(51) International Patent Classification:
H01P 3/00 (2006.01) H02J 17/00 (2006.01)
H01Q 1/00 (2006.01) H04B 5/00 (2006.01)

(21) International Application Number:
PCT/US2015/049497

(22) International Filing Date:
10 September 2015 (10.09.2015)

(25) Filing Language:
English

(26) Publication Language:
English

(30) Priority Data:
14/874,821 8 September 2015 (08.09.2015) US

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(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, EE,

(54) Title: GUIDED SURFACE WAVE POWERED SENSING DEVICES

(57) Abstract: Disclosed is a sensing device including a guided surface wave receive structure, a physical parameter sensor, and a radio frequency transmitter. The guided surface wave receive structure may be configured to obtain electrical energy from a guided surface wave traveling along a terrestrial medium. The physical parameter sensor may be coupled to the guided surface wave receive structure. The physical parameter sensor may also measure a physical parameter associated with a physical environment local to the physical parameter sensor. The radio frequency transmitter may be coupled to the guided surface wave receive structure and communicatively coupled to the physical parameter sensor. The radio frequency transmitter may also obtain a physical parameter measurement and transmit the physical parameter measurement over a wireless network.

FIG. 21

Declarations under Rule 4.17:

— as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(H))

Published:

— as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.1(?in))

— with international search report (Art. 21(3))
GUIDED SURFACE WAVE POWERED SENSING DEVICES

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of, and priority to, co-pending U.S. Provisional Patent Application No. 62/049,169 entitled "GUIDED SURFACE WAVE POWERED DEVICES" filed on 9/1 1/2014, which is incorporated herein by reference in its entirety.

[0002] This application claims the benefit of, and priority to, co-pending U.S. Patent Application No. 14/847,821 entitled "GUIDED SURFACE WAVE POWERED SENSING DEVICES" filed on 9/8/2015, which is incorporated herein by reference in its entirety.

[0003] This application is related to co-pending U.S. Non-provisional Patent Application entitled "Excitation and Use of Guided Surface Wave Modes on Lossy Media," which was filed on March 7, 2013 and assigned Application Number 13/789,538, and was published on September 11, 2014 as Publication Number US2014/0252886 A1, and which is incorporated herein by reference in its entirety. This application is also related to co-pending U.S. Non-provisional Patent Application entitled "Excitation and Use of Guided Surface Wave Modes on Lossy Media," which was filed on March 7, 2013 and assigned Application Number 13/789,525, and was published on September 11, 2014 as Publication Number US2014/0252865 A1, and which is incorporated herein by reference in its entirety. This application is further related to co-pending U.S. Non-provisional Patent Application entitled "Excitation and Use of Guided Surface Wave Modes on Lossy Media," which was filed on September 10, 2014 and assigned Application Number 14/483,089, and which is incorporated herein by reference in its entirety. This application is further related to
co-pending U.S. Non-provisional Patent Application entitled "Excitation and Use of Guided Surface Waves," which was filed on June 2, 2015 and assigned Application Number 14/728,507, and which is incorporated herein by reference in its entirety. This application is further related to co-pending U.S. Non-provisional Patent Application entitled "Excitation and Use of Guided Surface Waves," which was filed on June 2, 2015 and assigned Application Number 14/728,492, and which is incorporated herein by reference in its entirety.

BACKGROUND

[0004] Various properties associated with the world around us are constantly measured by sensing devices. Numerous properties of weather are continuously measured, and weather is predicted based on these observations. Measurements of ocean waves and currents may be used to warn ships of impending problems. The movement over time of a glacier or volcano can be measured by sensors. However, it can be difficult to provide power to these sensing devices, especially when the sensing device is not near a power source. Even when power is readily available, running electrical wires to a sensing device may negatively affect the integrity of the measurement. Further, when powering sensing devices using a battery, features may be severely limited to prolong the life of the battery. For example, capturing real-time video may be impractical using a battery powered sensing device.

SUMMARY

[0005] Embodiments of the present disclosure are related to powering devices and sensing devices using guided surface waves. According to various
embodiments, an apparatus is provided that comprises a guided surface wave receive structure configured to obtain electrical energy from a guided surface wave traveling along a terrestrial medium. A physical parameter sensor coupled to the guided surface wave receive structure, the physical parameter sensor being configured to measure a physical parameter associated with a physical environment local to the physical parameter sensor. A radio frequency transmitter is coupled to the guided surface wave receive structure and communicatively coupled to the physical parameter sensor, the radio frequency transmitter configured to obtain a physical parameter measurement and transmit the physical parameter measurement over a wireless network.

[0006] According to various embodiments, the physical parameter sensor and radio frequency transmitter are experienced as a load at an excitation source coupled to a guided surface waveguide probe generating the guided surface wave.

[0007] According to various embodiments, the guided surface wave receive structures described herein may comprise a charge terminal elevated over a lossy conducting medium, and a receiver network coupled between the charge terminal and the lossy conducting medium, the receiver network having a phase delay ($\Phi$) that matches a wave tilt angle ($\Psi$) associated with the guided surface wave, the wave tilt angle ($\Psi$) based at least in part upon characteristics of the lossy conducting medium in a vicinity of the receiving structure.

[0008] According to various embodiments, the guided surface wave receive structures described herein may comprise at least one of a magnetic coil, a linear probe, or a tuned resonator.

[0009] In the various embodiments, a computing device is communicably coupled to a guided surface wave receive structure and connected to a physical
parameter sensor and a radio frequency transmitter. The computing device is configured to obtain the physical parameter measurement from the physical parameter sensor, to form a message containing the physical parameter measurements, and to transmit the message via the radio frequency transmitter. According to the various embodiments, the computing device described herein is experienced as a load at an excitation source coupled to a guided surface waveguide probe generating the guided surface wave.

[0010] According to the various embodiments, the physical parameter sensors described herein are configured to measure at least one of light, temperature, moisture, quantity of rain, quantity of snow, presence of rain, presence of snow, humidity levels, wind speed, wind direction, cloud height, wave height, heart rate, blood pressure, location, or presence of a substance.

[0011] According to the various embodiments, a power circuit is coupled to the guided surface wave receive structure, the power circuit comprising a power rectifier and a capacitor.

[0012] According to the various embodiments, a power circuit is coupled to the guided surface wave receive structure, the power circuit comprising a battery.

[0013] According to various embodiments, a guided surface waveguide probe is provide that is configured to transmit a guided surface wave traveling along a terrestrial medium. A sensing device comprising a guided surface wave receive structure is coupled to an electrical load, the guided surface wave receive structure being configured to obtain electrical energy from the guided surface wave and the electrical load being experienced as a load at an excitation source coupled to a guided surface waveguide probe generating the guided surface wave. According to various embodiments, the electrical load comprises a physical parameter sensor
configured to measure a physical parameter associated with a physical environment local to the physical parameter sensor, and a radio frequency transmitter communicatively coupled to the physical parameter sensor, the radio frequency transmitter configured to transmit a physical parameter measurement over a wireless network.

[0014] According to the various embodiments, embodiments of the electrical load further comprise a computing device communicably connected to the physical parameter sensor and the radio frequency transmitter, the computing device configured to obtain the physical parameter measurement from the physical parameter sensor, to form a message containing the physical parameter measurements, and to cause the radio frequency transmitter to transmit the message.

[0015] According to the various embodiments, the physical parameter sensors described herein are further configured to measure at least one of light, temperature, moisture, quantity of rain, quantity of snow, presence of rain, presence of snow, humidity levels, wind speed, wind direction, cloud height, wave height, heart rate, blood pressure, location, or presence of a substance.

[0016] According to the various embodiments, the guided surface waveguide probe may comprise a charge terminal elevated over a lossy conducting medium configured to generate at least one resultant field that synthesizes a wave front incident at a complex Brewster angle of incidence $\left( \theta_{\text{B}} \right)$ of the lossy conducting medium. According to various embodiments, the charge terminal may comprise one of a plurality of charge terminals.

[0017] According to the various embodiments, a feed network is electrically coupled to the charge terminal of a guided surface waveguide probe, the feed
network providing a phase delay (Φ) that matches a wave tilt angle (Ψ) associated with a complex Brewster angle of incidence (θ_r) associated with the lossy conducting medium in the vicinity of the guided surface waveguide probe.

[0018] According to the various embodiments, a method is provided comprising the steps of receiving electrical energy as a guided surface wave using a guided surface wave receive structure; supplying the electrical energy to an electrical load coupled to the guided surface wave receive structure, the electrical load comprising a location triangulation circuit and a radio frequency transmitter, where the location triangulation circuit is communicably coupled to the radio frequency transmitter; receiving a plurality of radio transmissions in the location triangulation circuit from at least three sources; and determining a location of a location device in the location triangulation circuit based at least in part on the plurality of radio transmissions.

[0019] According to the various embodiments, the method further comprises sending the location via at least one of the radio frequency transmitter or the guided surface wave receive structure. In various embodiments, one of the at least three sources comprises at least one of a GPS satellites or a positional RF transmitter.

[0020] According to the various embodiments, the method further comprises the steps of receiving orbital information of the at least three sources from a remote server via an internet connection, and initializing an identification of the location of the location device based in part on the orbital information of the at least three sources.

[0021] According to the various embodiments, the orbital information comprises emphemeris data, reference location data, and at least one reference time.

[0022] Other systems, methods, features, and advantages of the present disclosure will be or become apparent to one with skill in the art upon examination of the following drawings.
and detailed description. It is intended that all such additional systems, methods, features, and advantages be included within this description, be within the scope of the present disclosure, and be protected by the accompanying claims.

[0023] In addition, all optional and preferred features and modifications of the described embodiments are usable in all aspects of the disclosure taught herein. Furthermore, the individual features of the dependent claims, as well as all optional and preferred features and modifications of the described embodiments are combinable and interchangeable with one another.

BRIEF DESCRIPTION OF THE DRAWINGS

[0024] Many aspects of the present disclosure can be better understood with reference to the following drawings. The components in the drawings are not necessarily to scale, emphasis instead being placed upon clearly illustrating the principles of the disclosure. Moreover, in the drawings, like reference numerals designate corresponding parts throughout the several views.

[0025] FIG. 1 is a chart that depicts field strength as a function of distance for a guided electromagnetic field and a radiated electromagnetic field.

[0026] FIG. 2 is a drawing that illustrates a propagation interface with two regions employed for transmission of a guided surface wave according to various embodiments of the present disclosure.

[0027] FIG. 3 is a drawing that illustrates a guided surface waveguide probe disposed with respect to a propagation interface of FIG. 2 according to various embodiments of the present disclosure.

[0028] FIG. 4 is a plot of an example of the magnitudes of close-in and far-out asymptotes of first order Hankel functions according to various embodiments of the present disclosure.
[0029] FIGS. 5A and 5B are drawings that illustrate a complex angle of incidence of an electric field synthesized by a guided surface waveguide probe according to various embodiments of the present disclosure.

[0030] FIG. 6 is a graphical representation illustrating the effect of elevation of a charge terminal on the location where the electric field of FIG. 5A intersects with the lossy conducting medium at a Brewster angle according to various embodiments of the present disclosure.

[0031] FIG. 7 is a graphical representation of an example of a guided surface waveguide probe according to various embodiments of the present disclosure.

[0032] FIGS. 8A through 8C are graphical representations illustrating examples of equivalent image plane models of the guided surface waveguide probe of FIGS. 3 and 7 according to various embodiments of the present disclosure.

[0033] FIGS. 9A and 9B are graphical representations illustrating examples of single-wire transmission line and classic transmission line models of the equivalent image plane models of FIGS. 8B and 8C according to various embodiments of the present disclosure.

[0034] FIG. 10 is a flow chart illustrating an example of adjusting a guided surface waveguide probe of FIGS. 3 and 7 to launch a guided surface wave along the surface of a lossy conducting medium according to various embodiments of the present disclosure.

[0035] FIG. 11 is a plot illustrating an example of the relationship between a wave tilt angle and the phase delay of a guided surface waveguide probe of FIGS. 3 and 7 according to various embodiments of the present disclosure.

[0036] FIG. 12 is a drawing that illustrates an example of a guided surface waveguide probe according to various embodiments of the present disclosure.
[0037] FIG. 13 is a graphical representation illustrating the incidence of a synthesized electric field at a complex Brewster angle to match the guided surface waveguide mode at the Hankel crossover distance according to various embodiments of the present disclosure.

[0038] FIG. 14 is a graphical representation of an example of a guided surface waveguide probe of FIG. 12 according to various embodiments of the present disclosure.

[0039] FIG. 15A includes plots of an example of the imaginary and real parts of a phase delay ($\Phi_y$) of a charge terminal $T$ of a guided surface waveguide probe according to various embodiments of the present disclosure.

[0040] FIG. 15B is a schematic diagram of the guided surface waveguide probe of FIG. 14 according to various embodiments of the present disclosure.

[0041] FIG. 16 is a drawing that illustrates an example of a guided surface waveguide probe according to various embodiments of the present disclosure.

[0042] FIG. 17 is a graphical representation of an example of a guided surface waveguide probe of FIG. 16 according to various embodiments of the present disclosure.

[0043] FIGS. 18A through 18C depict examples of receiving structures that can be employed to receive energy transmitted in the form of a guided surface wave launched by a guided surface waveguide probe according to the various embodiments of the present disclosure.

[0044] FIG. 18D is a flow chart illustrating an example of adjusting a receiving structure according to various embodiments of the present disclosure.

[0045] FIG. 19 depicts an example of an additional receiving structure that can be employed to receive energy transmitted in the form of a guided surface wave
launched by a guided surface waveguide probe according to the various embodiments of the present disclosure.

[0046] FIGS. 20A through 20E depict examples of various schematic symbols according to various embodiments of the present disclosure.

[0047] FIG. 21 is an illustration of a networked environment according to various embodiments of the present disclosure.

[0048] FIGS. 22A through 22E depict various guided surface wave powered devices according to various embodiments of the present disclosure.

[0049] FIG. 23 is an illustration of a sensing device according to various embodiments of the present disclosure.

[0050] FIGS. 24A through 24C depict various sensing environments according to various embodiments of the present disclosure.

[0051] FIGS. 25 is a flowchart illustrating one example of functionality implemented as portions of an operation application executed in a computing environment of FIG. 21 according to various embodiments of the present disclosure.

[0052] FIG. 26 is a flowchart illustrating one example of functionality implemented as portions of an operation application executed in a computing environment of FIG. 21 according to various embodiments of the present disclosure.

[0053] FIG. 27 is a flowchart illustrating one example of functionality implemented as portions of an operation application executed in a computing environment of FIG. 21 according to various embodiments of the present disclosure.

[0054] FIG. 28 is a schematic block diagram that provides one example illustration of a computing environment employed in the networked environment of FIG. 21 according to various embodiments of the present disclosure.
**DETAILED DESCRIPTION**

[0055] To begin, some terminology shall be established to provide clarity in the discussion of concepts to follow. First, as contemplated herein, a formal distinction is drawn between *radiated* electromagnetic fields and *guided* electromagnetic fields.

[0056] As contemplated herein, a radiated electromagnetic field comprises electromagnetic energy that is emitted from a source structure in the form of waves that are not bound to a waveguide. For example, a radiated electromagnetic field is generally a field that leaves an electric structure such as an antenna and propagates through the atmosphere or other medium and is not bound to any waveguide structure. Once radiated electromagnetic waves leave an electric structure such as an antenna, they continue to propagate in the medium of propagation (such as air) independent of their source until they dissipate regardless of whether the source continues to operate. Once electromagnetic waves are radiated, they are not recoverable unless intercepted, and, if not intercepted, the energy inherent in the radiated electromagnetic waves is lost forever. Electrical structures such as antennas are designed to radiate electromagnetic fields by maximizing the ratio of the radiation resistance to the structure loss resistance. Radiated energy spreads out in space and is lost regardless of whether a receiver is present. The energy density of the radiated fields is a function of distance due to geometric spreading. Accordingly, the term "radiate" in all its forms as used herein refers to this form of electromagnetic propagation.

[0057] A guided electromagnetic field is a propagating electromagnetic wave whose energy is concentrated within or near boundaries between media having different electromagnetic properties. In this sense, a guided electromagnetic field is
one that is bound to a waveguide and may be characterized as being conveyed by the current flowing in the waveguide. If there is no load to receive and/or dissipate the energy conveyed in a guided electromagnetic wave, then no energy is lost except for that dissipated in the conductivity of the guiding medium. Stated another way, if there is no load for a guided electromagnetic wave, then no energy is consumed. Thus, a generator or other source generating a guided electromagnetic field does not deliver real power unless a resistive load is present. To this end, such a generator or other source essentially runs idle until a load is presented. This is akin to running a generator to generate a 60 Hertz electromagnetic wave that is transmitted over power lines where there is no electrical load. It should be noted that a guided electromagnetic field or wave is the equivalent to what is termed a "transmission line mode." This contrasts with radiated electromagnetic waves in which real power is supplied at all times in order to generate radiated waves. Unlike radiated electromagnetic waves, guided electromagnetic energy does not continue to propagate along a finite length waveguide after the energy source is turned off. Accordingly, the term "guide" in all its forms as used herein refers to this transmission mode of electromagnetic propagation.

[0058] Referring now to FIG. 1, shown is a graph 100 of field strength in decibels (dB) above an arbitrary reference in volts per meter as a function of distance in kilometers on a log-dB plot to further illustrate the distinction between radiated and guided electromagnetic fields. The graph 100 of FIG. 1 depicts a guided field strength curve 103 that shows the field strength of a guided electromagnetic field as a function of distance. This guided field strength curve 103 is essentially the same as a transmission line mode. Also, the graph 100 of FIG. 1 depicts a radiated field
strength curve 106 that shows the field strength of a radiated electromagnetic field as a function of distance.

[0059] Of interest are the shapes of the curves 103 and 106 for guided wave and for radiation propagation, respectively. The radiated field strength curve 106 falls off geometrically \(1/d\), where \(d\) is distance), which is depicted as a straight line on the log-log scale. The guided field strength curve 103, on the other hand, has a characteristic exponential decay of \(e^{-ad/Vd}\) and exhibits a distinctive knee 109 on the log-log scale. The guided field strength curve 103 and the radiated field strength curve 106 intersect at point 112, which occurs at a crossing distance. At distances less than the crossing distance at intersection point 112, the field strength of a guided electromagnetic field is significantly greater at most locations than the field strength of a radiated electromagnetic field. At distances greater than the crossing distance, the opposite is true. Thus, the guided and radiated field strength curves 103 and 106 further illustrate the fundamental propagation difference between guided and radiated electromagnetic fields. For an informal discussion of the difference between guided and radiated electromagnetic fields, reference is made to Milligan, T., Modern Antenna Design, McGraw-Hill, 1st Edition, 1985, pp.8-9, which is incorporated herein by reference in its entirety.

[0060] The distinction between radiated and guided electromagnetic waves, made above, is readily expressed formally and placed on a rigorous basis. That two such diverse solutions could emerge from one and the same linear partial differential equation, the wave equation, analytically follows from the boundary conditions imposed on the problem. The Green function for the wave equation, itself, contains the distinction between the nature of radiation and guided waves.
In empty space, the wave equation is a differential operator whose eigenfunctions possess a continuous spectrum of eigenvalues on the complex wave-number plane. This transverse electro-magnetic (TEM) field is called the radiation field, and those propagating fields are called "Hertzian waves." However, in the presence of a conducting boundary, the wave equation plus boundary conditions mathematically lead to a spectral representation of wave-numbers composed of a continuous spectrum plus a sum of discrete spectra. To this end, reference is made to Sommerfeld, A., "Uber die Ausbreitung der Wellen in der Drahtlosen Telegraphie," Annalen der Physik, Vol. 28, 1909, pp. 665-736. Also see Sommerfeld, A., "Problems of Radio," published as Chapter 6 in Partial Differential Equations in Physics - Lectures on Theoretical Physics: Volume VI, Academic Press, 1949, pp. 236-289, 295-296; Collin, R. E., "Hertzian Dipole Radiating Over a Lossy Earth or Sea: Some Early and Late 20th Century Controversies," IEEE Antennas and Propagation Magazine, Vol. 46, No. 2, April 2004, pp. 64-79; and Reich, H. J., Ordnung, P.F, Krauss, H.L., and Skalnik, J.G., Microwave Theory and Techniques, Van Nostrand, 1953, pp. 291-293, each of these references being incorporated herein by reference in its entirety.

The terms "ground wave" and "surface wave" identify two distinctly different physical propagation phenomena. A surface wave arises analytically from a distinct pole yielding a discrete component in the plane wave spectrum. See, e.g., "The Excitation of Plane Surface Waves" by Cullen, A.L., (Proceedings of the IEE (British), Vol. 101, Part IV, August 1954, pp. 225-235). In this context, a surface wave is considered to be a guided surface wave. The surface wave (in the Zenneck-Sommerfeld guided wave sense) is, physically and mathematically, not the same as the ground wave (in the Weyl-Norton-FCC sense) that is now so familiar from radio
broadcasting. These two propagation mechanisms arise from the excitation of different types of eigenvalue spectra (continuum or discrete) on the complex plane. The field strength of the guided surface wave decays exponentially with distance as illustrated by curve 103 of FIG. 1 (much like propagation in a lossy waveguide) and resembles propagation in a radial transmission line, as opposed to the classical Hertzian radiation of the ground wave, which propagates spherically, possesses a continuum of eigenvalues, falls off geometrically as illustrated by curve 106 of FIG. 1, and results from branch-cut integrals. As experimentally demonstrated by C.R. Burrows in "The Surface Wave in Radio Propagation over Plane Earth" (Proceedings of the IRE, Vol. 25, No. 2, February, 1937, pp. 219-229) and "The Surface Wave in Radio Transmission" (Bell Laboratories Record, Vol. 15, June 1937, pp. 321-324), vertical antennas radiate ground waves but do not launch guided surface waves.

To summarize the above, first, the continuous part of the wave-number eigenvalue spectrum, corresponding to branch-cut integrals, produces the radiation field, and second, the discrete spectra, and corresponding residue sum arising from the poles enclosed by the contour of integration, result in non-TEM traveling surface waves that are exponentially damped in the direction transverse to the propagation. Such surface waves are guided transmission line modes. For further explanation, reference is made to Friedman, B., Principles and Techniques of Applied Mathematics, Wiley, 1956, pp. pp. 214, 283-286, 290, 298-300.

In free space, antennas excite the continuum eigenvalues of the wave equation, which is a radiation field, where the outwardly propagating RF energy with $E_z$ and $H_\theta$ in-phase is lost forever. On the other hand, waveguide probes excite discrete eigenvalues, which results in transmission line propagation. See Collin, R. E., Field Theory of Guided Waves, McGraw-Hill, 1960, pp. 453, 474-477. While
such theoretical analyses have held out the hypothetical possibility of launching open surface guided waves over planar or spherical surfaces of lossy, homogeneous media, for more than a century no known structures in the engineering arts have existed for accomplishing this with any practical efficiency. Unfortunately, since it emerged in the early 1900's, the theoretical analysis set forth above has essentially remained a theory and there have been no known structures for practically accomplishing the launching of open surface guided waves over planar or spherical surfaces of lossy, homogeneous media.

[0065] According to the various embodiments of the present disclosure, various guided surface waveguide probes are described that are configured to excite electric fields that couple into a guided surface waveguide mode along the surface of a lossy conducting medium. Such guided electromagnetic fields are substantially mode-matched in magnitude and phase to a guided surface wave mode on the surface of the lossy conducting medium. Such a guided surface wave mode can also be termed a Zenneck waveguide mode. By virtue of the fact that the resultant fields excited by the guided surface waveguide probes described herein are substantially mode-matched to a guided surface waveguide mode on the surface of the lossy conducting medium, a guided electromagnetic field in the form of a guided surface wave is launched along the surface of the lossy conducting medium. According to one embodiment, the lossy conducting medium comprises a terrestrial medium such as the Earth.

[0066] Referring to FIG. 2, shown is a propagation interface that provides for an examination of the boundary value solutions to Maxwell's equations derived in 1907 by Jonathan Zenneck as set forth in his paper Zenneck, J., "On the Propagation of Plane Electromagnetic Waves Along a Flat Conducting Surface and their Relation to
Wireless Telegraphy," Annalen der Physik, Serial 4, Vol. 23, September 20, 1907, pp. 846-866. FIG. 2 depicts cylindrical coordinates for radially propagating waves along the interface between a lossy conducting medium specified as Region 1 and an insulator specified as Region 2. Region 1 can comprise, for example, any lossy conducting medium. In one example, such a lossy conducting medium can comprise a terrestrial medium such as the Earth or other medium. Region 2 is a second medium that shares a boundary interface with Region 1 and has different constitutive parameters relative to Region 1. Region 2 can comprise, for example, any insulator such as the atmosphere or other medium. The reflection coefficient for such a boundary interface goes to zero only for incidence at a complex Brewster angle. See Stratton, J.A., Electromagnetic Theory, McGraw-Hill, 1941, p. 516.

[0067] According to various embodiments, the present disclosure sets forth various guided surface waveguide probes that generate electromagnetic fields that are substantially mode-matched to a guided surface waveguide mode on the surface of the lossy conducting medium comprising Region 1. According to various embodiments, such electromagnetic fields substantially synthesize a wave front incident at a complex Brewster angle of the lossy conducting medium that can result in zero reflection.

[0068] To explain further, in Region 2, where an $e^{j\omega t}$ field variation is assumed and where $\rho \neq 0$ and $z \geq 0$ (with $z$ being the vertical coordinate normal to the surface of Region 1, and $\rho$ being the radial dimension in cylindrical coordinates), Zenneck's closed-form exact solution of Maxwell's equations satisfying the boundary conditions along the interface are expressed by the following electric field and magnetic field components:

$$H_{z\phi} = Ae^{\mp z} H_1^{(2)}(-j\rho \rho),$$

(1)
\[ E_{2\rho} = A \left( \frac{u}{j\omega \varepsilon_0} \right) e^{-u_2 z} H_1^{(2)}(-j\gamma \rho), \] and
\[ E_{2z} = A \left( \frac{-\gamma}{\omega \varepsilon_0} \right) e^{-u_2 z} H_0^{(2)}(-j\gamma \rho). \] (2)

[0069] In Region 1, where the \( \varepsilon^{\text{tot}} \) field variation is assumed and where \( p \neq 0 \) and \( z < 0 \), Zenneck's closed-form exact solution of Maxwell's equations satisfying the boundary conditions along the interface is expressed by the following electric field and magnetic field components:

\[ H_{1\phi} = Ae^{u_1 z} H_1^{(2)}(-j\gamma \rho), \] (4)

\[ E_{1\rho} = A \left( \frac{-u_1}{\sigma_1 + j\omega \varepsilon_1} \right) e^{u_1 z} H_1^{(2)}(-j\gamma \rho), \] and
\[ E_{1z} = A \left( \frac{-\gamma}{\sigma_1 + j\omega \varepsilon_1} \right) e^{u_1 z} H_0^{(2)}(-j\gamma \rho). \] (5)

[0070] In these expressions, \( z \) is the vertical coordinate normal to the surface of Region 1 and \( \rho \) is the radial coordinate, \( H_n^{(2)}(-j\gamma \rho) \) is a complex argument Hankel function of the second kind and order \( n \), \( u_1 \) is the propagation constant in the positive vertical (z) direction in Region 1, \( u_2 \) is the propagation constant in the vertical (z) direction in Region 2, \( \sigma_1 \) is the conductivity of Region 1, \( \omega \) is equal to \( 2nf \), where \( f \) is a frequency of excitation, \( \varepsilon_0 \) is the permittivity of free space, \( \varepsilon_1 \) is the permittivity of Region 1, \( A \) is a source constant imposed by the source, and \( \gamma \) is a surface wave radial propagation constant.

[0071] The propagation constants in the \( \pm z \) directions are determined by separating the wave equation above and below the interface between Regions 1 and 2, and imposing the boundary conditions. This exercise gives, in Region 2,

\[ u_2 = \frac{-jk_0}{\sqrt{1+(\varepsilon_r - j\gamma)}} \] (7)

and gives, in Region 1,

\[ u_1 = -u_2(\varepsilon_r - j\gamma). \] (8)
The radial propagation constant $\gamma$ is given by

$$\gamma = j \sqrt{k_0^2 + u_2^2} = j \frac{k_0 n}{\sqrt{1 + n^2}},$$

(9)

which is a complex expression where $n$ is the complex index of refraction given by

$$n = \sqrt{\varepsilon_r - jx}. \quad (10)$$

In all of the above Equations,

$$x = \frac{\omega}{\omega k_0} \quad \text{and} \quad \quad (11)$$

$$k_0 = \omega \sqrt{\mu_0 \varepsilon_0} = \frac{\lambda}{2\pi}, \quad (12)$$

where $\varepsilon_r$ comprises the relative permittivity of Region 1, $\sigma_1$ is the conductivity of Region 1, $\varepsilon_0$ is the permittivity of free space, and $\mu_0$ comprises the permeability of free space. Thus, the generated surface wave propagates parallel to the interface and exponentially decays vertical to it. This is known as evanescence.

[0072] Thus, Equations (1)-(3) can be considered to be a cylindrically-symmetric, radially-propagating waveguide mode. See Barlow, H. M., and Brown, J., Radio Surface Waves. Oxford University Press, 1962, pp. 10-12, 29-33. The present disclosure details structures that excite this "open boundary" waveguide mode. Specifically, according to various embodiments, a guided surface waveguide probe is provided with a charge terminal of appropriate size that is fed with voltage and/or current and is positioned relative to the boundary interface between Region 2 and Region 1. This may be better understood with reference to FIG. 3, which shows an example of a guided surface waveguide probe 200a that includes a charge terminal $T_1$ elevated above a lossy conducting medium 203 (e.g., the Earth) along a vertical axis $z$ that is normal to a plane presented by the lossy conducting medium 203. The lossy conducting medium 203 makes up Region 1, and a second medium 206
makes up Region 2 and shares a boundary interface with the lossy conducting medium 203.

[0073] According to one embodiment, the lossy conducting medium 203 can comprise a terrestrial medium such as the planet Earth. To this end, such a terrestrial medium comprises all structures or formations included thereon whether natural or man-made. For example, such a terrestrial medium can comprise natural elements such as rock, soil, sand, fresh water, sea water, trees, vegetation, and all other natural elements that make up our planet. In addition, such a terrestrial medium can comprise man-made elements such as concrete, asphalt, building materials, and other man-made materials. In other embodiments, the lossy conducting medium 203 can comprise some medium other than the Earth, whether naturally occurring or man-made. In other embodiments, the lossy conducting medium 203 can comprise other media such as man-made surfaces and structures such as automobiles, aircraft, man-made materials (such as plywood, plastic sheeting, or other materials) or other media.

[0074] In the case where the lossy conducting medium 203 comprises a terrestrial medium or Earth, the second medium 206 can comprise the atmosphere above the ground. As such, the atmosphere can be termed an "atmospheric medium" that comprises air and other elements that make up the atmosphere of the Earth. In addition, it is possible that the second medium 206 can comprise other media relative to the lossy conducting medium 203.

[0075] The guided surface waveguide probe 200a includes a feed network 209 that couples an excitation source 212 to the charge terminal $T_1$ via, e.g., a vertical feed line conductor. According to various embodiments, a charge $Q_1$ is imposed on the charge terminal $T_1$ to synthesize an electric field based upon the voltage applied
to terminal $T_1$ at any given instant. Depending on the angle of incidence ($\theta_i$) of the electric field ($E$), it is possible to substantially mode-match the electric field to a guided surface waveguide mode on the surface of the lossy conducting medium 203 comprising Region 1.

By considering the Zenneck closed-form solutions of Equations (1)-(6), the Leontovich impedance boundary condition between Region 1 and Region 2 can be stated as

$$\mathbf{z} \times \mathbf{H}_2(\rho, \phi, 0) = \mathbf{j}_s,$$

(13)

where $\mathbf{z}$ is a unit normal in the positive vertical ($+z$) direction and $\mathbf{H}_2$ is the magnetic field strength in Region 2 expressed by Equation (1) above. Equation (13) implies that the electric and magnetic fields specified in Equations (1)-(3) may result in a radial surface current density along the boundary interface, where the radial surface current density can be specified by

$$J_\rho(\rho') = -A H_1^{(2)}(-j\gamma\rho')$$

(14)

where $A$ is a constant. Further, it should be noted that close-in to the guided surface waveguide probe 200 (for $\rho \ll \chi$), Equation (14) above has the behavior

$$J_{\text{close}}(\rho') = -\frac{A}{\pi} \left( \frac{3\chi}{j} \right) = -\frac{3\chi}{2\pi\rho'}. $$

(15)

The negative sign means that when source current ($I_0$) flows vertically upward as illustrated in FIG. 3, the "close-in" ground current flows radially inward. By field matching on $H_\phi$ "close-in," it can be determined that

$$\zeta = -\frac{l_0}{4} = -\frac{\omega q_4 Y}{4}$$

(16)

where $q_4 = C \cdot V \cdot I$, in Equations (1)-(6) and (14). Therefore, the radial surface current density of Equation (14) can be restated as

$$J_\rho(\rho') = \frac{l_0 Y}{4} H_1^{(2)}(-j\gamma\rho').$$

(17)
The fields expressed by Equations (1)-(6) and (17) have the nature of a transmission line mode bound to a lossy interface, not radiation fields that are associated with groundwave propagation. See Barlow, H. M. and Brown, J., Radio Surface Waves, Oxford University Press, 1962, pp. 1-5.

[0077] At this point, a review of the nature of the Hankel functions used in Equations (1)-(6) and (17) is provided for these solutions of the wave equation. One might observe that the Hankel functions of the first and second kind and order \( n \) are defined as complex combinations of the standard Bessel functions of the first and second kinds

\[
H_n^{(1)}(x) = J_n(x) + jN_n(x), \quad \text{and} \quad H_n^{(2)}(x) = J_n(x) - jN_n(x),
\]

These functions represent cylindrical waves propagating radially inward \( (H_n^{(1)}) \) and outward \( (H_n^{(2)}) \), respectively. The definition is analogous to the relationship \( e^{\pm jx} = \cos x \pm j \sin x \). See, for example, Harrington, R.F., Time-Harmonic Fields, McGraw-Hill, 1961, pp. 460-463.

[0078] That \( H_n^{(2)}(k_0 \rho) \) is an outgoing wave can be recognized from its large argument asymptotic behavior that is obtained directly from the series definitions of \( J_n(x) \) and \( N_n(x) \). Far-out from the guided surface waveguide probe:

\[
H_n^{(2)}(x) \xrightarrow{x \to \infty} \frac{2j}{\pi x} j^n e^{-jx} = \frac{2}{\pi x} j^n e^{-j\left(x - \frac{\pi}{4}\right)}, \quad (20a)
\]

which, when multiplied by \( e^{k_0 x} \), is an outward propagating cylindrical wave of the form \( e^{j(c_0 + k_0) \rho} \) with a \( 1/\rho \) spatial variation. The first order (\( n = 1 \)) solution can be determined from Equation (20a) to be

\[
H_1^{(2)}(x) \xrightarrow{x \to \infty} j \frac{2j}{\pi x} e^{-jx} = \frac{2}{\pi x} e^{-j\left(x - \frac{\pi}{2} - \frac{\pi}{4}\right)}. \quad (20b)
\]
Close-in to the guided surface waveguide probe (for \( p \ll X \)), the Hankel function of first order and the second kind behaves as

\[
H_1^{(2)}(x) \xrightarrow{x \to 0} \frac{2j}{\pi x}
\]

(21)

Note that these asymptotic expressions are complex quantities. When \( x \) is a real quantity, Equations (20b) and (21) differ in phase by \( \sqrt{j} \), which corresponds to an extra phase advance or "phase boost" of 45° or, equivalently, \( \lambda/8 \). The close-in and far-out asymptotes of the first order Hankel function of the second kind have a Hankel "crossover" or transition point where they are of equal magnitude at a distance of \( p = R_x \).

[0079] Thus, beyond the Hankel crossover point the "far out" representation predominates over the "close-in" representation of the Hankel function. The distance to the Hankel crossover point (or Hankel crossover distance) can be found by equating Equations (20b) and (21) for \(-j\eta p\), and solving for \( R_x \). With \( x = \sigma/\omega \epsilon_0 \), it can be seen that the far-out and close-in Hankel function asymptotes are frequency dependent, with the Hankel crossover point moving out as the frequency is lowered. It should also be noted that the Hankel function asymptotes may also vary as the conductivity (\( \sigma \)) of the lossy conducting medium changes. For example, the conductivity of the soil can vary with changes in weather conditions.

[0080] Referring to FIG. 4, shown is an example of a plot of the magnitudes of the first order Hankel functions of Equations (20b) and (21) for a Region 1 conductivity of \( \sigma = 0.010 \) mhos/m and relative permittivity \( \epsilon_r = 15 \), at an operating frequency of 1850 kHz. Curve 115 is the magnitude of the far-out asymptote of Equation (20b) and curve 118 is the magnitude of the close-in asymptote of Equation (21), with the Hankel crossover point 121 occurring at a distance of \( R_x = 54 \) feet. While the magnitudes are equal, a phase offset exists between the two asymptotes.
at the Hankel crossover point 121. It can also be seen that the Hankel crossover distance is much less than a wavelength of the operation frequency.

[0081] Considering the electric field components given by Equations (2) and (3) of the Zenneck closed-form solution in Region 2, it can be seen that the ratio of $E_z$ and $E_\rho$ asymptotically passes to

$$\frac{E_z}{E_\rho} = \left(\frac{H_0^{(2)}(-j\rho \sigma)}{H_1^{(2)}(-j\rho \sigma)}\right) \overset{\rho \to \infty}{\rightarrow} \sqrt{\varepsilon_r - j\frac{\sigma}{\omega\varepsilon_0}} = n = \tan \theta_i,$$

(22)

where $n$ is the complex index of refraction of Equation (10) and $\theta_i$ is the angle of incidence of the electric field. In addition, the vertical component of the mode-matched electric field of Equation (3) asymptotically passes to

$$E_{zz} \overset{\rho \to \infty}{\rightarrow} \left(\frac{q_{\text{free}}}{\varepsilon_0}\right) \frac{\gamma^2}{8\pi} e^{-u_2 z} e^{-j(\rho\sigma - \pi/4)} \frac{1}{\sqrt{\rho}},$$

(23)

which is linearly proportional to free charge on the isolated component of the elevated charge terminal's capacitance at the terminal voltage, $q_{\text{free}} = C_{\text{free}} \times V_T$.

[0082] For example, the height $H_1$ of the elevated charge terminal $\Gamma_1$ in FIG. 3 affects the amount of free charge on the charge terminal $\Gamma_1$. When the charge terminal $\Gamma_1$ is near the ground plane of Region 1, most of the charge $Q_1$ on the terminal is "bound." As the charge terminal $\Gamma_1$ is elevated, the bound charge is lessened until the charge terminal $\Gamma_1$ reaches a height at which substantially all of the isolated charge is free.

[0083] The advantage of an increased capacitive elevation for the charge terminal $\Gamma_1$ is that the charge on the elevated charge terminal $\Gamma_1$ is further removed from the ground plane, resulting in an increased amount of free charge $q_{\text{free}}$ to couple energy into the guided surface waveguide mode. As the charge terminal $\Gamma_1$ is moved away from the ground plane, the charge distribution becomes more
uniformly distributed about the surface of the terminal. The amount of free charge is related to the self-capacitance of the charge terminal $T_1$.

[0084] For example, the capacitance of a spherical terminal can be expressed as a function of physical height above the ground plane. The capacitance of a sphere at a physical height of $h$ above a perfect ground is given by

$$Q_{\text{evated sphere}} = 4\pi \varepsilon_0 \alpha (1 + M + M^2 + M^3 + 2M^4 + 3M^5 + \cdots),$$

(24)

where the diameter of the sphere is $2a$, and where $M = a/2h$ with $h$ being the height of the spherical terminal. As can be seen, an increase in the terminal height $h$ reduces the capacitance $C$ of the charge terminal. It can be shown that for elevations of the charge terminal $T_1$ that are at a height of about four times the diameter ($4D = 8a$) or greater, the charge distribution is approximately uniform about the spherical terminal, which can improve the coupling into the guided surface waveguide mode.

[0085] In the case of a sufficiently isolated terminal, the self-capacitance of a conductive sphere can be approximated by $C = 4\pi \varepsilon \sigma a$, where $a$ is the radius of the sphere in meters, and the self-capacitance of a disk can be approximated by $C = 8\pi \sigma \alpha$, where $a$ is the radius of the disk in meters. The charge terminal $T_1$ can include any shape such as a sphere, a disk, a cylinder, a cone, a torus, a hood, one or more rings, or any other randomized shape or combination of shapes. An equivalent spherical diameter can be determined and used for positioning of the charge terminal $T_1$.

[0086] This may be further understood with reference to the example of FIG. 3, where the charge terminal $T_1$ is elevated at a physical height of $h_p = h_1$ above the lossy conducting medium 203. To reduce the effects of the "bound" charge, the charge terminal $T_1$ can be positioned at a physical height that is at least four times
the spherical diameter (or equivalent spherical diameter) of the charge terminal $r_1$ to reduce the bounded charge effects.

[0087] Referring next to FIG. 5A, shown is a ray optics interpretation of the electric field produced by the elevated charge $Q_1$ on charge terminal $r_1$ of FIG. 3. As in optics, minimizing the reflection of the incident electric field can improve and/or maximize the energy coupled into the guided surface waveguide mode of the lossy conducting medium 203. For an electric field $(E_H)$ that is polarized parallel to the plane of incidence (not the boundary interface), the amount of reflection of the incident electric field may be determined using the Fresnel reflection coefficient, which can be expressed as

$$\Gamma_{ll}(\theta_i) = \frac{E_{ls}}{E_{ls}} = \frac{\sqrt{(\varepsilon_r - jx) - \sin^2 \theta_i} - (\varepsilon_r - jx) \cos \theta_i}{\sqrt{(\varepsilon_r - jx) + \sin^2 \theta_i} + (\varepsilon_r - jx) \cos \theta_i},$$

(25)

where $\theta_i$ is the conventional angle of incidence measured with respect to the surface normal.

[0088] In the example of FIG. 5A, the ray optic interpretation shows the incident field polarized parallel to the plane of incidence having an angle of incidence of $Q$, which is measured with respect to the surface normal $(z)$. There will be no reflection of the incident electric field when $\Gamma_{ll}(\theta_i) = 0$ and thus the incident electric field will be completely coupled into a guided surface waveguide mode along the surface of the lossy conducting medium 203. It can be seen that the numerator of Equation (25) goes to zero when the angle of incidence is

$$\theta_i = \arctan(\sqrt{\varepsilon_r - jx}) = \theta_{i,B},$$

(26)

where $x = \sigma/\omega \varepsilon_0$. This complex angle of incidence $(\theta_{i,B})$ is referred to as the Brewster angle. Referring back to Equation (22), it can be seen that the same complex Brewster angle $(\theta_{i,B})$ relationship is present in both Equations (22) and (26).
As illustrated in FIG. 5A, the electric field vector $E$ can be depicted as an incoming non-uniform plane wave, polarized parallel to the plane of incidence. The electric field vector $E$ can be created from independent horizontal and vertical components as

$$\vec{E}(\Theta) = E_\rho \beta + E_\zeta \zeta.$$  \hspace{1cm} (27)

Geometrically, the illustration in FIG. 5A suggests that the electric field vector $E$ can be given by

$$E_p(p,z) = E(p,z) \cos \theta_i,$$  
$$E_z(p,z) = E(p,z) \cos \left( \frac{\pi}{2} - \theta_i \right) = E(p,z) \sin \theta_i,$$ \hspace{1cm} (28a, 28b)

which means that the field ratio is

$$\frac{E_p}{E_z} = \frac{1}{\tan \theta_i} = \tan \psi_i.$$  \hspace{1cm} (29)

A generalized parameter $W$, called "wave tilt," is noted herein as the ratio of the horizontal electric field component to the vertical electric field component given by

$$W = \frac{E_p}{E_z} = \frac{\sum W e^{i\psi}}{E_p}, \quad \text{or}$$  \hspace{1cm} (30a)

$$\sum_W = \frac{E_z}{E_p} = \tan \theta_i = \frac{1}{\Im W} e^{-i\psi},$$  \hspace{1cm} (30b)

which is complex and has both magnitude and phase. For an electromagnetic wave in Region 2, the wave tilt angle ($\psi$) is equal to the angle between the normal of the wave-front at the boundary interface with Region 1 and the tangent to the boundary interface. This may be easier to see in FIG. 5B, which illustrates equi-phase surfaces of an electromagnetic wave and their normals for a radial cylindrical guided surface wave. At the boundary interface ($z = 0$) with a perfect conductor, the wave-front normal is parallel to the tangent of the boundary interface, resulting in $W = 0$.  

[0090]
However, in the case of a lossy dielectric, a wave tilt $W$ exists because the wave-front normal is not parallel with the tangent of the boundary interface at $z = 0$.

[0091] Applying Equation (30b) to a guided surface wave gives

$$\tan \theta_{i,B} = \frac{E_z}{E_\rho} = \frac{u_2}{v} = \sqrt{\epsilon_r - j x} = n = \frac{1}{w} = \frac{1}{|W|} e^{-j \Psi}$$

(31)

With the angle of incidence equal to the complex Brewster angle ($\theta_{i,B}$), the Fresnel reflection coefficient of Equation (25) vanishes, as shown by

$$\Gamma_{i}^{Q_{(\epsilon_r - j x)} - \sin^2 \theta_{i,B} (\epsilon_r - j x) \cos \theta_{i,B}} = 0.$$  

(32)

By adjusting the complex field ratio of Equation (22), an incident field can be synthesized to be incident at a complex angle at which the reflection is reduced or eliminated. Establishing this ratio as $n = \sqrt{\epsilon_r - j x}$ results in the synthesized electric field being incident at the complex Brewster angle, making the reflections vanish.

[0092] The concept of an electrical effective height can provide further insight into synthesizing an electric field with a complex angle of incidence with a guided surface waveguide probe 200. The electrical effective height ($h_{eff}$) has been defined as

$$h_{eff} = \frac{1}{\rho} \int_0^{h_p} I(z)dz$$

(33)

for a monopole with a physical height (or length) of $h_p$. Since the expression depends upon the magnitude and phase of the source distribution along the structure, the effective height (or length) is complex in general. The integration of the distributed current $I(z)$ of the structure is performed over the physical height of the structure ($h_p$), and normalized to the ground current ($I_0$) flowing upward through the base (or input) of the structure. The distributed current along the structure can be expressed by
where $\beta_0$ is the propagation factor for current propagating on the structure. In the example of FIG. 3, $I_c$ is the current that is distributed along the vertical structure of the guided surface waveguide probe 200a.

For example, consider a feed network 209 that includes a low loss coil (e.g., a helical coil) at the bottom of the structure and a vertical feed line conductor connected between the coil and the charge terminal $T_1$. The phase delay due to the coil (or helical delay line) is $\phi_C = \beta_\nu l_C$, with a physical length of $l_c$ and a propagation factor of

$$\beta_p = \frac{2\pi}{\lambda_p} = \frac{2\pi}{V_\nu \lambda_0},$$

where $V_\nu$ is the velocity factor on the structure, $\lambda_0$ is the wavelength at the supplied frequency, and $\lambda_\nu$ is the propagation wavelength resulting from the velocity factor $V_\nu$. The phase delay is measured relative to the ground (stake) current $I_0$.

In addition, the spatial phase delay along the length $l_w$ of the vertical feed line conductor can be given by $\phi_Y = \beta_\nu h_p$ where $\beta_\nu$ is the propagation phase constant for the vertical feed line conductor. In some implementations, the spatial phase delay may be approximated by $\phi_Y = \beta_\nu h_p$, since the difference between the physical height $h_p$ of the guided surface waveguide probe 200a and the vertical feed line conductor length $l_w$ is much less than a wavelength at the supplied frequency ($\lambda_0$). As a result, the total phase delay through the coil and vertical feed line conductor is $\Phi = \phi_C + \phi_Y$, and the current fed to the top of the coil from the bottom of the physical structure is

$$I_c(\theta_C + \theta_Y) = I_0 e^{i\Phi},$$

(36)
with the total phase delay \( \Phi \) measured relative to the ground (stake) current \( I_0 \).

Consequently, the electrical effective height of a guided surface waveguide probe 200 can be approximated by

\[
h_{eff} = \frac{1}{i_0} \int_0^{h_p} I_0 e^{i \Phi} \cos(\beta_0 z) \, \alpha \zeta = h_p \varepsilon / \Phi, \quad (37)
\]

for the case where the physical height \( h_p \ll \lambda_0 \). The complex effective height of a monopole, \( h_{eff} = h_p \) at an angle (or phase shift) of \( \Phi \), may be adjusted to cause the source fields to match a guided surface waveguide mode and cause a guided surface wave to be launched on the lossy conducting medium 203.

[0095] In the example of FIG. 5A, ray optics are used to illustrate the complex angle trigonometry of the incident electric field (\( E \)) having a complex Brewster angle of incidence (\( \theta_{i,B} \)) at the Hankel crossover distance (\( R_x \)) 121. Recall from Equation (26) that, for a lossy conducting medium, the Brewster angle is complex and specified by

\[
\tan \theta_{i,B} = \sqrt{\varepsilon} = n. \quad (38)
\]

Electrically, the geometric parameters are related by the electrical effective height (\( h_{eff} \)) of the charge terminal \( T_1 \) by

\[
R_x \tan \psi_{i,B} = R_x \times W = h_{eff} = h_p e^{i \Phi}, \quad (39)
\]

where \( \psi_{i,B} = (\pi/2) - \theta_{i,B} \) is the Brewster angle measured from the surface of the lossy conducting medium. To couple into the guided surface waveguide mode, the wave tilt of the electric field at the Hankel crossover distance can be expressed as the ratio of the electrical effective height and the Hankel crossover distance

\[
\frac{h_{eff}}{R_x} = \tan \psi_{i,B} = W_{Rx}. \quad (40)
\]

Since both the physical height (\( h_p \)) and the Hankel crossover distance (\( R_x \)) are real quantities, the angle (\( \Psi \)) of the desired guided surface wave tilt at the Hankel
crossover distance \( R_x \) is equal to the phase \( \Phi \) of the complex effective height \( h_{\text{eff}} \). This implies that by varying the phase at the supply point of the coil, and thus the phase shift in Equation (37), the phase, \( \Phi \), of the complex effective height can be manipulated to match the angle of the wave tilt, \( \Psi \), of the guided surface waveguide mode at the Hankel crossover point 121: \( \Phi = \Psi \).

[0096] In FIG. 5A, a right triangle is depicted having an adjacent side of length \( R_x \) along the lossy conducting medium surface and a complex Brewster angle \( \psi_{l,B} \) measured between a ray 124 extending between the Hankel crossover point 121 at \( R_x \) and the center of the charge terminal \( T' \), and the lossy conducting medium surface 127 between the Hankel crossover point 121 and the charge terminal \( T_1 \). With the charge terminal \( T' \) positioned at physical height \( h_p \) and excited with a charge having the appropriate phase delay \( \Phi \), the resulting electric field is incident with the lossy conducting medium boundary interface at the Hankel crossover distance \( R_x \), and at the Brewster angle. Under these conditions, the guided surface waveguide mode can be excited without reflection or substantially negligible reflection.

[0097] If the physical height of the charge terminal \( T' \) is decreased without changing the phase shift \( \Phi \) of the effective height \( h_{\text{eff}} \), the resulting electric field intersects the lossy conducting medium 203 at the Brewster angle at a reduced distance from the guided surface waveguide probe 200. FIG. 6 graphically illustrates the effect of decreasing the physical height of the charge terminal \( T' \) on the distance where the electric field is incident at the Brewster angle. As the height is decreased from \( h_3 \) through \( h_2 \) to \( h_1 \), the point where the electric field intersects with the lossy conducting medium (e.g., the Earth) at the Brewster angle moves closer to the charge terminal position. However, as Equation (39) indicates, the height \( H_1 \) (FIG. 3)
of the charge terminal $T_1$ should be at or higher than the physical height ($h_p$) in order to excite the far-out component of the Hankel function. With the charge terminal $T_1$ positioned at or above the effective height ($h_{eff}$), the lossy conducting medium 203 can be illuminated at the Brewster angle of incidence ($\psi_{IB} = (\pi/2) - \theta_{IB}$) at or beyond the Hankel crossover distance ($R_x$) 121 as illustrated in FIG. 5A. To reduce or minimize the bound charge on the charge terminal $T_1$, the height should be at least four times the spherical diameter (or equivalent spherical diameter) of the charge terminal $T_1$ as mentioned above.

[0098] A guided surface waveguide probe 200 can be configured to establish an electric field having a wave tilt that corresponds to a wave illuminating the surface of the lossy conducting medium 203 at a complex Brewster angle, thereby exciting radial surface currents by substantially mode-matching to a guided surface wave mode at (or beyond) the Hankel crossover point 121 at $R_x$.

[0099] Referring to FIG. 7, shown is a graphical representation of an example of a guided surface waveguide probe 200b that includes a charge terminal $T_1$. An AC source 212 acts as the excitation source for the charge terminal $T_1$, which is coupled to the guided surface waveguide probe 200b through a feed network 209 (FIG. 3) comprising a coil 215 such as, e.g., a helical coil. In other implementations, the AC source 212 can be inductively coupled to the coil 215 through a primary coil. In some embodiments, an impedance matching network may be included to improve and/or maximize coupling of the AC source 212 to the coil 215.

[0100] As shown in FIG. 7, the guided surface waveguide probe 200b can include the upper charge terminal $T_1$ (e.g., a sphere at height $h_u$) that is positioned along a vertical axis z that is substantially normal to the plane presented by the lossy conducting medium 203. A second medium 206 is located above the lossy...
conducting medium 203. The charge terminal $T_1$ has a self-capacitance $C_T$. During operation, charge $Q_1$ is imposed on the terminal $T_1$ depending on the voltage applied to the terminal $T_1$ at any given instant.

[0101] In the example of FIG. 7, the coil 215 is coupled to a ground stake 218 at a first end and to the charge terminal $T_1$ via a vertical feed line conductor 221. In some implementations, the coil connection to the charge terminal $T_1$ can be adjusted using a tap 224 of the coil 215 as shown in FIG. 7. The coil 215 can be energized at an operating frequency by the AC source 212 through a tap 227 at a lower portion of the coil 215. In other implementations, the AC source 212 can be inductively coupled to the coil 215 through a primary coil.

[0102] The construction and adjustment of the guided surface waveguide probe 200 is based upon various operating conditions, such as the transmission frequency, conditions of the lossy conducting medium (e.g., soil conductivity $\sigma$ and relative permittivity $\varepsilon_r$), and size of the charge terminal $T_i$. The index of refraction can be calculated from Equations (10) and (11) as

$$n = \sqrt{\varepsilon_r - jx},$$  

(41)

where $x = \sigma/\omega\varepsilon_0$ with $\omega = 2nf$. The conductivity $\sigma$ and relative permittivity $\varepsilon_r$ can be determined through test measurements of the lossy conducting medium 203. The complex Brewster angle ($\theta_{i,B}$) measured from the surface normal can also be determined from Equation (26) as

$$\theta_{i,B} = \arctan(j\varepsilon_r \cdot jx),$$  

(42)

or measured from the surface as shown in FIG. 5A as

$$\psi_{i,B} = \frac{\pi}{2} - \theta_{i,B}.$$  

(43)

The wave tilt at the Hankel crossover distance ($W_Rx$) can also be found using Equation (40).
The Hankel crossover distance can also be found by equating the magnitudes of Equations (20b) and (21) for \(-jyp\), and solving for \(R_x\) as illustrated by FIG. 4. The electrical effective height can then be determined from Equation (39) using the Hankel crossover distance and the complex Brewster angle as

\[
h_{\text{eff}} = h_v e^{j\phi} = R_x \tan^\nu B. \tag{44}
\]

As can be seen from Equation (44), the complex effective height \((h_{\text{eff}})\) includes a magnitude that is associated with the physical height \((h_p)\) of the charge terminal \(T_1\) and a phase delay \((\phi)\) that is to be associated with the angle \((\Psi)\) of the wave tilt at the Hankel crossover distance \((R_x)\). With these variables and the selected charge terminal \(T_1\) configuration, it is possible to determine the configuration of a guided surface waveguide probe 200.

With the charge terminal \(T_1\) positioned at or above the physical height \((h_p)\), the feed network 209 (FIG. 3) and/or the vertical feed line connecting the feed network to the charge terminal \(T_1\) can be adjusted to match the phase \((\phi)\) of the charge \(Q_1\) on the charge terminal \(T_1\) to the angle \((\Psi)\) of the wave tilt \((W)\). The size of the charge terminal \(T_1\) can be chosen to provide a sufficiently large surface for the charge \(Q_1\) imposed on the terminals. In general, it is desirable to make the charge terminal \(T_1\) as large as practical. The size of the charge terminal \(T_1\) should be large enough to avoid ionization of the surrounding air, which can result in electrical discharge or sparking around the charge terminal.

The phase delay \(g_c\) of a helically-wound coil can be determined from Maxwell’s equations as has been discussed by Corum, K.L. and J.F. Corum, “RF Coils, Helical Resonators and Voltage Magnification by Coherent Spatial Modes,” Microwave Review, Vol. 7, No. 2, September 2001, pp. 36-45., which is incorporated herein by reference in its entirety. For a helical coil with \(H/D > 1\), the ratio of the
velocity of propagation ($v$) of a wave along the coil’s longitudinal axis to the speed of light ($c$), or the “velocity factor,” is given by

$$V_f = \frac{v}{c} = \frac{1}{\sqrt{1 + 20 \left( \frac{D}{\lambda_0} \right)^{2/5} \left( \frac{D}{\lambda_0} \right)^{0.5}}} , \quad (45)$$

where $H$ is the axial length of the solenoidal helix, $D$ is the coil diameter, $N$ is the number of turns of the coil, $s = H/N$ is the turn-to-turn spacing (or helix pitch) of the coil, and $\lambda_0$ is the free-space wavelength. Based upon this relationship, the electrical length, or phase delay, of the helical coil is given by

$$\theta_c = \beta_p H = \frac{2\pi}{\lambda_p} H = \frac{2\pi}{V_f \lambda_0} H , \quad (46)$$

The principle is the same if the helix is wound spirally or is short and fat, but $V_f$ and $\theta_c$ are easier to obtain by experimental measurement. The expression for the characteristic (wave) impedance of a helical transmission line has also been derived as

$$Z_c = \frac{60}{V_f} \left[ \ln \left( \frac{V_f \lambda_0}{D} \right) - 1.027 \right] . \quad (47)$$

[0106] The spatial phase delay $\varphi_r$ of the structure can be determined using the traveling wave phase delay of the vertical feed line conductor 221 (FIG. 7). The capacitance of a cylindrical vertical conductor above a perfect ground plane can be expressed as

$$C_A = \frac{2\pi \varepsilon_0 a h_w}{\ln \left( \frac{D}{a} \right)} \text{ Farads}, \quad (48)$$

where $h_w$ is the vertical length (or height) of the conductor and $a$ is the radius (in mks units). As with the helical coil, the traveling wave phase delay of the vertical feed line conductor can be given by

$$\theta_y = \beta_w h_w = \frac{2\pi}{\lambda_w} h_w = \frac{2\pi}{V_w \lambda_0} h_w , \quad (49)$$
where \( \beta_w \) is the propagation phase constant for the vertical feed line conductor, \( h_w \) is the vertical length (or height) of the vertical feed line conductor, \( v_w \) is the velocity factor on the wire, \( \lambda_0 \) is the wavelength at the supplied frequency, and \( \lambda_w \) is the propagation wavelength resulting from the velocity factor \( v_w \). For a uniform cylindrical conductor, the velocity factor is a constant with \( v_w \approx 0.94 \), or in a range from about 0.93 to about 0.98. If the mast is considered to be a uniform transmission line, its average characteristic impedance can be approximated by

\[
Z_w = \frac{60}{v_w} \left[ \ln \left( \frac{h_w}{a} \right) - 1 \right],
\]

where \( v_w \approx 0.94 \) for a uniform cylindrical conductor and \( a \) is the radius of the conductor. An alternative expression that has been employed in amateur radio literature for the characteristic impedance of a single-wire feed line can be given by

\[
Z_w = 138 \log \left( \frac{1.123 v_w \lambda_0}{2\pi a} \right).
\]

Equation (51) implies that \( Z_w \) for a single-wire feeder varies with frequency. The phase delay can be determined based upon the capacitance and characteristic impedance.

[0107] With a charge terminal \( T_1 \) positioned over the lossy conducting medium 203 as shown in FIG. 3, the feed network 209 can be adjusted to excite the charge terminal \( T_1 \) with the phase shift \( (\Phi) \) of the complex effective height \( (h_{\text{eff}}) \) equal to the angle \( (\Psi) \) of the wave tilt at the Hankel crossover distance, or \( \Phi = \Psi \). When this condition is met, the electric field produced by the charge oscillating \( Q_1 \) on the charge terminal \( T_1 \) is coupled into a guided surface waveguide mode traveling along the surface of a lossy conducting medium 203. For example, if the Brewster angle \( (\theta_{\text{B}}) \), the phase delay \( (\theta_p) \) associated with the vertical feed line conductor 221 (FIG. 7), and the configuration of the coil 215 (FIG. 7) are known, then the position of the
tap 224 (FIG. 7) can be determined and adjusted to impose an oscillating charge $Q_1$ on the charge terminal $T_1$ with phase $\Phi = \Psi$. The position of the tap 224 may be adjusted to maximize coupling the traveling surface waves into the guided surface waveguide mode. Excess coil length beyond the position of the tap 224 can be removed to reduce the capacitive effects. The vertical wire height and/or the geometrical parameters of the helical coil may also be varied.

[0108] The coupling to the guided surface waveguide mode on the surface of the lossy conducting medium 203 can be improved and/or optimized by tuning the guided surface waveguide probe 200 for standing wave resonance with respect to a complex image plane associated with the charge $Q_1$ on the charge terminal $T_i$. By doing this, the performance of the guided surface waveguide probe 200 can be adjusted for increased and/or maximum voltage (and thus charge $Q_i$) on the charge terminal $T_i$. Referring back to FIG. 3, the effect of the lossy conducting medium 203 in Region 1 can be examined using image theory analysis.

[0109] Physically, an elevated charge $Q_1$ placed over a perfectly conducting plane attracts the free charge on the perfectly conducting plane, which then "piles up" in the region under the elevated charge $Q_i$. The resulting distribution of "bound" electricity on the perfectly conducting plane is similar to a bell-shaped curve. The superposition of the potential of the elevated charge $Q_i$, plus the potential of the induced "piled up" charge beneath it, forces a zero equipotential surface for the perfectly conducting plane. The boundary value problem solution that describes the fields in the region above the perfectly conducting plane may be obtained using the classical notion of image charges, where the field from the elevated charge is superimposed with the field from a corresponding "image" charge below the perfectly conducting plane.
This analysis may also be used with respect to a lossy conducting medium 203 by assuming the presence of an effective image charge $Q_T$ beneath the guided surface waveguide probe 200. The effective image charge $Q_T$ coincides with the charge $Q_1$ on the charge terminal $T_1$ about a conducting image ground plane 130, as illustrated in FIG. 3. However, the image charge $Q_T$ is not merely located at some real depth and $180^\circ$ out of phase with the primary source charge $Q_1$ on the charge terminal $T_i$, as they would be in the case of a perfect conductor. Rather, the lossy conducting medium 203 (e.g., a terrestrial medium) presents a phase shifted image. That is to say, the image charge $Q_T$ is at a complex depth below the surface (or physical boundary) of the lossy conducting medium 203. For a discussion of complex image depth, reference is made to Wait, J. R., "Complex Image Theory—Revisited," IEEE Antennas and Propagation Magazine, Vol. 33, No. 4, August 1991, pp. 27-29, which is incorporated herein by reference in its entirety.

Instead of the image charge $Q_T$ being at a depth that is equal to the physical height $(H_i)$ of the charge $Q_i$, the conducting image ground plane 130 (representing a perfect conductor) is located at a complex depth of $z = -d/2$ and the image charge $Q_T$ appears at a complex depth (i.e., the "depth" has both magnitude and phase), given by $-Q_1 = -(d/2 + d/2 + H_i) \neq E_1$. For vertically polarized sources over the Earth,

$$d = \frac{2\sqrt{\gamma_o^2 + k_o^2}}{\gamma_o} \approx \frac{2}{\gamma_o} = d_r + j d_i = |d|\angle \zeta,$$

where

$$\gamma_o^2 = j\omega \mu_1 \sigma_1 - \omega^2 \mu_1 \varepsilon_1,$$

and

$$k_o = \omega \sqrt{\mu_0 \varepsilon_0}.$$
as indicated in Equation (12). The complex spacing of the image charge, in turn, implies that the external field will experience extra phase shifts not encountered when the interface is either a dielectric or a perfect conductor. In the lossy conducting medium, the wave front normal is parallel to the tangent of the conducting image ground plane 130 at \( z = -d/2 \), and not at the boundary interface between Regions 1 and 2.

[0112] Consider the case illustrated in FIG. 8A where the lossy conducting medium 203 is a finitely conducting Earth 133 with a physical boundary 136. The finitely conducting Earth 133 may be replaced by a perfectly conducting image ground plane 139 as shown in FIG.8B, which is located at a complex depth \( z_1 \) below the physical boundary 136. This equivalent representation exhibits the same impedance when looking down into the interface at the physical boundary 136. The equivalent representation of FIG. 8B can be modeled as an equivalent transmission line, as shown in FIG. 8C. The cross-section of the equivalent structure is represented as a (z-directed) end-loaded transmission line, with the impedance of the perfectly conducting image plane being a short circuit \( (z_s = 0) \). The depth \( z_1 \) can be determined by equating the TEM wave impedance looking down at the Earth to an image ground plane impedance \( z_{in} \) seen looking into the transmission line of FIG. 8C.

[0113] In the case of FIG. 8A, the propagation constant and wave intrinsic impedance in the upper region (air) 142 are

\[
\gamma_0 = j \omega \sqrt{\mu_0 \varepsilon_0} = 0 + j \beta_0 , \quad \text{and} \tag{55}
\]

\[
z_0 = \frac{j \omega \mu_0}{\gamma_0} = \frac{\mu_0}{\sqrt{\varepsilon_0}} . \tag{56}
\]

In the lossy Earth 133, the propagation constant and wave intrinsic impedance are
\[ \gamma_\beta = \sqrt{j\omega \mu_1 (\gamma i + j\omega \epsilon_1)} \text{ and} \]
\[ Z_e = \frac{j \omega \mu_1}{\gamma e} \]  
(57)

For normal incidence, the equivalent representation of FIG. 8B is equivalent to a TEM transmission line whose characteristic impedance is that of air \((\gamma_0)\), with propagation constant of \(\gamma_0\), and whose length is \(z_1\). As such, the image ground plane impedance \(Z_{in}\) seen at the interface for the shorted transmission line of FIG. 8C is given by
\[ Z_{in} = \gamma_0 \tanh (\gamma p z_1). \]  
(59)

Equating the image ground plane impedance \(Z_{in}\) associated with the equivalent model of FIG. 8C to the normal incidence wave impedance of FIG. 8A and solving for \(z_1\) gives the distance to a short circuit (the **perfectly conducting** image ground plane 139) as
\[ z_1 = \frac{1}{\gamma_0} \tanh^{-1} \left( \frac{Z_e}{\gamma_0} \right) = \frac{1}{\gamma_0} \tanh^{-1} \left( \frac{\gamma_0}{\gamma e} \right) \approx \frac{1}{\gamma e}, \]  
(60)

where only the first term of the series expansion for the inverse hyperbolic tangent is considered for this approximation. Note that in the air region 142, the propagation constant is \(\gamma_0 = j\beta_0\), so \(Z_{in} = j \gamma_0 \tan \beta_0 z_1\) (which is a purely imaginary quantity for a real \(z_1\)), but \(Z_e\) is a complex value if \(\sigma \neq 0\). Therefore, \(Z_{in} = Z_e\) only when \(z_1\) is a complex distance.

[01 14] Since the equivalent representation of FIG. 8B includes a **perfectly conducting** image ground plane 139, the image depth for a charge or current **lying at the surface of the Earth** (physical boundary 136) is equal to distance \(z_1\) on the other side of the image ground plane 139, or \(d = 2 \times z_1\) beneath the Earth's surface (which is located at \(z = 0\)). Thus, the distance to the perfectly conducting image ground plane 139 can be approximated by
Additionally, the "image charge" will be "equal and opposite" to the real charge, so the potential of the perfectly conducting image ground plane 139 at depth \( z_1 = -d/2 \) will be zero.

If a charge \( Q_1 \) is elevated a distance \( H_1 \) above the surface of the Earth as illustrated in FIG. 3, then the image charge \( Q_1' \) resides at a complex distance of \( \sigma_1 = d + E_1 \) below the surface, or a complex distance of \( d/2 + E_1 \) below the image ground plane 130. The guided surface waveguide probe 200b of FIG. 7 can be modeled as an equivalent single-wire transmission line image plane model that can be based upon the perfectly conducting image ground plane 139 of FIG. 8B. FIG. 9A shows an example of the equivalent single-wire transmission line image plane model, and FIG. 9B illustrates an example of the equivalent classic transmission line model, including the shorted transmission line of FIG. 8C.

In the equivalent image plane models of FIGS. 9A and 9B, \( \Phi = \Phi_y + \Phi_c \) is the traveling wave phase delay of the guided surface waveguide probe 200 referenced to Earth 133 (or the lossy conducting medium 203), \( \theta_c = \beta_c H \) is the electrical length of the coil 215 (FIG. 7), of physical length \( H \), expressed in degrees, \( \Phi_y = \beta_y h_w \) is the electrical length of the vertical feed line conductor 221 (FIG. 7), of physical length \( h_w \), expressed in degrees, and \( \theta_0 = \beta_0 \alpha/2 \) is the phase shift between the image ground plane 139 and the physical boundary 136 of the Earth 133 (or lossy conducting medium 203). In the example of FIGS. 9A and 9B, \( Z_w \) is the characteristic impedance of the elevated vertical feed line conductor 221 in ohms, \( Z_c \) is the characteristic impedance of the coil 215 in ohms, and \( Z_0 \) is the characteristic impedance of free space.
At the base of the guided surface waveguide probe 200, the impedance seen "looking up" into the structure is \( Z^\dagger = Z_{\text{base}} \). With a load impedance of:

\[
Z_L = \frac{1}{j\omega C_T},
\]

where \( C_T \) is the self-capacitance of the charge terminal \( T_1 \), the impedance seen "looking up" into the vertical feed line conductor 221 (FIG. 7) is given by:

\[
z = \frac{Z_L + Z_W \tanh(j\theta_1)}{Z_W + Z_L \tanh(j\theta_2)} - Z_L + Z_L \tanh(j\theta_3),
\]

and the impedance seen "looking up" into the coil 215 (FIG. 7) is given by:

\[
Z_{\text{base}} = \frac{Z_L + Z_W \tanh(j\theta_1)}{Z_W + Z_L \tanh(j\theta_2)} - Z_L + Z_L \tanh(j\theta_3),
\]

At the base of the guided surface waveguide probe 200, the impedance seen "looking down" into the lossy conducting medium 203 is \( Z_\perp = Z_{\perp n} \), which is given by:

\[
Z_\perp = \frac{Z_\perp + Z_\perp \tanh\left(\frac{\delta}{2}\right)}{Z_\perp + Z_\perp \tanh\left(\frac{\delta}{2}\right)} - Z_\perp + Z_\perp \tanh\left(\frac{\delta}{2}\right),
\]

where \( Z_\perp = 0 \).

Neglecting losses, the equivalent image plane model can be tuned to resonance when \( Z_\perp + Z_\perp = 0 \) at the physical boundary 136. Or, in the low loss case, \( \chi_i + \chi_\perp = 0 \) at the physical boundary 136, where \( \chi \) is the corresponding reactive component. Thus, the impedance at the physical boundary 136 "looking up" into the guided surface waveguide probe 200 is the conjugate of the impedance at the physical boundary 136 "looking down" into the lossy conducting medium 203. By adjusting the load impedance \( Z_L \) of the charge terminal \( T_1 \) while maintaining the traveling wave phase delay \( \Phi \) equal to the angle of the media's wave tilt \( \Psi \), so that \( \Phi = \Psi \), which improves and/or maximizes coupling of the probe's electric field to a guided surface waveguide mode along the surface of the lossy conducting medium 203 (e.g., Earth), the equivalent image plane models of FIGS. 9A and 9B can be
tuned to resonance with respect to the image ground plane 139. In this way, the impedance of the equivalent complex image plane model is purely resistive, which maintains a superposed standing wave on the probe structure that maximizes the voltage and elevated charge on terminal $T_1$, and by equations (1)-(3) and (16) maximizes the propagating surface wave.

[0119] It follows from the Hankel solutions, that the guided surface wave excited by the guided surface waveguide probe 200 is an outward propagating traveling wave. The source distribution along the feed network 209 between the charge terminal $T_1$ and the ground stake 218 of the guided surface waveguide probe 200 (FIGS. 3 and 7) is actually composed of a superposition of a traveling wave plus a standing wave on the structure. With the charge terminal $T_1$ positioned at or above the physical height $h_p$, the phase delay of the traveling wave moving through the feed network 209 is matched to the angle of the wave tilt associated with the lossy conducting medium 203. This mode-matching allows the traveling wave to be launched along the lossy conducting medium 203. Once the phase delay has been established for the traveling wave, the load impedance $Z_L$ of the charge terminal $T_1$ is adjusted to bring the probe structure into standing wave resonance with respect to the image ground plane (130 of FIG. 3 or 139 of FIG. 8), which is at a complex depth of $-d/2$. In that case, the impedance seen from the image ground plane has zero reactance and the charge on the charge terminal $T_1$ is maximized.

[0120] The distinction between the traveling wave phenomenon and standing wave phenomena is that (1) the phase delay of traveling waves ($\theta = \beta \delta$) on a section of transmission line of length $d$ (sometimes called a "delay line") is due to propagation time delays; whereas (2) the position-dependent phase of standing waves (which are composed of forward and backward propagating waves) depends
on both the line length propagation time delay and impedance transitions at interfaces between line sections of different characteristic impedances. In addition to the phase delay that arises due to the physical length of a section of transmission line operating in sinusoidal steady-state, there is an extra reflection coefficient phase at impedance discontinuities that is due to the ratio of $Z_{oa}/Z_{ob}$, where $Z_{oa}$ and $Z_{ob}$ are the characteristic impedances of two sections of a transmission line such as, e.g., a helical coil section of characteristic impedance $Z_{oa} = Z_{c}$ (FIG. 9B) and a straight section of vertical feed line conductor of characteristic impedance $Z_{ob} = Z_{w}$ (FIG. 9B).

[0121] As a result of this phenomenon, two relatively short transmission line sections of widely differing characteristic impedance may be used to provide a very large phase shift. For example, a probe structure composed of two sections of transmission line, one of low impedance and one of high impedance, together totaling a physical length of, say, 0.05 $\lambda$, may be fabricated to provide a phase shift of 90° which is equivalent to a 0.25 $\lambda$ resonance. This is due to the large jump in characteristic impedances. In this way, a physically short probe structure can be electrically longer than the two physical lengths combined. This is illustrated in FIGS. 9A and 9B, where the discontinuities in the impedance ratios provide large jumps in phase. The impedance discontinuity provides a substantial phase shift where the sections are joined together.

[0122] Referring to FIG. 10, shown is a flow chart 150 illustrating an example of adjusting a guided surface waveguide probe 200 (FIGS. 3 and 7) to substantially mode-match to a guided surface waveguide mode on the surface of the lossy conducting medium, which launches a guided surface traveling wave along the surface of a lossy conducting medium 203 (FIG. 3). Beginning with 153, the charge
terminal T of the guided surface waveguide probe 200 is positioned at a defined height above a lossy conducting medium 203. Utilizing the characteristics of the lossy conducting medium 203 and the operating frequency of the guided surface waveguide probe 200, the Hankel crossover distance can also be found by equating the magnitudes of Equations (20b) and (21) for \(-j\beta p\), and solving for \(R_x\) as illustrated by FIG. 4. The complex index of refraction \((n)\) can be determined using Equation (41), and the complex Brewster angle \((\theta_{i,B})\) can then be determined from Equation (42). The physical height \((h_p)\) of the charge terminal \(T_1\) can then be determined from Equation (44). The charge terminal \(T_1\) should be at or higher than the physical height \((h_p)\) in order to excite the far-out component of the Hankel function. This height relationship is initially considered when launching surface waves. To reduce or minimize the bound charge on the charge terminal \(T-i\), the height should be at least four times the spherical diameter (or equivalent spherical diameter) of the charge terminal \(T-i\).

At 156, the electrical phase delay \(\Phi\) of the elevated charge \(Q_i\) on the charge terminal \(T_1\) is matched to the complex wave tilt angle \(\Psi\). The phase delay \((\theta_d)\) of the helical coil and/or the phase delay \((\theta_y)\) of the vertical feed line conductor can be adjusted to make \(\Phi\) equal to the angle \((\Psi)\) of the wave tilt \((W)\). Based on Equation (31), the angle \((\Psi)\) of the wave tilt can be determined from:

\[
W = \frac{E_d}{E_x} = \frac{1}{\tan \theta_{i,B}} = \frac{1}{n} = |W| e^{i\Psi}.
\]  

The electrical phase \(\Phi\) can then be matched to the angle of the wave tilt. This angular (or phase) relationship is next considered when launching surface waves. For example, the electrical phase delay \(\Phi = \theta_d + \theta_y\) can be adjusted by varying the geometrical parameters of the coil 215 (FIG. 7) and/or the length (or height) of the
vertical feed line conductor 221 (FIG. 7). By matching $\Phi = \Psi$, an electric field can be
established at or beyond the Hankel crossover distance $(R_s)$ with a complex
Brewster angle at the boundary interface to excite the surface waveguide mode and
launch a traveling wave along the lossy conducting medium 203.

[0124] Next at 159, the load impedance of the charge terminal $\tau_1$ is tuned to
resonate the equivalent image plane model of the guided surface waveguide probe
200. The depth $(d/2)$ of the conducting image ground plane 139 of FIG. 9A and 9B
(or 130 of FIG. 3) can be determined using Equations (52), (53) and (54) and the
values of the lossy conducting medium 203 (e.g., the Earth), which can be
measured. Using that depth, the phase shift $(\theta_o)$ between the image ground plane
139 and the physical boundary 136 of the lossy conducting medium 203 can be
determined using $\theta_o = \beta_0 d/2$. The impedance $(Z_{in})$ as seen "looking down" into the
lossy conducting medium 203 can then be determined using Equation (65). This
resonance relationship can be considered to maximize the launched surface waves.

[0125] Based upon the adjusted parameters of the coil 215 and the length of the
vertical feed line conductor 221, the velocity factor, phase delay, and impedance of
the coil 215 and vertical feed line conductor 221 can be determined using Equations
(45) through (51). In addition, the self-capacitance $(C_T)$ of the charge terminal $\tau_1$
can be determined using, e.g., Equation (24). The propagation factor $(\beta_{wp})$ of the coil 215
can be determined using Equation (35) and the propagation phase constant $(\gamma_{wp})$ for
the vertical feed line conductor 221 can be determined using Equation (49). Using
the self-capacitance and the determined values of the coil 215 and vertical feed line
conductor 221, the impedance $(Z_{base})$ of the guided surface waveguide probe 200 as
seen "looking up" into the coil 215 can be determined using Equations (62), (63) and
(64).
The equivalent image plane model of the guided surface waveguide probe 200 can be tuned to resonance by adjusting the load impedance $z_L$ such that the reactance component $X_{\text{base}}$ of $Z_{\text{base}}$ cancels out the reactance component $X_{in}$ of $Z_{in}$, i.e., $X_{\text{base}} + X_{in} = 0$. Thus, the impedance at the physical boundary 136 "looking up" into the guided surface waveguide probe 200 is the conjugate of the impedance at the physical boundary 136 "looking down" into the lossy conducting medium 203. The load impedance $z_L$ can be adjusted by varying the capacitance ($C_r$) of the charge terminal $T_1$ without changing the electrical phase delay $\Phi = \Phi_x + \phi_y$ of the charge terminal $T-i$. An iterative approach may be taken to tune the load impedance $z_L$ for resonance of the equivalent image plane model with respect to the conducting image ground plane 139 (or 130). In this way, the coupling of the electric field to a guided surface waveguide mode along the surface of the lossy conducting medium 203 (e.g., Earth) can be improved and/or maximized.

This may be better understood by illustrating the situation with a numerical example. Consider a guided surface waveguide probe 200 comprising a top-loaded vertical stub of physical height $h_p$ with a charge terminal $T_1$ at the top, where the charge terminal $T_1$ is excited through a helical coil and vertical feed line conductor at an operational frequency ($f_p$) of 1.85 MHz. With a height (H-i) of 16 feet and the lossy conducting medium 203 (e.g., Earth) having a relative permittivity of $\varepsilon_r = 15$ and a conductivity of $\sigma = 0.010$ mhos/m, several surface wave propagation parameters can be calculated for $f_p = 1.850$ MHz. Under these conditions, the Hankel crossover distance can be found to be $R_+ = 54.5$ feet with a physical height of $h_p = 5.5$ feet, which is well below the actual height of the charge terminal $T-i$. While a charge terminal height of $H_1 = 5.5$ feet could have been used, the taller probe structure reduced the bound capacitance, permitting a greater percentage of
free charge on the charge terminal \( \tau \), providing greater field strength and excitation of the traveling wave.

[0128] The wave length can be determined as:

\[
\lambda_0 = \frac{c}{f_o} = 162.162 \text{ meters},
\]

(67)

where \( c \) is the speed of light. The complex index of refraction is:

\[
n = \sqrt{\varepsilon_r - jx} = 7.529 - 6.546,
\]

(68)

from Equation (41), where \( x = \sigma_t / \omega \varepsilon_0 \) with \( \omega = 2\pi / \lambda_0 \), and the complex Brewster angle is:

\[
\theta_{B_{ff}} = \arctan (J \varepsilon_r - jx) = 85.6 - 3.744^\circ.
\]

(69)

from Equation (42). Using Equation (66), the wave tilt values can be determined to be:

\[
W = \tan^{-1} \frac{1}{\tan \theta_{B_{ff}}} = \frac{1}{\tan} = \frac{1}{\tan} = 0.10 \text{ e}^{40.614^\circ}.
\]

(70)

Thus, the helical coil can be adjusted to match \( \Phi = \Psi = 40.614^\circ \).

[0129] The velocity factor of the vertical feed line conductor (approximated as a uniform cylindrical conductor with a diameter of 0.27 inches) can be given as

\[ V_w = 0.93. \]

Since \( h_p / \lambda_0 \), the propagation phase constant for the vertical feed line conductor can be approximated as:

\[
\beta_w = \frac{2\pi}{V_w \lambda_0} = 0.042 \text{ m}^{-1}.
\]

(71)

From Equation (49) the phase delay of the vertical feed line conductor is:

\[
Q_w = \beta_w h_w = 11.640^\circ.
\]

(72)

By adjusting the phase delay of the helical coil so that \( \delta_c = 28.974^\circ = 40.614^\circ - 11.640^\circ \), \( \Phi \) will equal \( \Psi \) to match the guided surface waveguide mode. To illustrate the relationship between \( \Phi \) and \( \Psi \), FIG. 11 shows a plot of both over a range of
frequencies. As both $\Phi$ and $\Psi$ are frequency dependent, it can be seen that their respective curves cross over each other at approximately 1.85 MHz.

[0130] For a helical coil having a conductor diameter of 0.0881 inches, a coil diameter $(D)$ of 30 inches and a turn-to-turn spacing $(s)$ of 4 inches, the velocity factor for the coil can be determined using Equation (45) as:

$$V = \frac{1}{\sqrt{1 + 20\left(\frac{D}{s}\right)^2}^{0.5}} = 0.069,$$  \hspace{1cm} (73)

and the propagation factor from Equation (35) is:

$$\beta_p = \frac{2\pi}{V_f a_0} = 0.564 \text{ m}^{-1}. \hspace{1cm} (74)$$

With $\theta_c = 28.974^\circ$, the axial length of the solenoidal helix $(H)$ can be determined using Equation (46) such that:

$$H = \frac{\theta_c}{\beta_p} = 35.2732 \text{ inches}. \hspace{1cm} (75)$$

This height determines the location on the helical coil where the vertical feed line conductor is connected, resulting in a coil with 8.818 turns $(N = H/s)$.

[0131] With the traveling wave phase delay of the coil and vertical feed line conductor adjusted to match the wave tilt angle $(\Phi = \theta_c + \Psi)$, the load impedance $(Z_i)$ of the charge terminal $T_1$ can be adjusted for standing wave resonance of the equivalent image plane model of the guided surface wave probe 200. From the measured permittivity, conductivity and permeability of the Earth, the radial propagation constant can be determined using Equation (57)

$$\gamma_e = \sqrt{\omega U_1(\sigma_1 + j\omega \varepsilon_1)} = 0.25 + j \ 0.292 \text{ m}^{-1},$$  \hspace{1cm} (76)

And the complex depth of the conducting image ground plane can be approximated from Equation (52) as:

$$d = \frac{2}{\gamma_e} = 3.364 + \cdot \ 3.963 \text{ meters}, \hspace{1cm} (77)$$
with a corresponding phase shift between the conducting image ground plane and the physical boundary of the Earth given by:

$$\theta_d = \beta_0 \left( \frac{\alpha}{2} \right) = 4.015 - 74.73^\circ. \quad (78)$$

Using Equation (65), the impedance seen "looking down" into the lossy conducting medium 203 (i.e., Earth) can be determined as:

$$Z_{in} = Z_0 \tanh(j \theta_d) = R_{in} + jX_{in} = 31.191 + j26.27 \text{ ohms.} \quad (79)$$

[0132] By matching the reactive component \( (X_{in}) \) seen "looking down" into the lossy conducting medium 203 with the reactive component \( (X_{bas}) \) seen "looking up" into the guided surface wave probe 200, the coupling into the guided surface waveguide mode may be maximized. This can be accomplished by adjusting the capacitance of the charge terminal \( \mathcal{O} \) without changing the traveling wave phase delays of the coil and vertical feed line conductor. For example, by adjusting the charge terminal capacitance \( (C_T) \) to 61.8126 pF, the load impedance from Equation (62) is:

$$Z_L = \frac{1}{j \omega C_T} = -j1392 \text{ ohms,} \quad (80)$$

and the reactive components at the boundary are matched.

[0133] Using Equation (51), the impedance of the vertical feed line conductor (having a diameter \((2a)\) of 0.27 inches) is given as

$$Z_w = 138 \log \left( \frac{1.153 \sqrt{W}}{2 \pi a} \right) = 537.534 \text{ ohms,} \quad (81)$$

and the impedance seen "looking up" into the vertical feed line conductor is given by Equation (63) as:

$$Z_2 = \frac{Z_w Z_L \tanh(\beta_0 d)}{Z_w + Z_L \tanh(j \theta_d)} = -j835.438 \text{ ohms.} \quad (82)$$

Using Equation (47), the characteristic impedance of the helical coil is given as

$$Z_c = \frac{V_f}{j \pi} \left[ \frac{n}{e \left( \frac{\sqrt{\pi} a}{D} \right) - 1.027} \right] = 1446 \text{ ohms,} \quad (83)$$
and the impedance seen "looking up" into the coil at the base is given by Equation
(64) as:

\[
Z_{b_{\text{seen}}} = Z_{cc} + \frac{Z_{2} + \tan^{-1}(j\theta_{c})}{Z_{4} + \tan^{-1}(j\theta_{b})} = -j \cdot 26.271 \text{ ohms.}
\] (84)

When compared to the solution of Equation (79), it can be seen that the reactive
components are opposite and approximately equal, and thus are conjugates of each
other. Thus, the impedance \((Z_p)\) seen "looking up" into the equivalent image plane
model of FIGS. 9A and 9B from the perfectly conducting image ground plane is only
resistive or \(Z_p = R + j\phi\).

[0134] When the electric fields produced by a guided surface waveguide probe
200 (FIG. 3) are established by matching the traveling wave phase delay of the feed
network to the wave tilt angle and the probe structure is resonated with respect to
the perfectly conducting image ground plane at complex depth \(z = -d/2\), the fields
are substantially mode-matched to a guided surface waveguide mode on the surface
of the lossy conducting medium, a guided surface traveling wave is launched along
the surface of the lossy conducting medium. As illustrated in FIG. 1, the guided field
strength curve 103 of the guided electromagnetic field has a characteristic
exponential decay of \(e^{-\alpha d/\sqrt{\alpha}}\) and exhibits a distinctive knee 109 on the log-log
scale.

[0135] In summary, both analytically and experimentally, the traveling wave
component on the structure of the guided surface waveguide probe 200 has a phase
delay \(\phi\) at its upper terminal that matches the angle \(\psi\) of the wave tilt of the
surface traveling wave \(\phi = \psi\). Under this condition, the surface waveguide may be
considered to be "mode-matched". Furthermore, the resonant standing wave
component on the structure of the guided surface waveguide probe 200 has a \(V_{\text{MAX}}\)
at the charge terminal \(\text{T}\) and a \(V_{\text{MIN}}\) down at the image plane 139 (FIG. 8B) where
\[ z_{i_p} = r_{i_p} + j 0 \] at a complex depth of \( z = -d/2 \), not at the connection at the physical boundary 136 of the lossy conducting medium 203 (FIG. 8B). Lastly, the charge terminal \( \tau'_{1} \) is of sufficient height \( h \) of FIG. 3 \((h \geq R_x \tan \psi_{\text{B}})\) so that electromagnetic waves incident onto the lossy conducting medium 203 at the complex Brewster angle do so out at a distance \(( \geq R_x)\) where the \( l/Vr \) term is predominant. Receive circuits can be utilized with one or more guided surface waveguide probes to facilitate wireless transmission and/or power delivery systems.

[0136] Referring back to FIG. 3, operation of a guided surface waveguide probe 200 may be controlled to adjust for variations in operational conditions associated with the guided surface waveguide probe 200. For example, an adaptive probe control system 230 can be used to control the feed network 209 and/or the charge terminal \( \tau'_{1} \) to control the operation of the guided surface waveguide probe 200. Operational conditions can include, but are not limited to, variations in the characteristics of the lossy conducting medium 203 (e.g., conductivity \( \sigma \) and relative permittivity \( \varepsilon_r \)), variations in field strength and/or variations in loading of the guided surface waveguide probe 200. As can be seen from Equations (31), (41) and (42), the index of refraction \( n \), the complex Brewster angle \( \theta_{\text{B}} \), and the wave tilt \( (|\psi| e^{i \psi}) \) can be affected by changes in soil conductivity and permittivity resulting from, e.g., weather conditions.

[0137] Equipment such as, e.g., conductivity measurement probes, permittivity sensors, ground parameter meters, field meters, current monitors and/or load receivers can be used to monitor for changes in the operational conditions and provide information about current operational conditions to the adaptive probe control system 230. The probe control system 230 can then make one or more adjustments to the guided surface waveguide probe 200 to maintain specified
operational conditions for the guided surface waveguide probe 200. For instance, as the moisture and temperature vary, the conductivity of the soil will also vary. Conductivity measurement probes and/or permittivity sensors may be located at multiple locations around the guided surface waveguide probe 200. Generally, it would be desirable to monitor the conductivity and/or permittivity at or about the Hankel crossover distance $R_x$ for the operational frequency. Conductivity measurement probes and/or permittivity sensors may be located at multiple locations (e.g., in each quadrant) around the guided surface waveguide probe 200.

[01 38] The conductivity measurement probes and/or permittivity sensors can be configured to evaluate the conductivity and/or permittivity on a periodic basis and communicate the information to the probe control system 230. The information may be communicated to the probe control system 230 through a network such as, but not limited to, a LAN, WLAN, cellular network, or other appropriate wired or wireless communication network. Based upon the monitored conductivity and/or permittivity, the probe control system 230 may evaluate the variation in the index of refraction ($n$), the complex Brewster angle ($\theta_{iB}$), and/or the wave tilt ($\|W\|e^{j\psi}$) and adjust the guided surface waveguide probe 200 to maintain the phase delay ($\Phi$) of the feed network 209 equal to the wave tilt angle ($\psi$) and/or maintain resonance of the equivalent image plane model of the guided surface waveguide probe 200. This can be accomplished by adjusting, e.g., $Q_y$, $Q_c$ and/or $C_T$. For instance, the probe control system 230 can adjust the self-capacitance of the charge terminal $T_1$ and/or the phase delay ($\theta_y$, $\theta_c$) applied to the charge terminal $T_1$ to maintain the electrical launching efficiency of the guided surface wave at or near its maximum. For example, the self-capacitance of the charge terminal $T_1$ can be varied by changing the size of the terminal. The charge distribution can also be improved by increasing
the size of the charge terminal \( T_1 \), which can reduce the chance of an electrical discharge from the charge terminal \( T_1 \). In other embodiments, the charge terminal \( T_1 \) can include a variable inductance that can be adjusted to change the load impedance \( Z_L \). The phase applied to the charge terminal \( T_1 \) can be adjusted by varying the tap position on the coil 215 (FIG. 7), and/or by including a plurality of predefined taps along the coil 215 and switching between the different predefined tap locations to maximize the launching efficiency.

[0139] Field or field strength (FS) meters may also be distributed about the guided surface waveguide probe 200 to measure field strength of fields associated with the guided surface wave. The field or FS meters can be configured to detect the field strength and/or changes in the field strength (e.g., electric field strength) and communicate that information to the probe control system 230. The information may be communicated to the probe control system 230 through a network such as, but not limited to, a LAN, WLAN, cellular network, or other appropriate communication network. As the load and/or environmental conditions change or vary during operation, the guided surface waveguide probe 200 may be adjusted to maintain specified field strength(s) at the FS meter locations to ensure appropriate power transmission to the receivers and the loads they supply.

[0140] For example, the phase delay \( (\Phi = \theta_y + \theta_C) \) applied to the charge terminal \( T_1 \) can be adjusted to match the wave tilt angle \( (\Psi) \). By adjusting one or both phase delays, the guided surface waveguide probe 200 can be adjusted to ensure the wave tilt corresponds to the complex Brewster angle. This can be accomplished by adjusting a tap position on the coil 215 (FIG. 7) to change the phase delay supplied to the charge terminal \( T_1 \). The voltage level supplied to the charge terminal \( T_1 \) can also be increased or decreased to adjust the electric field.
strength. This may be accomplished by adjusting the output voltage of the excitation source 212 or by adjusting or reconfiguring the feed network 209. For instance, the position of the tap 227 (FIG. 7) for the AC source 212 can be adjusted to increase the voltage seen by the charge terminal T₁. Maintaining field strength levels within predefined ranges can improve coupling by the receivers, reduce ground current losses, and avoid interference with transmissions from other guided surface waveguide probes 200.

[0141] The probe control system 230 can be implemented with hardware, firmware, software executed by hardware, or a combination thereof. For example, the probe control system 230 can include processing circuitry including a processor and a memory, both of which can be coupled to a local interface such as, for example, a data bus with an accompanying control/address bus as can be appreciated by those with ordinary skill in the art. A probe control application may be executed by the processor to adjust the operation of the guided surface waveguide probe 200 based upon monitored conditions. The probe control system 230 can also include one or more network interfaces for communicating with the various monitoring devices. Communications can be through a network such as, but not limited to, a LAN, WLAN, cellular network, or other appropriate communication network. The probe control system 230 may comprise, for example, a computer system such as a server, desktop computer, laptop, or other system with like capability.

[0142] Referring back to the example of FIG. 5A, the complex angle trigonometry is shown for the ray optic interpretation of the incident electric field (E) of the charge terminal T₁ with a complex Brewster angle (θ₁,β₁) at the Hankel crossover distance (Rₓ). Recall that, for a lossy conducting medium, the Brewster angle is complex and
specified by equation (38). Electrically, the geometric parameters are related by the
electrical effective height \( h_{\text{eff}} \) of the charge terminal \( \mathcal{T}_1 \) by equation (39). Since
both the physical height \( h_p \) and the Hankel crossover distance \( R_x \) are real
quantities, the angle of the desired guided surface wave tilt at the Hankel crossover
distance \( W_{Rx} \) is equal to the phase (\( \Phi \)) of the complex effective height \( h_{\text{eff}} \). With
the charge terminal \( \mathcal{T}_1 \) positioned at the physical height \( h_p \) and excited with a charge
having the appropriate phase \( \Phi \), the resulting electric field is incident with the lossy
conducting medium boundary interface at the Hankel crossover distance \( R_x \), and at
the Brewster angle. Under these conditions, the guided surface waveguide mode
can be excited without reflection or substantially negligible reflection.

[0143] However, Equation (39) means that the physical height of the guided
surface waveguide probe 200 can be relatively small. While this will excite the
guided surface waveguide mode, this can result in an unduly large bound charge
with little free charge. To compensate, the charge terminal \( \mathcal{T}_1 \) can be raised to an
appropriate elevation to increase the amount of free charge. As one example rule of
thumb, the charge terminal \( \mathcal{T}_1 \) can be positioned at an elevation of about 4-5 times
(or more) the effective diameter of the charge terminal \( \mathcal{T}_1 \). FIG. 6 illustrates the
effect of raising the charge terminal \( \mathcal{T}_1 \) above the physical height \( h_p \) shown in FIG. 5A. The increased elevation causes the distance at which the wave tilt is incident
with the lossy conductive medium to move beyond the Hankel crossover point 121
(FIG. 5A). To improve coupling in the guided surface waveguide mode, and thus
provide for a greater launching efficiency of the guided surface wave, a lower
compensation terminal \( \mathcal{T}_2 \) can be used to adjust the total effective height \( h_{\text{TE}} \) of the
charge terminal \( \mathcal{T}_1 \) such that the wave tilt at the Hankel crossover distance is at the
Brewster angle.
Referring to FIG. 12, shown is an example of a guided surface waveguide probe 200c that includes an elevated charge terminal \( T_1 \) and a lower compensation terminal \( T_2 \) that are arranged along a vertical axis \( z \) that is normal to a plane presented by the lossy conducting medium 203. In this respect, the charge terminal \( T_1 \) is placed directly above the compensation terminal \( T_2 \) although it is possible that some other arrangement of two or more charge and/or compensation terminals \( T_n \) can be used. The guided surface waveguide probe 200c is disposed above a lossy conducting medium 203 according to an embodiment of the present disclosure. The lossy conducting medium 203 makes up Region 1 with a second medium 206 that makes up Region 2 sharing a boundary interface with the lossy conducting medium 203.

The guided surface waveguide probe 200c includes a feed network 209 that couples an excitation source 212 to the charge terminal \( T_1 \) and the compensation terminal \( T_2 \). According to various embodiments, charges \( Q_1 \) and \( Q_2 \) can be imposed on the respective charge and compensation terminals \( T_1 \) and \( T_2 \), depending on the voltages applied to terminals \( T_1 \) and \( T_2 \) at any given instant. \( I_1 \) is the conduction current feeding the charge \( Q_1 \) on the charge terminal \( T_1 \) via the terminal lead, and \( I_2 \) is the conduction current feeding the charge \( Q_2 \) on the compensation terminal \( T_2 \) via the terminal lead.

According to the embodiment of FIG. 12, the charge terminal \( T_1 \) is positioned over the lossy conducting medium 203 at a physical height \( h_1 \), and the compensation terminal \( T_2 \) is positioned directly below \( T_1 \) along the vertical axis \( z \) at a physical height \( h_2 \), where \( h_2 \) is less than \( h_1 \). The height \( h \) of the transmission structure may be calculated as \( h = h_1 - h_2 \). The charge terminal \( T_1 \) has an isolated (or self) capacitance \( C_1 \), and the compensation terminal \( T_2 \) has an isolated (or self)
capacitance $C_2$. A mutual capacitance $C_M$ can also exist between the terminals $T_1$ and $T_2$ depending on the distance therebetween. During operation, charges $Q_1$ and $Q_2$ are imposed on the charge terminal $T_1$ and the compensation terminal $T_2$, respectively, depending on the voltages applied to the charge terminal $T_1$ and the compensation terminal $T_2$ at any given instant.

[0147] Referring next to FIG. 13, shown is a ray optics interpretation of the effects produced by the elevated charge $Q_1$ on charge terminal $T_1$ and compensation terminal $T_2$ of FIG. 12. With the charge terminal $T_1$ elevated to a height where the ray intersects with the lossy conductive medium at the Brewster angle at a distance greater than the Hankel crossover point $121$ as illustrated by line $163$, the compensation terminal $T_2$ can be used to adjust $h_{TE}$ by compensating for the increased height. The effect of the compensation terminal $T_2$ is to reduce the electrical effective height of the guided surface waveguide probe (or effectively raise the lossy medium interface) such that the wave tilt at the Hankel crossover distance is at the Brewster angle as illustrated by line $166$.

[0148] The total effective height can be written as the superposition of an upper effective height ($h_{UE}$) associated with the charge terminal $T_1$ and a lower effective height ($h_{LE}$) associated with the compensation terminal $T_2$ such that

$$h_{TE} = h_{UE} + h_{LE} = h_p e^{i(\beta h_p + \phi_y)} + h_d e^{i(\beta h_d + \phi_L)} = R_x X W,$$

where $\phi_y$ is the phase delay applied to the upper charge terminal $T_1$, $\phi_L$ is the phase delay applied to the lower compensation terminal $T_2$, $\beta = 2\pi/\lambda_p$ is the propagation factor from Equation (35), $h_p$ is the physical height of the charge terminal $T_1$ and $h_d$ is the physical height of the compensation terminal $T_2$. If extra lead lengths are taken into consideration, they can be accounted for by adding the charge terminal lead length $z$ to the physical height $h_p$ of the charge terminal $T_1$ and...
the compensation terminal lead length \( y \) to the physical height \( h_d \) of the compensation terminal \( T_2 \) as shown in

\[
h_{\text{TE}} = (h_p + z)e^{j(\beta(t_p + z) + \Phi_U)} + (h_d + y)e^{j(\beta(t_d + y) + \Phi_L)} = R_x X W. \tag{86}
\]

The lower effective height can be used to adjust the total effective height \( (h_{\text{TE}}) \) to equal the complex effective height \( (h_{\text{eff}}) \) of FIG. 5A.

Equations (85) or (86) can be used to determine the physical height of the lower disk of the compensation terminal \( T_2 \) and the phase angles to feed the terminals in order to obtain the desired wave tilt at the Hankel crossover distance. For example, Equation (86) can be rewritten as the phase shift applied to the charge terminal \( T_1 \) as a function of the compensation terminal height \( (h_d) \) to give

\[
\Phi_{\text{y}}(h_d) = -\beta \left( h_p + z \right) - j \ln \left( \frac{R_x X W - (h_d + y)e^{j(\beta h_d + \beta y + \Phi_L)}}{h_p + z} \right). \tag{87}
\]

To determine the positioning of the compensation terminal \( T_2 \), the relationships discussed above can be utilized. First, the total effective height \( (h_{\text{TE}}) \) is the superposition of the complex effective height \( (h_{\text{UE}}) \) of the upper charge terminal \( T_1 \) and the complex effective height \( (h_{\text{LE}}) \) of the lower compensation terminal \( T_2 \) as expressed in Equation (86). Next, the tangent of the angle of incidence can be expressed geometrically as

\[
\tan \psi_E = \frac{\sqrt{2}L}{x}, \tag{88}
\]

which is equal to the definition of the wave tilt, \( W \). Finally, given the desired Hankel crossover distance \( R_x \), the \( h_{\text{TE}} \) can be adjusted to make the wave tilt of the incident ray match the complex Brewster angle at the Hankel crossover point 121. This can be accomplished by adjusting \( h_p, \Phi_{\text{y}}, \) and/or \( h_d \).

These concepts may be better understood when discussed in the context of an example of a guided surface waveguide probe. Referring to FIG. 14, shown is
a graphical representation of an example of a guided surface waveguide probe 200d including an upper charge terminal \( T_1 \) (e.g., a sphere at height \( h_T \)) and a lower compensation terminal \( T_2 \) (e.g., a disk at height \( h_d \)) that are positioned along a vertical axis \( z \) that is substantially normal to the plane presented by the lossy conducting medium 203. During operation, charges \( Q_1 \) and \( Q_2 \) are imposed on the charge and compensation terminals \( T_1 \) and \( T_2 \), respectively, depending on the voltages applied to the terminals \( T_1 \) and \( T_2 \) at any given instant.

[0152] An AC source 212 acts as the excitation source for the charge terminal \( T_1 \), which is coupled to the guided surface waveguide probe 200d through a feed network 209 comprising a coil 215 such as, e.g., a helical coil. The AC source 212 can be connected across a lower portion of the coil 215 through a tap 227, as shown in FIG. 14, or can be inductively coupled to the coil 215 by way of a primary coil. The coil 215 can be coupled to a ground stake 218 at a first end and the charge terminal \( T_1 \) at a second end. In some implementations, the connection to the charge terminal \( T_1 \) can be adjusted using a tap 224 at the second end of the coil 215. The compensation terminal \( T_2 \) is positioned above and substantially parallel with the lossy conducting medium 203 (e.g., the ground or Earth), and energized through a tap 233 coupled to the coil 215. An ammeter 236 located between the coil 215 and ground stake 218 can be used to provide an indication of the magnitude of the current flow \( (I_0) \) at the base of the guided surface waveguide probe. Alternatively, a current clamp may be used around the conductor coupled to the ground stake 218 to obtain an indication of the magnitude of the current flow \( (I_0) \).

[0153] In the example of FIG. 14, the coil 215 is coupled to a ground stake 218 at a first end and the charge terminal \( T_1 \) at a second end via a vertical feed line conductor 221. In some implementations, the connection to the charge terminal \( T_1 \)
can be adjusted using a tap 224 at the second end of the coil 215 as shown in FIG. 14. The coil 215 can be energized at an operating frequency by the AC source 212 through a tap 227 at a lower portion of the coil 215. In other implementations, the AC source 212 can be inductively coupled to the coil 215 through a primary coil. The compensation terminal T2 is energized through a tap 233 coupled to the coil 215. An ammeter 236 located between the coil 215 and ground stake 218 can be used to provide an indication of the magnitude of the current flow at the base of the guided surface waveguide probe 200d. Alternatively, a current clamp may be used around the conductor coupled to the ground stake 218 to obtain an indication of the magnitude of the current flow. The compensation terminal T2 is positioned above and substantially parallel with the lossy conducting medium 203 (e.g., the ground).

[0154] In the example of FIG. 14, the connection to the charge terminal T1 located on the coil 215 above the connection point of tap 233 for the compensation terminal T2. Such an adjustment allows an increased voltage (and thus a higher charge Qi) to be applied to the upper charge terminal T1. In other embodiments, the connection points for the charge terminal T1 and the compensation terminal T2 can be reversed. It is possible to adjust the total effective height \( h_{TE} \) of the guided surface waveguide probe 200d to excite an electric field having a guided surface wave tilt at the Hankel crossover distance \( R_\lambda \). The Hankel crossover distance can also be found by equating the magnitudes of equations (20b) and (21) for \(-j\beta_p\), and solving for \( R_\lambda \) as illustrated by FIG. 4. The index of refraction \((n)\), the complex Brewster angle \((\theta_{i,b} \text{ and } \psi_{i,b})\), the wave tilt \((i\omega e^{i\omega})\) and the complex effective height \((h_{eff} = h_e \theta^{i\theta})\) can be determined as described with respect to Equations (41) - (44) above.
With the selected charge terminal Τ₁ configuration, a spherical diameter (or the effective spherical diameter) can be determined. For example, if the charge terminal Τ is not configured as a sphere, then the terminal configuration may be modeled as a spherical capacitance having an effective spherical diameter. The size of the charge terminal Τ₁ can be chosen to provide a sufficiently large surface for the charge Q₁ imposed on the terminals. In general, it is desirable to make the charge terminal Τ₁ as large as practical. The size of the charge terminal Τ₁ should be large enough to avoid ionization of the surrounding air, which can result in electrical discharge or sparking around the charge terminal. To reduce the amount of bound charge on the charge terminal Τ₁, the desired elevation to provide free charge on the charge terminal Τ₁ for launching a guided surface wave should be at least 4-5 times the effective spherical diameter above the lossy conductive medium (e.g., the Earth).

The compensation terminal Τ₂ can be used to adjust the total effective height (h_{TE}) of the guided surface waveguide probe 200d to excite an electric field having a guided surface wave tilt at R_x. The compensation terminal Τ₂ can be positioned below the charge terminal Τ₁ at h_d = h_T - h_p, where h_T is the total physical height of the charge terminal Τ₁. With the position of the compensation terminal Τ₂ fixed and the phase delay Φ_u applied to the upper charge terminal Τ₁, the phase delay Φ_L applied to the lower compensation terminal Τ₂ can be determined using the relationships of Equation (86), such that:

\[ \Phi_L(h_d) = -\beta(h_d + y) - j \ln \left( \frac{R_x x W - (h_p + z) e^{j(\beta h_p + \beta x + \Phi_L)}}{(h_d + y)} \right). \]  

In alternative embodiments, the compensation terminal Τ₂ can be positioned at a height h_d where \text{Im}(0_L) = 0. This is graphically illustrated in FIG. 15A, which shows plots 172 and 175 of the imaginary and real parts of Φ_u, respectively.
compensation terminal $T_2$ is positioned at a height $h_d$ where $\text{Im}(O_y) = 0$, as graphically illustrated in plot 172. At this fixed height, the coil phase $\Phi_y$ can be determined from $\text{Re}(O_y)$, as graphically illustrated in plot 175.

[0156] With the AC source 212 coupled to the coil 215 (e.g., at the $50\Omega$ point to maximize coupling), the position of tap 233 may be adjusted for parallel resonance of the compensation terminal $T_2$ with at least a portion of the coil at the frequency of operation. FIG. 15B shows a schematic diagram of the general electrical hookup of FIG. 14 in which $V_1$ is the voltage applied to the lower portion of the coil 215 from the AC source 212 through tap 227, $V_2$ is the voltage at tap 224 that is supplied to the upper charge terminal $T_1$, and $V_3$ is the voltage applied to the lower compensation terminal $T_2$ through tap 233. The resistances $R_p$ and $R_d$ represent the ground return resistances of the charge terminal $T_1$ and compensation terminal $T_2$, respectively. The charge and compensation terminals $T_1$ and $T_2$ may be configured as spheres, cylinders, toroids, rings, hoods, or any other combination of capacitive structures. The size of the charge and compensation terminals $T_1$ and $T_2$ can be chosen to provide a sufficiently large surface for the charges $Q_1$ and $Q_2$ imposed on the terminals. In general, it is desirable to make the charge terminal $T_1$ as large as practical. The size of the charge terminal $T_1$ should be large enough to avoid ionization of the surrounding air, which can result in electrical discharge or sparking around the charge terminal. The self-capacitance $C_p$ and $C_d$ of the charge and compensation terminals $T_1$ and $T_2$ respectively, can be determined using, for example, equation (24).

[0157] As can be seen in FIG. 15B, a resonant circuit is formed by at least a portion of the inductance of the coil 215, the self-capacitance $C_d$ of the compensation terminal $T_2$, and the ground return resistance $R_d$ associated with the compensation
terminal T₂. The parallel resonance can be established by adjusting the voltage V₃ applied to the compensation terminal T₂ (e.g., by adjusting a tap 233 position on the coil 215) or by adjusting the height and/or size of the compensation terminal T₂ to adjust cₐ. The position of the coil tap 233 can be adjusted for parallel resonance, which will result in the ground current through the ground stake 218 and through the ammeter 236 reaching a maximum point. After parallel resonance of the compensation terminal T₂ has been established, the position of the tap 227 for the AC source 212 can be adjusted to the 50Ω point on the coil 215.

[0158] Voltage V₂ from the coil 215 can be applied to the charge terminal T₁, and the position of tap 224 can be adjusted such that the phase (Φ) of the total effective height (hₖₑ) approximately equals the angle of the guided surface wave tilt (Wₖₓ) at the Hankel crossover distance (Rₓ). The position of the coil tap 224 can be adjusted until this operating point is reached, which results in the ground current through the ammeter 236 increasing to a maximum. At this point, the resultant fields excited by the guided surface waveguide probe 200d are substantially mode-matched to a guided surface waveguide mode on the surface of the lossy conducting medium 203, resulting in the launching of a guided surface wave along the surface of the lossy conducting medium 203. This can be verified by measuring field strength along a radial extending from the guided surface waveguide probe 200.

[0159] Resonance of the circuit including the compensation terminal T₂ may change with the attachment of the charge terminal T₁ and/or with adjustment of the voltage applied to the charge terminal T₁ through tap 224. While adjusting the compensation terminal circuit for resonance aids the subsequent adjustment of the charge terminal connection, it is not necessary to establish the guided surface wave tilt (Wₖₓ) at the Hankel crossover distance (Rₓ). The system may be further adjusted
to improve coupling by iteratively adjusting the position of the tap 227 for the AC source 212 to be at the 50Ω point on the coil 215 and adjusting the position of tap 233 to maximize the ground current through the ammeter 236. Resonance of the circuit including the compensation terminal T₂ may drift as the positions of taps 227 and 233 are adjusted, or when other components are attached to the coil 215.

[0160] In other implementations, the voltage V₂ from the coil 215 can be applied to the charge terminal T₁, and the position of tap 233 can be adjusted such that the phase (Φ) of the total effective height (h_TE) approximately equals the angle (Ψ) of the guided surface wave tilt at R₄. The position of the coil tap 224 can be adjusted until the operating point is reached, resulting in the ground current through the ammeter 236 substantially reaching a maximum. The resultant fields are substantially mode-matched to a guided surface waveguide mode on the surface of the lossy conducting medium 203, and a guided surface wave is launched along the surface of the lossy conducting medium 203. This can be verified by measuring field strength along a radial extending from the guided surface waveguide probe 200. The system may be further adjusted to improve coupling by iteratively adjusting the position of the tap 227 for the AC source 212 to be at the 50Ω point on the coil 215 and adjusting the position of tap 224 and/or 233 to maximize the ground current through the ammeter 236.

[0161] Referring back to FIG. 12, operation of a guided surface waveguide probe 200 may be controlled to adjust for variations in operational conditions associated with the guided surface waveguide probe 200. For example, a probe control system 230 can be used to control the feed network 209 and/or positioning of the charge terminal T₁ and/or compensation terminal T₂ to control the operation of the guided surface waveguide probe 200. Operational conditions can include, but are not
limited to, variations in the characteristics of the lossy conducting medium 203 (e.g., conductivity $\sigma$ and relative permittivity $\varepsilon_r$), variations in field strength and/or variations in loading of the guided surface waveguide probe 200. As can be seen from Equations (41) - (44), the index of refraction ($n$), the complex Brewster angle ($\theta_{i,B}$ and $\psi_{i,B}$), the wave tilt ($iW|e^{j\psi}$) and the complex effective height ($h_{eff} = h_p e^{j\psi}$) can be affected by changes in soil conductivity and permittivity resulting from, e.g., weather conditions.

[0162] Equipment such as, e.g., conductivity measurement probes, permittivity sensors, ground parameter meters, field meters, current monitors and/or load receivers can be used to monitor for changes in the operational conditions and provide information about current operational conditions to the probe control system 230. The probe control system 230 can then make one or more adjustments to the guided surface waveguide probe 200 to maintain specified operational conditions for the guided surface waveguide probe 200. For instance, as the moisture and temperature vary, the conductivity of the soil will also vary. Conductivity measurement probes and/or permittivity sensors may be located at multiple locations around the guided surface waveguide probe 200. Generally, it would be desirable to monitor the conductivity and/or permittivity at or about the Hankel crossover distance $R_x$ for the operational frequency. Conductivity measurement probes and/or permittivity sensors may be located at multiple locations (e.g., in each quadrant) around the guided surface waveguide probe 200.

[0163] With reference then to FIG. 16, shown is an example of a guided surface waveguide probe 200e that includes a charge terminal $T_1$ and a charge terminal $T_2$ that are arranged along a vertical axis z. The guided surface waveguide probe 200e is disposed above a lossy conducting medium 203, which makes up Region 1. In
addition, a second medium 206 shares a boundary interface with the lossy conducting medium 203 and makes up Region 2. The charge terminals T₁ and T₂ are positioned over the lossy conducting medium 203. The charge terminal T₁ is positioned at height H₁, and the charge terminal T₂ is positioned directly below T₁ along the vertical axis z at height H₂, where H₂ is less than H₁. The height h of the transmission structure presented by the guided surface waveguide probe 200e is h = H₁ - H₂. The guided surface waveguide probe 200e includes a feed network 209 that couples an excitation source 212 to the charge terminals T₁ and T₂.

[0164] The charge terminals T₁ and/or T₂ include a conductive mass that can hold an electrical charge, which may be sized to hold as much charge as practically possible. The charge terminal T₁ has a self-capacitance C₁, and the charge terminal T₂ has a self-capacitance C₂, which can be determined using, for example, equation (24). By virtue of the placement of the charge terminal T₁ directly above the charge terminal T₂, a mutual capacitance C_M is created between the charge terminals T₁ and T₂. Note that the charge terminals T₁ and T₂ need not be identical, but each can have a separate size and shape, and can include different conducting materials. Ultimately, the field strength of a guided surface wave launched by a guided surface waveguide probe 200e is directly proportional to the quantity of charge on the terminal T₁. The charge Q₁ is, in turn, proportional to the self-capacitance C₁ associated with the charge terminal T₁ since Q₁ = C₁V, where V is the voltage imposed on the charge terminal T₁.

[0165] When properly adjusted to operate at a predefined operating frequency, the guided surface waveguide probe 200e generates a guided surface wave along the surface of the lossy conducting medium 203. The excitation source 212 can generate electrical energy at the predefined frequency that is applied to the guided
surface waveguide probe 200e to excite the structure. When the electromagnetic fields generated by the guided surface waveguide probe 200e are substantially mode-matched with the lossy conducting medium 203, the electromagnetic fields substantially synthesize a wave front incident at a complex Brewster angle that results in little or no reflection. Thus, the surface waveguide probe 200e does not produce a radiated wave, but launches a guided surface traveling wave along the surface of a lossy conducting medium 203. The energy from the excitation source 212 can be transmitted as Zenneck surface currents to one or more receivers that are located within an effective transmission range of the guided surface waveguide probe 200e.

One can determine asymptotes of the radial Zenneck surface current \( J_p(\rho) \) on the surface of the lossy conducting medium 203 to be \( J_1(\rho) \) close-in and \( J_2(\rho) \) far-out, where

\[
\text{Close-in (} \rho < \lambda/8\text{): } J_1(\rho) \sim J_1 = \frac{j \omega \sigma_1}{4 \pi \rho} \times \frac{2 \gamma}{\pi} \times \sqrt{\frac{2 \gamma}{\pi} \times e^{-(i \omega \gamma \beta) \rho}}. \tag{90}
\]

\[
\text{Far-out (} \rho \to \lambda/8\text{): } J_2(\rho) \sim J_2 = \frac{j \omega \sigma_1}{4 \pi \rho} \times \frac{2 \gamma}{\pi} \times \sqrt{\frac{2 \gamma}{\pi} \times e^{-(i \omega \gamma \beta) \rho}}. \tag{91}
\]

where \( l_1 \) is the conduction current feeding the charge \( Q_1 \) on the first charge terminal \( T_1 \), and \( l_2 \) is the conduction current feeding the charge \( Q_2 \) on the second charge terminal \( T_2 \). The charge \( Q_1 \) on the upper charge terminal \( T_1 \) is determined by \( Q_1 = C_1 V_1 \), where \( C_1 \) is the isolated capacitance of the charge terminal \( T_1 \). Note that there is a third component to \( J_1 \) set forth above given by \( (E_p^Q_1) / Z_p \), which follows from the Leontovich boundary condition and is the radial current contribution in the lossy conducting medium 203 pumped by the quasi-static field of the elevated oscillating charge on the first charge terminal \( Q_1 \). The quantity \( Z_p = j \omega \sigma / \gamma_\beta \) is the radial impedance of the lossy conducting medium, where \( \gamma_\beta = (j \omega \sigma_1 \sigma_1 - \omega^2 \mu_1 \epsilon_1)^{1/2} \).
The asymptotes representing the radial current close-in and far-out as set forth by equations (90) and (91) are complex quantities. According to various embodiments, a physical surface current $J(p)$, is synthesized to match as close as possible the current asymptotes in magnitude and phase. That is to say close-in, $|J(p)|$ is to be tangent to $U_1$, and far-out $|J(p)|$ is to be tangent to $U_2$. Also, according to the various embodiments, the phase of $J(p)$ should transition from the phase of $J_1$ close-in to the phase of $J_2$ far-out.

In order to match the guided surface wave mode at the site of transmission to launch a guided surface wave, the phase of the surface current $|J_2|$ far-out should differ from the phase of the surface current $U_1$ close-in by the propagation phase corresponding to $e^{-j\theta(p_2-p_1)}$ plus a constant of approximately 45 degrees or 225 degrees. This is because there are two roots for $\sqrt{r}$, one near $\pi/4$ and one near $5\pi/4$. The properly adjusted synthetic radial surface current is

$$J_\rho(p, \phi, 0) = \frac{i \omega}{4} H_1^{(2)}(-j\gamma p).$$

(92)

Note that this is consistent with equation (17). By Maxwell’s equations, such a $J(p)$ surface current automatically creates fields that conform to

$$H_\phi = \frac{-i a}{4} e^{-u_2 z} H_1^{(2)}(-j\gamma p),$$

(93)

$$H_\rho = \frac{-i a}{4} \left( \frac{u_3}{j \omega \varepsilon_0} \right) e^{-u_2 z} H_1^{(2)}(-j\gamma p),$$

(94)

$$E_z = -\gamma \phi (\omega) e^{-u_2 z} H_0^{(2)}(-j\gamma p).$$

(95)

Thus, the difference in phase between the surface current $U_2$ far-out and the surface current $U_1$ close-in for the guided surface wave mode that is to be matched is due to the characteristics of the Hankel functions in equations (93)-(95), which are consistent with equations (1)-(3). It is of significance to recognize that the fields expressed by equations (1)-(6) and (17) and equations (92)-(95) have the nature of a
transmission line mode bound to a lossy interface, not radiation fields that are associated with groundwave propagation.

[0169] In order to obtain the appropriate voltage magnitudes and phases for a given design of a guided surface waveguide probe 200e at a given location, an iterative approach may be used. Specifically, analysis may be performed of a given excitation and configuration of a guided surface waveguide probe 200e taking into account the feed currents to the terminals T1 and T2, the charges on the charge terminals T1 and T2, and their images in the lossy conducting medium 203 in order to determine the radial surface current density generated. This process may be performed iteratively until an optimal configuration and excitation for a given guided surface waveguide probe 200e is determined based on desired parameters. To aid in determining whether a given guided surface waveguide probe 200e is operating at an optimal level, a guided field strength curve 103 (FIG. 1) may be generated using equations (1)-(12) based on values for the conductivity of Region 1 (σ1) and the permittivity of Region 1 (ε) at the location of the guided surface waveguide probe 200e. Such a guided field strength curve 103 can provide a benchmark for operation such that measured field strengths can be compared with the magnitudes indicated by the guided field strength curve 103 to determine if optimal transmission has been achieved.

[0170] In order to arrive at an optimized condition, various parameters associated with the guided surface waveguide probe 200e may be adjusted. One parameter that may be varied to adjust the guided surface waveguide probe 200e is the height of one or both of the charge terminals T1 and/or T2 relative to the surface of the lossy conducting medium 203. In addition, the distance or spacing between the charge terminals T1 and T2 may also be adjusted. In doing so, one may minimize
or otherwise alter the mutual capacitance $C_M$ or any bound capacitances between the charge terminals $T_1$ and $T_2$ and the lossy conducting medium 203 as can be appreciated. The size of the respective charge terminals $T_1$ and/or $T_2$ can also be adjusted. By changing the size of the charge terminals $T_1$ and/or $T_2$, one will alter the respective self-capacitances $C_1$ and/or $C_2$, and the mutual capacitance $C_M$ as can be appreciated.

[0171] Still further, another parameter that can be adjusted is the feed network 209 associated with the guided surface waveguide probe 200e. This may be accomplished by adjusting the size of the inductive and/or capacitive reactances that make up the feed network 209. For example, where such inductive reactances comprise coils, the number of turns on such coils may be adjusted. Ultimately, the adjustments to the feed network 209 can be made to alter the electrical length of the feed network 209, thereby affecting the voltage magnitudes and phases on the charge terminals $T_1$ and $T_2$.

[0172] Note that the iterations of transmission performed by making the various adjustments may be implemented by using computer models or by adjusting physical structures as can be appreciated. By making the above adjustments, one can create corresponding "close-in" surface current $J_1$ and "far-out" surface current $J_2$ that approximate the same currents $J(p)$ of the guided surface wave mode specified in Equations (90) and (91) set forth above. In doing so, the resulting electromagnetic fields would be substantially or approximately mode-matched to a guided surface wave mode on the surface of the lossy conducting medium 203.

[0173] While not shown in the example of FIG. 16, operation of the guided surface waveguide probe 200e may be controlled to adjust for variations in operational conditions associated with the guided surface waveguide probe 200. For
example, a probe control system 230 shown in FIG. 12 can be used to control the feed network 209 and/or positioning and/or size of the charge terminals T1 and/or T2 to control the operation of the guided surface waveguide probe 200e. Operational conditions can include, but are not limited to, variations in the characteristics of the lossy conducting medium 203 (e.g., conductivity \( \sigma \) and relative permittivity \( \varepsilon_r \)), variations in field strength and/or variations in loading of the guided surface waveguide probe 200e.

[0174] Referring now to FIG. 17, shown is an example of the guided surface waveguide probe 200e of FIG. 16, denoted herein as guided surface waveguide probe 200f. The guided surface waveguide probe 200f includes the charge terminals T1 and T2 that are positioned along a vertical axis \( z \) that is substantially normal to the plane presented by the lossy conducting medium 203 (e.g., the Earth). The second medium 206 is above the lossy conducting medium 203. The charge terminal T1 has a self-capacitance \( C_1 \), and the charge terminal T2 has a self-capacitance \( C_2 \). During operation, charges \( Q_1 \) and \( Q_2 \) are imposed on the charge terminals T1 and T2, respectively, depending on the voltages applied to the charge terminals T1 and T2 at any given instant. A mutual capacitance \( C_M \) may exist between the charge terminals T1 and T2 depending on the distance there between. In addition, bound capacitances may exist between the respective charge terminals T1 and T2 and the lossy conducting medium 203 depending on the heights of the respective charge terminals T1 and T2 with respect to the lossy conducting medium 203.

[0175] The guided surface waveguide probe 200f includes a feed network 209 that comprises an inductive impedance comprising a coil \( L_{1a} \) having a pair of leads that are coupled to respective ones of the charge terminals T1 and T2. In one embodiment, the coil \( L_{1a} \) is specified to have an electrical length that is one-half (½)
of the wavelength at the operating frequency of the guided surface waveguide probe 200f.

[0176] While the electrical length of the coil $L_{1a}$ is specified as approximately one-half ($1/2$) the wavelength at the operating frequency, it is understood that the coil $L_{1a}$ may be specified with an electrical length at other values. According to one embodiment, the fact that the coil $L_{1a}$ has an electrical length of approximately one-half the wavelength at the operating frequency provides for an advantage in that a maximum voltage differential is created on the charge terminals $T_1$ and $T_2$. Nonetheless, the length or diameter of the coil $L_{1a}$ may be increased or decreased when adjusting the guided surface waveguide probe 200f to obtain optimal excitation of a guided surface wave mode. Adjustment of the coil length may be provided by taps located at one or both ends of the coil. In other embodiments, it may be the case that the inductive impedance is specified to have an electrical length that is significantly less than or greater than $1/2$ the wavelength at the operating frequency of the guided surface waveguide probe 200f.

[0177] The excitation source 212 can be coupled to the feed network 209 by way of magnetic coupling. Specifically, the excitation source 212 is coupled to a coil $L_p$ that is inductively coupled to the coil $L_{1a}$. This may be done by link coupling, a tapped coil, a variable reactance, or other coupling approach as can be appreciated. To this end, the coil $L_p$ acts as a primary, and the coil $L_{1a}$ acts as a secondary as can be appreciated.

[0178] In order to adjust the guided surface waveguide probe 200f for the transmission of a desired guided surface wave, the heights of the respective charge terminals $T_1$ and $T_2$ may be altered with respect to the lossy conducting medium 203 and with respect to each other. Also, the sizes of the charge terminals $T_1$ and $T_2$
may be altered. In addition, the size of the coil \( L_{1a} \) may be altered by adding or eliminating turns or by changing some other dimension of the coil \( L_{1a} \). The coil \( L_{1a} \) can also include one or more taps for adjusting the electrical length as shown in FIG. 17. The position of a tap connected to either charge terminal \( T_1 \) or \( T_2 \) can also be adjusted.

[0179] Referring next to FIGS. 18A, 18B, 18C and 19, shown are examples of generalized receive circuits for using the surface-guided waves in wireless power delivery systems. FIGS. 18A and 18B-18C include a linear probe 303 and a tuned resonator 306, respectively. FIG. 19 is a magnetic coil 309 according to various embodiments of the present disclosure. According to various embodiments, each one of the linear probe 303, the tuned resonator 306, and the magnetic coil 309 may be employed to receive power transmitted in the form of a guided surface wave on the surface of a lossy conducting medium 203 according to various embodiments. As mentioned above, in one embodiment the lossy conducting medium 203 comprises a terrestrial medium (or Earth).

[0180] With specific reference to FIG. 18A, the open-circuit terminal voltage at the output terminals 312 of the linear probe 303 depends upon the effective height of the linear probe 303. To this end, the terminal point voltage may be calculated as

\[
V_T = \int_0^{h_e} E_{\text{inc}} \cdot dl, \tag{96}
\]

where \( E_{\text{inc}} \) is the strength of the incident electric field induced on the linear probe 303 in Volts per meter, \( dl \) is an element of integration along the direction of the linear probe 303, and \( h_e \) is the effective height of the linear probe 303. An electrical load 315 is coupled to the output terminals 312 through an impedance matching network 318.
When the linear probe 303 is subjected to a guided surface wave as described above, a voltage is developed across the output terminals 312 that may be applied to the electrical load 315 through a conjugate impedance matching network 318 as the case may be. In order to facilitate the flow of power to the electrical load 315, the electrical load 315 should be substantially impedance matched to the linear probe 303 as will be described below.

Referring to FIG. 18B, a ground current excited coil 306a possessing a phase shift equal to the wave tilt of the guided surface wave includes a charge terminal T_R that is elevated (or suspended) above the lossy conducting medium 203. The charge terminal T_R has a self-capacitance C_R. In addition, there may also be a bound capacitance (not shown) between the charge terminal T_R and the lossy conducting medium 203 depending on the height of the charge terminal T_R above the lossy conducting medium 203. The bound capacitance should preferably be minimized as much as is practicable, although this may not be entirely necessary in every instance.

The tuned resonator 306a also includes a receiver network comprising a coil L_R having a phase shift Φ. One end of the coil L_R is coupled to the charge terminal T_R, and the other end of the coil L_R is coupled to the lossy conducting medium 203. The receiver network can include a vertical supply line conductor that couples the coil L_R to the charge terminal T_R. To this end, the coil L_R (which may also be referred to as tuned resonator L_R·C_R) comprises a series-adjusted resonator as the charge terminal C_R and the coil L_R are situated in series. The phase delay of the coil L_R can be adjusted by changing the size and/or height of the charge terminal T_R, and/or adjusting the size of the coil L_R so that the phase Φ of the structure is
made substantially equal to the angle of the wave tilt $\Psi$. The phase delay of the vertical supply line can also be adjusted by, e.g., changing length of the conductor.

[0184] For example, the reactance presented by the self-capacitance $C_R$ is calculated as $\frac{1}{j\omega C_R}$. Note that the total capacitance of the structure 306a may also include capacitance between the charge terminal $T_R$ and the lossy conducting medium 203, where the total capacitance of the structure 306a may be calculated from both the self-capacitance $C_R$ and any bound capacitance as can be appreciated. According to one embodiment, the charge terminal $T_R$ may be raised to a height so as to substantially reduce or eliminate any bound capacitance. The existence of a bound capacitance may be determined from capacitance measurements between the charge terminal $T_R$ and the lossy conducting medium 203 as previously discussed.

[0185] The inductive reactance presented by a discrete-element coil $L_R$ may be calculated as $j\omega L$, where $L$ is the lumped-element inductance of the coil $L_R$. If the coil $L_R$ is a distributed element, its equivalent terminal-point inductive reactance may be determined by conventional approaches. To tune the structure 306a, one would make adjustments so that the phase delay is equal to the wave tilt for the purpose of mode-matching to the surface waveguide at the frequency of operation. Under this condition, the receiving structure may be considered to be "mode-matched" with the surface waveguide. A transformer link around the structure and/or an impedance matching network 324 may be inserted between the probe and the electrical load 327 in order to couple power to the load. Inserting the impedance matching network 324 between the probe terminals 321 and the electrical load 327 can effect a conjugate-match condition for maximum power transfer to the electrical load 327.
When placed in the presence of surface currents at the operating frequencies power will be delivered from the surface guided wave to the electrical load 327. To this end, an electrical load 327 may be coupled to the structure 306a by way of magnetic coupling, capacitive coupling, or conductive (direct tap) coupling. The elements of the coupling network may be lumped components or distributed elements as can be appreciated.

In the embodiment shown in FIG. 18B, magnetic coupling is employed where a coil l_s is positioned as a secondary relative to the coil L_R that acts as a transformer primary. The coil l_s may be link-coupled to the coil L_R by geometrically winding it around the same core structure and adjusting the coupled magnetic flux as can be appreciated. In addition, while the receiving structure 306a comprises a series-tuned resonator, a parallel-tuned resonator or even a distributed-element resonator of the appropriate phase delay may also be used.

While a receiving structure immersed in an electromagnetic field may couple energy from the field, it can be appreciated that polarization-matched structures work best by maximizing the coupling, and conventional rules for probe-coupling to waveguide modes should be observed. For example, a TE_{20} (transverse electric mode) waveguide probe may be optimal for extracting energy from a conventional waveguide excited in the TE_{20} mode. Similarly, in these cases, a mode-matched and phase-matched receiving structure can be optimized for coupling power from a surface-guided wave. The guided surface wave excited by a guided surface waveguide probe 200 on the surface of the lossy conducting medium 203 can be considered a waveguide mode of an open waveguide. Excluding waveguide losses, the source energy can be completely recovered. Useful receiving structures may be E-field coupled, H-field coupled, or surface-current excited.
The receiving structure can be adjusted to increase or maximize coupling with the guided surface wave based upon the local characteristics of the lossy conducting medium 203 in the vicinity of the receiving structure. To accomplish this, the phase delay ($\Phi$) of the receiving structure can be adjusted to match the angle ($\Psi$) of the wave tilt of the surface traveling wave at the receiving structure. If configured appropriately, the receiving structure may then be tuned for resonance with respect to the perfectly conducting image ground plane at complex depth $z = -d/2$.

For example, consider a receiving structure comprising the tuned resonator 306a of FIG. 18B, including a coil $L_R$ and a vertical supply line connected between the coil $L_R$ and a charge terminal $T_R$. With the charge terminal $T_R$ positioned at a defined height above the lossy conducting medium 203, the total phase shift $\Phi$ of the coil $L_R$ and vertical supply line can be matched with the angle ($\Psi$) of the wave tilt at the location of the tuned resonator 306a. From Equation (22), it can be seen that the wave tilt asymptotically passes to

$$W = |W|e^{i\Psi} = \frac{\varepsilon_0}{\varepsilon_r} \rho \rightarrow \frac{1}{\varepsilon_r - j\sigma_1},$$

(97)

where $\varepsilon_r$ comprises the relative permittivity and $\sigma_1$ is the conductivity of the lossy conducting medium 203 at the location of the receiving structure, $\varepsilon_0$ is the permittivity of free space, and $\omega = 2nf$, where $f$ is the frequency of excitation. Thus, the wave tilt angle ($\Psi$) can be determined from Equation (97).

The total phase shift ($\Phi = \vartheta_C + \vartheta_Y$) of the tuned resonator 306a includes both the phase delay ($\vartheta_C$) through the coil $L_R$ and the phase delay of the vertical supply line ($\vartheta_Y$). The spatial phase delay along the conductor length $l_w$ of the vertical supply line can be given by $\vartheta_Y = \rho_w ZW$, where $\rho_w$ is the propagation phase constant.
for the vertical supply line conductor. The phase delay due to the coil (or helical delay line) is
\[ \phi = \beta_p I_c, \]
with a physical length of \( l_c \) and a propagation factor of
\[ \beta_p = \frac{2\pi}{\lambda_p} = \frac{2\pi}{V_f \lambda_0}, \]
where \( V_f \) is the velocity factor on the structure, \( \lambda_0 \) is the wavelength at the supplied frequency, and \( \lambda_p \) is the propagation wavelength resulting from the velocity factor \( V_f \).
One or both of the phase delays \( (\theta_c + \theta_p) \) can be adjusted to match the phase shift \( \Phi \) to the angle \( (\Psi') \) of the wave tilt. For example, a tap position may be adjusted on the coil \( L_R \) of FIG. 18B to adjust the coil phase delay \( (\theta_c) \) to match the total phase shift to the wave tilt angle \( (\Phi = \Psi') \). For example, a portion of the coil can be bypassed by the tap connection as illustrated in FIG. 18B. The vertical supply line conductor can also be connected to the coil \( L_R \) via a tap, whose position on the coil may be adjusted to match the total phase shift to the angle of the wave tilt.

**[0192]** Once the phase delay \( (\Phi) \) of the tuned resonator 306a has been adjusted, the impedance of the charge terminal \( T_R \) can then be adjusted to tune to resonance with respect to the perfectly conducting image ground plane at complex depth \( z = -d/2 \). This can be accomplished by adjusting the capacitance of the charge terminal \( T_1 \) without changing the traveling wave phase delays of the coil \( L_R \) and vertical supply line. The adjustments are similar to those described with respect to FIGS. 9A and 9B.

**[0193]** The impedance seen "looking down" into the lossy conducting medium 203 to the complex image plane is given by:
\[ Z_{in} = R_{in} + jX_{in} = Z_o \tanh(j\beta_o(d/2)), \]
where \( \beta_o = \omega \sqrt{\mu_o \varepsilon_o} \). For vertically polarized sources over the Earth, the depth of the complex image plane can be given by:
\[ \frac{d}{2} \approx \frac{1}{\sqrt{j\omega \mu_1 \sigma_1 - \omega^2 \mu_1 \varepsilon_1}}, \]  
(100)

where \( \mu \) is the permeability of the lossy conducting medium 203 and \( \varepsilon_1 = \varepsilon_r \varepsilon_0 \).

[01 94] At the base of the tuned resonator 306a, the impedance seen "looking up" into the receiving structure is \( Z_i = Z_{\text{base}} \), as illustrated in FIG. 9A. With a terminal impedance of:

\[ Z_R = \frac{1}{j\omega C_R}, \]  
(101)

where \( C_R \) is the self-capacitance of the charge terminal \( T_R \), the impedance seen "looking up" into the vertical supply line conductor of the tuned resonator 306a is given by:

\[ Z_z = \frac{Z_R + Z_w \tanh(j\beta_w b_w)}{Z_R + Z_w \tanh(j\beta_w b_w)}, \]  
(102)

and the impedance seen "looking up" into the coil \( L_R \) of the tuned resonator 306a is given by:

\[ Z_{\text{base}} = R_{\text{base}} + jX_{\text{base}} = \frac{7}{Z_R + Z_w \tanh(j\beta_w b_w)} + Z_c \left( \frac{Z_R + Z_w \tanh(j\beta_w b_w)}{Z_R + Z_w \tanh(j\beta_w b_w)} \right). \]  
(103)

By matching the reactive component \( (X_{\text{in}}) \) seen "looking down" into the lossy conducting medium 203 with the reactive component \( (X_{\text{base}}) \) seen "looking up" into the tuned resonator 306a, the coupling into the guided surface waveguide mode may be maximized.

[01 95] Referring next to FIG. 18C, shown is an example of a tuned resonator 306b that does not include a charge terminal \( T_R \) at the top of the receiving structure. In this embodiment, the tuned resonator 306b does not include a vertical supply line coupled between the coil \( L_R \) and the charge terminal \( T_R \). Thus, the total phase shift \( (\Phi) \) of the tuned resonator 306b includes only the phase delay \( (\theta_c) \) through the coil \( L_R \). As with the tuned resonator 306a of FIG. 18B, the coil phase delay \( \theta_c \) can be adjusted to match the angle \( (\Psi) \) of the wave tilt determined from Equation (97),
which results in $\Phi = \Psi$. While power extraction is possible with the receiving structure coupled into the surface waveguide mode, it is difficult to adjust the receiving structure to maximize coupling with the guided surface wave without the variable reactive load provided by the charge terminal $T_R$.

[01 96] Referring to FIG. 18D, shown is a flow chart 180 illustrating an example of adjusting a receiving structure to substantially mode-match to a guided surface waveguide mode on the surface of the lossy conducting medium 203. Beginning with 181, if the receiving structure includes a charge terminal $T_R$ (e.g., of the tuned resonator 306a of FIG. 18B), then the charge terminal $T_R$ is positioned at a defined height above a lossy conducting medium 203 at 184. As the surface guided wave has been established by a guided surface waveguide probe 200, the physical height ($h_p$) of the charge terminal $T_R$ may be below that of the effective height. The physical height may be selected to reduce or minimize the bound charge on the charge terminal $T_R$ (e.g., four times the spherical diameter of the charge terminal). If the receiving structure does not include a charge terminal $T_R$ (e.g., of the tuned resonator 306b of FIG. 18C), then the flow proceeds to 187.

[01 97] At 187, the electrical phase delay $\Phi$ of the receiving structure is matched to the complex wave tilt angle $\Psi$ defined by the local characteristics of the lossy conducting medium 203. The phase delay ($\theta_C$) of the helical coil and/or the phase delay ($\theta_V$) of the vertical supply line can be adjusted to make $\Phi$ equal to the angle ($\Psi$) of the wave tilt ($\omega$). The angle ($\Psi$) of the wave tilt can be determined from Equation (86). The electrical phase $\Phi$ can then be matched to the angle of the wave tilt. For example, the electrical phase delay $\Phi = \theta_C + \theta_V$ can be adjusted by varying the geometrical parameters of the coil $L_R$ and/or the length (or height) of the vertical supply line conductor.
Next at 190, the load impedance of the charge terminal $T_R$ can be tuned to resonate the equivalent image plane model of the tuned resonator 306a. The depth $(d/2)$ of the conducting image ground plane 139 (FIG. 9A) below the receiving structure can be determined using Equation (100) and the values of the lossy conducting medium 203 (e.g., the Earth) at the receiving structure, which can be locally measured. Using that complex depth, the phase shift ($\theta_d$) between the image ground plane 139 and the physical boundary 136 (FIG. 9A) of the lossy conducting medium 203 can be determined using $\theta_d = \beta_d d/2$. The impedance $(Z_{in})$ as seen "looking down" into the lossy conducting medium 203 can then be determined using Equation (99). This resonance relationship can be considered to maximize coupling with the guided surface waves.

Based upon the adjusted parameters of the coil $L_R$ and the length of the vertical supply line conductor, the velocity factor, phase delay, and impedance of the coil $L_R$ and vertical supply line can be determined. In addition, the self-capacitance $(C_R)$ of the charge terminal $T_R$ can be determined using, e.g., Equation (24). The propagation factor $(\beta_r)$ of the coil $L_R$ can be determined using Equation (98), and the propagation phase constant $(\gamma_r)$ for the vertical supply line can be determined using Equation (49). Using the self-capacitance and the determined values of the coil $L_R$ and vertical supply line, the impedance $(Z_{base})$ of the tuned resonator 306a as seen "looking up" into the coil $L_R$ can be determined using Equations (101), (102), and (103).

The equivalent image plane model of FIG. 9A also applies to the tuned resonator 306a of FIG. 18B. The tuned resonator 306a can be tuned to resonance with respect to the complex image plane by adjusting the load impedance $Z_R$ of the charge terminal $T_R$ such that the reactance component $X_{base}$ of $Z_{base}$ cancels out the
reactance component of $X_{in}$ of $Z_{in}$, or $X_{base} + X_{in} = 0$. Thus, the impedance at the physical boundary 136 (FIG. 9A) "looking up" into the coil of the tuned resonator 306a is the conjugate of the impedance at the physical boundary 136 "looking down" into the lossy conducting medium 203. The load impedance $Z_R$ can be adjusted by varying the capacitance ($C_R$) of the charge terminal $T_R$ without changing the electrical phase delay $\Phi = \varphi_c + \varphi_y$ seen by the charge terminal $T_R$. An iterative approach may be taken to tune the load impedance $Z_R$ for resonance of the equivalent image plane model with respect to the conducting image ground plane 139. In this way, the coupling of the electric field to a guided surface waveguide mode along the surface of the lossy conducting medium 203 (e.g., Earth) can be improved and/or maximized.

[0201] Referring to FIG. 19, the magnetic coil 309 comprises a receive circuit that is coupled through an impedance matching network 333 to an electrical load 336. In order to facilitate reception and/or extraction of electrical power from a guided surface wave, the magnetic coil 309 may be positioned so that the magnetic flux of the guided surface wave, $\mathbf{H}_\perp$, passes through the magnetic coil 309, thereby inducing a current in the magnetic coil 309 and producing a terminal point voltage at its output terminals 330. The magnetic flux of the guided surface wave coupled to a single turn coil is expressed by

$$\mathcal{F} = \int_{\mathcal{L}_S} \mu_r \mu_0 \mathbf{H} \cdot \hat{n} d\mathbf{A}$$

(104)

where $T$ is the coupled magnetic flux, $\mu_r$ is the effective relative permeability of the core of the magnetic coil 309, $\mu_0$ is the permeability of free space, $\mathbf{H}$ is the incident magnetic field strength vector, $\hat{n}$ is a unit vector normal to the cross-sectional area of the turns, and $\mathcal{L}_s$ is the area enclosed by each loop. For an N-turn magnetic coil 309 oriented for maximum coupling to an incident magnetic field that is uniform over
the cross-sectional area of the magnetic coil 309, the open-circuit induced voltage appearing at the output terminals 330 of the magnetic coil 309 is

\[ V = -N \frac{d\Phi}{dt} \approx -j\omega \mu_\text{r} \mu_0 N A \frac{c}{2} \]

where the variables are defined above. The magnetic coil 309 may be tuned to the guided surface wave frequency either as a distributed resonator or with an external capacitor across its output terminals 330, as the case may be, and then impedance-matched to an external electrical load 336 through a conjugate impedance matching network 333.

[0202] Assuming that the resulting circuit presented by the magnetic coil 309 and the electrical load 336 are properly adjusted and conjugate impedance matched, via impedance matching network 333, then the current induced in the magnetic coil 309 may be employed to optimally power the electrical load 336. The receive circuit presented by the magnetic coil 309 provides an advantage in that it does not have to be physically connected to the ground.

[0203] With reference to FIGS. 18A, 18B, 18C and 19, the receive circuits presented by the linear probe 303, the mode-matched structure 306, and the magnetic coil 309 each facilitate receiving electrical power transmitted from any one of the embodiments of guided surface waveguide probes 200 described above. To this end, the energy received may be used to supply power to an electrical load 315/327/336 via a conjugate matching network as can be appreciated. This contrasts with the signals that may be received in a receiver that were transmitted in the form of a radiated electromagnetic field. Such signals have very low available power, and receivers of such signals do not load the transmitters.

[0204] It is also characteristic of the present guided surface waves generated using the guided surface waveguide probes 200 described above that the receive
circuits presented by the linear probe 303, the mode-matched structure 306, and the magnetic coil 309 will load the excitation source 212 (e.g., FIGS. 3, 12 and 16) that is applied to the guided surface waveguide probe 200, thereby generating the guided surface wave to which such receive circuits are subjected. This reflects the fact that the guided surface wave generated by a given guided surface waveguide probe 200 described above comprises a transmission line mode. By way of contrast, a power source that drives a radiating antenna that generates a radiated electromagnetic wave is not loaded by the receivers, regardless of the number of receivers employed.

[0205] Thus, together one or more guided surface waveguide probes 200 and one or more receive circuits in the form of the linear probe 303, the tuned mode-matched structure 306, and/or the magnetic coil 309 can make up a wireless distribution system. Given that the distance of transmission of a guided surface wave using a guided surface waveguide probe 200 as set forth above depends upon the frequency, it is possible that wireless power distribution can be achieved across wide areas and even globally.

[0206] The conventional wireless-power transmission/distribution systems extensively investigated today include "energy harvesting" from radiation fields and also sensor coupling to inductive or reactive near-fields. In contrast, the present wireless-power system does not waste power in the form of radiation which, if not intercepted, is lost forever. Nor is the presently disclosed wireless-power system limited to extremely short ranges as with conventional mutual-reactance coupled near-field systems. The wireless-power system disclosed herein probe-couples to the novel surface-guided transmission line mode, which is equivalent to delivering power to a load by a wave-guide or a load directly wired to the distant power
generator. Not counting the power required to maintain transmission field strength plus that dissipated in the surface waveguide, which at extremely low frequencies is insignificant relative to the transmission losses in conventional high-tension power lines at 60 Hz, all of the generator power goes only to the desired electrical load. When the electrical load demand is terminated, the source power generation is relatively idle.

[0207] Referring next to FIGS. 20A-E, shown are examples of various schematic symbols that are used with reference to the discussion that follows. With specific reference to FIG. 20A, shown is a symbol that represents any one of the guided surface waveguide probes 200a, 200b, 200c, 200e, 200d, 200f, or any variations thereof. In the following drawings and discussion, a depiction of this symbol will be referred to as a guided surface waveguide probe P. In the following discussion, any reference to the guided surface waveguide probe P is a reference to any one of the guided surface waveguide probes 200a, 200b, 200c, 200e, 200d, 200f, or variations thereof.

[0208] Similarly, with reference to FIG. 20B, shown is a symbol that represents a guided surface wave receive structure that may comprise any one of the linear probe 303 (FIG. 18A), the tuned resonator 306 (FIGS. 18B-18C), or the magnetic coil 309 (FIG. 19). In the following drawings and discussion, a depiction of this symbol will be referred to as a guided surface wave receive structure R. For the sake of simplicity in the following discussion, any reference to the guided surface wave receive structure R is a reference to any one of the linear probe 303, the tuned resonator 306, the magnetic coil 309, or variations thereof.

[0209] Further, with reference to FIG. 20C, shown is a symbol that specifically represents the linear probe 303 (FIG. 18A). In the following drawings and
discussion, a depiction of this symbol will be referred to as a guided surface wave receive structure Rp. For the sake of simplicity in the following discussion, any reference to the guided surface wave receive structure Rp is a reference to the linear probe 303 or variations thereof.

[0210] Further, with reference to FIG. 20D, shown is a symbol that specifically represents the tuned resonator 306 (FIGS. 18B-18C). In the following drawings and discussion, a depiction of this symbol will be referred to as a guided surface wave receive structure RR. For the sake of simplicity in the following discussion, any reference to the guided surface wave receive structure RR is a reference to the tuned resonator 306 or variations thereof.

[0211] Further, with reference to FIG. 20E, shown is a symbol that specifically represents the magnetic coil 309 (FIG. 19). In the following drawings and discussion, a depiction of this symbol will be referred to as a guided surface wave receive structure RM. For the sake of simplicity in the following discussion, any reference to the guided surface wave receive structure RM is a reference to the magnetic coil 309 or variations thereof.

[0212] Turning to FIG. 21, shown is a one example of a networked environment 400 according to various embodiments. The networked environment 400 includes a computing environment 403 that is in data communication with various devices through a network 412. The networked environment 400 also includes an external server 406 that is in data communication with various devices through the network 412. In addition, the networked environment 400 includes a guided surface waveguide probe P that is coupled to an excitation source 424. The excitation source 424 may comprise, for example, a generator or other type of power source as described above. The excitation source 424 is coupled to the network 412 and is
controlled by various signal received through the network 412 as will be described. The networked environment 400 further includes a sensing device 409 that is powered by a guided surface wave generated by the guided surface waveguide probe P. The sensing device 409 also communicates with devices on the network as will be described.

[0213] According to various embodiments, the computing environment 403 includes one or more data stores 418 and an operation application 421. The one or more data stores 418 include data representing devices 427. Associated with each device 427 is parameter data 430, location data 433, and/or identifying data 436. The sensing device 409 includes a guided surface wave receive structure R, an impedance matching network 439, power circuitry 442, an electric load 445, and potentially other components. According to one embodiment, the electric load 445 is experienced as a load at an excitation source coupled to the guided surface waveguide probe P.

[0214] The operation application 421 communicates with the excitation source 424 and the external server 406 via network 412. The operation application 421 directs the excitation source 424 to direct power to the guided surface waveguide probe P to generate a guided surface wave. The operation application 421 also communicates with the sensing device 409 via network 412 with the sensing device 409 communicating using a wireless data signal.

[0215] The guided surface wave receive structure R is configured to obtain electrical energy from the guided surface wave 415 traveling along a terrestrial medium. For example, the excitation source 424 generates power that is applied to the guided surface waveguide probe P. The excitation source 424 may be controlled by the operation application 421 through the network 412. The guided surface
waveguide probe $P$ transmits the guided surface wave 415. The guided surface wave receive structure $R$ obtains electrical energy from the guided surface wave 415 as was described above.

[0216] According to one embodiment, the guided surface waveguide probe $P$ is located local to the sensing device 409. In another embodiments, the guided surface waveguide probe $P$ is located hundreds and/or thousands of miles away from the sensing device 409. In some embodiments, the excitation source 424 is communicably connected to the network 412 such that components executed in the computing environment 403 can initiate a launching of a guided surface wave 415. In other embodiments, an excitation source 424 is coupled to the computing environment 403 as a peripheral device, such as via USB. The network 412 may include, for example, the Internet, intranets, extranets, wide area networks (WANs), local area networks (LANs), wired networks, wireless networks, or other suitable networks, etc., or any combination of two or more such networks. For example, such networks may comprise satellite networks, cable networks, Ethernet networks, and other types of networks.

[0217] With reference to FIGS. 22A through 22E, shown are various embodiments of sensing device 409, shown as sensing devices 409a, 409b, 409c, 409d, and 409e. The sensing devices 409a, 409b, 409c, 409d, and 409e include, for example, a guided surface wave receive structure $R$, and an impedance matching network 439, and power circuitry 442 as discussed with reference to FIG. 21. According to one embodiment, the power circuitry 442 may includes a power rectifier and a capacitor configured to produce a direct current (DC) voltage output. In some embodiments, the power circuitry 442 also includes one or more of a power storage circuit including a capacitor and/or a battery, a smoothing capacitor on the output of
the rectifier, a transformer, a DC choke or other components as deemed necessary to generate an appropriate output voltage based on the input voltage obtained from the guided surface waveguide receive structure R.

[0218] In FIG. 22A, shown is a sensing device 409a according to various embodiments. The sensing device 409a includes an electric load 445a. The electric load 445a comprises the power circuitry 442, a signal generation circuit 448, an RF signal transmitter 451, and/or potentially other components. The signal generation circuit 448 is communicably coupled to the RF signal transmitter 451. The signal generation circuit 448 and the RF signal transmitter 451 are coupled to the power circuitry 442. In some embodiments, the coupling is indirect to the power circuitry 442. As a non-limiting example, the RF signal transmitter 451 may receive power from the signal generation circuit 448 wherein the signal generation circuit 448 is powered by power circuitry 442.

[0219] According to one embodiment, the signal generation circuit 448 generates a specific frequency for transmission via the RF signal transmitter 451. The frequency generated by the signal generation circuit 448 may be fixed in hardware. The signal generation circuit 448 may generate only a single frequency, and the frequency may be fixed to multiples of a base frequency. In some embodiments, the frequencies are generated by applying a voltage to a crystal to create an oscillation. The multiples of the base frequency may require phase lock loop logic running in hardware or software on a computing device. The frequency may be programmatically set in a memory. In one embodiment, the signal generation circuit 448 generates packetized messages for transmission over the RF signal transmitter 451. These messages may contain a unique identifier for the sensing device 409a. The messages may be used to associate data to the sensing device 409a. Three or
more RF antennas may be used to detect a location of sensing device 409a using triangulation based in part on the transmission via the signal generation circuit 448.

[0220] In FIG. 22B, shown is a sensing device 409b according to various embodiments. The sensing device 409b includes an electric load 445b. The electric load 445b may include the power circuitry 442, the positioning circuitry 454, computing device 457, wireless circuitry 460, and potentially other components. The computing device 457 may be communicably coupled to the positioning circuitry 454 and/or wireless circuitry 460. The impedance matching network 439 and/or the power circuitry 442 may be coupled to positioning circuitry 454, computing device 457, and/or wireless circuitry 460.

[0221] According to one embodiment, the positioning circuitry 454 includes a GPS circuit configured to receive global positioning signals from remote transmitting devices. The positioning circuitry 454 may include an RF receiver and/or transmitter. In this embodiment, the positioning circuitry 454 reads a phase and time from the signals to calculate a current position of the sensing device 409b. The global positioning signals come from one or more satellites intended for global positioning and/or from one or more surface waveguide probes. In another embodiment, the positioning circuitry 454 receives transmissions from remote transmitting devices and determine a signal strength of the transmission. The positioning circuitry 454 may calculate a current position of the sensing device 409b based in part on the signal strength of the transmissions. The computing device may receive a digital representation of the RF transmission and calculates the location of the sensing device 409b.

[0222] The wireless circuitry 460 may include circuitry for wirelessly sending and receiving data to external devices. In one embodiment, the wireless circuitry utilizes
cell phone technology such as 3G, 4G, LTE, and other cell phone data communication technologies. The wireless circuitry may implement one or more of the following technologies: Zigby, Bluetooth, WIFI, Flutter, Greenvity, Redpine, Z-Wave, or other similar communication technologies. The computing device 457 may be configured to receive a position of the sensing device 457 from the positioning circuitry 454 and transmit the location via the wireless circuitry 460 to an external location. The wireless circuitry 460 may include a wide area network circuit and a local area network circuit. The computing device 457 may be configured to connect via the wireless circuitry to a first network with the wide area network circuit and a second network with the local area network circuit simultaneously.

[0223] The wireless circuitry 460 may provide a connection to one or more other sensing devices. The wireless circuitry 460 may include wireless routing capabilities. The wireless circuitry 460 may provide a bridge between the wide area network circuitry and the local area network circuitry. For example, the one or more other sensing devices may access the internet by connecting to the local area network circuitry to transmit messages from the wide area network circuitry. The local area network circuitry may include one or more wired networks. The wired network may carry communication signals via wired twisted pair Ethernet, fiber optic, coax cable, serial or parallel data lines, power lines, and/or various other mediums. The wired network may use communication technologies such as TCP/IP, UDP, USB, clocked data signals, RS485, RS232, X10, Insteon, and other known methods. A slave sensing device 409b may exclude the wide area network ability in wireless circuitry 460, and rather connect to the local area circuitry of another sensing device 409b.

[0224] In FIG. 22C, shown is a sensing device 409c according to various embodiments. The sensing device 409c may include an electric load 445c. The
electric load 445c may include the power circuitry 442, a physical parameter sensor 463, a computing device 457, wireless circuitry 460, and potentially other components. The physical parameter sensor 463 may be coupled to the impedance matching network 439 and/or the power circuitry 442. The physical parameter sensor 463 is configured to measure a physical parameter associated with a physical environment local to the physical parameter sensor 463. The physical parameter sensor 463 may be configured to sense a variety of different physical parameters. The physical parameter measured by the physical parameter sensor 463 may be associated with a physical environment local to the physical parameter sensor. Local, as used here to describe the physical parameter sensor 463, refers to sensing within a proximity of the sensing device 409c. For example, the physical parameter sensor 463 may sense temperature local to the sensing device 409c, but any heat sources emanating the heat measured need not be local to the sensing device 409c. As another example, the physical parameter sensor 463 may be configured to sense the presence of predefined substances such as gasses, chemicals, and other substances.

[0225] In some embodiments, the sensing device 409c comprises an active component, such as emitting and receiving radar to track motion, travel, or record images or video emitting and receiving infrared or ultraviolet light. An active radar component may reflect a radar wave from a distant physical item and sense the resulting reflecting wave local to the sensing device 409c. The physical parameters may include cloud height, temperature, humidity levels, presence of rain and snow, quantity of rain and snow, wind speed and direction, other weather parameters, ocean wave height, light from recording video or taking pictures, various biosensors, heart rate, and blood pressure. The physical parameters may also include the
presence of predefined substances such as gases, chemicals, and other substances.

[0226] The wireless circuitry 460 may be communicatively coupled to the physical parameter sensor 463. The wireless circuitry 460 may transmit a physical parameter measurement from the physical parameter sensor 463. The wireless circuitry 460 may transmit the physical parameter measurement continuously or may transmit the physical parameter measurement at a predefined interval. The computing device 457 may obtain the physical parameter measurement from the physical parameter sensor 463. The computing device 457 may transmit the physical parameter measurement via the wireless circuitry 460 to a desired endpoint such as to a computing environment 403 (FIG. 21).

[0227] In FIG. 22D, shown is sensing device 409d according to various embodiments. The sensing device 409d may include an electric load 445d, a power transmission line 475, and power grid 478. The electric load 445d may include power circuitry 446, communication circuitry 469, a computing device 472, and potentially other components. The power circuitry 446 and communication circuitry 469 may be connected to transmission line 475 to the power grid 478. The communication circuitry 469 may be communicably coupled to power transmission line 475. The communication circuitry 469 may be configured to communicate over the power grid 4015 using technologies such as X10, Insteon, PLC-BUS, UPB, and various other power line communication technologies. In other embodiments, communication circuitry 469 may communicate through various wireless or wired communication means as discussed herein.

[0228] The power grid 478 is connected to one or more sensing devices 484 (FIG. 23). The power grid 478 supplies power to the one or more sensing devices
The computing device 472 may be communicably coupled to communication circuitry 469. The computing device 472 may be configured to send and receive data via the communication circuitry 469. For example, the computing device 472 may communicate with the one or more sensing devices 484 via power transmission line 475 using the communication circuitry 469.

[0229] In FIG. 22E, shown is sensing and/or control device 409e according to various embodiments. The sensing and/or control device 409e may include an electric load 445e. The electric load 445e includes control circuitry 481 configured to utilize the guided surface wave to generate an emission. The control circuitry 481 may include output terminals connected to a light source, such as a remote street light, a light house, an infrared light, or an ultraviolet light. The control circuitry 481 may include a heat source or a heat sink, such as a heater or a refrigerator; include a pump for water, such as a sprinkler; control an output in response to receiving a guided surface wave, such as guided surface wave 415 (FIG. 21); and/or emit/control an output until a capacitor and/or battery within the power circuitry 442 is empty. In some embodiments, the sensing and/or control device 409e is a lighthouse used as a navigational aid for maritime pilots. In yet another embodiment, the sensing and/or control device 409e is used in combat to light up enemy territory. The sensing and/or control device 409e may operate as a refrigerator. The control circuitry 481 may include a compressor configured to compress gas or liquid from a low pressure side to a high pressure side.

[0230] According to some embodiments, the operation application 421 (FIG. 21) initiate the output of a guided surface wave 415 at an interval configured to ensure the capacitor and/or battery within the power circuitry 442 does not empty under ordinary operation. For example, a length of operation for a full charge may be
estimated by determining a storage quantity of electricity in the power circuitry 442 and dividing the storage quantity by a usage rate of electricity of the electric load 445e. A required frequency of transmission of a guided surface wave may be calculated by the length of operation divided by a time to fully charge the power circuitry 442. An actual frequency of transmission of a guided surface wave may exceed the required frequency of transmission to account for a change in battery life, a risk of error, and other reasons.

[0231] In various embodiments, the sensing and/or control device 409e and/or the sensing device 409c can be used in combination to monitor agricultural elements such as combining moisture sensing of ground conditions for plants combined with control of a watering system to provide optimal moisture for growing a specified crops. In other embodiments, the temperature can be measured in combination with control of a heater or refrigerating element. In these embodiments, the operation application 421 may be configured to process the physical parameter.

[0232] Turning to FIG. 23, shown is a remote physical parameter sensor 484 configured to receive power from a sensing device 409d via a power grid 478 according to various embodiments. The remote physical parameter sensor 484 may include a power circuitry 487, communication circuitry 490, a computing device 493, a physical parameter sensor 463, and potentially other components. In some embodiments, the communication circuitry 490, the computing device 493, and the physical parameter sensor 463 are all electrically coupled to power circuitry 487. The power circuitry 487 may be electrically coupled to the power grid 478 via the power transmission line 475. In some embodiments, the communication circuitry 490 is communicably coupled to the power transmission line 475 and the power grid 478.
The communication circuitry 490 may be configured to communicate over the power grid 478 using technologies such as X10, Insteon, PLC-BUS, UPB, and other power line communication technologies. The communication circuitry 490 may be configured to communicate via other wired or wireless networks, as described herein. The computing device 493 may be communicably coupled to the communication circuitry 490 and the physical parameter sensor 463. The computing device 493 is configured to communicate via the communication circuitry 490 with a sensing device, such as sensing device 409d (FIG. 22d).

The remote physical parameter sensor 484 may measure one or more physical parameters via physical parameter sensor 463. The computing device 493 may receive the measurement from the physical parameter sensor 463 and transmit the measurement to sensing device 409d via communication circuitry 490. In some embodiments, the sensing device 409d stores the measurements from one or more remote physical parameter sensors 484 into a memory associated with the computing device 457 of sensing device 409d. In some embodiments, the sensing device 409d transmits the measurements to a remote server via a Wide Area Network connection.

With reference to FIG. 24A, shown is a sensing environment according to various embodiments. The sensing environment includes a guided surface waveguide probe P, a computing environment 403, one or more sensing devices 409, a network 412, and one or more transceivers 499. The sensing devices 409 may communicate with the transceivers 499 via a wireless (Radio Frequency (RF)) communication path 502. The transceivers 499 are connected to the network 412. In some embodiments, three or more transceivers 499 are required to determine a
location of a sensing device 409 using triangulation based on a signal transmitted by such sensing device 409.

[0236] In some embodiments, the sensing devices 409 utilizes a power signal from surface guided save 415 to generate and emit a unique RF frequency via a signal generation circuit, such as via the signal generation circuit 448 (FIG. 22A). The transceivers 499 may receive the unique RF frequency with a phase, a time, and a signal strength from the sensing device 409. The time and signal strength may be transmitted via the network 412 to the computing environment 403. The computing environment 403 may triangulate the location of each of the one or more sensing devices 409 using the time and the signal strength from three or more of the transceivers 499.

[0237] The computing environment 403 may determine a location of each of the one or more sensing devices 409 using one or more transceivers without using triangulation. For example, the computing environment 403 may determine a proximity of the sensing device 409 to a transceiver 499 or range of possible locations of the sensing device 409 based in part on the signal strength. As a non-limiting example, a sensing device 409 may have a first proximity to a first transceiver 499 and a second proximity to a second transceiver 499. The computing environment 403 may calculate a reduced range of possible locations in which the sensing device 409 may be located based in part on the intersection of the first and second proximity.

[0238] The computing device 457 (FIG. 22B) may send the location of the sensing device 409 to the operation application 421 (FIG. 21) along with any identifying information, such as a unique identifier. In some embodiments, the unique identifier may be a hardware MAC Address, an IP address, a Global Unique
Identifier (GUID), or other known unique identifiers. The unique identifier is different for each sensing device 409. The one or more sensing devices 409 may wirelessly communicate via satellite internet. The communications between the computing environment 403 and the one or more sensing devices may involve a single technology or a variety of technologies described herein.

[0239] In one embodiment, the range of possible locations for each sensing device 409 is stored by the computing environment 403 into location data 433 (FIG. 21) associated with the respective sensing device 409. In other embodiments, the range of possible locations is used to expedite the location of a sensing device 409. The computing environment 403 may use trilateration to determine the range of possible locations of sensing devices 409.

[0240] In another embodiment, the positioning circuitry 454 (FIG. 22B) receives signals from the transceivers 499 and determines a position of the corresponding sensing device 409 based in part on a phase of the signal and data from the signal, such as a time. The transceiver 499 may be a GPS satellite and/or an RF antenna tower with a fixed position. In some embodiments, the position is determined in the positioning circuitry 454. In other embodiments, the signal characteristics and any signal data from the positioning device 454 are used by the computing device 457 (FIG. 22B) to calculate the position of the sensing device 409. In another embodiment, the computing environment 403 may obtain GPS information or the fixed position of the RF antenna tower a remote server and transmit the data to the one or more sensing devices 409 to expedite and/or facilitate the determination of a location.

[0241] As a non-limiting example, when the transceivers 499 are GPS satellites, the computing environment 403 may obtain orbital information for the GPS satellites
from a remote server via an internet connection. The orbital information may include one or more of ephemeris data, reference location data, and/or one or more reference times. The computing environment may initialize the GPS circuit, such as positioning circuitry 454 (FIG. 22B), with the orbital information to prevent the positioning circuitry 454 from having to download the orbital information via a slower GPS data signal. For example, the computing environment 403 may use Assisted Global Positioning System (AGPS) to improve location determination speeds.

[0242] Turning to FIG. 24B, shown is a sensing environment according to various embodiments. The sensing environment includes a guided surface waveguide probe P, a computing environment 403, one or more sensing devices 409, a network 412, one or more master sensing devices 517, and potentially other components. The master sensing device 517 comprises a sensing device 409 configured to perform the master functionality discussed herein.

[0243] The master sensing device 517 uses local area network circuitry in wireless circuitry 460 (as a host or master where appropriate) to receive communications from other sensing devices 409 and retransmit to the computing environment 403 using the wide area network circuitry in wireless circuitry 460. The sensing devices may communicate to the computing environment by connecting to a master sensing device 517, such as communication paths 520. The sensing devices 409 may communicate through the master sensing devices 517 using intermediary sensing devices 409, for example, over a grid style network such as Zigby, as shown as local area communication path 523.

[0244] In various embodiments, the communications from sensing devices 409 may include additional data for routing of messages in various layers. The network and transport layers of the ISO standard Open Systems Interconnection mode (OSI)
may contain additional or different data and/or may be modified, while the application layer, among others, may remain unchanged. For example, the value of the Time To Live of a UDP message may be set higher for a sensing device 409 than for a master sensing device 517, or the routing information may be modified by the master sensing device 517 when the master sensing device 517 includes a Network Access Translation layer.

[0245] With reference to FIG. 24C, shown is a sensing environment according to various embodiments. The sensing environment includes a guided surface waveguide probe P, a computing environment 403, one or more sensing devices 409d, a network 412, a power grid 478, and one or more remote physical parameter sensor 484. The sensing device 409d may communicate via a wireless connection to network 412. The sensing device 409d is electrically coupled to the one or more remote physical parameter sensors 484 through the power grid 478. The sensing device 409d receives power from a guided surface wave. The sensing device 409d provides power received from the guided surface wave to the one or more remote physical parameter sensors 484 via the power grid 478.

[0246] According to one embodiment, the sensing device 409d provides power from a guided surface wave to multiple remote physical parameter sensors 484, and each of the multiple remote physical parameter sensors sense a different physical parameter. Further, the sensing device 409d is communicably coupled to the one or more remote physical parameter sensors 484. The sensing device 409d may route messages containing physical parameter values from the one or more remote physical parameter sensors 484 to the computing environment 403 via the network 412. In one embodiment, the sensing environment is a remote weather station containing a variety of remote physical parameter sensors to measure weather.
[0247] Referring next to FIG. 25, shown is a flowchart that provides one example of the operation of a portion of the operation application 421 (FIG. 21) according to various embodiments. It is understood that the flowchart of FIG. 25 provides merely an example of the many different types of functional arrangements that may be employed to implement the operation of the portion of the operation application 421 as described herein. As an alternative, the flowchart of FIG. 25 may be viewed as depicting an example of elements of a method implemented in the computing environment 403 (FIG. 21) according to one or more embodiments.

[0248] The operation application 421 initiates the transmission of a guided surface wave, such as via the excitation source 424, to power one or more sensing devices 409. Upon providing power to the one or more sensing devices 409, the operation application 421 listens for transmissions from each of the one or more sensing devices 409 on one or more frequencies. If the operation application 421 receives a signal from one of the one or more sensing devices 409, the operation application 421 triangulates a location for the transmitting sensing device 409 and stores the location in a data store.

[0249] At box 535, the operation application 421 may initiate the process. The process may be initiated on a timer, run continuously in a loop, be initiated by various events taking place, and/or be initiated by various other known methods. Then, in box 538, the operation application 421 initiates the launching of a guided surface wave. For example, the operation application 421 may provide a power signal to the guided surface waveguide probe P (FIG. 21) via excitation source 424 (FIG. 21) to initiate launching of a guided surface wave 415 (FIG. 21). In some embodiments, the guided surface waveguide probe P launches a continual guided surface wave 415. In another embodiment, the guided surface waveguide probe P
launches guided surface waves at fixed intervals or the times for launching may vary over time.

[0250] Then, in box 541, the operation application 421 listens for an incoming transmission from one or more transceivers, the transmission originating from a sensing device 409. The one or more transceivers 499 may listen on a predetermined frequency for a transmission from one or more sensing devices 409, such as sensing device 409a. When a transmission is received, the operation application 421 may receive an indication of the frequency, signal strength, and other information. In some embodiments, the specific frequency is based on a range of frequencies available for listening. In another embodiment, the frequency corresponds to the unique frequency transmissions associated to the sensing device 409 stored in the data store 2219 (FIG. 45). In the case that multiple sensing devices 409 transmit on the same frequency, various transmission collision avoidance approaches may be employed to ensure the sensing devices 409 do not interfere with each other.

[0251] The operation application 421 may direct the transceivers 499 to listen for a time out period on each frequency or may listen for various time out periods based on the last time a response was received for the frequency. As a non-limiting example, a short timeout period may exist for a sensing device 409 where no transmission has been received for a long time period, whereas a longer timeout period may exist for a sensing device 409 where a transmission was received at the specific frequency the previous time the specific frequency was listened for by the positional RF receivers 2109. As a further example, the operation application 421 may direct the transceivers 499 to process a signal carrying various frequency transmissions to identify each of the various frequency transmissions including
properties individually associated with the individual transmissions. The operation application 421 may also receive the unprocessed signal and identify each of the various frequency transmissions including properties individually associated with the individual transmissions.

[0252] The specific frequency or range of frequencies listened to by the transceiver may be controlled by the operation application 421. The range may be limited by high and low pass filters. The transceivers 499 may also be configured to use band pass filters or use signal processing logic, such as through fast Fourier transforms in hardware or software (not shown) to individually identify the specific frequencies received by the transceiver 499.

[0253] Next, in box 544, the operation application 421 involves detecting if a signal is received. If a signal is received, the operation application 421 moves to 547, otherwise the operation application proceeds to box 553. In box 547, the operation application 421 involves triangulating the location of a sensing device based on signal strength and storing the determined position in a data store associated with the sensing device. For example, the operation application 421 may triangulate the location of the sensing device 409 using the data received from the one or more transceivers 499. The operation application 421 may store the location data 433 (FIG. 21) associated with the sensing device 409. Next in box 550, the operation application 421 involves determining if other frequencies are available for processing. If other frequencies are available (e.g. Yes), the operation application 421 proceeds to box 553. Otherwise, the operation application 421 proceeds to end 556.

[0254] In box 553, the operation application 421 adjusts to listen to the next frequency in a list of frequencies. For example, the operation application 421 may
direct the transceiver to listen to the next frequency in a list. The list may be made up of a range of frequencies available for listening or correspond to the unique frequency transmissions associated to the sensing device 409 stored in the devices 427 (FIG. 21).

[0255] Referring next to FIG. 26, shown is a flowchart that provides one example of the operation of a portion of the operation application 421 (FIG. 21) according to various embodiments. It is understood that the flowchart of FIG. 26 provides merely an example of the many different types of functional arrangements that may be employed to implement the operation of the portion of the operation application 421 as described herein. As an alternative, the flowchart of FIG. 26 may be viewed as depicting an example of elements of a method implemented in the computing environment 403 (FIG. 21) according to one or more embodiments.

[0256] The operation application 421 listens for messages from sensing devices 409. Upon receiving a message, the operation application 421 processes the message and extracts position data and unique identification data from the message. The position data for the transmitting sensing device 409 is stored in the data store 418 associated with the unique identification corresponding to the sensing device 409.

[0257] At box 559, the operation application 421 may initiate the process by proceeding to box 538. The process may be initiated on a timer, run continuously in a loop, be initiated by various events taking place, and/or be initiated by various other known methods. Then, in box 562, the operation application 421 listens for a transmission of a message from a sensing device 409. For example, the operation application 421 may open a socket connection and listen. In some embodiments, the operation application 421 listens for and accepts incoming TCP/IP socket
connections on a predetermined port number and then listens for packets on the TCP/IP socket. In other embodiments, the operation application 421 listens on a predetermined port number for UDP packets. In other embodiments, web based technologies such as Restful Web Services, SOAP, XML, HTTP Post and Get, and various other technologies can be used. In box 565, operation application 421 involves detecting if a message is received, receiving the message if it is, and continuing to listen if not. For example, the message may comprise the location of the device, a unique identifier for the device, various other pieces of data, and any protocol or transmission elements necessary to package, transmit, and unpack the data. In some embodiments, the operation application 421 will listen until a message is received or a timeout occurs. In other embodiments, box 565 may be event driven and occur asynchronously upon receipt of a message through interrupts and/or other means. In other embodiments, the operation application 421 will continuously listen for transmissions in one thread while processing messages in another thread.

[0258] In box 568, the operation application 421 involves processing a message received from a sensing device 409. For example, the operation application 421 may extract data from the message, such as mapping data fields to the incoming message transmissions and converting the incoming transmission values into variables in memory. In box 571, the operation application 421 involves extracting and/or identifying position data and a unique identifier from the message. In box 574, the operation application 421 involves storing the position in a data store. For example, the operation application 421 may store the position of the sensing device 409 in location data 433 associated with the unique identifier for the sensing device 409 that sent the message. In some embodiments, the operation application 421
may return to listening for another message. In other embodiments, the process does not stop listening for messages, but rather receives and processes the message simultaneously while listening for additional connections and messages.

[0259] Referring next to FIG. 27, shown is a flowchart that provides one example of the operation of a portion of the operation application 421 (FIG. 21) according to various embodiments. It is understood that the flowchart of FIG. 27 provides merely an example of the many different types of functional arrangements that may be employed to implement the operation of the portion of the operation application 421 as described herein. As an alternative, the flowchart of FIG. 27 may be viewed as depicting an example of elements of a method implemented in the computing environment 403 (FIG. 21) according to one or more embodiments.

[0260] According to one embodiment, the operation application 421 receives physical parameter data from one or more sensing device 409 and stores the data in data store 418. For example, the operation application 421 initiates launching of a guided surface wave via an excitation source 424 to provide power to one or more sensing devices 409. The operation application 421 listens for transmissions from the one or more sensing devices 409 and processes received messages. The operation application extracts one or more physical parameters from the received messages and stores the physical parameters associated with a unique identifier in the data store 418.

[0261] At box 577, the operation application 421 may initiate the process by proceeding to box 538. The process may be initiated on a timer, run continuously in a loop, be initiated by various events taking place, and/or be initiated by various other known methods. Next at box 580, the operation application 421 listens for a transmission of a message from a sensing device 409. For example, operation
application 421 may open a socket connection and listen for a transmission. In some embodiments, the operation application 421 listens for and accepts incoming TCP/IP socket connections on a predetermined port number and then listens for packets on the TCP/IP socket. In other embodiments, the operation application 421 listens on a predetermined port number for UDP packets. In other embodiments, web based technologies such as Restful Web Services, SOAP, XML, HTTP Post and Get, and various other technologies can be used. In box 583, the operation application involves detecting if a message is received, receiving the message if it is, and proceeding to box 583 (e.g. Yes), or continuing to listen if not by proceeding to box 580 (e.g. No). The message may comprise the data associated with the physical parameter sensor as described herein which may include a measurement, compilation of measurements, raw sensor data, one or more videos, one or more images, or various other pieces of data, and any protocol or transmission elements necessary to package, transmit, and unpackage the data. In some embodiments, the operation application 421 will listen until a message is received or a timeout occurs. In other embodiments, box 583 may be event driven and occur asynchronously upon receipt of a message through interrupts or other means. In other embodiments, the operation application 421 will continuously listen for transmissions in one thread while processing messages in another thread.

[0262] In box 586, the operation application 421 processes a message received from a sensing device 409. The sensing device 409 may measure a physical parameter and transmit the physical parameter measurement to the operation application 421. The operation application 421 may process the message from the sensing device 409 and proceed to box 589. In box 589, the operation application 421 extracts the data from the message and the unique identifier for the transmitting
sensing device 409. In box 592, the operation application 421 stores the data in the parameter data 430 (FIG. 21) associated with the transmitting sensing device 409. For example, the operation application 421 can store the data from a sensing device 409c in the data store 418 associated with the unique identifier for the sensing device 409c that sent the message. In some embodiments, the operation application 421 will return to listening for another message. In other embodiments, the operation application 421 does not stop listening for messages, but rather receives and processes the message simultaneously while listening for additional connections and messages.

[0263] With reference to FIG. 28, shown is a schematic block diagram of computing device 643, such as a computing device used in the computing environment 403 (FIG. 21), computing device 457 (FIGS. 22B and 22C), computing device 472 (FIG. 22D), and computing device 493 (FIG. 23) according to an embodiment of the present disclosure. The computing environment 403 includes one or more computing devices 643. Each computing device 643 includes at least one processor circuit, for example, having a processor 646 and a memory 655, both of which are coupled to a local interface 658. To this end, each computing device 643 may comprise, for example, at least one server computer or like device. The local interface 658 may comprise, for example, a data bus with an accompanying address/control bus or other bus structure as can be appreciated.

[0264] Stored in the memory 655 are both data and several components that are executable by the processor 646. In particular, stored in the memory 655 and executable by the processor 646 are the operation application 421 and applications executed on the computing devices 457, 472, and 493, and potentially other applications. Also stored in the memory 655 may be a data store 418 (FIG. 21) and
other data. In addition, an operating system may be stored in the memory 655 and executable by the processor 646.

[0265] It is understood that there may be other applications that are stored in the memory 655 and are executable by the processor 646 as can be appreciated. Where any component discussed herein is implemented in the form of software, any one of a number of programming languages may be employed such as, for example, C, C++, C#, Objective C, Java®, JavaScript®, Perl, PHP, Visual Basic®, Python®, Ruby, Flash®, or other programming languages.

[0266] A number of software components are stored in the memory 655 and are executable by the processor 646. In this respect, the term "executable" means a program file that is in a form that can ultimately be run by the processor 646. Examples of executable programs may be, for example, a compiled program that can be translated into machine code in a format that can be loaded into a random access portion of the memory 655 and run by the processor 646, source code that may be expressed in proper format such as object code that is capable of being loaded into a random access portion of the memory 655 and executed by the processor 646, or source code that may be interpreted by another executable program to generate instructions in a random access portion of the memory 655 to be executed by the processor 646, etc. An executable program may be stored in any portion or component of the memory 655 including, for example, random access memory (RAM), read-only memory (ROM), hard drive, solid-state drive, USB flash drive, memory card, optical disc such as compact disc (CD) or digital versatile disc (DVD), floppy disk, magnetic tape, or other memory components.

[0267] The memory 655 is defined herein as including both volatile and nonvolatile memory and data storage components. Volatile components are those
that do not retain data values upon loss of power. Nonvolatile components are those that retain data upon a loss of power. Thus, the memory 655 may comprise, for example, random access memory (RAM), read-only memory (ROM), hard disk drives, solid-state drives, USB flash drives, memory cards accessed via a memory card reader, floppy disks accessed via an associated floppy disk drive, optical discs accessed via an optical disc drive, magnetic tapes accessed via an appropriate tape drive, and/or other memory components, or a combination of any two or more of these memory components. In addition, the RAM may comprise, for example, static random access memory (SRAM), dynamic random access memory (DRAM), or magnetic random access memory (MRAM) and other such devices. The ROM may comprise, for example, a programmable read-only memory (PROM), an erasable programmable read-only memory (EPROM), an electrically erasable programmable read-only memory (EEPROM), or other like memory device.

[0268] Also, the processor 646 may represent multiple processors 646 and/or multiple processor cores and the memory 655 may represent multiple memories 655 that operate in parallel processing circuits, respectively. In such a case, the local interface 658 may be an appropriate network that facilitates communication between any two of the multiple processors 646, between any processor 646 and any of the memories 655, or between any two of the memories 655, etc. The local interface 658 may comprise additional systems designed to coordinate this communication, including, for example, performing load balancing. The processor 646 may be of electrical or of some other available construction.

[0269] Although the operation application 421 and applications executed on the computing devices 457, 472, and 493, and other various systems described herein may be embodied in software or code executed by general purpose hardware as
discussed above, as an alternative the same may also be embodied in dedicated hardware or a combination of software/general purpose hardware and dedicated hardware. If embodied in dedicated hardware, each can be implemented as a circuit or state machine that employs any one of or a combination of a number of technologies. These technologies may include, but are not limited to, discrete logic circuits having logic gates for implementing various logic functions upon an application of one or more data signals, application specific integrated circuits (ASICs) having appropriate logic gates, field-programmable gate arrays (FPGAs), or other components, etc. Such technologies are generally well known by those skilled in the art and, consequently, are not described in detail herein.

[0270] The flowcharts of FIGS. 25, 26, and 27 show the functionality and operation of an implementation of portions of the operation application 421. If embodied in software, each block may represent a module, segment, or portion of code that comprises program instructions to implement the specified logical function(s). The program instructions may be embodied in the form of source code that comprises human-readable statements written in a programming language or machine code that comprises numerical instructions recognizable by a suitable execution system such as a processor 646 in a computer system or other system. The machine code may be converted from the source code, etc. If embodied in hardware, each block may represent a circuit or a number of interconnected circuits to implement the specified logical function(s).

[0271] Although the flowcharts of FIGS. 25, 26, and 27 show a specific order of execution, it is understood that the order of execution may differ from that which is depicted. For example, the order of execution of two or more blocks may be scrambled relative to the order shown. Also, two or more blocks shown in
succession in FIGS. 25, 26, and 27 may be executed concurrently or with partial concurrence. Further, in some embodiments, one or more of the blocks shown in FIGS. 25, 26, and 27 may be skipped or omitted. In addition, any number of counters, state variables, warning semaphores, or messages might be added to the logical flow described herein, for purposes of enhanced utility, accounting, performance measurement, or providing troubleshooting aids, etc. It is understood that all such variations are within the scope of the present disclosure.

[0272] Also, any logic or application described herein, including the operation application 421 and applications executed on the computing devices 457, 472, and 493, that comprises software or code can be embodied in any non-transitory computer-readable medium for use by or in connection with an instruction execution system such as, for example, a processor 646 in a computer system or other system. In this sense, the logic may comprise, for example, statements including instructions and declarations that can be fetched from the computer-readable medium and executed by the instruction execution system. In the context of the present disclosure, a "computer-readable medium" can be any medium that can contain, store, or maintain the logic or application described herein for use by or in connection with the instruction execution system.

[0273] The computer-readable medium can comprise any one of many physical media such as, for example, magnetic, optical, or semiconductor media. More specific examples of a suitable computer-readable medium would include, but are not limited to, magnetic tapes, magnetic floppy diskettes, magnetic hard drives, memory cards, solid-state drives, USB flash drives, or optical discs. Also, the computer-readable medium may be a random access memory (RAM) including, for example, static random access memory (SRAM) and dynamic random access
memory (DRAM), or magnetic random access memory (MRAM). In addition, the computer-readable medium may be a read-only memory (ROM), a programmable read-only memory (PROM), an erasable programmable read-only memory (EPROM), an electrically erasable programmable read-only memory (EEPROM), or other type of memory device.

[0274] Further, any logic or application described herein, including the operation application 421 and applications executed on computing devices 457, 472, and 493, may be implemented and structured in a variety of ways. For example, one or more applications described may be implemented as modules or components of a single application. Further, one or more applications described herein may be executed in shared or separate computing devices or a combination thereof. For example, a plurality of the applications described herein may execute in the same computing device 643 or in multiple computing devices in the same computing environment 403. Additionally, it is understood that terms such as "application," "service," "system," "engine," "module," and so on may be interchangeable and are not intended to be limiting.

[0275] Disjunctive language such as the phrase "at least one of X, Y, or Z," unless specifically stated otherwise, is otherwise understood with the context as used in general to present that an item, term, etc., may be either X, Y, or Z, or any combination thereof (e.g., X, Y, and/or Z). Thus, such disjunctive language is not generally intended to, and should not, imply that certain embodiments require at least one of X, at least one of Y, or at least one of Z to each be present.

[0276] It should be emphasized that the above-described embodiments of the present disclosure are merely possible examples of implementations set forth for a clear understanding of the principles of the disclosure. Many variations and
modifications may be made to the above-described embodiment(s) without departing substantially from the spirit and principles of the disclosure. All such modifications and variations are intended to be included herein within the scope of this disclosure and protected by the following claims.
CLAIMS

Therefore, the following is claimed:

1. An apparatus, comprising:
   a guided surface wave receive structure configured to obtain electrical energy from a guided surface wave traveling along a terrestrial medium;
   a physical parameter sensor coupled to the guided surface wave receive structure, the physical parameter sensor configured to measure a physical parameter associated with a physical environment local to the physical parameter sensor; and
   a radio frequency transmitter coupled to the guided surface wave receive structure and communicatively coupled to the physical parameter sensor, the radio frequency transmitter configured to obtain a physical parameter measurement and transmit the physical parameter measurement over a wireless network.

2. The apparatus of claim 1, wherein the physical parameter sensor and radio frequency transmitter are experienced as a load at an excitation source coupled to a guided surface waveguide probe generating the guided surface wave.

3. The apparatus of claims 1 or 2, wherein the guided surface wave receive structure further comprises:
   a charge terminal elevated over a lossy conducting medium; and
   a receiver network coupled between the charge terminal and the lossy conducting medium, the receiver network having a phase delay (Φ) that matches a wave tilt angle (Ψ) associated with the guided surface wave, the wave tilt angle (Ψ)
based at least in part upon characteristics of the lossy conducting medium in a vicinity of the receiving structure.

4. The apparatus of claims 1 or 2, wherein the guided surface wave receive structure comprises at least one of: a magnetic coil, a linear probe, or a tuned resonator.

5. The apparatus of claims 1, 2, 3, or 4, further comprises a computing device communicably coupled to the guided surface wave receive structure and connected to the physical parameter sensor and the radio frequency transmitter, the computing device being configured to obtain the physical parameter measurement from the physical parameter sensor, to form a message containing the physical parameter measurements, and to transmit the message via the radio frequency transmitter.

6. The apparatus of claims 1, 2, 3, 4, or 5, wherein the computing device is experienced as a load at an excitation source coupled to a guided surface waveguide probe generating the guided surface wave.

7. The apparatus of claims 1, 2, 3, 4, 5, or 6, wherein the physical parameter sensor is further configured to measure at least one of light, temperature, moisture, quantity of rain, quantity of snow, presence of rain, presence of snow, humidity levels, wind speed, wind direction, cloud height, wave height, heart rate, blood pressure, location, or presence of a substance.
8. The apparatus of claims 1, 2, 3, 4, 5, 6, or 7, further comprising a power circuit coupled to the wherein the guided surface wave receive structure, the power circuit comprising a power rectifier and a capacitor.

9. The apparatus of claims 1, 2, 3, 4, 5, 6, or 7 further comprising a power circuit coupled to the wherein the guided surface wave receive structure, the power circuit comprising a battery.

10. A system, comprising:
    a guided surface waveguide probe configured to transmit a guided surface wave traveling along a terrestrial medium;
    a sensing device comprising a guided surface wave receive structure coupled to an electrical load, the guided surface wave receive structure being configured to obtain electrical energy from the guided surface wave and the electrical load being experienced as a load at an excitation source coupled to a guided surface waveguide probe generating the guided surface wave;
    the electrical load comprising:
        a physical parameter sensor configured to measure a physical parameter associated with a physical environment local to the physical parameter sensor; and
        a radio frequency transmitter communicatively coupled to the physical parameter sensor, the radio frequency transmitter configured to transmit a physical parameter measurement over a wireless network.
11. The system of claim 10, wherein the electrical load further comprises a computing device communicably connected to the physical parameter sensor and the radio frequency transmitter, the computing device configured to obtain the physical parameter measurement from the physical parameter sensor, to form a message containing the physical parameter measurements, and to cause the radio frequency transmitter to transmit the message.

12. The system of claims 10 or 11, wherein the physical parameter sensor is further configured to measure at least one of light, temperature, moisture, quantity of rain, quantity of snow, presence of rain, presence of snow, humidity levels, wind speed, wind direction, cloud height, wave height, heart rate, blood pressure, location, or presence of a substance.

13. The system of claims 10, 11, or 12, wherein the guided surface waveguide probe comprises a charge terminal elevated over a lossy conducting medium configured to generate at least one resultant field that synthesizes a wave front incident at a complex Brewster angle of incidence \((\theta_{1,\beta})\) of the lossy conducting medium.

14. The system of claim 13, wherein the charge terminal is one of a plurality of charge terminals.

15. The system of claim 13, further comprising a feed network electrically coupled to the charge terminal, the feed network providing a phase delay \((\Phi)\) that matches a wave tilt angle \((\Psi)\) associated with a complex Brewster angle of incidence.
\(10^1, \beta\) associated with the lossy conducting medium in the vicinity of the guided surface waveguide probe.

16. A method, comprising:
   receiving electrical energy as a guided surface wave using a guided surface wave receive structure;
   supplying the electrical energy to an electrical load coupled to the guided surface wave receive structure, the electrical load comprising a location triangulation circuit and a radio frequency transmitter, where the location triangulation circuit is communicably coupled to the radio frequency transmitter;
   receiving a plurality of radio transmissions in the location triangulation circuit from at least three sources; and
   determining a location of a location device in the location triangulation circuit based at least in part on the plurality of radio transmissions.

17. The method of claim 16, further comprising sending the location via at least one of the radio frequency transmitter or the guided surface wave receive structure.

18. The method of claims 16 or 17, wherein one of the at least three sources comprises at least one of a GPS satellites or a positional RF transmitter.

19. The method of claims 16, 17, or 18, further comprising:
   receiving orbital information of the at least three sources from a remote server via an internet connection; and
initializing an identification of the location of the location device based in part on the orbital information of the at least three sources.

20. The method of claim 19, wherein the orbital information comprises ephemeris data, reference location data, and at least one reference time.
FIG. 1

FIG. 2
FIG. 3

D₁ = H₁ + d/2 + d/2 = H₁ + d
Distance to Crossover Point

FIG. 4

FIG. 5A
START

150

Position charge terminal

153

Match electrical phase of elevated charge with complex wave tilt angle

156

Tune load impedance to resonate equivalent image plane model

159

END

FIG. 10

FIG. 11
Probe Control System 230

Excitation Source 212

Feed Network 209

$D_1 = H_1 + \frac{d}{2} + \frac{d}{2} = H_1 + d$

$D_2 = H_2 + \frac{d}{2} + \frac{d}{2} = H_2 + d$

FIG. 12
\[ D_1 = H_1 + \frac{d}{2} + \frac{d}{2} = H_1 + d \]
\[ D_2 = H_2 + \frac{d}{2} + \frac{d}{2} = H_2 + d \]

**FIG. 16**
FIG. 22C
Start 535

Initiate Launch of Guided Surface Wave 538

Listen for transmission at a specific frequency 541

Receive signal 544

No

Yes

Triangulate location of Location Device and store in Data Store 547

Other Frequencies? 550

Yes

No

End 556

FIG. 25
Start 559

Initiate Launch of Guided Surface Wave 538

Listen for transmission 562

Message Received? 565

Yes

Processing Message from Location Device 568

Extracting position and Location Device unique identifier 571

Store position in Data Store associated with unique identifier 574

No

FIG. 26
Start 577

Initiate Launch of Guided Surface Wave 538

Listen for transmission 580

Message Received? 583

Yes

Processing Message from Physical Parameter Device 586

Extracting physical parameters and electronic device unique identifier 589

Store physical parameters in Data Store associated with unique identifier 592

No

FIG. 27
**INTERNATIONAL SEARCH REPORT**

**PCT/US2015/049497**

### A. CLASSIFICATION OF SUBJECT MATTER

INV. H01P3/00 H01Q1/00 H02J17/00 H04B5/00

ADD.

According to International Patent Classification (IPC) and both national classification and IPC

### B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

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Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

- EPO-Internal
- WPI Data

### C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
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* Further documents are listed in the continuation of Box C.

### Date of the actual completion of the international search

**14 December 2015**

### Date of mailing of the international search report

**23/12/2015**

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Lauri, Lauro

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* Special categories of cited documents:

1. "A" document defining the general state of the art which is not considered to be of particular relevance
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3. "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
4. "O" document referring to an oral disclosure, use, exhibition or other means
5. "P" document published prior to the international filing date but later than the priority date claimed

* Further document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

*"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

*"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

*"S" document member of the same patent family
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<td>EP 2 568 528 A2 (ROKE MANOR RESEARCH [GB])</td>
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<td>13 March 2013 (2013-03-13) abstract paragraph [0016]</td>
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