final report

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A Report to Meat and Livestock Australia (MLA) on the Measurement of Subcutaneous Fat Thickness using a Microwave Reflection Technique

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Executive Summary

Meat and Livestock Australia (MLA) are investigating a number of non-invasive techniques for the measurement of the thickness of subcutaneous fat on cattle, sheep and pigs (the subcutaneous fat layer is located just below the skin). A successful instrument would be used in abattoirs after skinning of the animal, and would allow the optimum amount of subcutaneous fat to be removed. Optimizing the fat thickness has the potential to increase the income of a typical abattoir by approximately $1 million per year.

The CSIRO ICT Centre has proposed a technique based on the reflection of microwaves from the air-fat and fat-meat interfaces of the carcass. This report details some preliminary calculations and measurements on five samples carried out in May and June 2007. The measurement results are summarized in Table 2 which compares invasive and microwave measurements of fat thickness on the five samples.

Table 2. Microwave measured fat thicknesses of the five samples.

	Fat thickness	
Sample	**Microwave meas’t (mm)**	**Invasive meas’t (mm)**
Pork 1	15.7	11 ± 2
Pork 2	15.7	15 ± 5
Lamb 1	unclear	2 ± 2
Lamb 2	11.3	7 ± 3
Beef	unclear	8 ± 2

Based on these studies, it is concluded that the technique should work in principle; however there are a number of practical difficulties which would need to be addressed:

(i) Measurements would need to be made at a relatively large number of discrete frequencies (>10) or the instrument would need to scan or “chirp” over a frequency range. Unfortunately, instruments designed to generate and receive microwaves over a large frequency range are expensive (tens of thousands of dollars). Also, there are significant licensing issues with operating equipment over a large frequency range. The rural location of most abattoirs and the indoor nature of the measurement would help in acquiring a license; however this would still not be a straightforward task.

(ii) A fan, or a similar airflow mechanism, would be needed to remove blood and water from the surface of the carcass for the duration of the measurement. Water and blood are strong absorbers of microwaves and their presence would result in significant errors in the estimate of fat thickness.

(iii) The alignment of the carcass and microwave horn is crucial. The shape and size of the pork samples enabled them to present a relatively flat surface to the measurement equipment. This resulted in much higher reflected powers and a sounder estimate of fat thickness. In comparison, the reflected powers from the Lamb 1 and Beef samples were too low for a reasonable estimate of fat thickness to be made. However, the samples used in this study were much

smaller than the whole carcasses which would be measured in an abattoir, and hence this problem might not be as significant as it first appears. Future refinements of the technique should be tested on more realistic samples. Also, in its final implementation, the microwave horn would ideally be mounted on a robotic arm which could adjust its orientation to maximize the reflected signal.

(iv) A lens or other focusing element is required to increase the reflected power and reduce the area of subcutaneous fat under measurement. However, the combination of multiple frequencies (suggested in (i)) and a lens would increase the similarity of the technique to that patented by Holmes [2].

It is recommended that a second phase of work be undertaken. This phase of work would involve further testing of the technique at Marsfield on at least three larger samples provided by MLA. This phase of work will result in a short report and is expected to take six days and cost approximately $4500. If these tests are successful, a third phase of work would include the design and manufacture of a dielectric lens, which will be added to the system to reduce the area of subcutaneous fat under measurement and to increase the reflected power; this modification should improve the accuracy of the measurements. In this third phase, a costing would also be produced for a portable instrument that could be trialled at an abattoir in a possible fourth phase of the project.

Contents

1. Introduction

Meat and Livestock Australia (MLA) are investigating a number of non-invasive techniques for the measurement of the thickness of subcutaneous fat on cattle, sheep and pigs (the subcutaneous fat layer is located just below the skin). A successful instrument would be used in abattoirs after skinning of the animal, and would allow the optimum amount of subcutaneous fat to be removed. Optimizing the fat thickness has the potential to increase the income of a typical abattoir by approximately $1 million per year.

The CSIRO ICT Centre has proposed a technique based on the reflection of microwaves from the air-fat and fat-meat interfaces of the carcass. This report details some preliminary calculations and measurements carried out in May and June 2007.

2. Outline of the Proposed Technique

Microwaves are electromagnetic waves with frequencies between approximately 300 MHz and 30 GHz. They are strongly absorbed by water and, because of the high water content of most biological tissue, they are also strongly absorbed by biological tissue. This absorption increases with frequency. For example, the 2.4 GHz microwaves used in a microwave oven typically penetrate about 5 cm into the body while, at 30 GHz, the penetration would be only 5 mm or so.

Muscle and fat have different water content, and hence different microwave properties; for example, the complex refractive index of bulk fat at 10 GHz is approximately 2.16 – 0.24j, while that of muscle is 6.69 – 1.43j [1]. A difference in refractive index across a boundary results in reflection of the microwaves (the greater the difference in refractive index, the greater the reflection from the boundary). Hence, this difference in properties results in a large reflection from the fat/muscle boundary within the carcass.

When a section of the surface of the carcass is illuminated with microwaves, a proportion of the signal will pass through the fat layer, be reflected at the fat/muscle boundary, and pass back through the fat layer to a detector. Because microwaves are absorbed by fat, the level of the received signal will depend on both the frequency of the microwaves and the thickness of the fat layer. If the fat layer is too thick (greater than about 30 mm at 10 GHz), the reflected signal will be absorbed on the return journey through the fat.

By choosing a suitable frequency or frequencies, we could estimate the thickness of the fat layer from the received microwave signal.

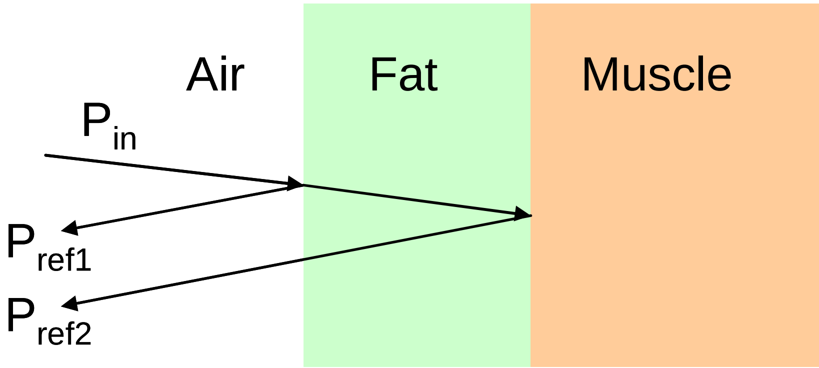

Figure 1. Diagram showing reflections from both sides of the subcutaneous fat layer

Some very simple calculations carried out in February 2007 suggested that this approach might be feasible. However, these were very basic calculations and it was recognized that there would be a number of complicating factors:

(i) The two reflected signals (one from the outer layer of the fat and one from the fat/muscle boundary) would interfere with each other. While we expected that there would still be a one-to-one correspondence between reflected signal and fat thickness, this needed to be checked. It was recognized that multiple frequencies may be needed to remove any ambiguity in the measurement.

(ii) Because the microwave antenna would be close to the meat surface, the effect of coupling with the microwave antenna needed to be considered.

(iii) The simple calculations used average data on the microwave absorption of muscle and fat. The variation in absorption between samples may be large; this would introduce an error into our estimate of fat thickness.

(iv) Most of the incident power would be absorbed by the meat/fat. Would the meat discolour or be affected in some other way by the power absorption? What is the minimum power that could be used for these measurements?

The work outlined in this report was aimed at addressing these four issues and confirming that a microwave-based fat measurement technique is feasible.

3. Calculations

Figure 2 shows the basis of some more detailed calculations. Electromagnetic waves are shown travelling in both directions in the air and fat and only in one direction within the meat. There is no need to include a reflected signal within the meat layer as the absorption of microwaves within this layer is very large and any microwaves penetrating into this region would be absorbed within a few millimetres of the fat/muscle boundary.

In the diagram, the fat layer begins at z = 0 and finishes at z = L. The electric fields are represented in the general form,

$$E_a = Ae^{-j\frac{2\pi}{\lambda}nz} \tag{1}$$

where $\lambda = c/f$ is the microwave wavelength, n is the refractive index of the material, c is the speed of light in a vacuum, f is the microwave frequency and A is the amplitude of the electric field.

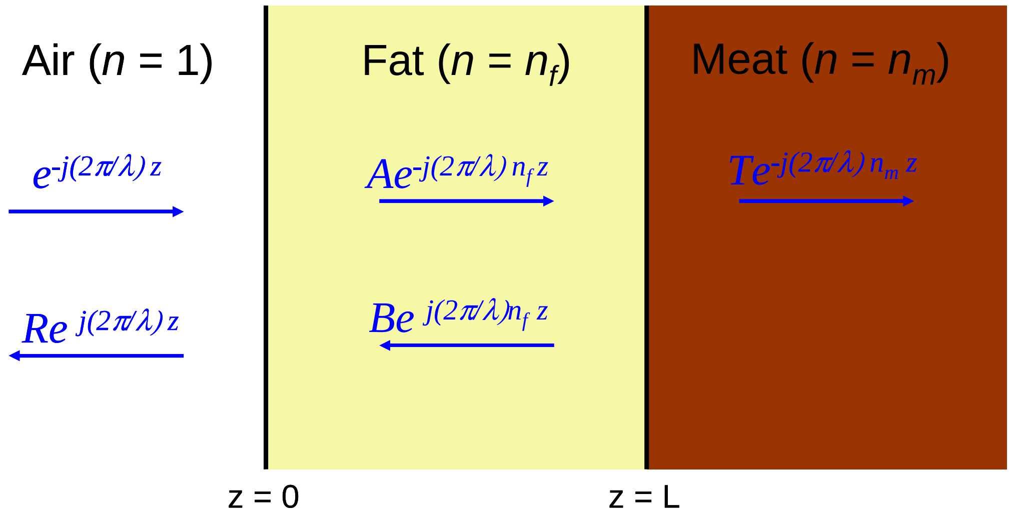

Figure 2. Model used to calculate reflection from a meat and fat sample.

By matching the fields at the boundaries, we obtain the following expression for the power reflectivity from the sample, $|R|^2$,

$$|R|^2 = \left\{ \frac{\left(1 - f\,e^{-j2w}\right) - n_f\left(1 + f\,e^{-j2w}\right)}{\left(1 - f\,e^{-j2w}\right) + n_f\left(1 + f\,e^{-j2w}\right)} \right\}^2 \tag{2}$$

where $w = 2\pi n_f L/\lambda$ and f is the power reflection coefficient from the fat/muscle interface. At frequencies between 8 and 12 GHz, f is approximately 0.27.

The refractive index of fat and meat were calculated as a function of frequency using [1]. These calculated values were inserted into Equation (2) to estimate the reflected power as a function of fat thickness and frequency.

Figure 3 presents the calculated reflected power at 8 GHz as a function of fat thickness. In these calculations it was assumed that incident power was 100 mW.

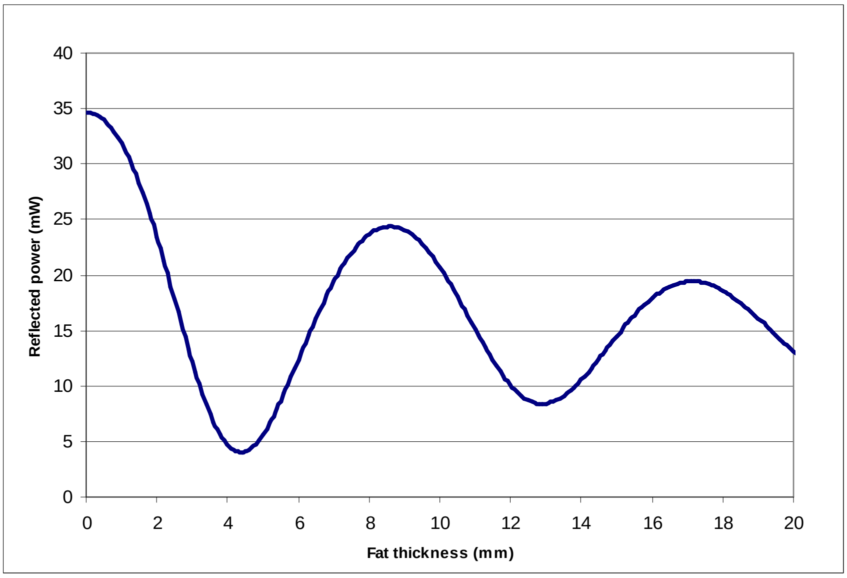

Figure 3. Reflected power at 8 GHz as a function of fat thickness (incident power = 100 mW, n_f = 2.13 – 0.23j).

The variation of reflected power with thickness is largely caused by interference between the microwaves reflected off the air/fat boundary and those reflected off the fat/muscle boundary. In the example shown in Figure 1, these waves interfere constructively with fat thicknesses of 8.5 and 17 mm and interfere destructively with fat thicknesses of 4.25 mm and 12.75 mm.

These interference fringes create an ambiguity at some reflected powers: for example, a reflected power of 20 mW could suggest a fat thickness of 2.3, 7.1 or 10.1 mm. To clear up the ambiguity, multiple frequencies need to be used. Figure 4 shows the reflected power at 2 frequencies, 8 GHz and 10.5 GHz.

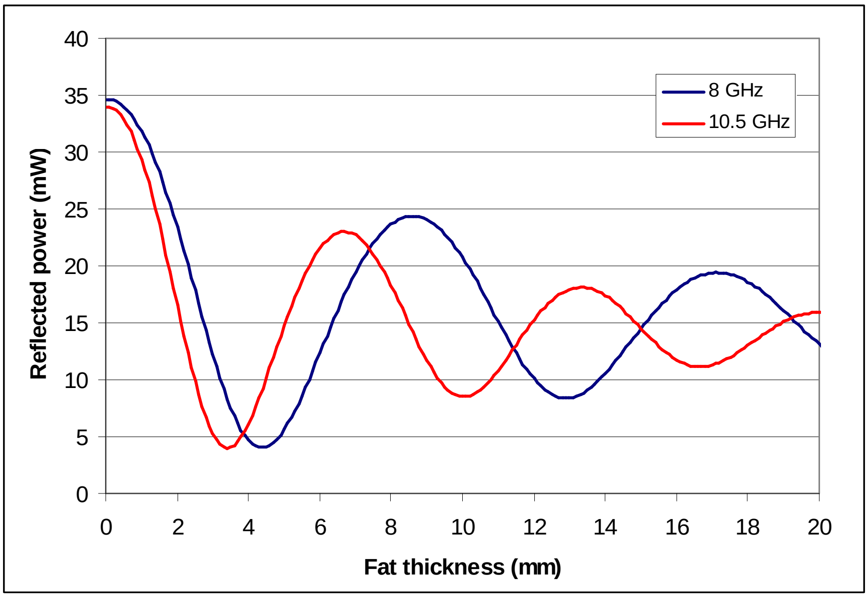

Figure 4. Reflected power at 8 and 10.5 GHz as a function of fat thickness (incident power = 100 mW, n_f = 2.13 – 0.23j at 8 GHz, n_f = 2.15 – 0.25j at 10.5 GHz).

If we obtained a reflected power of 20 mW at 8 GHz, the reflected power at 10.5 GHz could be used to clear up the ambiguity. A 10.5 GHz reflected power of 12.4 mW would indicate a fat thickness of 2.3 mm, 22.7 mW would indicate a thickness of 7.1 mm, and 8.5 mW would indicate a thickness of 10.1 mm.

Another way to consider the problem is to plot the received signal as a function of frequency (Figure 5). The spacing between peaks on such a plot provides an estimate of the thickness of the fat layer; the greater the spacing, the thinner the fat layer.

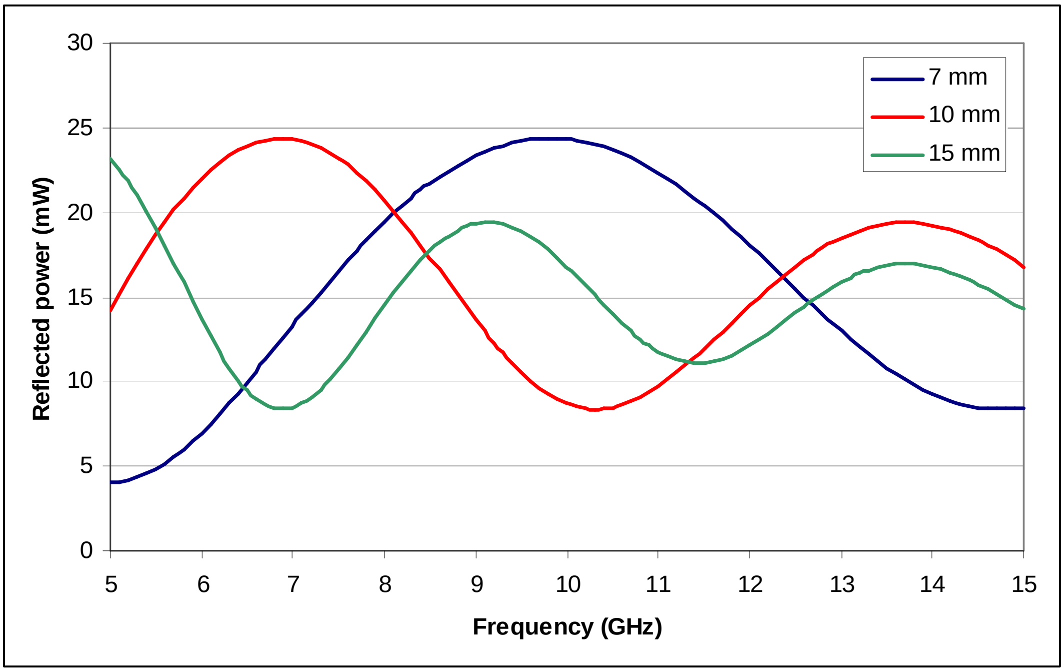

Figure 5. Calculated reflected power for three different fat layer thicknesses (7 mm, 10 mm and 15 mm).

The curves in Figure 9 can be approximately modeled as cosine curves, with equation

$$|R|^2 = A + B\cos\left(\frac{4\pi n f L}{c} + \Delta\phi\right) \quad (3)$$

where *A* is an amplitude offset, *B* is the magnitude of the oscillation and $\Delta\phi$ is a phase offset. The frequency spacing between adjacent peaks is:

$$\Delta f = \frac{c}{2nL} \quad (4)$$

So, by measuring reflected power as a function of frequency, and then fitting a cosine curve to it, we should be able to estimate the spacing between peaks, and hence the thickness of the fat layer.

4. Measurement Setup

The aims of the short measurement program were to test this idea, and also to identify how many frequency measurements would be required to unambiguously determine the thickness of the fat layer.

A frequency synthesiser was used to generate the incoming signal. It was swept from 8.2 GHz to 12.4 GHz with an output power of 1 mW. This transmit power was much lower than the 100 mW used in the simulations, but was chosen to ensure that any heating of the sample by the absorbed microwaves was negligible.

Figure 6 shows the measurement setup. The transmitted signal passed through a directional coupler and was transmitted at the sample via an X-band horn. The signal then reflected from the sample, was collected by the horn and sent via the directional coupler to a spectrum analyser. The spectrum analyser was linked to a laptop so that the measured data could be downloaded.

Prior to use, the system was calibrated by placing a metal plate across the aperture of the horn and measuring the reflected signal. This data was taken to correspond to 100% reflected power; this took into account some small losses in the directional coupler and the horn.

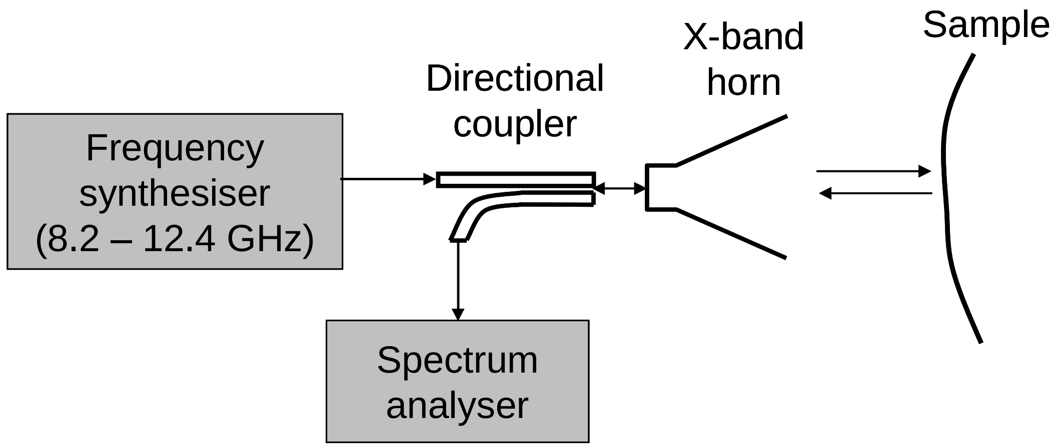

Figure 6. Measurement setup for fat thickness measurement.

A photograph of the measurement setup is shown in Figure 7. The sample holder is in the foreground. The meat samples were attached to the U-shaped holder and held in place by skewers. Five meat samples were purchased from two local supermarkets (two lamb leg roasts, one set of pork ribs, one pork leg and one beef roast).

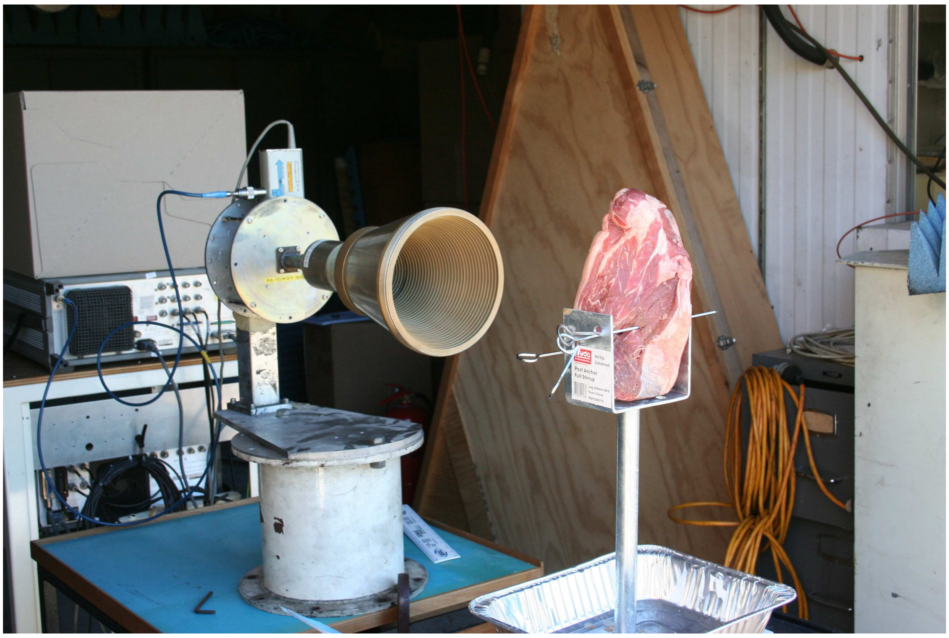

Figure 7. Photograph of the measurement setup showing the X-band horn, sample holder and "Beef" sample.

5. Results

Figure 8 is a measurement of reflected power for the setup shown in Figure 7 but with no sample present. The reflected power is presented in log units (dBm); this enables lower level signals to be more easily displayed. 0 dBm is equal to 1 mW, -10 dBm = 0.1 mW, -20 dBm = 0.01 mW, etc.

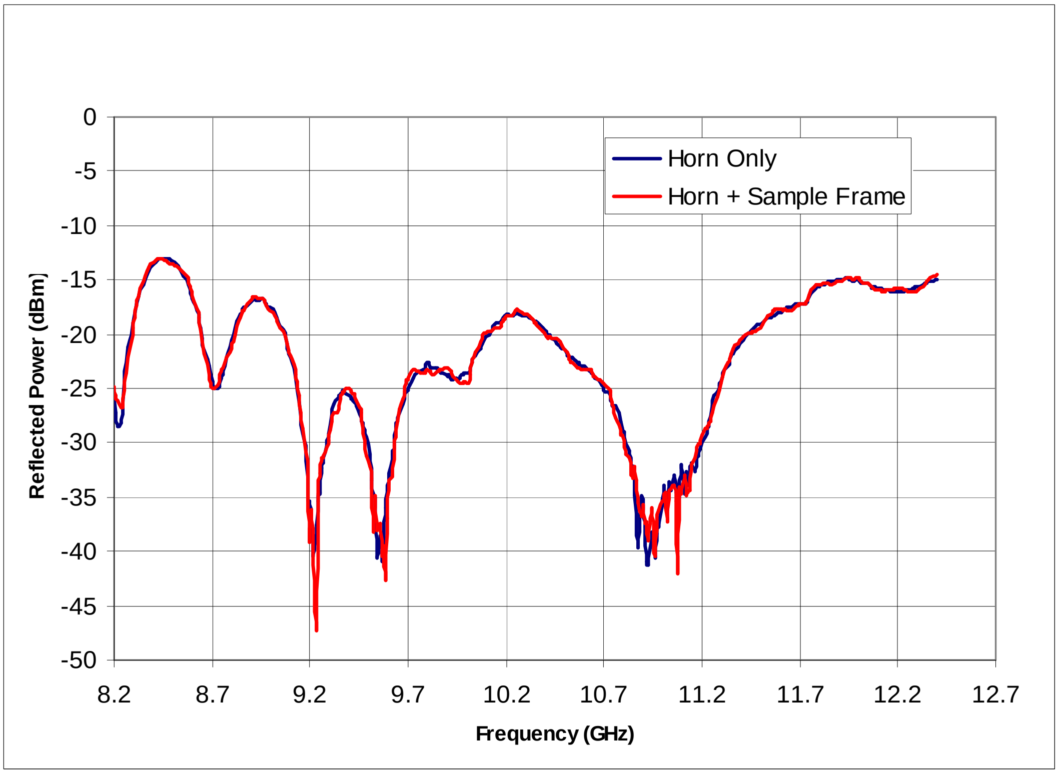

Figure 8. Reflected power as a function of frequency with no sample present.

This figure basically shows small reflections within the X-band horn. The signal levels are very low; the highest level is around -13 dBm (or 5% of the transmitted power). These reflections are higher below 8.2 GHz and above 12.4 GHz and this effect restricts these measurements to that frequency range.

As can be seen in the figure, the measurement with the sample frame present is not significantly different to that with the frame absent. This indicates that reflections from the sample frame are negligible.

Data on meat samples

Table 1 presents data on the meat samples. The fat thickness was measured in a number of locations on each sample with a skewer and ruler after the microwave measurements were completed.

Table 1. Properties of meat samples

Sample	Type	Weight	Measured fat thickness
Pork 1	Rack	1.4 kg	(11 ± 2) mm
Pork 2	Leg	2.4 kg	(15 ± 5) mm
Lamb 1	Leg	1.8 kg	(2 ± 2) mm
Lamb 2	Leg Half	1.1 kg	(7 ± 3) mm
Beef	Bolar Blade	1.6 kg	(8 ± 2) mm

Microwave measurement of fat thickness – Pork 1

For the measurement shown in green in Figure 9, the Pork 1 sample was placed in the sample holder at a distance of 30 cm from the aperture of the horn.

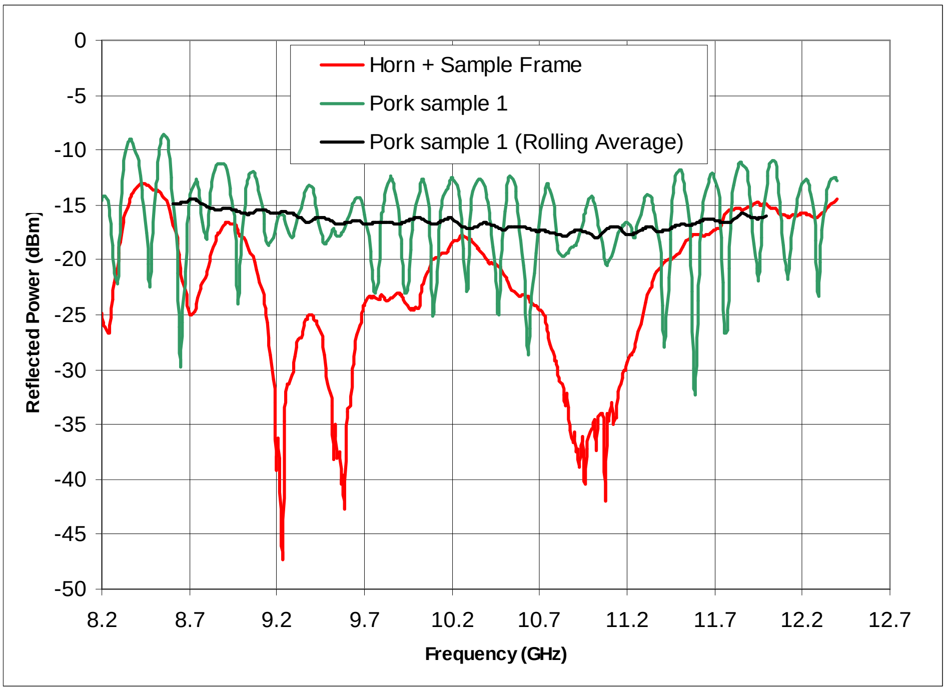

Figure 9. Microwave reflectivity of pork sample 1 at a distance of 30 cm from the horn.

The most obvious feature of this measurement is the large ripple in the reflected signal. This is caused by interference between the desired reflected signal and a second reflected signal which makes two round trips between the horn and the sample. This effect is shown diagrammatically in Figure 10.

The spacing between the ripple peaks is dependent on *d*, the separation between the horn and the sample, however because *d* is very much larger than the fat layer thickness, this undesired ripple is always more rapidly varying than the gradual ripple associated with the fat layer.

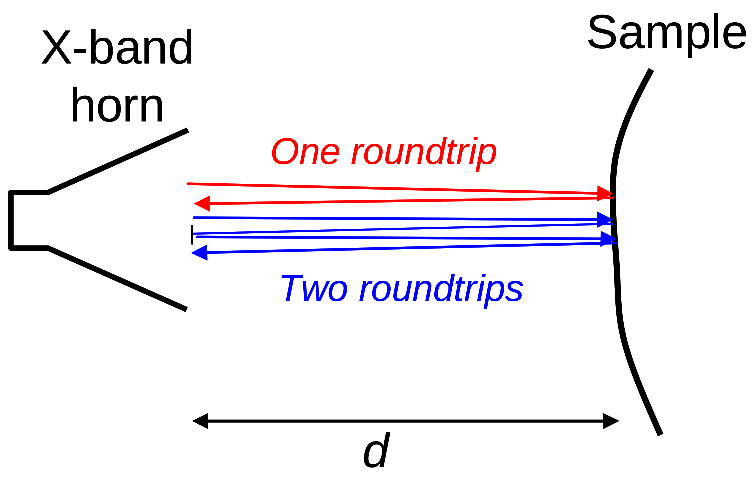

Figure 10. Diagram showing the two interfering signals which cause the ripple in the measured data.

One way to remove this ripple is to replace the raw data with a “rolling average”. Each data point is replaced by the average of itself and a number of points on either side; this has the effect of smoothing over any rapid changes in the data, and hence focusing on more slowly varying changes. A “rolling average” of the pork 1 data is also shown in Figure 9. In this case, each point presented is an average of 79 points of raw data (the original data point at that location and 39 points either side). A cosine curve was fitted to this rolling average to determine the fat thickness.

The other point to note in Figure 9 is that the measured reflectivity is only significantly greater than the background over a range of frequencies from 9.2 to 11.2 GHz; this is the only region over which it is meaningful to fit a cosine curve to the data.

The curve of best fit is shown in Figure 11 along with the rolling average data. The equation of the fitted curve is:

$$|R|^2 = 0.02 + 0.00345\cos\left(\frac{f}{0.7} - 0.78\right) \tag{5}$$

Peaks in this fitted curve are 4.398 GHz apart. From equation (4), this corresponds to $nL = 0.0341$, and if we assume that $|n| = 2.17$ ($n = 2.16 - j0.24$), then the thickness of the fat layer, *L*, is calculated to be 15.7 mm, slightly higher than the invasive measurement of fat thickness of (11 ± 2) mm.

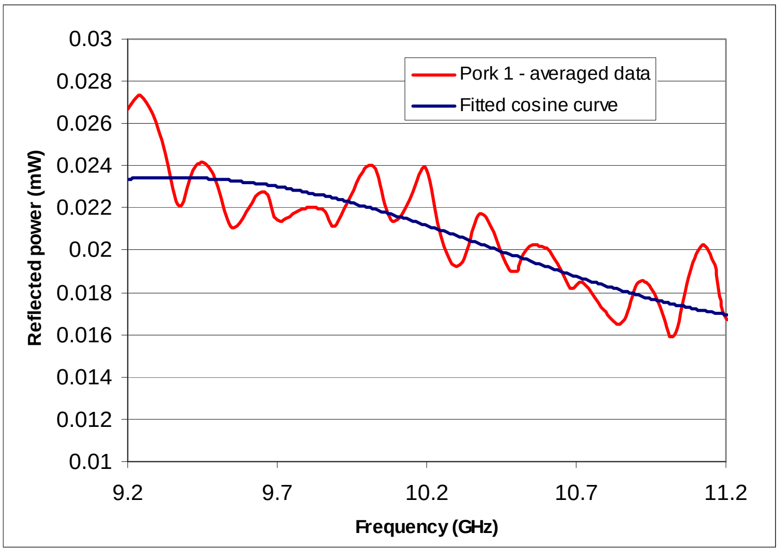

Figure 11. Subset of Pork 1 measured data and curve of best fit.

Microwave measurement of fat thickness – Lamb 1

The fat layers on the lamb samples were much thinner than those on the pork samples, and so we would expect the reflected power to vary more slowly with frequency.

Measured data for lamb sample 1 at a distance of 30 cm is presented in Figure 12.

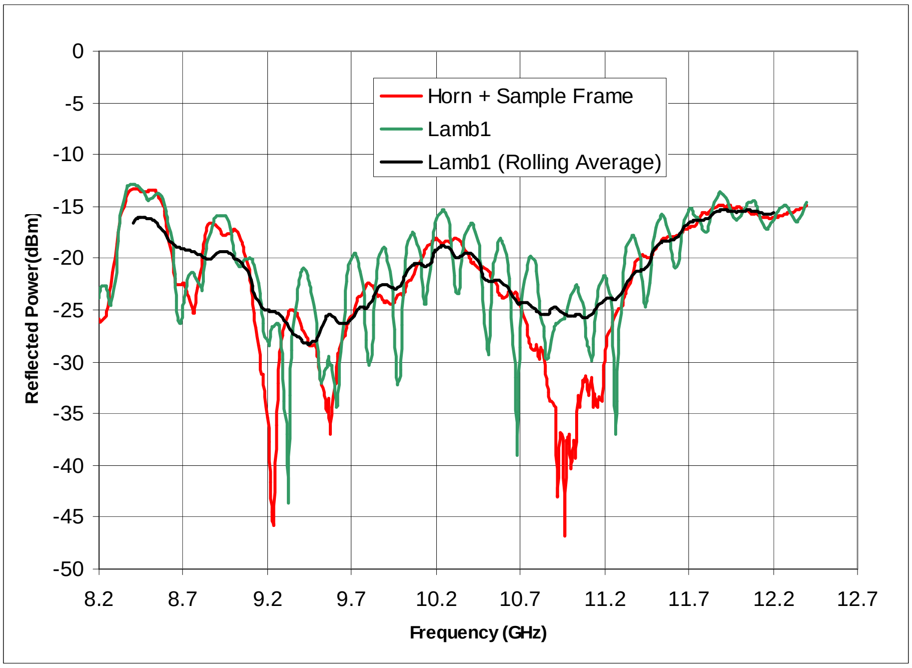

Figure 12. Microwave reflectivity of lamb sample 1 at a distance of 30 cm from the horn.

The reflected power was significantly greater than the background over a small frequency range from 10.8 to 11.1 GHz. Consequently, the rolling average data (which is an average over a frequency range of 0.73 GHz), is always affected by the background and so can't be accurately interpreted to obtain the fat thickness. An attempt was made to fit a cosine curve to a rolling average over a much shorter frequency range (0.2 GHz). Unfortunately, the ripple in this data remained large and it was not possible to fit a meaningful curve.

The reduction in reflected power over the whole range is likely to be a result of the small size and significant curvature of the lamb sample (in comparison, the pork sample was larger and approximately flat, providing a larger area for reflections to occur). It should be noted that, in its final form, the technique would be applied to whole carcasses where higher reflected powers would be expected due to the larger sample size.

Measurements on the remaining 3 samples are detailed in Appendix 1. Table 2 compares the microwave measurements of fat thickness with the invasive measurements using a skewer and ruler.

Table 2. Microwave measured fat thicknesses of the five samples.

	Fat thickness	
Sample	**Microwave meas't (mm)**	**Invasive meas't (mm)**
Pork 1	15.7	11 ± 2
Pork 2	15.7	15 ± 5
Lamb 1	unclear	2 ± 2
Lamb 2	11.3	7 ± 3
Beef	unclear	8 ± 2

Microwave measurement of fat thickness – effect of changing distance to the sample

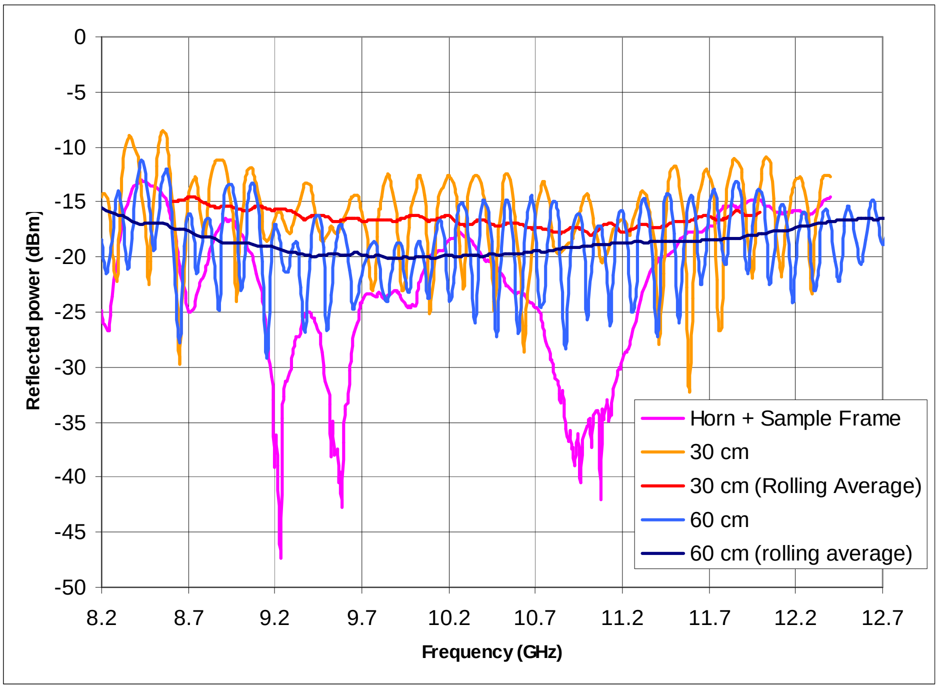

Figure 13. Measured reflected power from the pork1 sample at distances of 30 cm and 60 cm.

The distance between the horn and sample was varied to investigate the optimum distance for the measurement. Figure 13 shows measurements on the pork 1 sample at 30 cm and 60 cm; Figure 14 shows measurements on the lamb 1 sample at 20 cm and 30 cm.

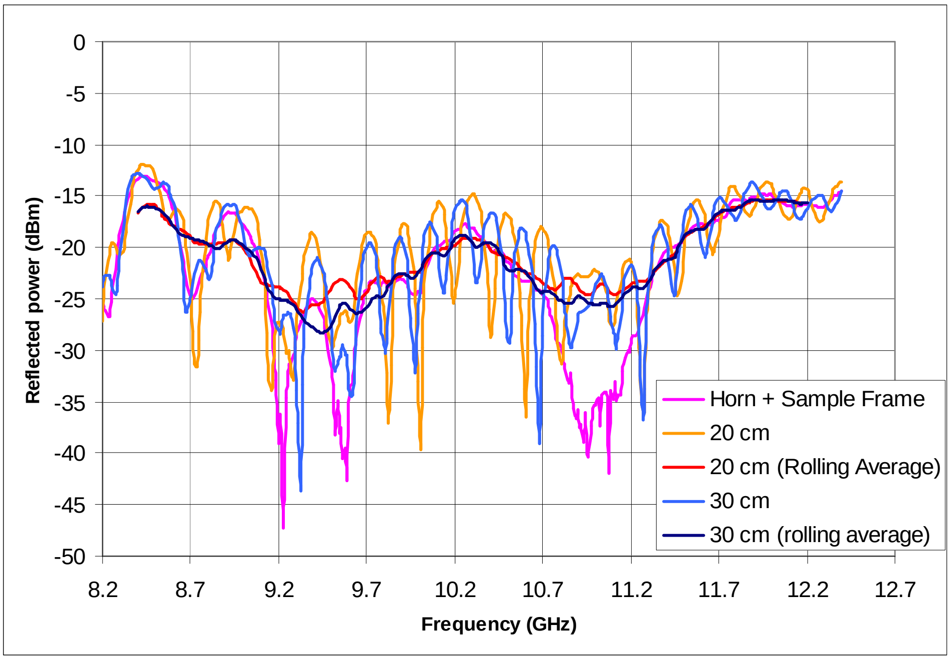

Figure 14. Measured reflected power from the lamb1 sample at distances of 20 cm and 30 cm.

In both figures the reflected power drops as the distance to the sample is increased. This is easiest to see in the "rolling average" plots. In Figure 13, the reflected power is less for 60 cm than for 30 cm; in Figure 14, the reflected power is less for 30 cm than for 20 cm.

6. Discussion

The measurements described here were designed to evaluate the technique and address the possible issues outlined in Section 2:

- *Effect of interference between reflected signals.*

Rather than treating this effect as a problem, the approach followed in these measurements made use of this interference to estimate the thickness of the fat layer.

- *Proximity of the antenna to the sample.*

The proximity of the antenna to the sample resulted in the "ripple" pattern seen in all of the measurements. For measurements using the entire frequency band (an expensive option given the equipment required, and a difficult option owing to spectrum regulations) this can be corrected but, for measurements using a few discrete frequencies the ripples would render the technique unusable.

- *Large variation in the microwave properties of fat.*

This is unlikely to be a problem using this technique. There is a simple relationship between the refractive index of the fat layer and its estimated thickness. Variations of greater than 10% would be needed before significant errors were introduced into the estimated fat layer thickness.

One effect yet to be investigated is the impact of water or blood on the surface of the carcass. At this frequency, blood has similar properties to water, and a thin layer of water or blood on the surface would greatly affect the measurement. This is because water has roughly 10 times the absorption of fat at microwave frequencies. Water or blood would need to be removed from the measurement location by airflow or some other mechanism.

- *Measurement "cooks" the sample leading to discoloration or other drop in quality.*

The microwave power used in these measurements was 1 mW (around 700,000 times lower than that used in a microwave oven) and the power was directed on the sample for less than one second. The temperature rise in the fat during the measurement would be less than 0.001°C. The samples would be exposed to much greater temperature variations than this during transport and sale; hence, the impact of these microwaves measurements on the colour or quality of the meat would be insignificant.

A further cause for concern is the difference between the invasive and microwave measurements, especially given the requirement for the technique to be accurate to within 1 mm. It would be possible to reduce the discrepancy through modifications to the technique. For example, a lens could be added to the horn to focus the microwaves on a small region of the sample; this would both increase the reflected power levels and result in less variability in fat thickness over the (much smaller) measurement region. However, the combination of multiple frequencies and a lens would increase the similarity of the technique to that patented by Holmes [2].

There is no clear benefit in moving from a measurement distance of 30 cm (see Figures 13 and 14). At larger distances the reflected power is lower, and closer to the background levels measured when no sample is present. At smaller distances the ripples caused by the proximity of the sample to the measurement equipment appear to be slightly larger and there is little increase in signal.

7. Conclusions and Recommendations

This report has outlined some calculations and measurements of the performance of a simple microwave-based technique for the measurement of the thickness of subcutaneous fat on a carcass.

The technique should work in principle; however there are a number of practical difficulties which would need to be addressed:

(i) Measurements would need to be made at a relatively large number of discrete frequencies (>10) or the instrument would need to scan or "chirp" over a frequency range. Unfortunately, instruments designed to generate and receive microwaves over a large frequency range are expensive (tens of thousands of dollars). Also, there are significant licensing issues with operating equipment over a large frequency range. The rural location of most abattoirs and the indoor nature of the measurement would help in acquiring a license; however this would still not be a straightforward task.

(ii) A fan, or a similar airflow mechanism, would be needed to remove blood and water from the surface of the carcass for the duration of the measurement. Water and blood are strong absorbers of microwaves and their presence would result in significant errors in the estimate of fat thickness.

(iii) The alignment of the carcass and microwave horn is crucial. The shape and size of the pork samples enabled them to present a relatively flat surface to the measurement equipment. This resulted in much higher reflected powers and a sounder estimate of fat thickness. In comparison, the reflected powers from the Lamb 1 and Beef samples were too low for a reasonable estimate of fat thickness to be made. However, the samples used in this study were much smaller than the whole carcasses which would be measured in an abattoir, and hence this problem might not be as significant as it first appears. Future refinements of the technique should be tested on more realistic samples. Also, in its final implementation, the microwave horn would ideally be mounted on a robotic arm which could adjust its orientation to maximize the reflected signal.

(iv) A lens or other focusing element is required to increase the reflected power and reduce the area of subcutaneous fat under measurement. However, the combination of multiple frequencies (suggested in (i)) and a lens would increase the similarity of the technique to that patented by Holmes [2].

It is recommended that a second phase of work be undertaken. This phase of work would involve further testing of the technique at Marsfield on at least three larger samples provided by MLA. This phase of work will result in a short report and is expected to take six days and cost approximately $4500. If these tests are successful, a third phase of work would include the design and manufacture of a dielectric lens, which will be added to the system to reduce the area of subcutaneous fat under measurement and to increase the reflected power; this modification should improve the accuracy of the measurements. In this third phase, a costing would also be produced for a portable instrument that could be trialled at an abattoir in a possible fourth phase of the project.

References

[1] Using the parametric model of Gabriel et al, *Phys. Med. Biol.*, **41**, 2271-2293 (1996) which is based on measurements from 100 Hz to 100 GHz.

[2] Holmes, W.S., “Fat depth sensor”, Patent No. US7089047, WO200142737-A, AU200124128-A, filed: 13 June 2002.

Appendix A – Further measurement details

Beef Sample

Measured reflected power versus frequency for this sample is shown in Figure A1.

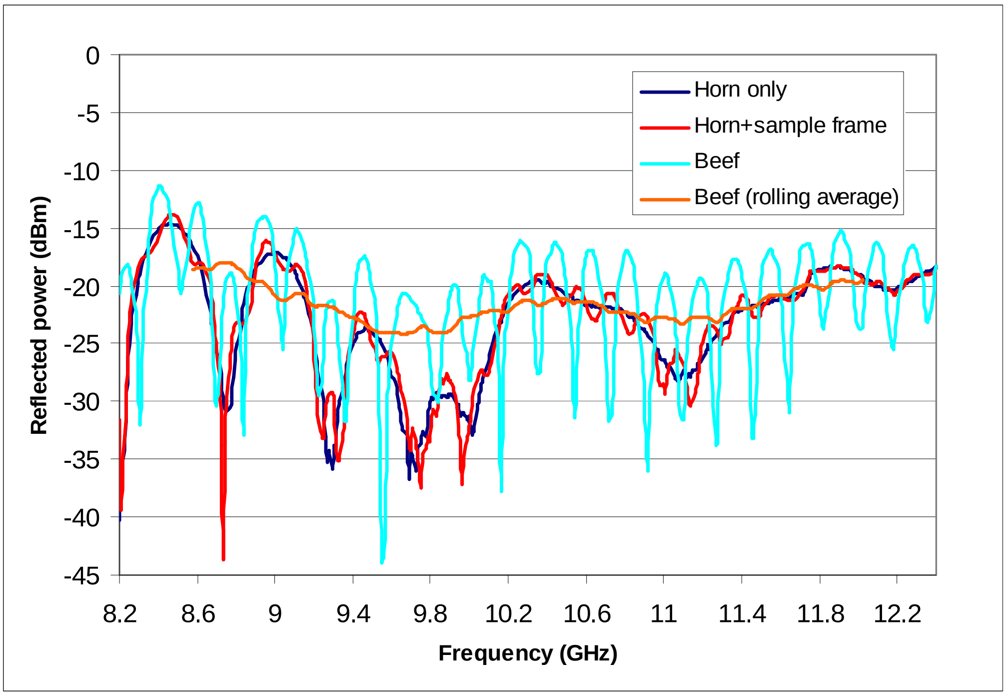

Figure A1. Power reflected from the beef sample at a distance of 30 cm.

The reflected power was significantly greater than the background over a small frequency range from 9.6 to 10.1 GHz. Consequently, the rolling average data (which is an average over a frequency range of 0.73 GHz), is always affected by the background and so can’t be accurately interpreted to obtain the fat thickness. An attempt was made to fit a cosine curve to a rolling average over a much shorter frequency range (0.2 GHz). Unfortunately, the ripple in this data remained large and it was not possible to fit a meaningful curve.

Lamb 2 Sample

Measured reflected power versus frequency for this sample is shown in Figure A2.

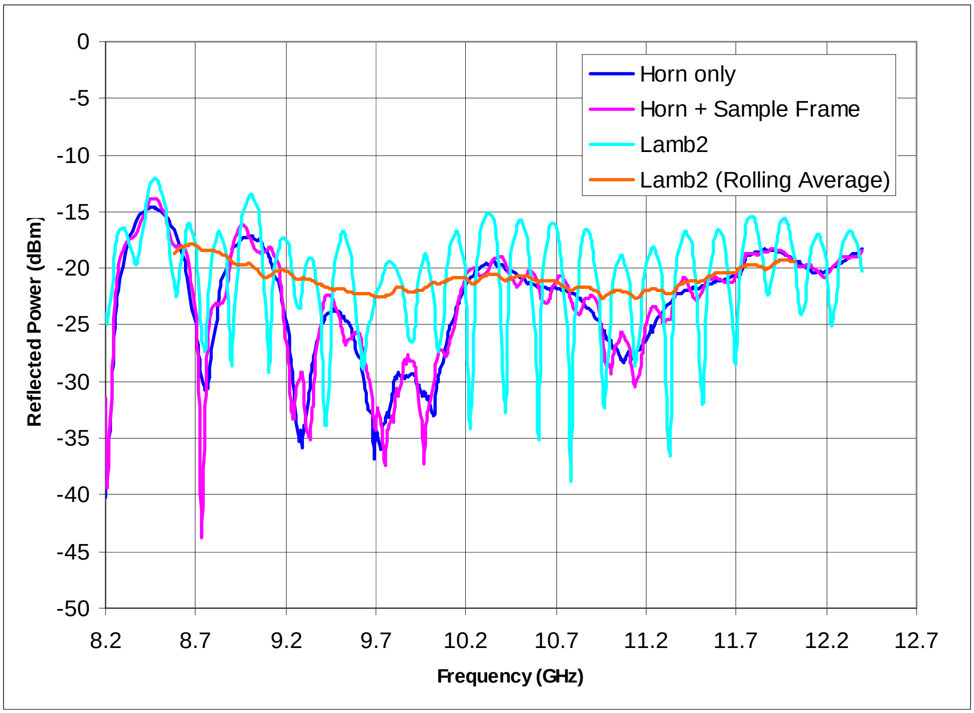

Figure A2. Power reflected from the lamb 2 sample at a distance of 30 cm.

The reflected power was significantly greater than the background over a small frequency range from 9.2 to 10.1 GHz. Consequently, the rolling average data (which is an average over a frequency range of 0.73 GHz), is only unaffected by the background between 9.57 and 9.73 GHz. A cosine curve was fitted to the data over this small frequency range. The fitted curve is shown in Figure A3; the equation of the fitted curve is:

$$|R|^2 = 0.006 + 0.003\cos\left(\frac{f}{0.97} - 2.04\right) \quad (8)$$

which corresponds to a fat thickness of 11.3 mm.

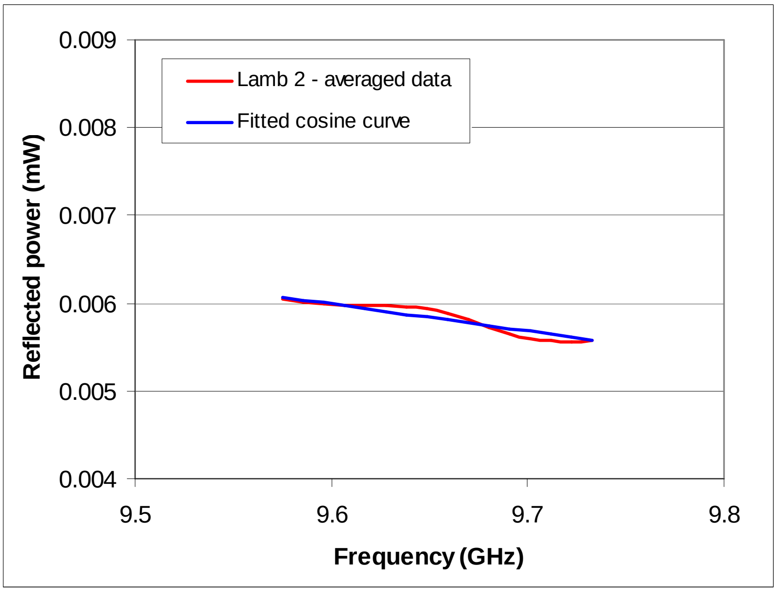

Figure A3. Cosine curve fitted to a subset of the lamb 2 measured data.

Pork 2 Sample

Measured reflected power versus frequency for this sample is shown in Figure A4. In this case, two separate measurements were made, “Pork2” and “Pork2b”.

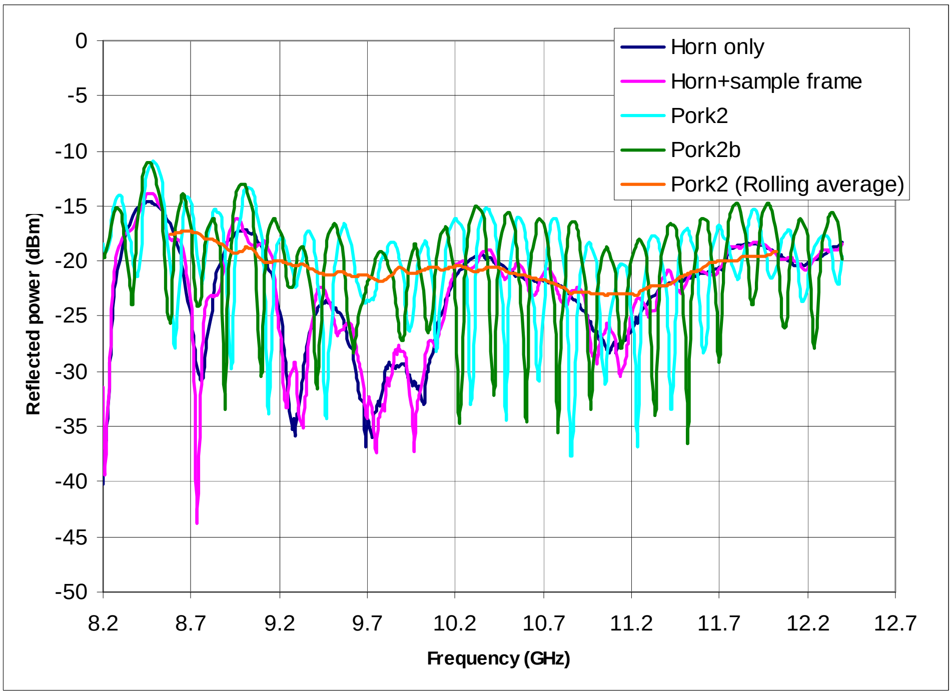

Figure A4. Power reflected from the pork 2 sample at a distance of 30 cm.

A cosine curve was fitted to the data over the frequency range 9.4 to 10.0 GHz where the rolling average of the signal was not significantly influenced by the background. The fitted curve is shown in Figure A5. The equation of the fitted curve is:

$$|R|^2 = 0.007 + 0.0025\cos\left(\frac{f}{0.7} + 0.2\right) \qquad (9)$$

which corresponds to a fat thickness of 15.7 mm.

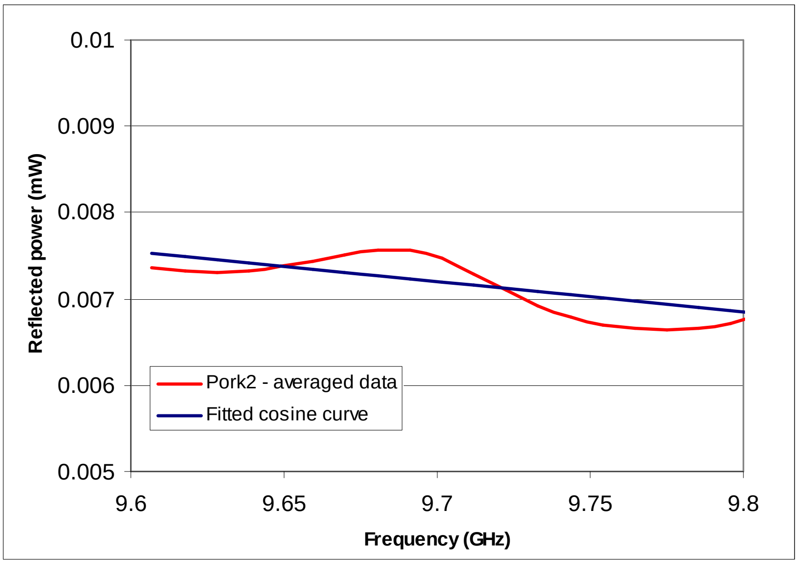

Figure A5. Cosine curve fitted to a subset of the pork 2 measured data.