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SUBMISSION TO THE AGRICULTURAL INNOVATION INQUIRY OF THE STANDING COMMITTEE ON AGRICULTURE AND INDUSTRY

1. Executive summary

This submission to the Agricultural Innovation Inquiry concerns technological capabilities, using novel fibre-optical and laser-based techniques for remote sensing of gases at trace levels in air, to enable both “improvements in the efficiency of agricultural practices” and “emerging technology relevant to the agricultural sector” such as “telecommunications” and “remote monitoring.”

Challenges for Australian agriculture

- Our objective is to address the need of Australian agriculture for innovative technology that can support the global move to intensification of the ruminant industries (driven by the demand for milk and meat, the loss of pastoral and grazing land to desertification, the fragility of our rangelands and their biodiversity, the conversion to cropping, and urban development).
- While beef and dairy production in Australia traditionally depends on grazing of pastures, these sectors need to adopt technologies to reduce the nitrogen, carbon and water footprints of rural production and to increase farm productivity, technical efficiency and profitability.
- The Australian beef industry is increasingly adopting feed lotting and intensive feeding areas, which calls for improved ways to manage localized pollution of ground water and air, dispersal of manure, and effective harvesting of water supplies that are abundant but seasonal in many regions.
- Likewise, Australia’s dairy industry has been introducing strategic supplementation and storage feeding to enable automation, increased herd size and increased milk production rates; this can improve efficiencies of energy, nitrogen and water use as well as yielding environmental benefits by removing grazing ruminants from marginal land. There is also a need to monitor animal health.
- Within this context, it is likely that the Australian beef and dairy industries will increasingly adopt a “mosaic agriculture” model of large and smaller regional schemes. This framework will need reliable technology to examine the likely impacts of change and of necessary trade-offs, with new instruments and decision tools generating real-time data streams and sensors talking to the internet.

What our innovative technology can offer

- Our research group within Macquarie University’s *MQ Photonics* Research Centre has developed innovative technological capabilities, comprising optical instruments for remote sensing of trace gases (*e.g.*, ammonia, carbon dioxide, methane, and water vapour in air) that can team up with other instruments that are already proven for atmospheric sensing in rural field environments.
- This particular methodology is a rapidly swept form of cavity-ringdown spectroscopy (CRDS) that employs multiple optical-cavity sensor units in separate field locations, each linked by optical fibre to a single central control module that can be located hundreds of meters from the sensing sites.
- These CRDS sensor units are compact, rugged and passive (with no moving parts or electrical connections) and able to be deployed in a multi-point network at widely distributed field locations.
- Our innovative fibre-coupled CRDS technology can address many of the above agricultural challenges, by sensing characteristic gas emissions from rural land and livestock, to monitor their nitrogen, carbon and water footprints and to boost agricultural efficiency of processes (*e.g.*, by control of enhanced-efficiency fertilisers and improved land use with regard to water resources, fertility, forestry and urban or industrial impacts on rural land).

Examples of agricultural advantages from fibre-coupled CRDS

The Australian beef and dairy industries are likely to benefit from innovative technologies for sensing of trace gas, including our distinctive fibre-coupled CRDS techniques, as in the following examples:

- Our fibre-coupled design enables remote multi-point sensing, with rugged, compact CRDS sensor units arrayed downwind from grazing livestock to monitor their characteristic gas emissions and to facilitate reduction of their nitrogen, carbon and water footprints.
- Open-path CRDS optical cavities avoid adsorption of "sticky" molecules such as ammonia – a ubiquitous species that is crucial to studies of nitrogen-use efficiencies (*e.g.*, to control enhanced-efficiency fertilisers based on new coatings technology and embedded nitrification inhibitors or to monitor nitrogen losses from manure stockpiles or redistribution of retained nitrogen in a system).
- Arrays of fibre-coupled CRDS sensor units are suitable for deployment in milking sheds to regularly monitor and log the health of individual cows in a dairy herd by breath-analysis of diagnostic gas species (e.g., methane, carbon dioxide, and ketones) at each milking time.
- Monitoring of trace-gas methane emissions can also help to assess Australia's greenhouse-gas burden (as in the recently concluded 2011–14 CSIRO Flagship Laser Methane Research Cluster) or to control environmental and safety associated with rural and urban landfill.

Such technological advantages are likely to be addressed as part of a major collaborative proposal to Round Two of the Department of Agriculture's Rural R&D for Profit programme, just announced at http://www.agriculture.gov.au/ag-farm-food/innovation/rural-research-development-for-profit .

This submission …

Development of our capabilities would enable us to address and contribute to all three aspects of the role of technology in increasing agricultural productivity in Australia on which the Inquiry focuses:

- improvements in the efficiency of agricultural practices due to new technology, and the scope for further improvements;
- emerging technology relevant to the agricultural sector, in areas including but not limited to telecommunications, remote monitoring and drones, plant genomics, and agricultural chemicals;
- barriers to the adoption of emerging technology.

Section 2 will provide a more detailed strategic overview, followed in Section 3 by a brief outline of our technological advantages (further explained in the Appendix). After that, each of the above three themes of the Inquiry will be considered in turn in Sections 4–6, with regard to specific innovative agricultural applications that we anticipate.

2. Strategic background

The Inquiry should be aware of several factors that tend to distinguish Australia from other developed agricultural economies (*e.g.*, in Europe and North America), as follows:

- Australia's beef and dairy sectors depend heavily upon grazing systems, but they attract increasing pressure to join the global move to intensification of the ruminant industries (driven by the demand for milk and meat, the loss of pastoral and grazing land to desertification, the fragility of our rangelands and their biodiversity, the conversion to cropping, and urban development).
- To achieve increased production and profitability, we need to understand the relevant drivers for transformational change (increased efficiency of farm inputs: energy, nitrogen and water) and the trade-offs in our production systems that would need to be adopted, depending on the feasibility of intensifying ruminant production systems while enhancing our environmental stewardship.

- Because beef and dairy production in Australia traditionally depends on grazing of pastures, these sectors have not extensively adopted technologies to reduce the nitrogen, carbon and water footprints of production and to increase farm productivity, technical efficiency and profitability.
- In particular, the Australian beef sector faces an increasing global demand for beef and is heavily dependent upon climate variability (*e.g.*, drought leads to destocking and liquidation of the national breeding herd, from which recovery is slow, which leads to market uncertainty and significant loss in farm profitability). Rangeland beef production is under pressure from social and environmental drivers which increasingly cause many beef enterprises in northern Australia to be unprofitable as terms of trade diminish and land prices fluctuate. Feed lotting and intensive feeding areas are likely to continue to increase as they have over the past decade, but improvements are needed to manage localized pollution of ground water and air, dispersal of manure, and effective harvesting of water supplies that are abundant but seasonal in many parts of Australia's far north.
- Likewise, climate variability and scarcity of irrigation water is making Australian grass-fed dairying less secure, with farm incomes often failing to sustain traditional family units. This sector has been slowly adopting strategic supplementation and storage feeding (which enable automation, increased herd size and increased milk production per animal and per hectare). However, they are generally still fragmented and unable so far to have a consistent impact on regional economies. In strategic terms, increased adoption of storage feeding can increase efficiencies of energy, nitrogen and water use as well as yielding environmental benefits (*e.g.*, by removing grazing ruminants from marginal land that is susceptible to soil loss, low productivity or is difficult to manage).
- The Australian beef and dairy industries are likely in future to adopt a mixed model of large and smaller regional (or even property-based) schemes. Prior to full-scale capitalisation, such an integrated "mosaic agriculture" framework would need technologically sound examination of the likely impacts of change and of necessary trade-offs. New decision tools generating real-time data streams, with sensors talking to the internet, offer exciting prospects for agricultural development.

The foregoing strategic background provides a compelling context for the forms of technological innovation that our group wishes to bring to the Inquiry's attention. Such innovations would facilitate the monitoring of farm systems in terms of water, nitrogen and energy efficiency, focusing on key aspects of intensification (*e.g.*, nitrogen losses from manure stockpiles or redistribution of retained nitrogen in the system for increased feed production and/or reduced environmental pollution).

3. Our innovative technology and its relevance to agricultural productivity

Our research group within Macquarie University's *MQ Photonics* Research Centre has developed innovative technological capabilities, partly *via* our role in the recently concluded 2011–14 CSIRO Flagship Laser Methane Research Cluster (LMRC), but extending far beyond the LMRC's specific focus on agricultural greenhouse-gas emissions. These developments comprise novel optical sensing instruments for detection of trace gases – such as methane (CH_4), ammonia (NH_3), carbon dioxide (CO_2) and water vapour (H_2O) in air – that can be teamed up with other established instruments that are already proven for atmospheric sensing in rural field environments. Our methodology is a rapidly swept form of cavity-ringdown spectroscopy (CRDS) that allows us to place multiple optical-cavity sensor units in separate field locations, each of them rugged, compact and passive (with no moving parts or electrical connections) connected by optical fibre to a single central transmitter/receiver module. This approach enables a network of such fibre-coupled CRDS sensor units to be deployed in a multi-point network at widely distributed field locations of interest.

This innovative fibre-coupled CRDS sensing technology is further described in the Appendix on pages 6 and 7, including a recently presented one-page conference paper that provides scientific and technical substance as well as references to several relevant peer-reviewed publications.

4. Improvements in the efficiency of agricultural practices due to new technology

For field-based sensing of trace-level gas emissions in agricultural air, Macquarie University's CRDS technology entails a rugged, pre-aligned open-path sensor design that can be operated passively (with no moving parts or electrical connections) over many days. This is desirable for cost-effective remote sensing, especially in fibre-coupled multi-site applications. Our innovative technology can yield improved efficiency in a variety of agricultural applications as summarised in the following examples:

- ***Adsorption-free sensing of ammonia (NH_3)*** emitted at trace levels (our established sensitivity: ~11 ppbv in air) targets a key indicator of nitrogen dispersal in soils and in animal waste). For example, NH_3 emissions from livestock in feedlots are traditionally measured by commercial gas analysers with flow systems in which "sticky" molecules such as NH_3 tend to be held up and/or adsorbed; our fibre-coupled open-path CRDS sensors avoid this problem and can calibrate enclosed sensors. There is international concern regarding atmospheric emissions of nitrogen, generally in the form of ammonia (NH_3) and nitrous oxide (N_2O), from beef cattle management systems. These concerns are focused on the effects of NH_3 in contributions of manure to the acidification and eutrophication of sensitive aquatic ecosystems, on degradation of air quality (*e.g.*, by formation of secondary particulate matter *via* atmospheric reactions of NH_3 with sulfate or nitrate) and its impacts on animal and human health, and the effect of its conversion to N_2O –a global greenhouse gas. Recent data suggest that more than 75% of dietary crude protein intake of feedlot-managed beef cattle is recycled to the atmospheric environment as NH_3 or N_2O. However, estimates from biological models vary considerably compared to measured emissions based on assorted instrumental approaches. Various strategies can be deployed to measure concentrations and fluxes of NH_3 in the atmospheric environment, but landscape-scale measurements usually rely on paired instruments or a range of technologies. Our novel CRDS method, using multiple NH_3-sampling points, offers an elegant solution to problems associated with instrument matching. It is also relevant to monitoring of enhanced-efficiency fertilisers, which use new coatings technology and embedded nitrification inhibitors to protect the environment by reducing inputs of nutrients.
- ***Quasi-simultaneous sensing of accompanying carbon dioxide (CO_2) and water vapour (H_2O)*** at background trace levels in air (our sensitivity limits: ~2 ppbv and ~100 ppmv, respectively) can provide useful real-time data on atmospheric conditions, local air quality, and animal health.
- ***Sensing of methane (CH_4)*** emitted at trace level (sensitivity in air: ~65 ppbv established with our existing lasers; <10 ppbv projected with a longer-wavelength laser) can monitor the breath of ruminant livestock (*e.g.*, in cattle yards, in dairies, at feeding sites, and grazing in the open range.) This is also relevant to monitoring of trace-gas methane emissions from rural and urban landfill.
- ***Quasi-simultaneous breath-analysis sensing of acetone vapour can diagnose animal health (ketosis)***, with CRDS selectivity and sensitivity *via* a long-wavelength laser still to be established.
- ***Sensing of vapour from carboxylic acids can serve as a marker of agricultural odour***, in emissions from feedlots and other agricultural sites; projected CRDS selectivity and sensitivity at possible characteristic diode-laser wavelengths still need to be established.
- ***Quasi-simultaneous fibre-coupled open-path CRDS sensing of gas emissions at several widely separated (>1 km) agricultural sites*** uses a distributed network of multiple passive optical-cavity CRDS sensor units. Such multiplexing is feasible for any of the above applications. For example, fibre-coupled open-path CRDS sensors tuned to detect local NH_3 emissions might enable control of a tractor-borne lime spreader to cost-effectively vary the rate at which lime is delivered to acidified soils. Likewise, a row of our fibre-coupled CRDS gas sensor units could be deployed downwind from grazing livestock to avoid ambiguities from single-point sensors and to enhance information that is obtainable by conventional open-path spectroscopic sensing techniques.
- ***Quasi-simultaneous fibre-coupled CRDS can monitor emissions in breath of individual animals in a herd***, *e.g.*, in a dairy milking shed or at an auto-feeder unit. In the former case, fibre-coupled CRDS sensors in milking booths (*e.g.*, at University of Sydney's Camden Farms) could enable breath analysis of exhaled gases (such as NH_3, CO_2, H_2O, ketones, CH_4 and other hydrocarbons) to monitor the health of electronically identified cows in a dairy herd at each milking time.

5. Emerging technology relevant to the agricultural sector

The second theme in the Inquiry's topical guidelines specifically (but not exclusively) refers to four areas of emerging technology, of which two ("telecommunications" and "remote monitoring") are highly relevant to the expertise that is represented in our innovative fibre-coupled CRDS technology.

Optical telecommunications are vital to our rapidly swept CRDS approach to agricultural atmospheric sensing, with finely tuned laser radiation transmitting and receiving spectroscopic signals to and from specific molecules present at trace levels inside open-path optical ringdown cavities that are deployed in the field. Use of single-mode optical fibres (over distances that can exceed 1 km) enables quasi-simultaneous, multi-point remote monitoring of molecular concentrations that helps us to gauge agriculturally relevant conditions such as breath-analysed indicators of animal health or nitrogen losses from soil and manure stockpiles – significant applications of emerging technology. More specific details are provided in preceding sections and in the Appendix (page 6).

The setting of our research in this area is Macquarie University's *MQ Photonics* Research Centre (https://research.science.mq.edu.au/mqphotonics/) incorporating the Centre for Lasers and Applications (established in 1988 by the Australian Research Council as a Commonwealth Special Research Centre). This provides a broad base of capability in emerging technologies, including fibre-optical and laser-based telecommunications and remote monitoring.

Incidentally (and only marginally pertinent in the present context), we have additional optical telecommunications experience in using advanced laser-based techniques and optical fibres to convey high-fidelity radio-frequency signals over hundreds of km (*e.g.*, from Narrabri to Coonabarabran and back) to provide innovative cost-effective ways to control phased arrays of telescope antennae for radio-astronomy by very large baseline interferometry.

6. Barriers to the adoption of emerging technology

We are aware that investment returns from new technology for agriculture are typically low, with progressive Benefit-Cost Analysis (BCA) of about $2.5:1 over five years rising to $10:1 over 20 years. In political and commercial contexts, there tends to be reluctance to develop and implement new agricultural technology, in view of the long-term nature of returns from the necessary investment.

However, the Inquiry should recognise the need for Australia to accept such challenges in order to gain future benefits and to promote a prosperous rural sector. For example, using enhanced-efficiency fertilisers (as mentioned on page 4) could yield savings of more than A$180m annually. Development of new technologies will increase the certainty of the impact of such products, the effectiveness of which is currently variable. Other precision agricultural technologies (*e.g.*, variable spreading, crop canopy monitoring, improved water management) offer further economic and environmental benefits. Moreover, use of innovative agricultural technologies to reduce nitrogen, carbon and water footprints could help to promote "clean, green" food products and attract premium prices in the export market.

Another barrier is that investment in adoption of emerging agricultural technology in Australia is very much protected. This often inhibits exchange or brokerage of knowledge and innovation between stakeholders and technology-rich business and investors. It can limit the testing of novel ideas (in view of likely slow BCA growth), assistance with development of business cases for investment, identification of potential partners, and creation of opportunities for investment (*e.g.*, *via* direct investment, joint ventures, company spin-off/feasibility of start-ups). Likewise, the relatively small scale of Australia's agricultural industry tends to limit the number of investors who would be inclined to favour investment in emerging agricultural technology unless suitable incentives are in place.

Our own experience in promoting innovative optical technology for agriculture is that, despite a series of seemingly compelling proposals submitted over the last few years, it has been extremely difficult for us to attract sufficient R&D funding for instrument development, let alone prototyping and rural field trials. We aim to reverse this experience by means of a proposed major collaborative submission to the forthcoming Round Two of the Department of Agriculture's Rural R&D for Profit programme.

APPENDIX Fibre-coupled CRDS technology relevant to agricultural productivity

As explained briefly in Section 3 above, our research group within Macquarie University's *MQ Photonics* Research Centre has developed innovative technological capabilities that have led to optical sensing instruments for detection of trace gases – such as methane (CH_4), ammonia (NH_3), carbon dioxide (CO_2) and water vapour (H_2O) in air – for diverse agricultural applications.

Our methodology is a rapidly swept form of cavity-ringdown spectroscopy (CRDS) that allows us to place multiple optical-cavity sensor units in separate field locations, each of them connected by optical fibre to a single central transmitter/receiver module and enabling a network of CRDS sensor units to be deployed in the field. These sensor units are compact, rugged and passive (with no moving parts or electrical connections) and all of the active control devices (photodetectors, lasers, optical switches, electronics, etc.) are confined to the single central control module that can be remotely located (*e.g.*, hundreds of meters from the sensing sites) while communicating with a multi-point network of CRDS sensor units at widely distributed field locations of interest.

A brief description (comprising a recently presented one-page conference paper) of our innovative fibre-coupled CRDS sensing technology is appended on page 7 below. This provides scientific and technical substance, as well as references to several relevant peer-reviewed publications.

These distinctive fibre-coupled CRDS sensing techniques (as presented on page 7) offer major advantages for agricultural sensors that could benefit the Australian beef and dairy industries in terms of productivity, profitability, human and animal welfare, and sustainability, as follows:

- Our CRDS method uses near-infrared tunable diode lasers and associated fibre-optical components in a compact instrumental system that enables highly sensitive quantitative detection of optical absorption by gas-phase molecules (*e.g.*, NH_3, CO_2, H_2O, CH_4) at trace levels in air. It is able to supplement other techniques (most of them optical and many laser-based) already used in this area.
- In contrast to other such techniques, our "single-ended" CRDS detection approach uses an optical transmitter and receiver collocated in a single active console that can be located far away from various passive fibre-coupled ringdown-cavity sensor units distributed in the field(s) of interest.
- This fibre-coupled design enables remote multi-point sensing, in which rugged, compact CRDS sensor units are arrayed at long distances from the central transmitter/receiver module, obviating the need to deploy several expensive single-point instruments. A specific application would use a row of fibre-coupled CRDS sensor units placed downwind from grazing livestock, thus avoiding single-point sensing problems and complementing conventional open-path spectroscopic systems.
- Our use of fibre-coupled CRDS sensor units with open-path optical cavities (without needing to transfer the gas of interest into or through an enclosed cavity, as in many other instruments) helps to avoid adsorption of "sticky" molecules such as NH_3 – a ubiquitous species in agricultural, natural and industrial atmospheric environments and crucial to studies of nitrogen-use efficiencies.
- There is also an opportunity, subject to acquisition of a laser operating at longer wavelengths than are available at present, to use fibre-coupled CRDS to monitor animal health by breath-analysis sensing of ketones (*e.g.*, acetone to test for ketosis), CH_4, and other hydrocarbons. This could be particularly relevant to regular monitoring of identified cows in dairy herds in their milking sheds.

The advantages of our fibre-coupled CRDS technology are understood and appreciated by Australian agricultural research groups with whom we have collaborative links (both *via* the LMRC and elsewhere); these links access diverse expertise in agricultural science (*e.g.*, beef and dairy), environmental monitoring, and sensor-based instrumentation. Our collaborations (both established and prospective) include researchers at the Universities of Melbourne, New England, RMIT, Sydney, Western Australia and Wollongong as well as CSIRO (*e.g.*, Chiswick, Lansdown) and the National Measurement Institute in Sydney. We aim to attract support from various government and industry agencies (*e.g.*, Dairy Australia, Grains R&D Corporation, Meat and Livestock Australia, Pastures Australia, Rural Industries R&D Corporation, and Rural R&D for Profit, as well as State EPAs).

A recent conference presentation, describing fibre-coupled CRDS sensing technology

Remote open-path sensing of agriculturally significant molecules at trace levels in air by fibre-coupled continuous-wave cavity-ringdown spectroscopy

Brian Orr[1,2], Yabai He[1,2] and Ian Jamie[2,3] *... presented at 2014 Congress of Australian Institute of Physics (ANU, December, 2014)*

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Cavity-ringdown spectroscopy (CRDS), using near-infrared continuous-wave (cw) tunable diode lasers and associated fibre-optical components, enables highly sensitive quantitative detection of optical absorption by gas-phase molecules at trace levels in air. The sample of interest is inside a high-finesse optical cavity and the concentration of absorbing molecules is measured *via* the decay rate (*i.e.*, "ringdown") of light from the optical cavity. In our distinctive cw-CRDS approach, the optical buildup and subsequent ringdown decay are measured while rapidly sweeping *either* the cavity length *or* the laser wavelength [1]. A particularly simple, compact, rugged form of fibre-coupled, rapidly swept cw-CRDS instrument is depicted schematically in Figure 1.

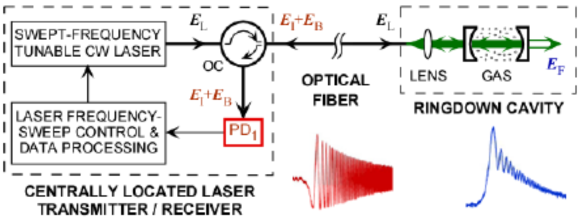

Figure 1: A single-ended fibre-coupled cw-CRDS system.

We employ fibre-optical and photonic components, high-reflectivity mirrors and efficient data acquisition to enhance detection sensitivity and simplify design [1–4]. As indicated in Fig. 1, our cw-CRDS method enables "single-ended" detection, with optical transmitter and receiver collocated in a single console located far away from one or more fibre-coupled ringdown-cavity sensor units. Remote multi-point sensing is facilitated by configuring a number of such sensor units in an array that can be distributed at long distances (*e.g.*, tens of km) from the single central transmitter/receiver module. The single-fibre configuration (as in Fig. 1) entails backward-propagating optical-heterodyne CRDS detection [1,2] and works satisfactorily over single-mode optical fibres spanning tens of metres. Over fibre-optical paths as long as ~20 km, fibre-pair designs have been devised and verified as ways to avoid interfering backward-propagating Brillouin scattering [4].

In a previous multi-species cw-CRDS study of greenhouse-gas molecules (CO_2, H_2O, CH_4) in outdoor air, we used tailored multi-wavelength radiation from a set of pre-tuned diode lasers [3]. Minimum detectable mixing ratios were ~2 ppmv CO_2, ~100 ppmv H_2O, and ~65 ppbv CH_4 (projected to be ~10 ppbv with a longer-wavelength laser). CSIRO's Flagship Livestock Methane Research Cluster focuses on field-based sensing of CH_4 greenhouse-gas emissions from cattle [5]; it aims "to develop accurate and practical methods to measure and reduce livestock methane emissions in the northern Australia beef herd." Detection of CH_4 in breath of ruminant livestock (*e.g.*, in cattle yards, in dairies, at feeding sites, and on open ranges) provides a major focus for our ongoing CRDS research. We are able to incorporate fibre-coupled CRDS sensors with open-path ringdown cavities into field-based eddy-covariance instruments that are designed to monitor fluxes of CH_4, CO_2 and H_2O together with meteorological data. Our open-path CRDS cavity sensor is shown in Figure 2.

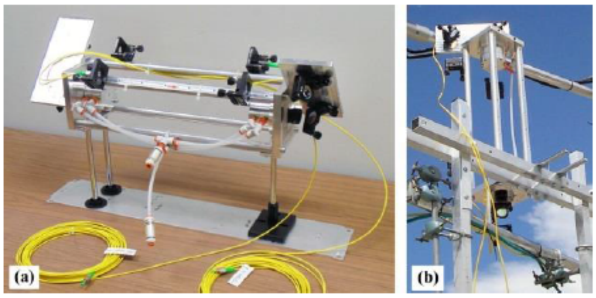

Figure 2: A passive ringdown-cavity sensor unit mounted for gas sensing (a) in the lab and (b) on an eddy-covariance tower.

Ammonia (NH_3) is another molecule that is ubiquitous in our agricultural, natural and industrial atmospheric environments [6]. Our recent CRDS studies of NH_3 at trace levels in air use laser wavelengths of either 1522.45 nm or 1531.65 nm, which are accessible to available tunable diode lasers and free of interference from background absorbers (*e.g.*, CO_2, H_2O). NH_3 can be monitored with a noise-limited mixing-ratio sensitivity of ~11 ppbv in air [4]. Open-path measurement of NH_3 in air at a fertilised campus garden [4] demonstrates CRDS sensing *via* >1 km of twin optical fibre without needing to transfer molecules as sticky as NH_3 over lengths of heated PTFE tubing. Our ongoing research in this area is aimed at remote multi-point sensing of NH_3 in Australian agricultural settings, *e.g.*, monitoring of emissions from cattle, pigs, sheep, etc. in feedlots.

Using a longer-wavelength laser at ~1670 nm, there are prospects of CRDS breath-analysis sensing of ketones such as acetone to monitor animal health (ketosis). Likewise, other possible CRDS applications include detection of carboxylic acid vapor as an indicator of farmland odors.

References

[1] B.J.Orr and Y.He, *Chem. Phys. Lett.* **512**, 1–20 (2011).

[2] Y.He and B.J.Orr, *Appl. Phys. B* **85**, 355–364 (2006).

[3] Y.He, R.Kan, F.V.Englich, W.Liu and B.J.Orr, *Optics Express* **18**, 20059–20071 (2010).

[4] Y.He, C.Jin, R.Kan, J.Liu, W.Liu, J.Hill, I.M.Jamie and B.J.Orr, *Optics Express* **22**, 13170–13189 (2014).

[5] See: http://www.csiro.au/lmrc .

[6] M.A.Sutton, J.W.Erisman, F.Dentener and D.Möller, *Environmental Pollution*, **156**, 583–604 (2008).