SYSTEMS, APPARATUS AND METHODS FOR VEGETATION MEASUREMENT

TECHNICAL FIELD

[001] The present disclosure relates to apparatus, systems, and methods for measuring one or more characteristics of vegetation – more particularly pasture height and/or biomass.

BACKGROUND

[002] In a number of instances, it is desirable to know the extent of vegetative growth in an area. In animal husbandry applications it is of particular interest for a farmer to know the amount of vegetative feed present for effective feed management. With accurate pasture yield or productivity information a livestock farmer can more readily manage the movement of stock around their land, and also plan for instances where additional feed will need to be supplied. Pasture productivity information can also be used to forecast yields for vegetation able to be stored as hay or silage. However, it is presently difficult for a farmer or other interested parties to rapidly and accurately gauge the amount of feed material present in a particular area of pasture, or paddock, and to transfer such information to farm management software.

[003] One way to determine feed levels is through a visual estimate based on an observer's perception of the volume of vegetation present, or through the use of manual measuring rulers or other similar mechanisms to gauge the height of vegetation and to roughly assess its density. However, as those skilled in the art can appreciate, such estimation methods are not necessarily fully accurate and also require a significant amount of time to collect a reasonable number of vegetation height samples.

[004] There are a number of techniques available for quantifying pasture resource which rely on physical contact with the pasture and/or ground surface. One such technique to estimate pasture bulk is commonly referred to as the 'rising plate' system, which uses mechanical support of a light plate by the target grass sward, referenced to the height of the ground surface determined by a rigid stick or probe. An example of this type of apparatus is disclosed in New Zealand Patent No. 286786. Another technique is based on measuring the capacitance between the grass sward and an adjacent insulated rod, the circuit being completed by contacting the exposed end of the conducting rod to the ground. An example of this type of apparatus is disclosed in New Zealand Patent No. 333694.

[005] However, each of these techniques requires part of the device to physically contact the ground in order to make a measurement. This tends to make the instruments slow to operate, and precludes non-contact measurement. The limitation in speed of measurements means that the number of measurements taken is limited – it is a labour intensive process and practically infeasible to sample across a large area. The accuracy for estimation of dry matter or vegetation content over a large area is therefore limited as a consequence.

[006] One semi-automated system for measuring pasture density and volume has been proposed by N. J. Hutchings, 1990 (Grass and Forage Science, Vol. 45, pp 119-127). This publication describes the provision of an ultrasonic based sward measurement stick. The sward stick described is implemented as a fixed height walking stick with an ultrasonic emitter and detector pair at the top of the stick. Ultrasonic sound pulses are directed towards the pasture canopy with the return echoes detected being used to determine the height of the pasture when compared against the known height of the sward stick, and hence the distance to ground. This type of system uses a single frequency ultrasonic pulse train to provide information with respect to the height of the pasture to be metered or measured. However, there are again some limitations present in the use of such an ultrasonic sward stick meter.

[007] The sward meter provided relies on contact with the ground to set a fixed height, and therefore establish a known distance above the ground for the ultrasonic pulse transmitter. This in turn requires the operator of the meter to contact the ground for all measurements to be taken, resulting in a relatively small number of measurements being made due to the slow operation of the meter. Furthermore, some variation in the results obtained can occur with different operators using different grips or orientation angles for the sward stick meter.

[008] Another ultrasound based pasture meter is described by NZ Patent No. 534189. However, there is room for improvement over this design – particularly with regard to achieving a higher degree of accuracy in ground measurement and pasture height in the presence of noise surrounding the measurements of the reflected ultrasonic waves, or in the presence of a densely populated sward.

[009] Throughout this specification, the term “pasture meter” may be used to refer to apparatus for the measurement of volume or growth of vegetative matter growing above a reference plane. It should be appreciated that reference to “pasture” is not intended to limit the present disclosure to vegetation in the form of grass, but that embodiments of the present disclosure may be used in the measurement of any above ground vegetative matter – particularly for provision of forage for an animal.

[010] It is an object of the present invention to address the foregoing problems or at least to provide the public with a useful choice.

[011] Further aspects and advantages of the present invention will become apparent from the ensuing description which is given by way of example only.

SUMMARY OF THE DISCLOSURE

[012] According to an aspect of the present disclosure there is provided a vegetation measurement apparatus, including:

an acoustic sensor device having a plurality of acoustic transducers, the acoustic sensor device configured to transmit an acoustic signal downwardly towards vegetation on a ground surface in use, and receive at least one echo of the transmitted acoustic signal,

wherein the acoustic sensor device has a footprint of interest on the ground surface at a predetermined distance from the ground surface, and

wherein the acoustic sensor device is configured such that destructive interference occurs for echoes received from outside the footprint of interest.

[013] According to an aspect of the present disclosure there is provided a vegetation measurement apparatus, including:

an acoustic sensor device having a plurality of acoustic transducers, the acoustic sensor device configured to transmit an acoustic signal downwardly towards vegetation on a ground surface in use, and receive at least one echo of the transmitted acoustic signal,

wherein the acoustic sensor device has a footprint of interest on surfaces between the acoustic transducers and the ground surface, and wherein the acoustic sensor device is configured such that destructive interference occurs for echoes received from outside the footprint of interest.

[014] According to an aspect of the present disclosure there is provided a vegetation measurement apparatus, including:

an acoustic sensor device having a plurality of acoustic transducers, the acoustic sensor device configured to transmit an acoustic signal downwardly towards vegetation on a ground surface in use, and receive at least one echo of the transmitted acoustic signal,

wherein the transmitted acoustic signal has a substantially cone shaped directivity pattern,

wherein the -3dB power of the signal occurs at the base circumference of the cone, and the half cone angle is less than 10 degrees.

[015] According to an aspect of the present disclosure there is provided a vegetation measurement apparatus, including:

an acoustic sensor device having a plurality of acoustic transducers, the acoustic sensor device configured to transmit an acoustic signal downwardly towards vegetation on a ground surface in use, and receive at least one echo of the transmitted acoustic signal,

wherein a receiving directivity pattern of the acoustic sensor device is substantially cone shaped,

wherein the -3dB power of the signal occurs at the base circumference of the cone, and the half cone angle is less than 10 degrees.

[016] According to an aspect of the present disclosure there is provided a vegetation measurement apparatus, including:

an acoustic sensor device having a plurality of acoustic transducers, the acoustic sensor device configured to transmit an acoustic signal downwardly towards vegetation on a ground surface in use, and receive at least one echo of the transmitted acoustic signal,

wherein the plurality of acoustic transducers are arranged in an irregular array pattern, and at least a majority of the plurality of acoustic transducers are arranged along a plurality of arcs rotated about an origin point.

[017] According to an aspect of the present disclosure there is provided a vegetation measurement apparatus, including:

an acoustic sensor device having a plurality of acoustic transducers, the acoustic sensor device configured to transmit an acoustic signal downwardly towards vegetation on a ground surface in use, and receive at least one echo of the transmitted acoustic signal,

wherein the plurality of acoustic transducers includes a plurality of acoustic transmitters and a plurality of acoustic receivers, and

wherein the plurality of acoustic transmitters is arranged in a first array pattern, and the plurality of acoustic receivers is arranged in a second array pattern.

[018] Embodiments of the present disclosure may be particularly applicable to pasture metering – e.g. determination of one or more characteristics of vegetation within a pasture, paddock, field or other related area in agricultural or animal husbandry applications which use vegetation as feedstock. By way of example, the vegetation may be intended for grazing by livestock, or harvested to provide a store of feed for later distribution to livestock. It is envisaged that the vegetation to be measured using embodiments of the present disclosure includes the crown of the vegetation – i.e. the totality of the plant's aboveground parts, including stems, leaves, and reproductive structures. The apparatus, systems and methods discussed herein may be used to determine or estimate one or more characteristics of interest, such as vegetation height from ground, volume, density, weight, or biomass.

[019] Reference to a footprint of interest of a sensing device should be understood to mean the target region onto which the acoustic signal is transmitted, and from which echoes are received, wherein the boundary of the footprint of interest is where the power level has not dropped beyond -3db (i.e. half power). It should be appreciated that the footprint of interest will be the result of the combined directivity patterns of the transmitting transducer elements and the receiving transducer elements.

[020] In an exemplary embodiment the footprint of interest may have an area of at least 0.001 m^2. In an exemplary embodiment the footprint of interest may have an area of less than 1.8 m^2. In an exemplary embodiment the footprint of interest may have an area of about 0.01 m^2.

[021] It is envisaged that the echoes of interest will be those which are received along a transmission path substantially orthogonal to the acoustic sensor device – i.e. that pass vertically (within acceptable limits) through the vegetation. It is envisaged that the area footprint of interest should therefore be sufficient to receive these echoes when travelling at speed - more particularly in an orientation parallel to the ground. In an exemplary embodiment the footprint may have an area sufficient for the acoustic sensor device to receive the at least one echo when the vegetation measurement apparatus is travelling at a ground speed of at least 2 kilometres per hour. However, it is envisaged that in exemplary embodiments the apparatus may be mounted to a vehicle, and used at higher speeds – for example in the order of 20 to 40 kilometres per hour for an all-terrain vehicle (ATV), or an unmanned aerial vehicle (UAV).

[022] Reference to the acoustic sensor device being configured such that destructive interference occurs for echoes received from outside the footprint of interest should be understood to mean the configuration of the transmitting and/or receiving transducers being such that acoustic signals arriving outside of the footprint destructively interfere with each other to cause cancelling to varying degrees depending on the location outside the footprint, or the echoes arriving at the individual receiving transducers when added together destructively interfere with each other to cause cancelling to varying degrees depending on the location of the echo source outside of the footprint. As a result, the intensity of echoes from the ground and vegetation outside of the footprint are substantially less than reflections from within the footprint. This means that time of flight measurement for the signals travelling from the transducers to the ground and back to the receiving transducers are less likely to be confused with reflections from outside of the footprint. In exemplary embodiments in which the apparatus is intended for use in measuring the distance from the acoustic sensing device to the ground, and the device to the vegetation, where the distance measured is substantially orthogonal to the transducers, echoes from vegetation outside the footprint reflected back to the receiving transducers (due to the random angle of reflective surfaces of vegetation and uneven ground surfaces) may give an erroneous measurement of the distance to the vegetation and to the ground. It is therefore envisaged that destructive interference of these signals may assist in improving accuracy of the resulting measurements.

[023] In an exemplary embodiment the transmitted acoustic signal may have a substantially cone shaped directivity pattern, wherein the -3dB power of the signal occurs at the base circumference of the cone. In an exemplary embodiment, the acoustic sensor device may have a substantially cone shaped receiving directivity pattern, wherein the -3dB power of the signal occurs at the base circumference of the cone.

[024] In an exemplary embodiment the half cone angle may be less than 10 degrees. In an exemplary embodiment the half cone angle may be between 2 and 10 degrees. In an exemplary embodiment the half cone angle may be between 5 and 8 degrees. In an exemplary embodiment the directivity pattern of the combined transmitting and receiving directivity patterns may have a half cone angle of less than 6 degrees.

[025] In exemplary embodiments, the plurality of acoustic transducers may be arranged in an array within a circle. It is envisaged that this may assist with shaping the transmitting and receiving beams – however, it should be appreciated that this is not intended to be limited to all exemplary embodiments. For example, it is envisaged that the transducers may be arranged in arrays within other shapes, whether regular or irregular. For example, the transducers may be arranged within a rectangular array, or an elliptical array, or a square array.

[026] In an exemplary embodiment, the diameter of the circle within which the acoustic transducers are arranged may be at least 30 millimetres. In an exemplary embodiment, the diameter of the circle within which the acoustic transducers are arranged may be at least 60 millimetres.

[027] In an exemplary embodiment, the diameter of the circle within which the acoustic transducers are arranged may be less than 0.5 metres.

[028] In an exemplary embodiment, the plurality of acoustic transducers may be arranged in an irregular array pattern.

[029] In an exemplary embodiment, at least a majority of the plurality of acoustic transducers may be arranged along a plurality of arcs rotated about an origin point.

[030] In an exemplary embodiment, the plurality of acoustic transducers may include a plurality of acoustic transmitters, and a plurality of acoustic receivers.

[031] In an exemplary embodiment, the plurality of acoustic transmitters may be arranged in a first array pattern, and the plurality of acoustic receivers may be arranged in a second array pattern.

[032] In an exemplary embodiment, the first array pattern may include a plurality of arcs rotated about an origin point, and the second array pattern may include a plurality of logarithmic spirals rotated about an origin point.

[033] In an exemplary embodiment, the first array pattern and the second array pattern may be arranged such that each of the acoustic transmitters are laterally displaced from each of the acoustic receivers.

[034] In an exemplary embodiment, the first array pattern may be located on a first surface of a transducer mount, and the second array pattern is located on a second surface of the transducer mount.

[035] In an exemplary embodiment, the transducer mount may include a plurality of apertures between the first surface and the second surface, wherein the apertures align with the second array pattern.

[036] In an exemplary embodiment, the plurality of acoustic transmitters may be arranged in a plurality of transmitter array patterns, and the plurality of acoustic receivers may be arranged in a plurality of receiver array patterns. The apparatus may be configured to selectively switch between the respective transmitter array patterns and receiver array patterns, more particularly between array patterns of differing radius. For example, the radius of the respective receiver array patterns may range between 15 to 75 mm, while the radius of the respective transmitter array patterns may range between 9 to 75 mm. It is envisaged that the near-field 'view' of the pasture differs from the far-field, allowing for the possibility of another measure of pasture structure through comparison of near -field and far-field measurements. The transition to near-field conditions at an array radius of around 45 mm is expected to cause the footprint radius to decrease more slowly as the radius increases.

[037] In an exemplary embodiment, the plurality of acoustic transducers may include at least 10 acoustic transducers configured to transmit the acoustic signal. In an exemplary embodiment, the plurality of acoustic transducers may include at least 20 acoustic transducers configured to transmit the acoustic signal. In an exemplary embodiment, the plurality of acoustic transducers may include less than 80 acoustic transducers configured to transmit the acoustic signal. In an exemplary embodiment, the plurality of acoustic transducers may include 29 acoustic transducers configured to transmit the acoustic signal.

[038] In an exemplary embodiment, at least a portion of the plurality of acoustic transducers are configured to transmit the acoustic signal, and receive the at least one echo. It is envisaged that the acoustic sensor device may include one or more switching devices configured to clamp or short the transmitting transducers after transmission of the acoustic signal. It is envisaged that this may assist with reducing ringing of the transducers resulting from transmission, which could otherwise interfere with receiving of the echoes.

[039] In an exemplary embodiment, the apparatus may include a signal driver configured to drive at least a portion of the acoustic transducers of the acoustic sensor device to transmit the acoustic signal.

[040] In an exemplary embodiment, the signal driver may be configured to drive the acoustic transducers in phase.

[041] In an exemplary embodiment, the signal driver may be configured to drive the acoustic transducers with a modulated signal. It is envisaged that this may be used to correlate the transmitted signal with the at least one received echo. It should be appreciated that the exemplary modulation techniques described herein are not intended to be limiting to all embodiments of the present disclosure.

[042] In an exemplary embodiment, the modulated signal may be a swept frequency modulated signal. Such a signal may be referred to herein as a “chirp”. In an exemplary embodiment, the swept frequency modulated signal may sweep through a range from 15 kilohertz upward. In an exemplary embodiment, the swept frequency modulated signal may sweep through a range from 15 kilohertz to 65 kilohertz. In an exemplary embodiment, the swept frequency modulated signal may sweep through a range of 20 kilohertz to 60 kilohertz. In an exemplary embodiment, the swept frequency modulated signal may sweep through a range of 20 kilohertz to 35 kilohertz. In an exemplary embodiment, the swept frequency modulated signal may sweep through a range of 15 kilohertz to 35 kilohertz. In an exemplary embodiment, the swept frequency modulated signal may sweep through a range of 45 kilohertz to 60 kilohertz. In an exemplary embodiment, the swept frequency modulated signal may sweep through a range of 15 kilohertz to 35 kilohertz or 20 kilohertz to 35 kilohertz, and 45 kilohertz to 60 kilohertz.

[043] In an exemplary embodiment, the duration of the swept frequency modulated signal may be in the range of 0.2 to 5 milliseconds. In an exemplary embodiment, the duration of the swept frequency modulated signal may be about 1 millisecond.

[044] In an exemplary embodiment, the signal driver may be configured to drive the acoustic transducers with a plurality of swept frequency modulated signal pulses at a rate of between 100 to 200 pulses per second.

[045] In an exemplary embodiment, the modulated signal may be a step frequency modulated signal. In an exemplary embodiment, a change of frequency throughout a frequency range of the step frequency modulated signal occurs at the zero-crossing point of each frequency transition.

[046] In an exemplary embodiment, the step frequency modulated signal may be driven with a frequency between 20 kilohertz and 60 kilohertz.

[047] The vegetation measurement apparatus, wherein the modulated signal is a phase shift modulated signal. In an exemplary embodiment, the phase shift modulated signal may be driven with a frequency between 20 kilohertz and 60 kilohertz.

[048] In an exemplary embodiment, the modulated signal may be an amplitude modulated signal.

[049] In an exemplary embodiment, the signal driver may be configured to drive the acoustic transducers out of phase to steer a beam of the transmitted acoustic signal to be forward of a direction of movement of the device along the ground surface.

[050] In an exemplary embodiment, the at least one echo received by each of the acoustic transducers may be combined by adding receiving acoustic transducer output signals together in phase. This is not intended to be limiting, as it is envisaged that the output of the receiving transducers may be summed with an alternative phase relationship, particularly if the directivity pattern is to be steered – for example, behind a vertical line from the acoustic sensor device to the ground to compensate for horizontal speed of the vehicle to which the device is mounted. In this case the angle of the steered directivity may be varied in accordance with the speed and or direction of movement of the transducers along the ground.

[051] In exemplary embodiments, control of the acoustic sensor device and processing of received data may be performed by one or more processors. In various embodiments, such processors may be on-board the apparatus, communicate remotely with the apparatus, or a combination thereof. For example, data may be transmitted to a processor of a user device (for example, a mobile or smart phone) or vehicle in proximity to the apparatus. Further, data may be relayed to and from processing resources – for example, cloud based computing services or server based computing services.

[052] In an exemplary embodiment, the at least one processor may be configured to correlate the timing of the at least one echo with the transmitted acoustic signal. From this correlation, it is envisaged that various characteristics of the vegetation may be determined or estimated.

[053] In an exemplary embodiment, the echo(s) of the transmitted acoustic signal may be recorded from the start of the signal transmission, until a time which is equivalent to the time it would take for the signal to travel a distance greater than the direct return path between the acoustic sensor device and the ground. For example, where the acoustic sensor device is mounted at 800 mm above the ground, the time period across which the signal is recorded may be the equivalent of that for the signal to travel from the acoustic sensor device to 1.8 m and back. As this distance is much further than the distance from the acoustic sensor device to ground, the recorded signal includes all vegetation and ground reflections.

[054] In an exemplary embodiment, the recorded signal of the received echo(s) may be filtered using a matched filter. This makes use of the echoes containing shared spectral characteristics with the transmitted signal. This process has the effect of excluding most of any background acoustic and electronic noise, as well as removing any components which are transmitted but which are not of the expected waveform (for example, sensor resonance components, or minor transmitted waveform departures from the ideal which might arise due to the particular transmitter and receiver transducer responses).

[055] In an exemplary embodiment the match filtered signal may be filtered to retain the amplitude information from the reflections, then squared to get a measure of reflected intensity. In exemplary embodiments the measure of reflected intensity may be corrected for a decrease in acoustic intensity with distance, which occurs due to spreading of an acoustic signal transmitted from a source.

[056] In an exemplary embodiment the at least one processor may be configured to determine a distance to the ground surface using the at least one echo.

[057] In an exemplary embodiment, the distance to the ground surface may be determined using the time of flight of at least one peak intensity of the received echoes. However, it is anticipated that there may be instances in which the intensity of received echoes from the top of the vegetation, or intermediary positions between the top and ground, may be stronger than that received from the ground.

[058] In an exemplary embodiment, the distance to ground may be determined by determining the location of a peak intensity preceeding an asymptotic approach to zero. Such an approach assumes that the last received echoes are the result of reflection(s) between the ground and the vegetation, which will be of a decaying intensity in comparison with the reflection from ground. In an exemplary embodiment, the asymptotic approach to zero may approximate an exponential decay curve.

[059] In an exemplary embodiment, the distance to ground may be determined by:

determining a duration for which echoes are received, above a background noise threshold; and

determining the mid-point of the duration, and using the mid-point to determine the distance to ground.

[060] Such an approach also assumes that the reflected signal travelling upward from the ground can undergo a reflection downward from the vegetation, and a further reflection upward from the ground and thence back to the acoustic sensor device. In an exemplary embodiment, a double path for such a signal leads to twice the total duration for which the received echo signal is above the background noise threshold. The ground position may then be found from the mid-point of the total record from each transmission for which there is a significant signal. However, it is envisaged that multiple paths of this type may also be considered such that the ground location is not at the mid-point of the signal duration.

[061] In an exemplary embodiment, the at least one processor may be configured to disregard the determined distance to the ground surface when a variation of the determined distance from an expected distance value exceeds a predetermined threshold.

[062] In an exemplary embodiment, the vegetation measurement apparatus may include an accelerometer configured to output a signal indicative of vertical displacement. The at least one processor may be configured to determine a distance from the acoustic transducers to the ground surface using a predetermined mounting height of the acoustic sensor device in combination with vertical displacement information obtained from the signal output from the accelerometer.

[063] In an exemplary embodiment, the at least one processor may be configured to determine a distance from the acoustic transducers to the ground surface using a previously determined distance from the at least one echo, in combination with vertical displacement information obtained from the signal output from the accelerometer.

[064] In an exemplary embodiment, the at least one processor may be configured to determine the distance to the top of the vegetation using the received at least one echo. Using a determined distance to ground, corrected distance to ground, or assumed distance to ground, this allows for determination of the height of the vegetation from the ground.

[065] In an exemplary embodiment, the at least one processor may be configured to determine a profile of the distances to the top of the vegetation over a predetermined distance of travel along the ground surface, using a plurality of received echoes from a plurality of transmitted signals.

[066] In an exemplary embodiment, the at least one processor may be configured to determine an average distance to the top of the pasture over the predetermined distance of travel.

[067] In an exemplary embodiment, determination of top of the vegetation may include:

determining background noise level in region below the acoustic transducers and the top of vegetation;

determining variation from the background noise level by a predetermined amount to determine the top of the vegetation.

[068] In an exemplary embodiment, determining background noise level may include determining variation over successive predetermined distances until a minimum variation is determined.

[069] In an exemplary embodiment, the acoustic signal may be transmitted using swept frequency modulation through a sweep frequency range, and the least one received echo signal is correlated with the transmitted signal in frequency bands within the sweep frequency range.

[070] In an exemplary embodiment, the frequency bands may have a bandwidth of substantially 5 kilohertz. It should be appreciated that this is not intended to be limiting to all exemplary embodiments, and that the bandwidth of each band may be influenced by factors such as the bandwidth of the entire range, and the number of bands.

[071] In an exemplary embodiment, the sweep frequency range may be 20 to 35 kilohertz, and the subsets or bands may be 20 to 25 kilohertz, 25 to 30 kilohertz, and 30 to 35 kilohertz.

[072] In an exemplary embodiment, the at least one processor may be configured to compare at least one spectral characteristic between the frequency bands. The lower frequency component of the transmitted acoustic signal penetrates better to the ground, whereas the higher frequency component reflects better off the top of the vegetation. In an exemplary embodiment, matched filtering may be performed on different frequency subsets of the received signal. For example, matched filtering may be performed based on a higher frequency range of the transmitted signal – including the option of the full frequency range – to produce a first set of reflected power measures, and matched filtering may also be performed based on a lower frequency range to produce a second set of reflected power measures. For example, the lower frequency range may be about one third of the full range of the transmitted signal – although it should be appreciated that other subsets of the frequency range may be used in alternate examples. In the example of a sweep frequency range of about 20 to 35 kHz, the first set of reflected power measures may be matched over 20 to 35 kHz, the second set of reflected power measures may be matched over 20 to 25 kHz.

[073] The strength of reflection of an acoustic signal is proportional to the product of two quantities: the reflecting properties of objects in the path of the transmitted signal; and the strength of the signal reaching the objects. In exemplary embodiments, in order to estimate the reflection properties of the vegetation the reflected intensity signal (e.g. the first and second sets of reflected power measures) may be divided by the transmitted intensity. An integrated reflected intensity, summed over the full recorded duration from each transmitted signal, may be used as an estimator of the transmitted intensity. This integrated reflected intensity may vary depending on what reflectors are present, but is expected to be proportional to the transmitted intensity. It is believed that this method of normalisation of the reflected signal, to obtain a measure of the reflectors' properties, may assist with avoiding dependency on calibration. In the exemplary embodiments in which first and second sets of reflected power measures are obtained for different frequency ranges, normalisation of those data sets may use the integrated reflected intensity over the respective frequency ranges. These normalised data sets will be referred to herein as a measure of 'reflectivity'.

[074] In exemplary embodiments, the distance to ground may be found from a reflectivity-weighted distance using the low-frequency reflectivity. The reflectivity-weighted distance may be obtained by multiplying the integrated distance by the reflectivity. Distance may be determined from the time since transmitting the acoustic signal, assuming a standard acoustic (i.e. sound) speed. The basis of using a reflectivity-weighted distance is that the low-frequency reflection from the ground is considered to dominate the weighted distance. The low frequency data set (i.e. second data set) may be used for this ground estimation, which includes multiply reflected echoes (called 'bounce' in the field of synthetic aperture radar).

[075] In an exemplary embodiment, the at least one processor may be configured to determine a distance to the ground surface using identified commonalities in the at least one spectral characteristic between the frequency bands.

[076] In an exemplary embodiment, determining the top of the vegetation may include taking a standard deviation of the reflectivity of the first data set (e.g. across the full frequency range) in a region known to be above the vegetation – referred to herein as 'noise' standard deviation. The distance to the top of the vegetation may be estimated as being where the reflectivity of the first data set divided by the noise standard deviation exceeds a predetermined threshold. For example, this ratio may be in the order of twenty – i.e. the reflectivity has to rise above twenty times the background noise before it is considered that the reflectivity is coming from vegetation. It should be appreciated that this value is not intended to be limiting to all embodiments, being considered by the inventors to be conservative, but guarding against 'false positives' of top of vegetation detection arising from variations in the noise background.

[077] It should be appreciated that a height of the vegetation may be obtained by comparing the top of the vegetation with the ground position. In exemplary embodiments, characteristics of the received at least one echo may be used to determine other characteristics of the vegetation beyond height – for example density. For example, the characteristics of the echoes may include one or more of: intensity, rate of change, time of flight, and a characteristic of scattering (e.g. backward scattered acoustic power).

[078] Reference to density of vegetation should be understood to mean the biomass within a unit volume. It is envisaged that density may be useful in determining or estimating measures such as dry matter, which is particularly important for use in evaluating the value or availability of the vegetation as feedstock for animals.

[079] In an exemplary embodiment, an indication of density may be determined using a measure of the determination of the distance to ground, and a measure of the determination of the distance to top of vegetation. For example, it is envisaged that a relatively low density vegetation cover may result in a relatively strong intensity of the echo from ground. Further, it is envisaged that a relatively low density vegetation cover may result in a relatively low correlation between the transmitted signal and a received echo from the top of the vegetation.

[080] In an exemplary embodiment, an indication of biomass may be determined using a measure of acoustic scattering reflectivity. For example, the reflectivity may be integrated (i.e. summed) over the estimated vegetation depth region – i.e. the region between the top of the vegetation and ground. This excludes reflectivity from 'bounce'. The reflectivity from a small region around the estimated ground is also excluded, giving a measure of reflectivity within a spatially limited region, referred to herein as 'vegetation single-reflection-only reflectivity'. The region around estimated ground may be defined as being the fundamental spatial resolution of the matched filter – equal to the acoustic signal speed divided by twice the frequency bandwidth. A ratio is then found of this vegetation single-reflection-only reflectivity to the reflectivity from the small region around the estimated ground region. The result is an estimate of the fractional contribution of the vegetaton to the overall reflectivity. This provides another single quantity, overall acoustic scattering reflectivity "*R*", which is an acoustic measure of vegetation density.

[081] The at least two predictor variables of vegetation height and overall acoustic scattering reflectivity are available on a profile-by-profile basis. In exemplary embodiments, linear regression using these two predictor variables may be used to estimate biomass. It is envisaged that additional predictor variables may be obtained, describing how the acoustic reflectivity is distributed vertically through the vegetation. Such additional predictor variables may include, for example, a measure of the variance of the reflectivity within the vegetation layer, or a measure of whether the reflectivity is biased toward the base of the layer (i.e. whether the vegetation is thicker toward the ground).

[082] According to one aspect of the present disclosure, there is provided a vegetation measurement system, including:

a vegetation measurement apparatus as herein described; and

a vehicle unit to which the vegetation measurement apparatus is mounted.

[083] It is envisaged that exemplary embodiments of the present disclosure may have particular application to being mounted to a wheeled vehicle such as an all-terrain vehicle (ATV), commonly used on pasture based farms to navigate the farm to perform various tasks. However, it is also envisaged that the apparatus may be mounted to an unmanned aerial vehicle (UAV) – for example, a rotorcraft such as a helicopter or multi-rotor. In such a case, the UAV may be programmed to automatically follow a flight path, or manually controlled. Further, it is envisaged that the vegetation measurement apparatus may be carried – for example by a user, or an animal such as a dog or horse.

[084] In exemplary embodiments, the vegetation measurement apparatus may be mounted between 200 millimetres to 10 metres above the ground surface, in use.

[085] In exemplary embodiments, particularly when mounting to a wheeled vehicle, it is envisaged that the vegetation measurement apparatus may be mounted between 800 millimetres to 900 millimetres above the ground surface. In an exemplary embodiment the vegetation measurement apparatus may be mounted about 850 millimetres above the ground surface.

[086] In an exemplary embodiment the acoustic sensor device may be mounted forward of the vehicle in the direction of travel. It is envisaged that this may have particular application to wheeled vehicles which may potentially depress or disrupt the vegetation prior to the measurement taking place. It is also envisaged that this may reduce the likelihood of reflections or reverberations of acoustic signals from the vehicle being mixed with the ground and vegetation echoes.

[087] It should be appreciated that the amount of offset required may be influenced by the height of the acoustic sensor device above ground, the height of the vegetation, and the directivity pattern of the transmitting and receiving. It may also depend on the speed of the vehicle and the physical shape of the vehicle. In the case of mounting to a wheeled vehicle, it is envisaged that the vegetation measurement apparatus may be mounted such that the closest acoustic transducer is at least 70 millimetres forward of any part of the vehicle in the intended direction of travel. In an exemplary embodiment the vegetation measurement apparatus may be mounted between 70 millimetres to 300 millimetres forward of the vehicle.

[088] It is envisaged that at least one characteristic of the vegetation may be determined or estimated using information derived from the echo of the transmitted acoustic signal in combination with information from at least one other source.

[089] In an exemplary embodiment, geolocation information may be associated with the information derived from the echo of the transmitted acoustic signal. In an exemplary embodiment the geolocation information may be received from a geolocation device of the vegetation measurement apparatus, or from a user device in proximity to the vegetation measurement apparatus, or from a vehicle to which the vegetation measurement apparatus is mounted.

[090] In an exemplary embodiment, the information from at least one other source may include vegetation colour information. It is envisaged that the vegetation colour information may be derived from satellite imagery – for example as expressed in vegetation indexes such as normalized difference vegetation index (NDVI) and leaf area index (LAI).

[091] The information from at least one other source may also include one or more of: species composition of the vegetation, season, soil related characteristics, and weather activity.

[092] For a firmware and/or software (also known as a computer program) implementation, the techniques of the present disclosure may be implemented as instructions (for example, procedures, functions, and so on) that perform the functions described. It should be appreciated that the present disclosure is not described with reference to any particular programming languages, and that a variety of programming languages could be used to implement the present invention. The firmware and/or software codes may be stored in a memory, or embodied in any other processor readable medium, and executed by a processor or processors. The memory may be implemented within the processor or external to the processor.

[093] Control may be performed by a processor, and more particularly a microprocessor: a self-contained computer system capable of storing and executing software instructions, receiving input from peripheral circuitry and providing output signals to peripheral circuitry. A general purpose processor may be a microprocessor, but in the alternative, the processor may be any suitable processor, controller, microcontroller, or state machine. A processor may also be implemented as a combination of computing devices, for example, a combination of a digital signal processor (DSP) and a microprocessor, a plurality of microprocessors, one or more microprocessors in conjunction with a DSP core, or any other such configuration. The processors may function in conjunction with servers and network connections as known in the art and described herein.

[094] The steps of a method, process, or algorithm described in connection with the present disclosure may be embodied directly in hardware, in a software module executed by one or more processors, or in a combination of the two. The various steps or acts in a method or process may be performed in the order shown, or may be performed in another order. Additionally, one or more process or method steps may be omitted or one or more process or method steps may be added to the methods and processes. An additional step, block, or action may be added in the beginning, end, or intervening existing elements of the methods and processes.

[095] The above and other features will become apparent from the following description and the attached drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[096] The detailed description of the drawings refers to the accompanying figures in which:

[097] FIG. 1 is a schematic diagram of an exemplary vegetation measurement system;

[098] FIG. 2 is a schematic diagram of an exemplary vegetation measurement apparatus;

[099] FIG. 3 is a side view illustrating mounting of the exemplary apparatus to a vehicle;

[0100] FIG. 4A is a schematic view of a first exemplary transducer array;

[0101] FIG. 4B is a schematic view of a second exemplary transducer array;

[0102] FIG. 4C is a schematic view of a third exemplary transducer array;

[0103] FIG. 5A is a beam forming map for the exemplary transducer array;

[0104] FIG. 5B and 5C illustrate an exemplary directivity pattern;

[0105] FIG 6A-C are schematic views of further exemplary transducer arrays;

[0106] FIG. 7A is a first graph of distance against echo intensity for a single measurement;

[0107] FIG. 7B is a second graph of averaged distance against echo intensity;

[0108] FIG. 8 is a third graph of averaged distance against echo intensity;

[0109] FIG. 9 is fourth graph of distance against echo intensity;

[0110] FIG. 10 is a graph of distance against echo intensity for matched filtered data; and

[0111] FIG. 11 is a graph comparing the coefficient of determination for correlations between direct measurement of biomass and a number of estimators.

DETAILED DESCRIPTION OF THE DRAWINGS

[0112] Exemplary embodiments are discussed herein in the context of measurement of characteristics of pasture. However, it should be appreciated that principles of the disclosure discussed herein may be applied to other vegetation.

[0113] FIG. 1 illustrates an exemplary vegetation measurement system 100, within which exemplary vegetation measurement apparatus 200a and 200b are mounted to vehicles in the form of an all-terrain vehicle (ATV) 102a and unmanned aerial vehicle (UAV) 102b.

[0114] Data collected by the vegetation measurement apparatus 200a and 200b, and associated processing, may be transferred to and processed by various devices within the system 100. For example, the vegetation measurement apparatus 200a may wirelessly communicate with a user device (such as a smart phone 104), which may in turn communicate over a network 106 with a local hardware platform 108 (for example a personal computer) and/or a service provider server 110 having an associated memory 112 for the storage and processing of data. It should be appreciated that the server 110 and memory 112 may take any suitable form known in the art – for example a “cloud-based” distributed server architecture or a physical server architecture. The network 106potentially comprises various configurations and protocols including the Internet, intranets, virtual private networks, wide area networks, local networks, private networks using communication protocols proprietary to one or more companies – whether wired or wireless, or a combination thereof.

[0115] Alternatively, communication may be affected via direct communication between the vegetation measurement apparatus 200a or smart phone 104, and the local hardware platform 108. Alternatively, the vegetation measurement apparatus 200b may wirelessly communicate over the network 106 without an intermediary device.

[0116] The vegetation measurement apparatus 200a and 200b, smart phone 104, local hardware platform 108, and service provider server 110 may also communicate with third party services 114a to 114b to access additional information and/or services. For example, the third party services may provide information such as satellite based vegetation indexes, or services such as farm management tools.

[0117] FIG. 2 illustrates an exemplary embodiment of the vegetation measurement apparatus 200. The apparatus 200 includes one or more acoustic transducer arrays 202. In an exemplary embodiment the one or more acoustic transducer arrays 202 may include a first arrangement 204a having an array of acoustic transmitters 206 and an array of acoustic receivers 208. In another exemplary embodiment the one or more acoustic transducer arrays 202 may include a second arrangement 204b having an array of acoustic transmitters configured to act as both transmitters and receivers. The apparatus 200 further includes a signal driver 210 configured to drive the transducers to transmit an acoustic signal, and signal processing or conditioning circuitry 212 on the output of the receiving transducers.

[0118] The vegetation measurement apparatus 200 further includes a controller 214. The controller 214 has a processor 216, memory 218, and other components typically present in such computing devices. In the exemplary embodiment illustrated the memory 218 stores information accessible by processor 216, the information including instructions 220 that may be executed by the processor 216 and data 222 that may be retrieved, manipulated or stored by the processor 216. The memory 218 may be of any suitable means known in the art, capable of storing information in a manner accessible by the processor 216, including a computer-readable medium, or other medium that stores data that may be read with the aid of an electronic device. The processor 216 may be any suitable device known to a person skilled in the art. Although the processor 216 and memory 218 are illustrated as being within a single unit, it should be appreciated that this is not intended to be limiting, and that the functionality of each as herein described may be performed by multiple processors and memories, that may or may not be remote from each other. The instructions 220 may include any set of instructions suitable for execution by the processor 216. For example, the instructions 220 may be stored as computer code on the computer-readable medium. The instructions may be stored in any suitable computer language or format. Data 222 may be retrieved, stored or modified by processor 216 in accordance with the instructions 220. The data 222 may also be formatted in any suitable computer readable format. Again, while the data is illustrated as being contained at a single location, it should be appreciated that this is not intended to be limiting – the data may be stored in multiple memories or locations. The data 222 may also include a record 224 of control routines for aspects of the vegetation measurement apparatus 200.

[0119] In exemplary embodiments, the vegetation measurement apparatus 200 includes a communications module 226. The communications module 226 may include one or both of a wired communication module 228 for connection to external devices, and a wireless communications module 230 (for example, communicating using a wireless standard such as Bluetooth, Zigbee, Wi-Fi, or a mobile network standard).

[0120] The vegetation measurement apparatus 200 includes a power module 232. It is envisaged that the apparatus 200 may be provided with a battery 234 to allow for use in remote locations without reliance on connection to the carrying vehicles power supply. In exemplary embodiments the power module 232 may include a battery charger 236, and power supply 238 for connection to an external power source to charge the battery.

[0121] In exemplary embodiments, vegetation measurement apparatus 200 may include an orientation sensor such as an accelerometer 240. The accelerometer 240 may be used to determine vertical displacement at particular points in time, which may be used in correcting or determining the distance to ground. The accelerometer may also be used to correct or determine horizontal speed and displacement during or between ground and vegetation height acoustic measurements.

[0122] FIG. 3 illustrates the vegetation measurement apparatus 200a secured to the front of the ATV 102a using vehicle mount 300. The vehicle mount 300 extends forward from the ATV 102a by approximately 100 mm to 300 mm. It is envisaged that this may reduce disruption to the vegetation prior to the measurement taking place, as well as reducing the likelihood of reflections or reverberations of acoustic signals from the ATV 102a being mixed with the ground and vegetation echoes. In an exemplary embodiment, the vehicle mount 300 may also be configured to position the acoustic transducers of the apparatus 200a approximately 800 mm above the ground surface 302. The surface(s) on which the transducers are arranged is oriented to be in a plane 304 substantially parallel to the ground surface 302, with the beam axis 306 perpendicular to the ground surface 302 as a result.

[0123] FIG. 4A illustrates a first exemplary acoustic transducer array 400a, having 29 acoustic transducers 402. The transducers 402 are arranged within a circle – in this particular embodiment approximately 64 mm in diameter, although it is envisaged that the diameter may be between 30 mm and 0.5 m. In the exemplary embodiment illustrated, the design of the first array 400a includes 7 arcs 404 equally rotated about an origin point. Three of transducers 402 (arm transducers 406a-c) are spaced along each arc 404, with a single transducer 402 in the centre (centre transducer 408), and another one of the transducers 402 (offset transducer 410) laterally offset from each arc 404 between the second and third arm transducers 406b and 406c.

[0124] FIG. 4B illustrates a second exemplary acoustic transducer array 400b, having 28 acoustic transducers (not illustrated in FIG. 4B, but the locations of which are indicated by apertures 412 – as will be described further below). The transducer apertures 412 are arranged within a circle. In the exemplary embodiment illustrated, the design of the second array 400b includes 7 logarithmic spirals 414 equally rotated about an origin point. Four of the transducer apertures 412 (spiral transducer apertures 416a-d) are spaced along each spiral 414.

[0125] In an exemplary embodiment, as illustrated by FIG. 4C, the first array 400a and 400b may be positioned on the same transducer mount – for example a printed circuit board (PCB) – in a combined array 400c. The arcs 404 and spirals 414 of the respective arrays are rotated relative to each other such that the transducer positions are not overlapping. In this exemplary embodiment, the transducers 402 of the first array 400a may be acoustic transmitters, with the surface on which they are mounted intended to face the ground in use. The apertures 412 of the second array 400b pass through to the opposing side of the PCB, on which receiving acoustic transducers (e.g. microphones) are positioned.

[0126] It should be appreciated that in an exemplary embodiment, the first array 400a may be positioned on a first transducer mount, and the second array 400b may be positioned on a second, distinct, transducer mount. In such an embodiment, it is envisaged that the transmitting array may be positioned in front of the receiving array in the direction of travel along the ground.

[0127] In an exemplary embodiment, one of the first array 400a and the second array 400b may be configured to both transmit and receive. It is envisaged that in such an embodiment, the array will be connected to switching devices such as transistors configured to clamp or short the transmitting transducers after transmission of the acoustic signal in order to reduce ringing before the echoes are received.

[0128] FIG. 5A shows a beamforming map 500 of the combined array 400c, showing the relative signal strength at a distance from the centre of the beam. It may be seen that there is significant attenuation from the main lobe 502 to side lobes 504, to produce a highly directional transmit and receive beam.

[0129] FIG. 5B and 5C illustrates an approximation of the conical directional pattern 506 of the array 400, wherein the -3dB power of the signal occurs at the circumference of the base 508 of the cone. In exemplary embodiments, the half-cone angle Θ between the beam axis 510 and slant 512 may be between 2 and 10 degrees. In an exemplary embodiment in which the array 400 is positioned approximately 800 mm above the ground, and has a diameter of between 60 to 70 mm, the half cone angle may be between 5 and 8 degrees. The base 508 of the cone 506 represents the footprint of interest of the array 400 on the ground, in this exemplary embodiment having an area of about 0.01 m^2.

[0130] It should be appreciated that all embodiments of the present disclosure are not intended to be limited to the arrays illustrated in FIG. 4A to FIG. 4C. For example, FIG. 6A illustrates a first alternate array 600a in which transducers 602 are arranged within an ellipsoid 604; FIG. 6B illustrates a second alternate array 600b in which transducers 602 are arranged within a square 606; and FIG. 6C illustrates a third alternate array 600c in which transducers 602 are arranged within a rectangle 608.

[0131] Generally, the time of flight between transmitting the acoustic signal, and receiving an echo of the signal, may be used to infer the distance between the transmitters and the surface(s) from which the signal is reflected. In an exemplary embodiment, chirp pulse compression may be used as a signal correlation technique for matching the timing of the transmitted and received signals. More particularly, the transmitted signal may be transmitted as frequency modulated pulses – for example, where the transmitted signal takes the form of a linear sweep in frequency:

$$s(t) = \sin(\varphi) = \sin(2\pi\,[f_0 + (Bt)/(2\tau)]t \qquad 0 \le t \le \tau$$

where t is time, φ is the phase, f_0 is the frequency at $t = 0$, B is the bandwidth and τ is the pulse duration. The pulse is typically of millisecond duration. When $t < 0$ and $t > \tau$ the signal is zero.

[0132] The time taken for a transmitted pulse to return from a target at a distance *z* is $t_z = 2\, z/c$, where *c* is the speed of sound in air. The time taken for an echo from a second target at distance $z+\Delta z$ is $t_{z+\Delta z} = t_z+2\Delta z/c$. If the pulse duration is τ, the echoes from *z* and from $z+\Delta z$ are just separated in time if $2\Delta z/c=\tau$. Therefore the vertical spatial resolution is:

$$\Delta z = c\tau / 2.$$

[0133] For τ = 1 ms and assuming c = 340 m/s, the expected spatial resolution is 170 mm. This is considered too coarse for accurately detecting pasture, and hence the use of chirp pulse compression in this exemplary embodiment. By comparing the echo with the original transmitted signal, improved spatial resolution arises.

[0134] Assuming the echo signal is a delayed version of the transmitted signal with a delay time of Δt, the normalized envelope of the cross correlation of the echo and *s(t)* is approximately:

$$\chi(\mathrm{t}) = \{\sin[\pi B(t - \Delta t)] / [\pi B(t - \Delta t)]\}^2.$$

[0135] This has a peak at $t = \Delta t$, falling to zero at $t = \Delta t \pm 1/B$. The Rayleigh criterion is the generally accepted criterion for the minimum resolvable detail in an imagining process, defined as when the first minimum of the image of one source point coincides with the maximum of another. The resulting time resolution for two echoes is $1/B$, giving a vertical spatial resolution of $c/2B$. Generally $1/B \ll \tau$ and the vertical spatial resolution may be enhanced.

[0136] In an exemplary embodiment, the received signal is post-processed to produce a "vegetation profile" – i.e. a record of the distribution of received echoes in terms of the calculated distance, and associated intensity. In an exemplary embodiment, bandpass filtering may be performed to remove any unwanted frequencies, then chirp processing by cross correlating the transmitted pulse with the received signal, squaring the signal to convert to acoustic intensity, and finally envelope detection performed. An example of the resulting "vegetation profile" is shown in FIG. 7A, where *z* is the distance from the transducer array in millimetres, and the acoustic intensity of the echo has been normalised.

[0137] Vegetation profiles may be interpreted to give physically meaningful parameters of interest, such as vegetation height (difference between top of vegetation and ground position). Single vegetation profiles can be analyzed individually, or alternatively profiles along a predetermined distance (for example, approximately 400 single profiles over a 1 metre length) can be averaged. In FIG. 7B, an average profile over 1 m travel along the ground surface is shown, where again *z* is the distance from the transducers in millimetres. Averaging the vegetation profiles along the 1 m distance reduces the horizontal spatial resolution to a vegetation height estimate once every 1 m. In practical terms, considering the average over a 1 m length should be sufficient in many applications – for example, measurement of vegetation across a paddock.

[0138] Referring to FIG. 7B, it has been identified that an asymptotic approach to zero (see curve 700) occurs following a peak echo intensity 702 indicating a reflection from ground. Such an approach assumes that the last received echoes are the result of reflection(s) between the ground and the vegetation, which will be of a decaying intensity in comparison with the reflection from ground.

[0139] Referring to FIG. 8, the average profiles for pasture when (a) uncut, (b) cut at a mid point ("mid cut"), (c) cut lower than the mid cut ("bottom cut"), and (d) at bare ground, are shown. Overlaid are average pasture heights for the three example pasture lengths, measured using a tape measure. The profiles were clearly altered with each pasture cut (a progressively smaller signal extent in the vertical direction for each cut), and reasonable agreement between the tape measure pasture heights and ultrasound pasture profiles are observed. It should be noted that tape measurements were untaken at 9 positions along the 1 m length, whereas the apparatus took samples approximately 400 times along the same distance. The profile will therefore have a much finer resolution in horizontal direction than the tape measurement, and may actually be a more accurate representation of pasture height.

[0140] In another exemplary embodiment, the distance to ground may be determined by firstly determining a duration for which echoes are received (above a background noise threshold), and secondly determining the mid-point of the duration, at which the distance to ground is expected.

[0141] Such an approach also assumes that the reflected signal travelling upward from the ground can undergo a reflection downward from the vegetation, and a further reflection upward from the ground and thence back to the acoustic sensor device. Multiple paths of this type are possible, but in this exemplar only the "double path" has statistically significant energy. The double path for such a signal leads to twice the total duration for which the received echo signal is above the background noise threshold. The ground position is then found from the mid-point of the total record from each transmission for which there is a significant signal. Referring to FIG. 9, it may be seen that readings of both vegetation top 900 and bare ground 902 centre around the measured ground 904 – with the double path reflections 906 being clearly observed beyond ground 904.

[0142] In another exemplary embodiment, determination of top of the vegetation may include firstly determining the background noise level in region below the acoustic transducers and the top of vegetation – for example, by determining variation over successive predetermined distances (for example by performing standard deviation or RMS calculations) until a minimum variation is determined. Once the background noise level is established, variation from the background noise level by a predetermined amount indicates the detection of the top of the target vegetation – for example at point 908 of FIG. 9, which approximates the measured height of the vegetation 910.

[0143] In exemplary embodiments, a linear frequency modulated chirp swept from 20 kHz to 35 kHz may be used, such that the low frequencies penetrate to the ground and the upper frequencies give higher definition of the pasture top. Matched filtering may be performed based on the full frequency range of 20 kHz to 35 kHz to produce a first 'full' set of reflected power measures, and matched filtering also be performed based on a lower frequency range of 20 to 25 kHz.to produce a second 'low' set of reflected power measures. FIG. 10 shows a typical profile through a vegetation layer in the form of pasture, after matched filtering. Multiple echo peaks are seen, including 'bounce' echoes at a range further than the direct range to the ground. Also shown are the top of the pasture (green) and the ground position (red) measured manually with a tape.

[0144] The reflection properties of the vegetation may be estimated by dividing the reflected intensity signal (e.g. the first and second sets of reflected power measures) by the transmitted intensity. An integrated reflected intensity, summed over the full recorded duration of each pulse, may be used as an estimator of the transmitted intensity. Normalisation of the respective data sets provides measures of 'reflectivity'. The distance to ground may be found from a reflectivity-weighted distance obtained by multiplying the integrated distance by the low-frequency reflectivity, where the value for distance is determined from the time since transmitting the acoustic signal, assuming a standard acoustic (i.e. sound) speed.

[0145] In an exemplary embodiment, determining the top of the vegetation may include taking a standard deviation of the reflectivity of the full data set in a region known to be above the vegetation – referred to herein as 'noise' standard deviation. The distance to the top of the vegetation may be estimated as being at the point where the reflectivity of the first full data set divided by the noise standard deviation exceeds a predetermined threshold (for example twenty times).

[0146] The biomass (*B*) of vegetation in kg m^{-3} may be expressed as:

$$B = \int_0^H \rho dh = \left(\frac{1}{H}\int_0^H \rho dh\right) H = \bar{\rho} H$$

where ρ is the bulk density of dry matter (DM) and *H* is the depth of the vegetation. The bulk density includes the empty space between individual plants (e.g. grass blades of pasture). Underlying the use of vegetation height *H* as a measure of biomass *B* is the assumption $\bar{\rho}$ is constant for a range of vegetation conditions. However, the inventors consider the correlation between *B* and *H* alone to be relatively weak.

[0147] The backward scattered acoustic power, *dP*, from a depth *dh* is:

$$\frac{dP}{P} = \alpha_{bs} dh$$

where *P* is the power incident on the area at depth *h*, and α_{bs} is the backscatter cross section per unit volume.

[0148] Integrated over the vegetation depth, assuming scattering losses are small, the overall acoustic scattering reflectivity (*R*) is

$$R = \int_0^H \frac{dP}{P} = \left(\frac{1}{H}\int_0^H \alpha_{bs} dh\right) H = \overline{\alpha_{bs}} H$$

[0149] Acoustic scattering depends on orientation of components of the vegetation such as leaves, and some parts of the vegetation will be obscured, so acoustic scattering will only measure part of the biomass. Also, an acoustic measure of scattering does not take account of the moisture content of the vegetation. The errors in the assumption that $\bar{\rho}$ is constant, and in the assumption that $\overline{\alpha_{bs}}$ is constant, arise from unrelated causes. As such, it is believed that $\bar{\rho}$ may not be highly correlated with $\overline{\alpha_{bs}}$. Therefore, *H* and *R* may be independent predictors of *B*. Regression models may be applied to estimate biomass, and FIG. 11 compares the coefficient of determination (R^2) for correlations between direct measurement of biomass (through cutting, drying, and weighing) and a number of estimators of biomass: pasture depth *H* (obtained using a tape measure, a C-DaX pasture meter, and acoustic detection from the present technology), acoustic reflectance *R*, compressibility (obtained using a rising plate meter: "RP"), and an all-acoustic estimator combining *H* and *R* of the present technology.

[0150] No admission is made that any reference disclosed herein constitutes prior art. The discussion of the references states what their authors assert, and the applicants reserve the right to challenge the accuracy and pertinency of the cited documents. It will be clearly understood that, although a number of prior art publications are referred to herein, this reference does not constitute an admission that any of these documents form part of the common general knowledge in the field of endeavour, in New Zealand or in any other country.

[0151] Throughout this specification, the word "comprise" or "include", or variations thereof such as "comprises", "includes", "comprising" or "including" will be understood to imply the inclusion of a stated element, integer or step, or group of elements integers or steps, but not the exclusion of any other element, integer or step, or group of elements, integers or steps.

[0152] Embodiments described herein may also be said broadly to consist in the parts, elements and features referred to or indicated in the specification of the application, individually or collectively, in any or all combinations of two or more of said parts, elements or features.

[0153] Where in the foregoing description reference has been made to integers or components having known equivalents thereof, those integers are herein incorporated as if individually set forth.

[0154] It should be noted that various changes and modifications to the presently preferred embodiments described herein will be apparent to those skilled in the art. Such changes and modifications may be made without departing from the scope of the disclosure and without diminishing its attendant advantages. It is therefore intended that such changes and modifications be included within the present invention.

[0155] Embodiments have been described by way of example only and it should be appreciated that modifications and additions may be made thereto without departing from the scope thereof.

FIG. 1

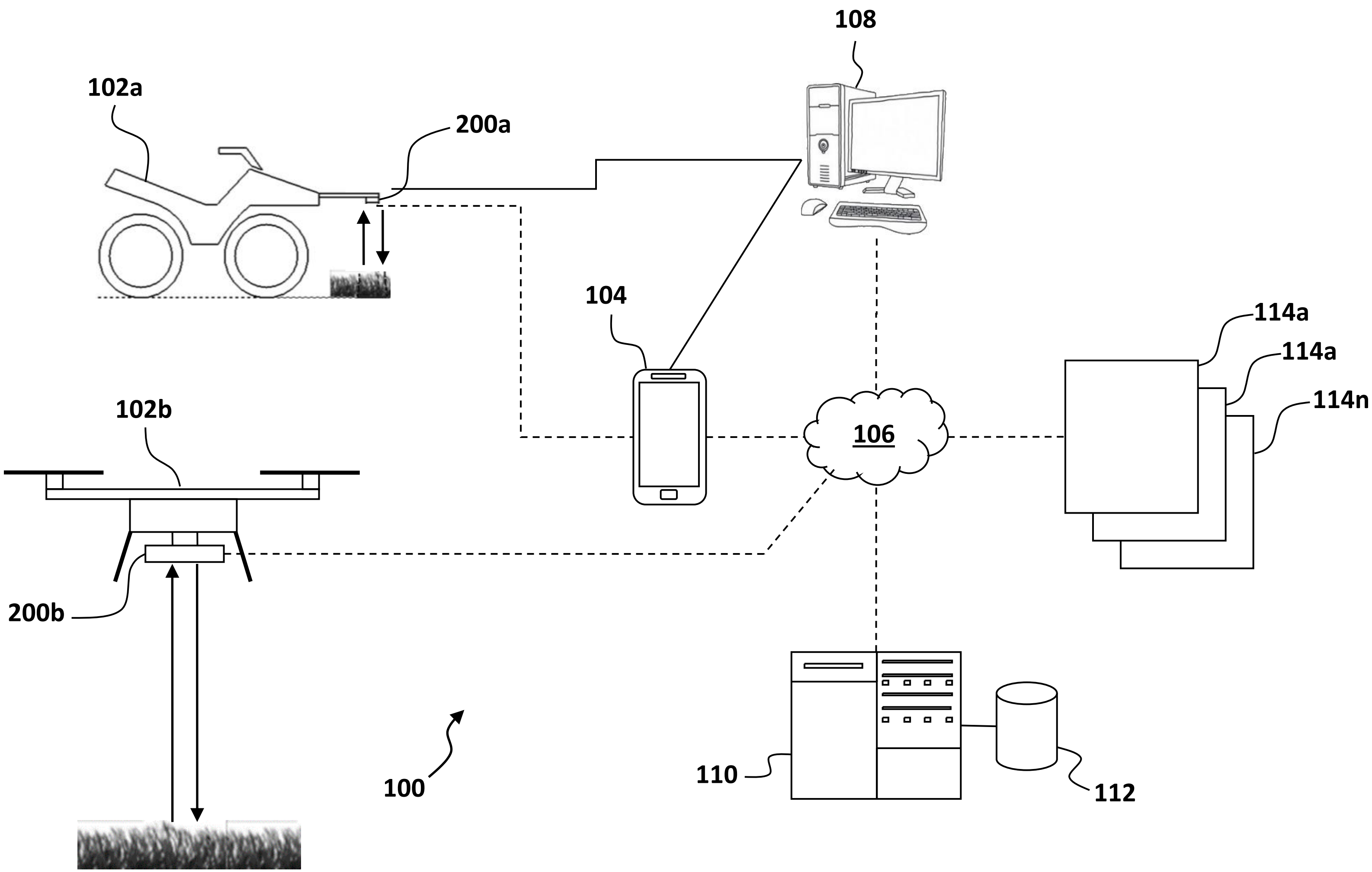


FIG. 2

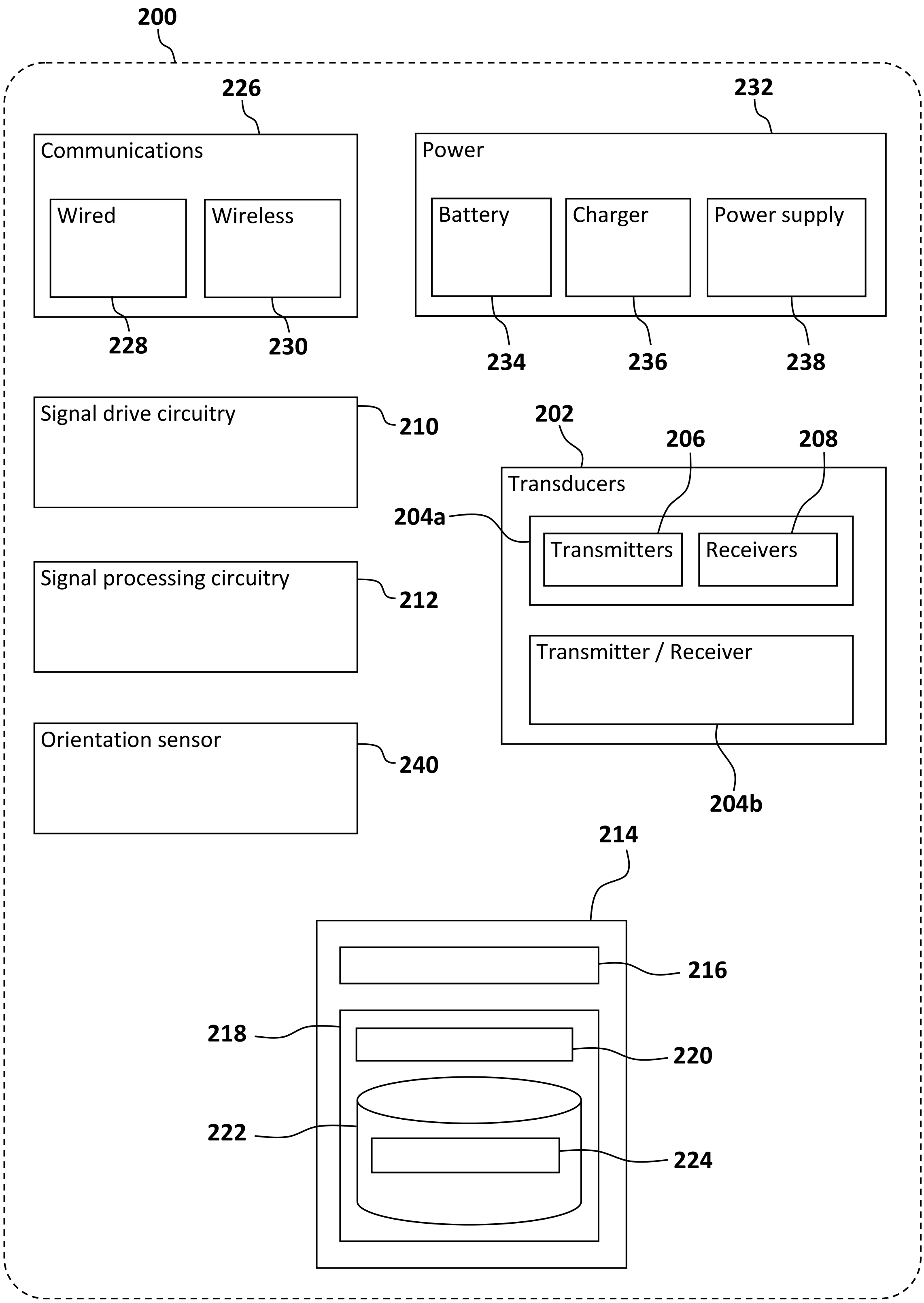

200
226
Communications
Wired
Wireless
228
230
232
Power
Battery
Charger
Power supply
234
236
238
Signal drive circuitry
210
202
206
208
Transducers
204a
Transmitters
Receivers
Signal processing circuitry
212
Transmitter / Receiver
Orientation sensor
240
204b
214
216
218
220
222
224

FIG. 3

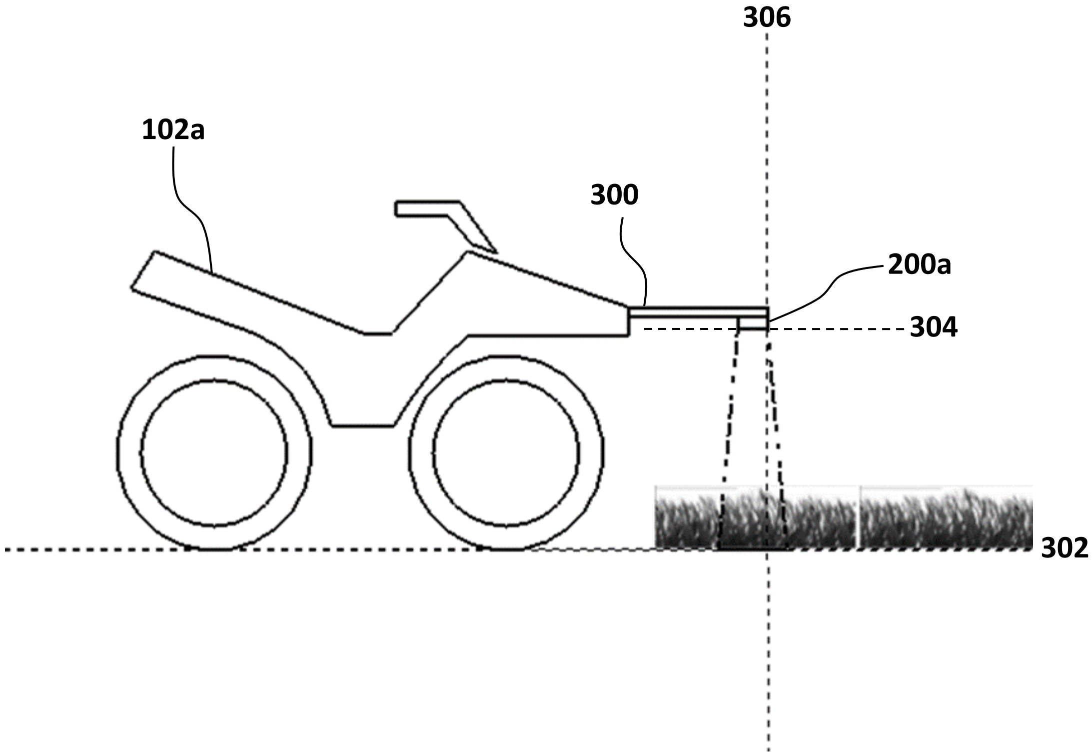


FIG. 4A

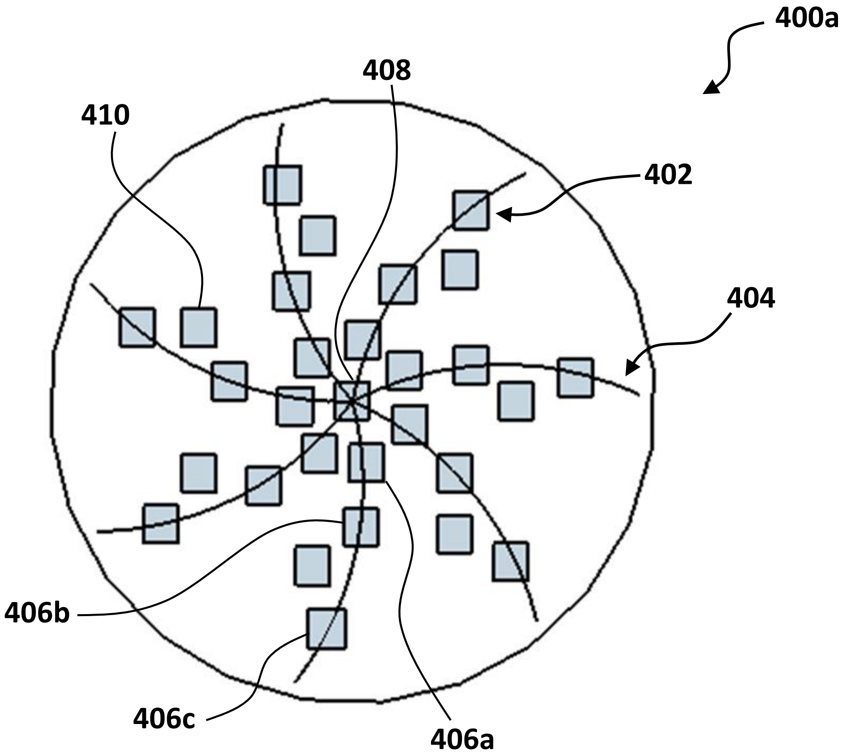


FIG. 4B

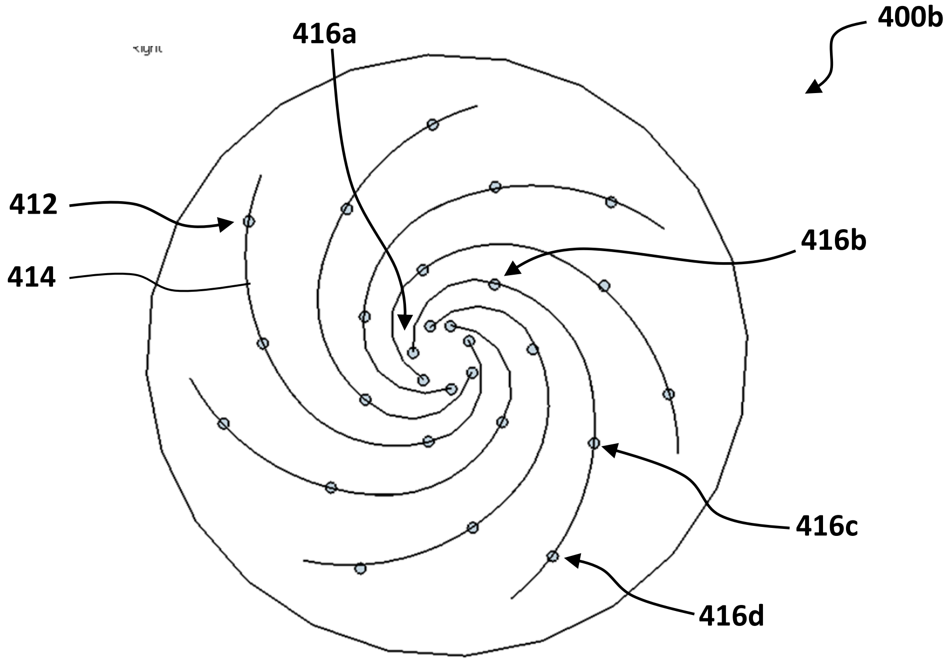


FIG. 4C

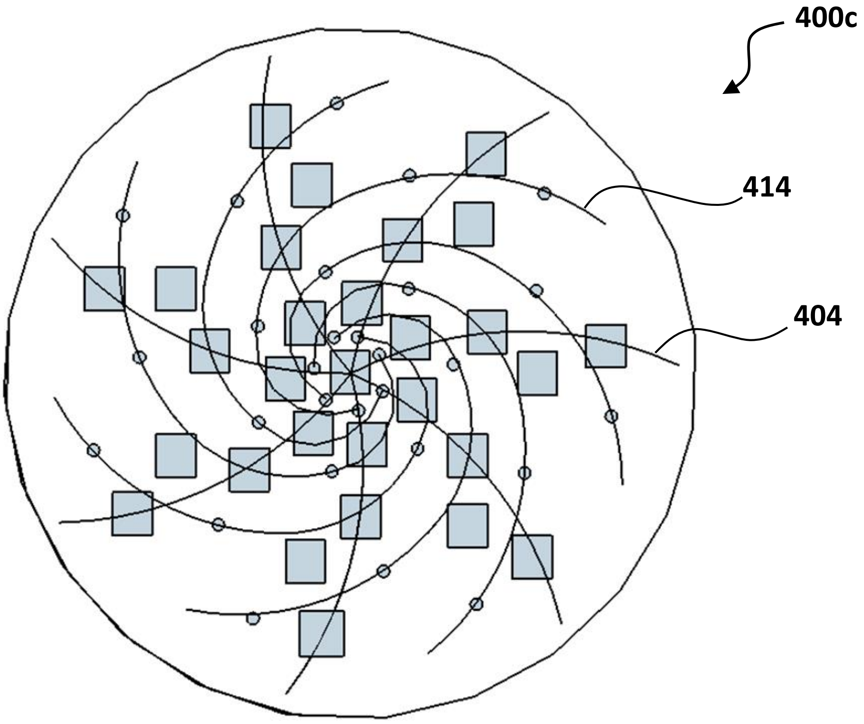


FIG. 5A

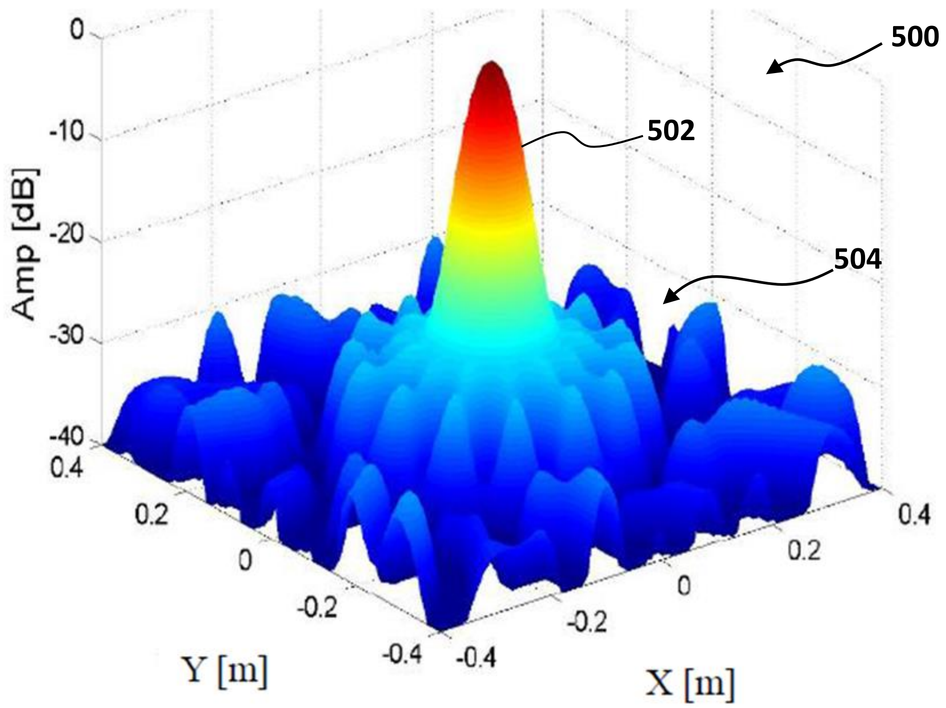


FIG. 5B

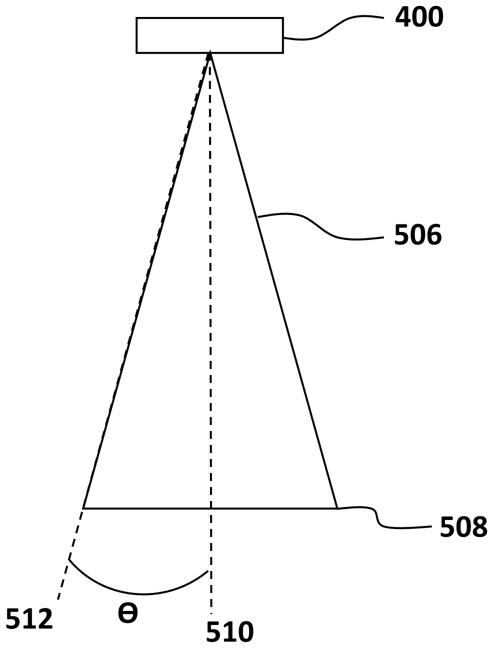


FIG. 5C

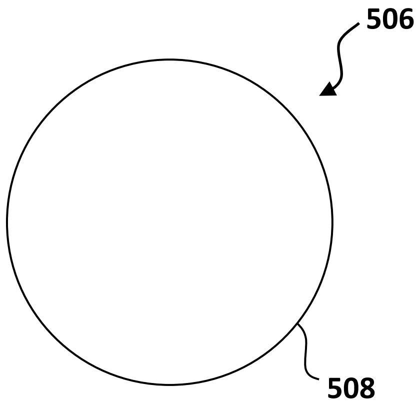


FIG. 6A

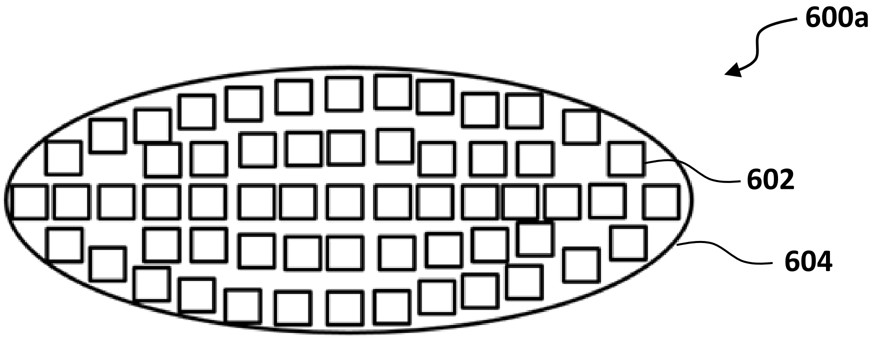


FIG. 6B

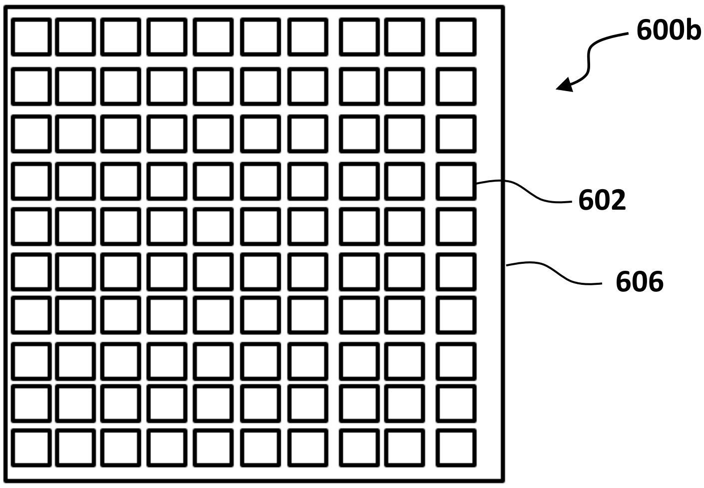


FIG. 6C

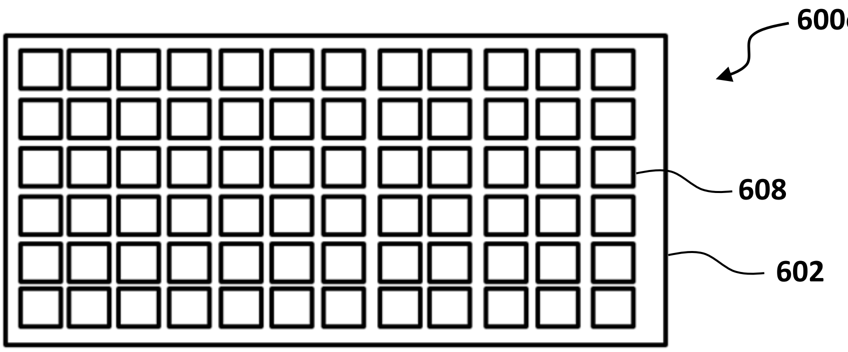
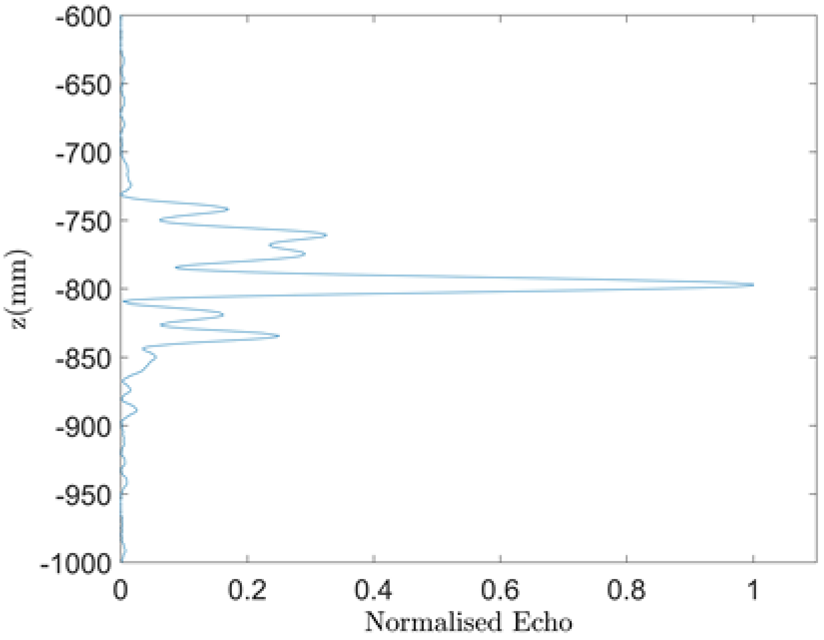
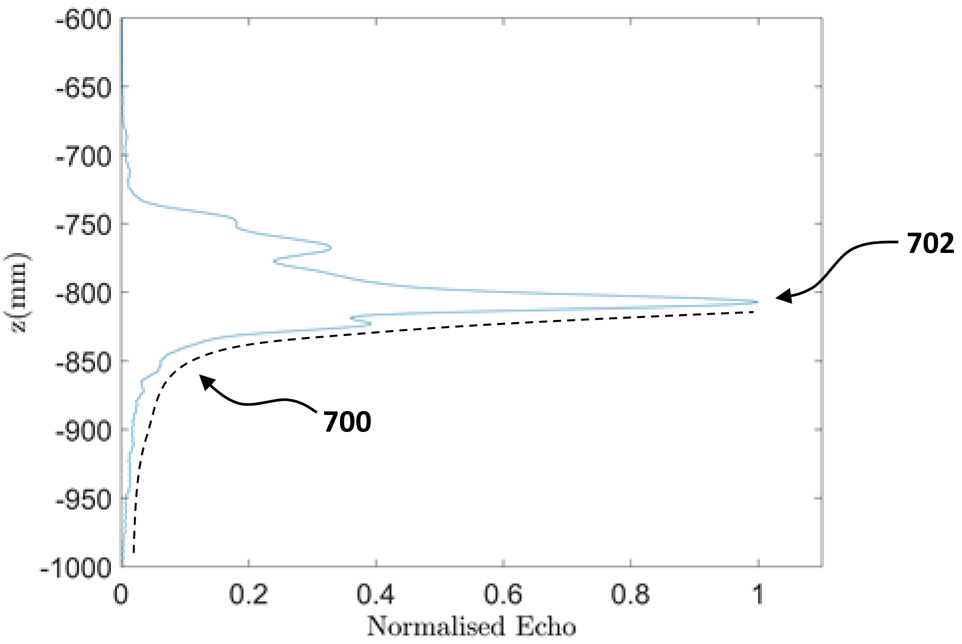


FIG. 7A



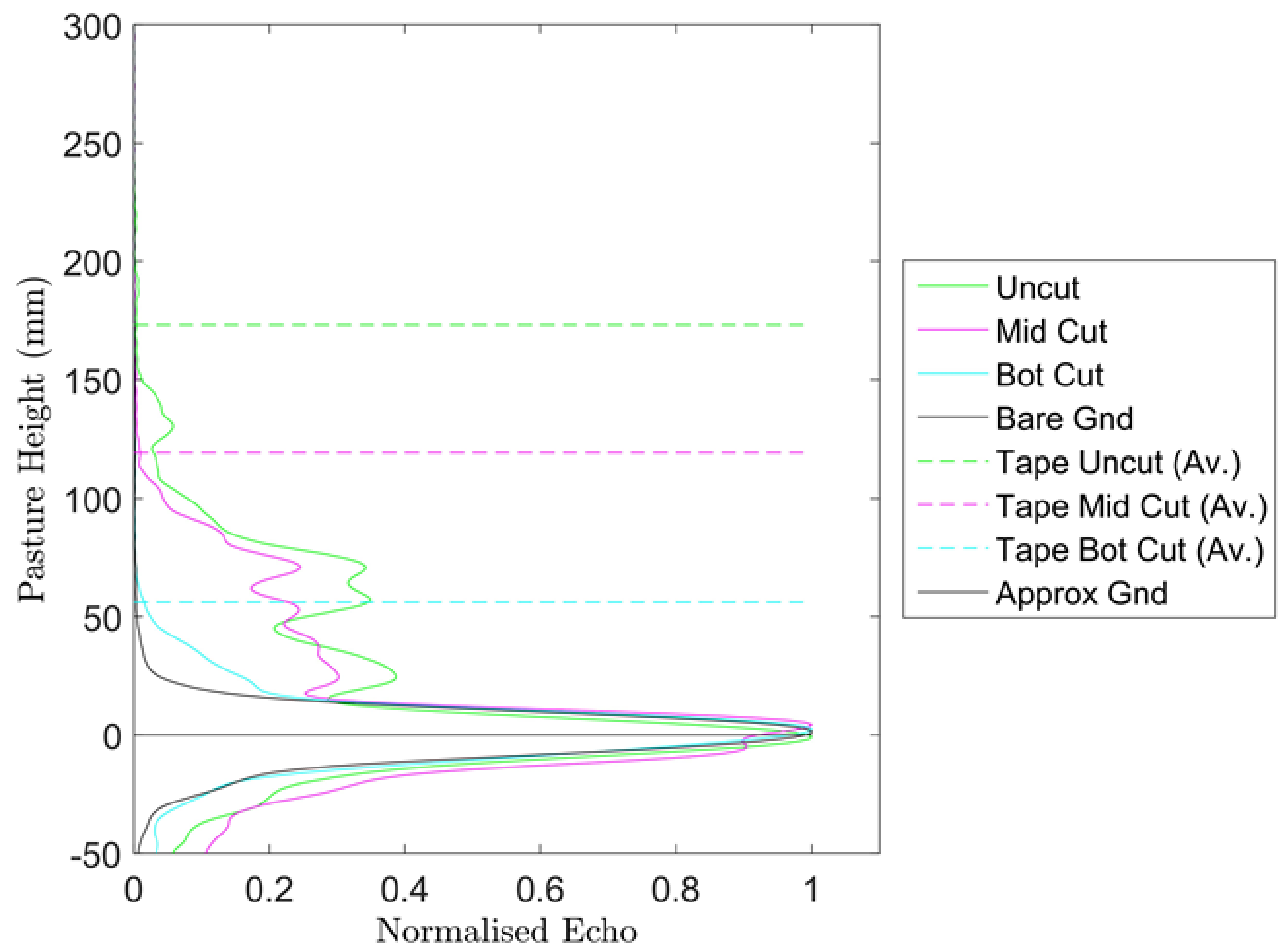
-600
-650
-700
-750
-800
-850
-900
-950
-1000
z(mm)
0
0.2
0.4
0.6
0.8
1
Normalised Echo

FIG. 7B



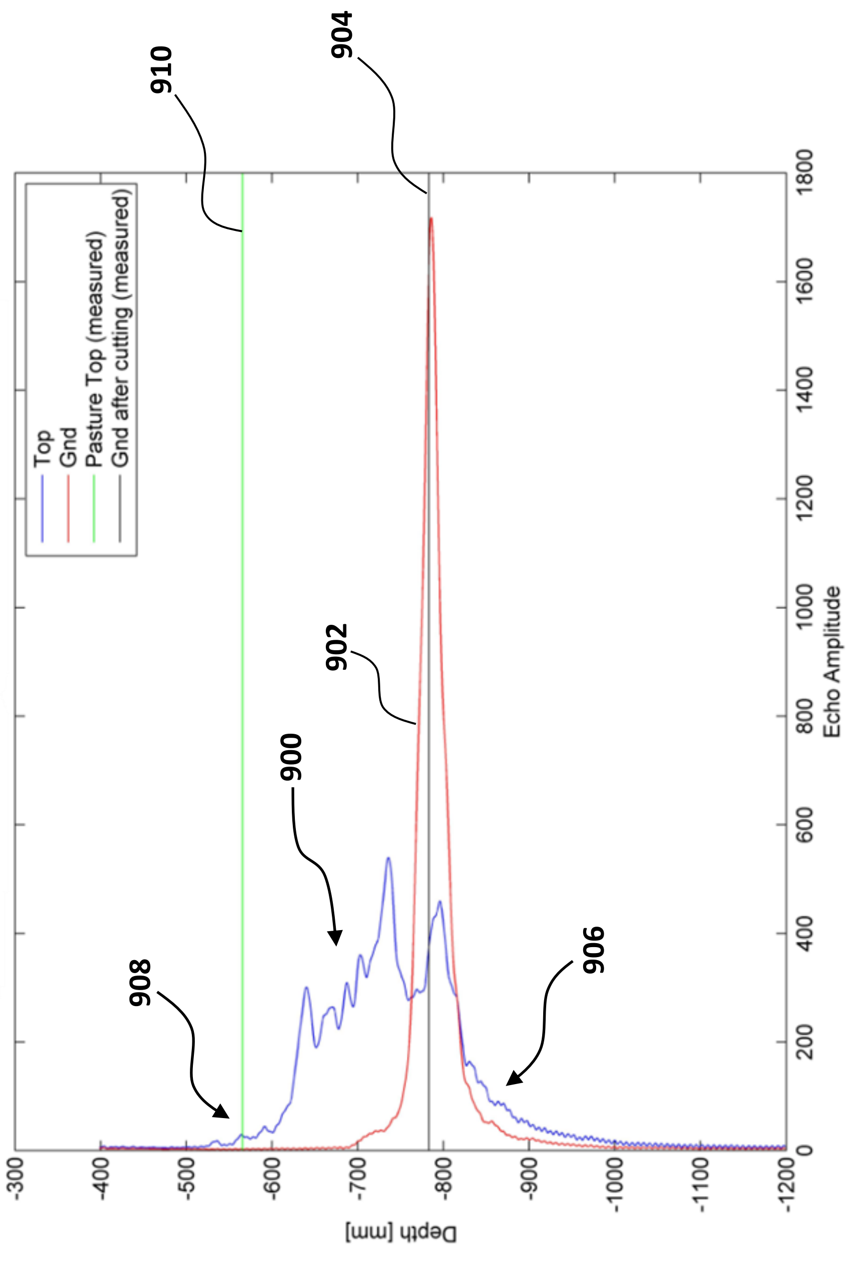
-600
-650
-700
-750
-800
-850
-900
-950
-1000
z(mm)
0
0.2
0.4
0.6
0.8
1
Normalised Echo
702
700

FIG. 8



300
250
200
150
100
50
0
-50
Pasture Height (mm)
0
0.2
0.4
0.6
0.8
1
Normalised Echo
Uncut
Mid Cut
Bot Cut
Bare Gnd
Tape Uncut (Av.)
Tape Mid Cut (Av.)
Tape Bot Cut (Av.)
Approx Gnd

FIG. 9



Top
Gnd
Pasture Top (measured)
Gnd after cutting (measured)
Depth [mm]
Echo Amplitude
-300
-400
-500
-600
-700
-800
-900
-1000
-1100
-1200
0
200
400
600
800
1000
1200
1400
1600
1800
900
902
904
906
908
910

FIG. 10

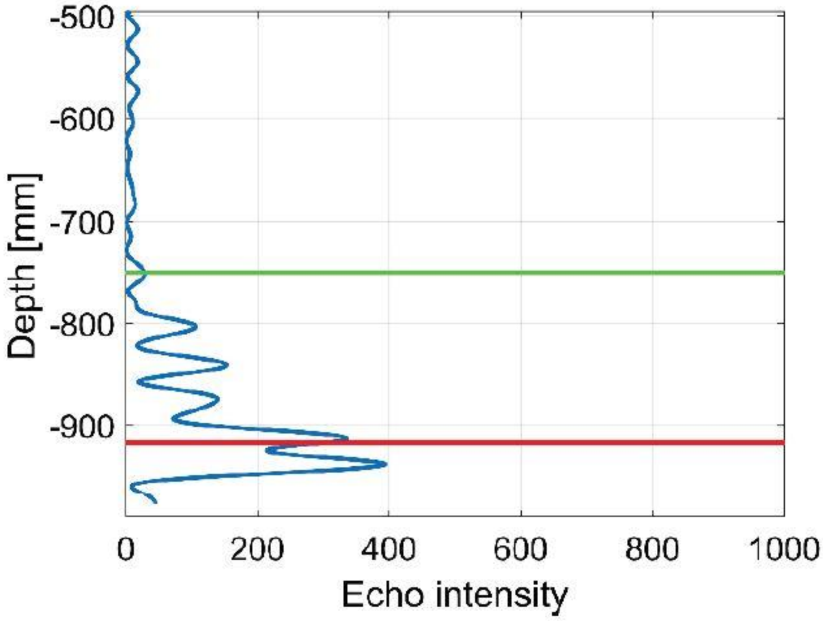
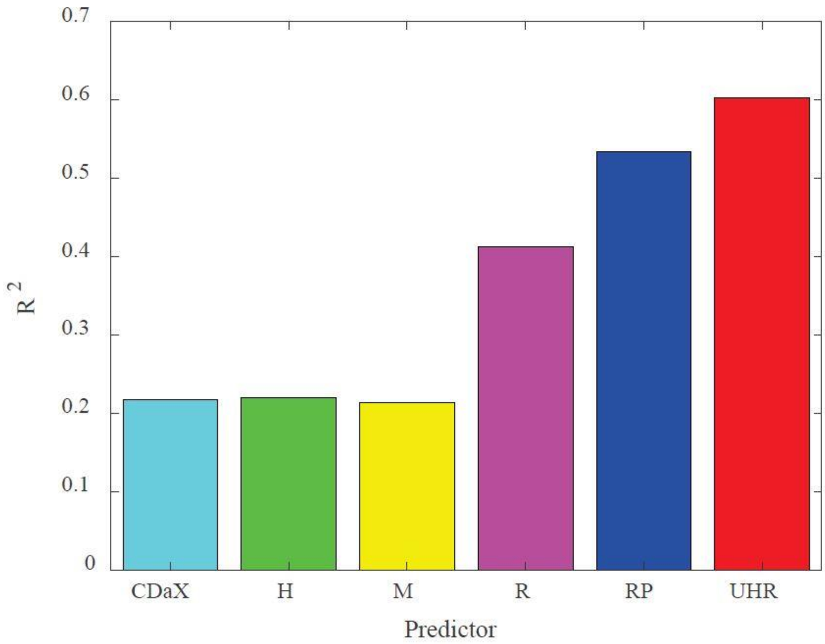

-500
-600
-700
-800
-900
Depth [mm]
0
200
400
600
800
1000
Echo intensity

FIG. 11


0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
R 2
CDaX
H
M
R
RP
UHR
Predictor