Appendix A-2

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Discussion document: Further analysis of Start Point results and suggested work required to establish a methodology for ICNIRP compliance at MF

Background

The ICNIRP guidelines (Ref 1.) specify basic restrictions at MF in terms of 4 different quantities. Work carried out by the HPA for BBC World Service showed that, of these, localised SAR (limbs) is the most restrictive due to the concentration of current in the ankle muscle. Whilst it is impractical to measure SAR, it is possible to calculate the localised SAR in the ankle from the current flowing, using the data derived by the HPA. The relationship between ankle current and field strength was also established theoretically by the HPA using a high resolution model (NORMAN).

The results of some measurements subsequently carried out at Start Point (Ref.2) were found to be very consistent with the HPA modelling. These measurements were assessed alongside some NEC-2 modelling of the site. Some further analysis of these results has now been carried out.

Choice of methodology

There are two basic ways of assessing the SAR in the ankle. The first is based on ankle current and the second is based on field strength. These quantities can be determined by measurement or by mathematical modelling. Any further work required therefore depends on the choice of methodology so this ought to be considered first. As the SAR depends on the size of the body, there is also a standardisation issue to be taken into account.

<u>Mathematical modelling</u>

Relatively simple antenna systems, such as the one at Start Point, can be modelled fairly easily provided a perfectly conducting earth is assumed. If this assumption can not be made the details of the MF earth system in use on a particular site need to be included in the model and an earth conductivity assumed. (NEC 2 does not cater for this so other software, such as NEC 3 or 4 would be needed) Building a sufficiently high resolution model for a combined MF/ HF site, such as the World Service site at Zygi on Cyprus, could however be a very substantial task

a) Field strength

The field strength measurements at Start Point showed good correlation with the results from the NEC 2 calculations, despite the fact that a ‘perfect earth’ model had to be used.

b) Ankle current

A model of a human based on a simple monopole (SIMON) consisting of 4 vertical perfectly conducting segments with a lumped resistance at the base was used with the NEC 2 model of Start Point. The resistance value for the frequency in use (693 kHz) was derived from the HPA results by interpolating between the 500 kHz and the 1000 kHz data. The model was only run with SIMON at a few positions on the site, but the ankle current per V/m was consistent with the HPA modelling and the Start Point measurement results. This could however be a rather laborious method for determining the ankle current at sufficient points around the boundary as it would entail creating an individual input file for every point and involve a significant number of separate runs. This process should however be capable of being automated, at least in part.

It would also probably be necessary to develop a more complex model in order to obtain accurate results across the whole of the MF band.

<u>Measurement</u>

It is relatively easy to measure either field strength or ankle current, provided suitable equipment is available and satisfactory procedures are followed.

a) Field strength

The vertical component of the electric field is by far the most significant of the various E and H orthogonal components on a MF broadcast site, when considering the localised SAR produced in the ankles.

Ideally, all E and H components should be measured, but the additional uncertainty of only measuring the vertical electric field, or even the resultant electric field using an isotropic probe, may be quite small in most cases. On a multi-frequency site, it would be necessary to measure the individual field strengths, not just the combined field strength as recorded by a broadband probe. Hence a somewhat specialised instrument ought to be used for assessments based on field strength.

b) Ankle current

A standard wideband ankle current meter with an rms response should provide meaningful results on a multi-frequency site. It would also enable more direct assessments to be carried out taking into account the specific circumstances of a particular site, such as the potential bare feet and salt water situation at Lady’s Mile in Cyprus.

c) Measurement uncertainties

The choice of the quantity to be measured (ankle current or field strength) and the method used, will determine the accuracy of any SAR assessment. Field strength can be measured using a hand-held instrument or one on a tripod or similar support with some means of making remote readings to avoid the field being perturbed by the presence of the person making the measurements. Ankle current is normally measured by wearing a meter on one ankle although some form of stand consisting of a vertical conductor is sometimes used.

A number of potential causes of uncertainty have been identified, on the assumption that the SAR in the ankle of a particular individual is being assessed. These are shown in the table below together with their relevance to each of the methods described above.

Table 1: Potential sources of uncertainty involved in the assessment of SAR in the ankle by measurement
(Assessment of actual individual)

Key to symbols

Uncertainty exists	✓
No uncertainty	☺
Possible small uncertainty	?

Potential source of uncertainty	Method being used			
	Field strength meter		Ankle current meter	
	Hand-held	Remote	On ankle	On (remote) stand
Relationship with SAR	✓	✓	✓	✓
Proximity of body	✓	☺	☺	☺
Type of footware	✓	✓	☺	✓
Body posture	✓	✓	☺	✓
Ground conductivity	✓	✓	☺	☺
Wave impedance	☺ *	☺ *	?	?
Body orientation	✓	✓	☺	✓
Body size/ weight	✓	✓	☺	✓
Meter accuracy	✓	✓	✓	✓
Multiple frequencies	✓**	✓**	☺	☺
Modulation	✓	✓	✓	✓

* Assuming E and H field are both measured
** Unless frequency selective meter is used

It can be seen from the table above that the wearing of an ankle current meter gives rise to the smallest number of uncertainties when the SAR in a particular ankle is being assessed.

Standardisation

The SAR produced by an RF field varies according to the height and girth of the body, hence the use of standard models such as the HPA's NORMAN for ICNIRP assessments. The foot size (area of the sole) and type of footwear will also affect the SAR produced by any given field. Hence, if some form of 'standard' SAR assessment is required, corrections may be needed to the measurements made on particular individuals. The pattern of the uncertainties will be quite different for this 'standard' situation, as shown in the table overleaf.

Table 2: Potential sources of uncertainty involved in the assessment of SAR in the ankle by measurement
(Assessment based on a reference man)

Key to symbols

Uncertainty exists	✓
No uncertainty	☺
Possible small uncertainty	?

Potential source of uncertainty	Method being used			
	Field strength meter		Ankle current meter	
	Hand-held	Remote	On ankle	On (remote) stand
Relationship with SAR	✓	✓	✓	✓
Proximity of body	✓	☺	☺	☺
Type of footware worn	☺	☺	✓	☺
Body posture	☺	☺	✓	☺
Ground conductivity	✓	✓	☺	☺
Wave impedance	☺ *	☺ *	?	?
Body orientation	✓	✓	✓	☺ ***
Body size/ weight	☺	☺	✓	☺
Meter accuracy	✓	✓	✓	✓
Multiple frequencies	✓**	✓**	☺	☺
Modulation	✓	✓	✓	✓

* Assuming E and H field are both measured
** Unless frequency selective meter is used
*** Assuming the stand is designed appropriately

As can be seen from the table above, the option of using a standard physical model of a human, such as the copper pole used by the HPA, would appear to have the smallest number of sources of uncertainty.

Furthermore, the need to make assessments on multi-frequency sites introduces significant complications should field strength be measured, requiring a frequency selective instrument, as opposed to the wideband meters normally used. In contrast, a standard wideband ankle current meter should sum the currents on the individual frequencies in the correct way for SAR assessments.

Initial conclusion regarding methodology

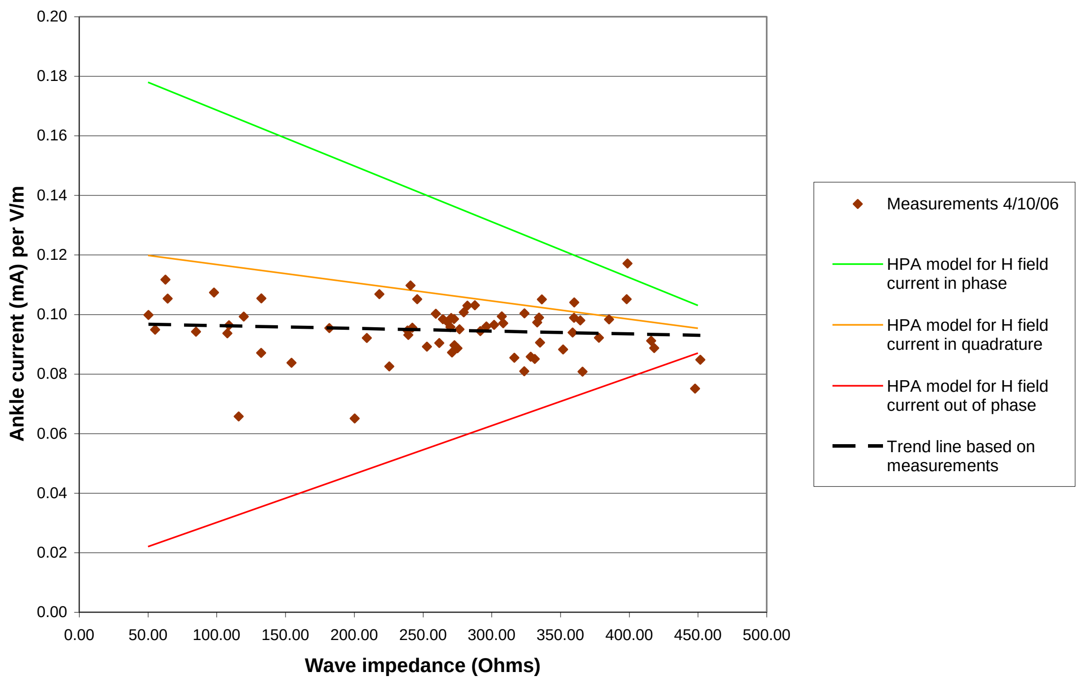
The use of an ankle current meter appears to be the most satisfactory method of making localised SAR assessments at MF and is relatively straight forward. The use of a standard physical model would avoid the need for the corrections associated with the wearing of an ankle current meter by individuals of various heights etc., but would require some development work. Contour maps based on field strength calculations using a 'perfect earth' model in NEC, as used for the Start Point measurements, would help identify the locations to be measured. A small number of electric field strength measurements, as a reality check and a future reference, should also be worthwhile.

Further analysis of results

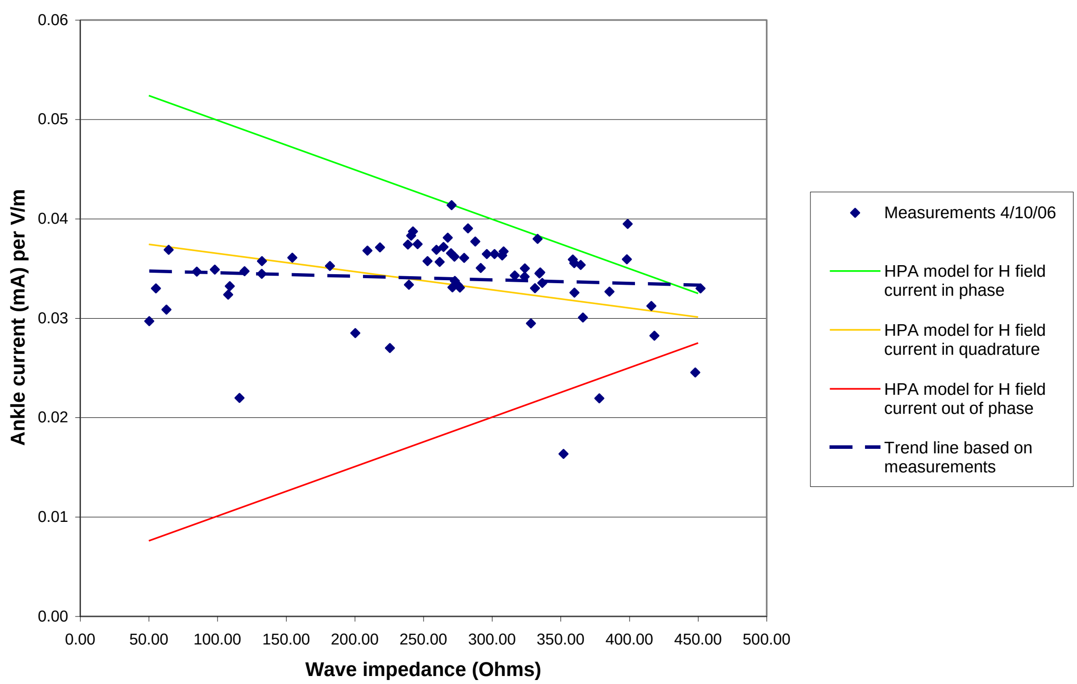
The report (Ref. 2) on the measurements made at Start Point was primarily a record of what was done and the results obtained, with some initial comparisons with the HPA results. It was clear that there was, as expected, a close relationship between ankle current and the E field with only a very slight variation with wave impedance. However, at low values of wave impedance, the HPA results suggest that the contribution of the H field to the total SAR in the ankle may not be insignificant.

The difficulty is that the exact location in the ankle associated with the maximum absorption rate produced by the H field may not be co-incident with that associated with the maximum absorption rate produced by the E field and even if this were the case the currents may not be following the same path. The worst case, hypothetically, would however occur if the two currents combined to produce the maximum SAR. The effect of this on the ankle current/ E field relationship is shown superimposed on the previous measurement plots below for various phase relationships.

Start Point: Ankle current/ E field for "with shoes" condition



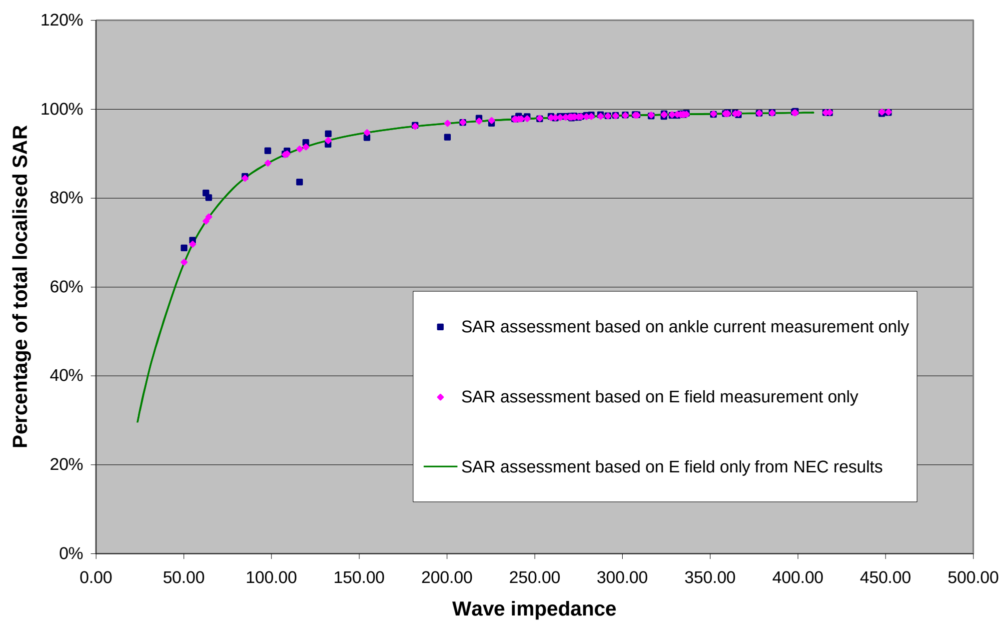
Start Point: Ankle current/ E field for isolated condition



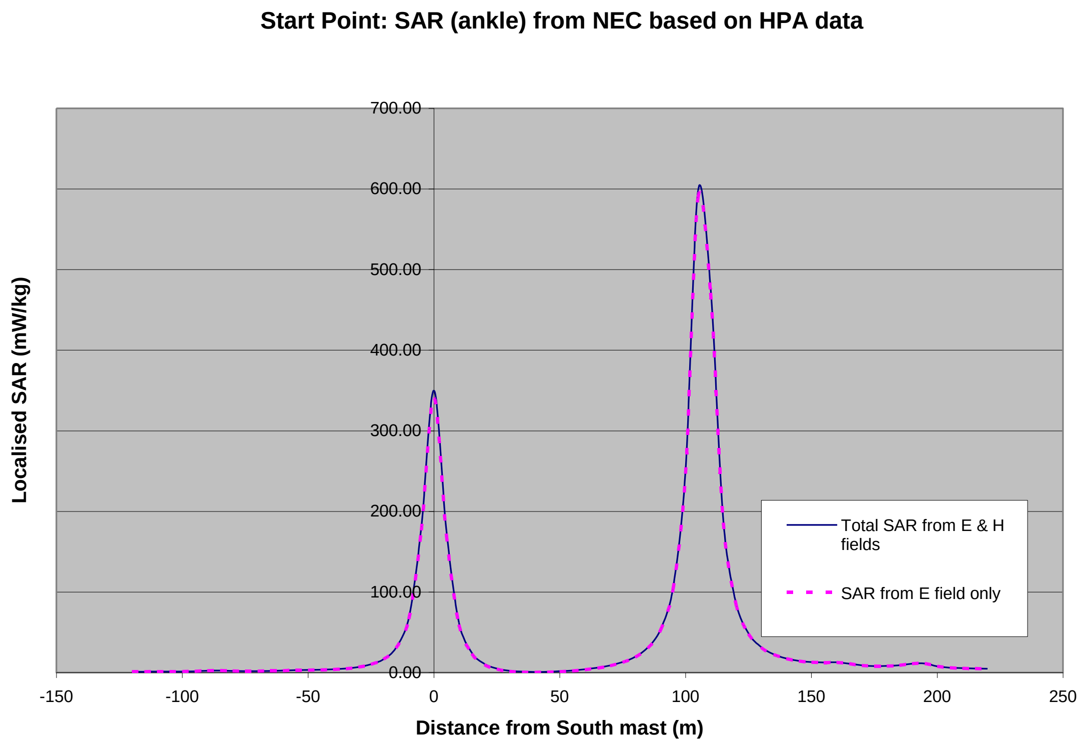
These plots show that whilst the H field would be expected to have little effect on the ankle current under far-field conditions, this would not necessarily be the case for low values of wave impedance. There is also a slight tendency (see trend lines), particularly in the case of the “with shoes” measurements, for the ankle current/ E field relationship to increase at lower values of wave impedance. This may be due to a small additional current flowing longitudinally in the ankle muscle due to the H field. This might occur due to the H field between the two legs causing currents to flow down one leg and back up the other via the coupling with the ground. The orientation of the body with respect to the H field during the measurements at Start Point would have allowed this to occur. Also, a small difference was found in amplitude between the currents in the two legs which could be caused by the addition of the H field and E field currents taking into account the likely phase differences. (The E field currents would be expected to be more or less in phase with each other but the H field currents would effectively be close to being out of phase, as they are flowing in opposite directions.)

The extreme hypothetical situation shown on the plots above is however unlikely to occur and so a more plausible worst-case analysis has been carried out based on the addition of SARs rather than currents. Estimates of SAR based on ankle current using the HPA results have been compared with the worst-case total SAR including that due to the measured H field. Similar estimates using the E field results, both from the NEC modelling and also from the measurements, have also been made. These show a possible 65% under-estimation of SAR at the lowest wave impedance (about 50 ohms) found at Start Point, see plot overleaf:

Start Point results Oct. 2006: Potential under-estimation of localised SAR (with shoes)

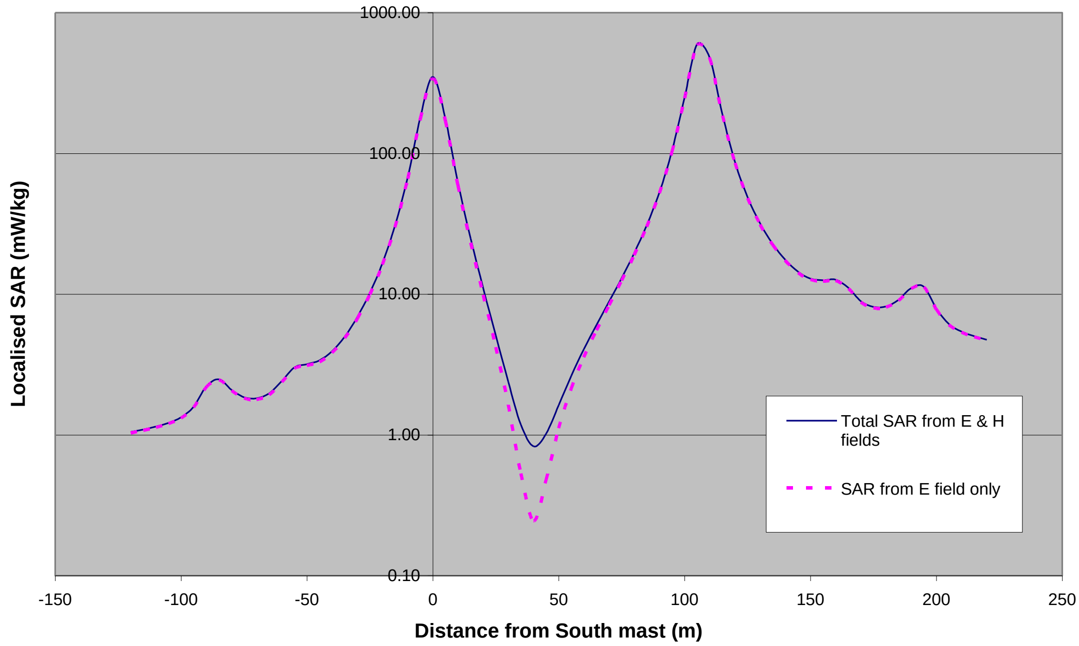


It should be noted that whilst the potential under-estimation is significant, it only occurs at low values of wave impedance and the field levels may not be very high in these locations for a typical high-power MF directional antenna. This is illustrated below using the NEC results for Start Point:



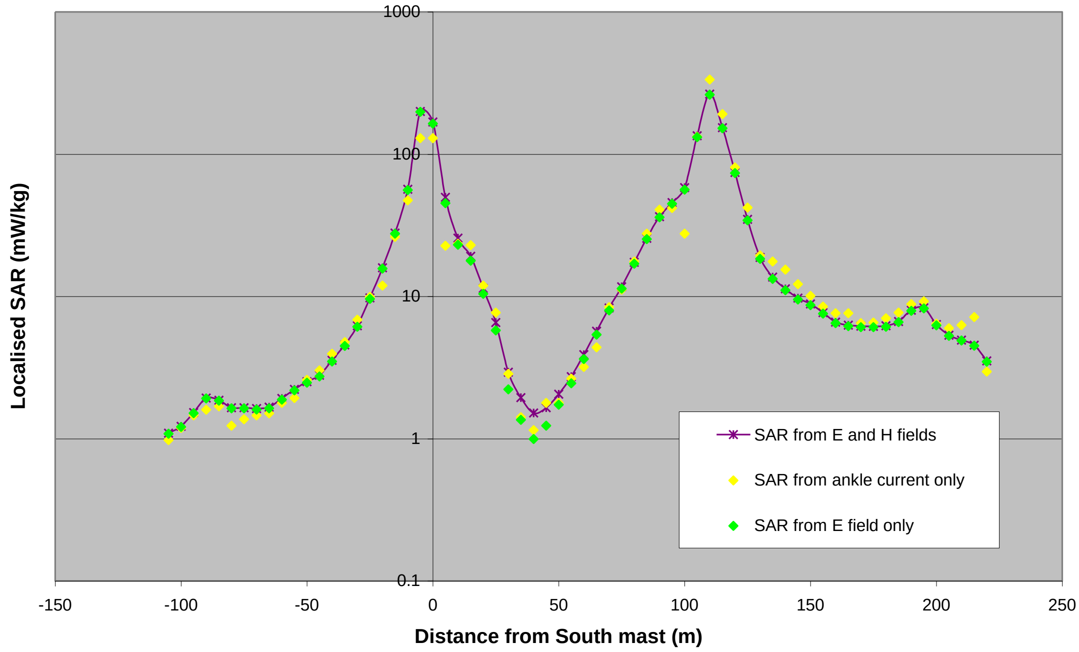
It can be seen from the above that SAR from the E field is virtually the same as that from both fields, at least for locations where the fields are relatively high. The lowest value of wave impedance occurs between the two masts at a distance of about 40m from the South mast where the SAR is very low due to a partial cancellation of the fields from the two masts. This can be seen if a logarithmic scale is used for the vertical axis (SAR), as shown overleaf:

Start Point: SAR (ankle) from NEC based on HPA data
(logarithmic scale showing difference in minimum values)



A similar plot produced from the measurement results is shown below:

Start Point: SAR (ankle) from measurement results using HPA data
(logarithmic scale showing difference in minimum values)



Additional work to be carried out

Some of the further work - analysis of the effects of modulation for example - is common to all possible methods that might be used, whilst other elements apply only to specific methods. For ankle current measurements, the ‘specific’ further work to be carried out depends on whether a ‘standard’ physical model is used or not. The various unique elements of such work are therefore listed below, for these two options.

a) Use of an ankle current meter worn by the person making the measurement.

Suitable correction factors, appropriate procedures and uncertainties for the following factors ought to be determined

- Variation of ankle current for bare feet and for different types of footwear – shoes, boots made from different materials to different designs, particularly sole thickness.

- The effect of body posture on the measurement – this was investigated at Start Point and although it can be significant, it ought to be possible to almost eliminate it by adopting suitable procedures for holding the meter etc.

- Body orientation – a small effect was observed at Start Point which could be reduced by appropriate procedures and eliminated by wearing a meter on both ankles.

- Weight and size of individual – only investigated for a relatively small variation at Start Point so a much larger variation in height and weight needs to be investigated.

Note that many of the above effects are relatively small and could easily be masked by the effect of modulation. It may therefore be necessary to either make measurements either on plain carrier or with the use of a demodulating instrument. It should also be noted that only relative, not absolute, results are required.

b) Use of a physical model to represent the ‘standard’ man.

The work for this option comprises the development of a suitable model and the subsequent determination of the overall measurement uncertainty. The development work needs to address the following

- The achievement in practice of the theoretical ankle current/ field strength relationship determined by the HPA for all frequencies in the MF broadcast band. This may involve one or more vertical conductors on a conducting base with resistive elements and possibly some form of frequency compensation.

- The use of a detachable insulating layer below the base to represent the 'with shoes' case.

- A suitable method for calibrating the physical model.

c) Common elements of work required

The common parts of the work might consist of the following.

- Determination of the overall measurement uncertainty associated with the ankle current meter itself taking into account frequency response, noise floor, non-linearity, temperature variation, modulation etc.

- A better understanding of the uncertainty resulting from a localised SAR assessment based solely on ankle current, when there is also a contribution to the overall SAR from the H field. This might be approached via an assessment of the most likely way in which the SAR due to the H field will increase the overall SAR in the ankle, possibly by studying previous modelling of the H field for different orientations of the body and the extent of any correlation between the regions of maximum absorption rate for the E field and the H field.

References

1) ICNIRP 7/99 Guidelines on limiting exposure to non-ionizing radiation.
2) Note on visit to Start Point, on the 4th and 5th October 2006, to carry out ankle current measurements. Version 2.0