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(54) **RANGE-ENABLED THREE-DIMENSIONAL
IMAGING SYSTEM AND ASSOCIATED
METHODS**

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(57)

ABSTRACT

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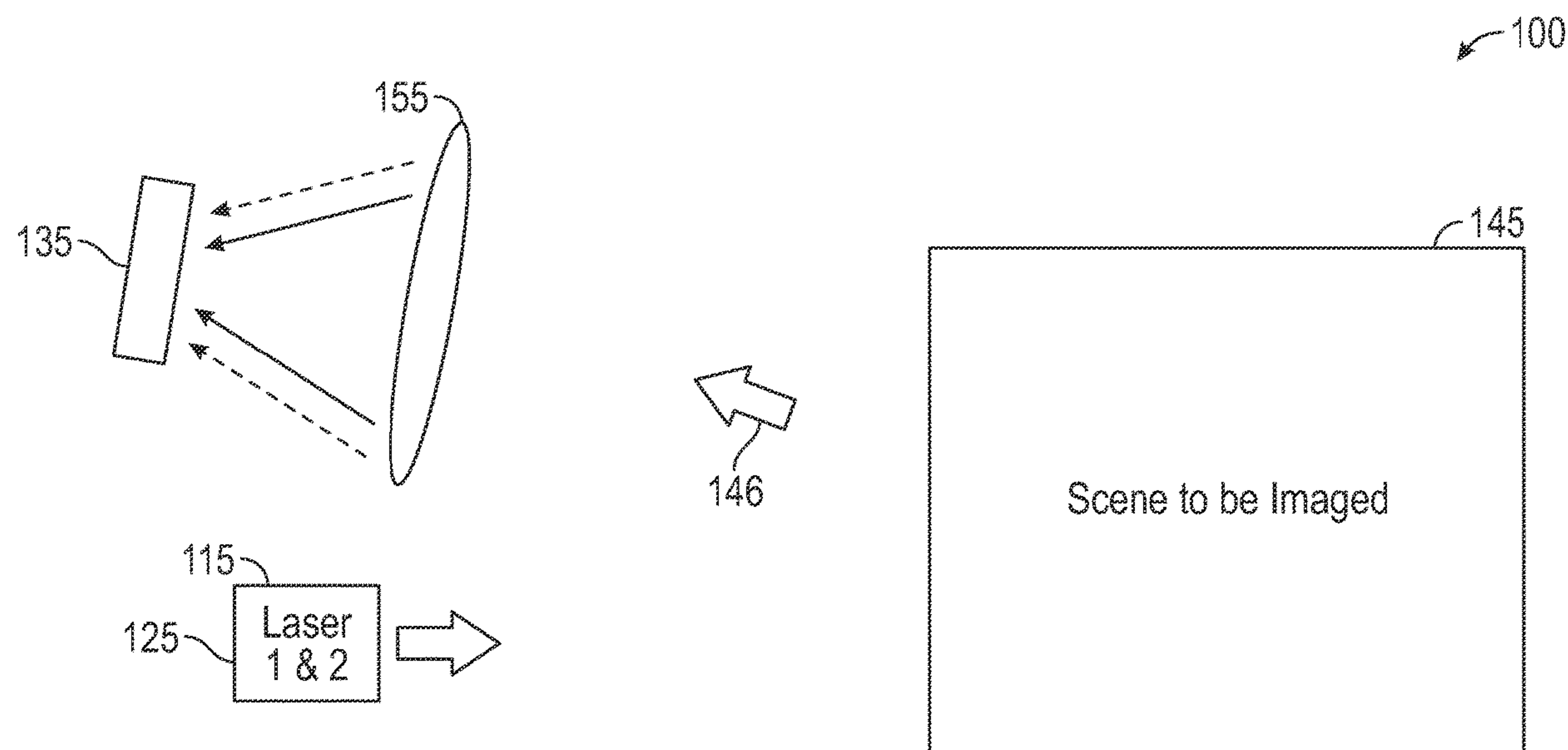
Publication Classification

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Systems and methods for three-dimensional (3-D) imaging enabled by natural range-dependent processes. Multiple lasers are configured to independently flash illuminate a target object to 3-D image a resultant “scene” onto a focal plane array (FPA). The first laser produces a wavelength non-resonant with an atmospheric absorption line along the illumination path. The second laser produces a wavelength resonant with the atmospheric absorption line, and closely spaced with the non-resonant wavelength. A ratio of the respective intensities recorded at the FPA for the two wavelengths calculates a range to the target object.



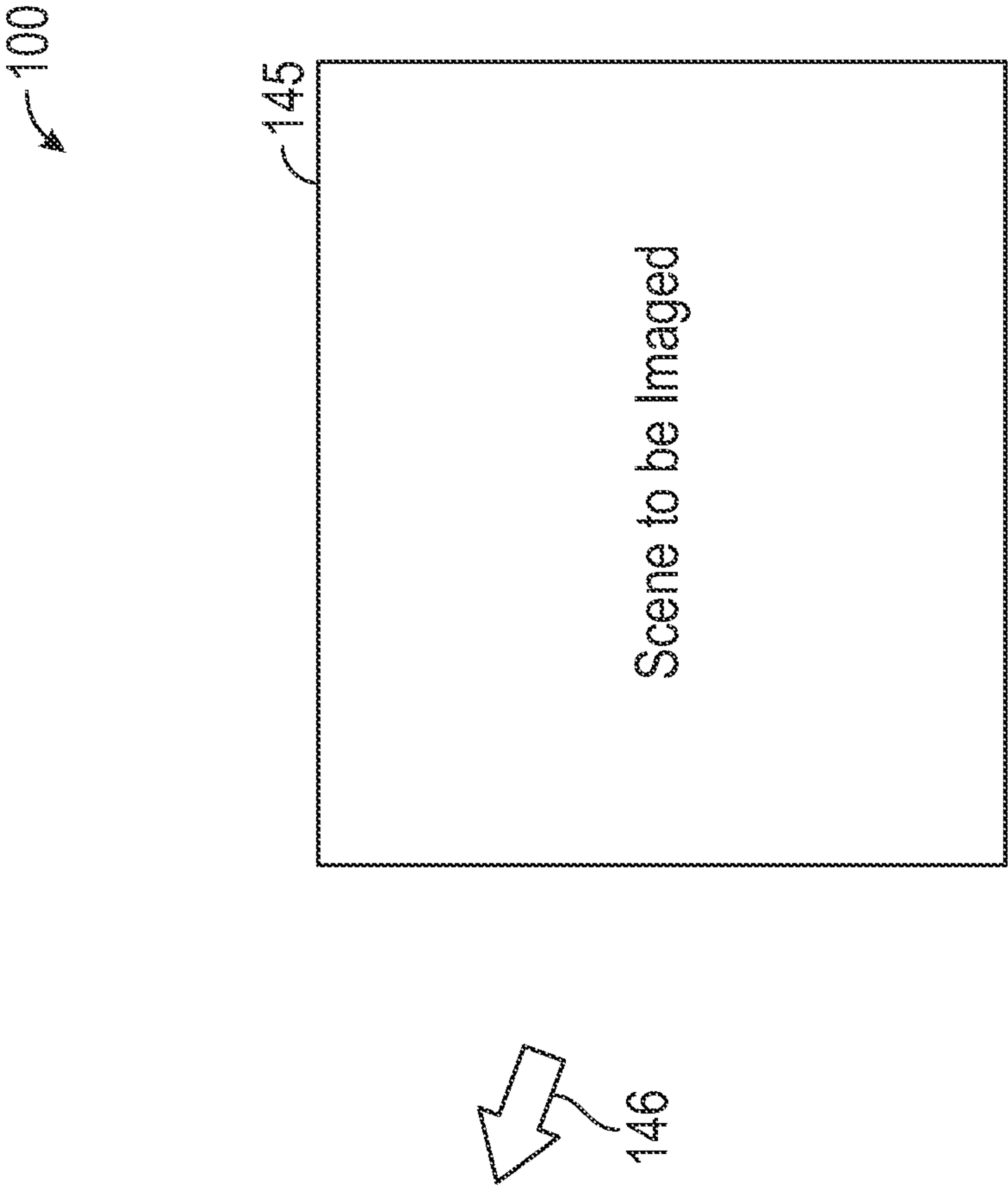


FIG. 1

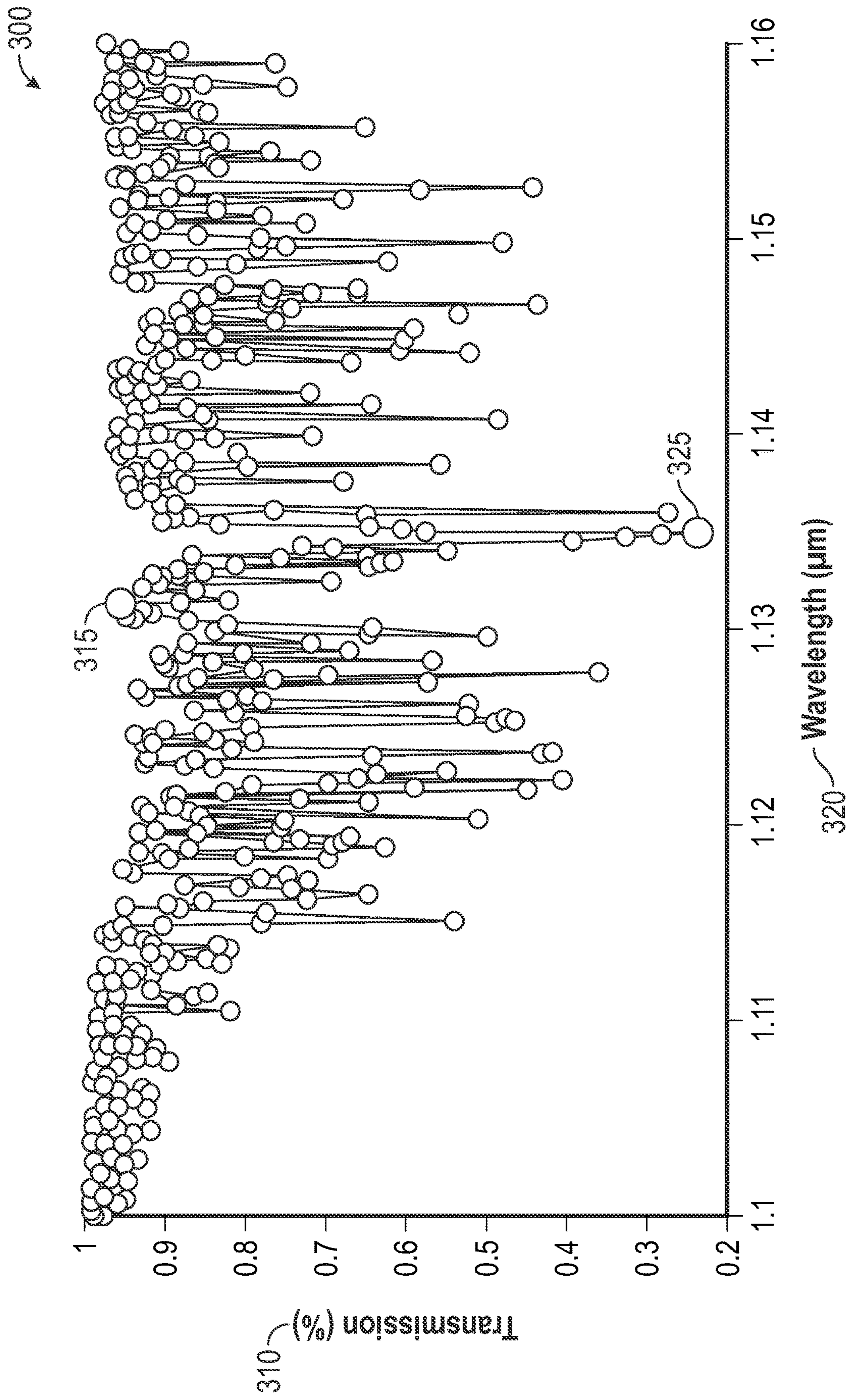


FIG. 2

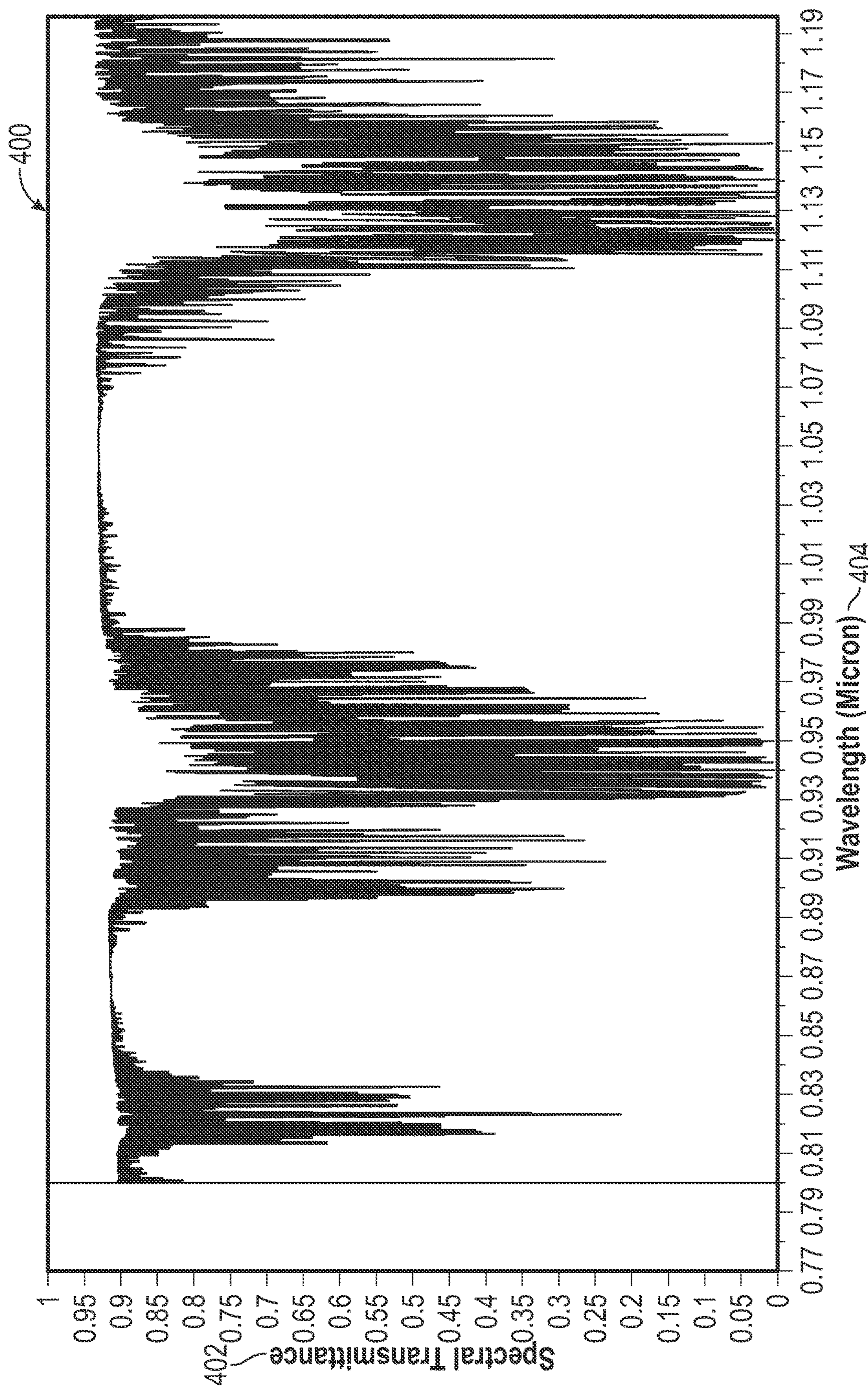


FIG. 3A

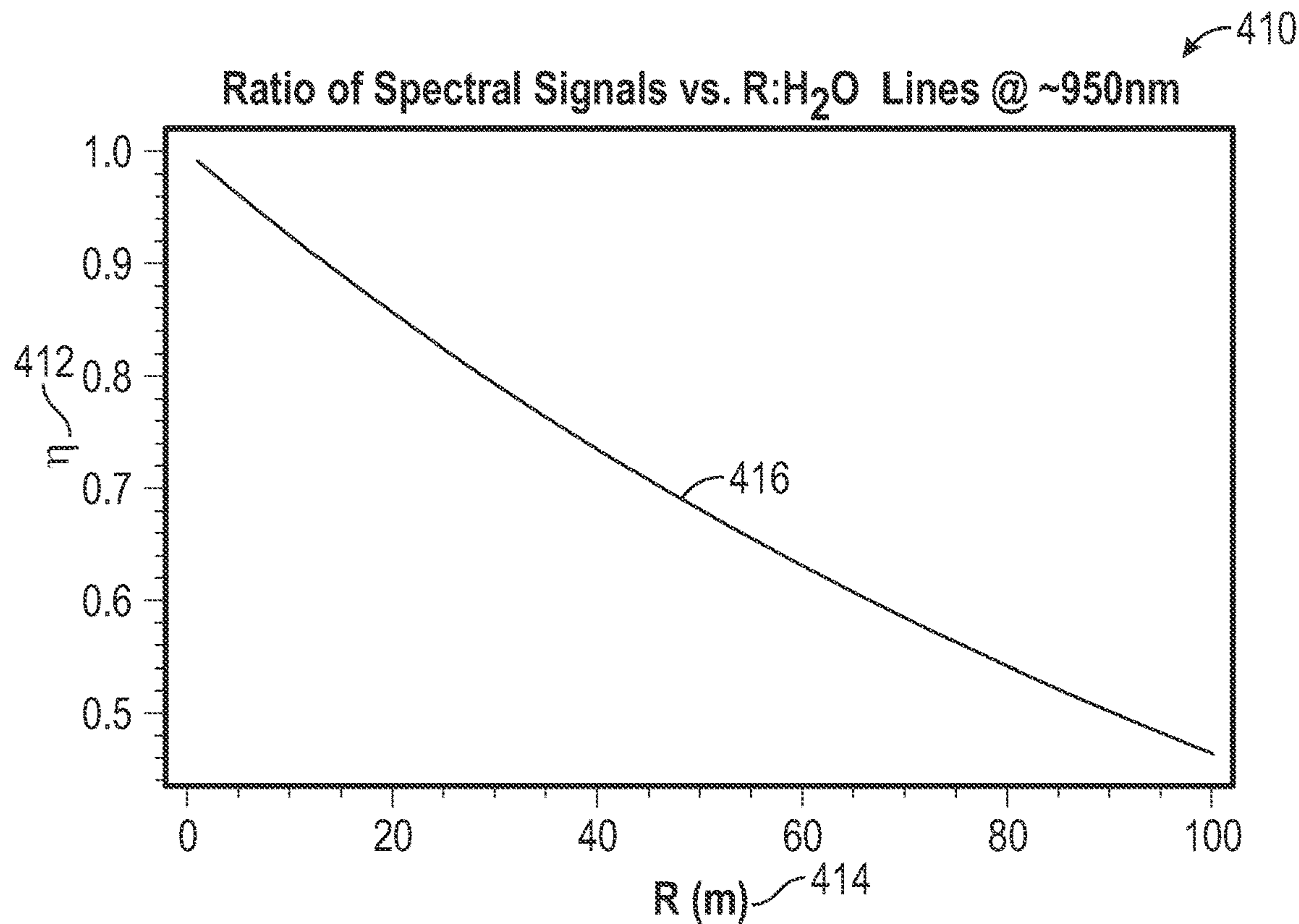


FIG. 3B

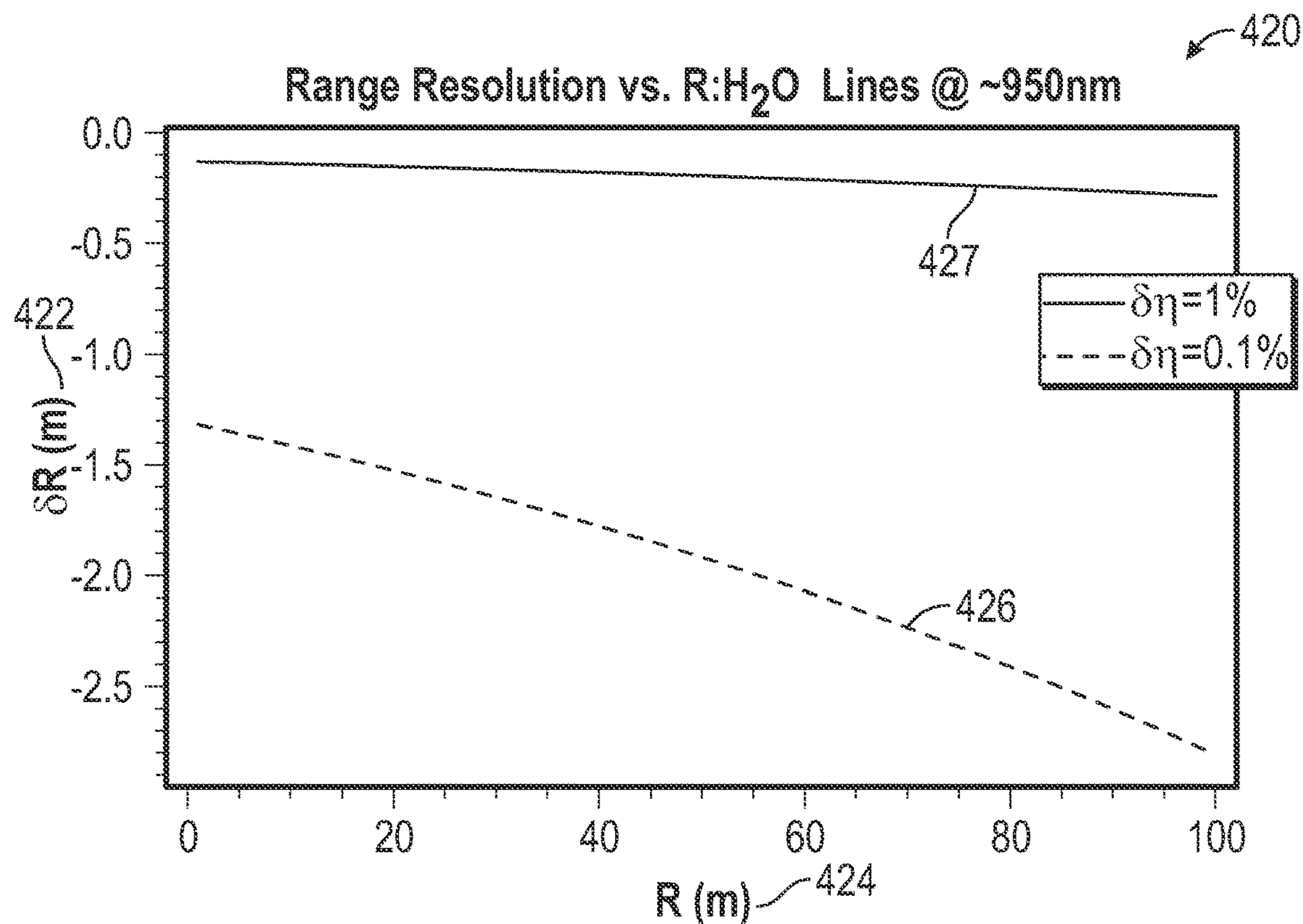
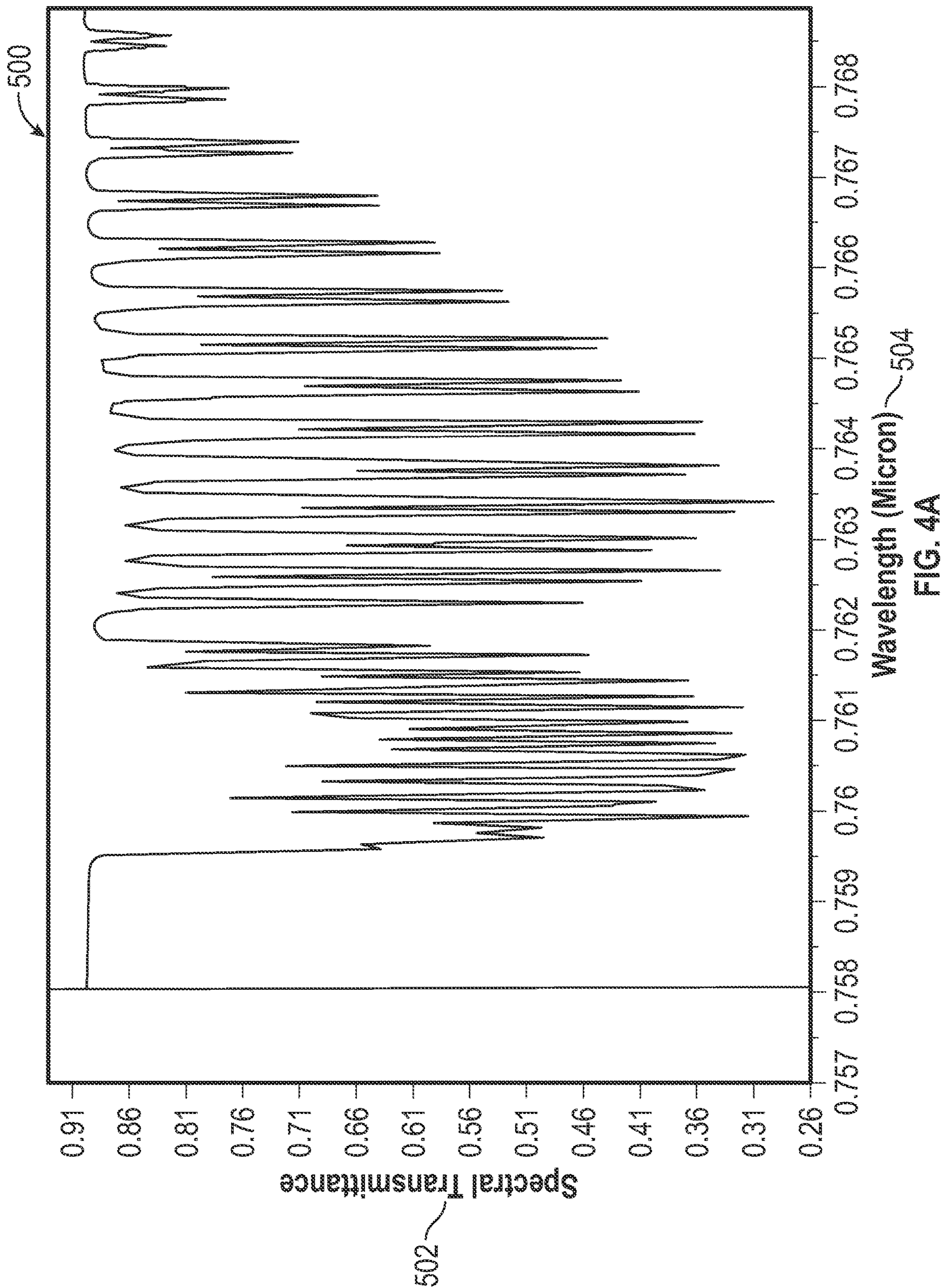


FIG. 3C



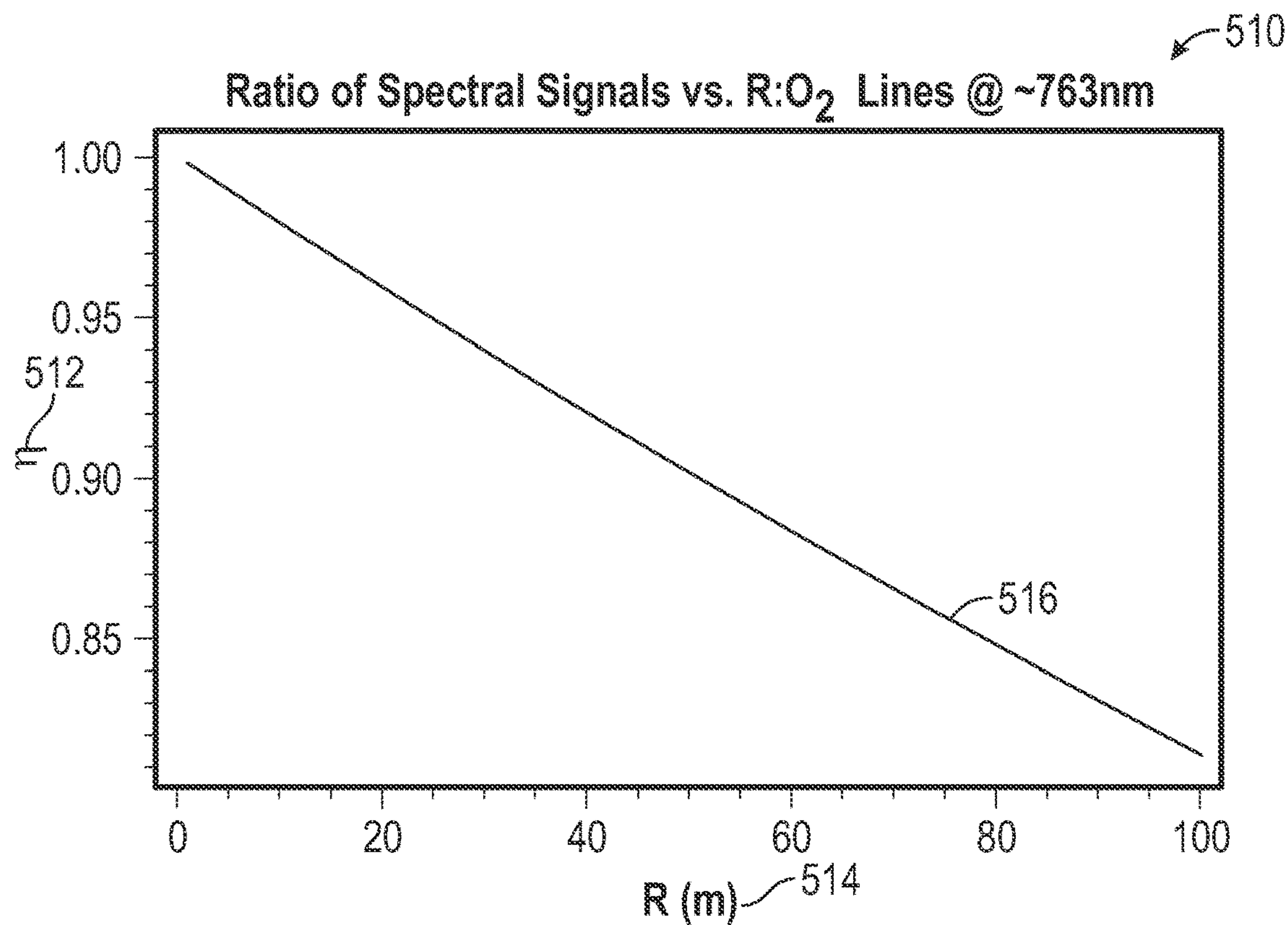


FIG. 4B

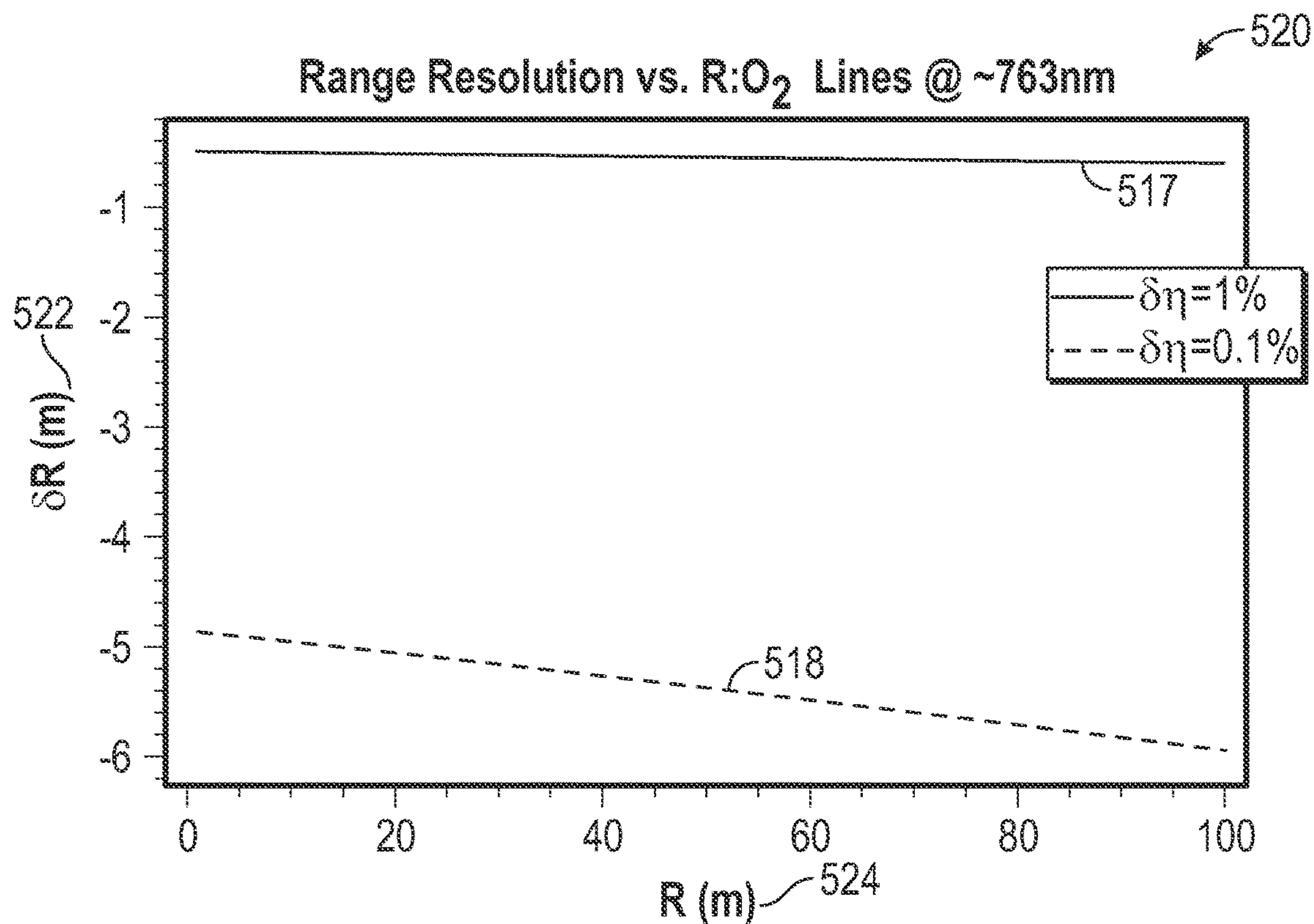
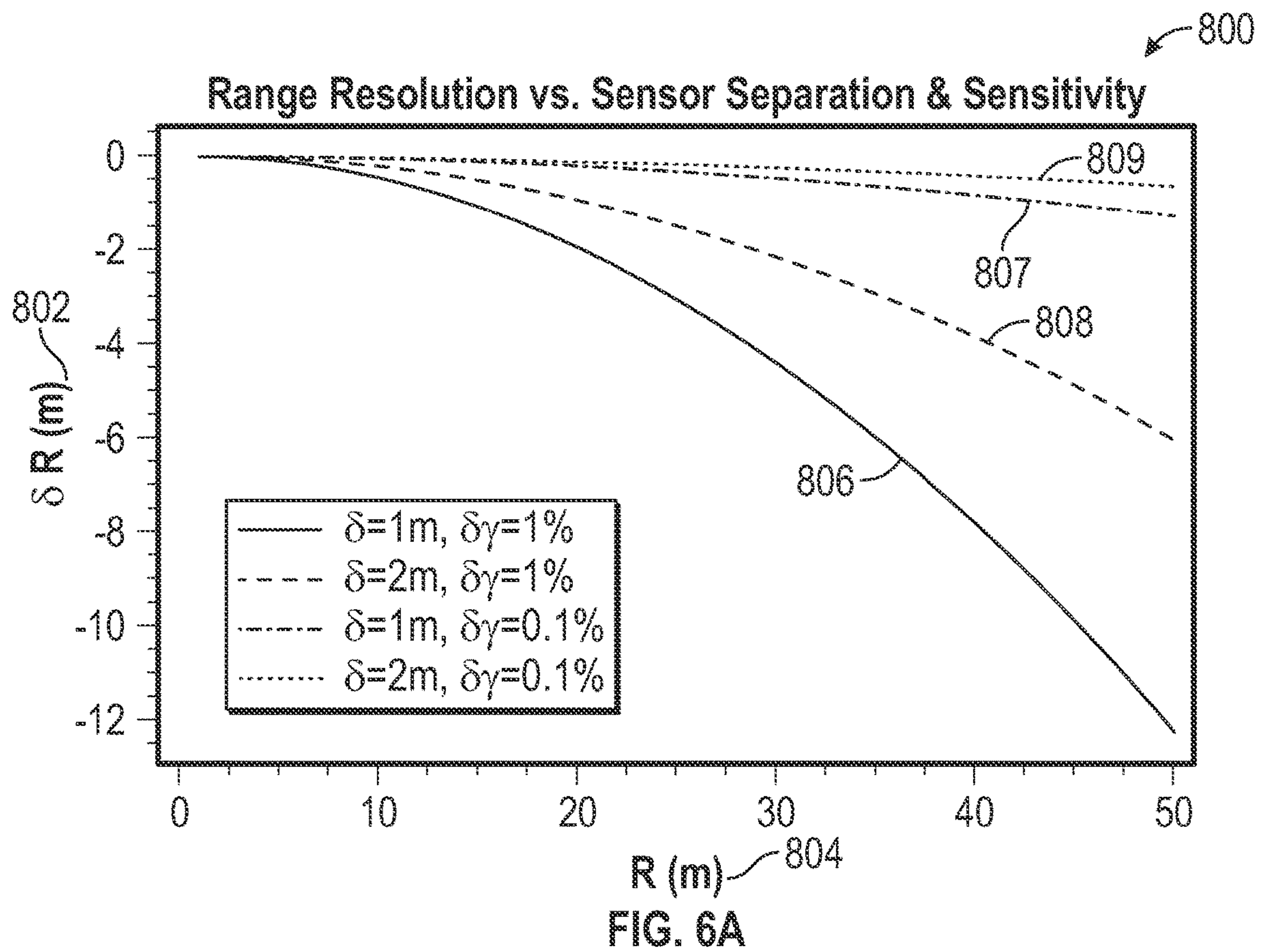
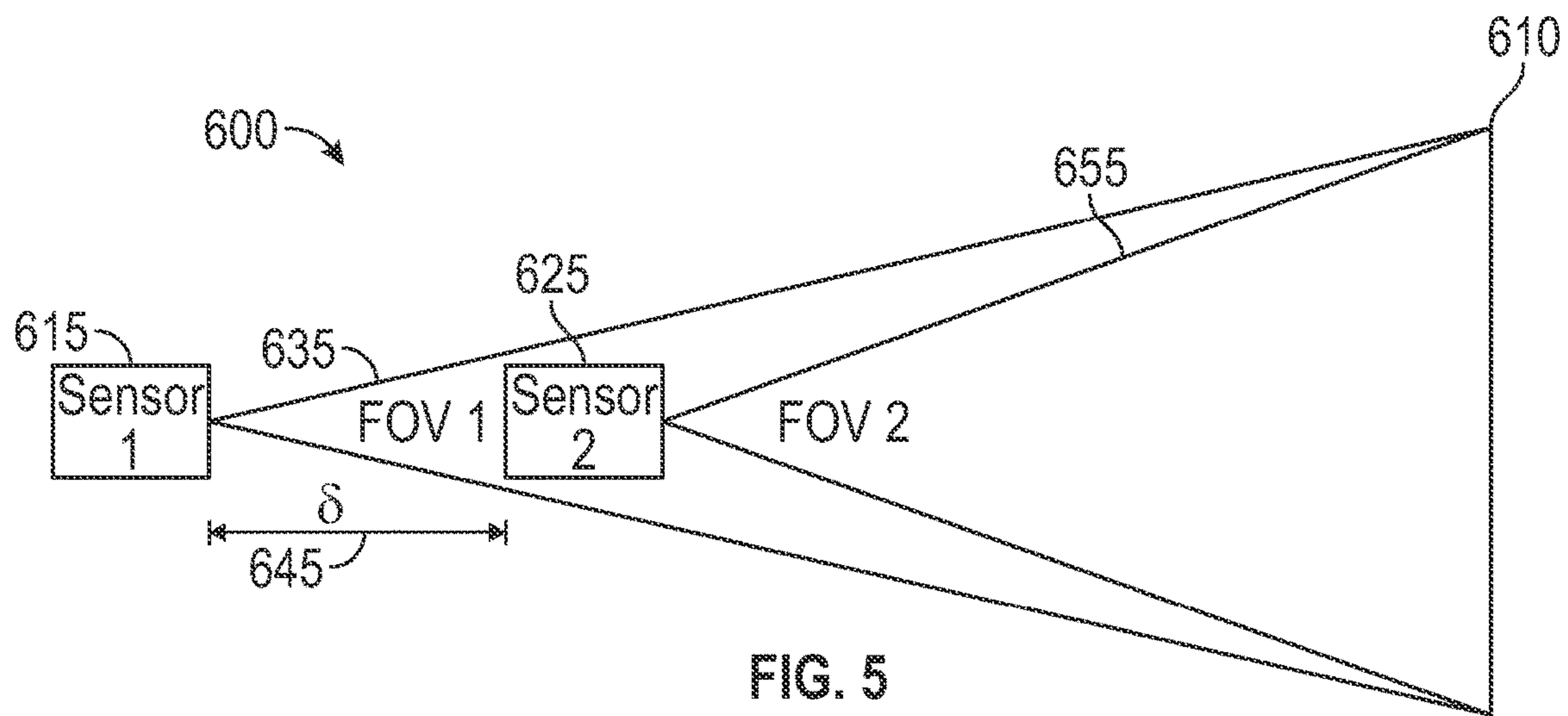


FIG. 4C



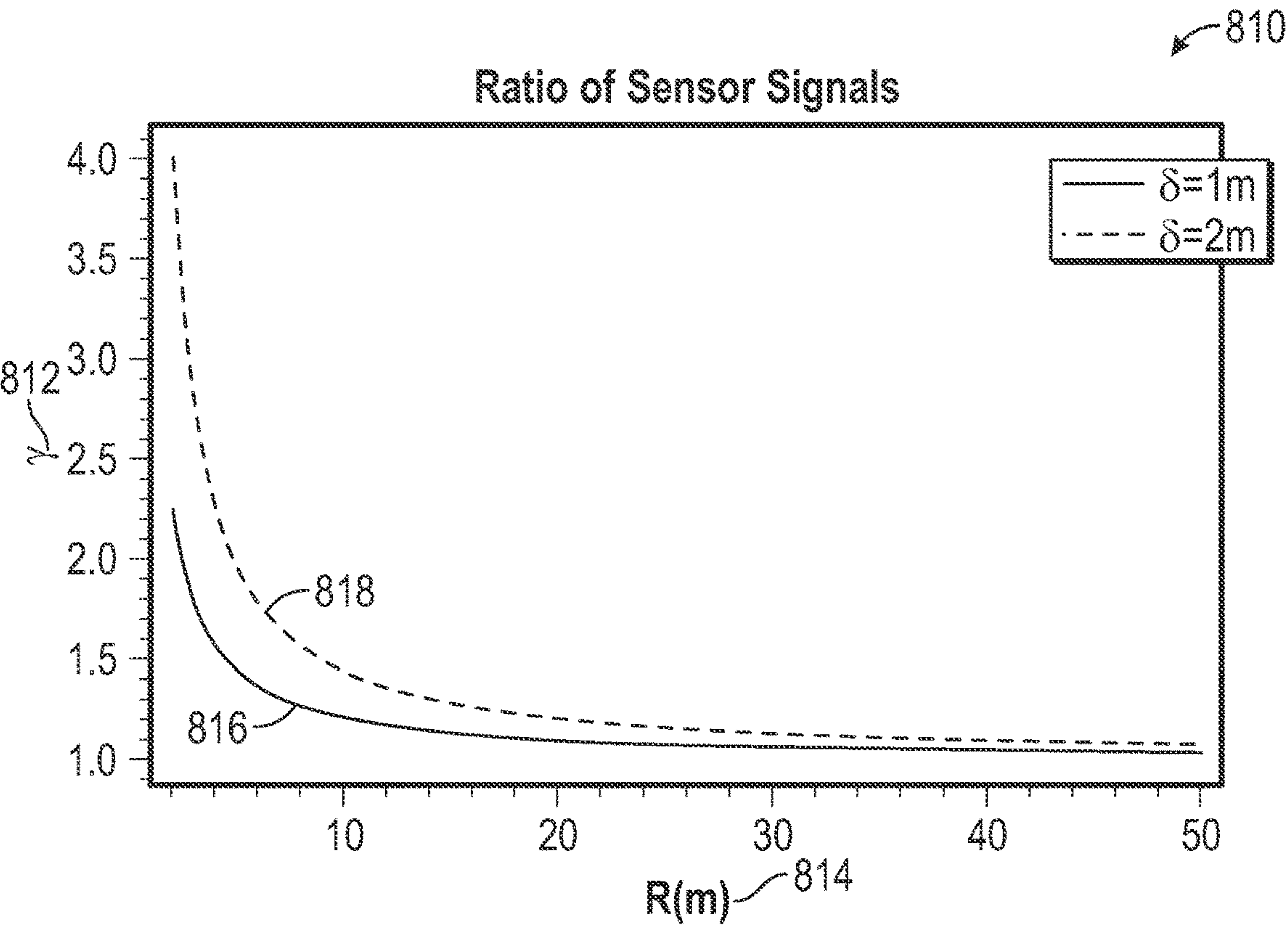


FIG. 6B

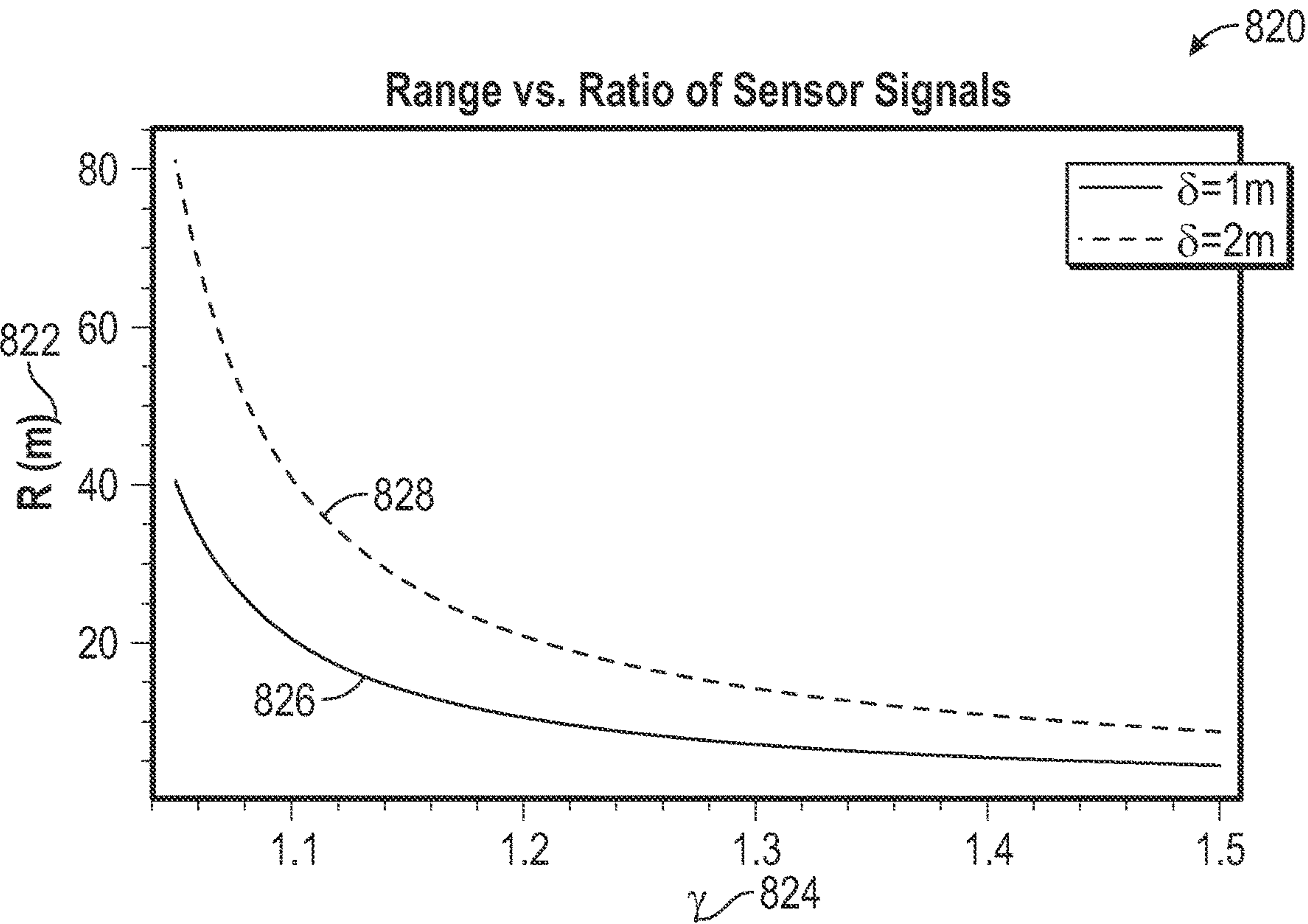


FIG. 6C

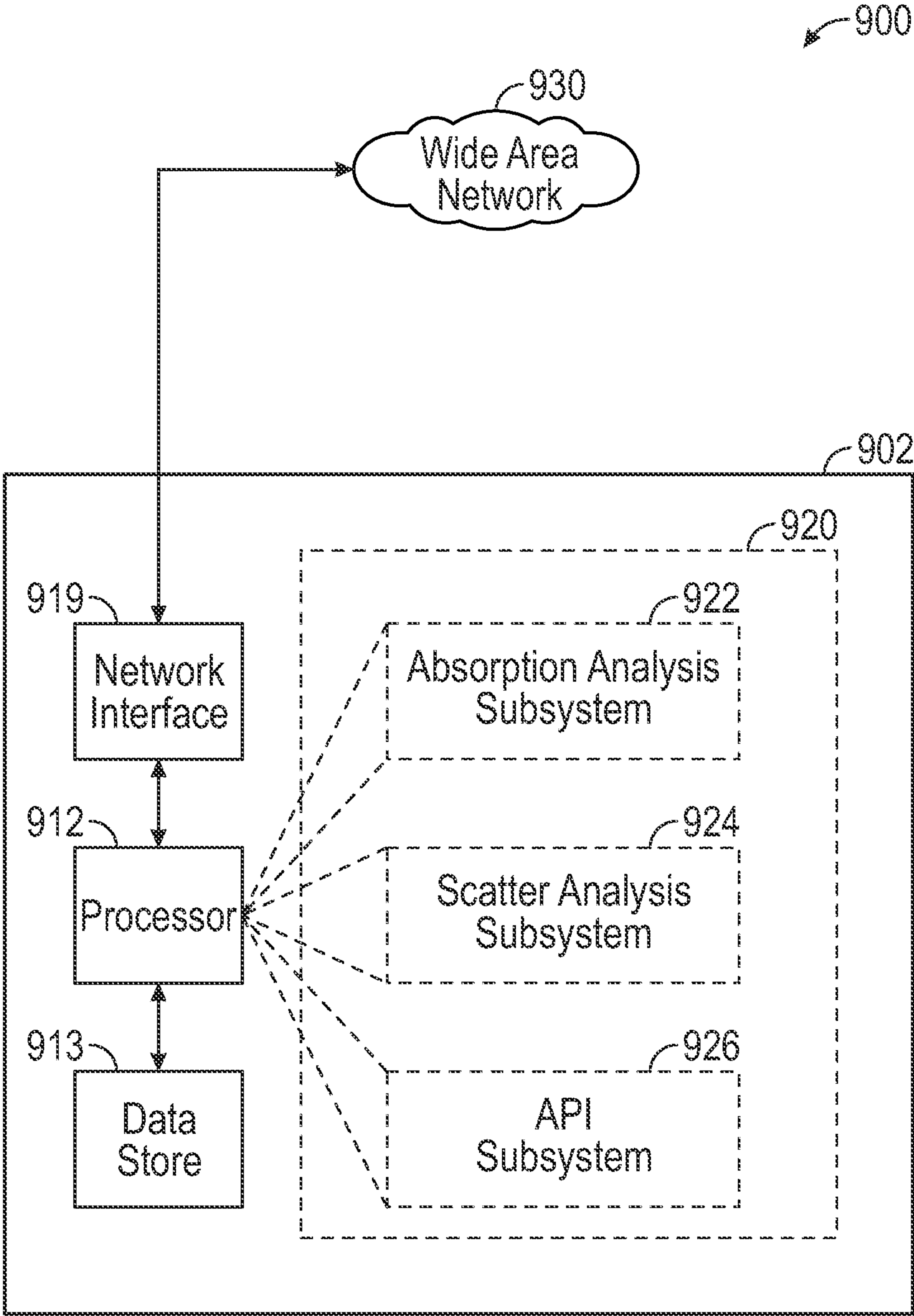


FIG. 7

RANGE-ENABLED THREE-DIMENSIONAL IMAGING SYSTEM AND ASSOCIATED METHODS

STATEMENT OF GOVERNMENT INTEREST

[0001] The invention described herein may be manufactured, used, and licensed by or for the Government of the United States for all governmental purposes without the payment of any royalty.

BACKGROUND

[0002] Laser Detection and Ranging (LADAR), a special category of Light Detection and Ranging (LIDAR or Lidar), is an optical sensing technology that determines distance, velocity, and/or other characteristics of a distant target object by illuminating the target object with pulsed laser light and analyzing the reflected pulses as detected by some number of sensors. Differences in pulsed laser return times and wavelengths may be used to create digital three-dimensional (3-D) representations of the target object.

[0003] LADAR technology has terrestrial, airborne, and mobile applications. For example, LADAR technology may be used to create high-resolution maps of the surfaces of distant objects, with applications in geodesy, geomatics, archaeology, geography, geology, geomorphology, seismology, forestry, atmospheric physics, laser guidance, airborne laser swath mapping (ALSM), and laser altimetry. Application of LADAR to enable 3-D imaging for control and navigation of autonomous vehicles is currently a focus of significant research.

[0004] As commonly employed in known LADAR solutions, measurement of a signal received by a detector, such as a focal plane array (FPA), may be calculated as follows:

$$S=f(R)A(R)Q(R)D p$$

where S denotes a measured signal, f(R) denotes a function of range describing signal reduction due to scattering targets, A(R) denotes atmospheric absorption, Q(R) denotes a laser-target overlap integral, D denotes a detector collection aperture and includes the effect of system transmission and detector sensitivity, and p denotes target reflectivity. By way of definition, absorption is the process by which incident radiant energy is retained by a substance. As referred to herein, that substance is the atmosphere. When the atmosphere absorbs energy, the result is an irreversible transformation of radiation into another form of energy. The FPA is an image sensing device consisting of an array (typically rectangular) of light-sensing pixels at the focal plane of a lens. FPAs are used most commonly for imaging purposes (e.g., taking pictures or video imagery), but may also be used for non-imaging purposes such as spectrometry, lidar, and wave-front sensing.

[0005] Range to target is commonly determined by measuring a time between laser emission from a system, and from system measurement of laser light scattered from a target. Time of flight measurements typically require high bandwidth detectors and supporting electronics to precisely measure the time at which a signal was received by the detector. High accuracy measurements also typically require short laser pulses. Unfortunately, such high precision electronics result in high-cost designs to achieve working LADAR solutions.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] The accompanying drawings provide visual representations which will be used to more fully describe various representative embodiments and can be used by those skilled in the art to better understand the representative embodiments disclosed and their inherent advantages. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the devices, systems, and methods described herein. In these drawings, like reference numerals may identify corresponding elements.

[0007] FIG. 1 is a schematic diagram of a differential atmospheric absorption analysis system, in accordance with embodiments of the disclosure;

[0008] FIG. 2 is a graph of exemplary wavelengths employed to analyze differential absorption for an H₂O (water) absorption line, in accordance with embodiments of the disclosure;

[0009] FIG. 3A is a graph of exemplary differential absorption for a 950 nm H₂O absorption line;

[0010] FIG. 3B is a graph of exemplary spectral signal ratios as a function of range for a 950 nm H₂O absorption line;

[0011] FIG. 3C is a graph of exemplary range resolution as a function of range for a 950 nm H₂O absorption line;

[0012] FIG. 4A is a graph of exemplary differential absorption for a 763 nm O₂ absorption line;

[0013] FIG. 4B is a graph of exemplary spectral signal ratios as a function of range for a 763 nm O₂ absorption line;

[0014] FIG. 4C is a graph of exemplary range resolution as a function of range for a 763 nm O₂ absorption line;

[0015] FIG. 5 is a schematic diagram of a target scattered signal variation analysis system, in accordance with embodiments of the disclosure;

[0016] FIG. 6A is a graph of exemplary sensor separation/sensitivity as a function of range resolution;

[0017] FIG. 6B is a graph of exemplary sensor signal ratios as a function of range;

[0018] FIG. 6C is a graph of exemplary range dependence on ratio gamma; and

[0019] FIG. 7 is a schematic block diagram of a three-dimensional (3-D) imaging system (DCDS), in accordance with embodiments of the disclosure.

DETAILED DESCRIPTION

[0020] Specific embodiments of the disclosure will now be described in detail with reference to the accompanying figures. While this disclosure is susceptible of being embodied in many different forms, there is shown in the drawings and will herein be described in detail specific embodiments, with the understanding that the present disclosure is to be considered as an example of the principles of the described and not intended to limit the disclosure to the specific embodiments shown and described. In the description below, like reference numerals may be used to describe the same, similar or corresponding parts in the several views of the drawings.

[0021] The present disclosure relates generally to systems and associated methods of three-dimensional (3-D) imaging enabled by natural range-dependent processes. In certain embodiments, the present design enables the use of low-cost camera FPA instead of expensive high-speed detector arrays normally employed in conventional LADAR solutions. The technique may be advantageously employed and adapted in

various solutions requiring 3-D imaging, such as machine vision for autonomous vehicles and potentially for gaming.

[0022] One embodiment of the present disclosure may advantageously exploit differential absorption in the atmosphere.

[0023] The atmosphere comprises elements and compounds that may include, inter alia, oxygen (O_2), nitrogen (N_2), carbon monoxide (CO), carbon dioxide (CO_2), water (H_2O), and other atmospheric gas or gases. These elements and compounds may provide a laser transmission medium for the lasers described herein. The above-mentioned group of elements and compounds may be selected from for analysis.

[0024] Another embodiment of the present disclosure may exploit a differential in measured intensity from a scattering object. Embodiments may leverage the natural range-dependent processes associated with the transmission of a laser beam to a target and the resulting measured signal recorded at a sensor receiver. These embodiments may each comprise simple, low cost 3-D imaging architectures that may be advantageously employed together or separately.

[0025] Referring now to FIG. 1, one embodiment of a 3-D imaging system **100** that advantageously exploits differential absorption in the atmosphere is described in detail. For example, and without limitation, the system **100** may be composed of two lasers **115**, **125**, one focal plane array (FPA) **135**, an imaging lens **155**, a scene to be imaged (also referred to herein as a target) **145**, and scattered light rays **146**.

[0026] The FPA **135** need not be high bandwidth but instead may be a relatively low-bandwidth detector (e.g., low-bandwidth detector frame rates, such as those of a camera, may suffice). Bandwidth describes the width of a wavelength range with regard to a specific part of the spectrum which transmits incident energy via a filter. Bandwidth may be used to determine the resolution of spectrometers, spectral width of optical communication sources and duration of pulse waveforms. With respect to LADAR detectors, bandwidth typically refers to the frequency content of signals that such a detector is capable of faithfully reproducing. For example, given an optical signal characterized by a sinusoidal variation in time, the detector must have a bandwidth greater than the sine frequency in order to reproduce that sine wave. The higher the bandwidth, the greater the temporal or range resolution a LADAR system may have. In this example, a low bandwidth FPA means that the FPA pixels cannot faithfully reproduce the time variation of the incident optical signal. Instead, such a low bandwidth FPA sums all the incident energy and loses most of the temporal information. The temporal resolution of the FPA is ultimately limited by the frame rate which is typically tens to hundreds of frames per second. In certain embodiments of the present design, the relatively low-bandwidth is typically below 35 megabytes per second.

[0027] The lasers **115**, **125** may be positioned substantially equidistant from a target object of interest **145** (also referred to herein as a scene) and configured to emit two very closely spaced wavelengths, such that one wavelength is resonant with an atmospheric absorption line defined between the lasers **115**, **125** and the scene **145** and such that the other wavelength is just off the absorption line so that this latter wavelength does not suffer absorption. More specifically, the two wavelengths produced by the cooperating lasers **115**, **125** may be considered “closely spaced” in that the two

wavelengths are far apart enough such that their respective atmospheric transmissions are quite different but also such that their target reflectivities are quite similar.

[0028] By way of definition, atmospheric transmission describes how radiation propagates through an atmosphere, such as the earth’s atmosphere. Bands, or ranges, of transmission or propagation (atmospheric transmission bands) are used to describe the radiation reflective and absorption properties. The atmospheric transmission band describes the capacity of the atmosphere to transmit electromagnetic energy. In the case of the earth’s atmosphere, this atmospheric transmittance is dependent on the air mass penetrated by rays, as well as on the amount of water vapor and dust in the air. A high atmospheric transmission band has a higher rate of transmittance than a low atmospheric transmission band. The term high and low in this instance are relative to one another such that a relatively low atmospheric transmission band is less than a relatively high atmospheric transmission band.

[0029] In certain embodiments, the 3-D imaging system **100** of the present design may receive and use a first wavelength A_a that is in a relatively low atmospheric transmission band and a second wavelength A_b that is in a relatively high atmospheric transmission band. In other embodiments, the 3-D imaging system **100** of the present design may receive and use a first wavelength λ_a that is in a relatively high atmospheric transmission band and a second wavelength λ_b that is in a relatively low atmospheric transmission band.

[0030] The terms “relatively high . . .” and “relatively low . . .” mean that the higher value exceeds the lower value. Because these are relative terms, no specific values impact this disclosure. However, because these quantities are relative to each other, it is an embodiment of the present design that the first wavelength λ_a and the second wavelength λ_b may differ by approximately less than 0.015 micrometer (μm), while a respective reflectivity of the first wavelength λ_a and of the second wavelength λ_b may be approximately similar.

[0031] Indeed, the first wavelength λ_a and the second wavelength λ_b are of a relatively laser pulse type. This short laser pulse may be characterized by a pulse width (also referred to as pulse duration) that is less than 100 ms and typically less than 10 ms. In certain embodiments of the present design, for example, and without limitation, relevant laser pulse widths may be less than 10 ms while round trip laser transit times (e.g., from sensor to target and back to sensor) may depend on range to target and approach ~ 6.7 ns/m.

[0032] For example, and without limitation, the first laser **115** may emit the non-resonant wavelength to flash illuminate the scene, or target, **145** such that the scene, or target, **145** may be imaged onto the FPA **135**. The second laser **125** may emit the resonant wavelength to similarly flash illuminate the scene, or target, **145** such that the scene, or target, **145** may be imaged by the FPA **135**. For the first laser **115**, a first recorded intensity on each pixel of the FPA **135** may be a function of range to target and target reflectivity. For the second laser **125**, a second recorded intensity may be a function of range, target reflectivity, and atmospheric absorption (which is also a function of range).

[0033] The ratio of the first and second recorded intensities is a function of the atmospheric absorption and, therefore, range. Knowing the atmospheric absorption at the two

laser wavelengths, the system **100** may estimate the range to target from the ratio of the two measured intensities.

[0034] The ratio of two intensities the first intensity S_a and the second intensity S_b is defined as follows:

$$\frac{S_a}{S_b} = e^{-2R(\alpha(Ja) - \alpha(Jb))},$$

where α denotes an atmospheric absorption and scattering attenuation factor for the absorption line, and where R denotes the range.

[0035] The above equation is useful to measure, using the focal plane array, a first intensity S_a , of the first backscatter signal and a second intensity S_b of the second backscatter signal and determining, using the focal plane array, a range to the target from a ratio of the first intensity S_a , and the second intensity S_b .

[0036] Continuing to refer to FIG. 1, a range-to-target determination method may comprise analysis of round-trip atmospheric absorption as follows: $A(R) = e^{-2R\alpha}$ where R denotes range to target and α denotes the atmospheric absorption and scattering attenuation factor. For example, and without limitation, $S1_i$ may represent a first signal measured at pixel i when the scene **145** is illuminated by the first laser **115** which has a wavelength non-resonant with an atmospheric absorption line. Also, $S2_i$ may represent a second signal measured at pixel i when the scene **145** is illuminated by the second laser **125** which has a wavelength resonant with the atmospheric absorption line.

[0037] Absorption is the process by which incident radiant energy is retained by a substance. In this case, the substance is the atmosphere. When the atmosphere absorbs energy, the result is an irreversible transformation of radiation into another form of energy.

[0038] The ratio of $S1_i/S2_i$ is given by

$$\frac{S1_i}{S2_i} = e^{-2R(\alpha(J1) - \alpha(J2))}.$$

By measuring this ratio with a standard FPA **135** and knowing α at each wavelength, the system **100** may estimate, or determine, the R resolution dependence on $\frac{S1_i}{S2_i}$ (e.g., the signal ratio) in the following:

$$\frac{d\left(\frac{S1_i}{S2_i}\right)}{dR} = -2(\alpha(A1) - \alpha(A2))e^{-2R(\alpha(J1) - \alpha(J2))}$$

[0039] More specifically, the ratio above allows simplification, leaving a simple expression dependent on α and R (i.e., because the wavelengths are so close, the ratio cancels out the reflectivity dependence). The system **100** may determine $\alpha(\lambda_1)$ and $\alpha(\lambda_2)$ based on meteorological conditions, and then calculate the range R .

[0040] Referring now to FIG. 2, the chart **300** illustrates a portion of the non-infrared (NIR) atmospheric window transmission for an H_2O absorption line. As shown in chart **300**, more specifically, the sharp dip in transmission at a wavelength of approximately $1.135 \mu m$ corresponds to a water absorption line. The highlighted upper dot **315** indicates a first wavelength along a range of wavelengths **320**

that is not resonant with the atmospheric absorption line (i.e., characterized by a high transmission percentage **310**). The highlighted lower dot **325** shows a second wavelength along the range of wavelengths **320** that is resonant with the H_2O absorption line (i.e., characterized by a low transmission percentage **310**).

[0041] Operating the present design using an H_2O absorption line may lead to complications as absorption may vary with humidity. A humidity measurement device and/or real-time National Oceanic and Atmospheric Administration (NOAA) meteorological humidity data may be employed to remove this variation. Alternatively, operating the present design using a more stable gas absorption line (e.g., oxygen (O_2), nitrogen (N_2), carbon monoxide (CO), carbon dioxide (CO_2)) may alleviate the complication of absorption variability.

[0042] For example, and without limitation, the present design may operate along a 950 nanometer (nm) H_2O absorption line. Graph **400** at FIG. 3A illustrates spectral transmittance **402** as a function of wavelength **404**. Similar to the phenomenon shown in chart **300** of FIG. 2, the water absorption line of FIG. 3A appears as a sharp dip in transmission at a wavelength of approximately 950 nm. Graph **410** at FIG. 3B illustrates a ratio of spectral signals **412** emitted from two lasers as a function of range R **414**, as shown by line **416**.

[0043] Graph **420** at FIG. 3C illustrates, as shown by lines **426** and **427**, the range resolution **422** inherent to an H_2O absorption line, which manifests as the dramatic divergence, as a function of range R **424**, of the plotted lines due to atmospheric absorption and scattering attenuation. Line **426** shows δ_n of 0.1% and line **427** shows δ_n of 1.0%, which represent two cases where the minimum ratio that may be measured is 0.1% and 1% (illustrating how the R resolution depends on the ability of a relatively low-bandwidth detector to measure small differences in signal intensity).

[0044] Also for example, and without limitation, consider the present design operating along a 763 nanometer (nm) O_2 absorption line. Graph **500** at FIG. 4A illustrates spectral transmittance **502** as a function of wavelength **504**. Similar to the phenomenon shown in chart **300** of FIG. 2, the water absorption line of FIG. 4A appears as a sharp dip in transmission at a wavelength of approximately 763 nm.

[0045] Graph **510** at FIG. 4B illustrates a ratio of spectral signals **512** emitted from two lasers as a function of range R **514**, as shown by line **516**.

[0046] Graph **520** at FIG. 4C illustrates the range resolution **522** inherent to an O_2 absorption line, which does not suffer as dramatic a divergence, as a function of range R **524**, of the plotted lines **517** and **518** due to atmospheric absorption and scattering attenuation as did the H_2O absorption line. More specifically, in the two cases shown **517**, **518**, the minimum ratio that may be measured remains a relatively constant 1% and between 5% and 6%.

[0047] Referring now to FIG. 5, a 3-D imaging system **600** that advantageously exploits target scattered signal variation with range will now be discussed in detail. For example, and without limitation, the system **600** may be composed of a single laser, or alternative light source, such as solar illumination, or a single solar illuminator, and two sensors **615**, **625**. Sensor **1 615** has an associated field of view (FOV1) **635**. Sensor **2 625** has an associated field of view (FOV2) **655**. Targets may be specular or non-specular.

[0048] Specular targets typically exhibit specular reflection, also known as regular reflection, which is the mirror-like reflection of waves, such as light, from a surface. The law of reflection states that for each incident ray the angle of incidence equals the angle of reflection, and the incident, normal, and reflected directions are coplanar. In contrast, a non-specular target exhibits non-specular wave reflection of light or sound from rough surfaces, resulting in scattering of wave components. Non-specular reflection is also known as diffuse reflection.

[0049] When a non-specular target **610** is illuminated by the light source, such as illuminator or solar illuminator, the incident light is scattered into a hemisphere and the signal has a change rate that changes with range according to the function $f(R)=R^{-2}$. Measurement of the scattered signal at two or more ranges may be used to estimate range and may also be used to estimate change rate. In the event the laser beam does not fully resolve, or overlap, the object the range dependent signal function will be $f(R)=R^{-4}$.

[0050] As illustrated in FIG. 5, the first active sensor **615** and the second active sensor **625** may be positioned such that these sensors **615**, **625** image the same field of view, as shown by the overlap of FOV1 **635** and FOV2 **655**, but are displaced from each other a distance **645**, denoted as o . Using sensors so deployed, a range-to-target determination method may comprise analysis of a signal measured at each pixel as follows:

$$S_{j,i}=f(R)A(R)Q(R)Dp$$

where $j=1,2$ depending on the sensor referenced, and where i is the pixel.

[0051] Using a common wavelength in each sensor **615**, **625**, the ratio of measured intensity for a point in the scene $S_{1,i}$, $S_{2,i}$ may be determined

$$\frac{S_{1,i}}{S_{2,i}} = \frac{f(R+o)}{f(R)} = \frac{(R+o)^2}{R^2}.$$

The ratio of measured intensities $S_{1,i}$, $S_{2,i}$ may be used to estimate range for each pixel in the scene.

[0052] In an alternative embodiment, the present design may substitute for the two sensors **615**, **625** a single sensor that is moving. The single sensor may image a target scene from two positions along its vector (the displacement between these two positions serving as the distance o in the formulae above) and then may determine R as described above.

[0053] For example, and without limitation, consider the present design operating as shown in FIGS. 6A-6C.

[0054] Graph **800** at FIG. 6A illustrates resolution **802** as a function of range **804** for sensor separations of 1 meter and 2 meter, and for detector sensitivity enabling ratios as small as 1% and 0.1%. Line **806** shows δ equal to 1 meter and $\delta\gamma$ equal to 1%. Line **808** shows δ equal to 2 meters and $\delta\gamma$ equal to 1%. Line **807** shows δ equal to 1 meter and $\delta\gamma$ equal to 0.1%. Line **809** shows δ equal to 2 meters and $\delta\gamma$ equal to 0.1%.

[0055] Graph **810** at FIG. 6B illustrates a ratio of sensor signals **812** received as backscatter from a field of view (FOV) as a function of range R **814**. Backscatter is the reflection of waves, particles, or signals back to the direction from which they came. It is a diffuse reflection due to

scattering, as opposed to specular reflection as from a mirror. Line **816** shows δ equals 1 meter and line **818** shows δ equals 2 meters.

[0056] Graph **820** at FIG. 6C illustrates range $R(m)$ **822** determined as a function of the ratio of sensor signals (γ) **824**. Line **826** shows δ equals 1 meter and line **828** shows δ equals 2 meters.

[0057] FIG. 7 shows a system **900** that includes processing apparatus **902** that interfaces with a wide area network **930**. The apparatus **902** includes network interface **919**, processor **912** and data store **913**. Data store **913** includes subsystem module **920**, which includes absorption analysis subsystem **922**, scatter analysis subsystem **924** and API subsystem **926**.

[0058] Those skilled in the art will understand that the principles of the present disclosure may be implemented on or in data communication with any type of suitably arranged device or system configured to perform range analysis operations, in any combination. System **900** of the present design may comprise a processor **912** that may be operable to accept and execute computerized instructions, and also a data store **913** that may store data and instructions used by the processor **912**. The processor **912** may be in data communication with external computing resources, such as the wide area network (WAN) **930**, through a network interface **919**. Furthermore, the processor **912** may be configured to direct input received from components of the WAN **930** to the data store **913** for storage. Similarly, the processor **912** may be configured to retrieve data from the data store **913** to be forwarded as output to various components of the WAN **930**.

[0059] For example, and without limitation, the computerized instructions of the system **900** may be configured to implement absorption analysis subsystem **922** that may be stored in the data store **913** and retrieved by the processor **912** for execution. The absorption analysis subsystem **922** may be operable to determine range to a target object from differential absorption in the atmosphere as described above. Also, for example, and without limitation, the computerized instructions of the system **900** may be configured to implement a scatter analysis subsystem **924** that may be stored in the data store **913** and retrieved by the processor **912** for execution. The scatter analysis subsystem **924** may be operable to determine range to a target object from scattered signals intensities as described above. Also for example, and without limitation, the computerized instructions of the system **900** may be configured to implement Application Programming Interface (API) **926** that may be stored in the data store **913** and retrieved by the processor **912** for execution. The API subsystem **926** may be operable to forward computed range information for use by downstream applications.

[0060] Those skilled in the art will appreciate that the present disclosure contemplates the use of computer instructions and/or systems configurations that may perform any or all of the operations involved in 3-D imaging using LADAR. The disclosure of computer instructions that include absorption analysis subsystem **922** instructions, scatter analysis subsystem **924** instructions, and API subsystem **926** instructions is not meant to be limiting in any way. Those skilled in the art will readily appreciate that stored computer instructions and/or systems configurations may be configured in any way while still accomplishing the many goals, features and advantages according to the present disclosure.

[0061] It will be appreciated that the systems and methods described above are set forth by way of example and not of limitation. Absent an explicit indication to the contrary, the disclosed steps may be modified, supplemented, omitted, and/or re-ordered without departing from the scope of this disclosure. Numerous variations, additions, omissions, and other modifications will be apparent to one of ordinary skill in the art. In addition, the order or presentation of method steps in the description and drawings above is not intended to require this order of performing the recited steps unless a particular order is expressly required or otherwise clear from the context.

[0062] Embodiments disclosed herein may include computer program products comprising computer-executable code or computer-usable code that, when executing on one or more computing devices, performs any and/or all of the steps thereof. The code may be stored in a non-transitory fashion in a computer memory, which may be a memory from which the program executes (e.g., random-access memory associated with a processor), or a storage device such as a disk drive, flash memory or any other optical, electromagnetic, magnetic, infrared or other device or combination of devices. In another implementation, any of the systems and methods described above may be embodied in any suitable transmission or propagation medium carrying computer-executable code and/or any inputs or outputs from same.

1-20. (canceled)

21. A three-dimensional (3-D) imaging system for determining range to a target and comprising:

- a light source configured to illuminate a non-specular target with a wavelength λ characterized by a reflectivity from the non-specular target;
- a first active sensor adapted to receive a first backscatter signal associated with the wavelength λ ;
- a second active sensor adapted to receive a second backscatter signal associated with the wavelength λ , the first active sensor adapted to measure a first intensity $S_{1,i}$ of the first backscatter signal and the second active sensor adapted to measure a second intensity $S_{2,i}$ of the second backscatter signal; and
- a focal plane array adapted to determine a range to the target from a ratio of the first intensity $S_{1,i}$ and the second intensity $S_{2,i}$.

22. The 3-D imaging system according to claim 21, where the light source comprises one of a laser and a solar illuminator.

23. The 3-D imaging system according to claim 21, where the ratio of the first intensity $S_{1,i}$ and the second intensity $S_{2,i}$ is defined as

$$S_{1,i}/S_{2,i} = f(R+\delta)/f(R) = (R+\delta)^2/R^2$$

where δ denotes a distance between the first active sensor and the second active sensor; and

where R denotes the range.

24. The 3-D imaging system according to claim 21, where the first backscatter signal and the second backscatter signal are characterized by a change rate of $f(R)=R^{-2}$.

25. A three-dimensional (3-D) imaging system for determining range to a target and comprising:

- a light source configured to illuminate a non-specular target with a wavelength λ characterized by a reflectivity from the non-specular target;

a movable active sensor adapted to receive a backscatter signal associated with the wavelength λ ;

the first active sensor adapted to measure a first intensity $S_{1,i}$ of a first backscatter signal at a first position and to measure a second intensity $S_{2,i}$ of a second backscatter signal at a second position; and

a focal plane array adapted to determine a range to the target from a ratio of the first intensity $S_{1,i}$ and the second intensity $S_{2,i}$.

26. The 3-D imaging system according to claim 25, where the light source comprises one of a laser and a solar illuminator and the ratio of the first intensity $S_{1,i}$ and the second intensity $S_{2,i}$ is defined as

$$S_{1,i}/S_{2,i} = f(R+\delta)/f(R) = (R+\delta)^2/R^2$$

where δ denotes a distance between the first active sensor and the second active sensor; and

where R denotes the range.

27. The 3-D imaging system according to claim 25, where the first backscatter signal and the second backscatter signal are characterized by a change rate of $f(R)=R^{-2}$.

28. The 3-D imaging system according to claim 25 adapted to measure a first intensity S_a associated with the first backscatter signal and measure a second intensity S_b associated with the second backscatter signal; and

determine, independent of reflectivity, a range to the target from a ratio of the first intensity S_a and the second intensity S_b , the ratio of the first intensity S_a and the second intensity S_b is defined as $S_a/S_b = e^{-2R(\alpha(\lambda_a) - \alpha(\lambda_b))}$;

where α denotes an atmospheric absorption and scattering attenuation factor for the absorption line; and

where R denotes the range;

where a respective reflectivity of the first wavelength λ_a and of the second wavelength λ_b are similar.

29. The 3-D imaging system according to claim 28, where the first wavelength λ_a is in a relatively low atmospheric transmission band and the second wavelength λ_b is in a relatively high atmospheric transmission band, whereby the second wavelength transmission band is greater than the first wavelength transmission band.

30. The 3-D imaging system according to claim 28, where the first wavelength λ_a is in a relatively high atmospheric transmission band and the second wavelength λ_b is in a relatively low atmospheric transmission band, whereby the first wavelength transmission band is greater than the second wavelength transmission band.

31. The 3-D imaging system according to claim 29, where the first wavelength λ_a and the second wavelength λ_b differ by less than 0.015 micrometer (μm).

32. The 3-D imaging system according to claim 30, where the first wavelength λ_a and the second wavelength λ_b differ by less than 0.015 micrometer (μm).

33. The 3-D imaging system according to claim 28, where the first wavelength λ_a and the second wavelength λ_b have a pulse duration less than 10 ms.

34. A three-dimensional (3-D) imaging system for determining range to a specular target and comprising:

- a light source configured to illuminate a specular target with a wavelength λ characterized by a reflectivity from the specular target;
- a first active sensor adapted to receive a first regular reflection associated with the wavelength λ ;

a second active sensor adapted to receive a second regular reflection associated with the wavelength 1, the first active sensor adapted to measure a first intensity $S_{1,i}$ of the first regular reflection and the second active sensor adapted to measure a second intensity $S_{2,i}$ of the second regular reflection; and

a focal plane array adapted to determine a range to the target from a ratio of the first intensity $S_{1,i}$ and the second intensity $S_{2,i}$.

35. The 3-D imaging system according to claim **34** where the ratio of the first intensity $S_{1,i}$ and the second intensity $S_{2,i}$ is defined as

$$S_{1,i}/S_{2,i} = f(R+\delta)/f(R) = (R+\delta)^2/R^2$$

1 where δ denotes a distance between the first active sensor and the second active sensor; and

where R denotes the range.

36. The 3-D imaging system according to claim **35**, where the first regular reflection and the second regular reflection are characterized by a change rate of $f(R)=R^{-2}$.

37. The 3-D imaging system according to claim **35** where the ratio of the first intensity S_a and the second intensity S_b is defined as

$$\frac{S_a}{S_b} = e^{-2R(\alpha(\lambda_a) - \alpha(\lambda_b))};$$

where α denotes an atmospheric absorption and scattering attenuation factor for the absorption line; and

where R denotes the range;

where a respective reflectivity of the first wavelength λ_a and of the second wavelength λ_b are similar.

38. The 3-D imaging system according to claim **37**, where the first wavelength λ_a and the second wavelength λ_b differ by less than 0.015 micrometer (μm).

39. The 3-D imaging system according to claim **38**, where the first wavelength λ_a and the second wavelength λ_b have a pulse duration less than 10 ms.

40. The 3-D imaging system according to claim **25**, where the first regular reflection and the second regular reflection are characterized by a change rate of $f(R)=R^{-2}$.

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