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Adaptable Beam-width Ultrasound Array for Remotely Sensing Vegetation Properties

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ABSTRACT

We describe an active ultrasonic sensor for remotely sensing vegetation biomass. The sensor comprises co-located log-spiral arrays of speakers and microphones, and normal operation is about 0.8 m above pasture, mounted on a farm quad bike moving at up to 20 km/h. Since axial sensing is used, individual sensors are not phased. But the sensors are arranged in a number of rings for both transmission and reception, allowing considerable scope for examining the effect of changing the 'footprint' diameter. Linear FM chirp pulses are transmitted and, with matched filtering, very high axial spatial resolution is obtained. Echoes are obtained from blades of grass in the pasture canopy and from the ground. However, because of the strongly reflecting ground surface, secondary reflections also occur (reflection from ground then pasture, or from pasture then ground). This is the situation which also causes challenges for satellite sensing of vegetation using Synthetic Aperture Radar, which is called 'bounce' in that context. The result is that the ground position is hard to identify, with possible difficulty in defining the extent of the vegetative layer. We describe how our multiple footprint diameter sensor addresses this scattering problem.

Keywords: Scattering, Multiple scattering, Signal processing
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1. INTRODUCTION

Modern farming is an intensive business in which optimisation of resources through observation-based farm management software is an important component of

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‘precision agriculture’. For management of grazing animals such as dairy cows, the quantity of economic interest is the biomass, or the mass of ‘dry matter’ (DM) per unit area of ground, which is the mass of pasture per unit area when the pasture has been cut and dried. It is this dry matter which contains the food value for the livestock. Current methods for estimating biomass include: cutting, drying, and weighing; measuring the compressibility of pasture using a ‘rising plate meter’ (RP); measuring the depth of pasture using a ‘CDaX’ or ultrasonic sensor; and using multi-spectral satellite image data. Cutting, although an absolute measure, destroys the pasture. The RP is generally a manual and time-consuming instrument and, while giving good results when used by an expert, can give widely different results depending on the operator. Depth sensing simply requires estimating the height of the top of the pasture, but this is not a very good estimator when comparing pasture of different species or different growing conditions [1, 2]. Multi-spectral satellite estimation is still under study.

The biomass in kg m^{-3} is

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

where ρ is the bulk density of DM and H is the depth of the pasture. The bulk density includes the empty space between grass blades. Underlying the use of pasture height H as a measure of biomass B is the assumption $\bar{\rho}$ is constant for a range of farm pasture conditions. In practice, it is found that this is not true and the correlation between B and H is not strong.

The use of an ultrasonic sensor mounted on a farm bike and remotely sensing pasture properties is attractive because of potential low cost, low power, compactness, and the ability to both sense the depth of the pasture as well as pasture density information within the pasture layer. The backward scattered acoustic power, dP, from a depth dh is

$$\frac{dP}{P} = \alpha_{bs} dh \tag{2}$$

where P is the power incident on the area at depth h, and α_{bs} is the backscatter cross section per unit volume. Integrated over the pasture depth, assuming scattering losses are small, the overall acoustic scattering reflectivity is

$$R = \int_0^H \frac{dP}{P} = \left(\frac{1}{H}\int_0^H \alpha_{bs} dh\right) H = \overline{\alpha_{bs}} H \tag{3}$$

Equations 1 and 3 suggest that acoustic scattering might be used to measure integrated biomass. However, scattering depends on grass blade orientation, and some parts of blades will be obscured, so acoustic scattering will only measure part of the biomass. Also, the acoustic measure takes no account of the moisture content of the grass. The errors in the assumption that $\bar{\rho}$ is constant and in the assumption that $\overline{\alpha_{bs}}$ is constant arise from unrelated causes, and $\bar{\rho}$ may not be highly correlated with $\overline{\alpha_{bs}}$. Therefore, H and R may be independent predictors of B.

The immediate challenge is to obtain good estimations of depth H and integrated reflectivity S. The design of an ultrasonic pasture meter to achieve this is discussed below [3].

2. ANTENNA DESIGN

The height above ground of the mounting on the farm bike is typically h = 800 mm and pasture can be 200 mm deep. The range to the top of the pasture is then typically R = 600 mm. Using the far-field approximation, the diameter W of the sensor array should satisfy

$$W^2 \leq \frac{cR}{f_{max}} \tag{4}$$

where c is the sound speed (nominally 340 m s^{-1}) and f_{max} is the maximum frequency transmitted. We wanted to both detect the top of the pasture (requiring a sufficiently high frequency that individual blades could be sensed) and to penetrate through the pasture to the ground (requiring a sufficiently low frequency that scattering losses are not too great). The compromise was to operate between 20 and 40 kHz. This gives W = 70 mm as a guide for the upper limit of design diameter. In practice we choose f_{max} = 35 kHz to avoid the transmitting element resonance at 40 kHz, and also W = 60 mm to better satisfy the far-field condition. From Airy diffraction, the half-intensity half-beamwidth and footprint diameter on the ground are, respectively, 4.8° and 100 mm at f_{max} = 35 kHz, and 8.4° and 175 mm at f_{min} = 20 kHz. The RP is considered a standard instrument for biomass estimation, with a 'footprint' of 0.1 m^{-2} area and a diameter of 360 mm. This is 4 times that of the ultrasonic pasture meter at its lowest operating frequency.

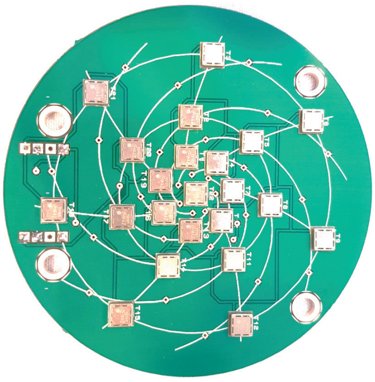

Figure 1. The basic spiral array with transmitting elements shown, and microphones sensing through the small apertures on the marked spirals.

Since the instrument is mounted on a moving farm bike, it is not necessary to steer the ultrasonic beam, and along-axis sensing is used. However, using close-packed surface-mounted transducers is not practical because of the large number of components required to fill a 60 mm diameter disc. Consequently sparse log-spiral arrays were used for beam forming. Rather than use a transponder component, co-located log-spiral arrays of speakers and microphones were used, giving higher gain. Most evaluations were done with a fixed diameter sensor configuration (shown in Figure 1) where the square objects are speakers and the microphones sense through small holes. This design has 7 spirals, each comprising 3 rings of sensors. Another design with 12 switch-selectable rings of microphones ranging in radius from 15 to 75 mm, and 10 switch-selectable rings of speakers ranging in radius from 9 to 75 mm allows wide scope for experimentation and optimisation. The rings lie on 17 spirals. The ring configuration needs to be selected prior to any transmission, but any combination of microphone rings is possible post-recording since the signals from each microphone ring are captured. An advantage of this configuration is that the near-field 'view' of the pasture differs from the far-field, allowing for the possibility of another measure of pasture structure (Figure 2). The transition to near-field conditions at an array radius of around 45 mm causes the footprint radius to decrease more slowly.

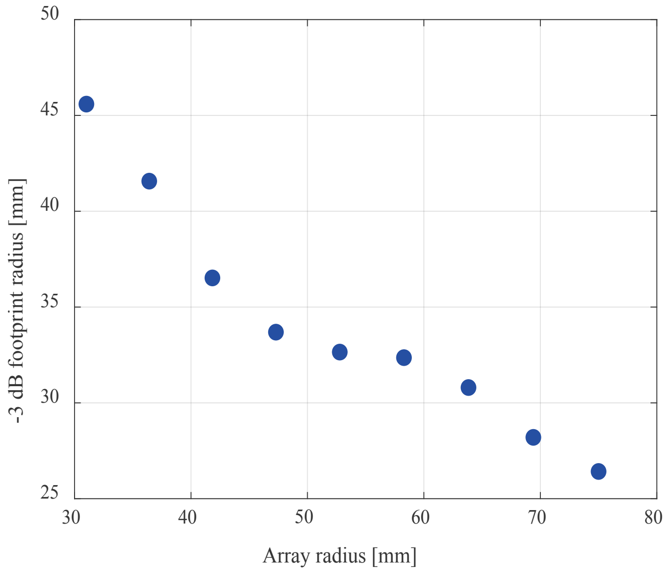

Figure 2. The half-power footprint radius at a range of 850 mm for a 20-35 kHz linear FM chirp and matched filter.

3. CHIRP SIGNAL PROCESSING

The antenna beam forming determines the lateral spread, or footprint, of the instrument. It is also important to have good along-axis or range resolution so that height is accurately measured. While a very short pulse could be used in principle, a single cycle of 20 kHz is 1/6th of the typical pasture depth of 100 mm and with low power output when typical transmitters are driven at their maximum. Therefore, in order to obtain good range resolution as well as produce sufficient power output, linear FM chirp pulses are transmitted. Using a 1 ms sweep from 20 kHz to 35 kHz, a range resolution of 11 mm is achieved with matched filtering. This pulse overloads the co-located microphones during transmission so at least the first 170 mm of range is unusable. In practice, ringing in the transmitters means that the first 400 mm are swamped by the transmission.

4. SCATTERING OF ULTRASOUND BY PASTURE

The points in Figure 2 assume omnidirectional scattering. In practice, pasture blades are thin strips. Figure 3 shows a vertical view of dense pasture, showing a complex scattering matrix and difficulty in seeing the ground. The size parameter, ka, is an important dimensionless guide to the nature of scattering, where k is the acoustic wavenumber and a is the physical dimension of the scattering object. Scattering will be strong and closely related to the area presented to the wave-front if $ka >> 1$ (geometric scattering). For $ka << 1$ (Rayleigh scattering) penetration of the sound past the scattering object is much stronger. For pasture blades of width 3 mm, $ka = 1$ at 18 kHz. In practice we use a linear FM chirp swept from 20 kHz to 35 kHz, so that the low frequencies penetrate to the ground and the upper frequencies give good definition of the pasture top.

Figure 3. A vertical view of dense pasture.

Echoes are obtained from blades of grass in the pasture canopy and from the ground. However, because of the strongly reflecting ground surface, secondary reflections also occur (reflection from ground then pasture, or from pasture then ground). This is the situation which also causes challenges for satellite sensing of vegetation using Synthetic Aperture Radar, which is called 'bounce' in that context [4]. The result is that the ground position is hard to identify, with possible difficulty in defining the extent of the vegetative layer. However, as described above, we can decompose the FM chirp echoes into low-frequency, penetrating, sound and high-frequency sound which allows estimation of the pasture layer depth.

5. RESULTS AND CONCLUSIONS

Figure 4 shows a typical profile through a pasture layer after matched filtering. Multiple echo peaks are seen, including 'bounce' echoes at a range further than the direct range to the ground.

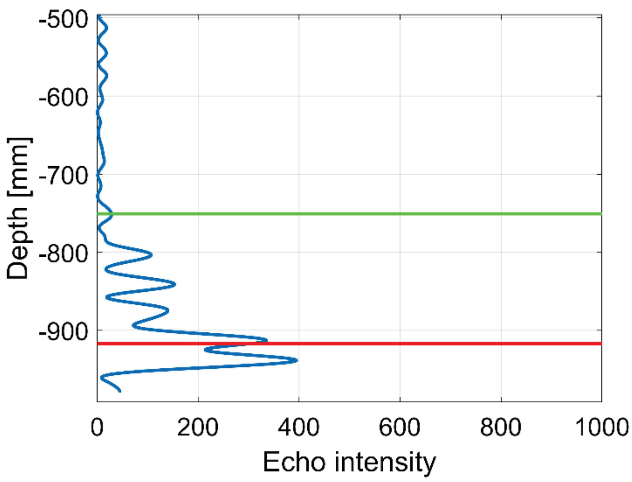

Figure 4. An ultrasonic profile of pasture after matched filtering (blue). Also shown are the top of the pasture (green) and the ground position (red) measured manually with a tape.

Figure 5 shows the results of correlations between direct measurement of biomass (through cutting, drying, and weighing) and a number of estimators of biomass. The analyses were performed on 78 pasture quadrats of size 1500 x 500 mm from a range of sites and seasons, by passing the ultrasonic pasture meter over the pasture manually. The estimators are: pasture depth *H* (tape, CDaX, and acoustic); acoustic reflectance *S*, and compressibility (RP). An all-acoustic estimator, combining *H* and *S*, gives good biomass estimation in comparison with the other technologies investigated, although its performance at farm bike speeds is still to be assessed.

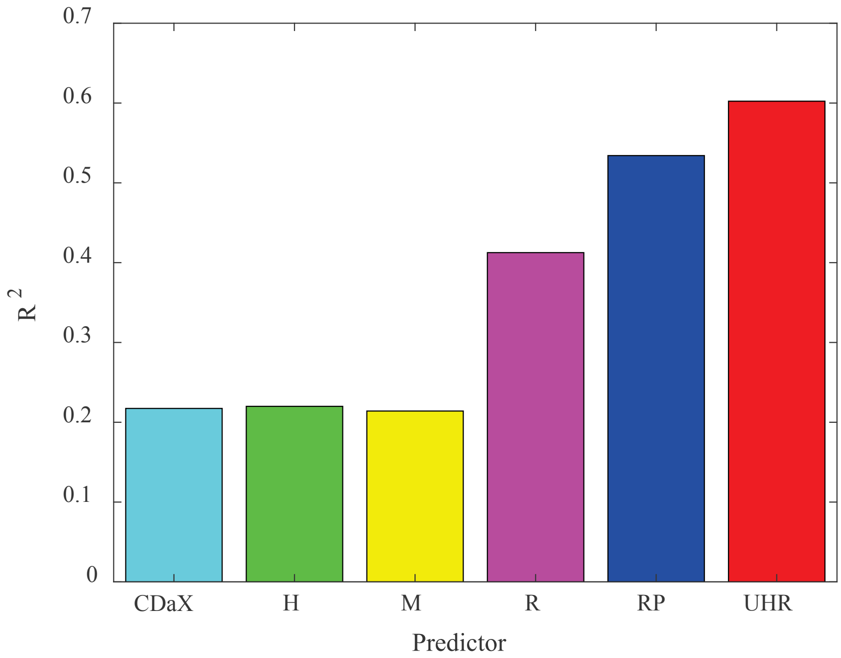

Figure 5. Coefficient of determination, R^2, between direct biomass measurement and predictor variables CDaX pasture depth (cyan), ultrasonic pasture depth (green), manual tape measurement (yellow), ultrasonic reflectivity (magenta), rising plate clicks (blue), and combined ultrasonic depth and reflectivity (red).

6. ACKNOWLEDGEMENTS

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7. REFERENCES

1. W.McG. King, G.M. Rennie, D.E. Dalley, R.A. Dynes and M.P. Upsdell, *"Pasture Mass Estimation by the C-DAX Pasture Meter: Regional Calibrations for New Zealand"*, Proceedings of the 4 th Australasian Dairy Science Symposium (2010)
2. T. Moeckel, H. Safari, B. Reddersen, T. Fricke, and M. Wachendorf, *"Fusion of ultrasonic and spectral sensor data for improving the estimation of biomass in grasslands with heterogeneous sward structure"*, Remote Sensing, vol. 9, no. 1, p. 98, 2017.
3. Patent 740348 *Vegetation Measurement Apparatus, Systems, and Methods.* (2018).
4. Si-Wei Chen, Xue-Song Wang, Shun-Ping Xiao, Motoyuki Sato, *"Target scattering mechanism in polarimetric synthetic aperture radar : interpretation and application"*, Springer (2018)