoofers is performed. Any combination of different devices may be used in certain embodiments.

[0053] In some embodiments, platform **600** may comprise any combination of a processor **620**, a memory **630**, a network interface **640**, an input/output (I/O) system **650**, a user interface **660**, a display element **664**, a storage system **670**, antenna array **120**, and GPS spoofer direction finding and geolocation system **100**. As can be further seen, a bus and/or interconnect **690** is also provided to allow for communication between the various components listed above and/or other components not shown. Platform **600** can be coupled to a network **694** through network interface **640** to allow for communications with other computing devices, platforms, devices to be controlled, or other resources. Other componentry and functionality not reflected in the block diagram of FIG. **6** will be apparent in light of this disclosure, and it will be appreciated that other embodiments are not limited to any particular hardware configuration.

[0054] Processor **620** can be any suitable processor, and may include one or more coprocessors or controllers, such as an audio processor, a graphics processing unit, or hardware accelerator, to assist in control and processing operations associated with platform **600**. In some embodiments, the processor **620** may be implemented as any number of processor cores. The processor (or processor cores) may be any type of processor, such as, for example, a microprocessor, an embedded processor, a digital signal processor (DSP), a graphics processor (GPU), a tensor processing unit (TPU), a network processor, a field programmable gate array or other device configured to execute code. The processors may be multithreaded cores in that they may include more than one hardware thread context (or "logical processor") per core. Processor **620** may be implemented as a complex instruction set computer (CISC) or a reduced instruction set computer (RISC) processor. In some embodiments, processor **620** may be configured as an x86 instruction set compatible processor.

[0055] Memory **630** can be implemented using any suitable type of digital storage including, for example, flash memory and/or random-access memory (RAM). In some embodiments, the memory **630** may include various layers of memory hierarchy and/or memory caches. Memory **630** may be implemented as a volatile memory device such as, but not limited to, a RAM, dynamic RAM (DRAM), or static RAM (SRAM) device. Storage system **670** may be implemented as a non-volatile storage device such as, but not limited to, one or more of a hard disk drive (HDD), a solid-state drive (SSD), a universal serial bus (USB) drive, an optical disk drive, tape drive, an internal storage device, an attached storage device, flash memory, battery backed-up synchronous DRAM (SDRAM), and/or a network accessible storage device. In some embodiments, storage **670** may comprise technology to increase the storage performance enhanced protection for valuable digital media when multiple hard drives are included.

[0056] Processor **620** may be configured to execute an Operating System (OS) **680** which may comprise any suitable operating system, such as Google Android (Google Inc., Mountain View, CA), Microsoft Windows (Microsoft Corp., Redmond, WA), Apple OS X (Apple Inc., Cupertino, CA), Linux, or a real-time operating system (RTOS). As will be appreciated in light of this disclosure, the techniques provided herein can be implemented without regard to the particular operating system provided in conjunction with platform **600**, and therefore may also be implemented using any suitable existing or subsequently-developed platform.

[0057] Network interface circuit **640** can be any appropriate network chip or chipset which allows for wired and/or wireless connection between other components of platform **600** and/or network **694**, thereby enabling platform **600** to communicate with other local and/or remote computing systems, servers, cloud-based servers, and/or other resources. Wired communication may conform to existing (or yet to be developed) standards, such as, for example, Ethernet or serial interfaces (e.g., RS-232 or RS-422). Wireless communication may conform to existing (or yet to be developed) standards, such as, for example, cellular communications including LTE (Long Term Evolution) and 5G, Wireless Fidelity (Wi-Fi), Bluetooth, and/or Near Field Communication (NFC). Exemplary wireless networks include, but are not limited to, wireless local area networks,

wireless personal area networks, wireless metropolitan area networks, cellular networks, and satellite networks.

[0058] I/O system **650** may be configured to interface between various I/O devices and other components of platform **600**. I/O devices may include, but not be limited to, user interface **660** and display element **664**. User interface **660** may include devices (not shown) such as a touchpad, keyboard, and mouse, etc., for example, to allow the user to control the system. Display element **664** may be configured to display jammer detection results, tracking data, navigation data, camera images, or other suitable information. I/O system **650** may include a graphics subsystem configured to perform processing of images for rendering on the display element **664**. Graphics subsystem may be a graphics processing unit or a visual processing unit (VPU), for example. An analog or digital interface may be used to communicatively couple graphics subsystem and the display element. For example, the interface may be any of a high definition multimedia interface (HDMI), DisplayPort, wireless HDMI, and/or any other suitable interface using wireless high definition compliant techniques. In some embodiments, the graphics subsystem could be integrated into processor **620** or any chipset of platform **600**.

[0059] It will be appreciated that in some embodiments, the various components of platform **600** may be combined or integrated in a system-on-a-chip (SoC) architecture. In some embodiments, the components may be hardware components, firmware components, software components or any suitable combination of hardware, firmware, or software.

[0060] GPS spoofer direction finding and geolocation system **100** is configured to estimate an AOA of received GPS spoofer signals, and in some embodiments, determine a geolocation of the source of the GPS spoofer signals, as described previously. GPS spoofer direction finding and geolocation system **100** may include any or all of the circuits/components illustrated in FIGS. **1**, **2**, and **4**, as described above. These components can be implemented or otherwise used in conjunction with a variety of suitable software and/or hardware that is coupled to or that otherwise forms a part of platform **600**. These components can additionally or alternatively be implemented or otherwise used in conjunction with user I/O devices that are capable of providing information to, and receiving information and commands from, a user.

[0061] In some embodiments, these circuits may be installed local to platform **600**, as shown in the example embodiment of FIG. **6**. Alternatively, platform **600** can be implemented in a client-server arrangement wherein at least some functionality associated with these circuits is provided to platform **600** using an applet, such as a Java applet, or other downloadable module or set of sub-modules. Such remotely accessible modules or sub-modules can be provisioned in real-time, in response to a request from a client computing system for access to a given server having resources that are of interest to the user of the client computing system. In such embodiments, the server can be local to network **694** or remotely coupled to network **694** by one or more other networks and/or communication channels. In some cases, access to resources on a given network or computing system may require credentials such as usernames, passwords, and/or compliance with any other suitable security mechanism.

[0062] In various embodiments, platform **600** may be implemented as a wireless system, a wired system, or a combination of both. When implemented as a wireless system, platform **600** may include components and interfaces suitable for communicating over a wireless shared media, such as one or more antennae, transmitters, receivers, transceivers, amplifiers, filters, control logic, and so forth. An example of wireless shared media may include portions of a wireless spectrum, such as the radio frequency spectrum and so forth. When implemented as a wired system, platform **600** may include components and interfaces suitable for communicating over wired communications media, such as input/output adapters, physical connectors to connect the input/output adaptor with a corresponding wired communications medium, a network interface card (NIC), disc controller, video controller, audio controller, and so forth. Examples of wired communications media may include a wire, cable metal leads, printed circuit board (PCB), backplane, switch fabric, semiconductor material, twisted pair wire, coaxial cable, fiber optics, and so forth.

[0063] Various embodiments may be implemented using hardware elements, software elements, or a combination of both. Examples of hardware elements may include processors, microprocessors, circuits, circuit elements (for example, transistors, resistors, capacitors, inductors, and so forth), integrated circuits, application-specific integrated circuits (ASICs, or other purpose-built semiconductor), programmable logic devices, digital signal processors, field programmable gate arrays (FPGAs), logic gates, registers, semiconductor devices, chips, microchips, chipsets, and so forth. Examples of software may include software components, programs, applications, computer programs, application programs, system programs, machine programs, operating system software, middleware, firmware, software modules, routines, subroutines, functions, methods, procedures, software interfaces, application program interfaces, instruction sets, computing code, computer code, code segments, computer code segments, words, values, symbols, or any combination thereof. Determining whether an embodiment is implemented using hardware elements and/or software elements may vary in accordance with any number of factors, such as desired computational rate, power level, heat tolerances, processing cycle budget, input data rates, output data rates, memory resources, data bus speeds, and other design or performance constraints.

[0064] Some embodiments may be described using the expression "coupled" and "connected" along with their derivatives. These terms are not intended as synonyms for each other. For example, some embodiments may be described using the terms "connected" and/or "coupled" to indicate that two or more elements are in direct physical or electrical contact with each other. The term "coupled," however, may also mean that two or more elements are not in direct contact with each other, but yet still cooperate or interact with each other.

[0065] The various embodiments disclosed herein can be implemented in various forms of hardware, software, firmware, and/or special purpose processors. For example, in one embodiment at least one non-transitory computer readable storage medium has instructions encoded thereon that, when executed by one or more processors, cause one or more of the methodologies disclosed herein to be implemented. The instructions can be encoded using a suitable programming language, such as C, C++, object oriented C, Java, JavaScript, Visual Basic. NET, Beginner's All-Purpose Symbolic Instruction Code (BASIC), or alternatively, using

custom or proprietary instruction sets. The instructions can be provided in the form of one or more computer software applications and/or applets that are tangibly embodied on a memory device, and that can be executed by a computer having any suitable architecture. In one embodiment, the system can be hosted on a given website and implemented, for example, using JavaScript or another suitable browser-based technology. For instance, in certain embodiments, the system may leverage processing resources provided by a remote computer system accessible via network **694**. The computer software applications disclosed herein may include any number of different modules, sub-modules, or other components of distinct functionality, and can provide information to, or receive information from, still other components. These modules can be used, for example, to communicate with input and/or output devices such as a display screen, a touch sensitive surface, a printer, and/or any other suitable device. Other componentry and functionality not reflected in the illustrations will be apparent in light of this disclosure, and it will be appreciated that other embodiments are not limited to any particular hardware or software configuration. Thus, in other embodiments platform **600** may comprise additional, fewer, or alternative subcomponents as compared to those included in the example embodiment of FIG. **6**.

[0066] The aforementioned non-transitory computer readable medium may be any suitable medium for storing digital information, such as a hard drive, a server, a flash memory, and/or random-access memory (RAM), or a combination of memories. In alternative embodiments, the components and/or modules disclosed herein can be implemented with hardware, including gate level logic such as a field-programmable gate array (FPGA), or alternatively, a purpose-built semiconductor such as an application-specific integrated circuit (ASIC). Still other embodiments may be implemented with a microcontroller having a number of input/output ports for receiving and outputting data, and a number of embedded routines for carrying out the various functionalities disclosed herein. It will be apparent that any suitable combination of hardware, software, and firmware can be used, and that other embodiments are not limited to any particular system architecture.

[0067] Some embodiments may be implemented, for example, using a machine readable medium or article which may store an instruction or a set of instructions that, if executed by a machine, may cause the machine to perform a method, process, and/or operations in accordance with the embodiments. Such a machine may include, for example, any suitable processing platform, computing platform, computing device, processing device, computing system, processing system, computer, process, or the like, and may be implemented using any suitable combination of hardware and/or software. The machine readable medium or article may include, for example, any suitable type of memory unit, memory device, memory article, memory medium, storage device, storage article, storage medium, and/or storage unit, such as memory, removable or non-removable media, erasable or non-erasable media, writeable or rewriteable media, digital or analog media, hard disk, floppy disk, compact disk read only memory (CD-ROM), compact disk recordable (CD-R) memory, compact disk rewriteable (CD-RW) memory, optical disk, magnetic media, magneto-optical media, removable memory cards or disks, various types of digital versatile disk (DVD), a tape, a cassette, or the like. The instructions may include any suitable type of code, such as source code, compiled code, interpreted code, executable code, static code, dynamic code, encrypted code, and the like, implemented using any suitable high level, low level, object oriented, visual, compiled, and/or interpreted programming language.

[0068] Unless specifically stated otherwise, it may be appreciated that terms such as "processing," "computing," "calculating," "determining," or the like refer to the action and/or process of a computer or computing system, or similar electronic computing device, that manipulates and/or transforms data represented as physical quantities (for example, electronic) within the registers and/or memory units of the computer system into other data similarly represented as physical entities within the registers, memory units, or other such information storage transmission or displays of the computer system. The embodiments are not limited in this context.

[0069] The terms "circuit" or "circuitry," as used in any embodiment herein, are functional structures that include hardware, or a combination of hardware and software, and may comprise, for example, singly or in any combination, hardwired circuitry, programmable circuitry such as computer processors comprising one or more individual instruction processing cores, state machine circuitry, and/or gate level logic. The circuitry may include a processor and/or controller programmed or otherwise configured to execute one or more instructions to perform one or more operations described herein. The instructions may be embodied as, for example, an application, software, firmware, etc. configured to cause the circuitry to perform any of the aforementioned operations. Software may be embodied as a software package, code, instructions, instruction sets and/or data recorded on a computer-readable storage device. Software may be embodied or implemented to include any number of processes, and processes, in turn, may be embodied or implemented to include any number of threads, etc., in a hierarchical fashion. Firmware may be embodied as code, instructions or instruction sets and/or data that are hard-coded (e.g., nonvolatile) in memory devices. The circuitry may, collectively or individually, be embodied as circuitry that forms part of a larger system, for example, an integrated circuit (IC), an application-specific integrated circuit (ASIC), a system-on-a-chip (SoC), desktop computers, laptop computers, tablet computers, servers, smartphones, etc. Other embodiments may be implemented as software executed by a programmable device. In any such hardware cases that include executable software, the terms "circuit" or "circuitry" are intended to include a combination of software and hardware such as a programmable control device or a processor capable of executing the software. As described herein, various embodiments may be implemented using hardware elements, software elements, or any combination thereof. Examples of hardware elements may include processors, microprocessors, circuits, circuit elements (e.g., transistors, resistors, capacitors, inductors, and so forth), integrated circuits, application specific integrated circuits (ASIC), programmable logic devices (PLD), digital signal processors (DSP), field programmable gate array (FPGA), logic gates, registers, semiconductor device, chips, microchips, chip sets, and so forth.

[0070] Numerous specific details have been set forth herein to provide a thorough understanding of the embodiments. It will be understood, however, that other embodi-

ments may be practiced without these specific details, or otherwise with a different set of details. It will be further appreciated that the specific structural and functional details disclosed herein are representative of example embodiments and are not necessarily intended to limit the scope of the present disclosure. In addition, although the subject matter has been described in language specific to structural features and/or methodological acts, it is to be understood that the subject matter defined in the appended claims is not necessarily limited to the specific features or acts described herein. Rather, the specific features and acts described herein are disclosed as example forms of implementing the claims.

FURTHER EXAMPLE EMBODIMENTS

[0071] The following examples pertain to further embodiments, from which numerous permutations and configurations will be apparent.

[0072] Example 1 is a computer program product including one or more non-transitory machine-readable mediums encoded with instructions that when executed by one or more processors cause a process to be carried out for locating a global positioning system (GPS) spoofer, the process comprising: steering a beam in a direction selected from a search constellation; measuring a first signal power received through the steered beam; steering a null in the direction selected from the search constellation; measuring a second signal power received through the steered null; calculating a difference between the first signal power and the second signal power; estimating an angle of arrival (AOA) of a GPS spoofer signal as the selected direction if the calculated difference exceeds a threshold power value; and identifying a pseudo-random noise (PRN) code of the GPS spoofer signal.

[0073] Example 2 includes the computer program product of Example 1, wherein the process further comprises iterating the process for a plurality of directions selected from the search constellation and accumulating a plurality of estimated AOAs and identified PRN codes associated with GPS spoofer signals.

[0074] Example 3 includes the computer program product of Example 2, wherein the process further comprises, in response to accumulating four or more estimated AOAs, each estimated AOA associated with a unique PRN code: determining that the four or more estimated AOAs having unique PRN codes differ by less than a threshold angular value; and providing the four or more GPS spoofer signals associated with the four or more unique PRN codes to a GPS receiver.

[0075] Example 4 includes the computer program product of Example 3, wherein the process further comprises calculating, using the GPS receiver, a candidate position of a source of the GPS spoofer signals based on the provided four or more GPS spoofer signals.

[0076] Example 5 includes the computer program product of Example 4, wherein the threshold angular value is a first threshold angular value, and the process further comprises: calculating a direction to the candidate position; determining if the direction to the candidate position differs from the estimated AOAs by less than a second threshold angular value; and in response to the determination, reporting the candidate position as an estimated position of the source of the GPS spoofer signals.

[0077] Example 6 includes the computer program product of any of Examples 1-5, wherein the search constellation comprises a plurality of azimuth angles and elevation angles associated with a search region of interest.

[0078] Example 7 includes the computer program product of Example 6, wherein the search region of interest excludes directions associated with known positions of GPS satellites.

[0079] Example 8 is a system for locating a global positioning system (GPS) spoofer, the system comprising: a beamforming network configured to steer a beam in a selected direction and to steer a null in the selected direction; and a spoofer angle of arrival (AOA) estimation circuit configured to choose the selected direction from a search constellation comprising a plurality of directions, measure a first signal power received through the steered beam, measure a second signal power received through the steered null, calculate a difference between the first signal power and the second signal power, estimate an AOA of a GPS spoofer signal as the selected direction if the calculated difference exceeds a threshold power value, and identify a pseudo-random noise (PRN) code of the GPS spoofer signal.

[0080] Example 9 includes the system of Example 8, wherein the system is configured to iterate the process for the plurality of directions selected from the search constellation and accumulate a plurality of estimated AOAs and identified PRN codes associated with GPS spoofer signals.

[0081] Example 10 includes the system of Example 9, wherein the system further comprises a GPS receiver and a spoofer location estimator circuit configured to: in response to accumulating four or more estimated AOAs, each estimated AOA associated with a unique PRN code, determine that the four or more estimated AOAs having unique PRN codes differ by less than a threshold angular value; and provide the four or more GPS spoofer signals associated with the four or more unique PRN codes to the GPS receiver.

[0082] Example 11 includes the system of Example 10, wherein the spoofer location estimator circuit is further configured to employ the GPS receiver to calculate a candidate position of a source of the GPS spoofer signals based on the provided four or more GPS spoofer signals.

[0083] Example 12 includes the system of Example 11, wherein the threshold angular value is a first threshold angular value, and the spoofer location estimator circuit is further configured to: calculate a direction to the candidate position; determine if the direction to the candidate position differs from the estimated AOAs by less than a second threshold angular value; and in response to the determination, report the candidate position as an estimated position of the source of the GPS spoofer signals.

[0084] Example 13 includes the system of any of Examples 8-12, wherein the search constellation comprises a plurality of azimuth angles and elevation angles associated with a search region of interest and excludes directions associated with known positions of GPS satellites.

[0085] Example 14 includes the system of any of Examples 8-13, wherein the spoofer AOA estimation circuit and the location estimator circuit comprise one or more processors and one or more memories encoded with instructions.

[0086] Example 15 is a method for locating a global positioning system (GPS) spoofer, the method comprising: steering, by a processor based system, a beam in a direction selected from a search constellation; measuring, by the processor based system, a first signal power received through the steered beam; steering, by the processor based system, a null in the direction selected from the search

constellation; measuring, by the processor based system, a second signal power received through the steered null; calculating, by the processor based system, a difference between the first signal power and the second signal power; and estimating, by the processor based system, an angle of arrival (AOA) of a GPS spoofer signal as the selected direction if the calculated difference exceeds a threshold power value; and identifying, by the processor based system, a pseudo-random noise (PRN) code of the GPS spoofer signal.

[0087] Example 16 includes the method of Example 15, further comprising iterating the process for a plurality of directions selected from the search constellation and accumulating a plurality of estimated AOAs and identified PRN codes associated with GPS spoofer signals.

[0088] Example 17 includes the method of Example 16, further comprising, in response to accumulating four or more estimated AOAs, each estimated AOA associated with a unique PRN code: determining that the four or more estimated AOAs having unique PRN codes differ by less than a threshold angular value; and providing the four or more GPS spoofer signals associated with the four or more unique PRN codes to a GPS receiver.

[0089] Example 18 includes the method of Example 17, further comprising calculating, using the GPS receiver, a candidate position of a source of the GPS spoofer signals based on the provided four or more GPS spoofer signals.

[0090] Example 19 includes the method of Example 18, wherein the threshold angular value is a first threshold angular value, and the method further comprises: calculating a direction to the candidate position; determining if the direction to the candidate position differs from the estimated AOAs by less than a second threshold angular value; and in response to the determination, reporting the candidate position as an estimated position of the source of the GPS spoofer signals.

[0091] Example 20 includes the method of any of Examples 15-19, wherein the search constellation comprises a plurality of azimuth angles and elevation angles associated with a search region of interest and the search region of interest excludes directions associated with known positions of GPS satellites.

[0092] The terms and expressions which have been employed herein are used as terms of description and not of limitation, and there is no intention, in the use of such terms and expressions, of excluding any equivalents of the features shown and described (or portions thereof), and it is recognized that various modifications are possible within the scope of the claims. Accordingly, the claims are intended to cover all such equivalents. Various features, aspects, and embodiments have been described herein. The features, aspects, and embodiments are susceptible to combination with one another as well as to variation and modification, as will be appreciated in light of this disclosure. The present disclosure should, therefore, be considered to encompass such combinations, variations, and modifications. It is intended that the scope of the present disclosure be limited not by this detailed description, but rather by the claims appended hereto. Future filed applications claiming priority to this application may claim the disclosed subject matter in a different manner and may generally include any set of one or more elements as variously disclosed or otherwise demonstrated herein.

What is claimed is:

1. A computer program product including one or more non-transitory machine-readable mediums encoded with instructions that when executed by one or more processors cause a process to be carried out for locating a global positioning system (GPS) spoofer, the process comprising:
- steering a beam in a direction selected from a search constellation;
- measuring a first signal power received through the steered beam;
- steering a null in the direction selected from the search constellation;
- measuring a second signal power received through the steered null;
- calculating a difference between the first signal power and the second signal power;
- estimating an angle of arrival (AOA) of a GPS spoofer signal as the selected direction if the calculated difference exceeds a threshold power value; and
- identifying a pseudo-random noise (PRN) code of the GPS spoofer signal.

2. The computer program product of claim **1**, wherein the process further comprises iterating the process for a plurality of directions selected from the search constellation and accumulating a plurality of estimated AOAs and identified PRN codes associated with GPS spoofer signals.

3. The computer program product of claim **2**, wherein the process further comprises, in response to accumulating four or more estimated AOAs, each estimated AOA associated with a unique PRN code:
- determining that the four or more estimated AOAs having unique PRN codes differ by less than a threshold angular value; and
- providing the four or more GPS spoofer signals associated with the four or more unique PRN codes to a GPS receiver.

4. The computer program product of claim **3**, wherein the process further comprises calculating, using the GPS receiver, a candidate position of a source of the GPS spoofer signals based on the provided four or more GPS spoofer signals.

5. The computer program product of claim **4**, wherein the threshold angular value is a first threshold angular value, and the process further comprises:
- calculating a direction to the candidate position;
- determining if the direction to the candidate position differs from the estimated AOAs by less than a second threshold angular value; and
- in response to the determination, reporting the candidate position as an estimated position of the source of the GPS spoofer signals.

6. The computer program product of claim **1**, wherein the search constellation comprises a plurality of azimuth angles and elevation angles associated with a search region of interest.

7. The computer program product of claim **6**, wherein the search region of interest excludes directions associated with known positions of GPS satellites.

8. A system for locating a global positioning system (GPS) spoofer, the system comprising:
- a beamforming network configured to steer a beam in a selected direction and to steer a null in the selected direction; and

a spoofer angle of arrival (AOA) estimation circuit configured to

choose the selected direction from a search constellation comprising a plurality of directions,

measure a first signal power received through the steered beam,

measure a second signal power received through the steered null,

calculate a difference between the first signal power and the second signal power,

estimate an AOA of a GPS spoofer signal as the selected direction if the calculated difference exceeds a threshold power value, and

identify a pseudo-random noise (PRN) code of the GPS spoofer signal.

9. The system of claim **8**, wherein the system is configured to iterate the process for the plurality of directions selected from the search constellation and accumulate a plurality of estimated AOAs and identified PRN codes associated with GPS spoofer signals.

10. The system of claim **9**, wherein the system further comprises a GPS receiver and a spoofer location estimator circuit configured to:

in response to accumulating four or more estimated AOAs, each estimated AOA associated with a unique PRN code, determine that the four or more estimated AOAs having unique PRN codes differ by less than a threshold angular value; and

provide the four or more GPS spoofer signals associated with the four or more unique PRN codes to the GPS receiver.

11. The system of claim **10**, wherein the spoofer location estimator circuit is further configured to employ the GPS receiver to calculate a candidate position of a source of the GPS spoofer signals based on the provided four or more GPS spoofer signals.

12. The system of claim **11**, wherein the threshold angular value is a first threshold angular value, and the spoofer location estimator circuit is further configured to:

calculate a direction to the candidate position;

determine if the direction to the candidate position differs from the estimated AOAs by less than a second threshold angular value; and

in response to the determination, report the candidate position as an estimated position of the source of the GPS spoofer signals.

13. The system of claim **8**, wherein the search constellation comprises a plurality of azimuth angles and elevation angles associated with a search region of interest and excludes directions associated with known positions of GPS satellites.

14. The system of claim **8**, wherein the spoofer AOA estimation circuit and the location estimator circuit comprise one or more processors and one or more memories encoded with instructions.

15. A method for locating a global positioning system (GPS) spoofer, the method comprising:

steering, by a processor based system, a beam in a direction selected from a search constellation;

measuring, by the processor based system, a first signal power received through the steered beam;

steering, by the processor based system, a null in the direction selected from the search constellation;

measuring, by the processor based system, a second signal power received through the steered null;

calculating, by the processor based system, a difference between the first signal power and the second signal power; and

estimating, by the processor based system, an angle of arrival (AOA) of a GPS spoofer signal as the selected direction if the calculated difference exceeds a threshold power value; and

identifying, by the processor based system, a pseudo-random noise (PRN) code of the GPS spoofer signal.

16. The method of claim **15**, further comprising iterating the process for a plurality of directions selected from the search constellation and accumulating a plurality of estimated AOAs and identified PRN codes associated with GPS spoofer signals.

17. The method of claim **16**, further comprising, in response to accumulating four or more estimated AOAs, each estimated AOA associated with a unique PRN code:

determining that the four or more estimated AOAs having unique PRN codes differ by less than a threshold angular value; and

providing the four or more GPS spoofer signals associated with the four or more unique PRN codes to a GPS receiver.

18. The method of claim **17**, further comprising calculating, using the GPS receiver, a candidate position of a source of the GPS spoofer signals based on the provided four or more GPS spoofer signals.

19. The method of claim **18**, wherein the threshold angular value is a first threshold angular value, and the method further comprises:

calculating a direction to the candidate position;

determining if the direction to the candidate position differs from the estimated AOAs by less than a second threshold angular value; and

in response to the determination, reporting the candidate position as an estimated position of the source of the GPS spoofer signals.

20. The method of claim **15**, wherein the search constellation comprises a plurality of azimuth angles and elevation angles associated with a search region of interest and the search region of interest excludes directions associated with known positions of GPS satellites.

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