International Benchmarking of UK Calibration and Measurement Capability (CMCs)

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ABSTRACT
This report describes the benchmarking of the Calibration and Measurement Capabilities (CMCs) declared under the CIPM Mutual Recognition Arrangement (MRA) by the National Metrology Institutes (NMIs) in the UK with a number of NMIs from abroad.

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1 Introduction

This report describes the benchmarking of the Calibration and Measurement Capabilities (CMCs) declared under the CIPM[1] Mutual Recognition Arrangement (MRA) [1], by the National Metrology Institutes (NMIs) in the UK with a number of NMIs from abroad. The MRA is subject to a transition period that is expected to be completed by the end of 2003; therefore not all the data are validated and entered on the BIPM[2] database, the Key Comparisons Database (KCDB) [2]. Where they were available, data declared on the KCDB were used for the benchmarking otherwise, data that had been agreed by the local Regional Metrology Organisations (RMOs), EUROMET[3] for European NMIs or SIM[4] for the USA NMI, were used. The data that had not completed the local RMO review were not benchmarked.

This exercise has been carried out for the UK Department of Trade and Industry and builds on an earlier study conducted by the authors in 2000, using non-validated data. The earlier study generated sufficient interest to warrant repeating the process with up-to-date and validated data.

1.1 Objectives

The principal objectives of this project were:

- To benchmark the UK Calibration and Measurement Capabilities with others in Europe and the USA;
- To provide an analysis of the UK strengths;
- To collate the traceability arrangements as recorded in the version of CMCs statements available to the contact persons.

1.2 Background

In 1999, the directors of the National Metrology Institutes of 38 countries and 2 international organisations signed the Mutual Recognition of national measurement standards and of calibration and measurement certificates (the CIPM Mutual Recognition Arrangement or MRA). A further 10 countries have since signed the MRA. As a consequence of the MRA, the NMIs are required:

- To take part in appropriate comparisons: the **key and supplementary comparisons**;
- To declare and subject their **Calibrations and Measurements Capabilities** (CMCs) for extensive peer review;
- To implement and demonstrate an appropriate **quality system**.

For the first time the MRA provides end users with data in a harmonised form, that are supported by comparisons, subject to extensive peer review and declared by NMIs

[1] Comité International des Poids et Mesures
[2] Bureau International des Poids et Mesures
[3] The European Metrology Collaboration
[4] The Inter-American System of Metrology

that are obliged to operate an appropriate quality system. Thus for the first time the MRA process provides data available in a format that is meaningful for a benchmarking study.

After an internal review within the NMI, all CMCs undergo 100% peer review by other NMIs within the local Regional Metrology Organisation (RMO), followed by a sample peer review by all other RMOs. CMCs are then submitted for review to the Joint Committee of the RMOs and the BIPM (JCRB). Once agreed by the JCRB they then populate the BIPM key comparison database (KCDB) on the BIPM web site. The CMCs are described using a common format that has been agreed internationally, colloquially known as the 'vocabulary' and are declared for the following nine quantities:

- Acoustics, Ultrasound and Vibration
- Amount of Substance
- Electricity and Magnetism
- Ionising Radiation
- Length
- Mass and Related Quantities (including Flow)
- Photometry and Radiometry
- Thermometry
- Time and Frequency

The benchmarking exercise was carried out between January and March 2002, at the time 8 of the 9 quantities had data sufficiently progressed to enable benchmarking. Data for Acoustics, Ultrasound and Vibration, Length, Electricity and Magnetism, Amount of Substance and Radiometry and Photometry were available on the KCDB and were benchmarked. The data for Mass and Related Quantities, Thermometry and Ionising Radiation had been agreed by the local RMO and were benchmarked. The data for Flow (part of Mass and Related Quantities) and Time and Frequency are still under discussion by the local RMO and were not benchmarked.

2 The Benchmarking Model

The data in the CMC database

In making their declaration under the MRA, NMIs used a common 'vocabulary' to describe the services they offer. These services, grouped under the nine quantities, are all included in a 'List of Services' published on the BIPM website (see extract for the quantity Length in Appendix A). Each quantity in a CMC declaration is sub-divided, with CMCs being declared for each individual service. Appendix B shows some of the CMCs for the quantity Length, for the UK. An individual calibration service in the CMC database may contain more than one data entry, and all these entries have been used in the application of the model.

Description of the model

As resources were limited only ten countries (nine for Ionising Radiation) were benchmarked for each quantity, these include the UK, the USA (except for Ionising Radiation) and a sample of eight countries from the EUROMET membership, representing about one third of EUROMET. As a consequence the majority of European NMIs do not appear in the study. The countries chosen were generally those most active in terms of declaring CMCs, although for some quantities many other NMIs are active at a similar level and those selected for benchmarking were a representative sample.

The benchmarking model was developed to cope with the variation in CMC declarations by the various NMIs with individual services supported by one CMC data entry or by many entries. Whilst the CMC data were examined at the CMC data entry level they were scored per country by the UK EUROMET Contact Persons at the level of individual measurement services on the basis of declared data.

The assessment addressed the following two properties:

The range of services offered or **'Coverage'** by each NMI was rated and compared to the range of services offered at the UK NMI, using the following marking scheme:

Table 1: Coverage marking scheme.

0	Service not offered by the NMI
1	Coverage significantly less than UK NMI
2	Coverage less than UK NMI
3	*Coverage similar to UK NMI*
4	Coverage greater than UK NMI
5	Coverage significantly greater than UK NMI

In the limited number of instances where the UK did not offer a service, the benchmark was taken to be the mean of service coverage for those countries benchmarked that did offer the service.

2. The **'Performance'** of each NMI in terms of the declared uncertainty was assessed using the matrix below (Figure 1). This was developed to asses the performance, taking into account that a single service declaration for any given laboratory may include a number of CM data entry lines.
The matrix was operated in the following way:

- For each individual service the State of the Art (SoA) was established from the CMC data;
- For each country and each individual service:
  - The best uncertainty declaration was assessed in the range Poor to SoA;
  - The remaining uncertainty declarations (within that individual service) were considered together as a group and assessed in the range Poor to SoA;
  - Using the matrix (Figure 1) the appropriate number (1-5) was allocated to the individual service in question.

'Poor' was (typically) an uncertainty more than one order of magnitude greater than SoA.

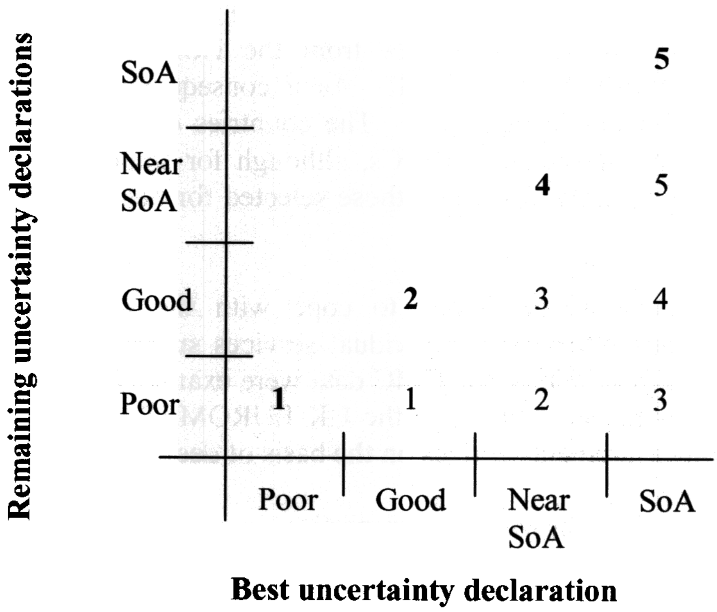


Figure 1: The Uncertainty Matrix

2.3 Combining the scores to allow graphical representation

For each quantity, the data were analysed and the resulting scores were collated per individual service and per NMI (see table 2). The raw scores were then amalgamated into the appropriate sub-quantity or branch; usually as described in the vocabulary list, giving the CMC profile of the laboratories at this level. They were further consolidated to give an overview of each NMI's performance for a particular quantity. The scores were amalgamated as follow:

- The overall coverage mark was obtained by dividing the sum of all the coverage marks by the total number of individual services;

- The overall performance mark was obtained by dividing the sum of all the performance marks by the number of individual services for which a service was offered (services not offered by the NMI were not included).

Illustrative example:
In table 2, for the UK, the sub-quantity score for the coverage is the sum of all the coverage marks (3+3) divided by 3, but the score for the performance level is the sum of the 'uncertainty' marks (5+4) divided by 2.

Table 2: Example showing calculating of amalgamating mark.

	UK		NMI 2	
	Coverage	Uncertainty	Coverage	Uncertainty
Individual service 1	3	5	4	5
Individual service 2	3	4	5	4
Individual service 3	0	0	3	4
Sub-quantity score	2	4.5	4	4.333

The results are shown in graphical format with the performance in terms of uncertainty level plotted as the ordinate and the coverage as the abscissa. The scores and graphs were subject to a feedback check, at which point the UK EUROMET Contact Persons have been able to provide an insight into the various profiles that have emerged.

A blind check was undertaken with PTB for one sample sub-quantity. PTB chose 'impedance', a particularly challenging field to judge with many parameters to take into account.

The exercise described in this report required the individual examination and comparison of several thousand lines of data by the UK EUROMET Contact Persons, the recording of nearly 10,000 numerical scores and the generation of more than 50 sub-quantity/branch and quantity graphs.

2.4 Qualifying comments on the data/model

The following remarks should be noted when using the benchmarking findings:

<u>The CMCs data:</u>

- The MRA states that the CMCs describe services that are 'ordinarily available to customers' [3]:
    - There are different approaches from the NMIs to what is considered as routine and what is not, depending on historical practice, funding and customers' needs;
    - Because of the definition of the CMCs, the uncertainties within the CMCs should not be considered as necessarily representative of the NMIs' ultimate capabilities (within their scientific activity, NMIs may work at a much smaller uncertainty);

- In some countries, some services are devolved to accredited laboratories, hence these services will not appear in the CMCs (nor in the benchmarking exercise) although the services are still available in the country, whilst in other countries, similar services are offered by the NMI, declared as CMCs and therefore contribute to the coverage score. Therefore the coverage needs to be studied with care;

- Some of the CMCs used in this exercise have only passed the local RMO review and are still under discussion within the other RMOs;

- Overall, approximately two thirds of the CMCs finally expected to populate the KCDB are currently on the database. However approximately 90% of the European data have completed the EUROMET RMO review and were available for the benchmarking exercise;

- Due to the lack of validated data, neither Flow nor Time and Frequency were benchmarked;

- The CMC information circulated between the RMOs Contact Persons contains details of traceability between NMIs, that is where an NMI chooses not to carry out a primary realisation but holds a national standard traceable to a primary standard at another NMI. This information is not available in the KCDB.

The Model:

- Scoring was carried out by the EUROMET UK Contact Persons with a sample blind check with PTB;

- Only the UK, USA and eight countries from EUROMET were benchmarked;

- Each line of data was given the same weight, making no differentiation between a critical service and a less important one. The original benchmarking study had included an additional weighted score by the Contact Persons to account for this. However only minor differences were apparent once the scores were collated and the weighting was not repeated in this study;

- The results are presented graphically; however the nature of the benchmarking is such that these representations are best considered as pictures rather than mathematical graphs.

Findings and observations per quantity

Acoustics, Ultrasound and Vibration

CMCs benchmarked for the following countries: UK, Denmark, France, Germany, Italy, Netherlands, Poland, Sweden, Switzerland, USA.

Status of the data: The data have been agreed and reviewed by the RMOs and the JCRB and are now available on the BIPM database. Recent data from the European NMIs have been agreed by EUROMET and have been included in the benchmarking.

Traceability as declared in CMCs:

Table 3: Traceability arrangements for Acoustics, Ultrasound and Vibration.

Provides traceability \ Takes traceability	UK	Denmark	France	Germany	Italy	Netherlands	Poland	Sweden	Switzerland	USA
UK										
	A						**B**	**C**		
Italy										
Netherlands										
Poland										

- A: **Mechanical couplers** (force response level), traceability from PTB via UKAS laboratories;
- B: **Accelerometer** (charge sensitivity), **Acceleration measuring chain** (voltage sensitivity), **Acceleration calibrator** (acceleration) traceability from PTB;
- C: **Accelerometer** (charge sensitivity), **Acceleration measuring chain** (voltage sensitivity) traceability from PTB.

Notes and observations: The quantity 'Acoustics, Ultrasound and Vibration' is divided in three branches: 'sound in air', 'sound in water' and 'vibration'. Overall Germany has the widest coverage and offers SoA uncertainty. The UK performs very well in terms of coverage and uncertainty in 'sound in air' and 'sound in water' offering SoA services and widest coverage. Germany is the leading NMI for 'vibration' both in term of range of services and uncertainty level, the UK NMI does not offer any services in this branch. 'Vibration' as a branch has been divided into a particular extensive vocabulary list and consequently has greater influence on the quantity graph than 'sound in air' and 'sound in water'.

Quantity Graph

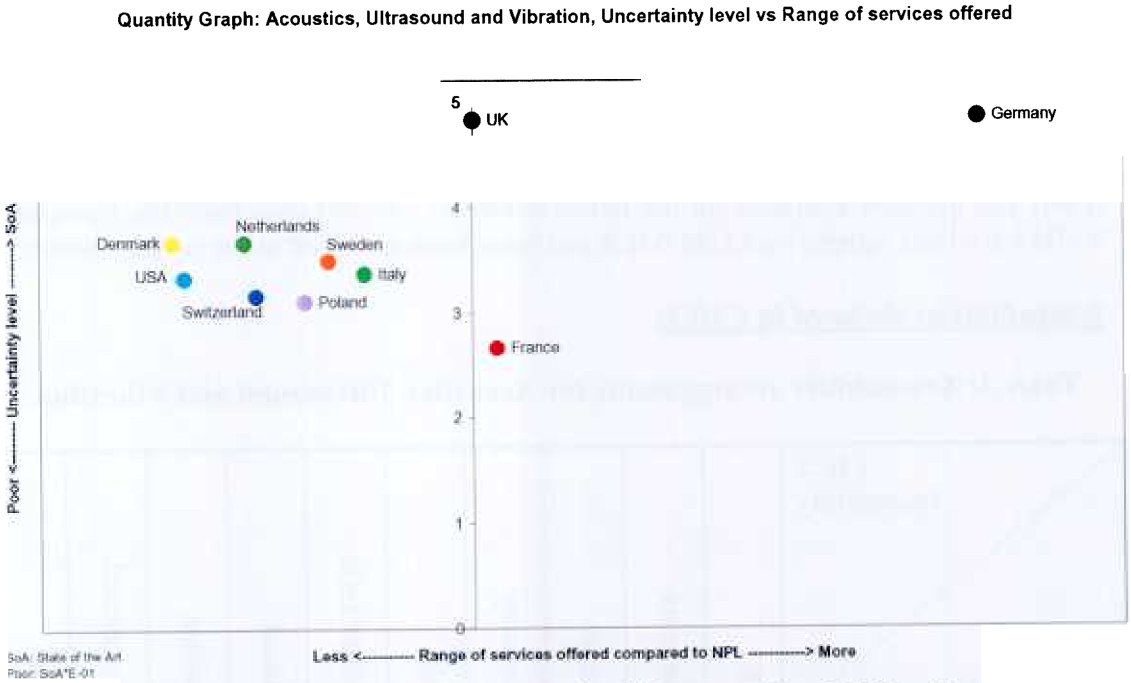


Figure 2: Quantity graph, Acoustics, Ultrasound and Vibration

Sub-Quantity graphs

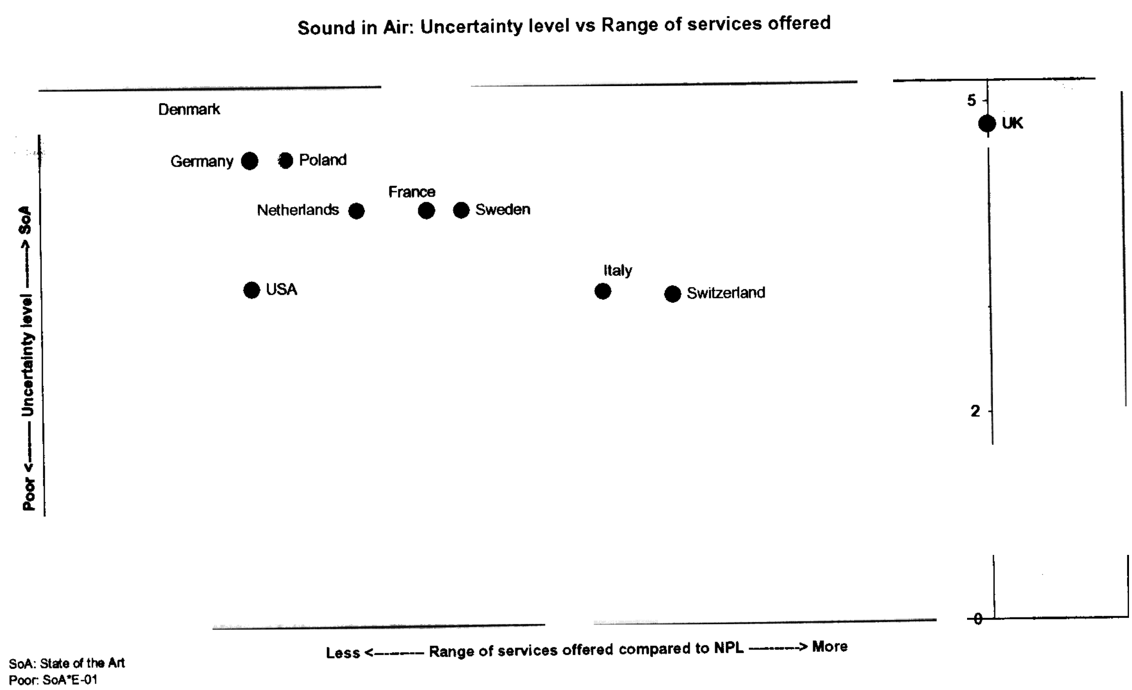


Figure 3: Sub-quantity graph, 'sound in air'

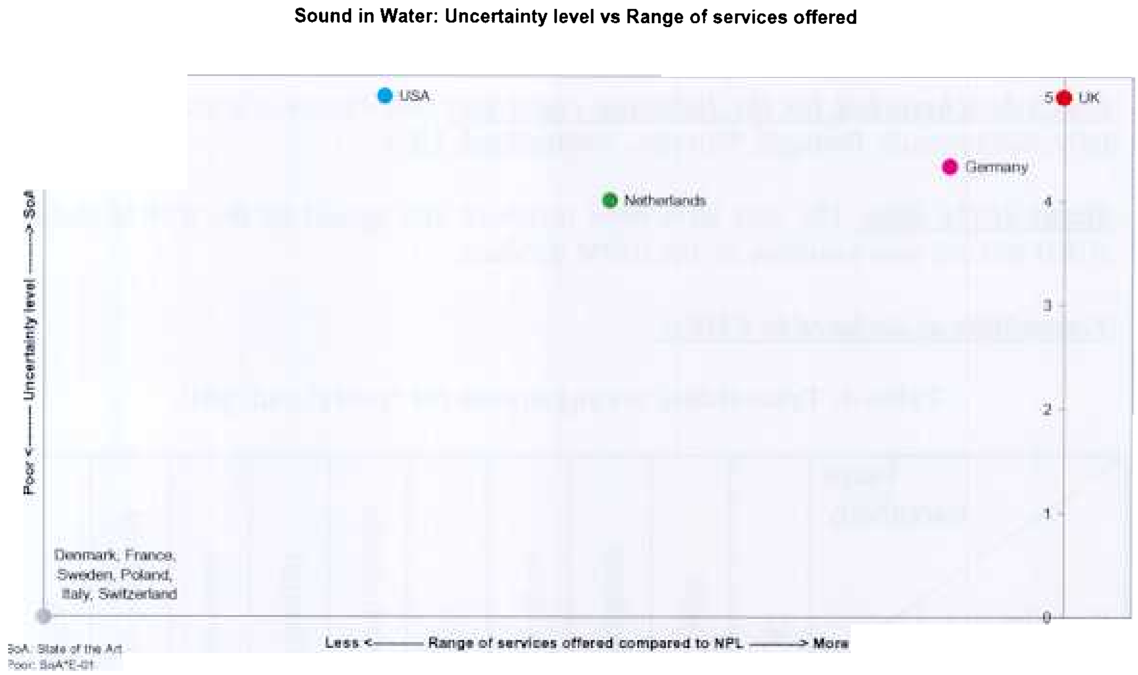


Figure 4: Sub-quantity graph, 'sound in water'

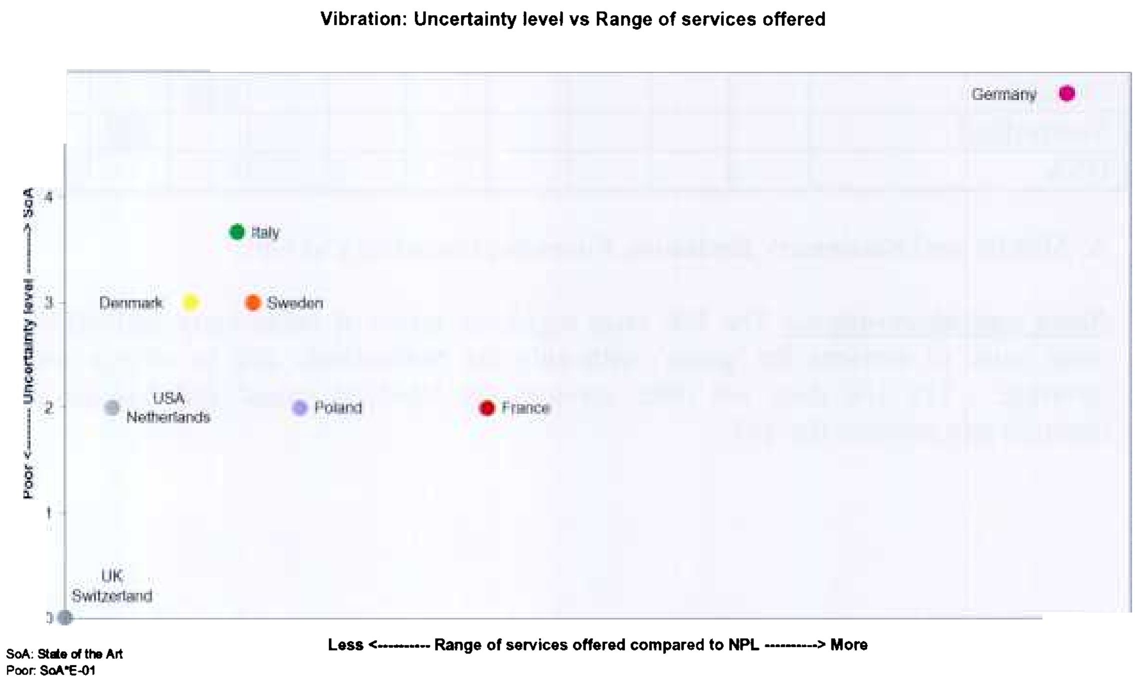


Figure 5: Sub-quantity graph, 'vibration'

3.2 Amount of Substance

3.2.1 'Gases' and 'pH'

These two sub-quantities of Amount of Substance are covered by NPL for the UK.

CMCs benchmarked for the following countries: UK, France, Germany, Hungary, Italy, Netherlands, Portugal, Slovakia, Switzerland, USA.

Status of the data: The data have been reviewed and agreed by the RMOs and the JCRB and are now available on the BIPM database.

Traceability as declared in CMCs:

Table 4: Traceability arrangements for 'gases' and 'pH'.

Takes traceability / Provides Traceability	UK	France	Germany	Hungary	Italy	Netherlands	Portugal	Slovakia	Switzerland	USA
UK							**A**			
France										
Germany										
Hungary										
Italy										
Netherlands										
Portugal										
Slovakia										
Switzerland										
USA										

A: **Mobile and Stationary Emission, Forensic,** traceability to NPL.

Notes and observations: The UK rates highly in terms of uncertainty and offers a wide range of services for 'gases' with only the Netherlands able to offer a wider coverage. The UK does not offer services for 'medical gases' and has not yet declared any services for 'pH'.

Sub-quantity graphs:

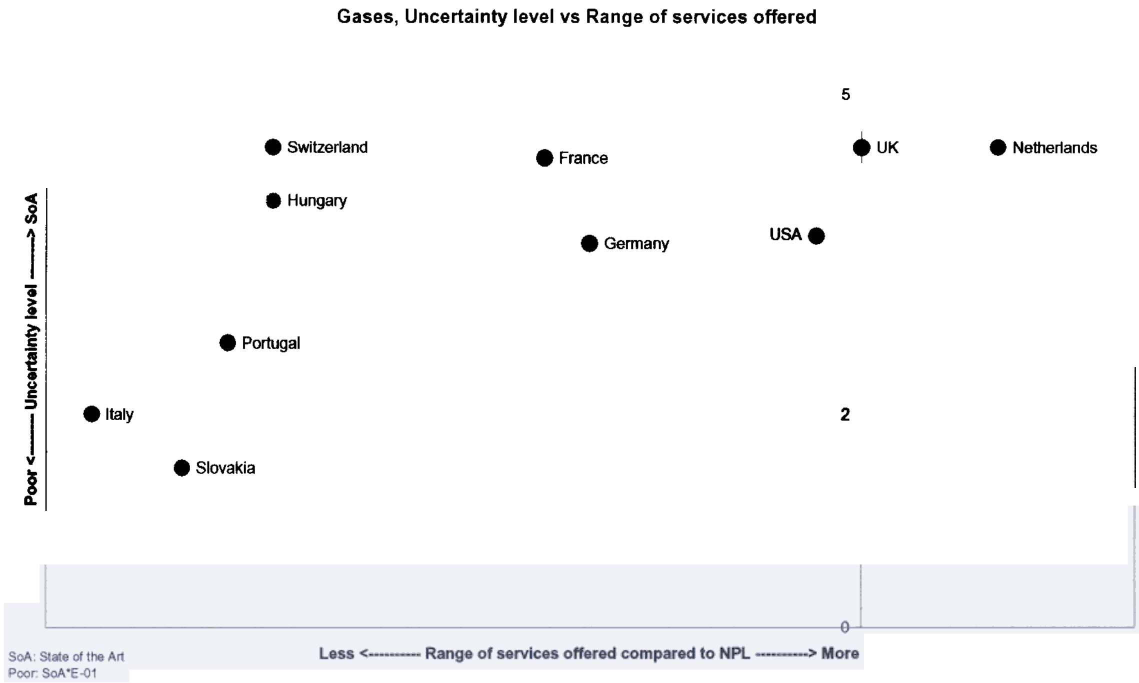


Figure 6: Sub-quantity graph, 'gases'

Figure 7: Sub-quantity graph, 'pH'

3.2.2 Amount of Substance other than 'gases' and 'pH'

This area of Amount of Substance is covered by LGC for the UK.

CMCs benchmarked for the following countries: UK, Czech Republic, Denmark, European Union, France, Germany, Hungary, Netherlands, Slovakia, USA.

Status of the data: The data have been reviewed and agreed by the RMOs and the JCRB and are now available on the BIPM database.

Traceability as declared in CMCs:

Table 5: Traceability arrangements for Amount of Substance (excluding 'gases' and 'pH').

Takes traceability / Provides Traceability	UK	Czech Republic	Denmark	European Union	France	Germany	Hungary	Netherlands	Slovakia	USA
UK										
Czech Republic										
Denmark										
European Union										
France										
Germany										
Hungary										
Netherlands										
Slovakia										
USA	**C**					**A**				
Australia	**B**									

- A: **Biological fluids serum and materials** (blood serum, renal fluids) traceability from NIST;
- B: **High purity compounds** (dimethoate) traceability from National Analytical Laboratory (NARL);
- C: **Aqueous solutions** (water), **biological fluids serum and materials** (blood serum) traceability from NIST.

Notes and observations: In this quantity, the USA have declared a wide range of services partly because a large number of their CMCs are linked to their extensive range of Reference Materials (RMs) which are mostly certified 'in house'. The certification of European's NMIs RMs, known as Certified Reference Materials (CRMs) involves a 'round robin' certification 'campaign' which includes non-NMI laboratories and therefore the CRMs were not included in the CMCs in the first round of declaration. Some discussions are still on-going in the different RMOs concerning the inclusion in the CMCs of CRMs certified by 'round robin'. Overall the USA is the leading NMI in this area of Amount of Substance providing widest coverage and SoA uncertainty in 'inorganic solutions', 'organic solutions', 'water', 'biological fluids', 'food', 'sediments, soil, ores and particulates' by a significant margin. In Europe, the UK and Germany are the leading NMIs for this quantity. The UK with Slovakia and the European Union offers SoA service and best coverage in 'high purity chemicals'. The UK still provides SoA services but less coverage than the USA for 'inorganic solutions', 'organic solutions' and for 'food' where Germany is the other leading NMI. In some other sub-quantities the UK is near SoA in term of uncertainty but it does not provide services for 'other materials' where Germany is the only NMI to offer services.

Quantity Graph:

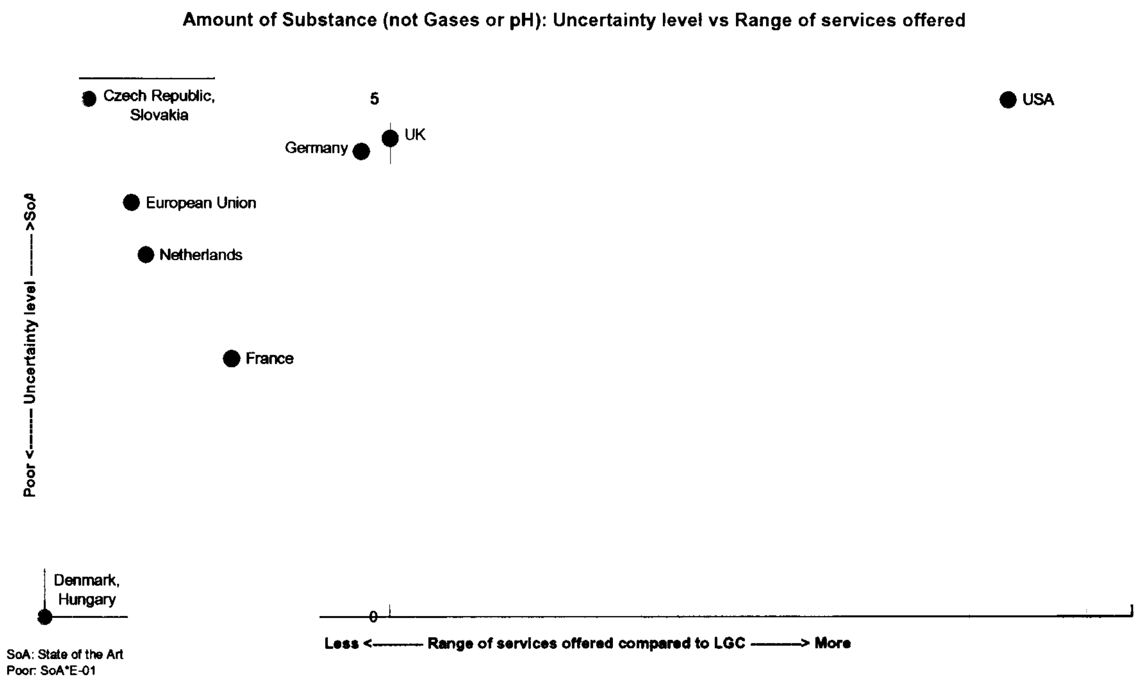


Figure 8: Quantity graph, Amount of Substance (excluding 'gases' and 'pH')

Sub-quantity graphs:

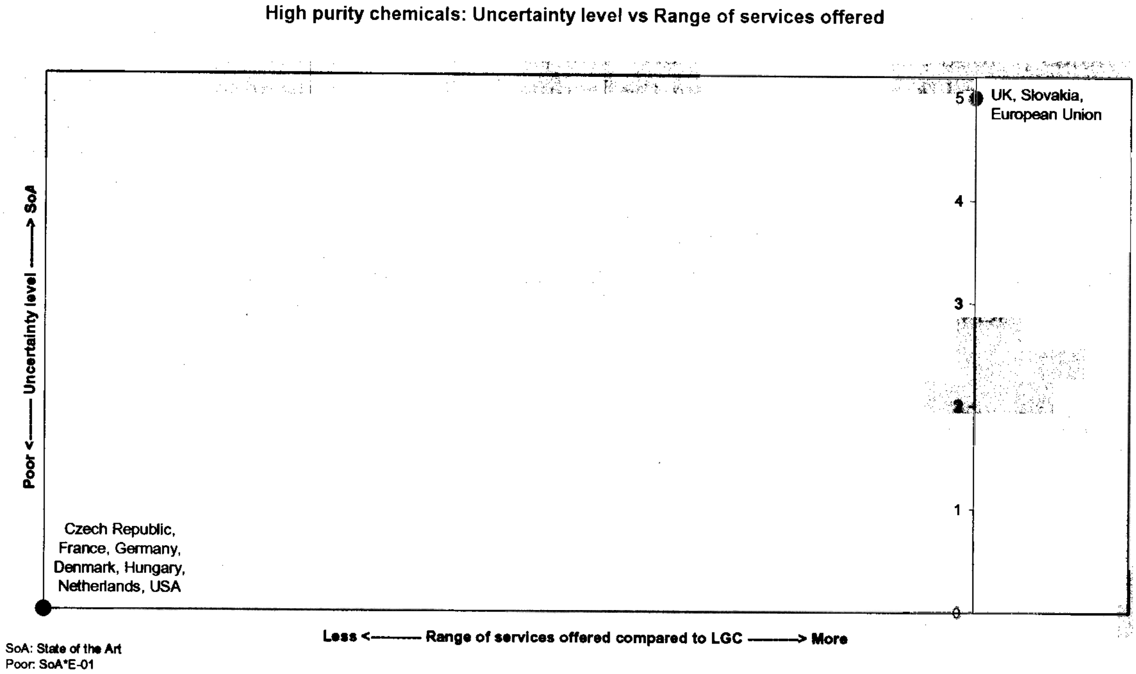


Figure 9: Sub-quantity graph, 'high purity chemicals'

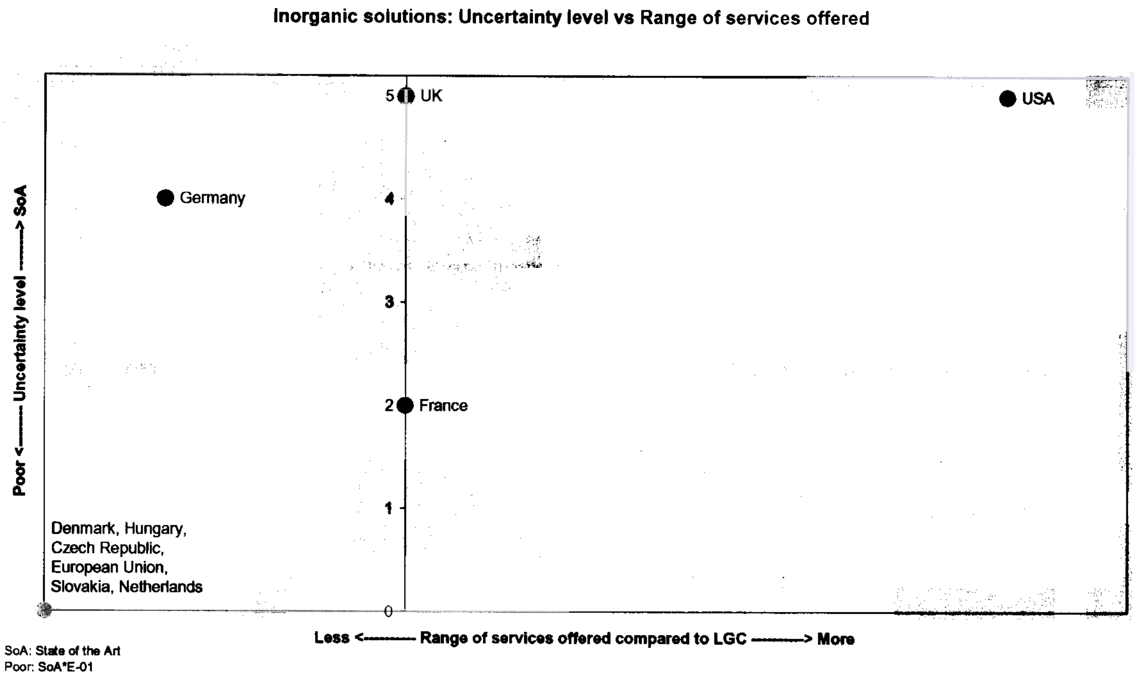


Figure 10: Sub-quantity graph, 'inorganic solutions'

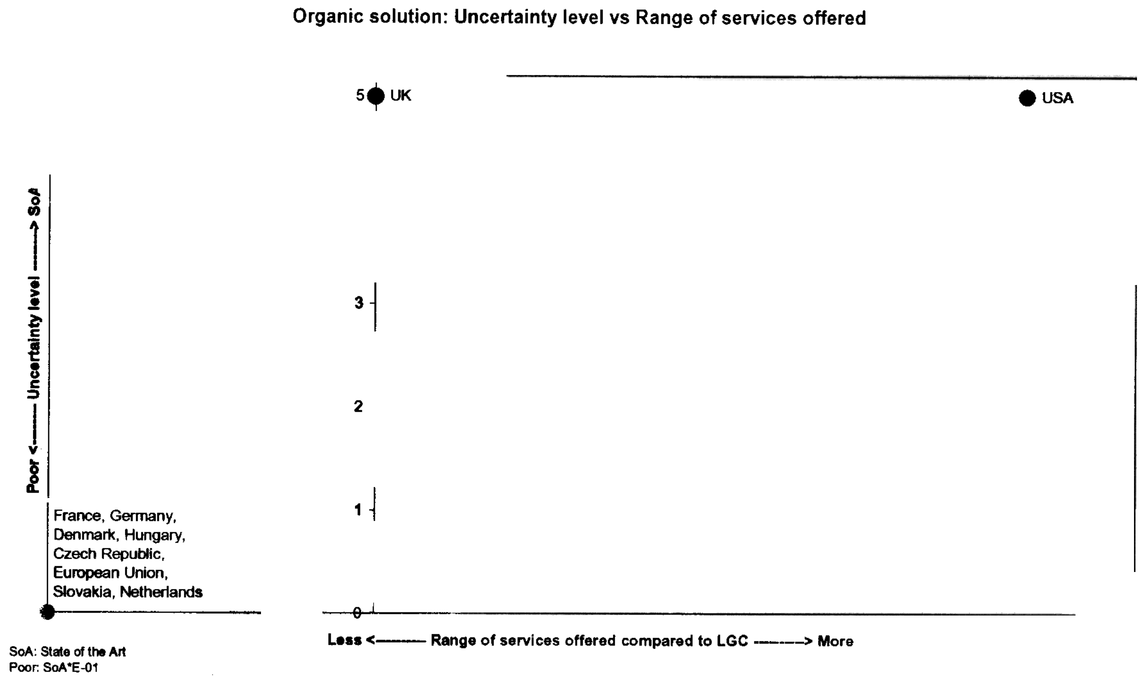


Figure 11: Sub-quantity graph, 'organic solutions'

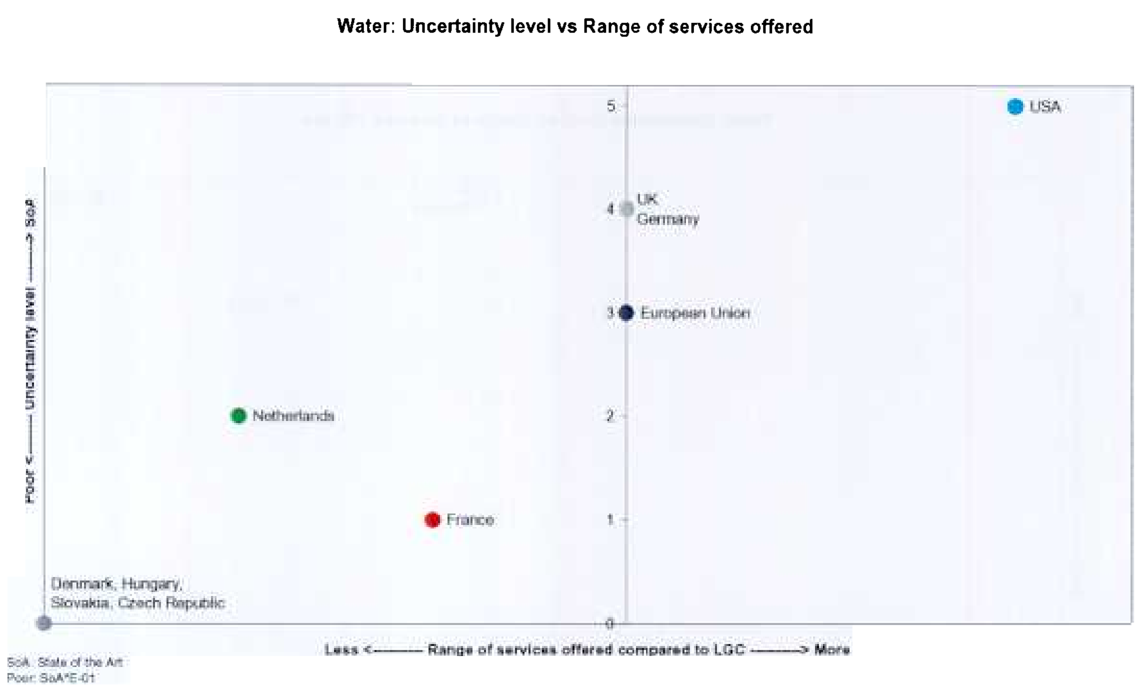


Figure 12: Sub-quantity graph, 'water'

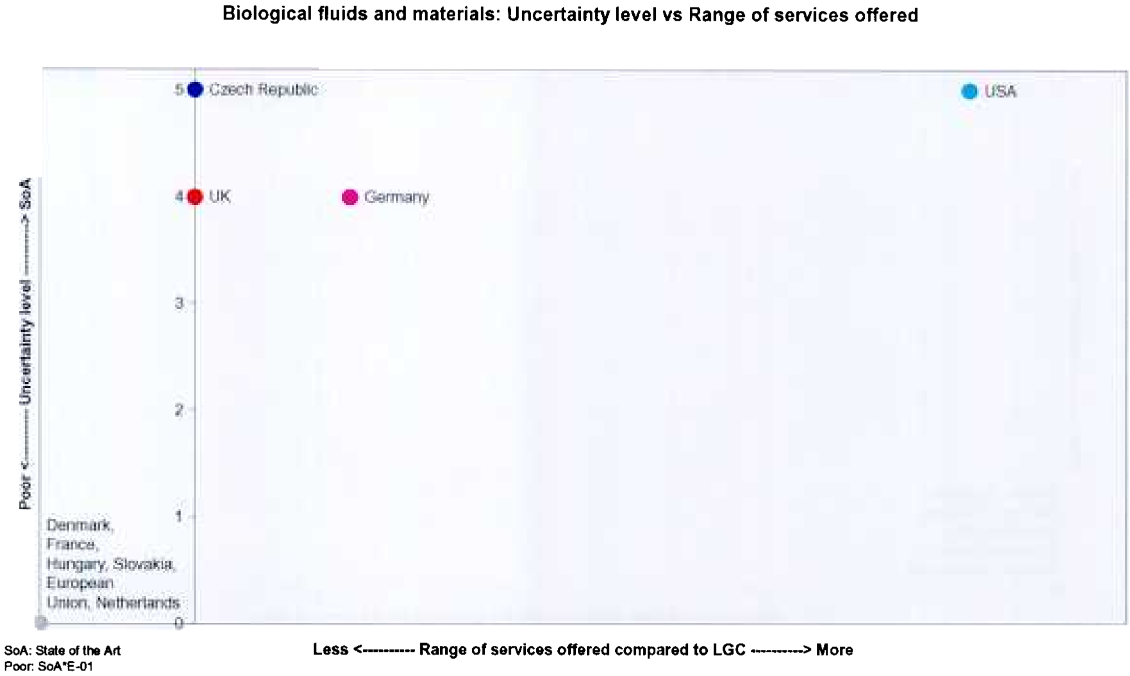


Figure 13: Sub-quantity graph, 'biological fluids and materials'

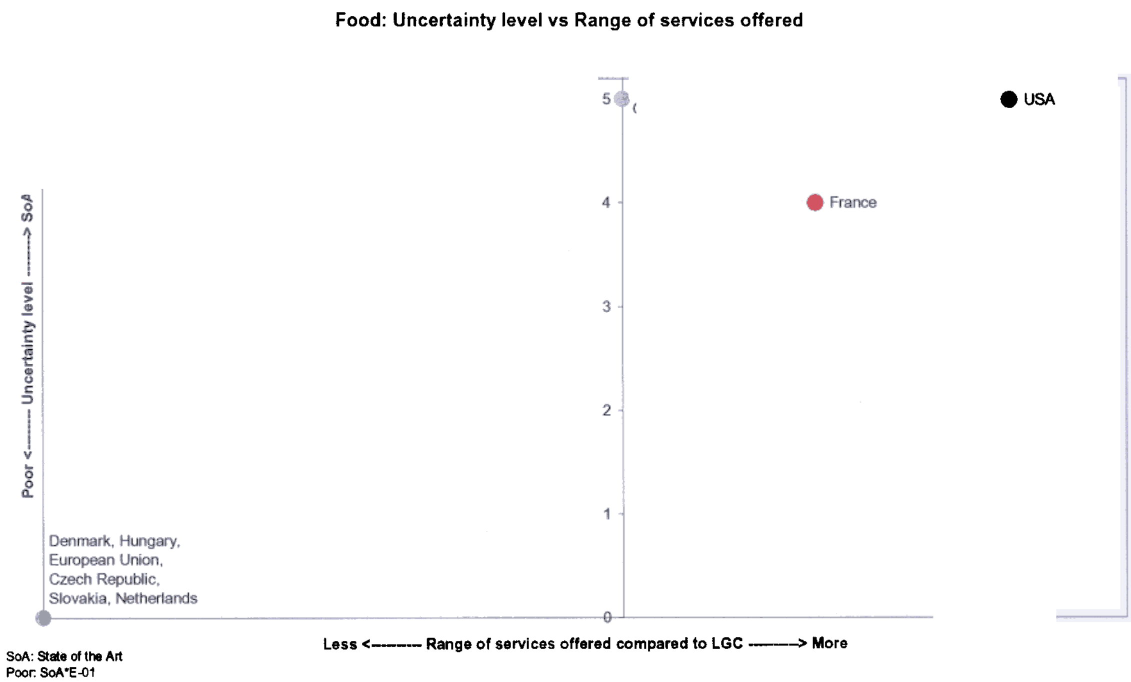


Figure 14: Sub-quantity graph, 'food'

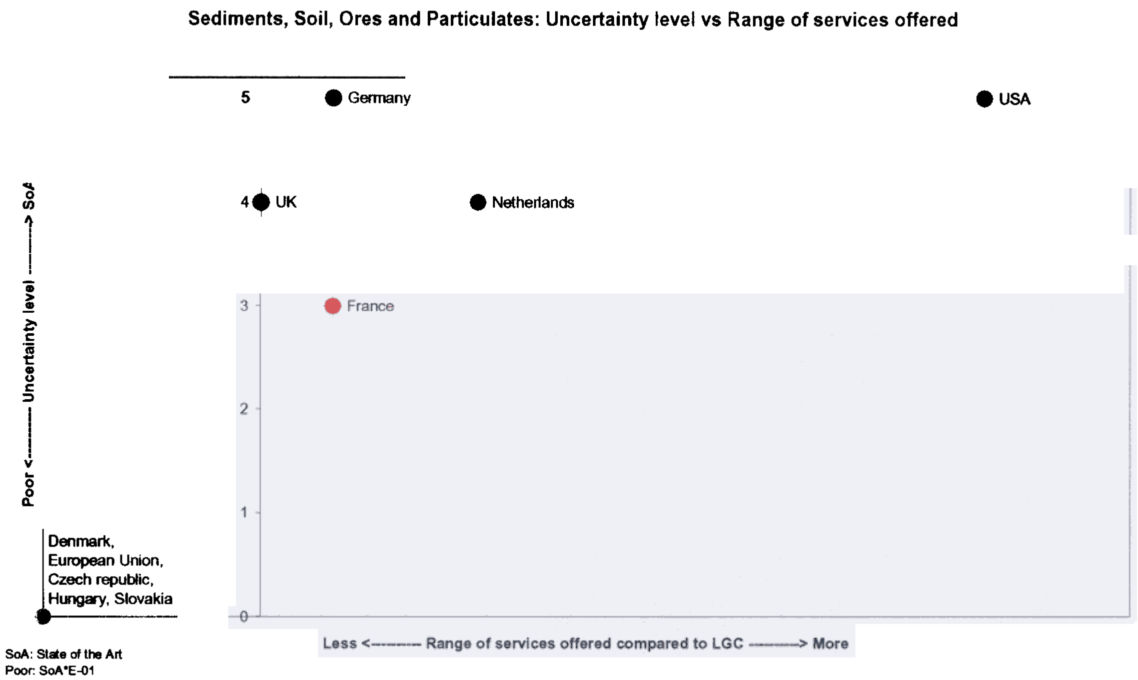


Figure 15: Sub-quantity graph, 'sediments, soils, ores, and particulates'

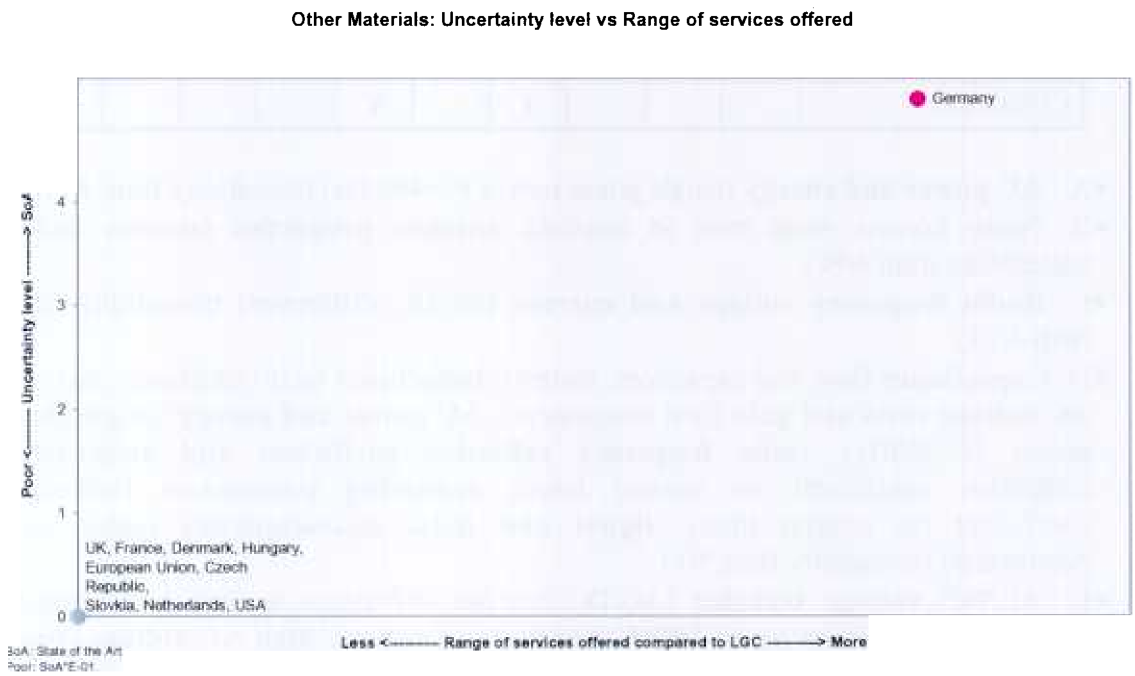


Figure 16:Sub-quantity graph, 'other materials'

3.3 Electricity and Magnetism

CMCs benchmarked for the following countries: UK, Finland, France, Germany, Italy, Netherlands, Spain, Sweden, Switzerland, USA.

Status of the data: The data used have been agreed by the RMOs and the JCRB and are now on the BIPM database.

Traceability as declared in CMCs:

Table 6: Traceability arrangements for Electricity and Magnetism.

Provides Traceability \ Takes Traceability	UK	Finland	France	Germany	Italy	Netherlands	Spain	Sweden	Switzerland	USA
UK		**M**	**B**					**J**	**D**	
Finland										
France									**H**	
Germany		**O**	**A**				**Q**	**K**	**E**	
Italy										
Netherlands			**C**				**S**	**L**	**G**	
Spain										
Sweden		**N**							**F**	
Switzerland										
USA				**U**	**P**		**R**		**I**	
CODATA				**T**		**V**				

- •A: **AC power and energy** (single phase power f<=400 Hz) traceability from PTB
- •B: **Noise** (excess noise ratio in coaxial), **antenna properties** (antenna factor) traceability from NPL;
- •C: **Radio frequency voltage and current** (RF/DC difference) traceability from NMi-VSL;
- •D: **Capacitance** (low loss capacitors, meters), **inductance** (self inductance, meters), **AC voltage ratio and gain** (real component), **AC power and energy** (single phase power f<=400Hz), **radio frequency reflection coefficient and attenuation** (reflection coefficient on coaxial lines), **scattering parameters** (reflection coefficient on coaxial lines), **signal and pulse characteristics** (pulse time parameters) traceability from NPL;
- •E: **AC/DC voltage transfer** (AC/DC transfer difference at low and medium voltages), **AC voltage up to 1000V** (sources and meters), **high AC voltage** (ratio: real component, ratio: imaginary component), **radio frequency power** (absolute power on coaxial, calibration factor and effective efficiency on coaxial lines), **radio frequency reflection coefficient and attenuation** (reflection coefficient on coaxial lines), traceability from PTB;

- F: **AC/DC current transfer** (AC/DC transfer difference), **AC current up to 100A** (sources and meters) traceability from SP;
- G: **Radio frequency power** (absolute power on coaxial, calibration factor and effective efficiency on coaxial lines), **radio frequency voltage and current** (RF/DC difference) traceability from NMi-VSL;
- H: **Radio frequency power** (absolute power on coaxial, calibration factor and effective efficiency on coaxial lines) traceability from LCIE;
- I: **Radio frequency reflection coefficient and attenuation** (reflection coefficient on coaxial lines) traceability from NIST;
- J: **AC resistance** (real component), **capacitance** (low loss capacitors), AC voltage ratio, attenuation and gain (real component, imaginary component), High AC voltage (ratio: real component, ratio: imaginary component) traceability from NPL;
- K: **AC/DC voltage transfer** (low voltage) traceability from PTB;
- L: **Radio frequency voltage and current** (RF-DC difference), traceability from NMi-VSL;
- M: **Capacitance** (low loss capacitors), **AC voltage up to 1000V** (sources, meters) traceability from NPL;
- N: **Capacitance** (low loss capacitors), **AC/DC voltage transfer** (AC/DC transfer difference at medium, higher voltages), **AC voltage up to 1000V** (sources, meters), **AC/DC current transfer** (AC/DC transfer difference), AC current up to 100A (meters) traceability from SP;
- O: **AC/DC voltage transfer** (AC/DC transfer difference at medium, higher voltages), AC power and energy (single phase power f<=4000Hz), traceability from PTB;
- P: **Radio frequency reflection coefficient and attenuation** (reflection coefficient on coaxial lines, absolute power on waveguides), **scattering parameters** (reflection coefficient on coaxial lines, on waveguides) traceability from NIST;
- Q: **Capacitance** (low loss capacitors), **radio frequency voltage and current** (RF/DC difference) traceability from PTB;
- R: **Capacitance** (low loss capacitors) traceability from NIST;
- S: **Radio frequency voltage and current** (RF/DC difference) traceability from NMi-VSL;
- T: **Magnetic fields below 50kHz** (Magnetic flux, DC magnetic flux density and applied magnetic field strength) traceability from CODATA;
- U: **Signal and pulse characteristics** (pulse time parameters), traceability from NIST
- V: **Magnetic fields below 50kHz** (Magnetic flux) traceability from CODATA.

Notes and observations: Electricity and Magnetism is an example where traceability to other NMIs is common, more than 40 agreements were recorded for this quantity. It also shows that smaller laboratories can excel but in smaller areas. Overall, the UK offers SoA services and a wide range of service, with only Germany able to offer a greater coverage. UK and Germany offer SoA services and widest coverage in 'impedance', 'electric and magnetic fields'. In 'high frequency measurements' UK still offers SoA services but with France providing near SoA services and slightly greater coverage. For 'measurements on materials', the UK offers SoA services but less coverage than Germany. In 'DC voltage, current and resistance', 'AC voltage current and power', 'high voltage and current' the UK offers SoA services but other countries are able to offer a wider range of services, mostly due to the fact that the UK devolves some services to UKAS accredited laboratories. UK does not offer other

'DC and low frequency measurements' where USA, France and Netherlands offer SoA services although the Netherlands has a smaller coverage.

Quantity Graph:

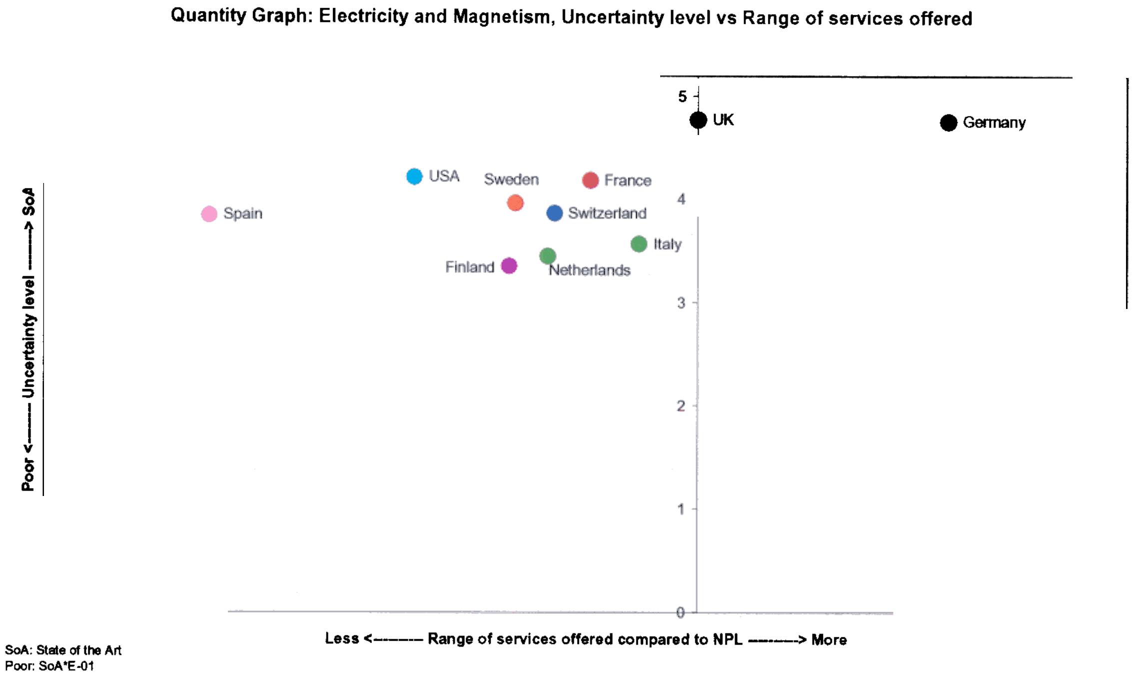


Figure 17: Quantity graph, Electricity and Magnetism

Sub-quantity graphs:

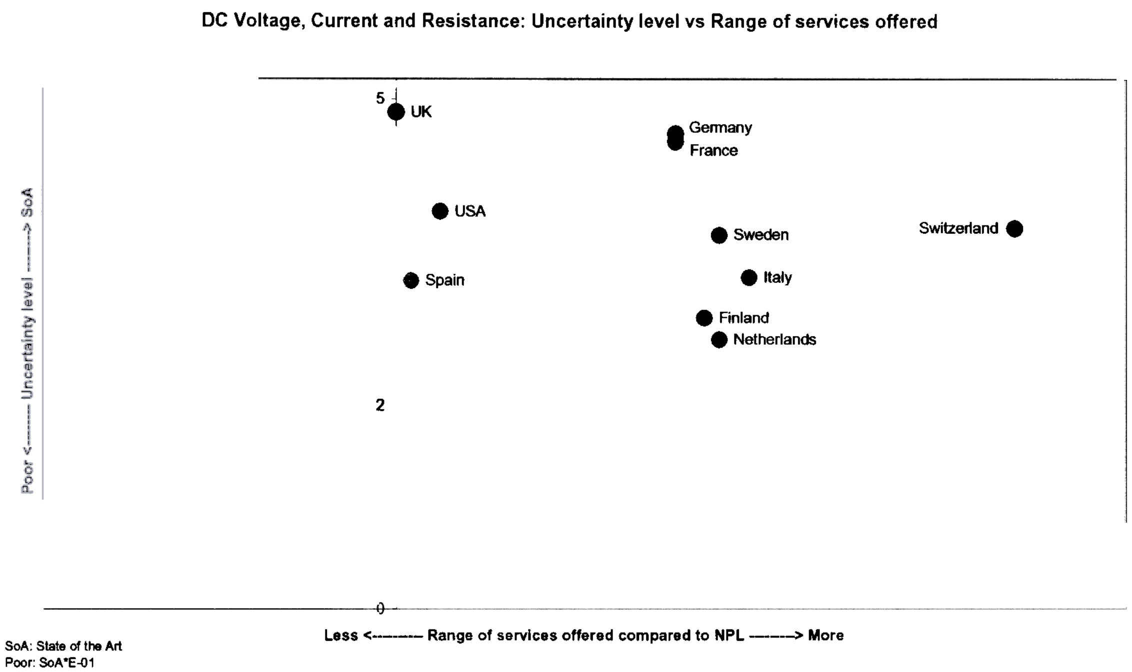


Figure 18: Sub-quantity graph, 'DC voltage, current and resistance'

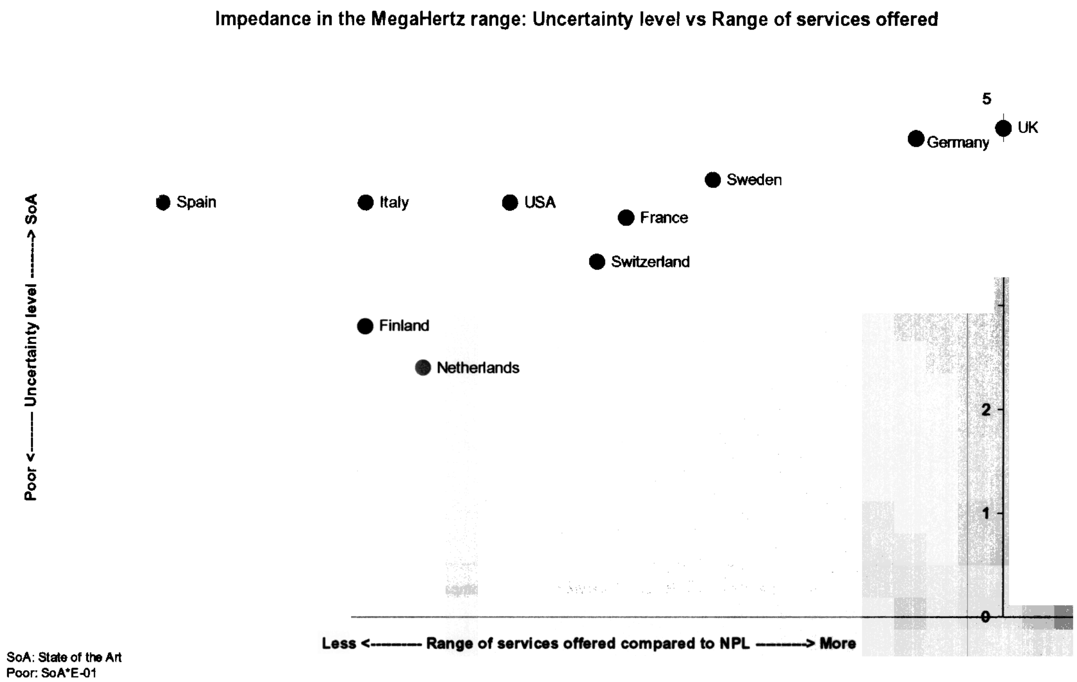


Figure 19: Sub-quantity graph, 'impedance in the MegaHertz range'

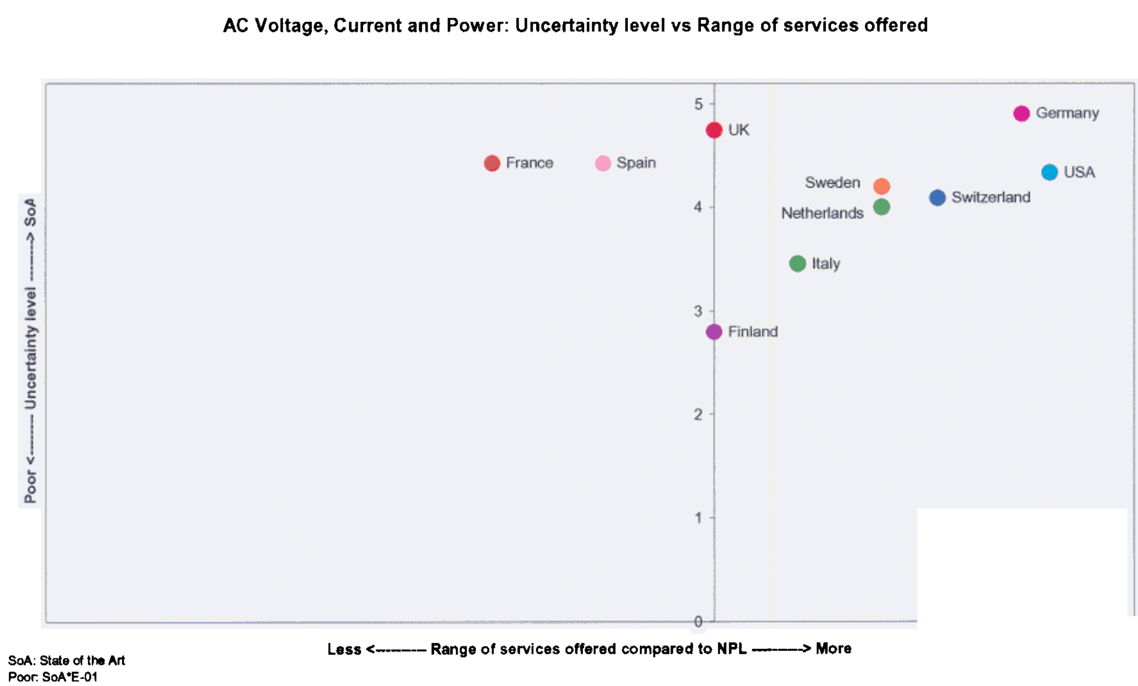


Figure 20: Sub-quantity graph, 'AC voltage, current and power'

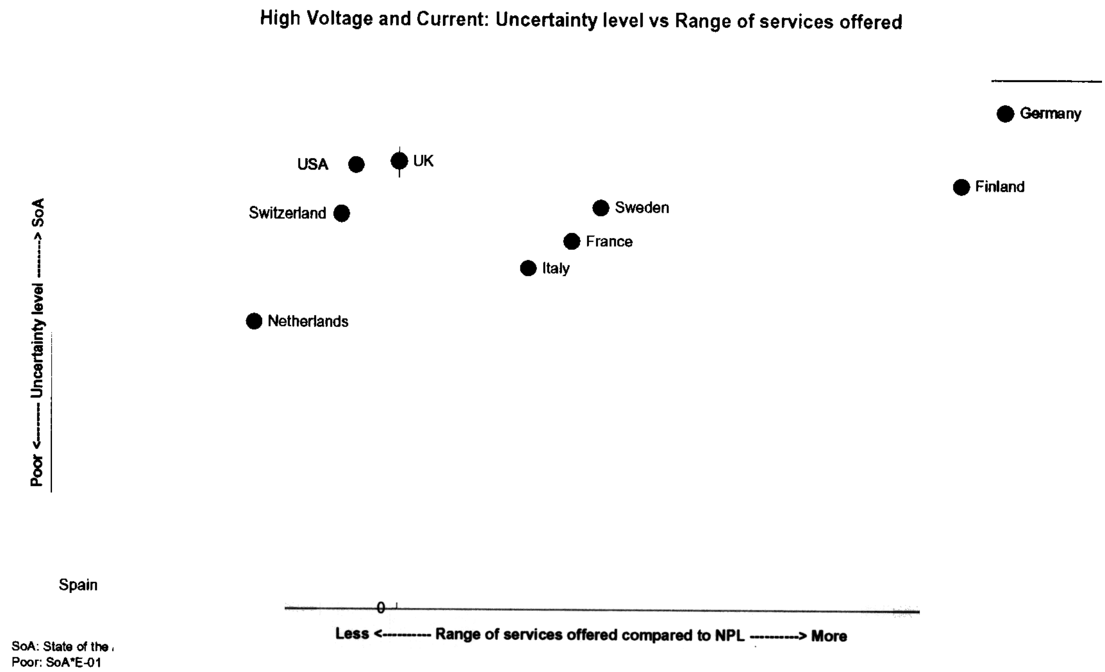


Figure 21: Sub-quantity graph, 'high voltage and current'

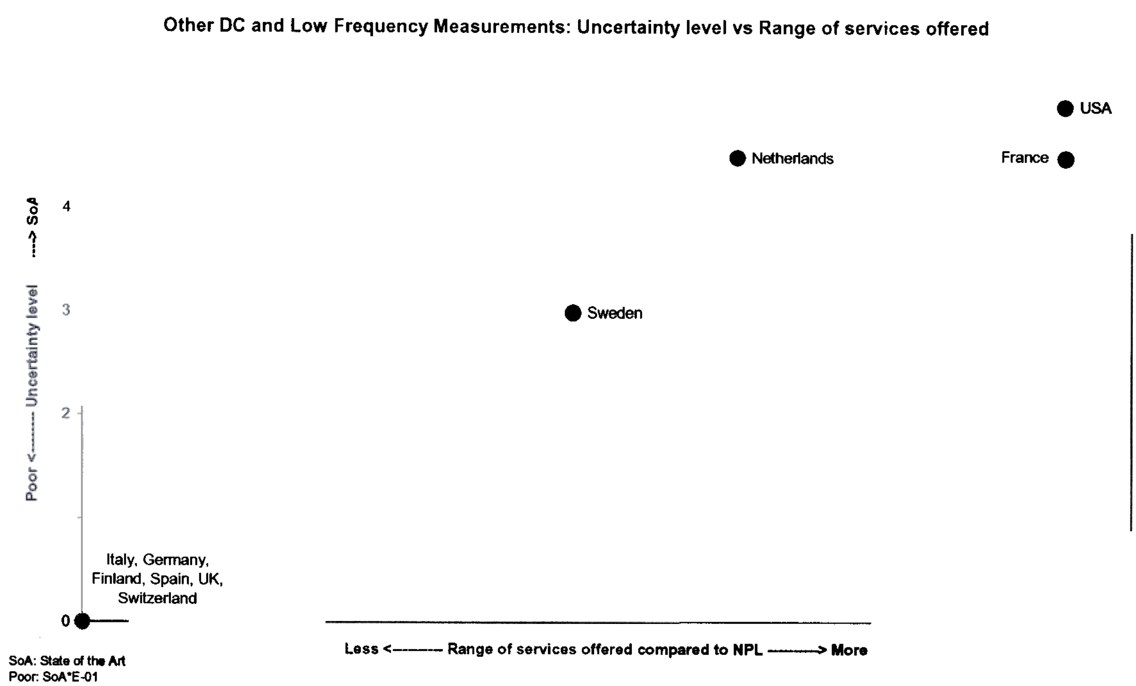


Figure 22: Sub-quantity graph, 'other DC and low frequency measurements'

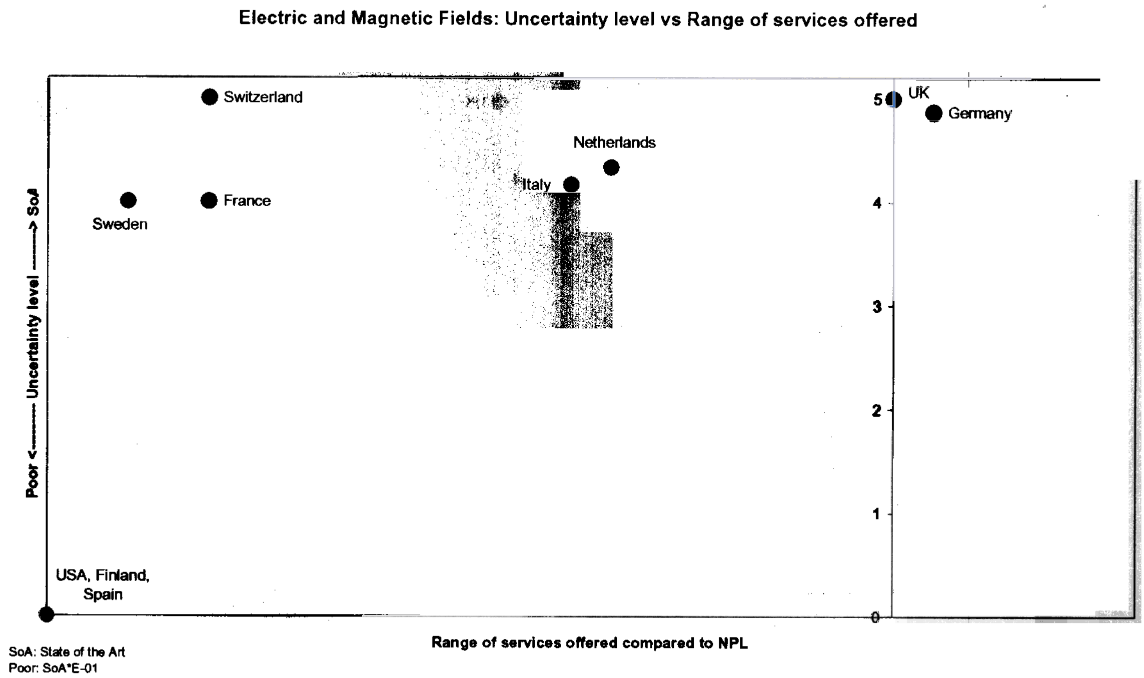


Figure 23: Sub-quantity graph, 'electric and magnetic fields'

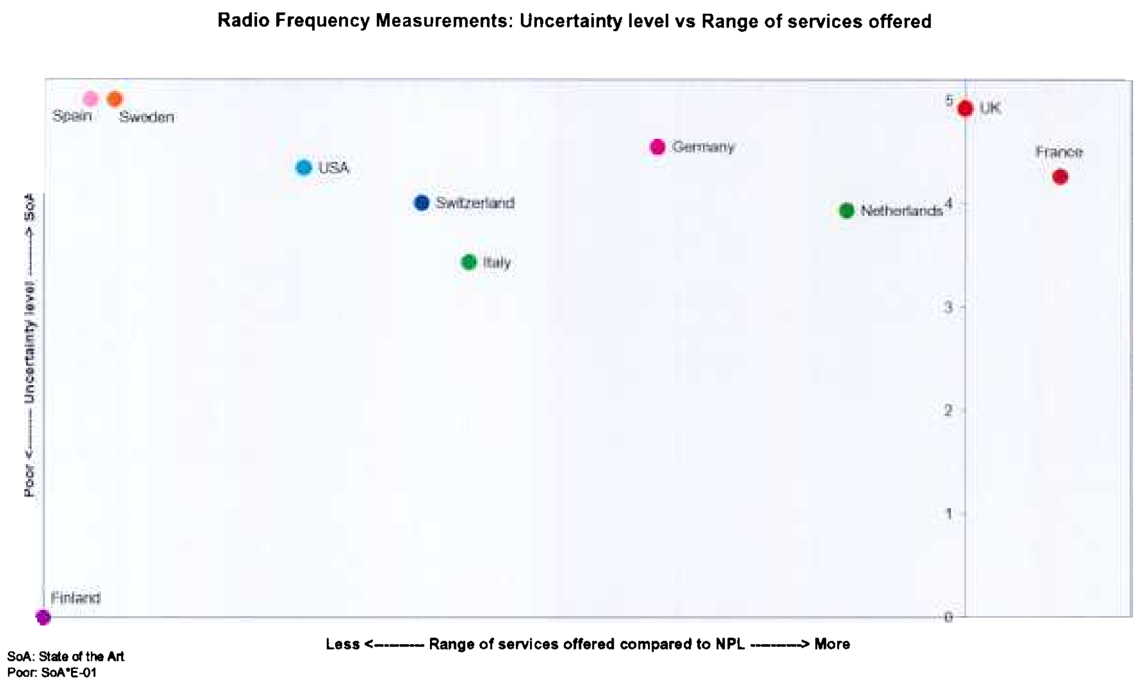


Figure 24: Sub-quantity graph, 'radio frequency measurements'

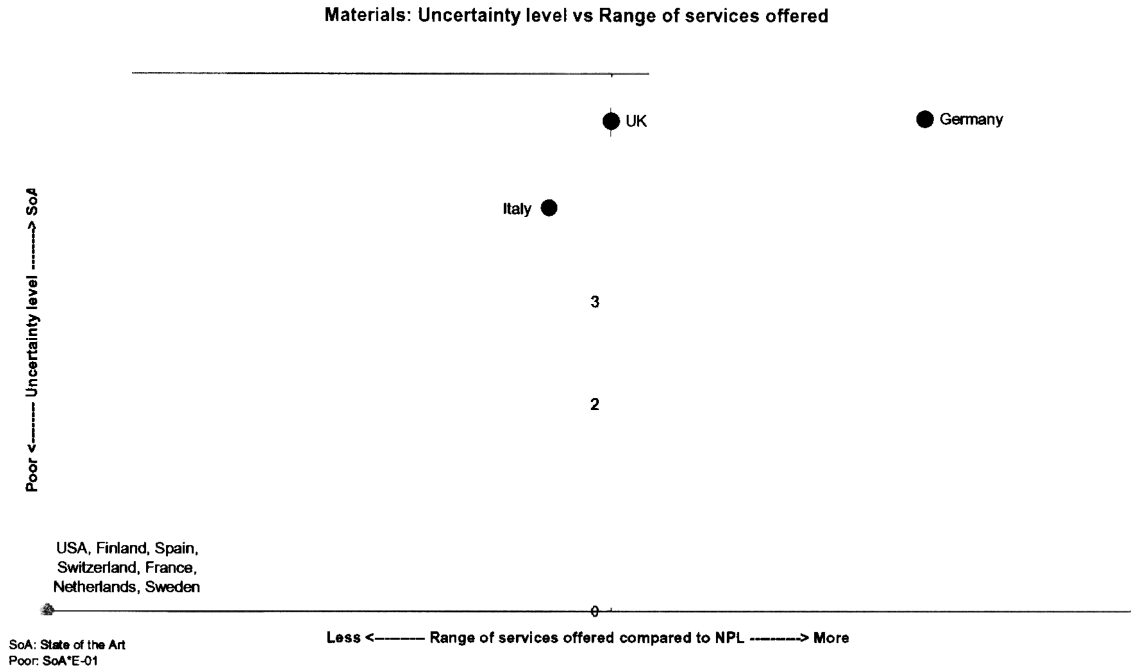


Figure 25: Sub-quantity graph, 'materials'

3.4 Flow

Status of the data: The data for flow were still under local RMO review and have not been benchmarked in this study. It should be noted that Flow is a separate field in EUROMET but is included in Mass and Related Quantities under BIPM.

3.5 Ionising Radiation

CMCs benchmarked for the following countries: UK, Denmark, France, Germany, Italy, Netherlands, Spain, Switzerland, Sweden.

Status of the data: The CMCs have been approved by EUROMET and are undergoing the review within the RMOs. No data for USA were available at the time of the benchmarking.

Traceability as declared in CMCs:

Table 7: Traceability arrangements for Ionising Radiation.

Takes traceability / Provides traceability	UK	Hungary	Finland	France	Germany	Italy	Switzerland	Sweden	Netherlands
UK			**M**		**O**			**F**	**H**
Hungary						**J**			
Finland									
France									
Germany			**L**					**E**	**G**
Italy									
Switzerland									
Sweden									
Netherlands									
USA	**B**				**N**	**I**			
BIPM			**K**				**A**	**D**	
Hungary						**J**			

- •A: **Activity per unit mass** (single nuclide solution) traceability from BIPM;
- •B: **Activity per unit mass** (single nuclide solution-low level) traceability from NIST;
- •C: **Activity per unit mass** (single nuclide solution-low level) traceability from LNHB;
- •D: **Air Kerma rate** (radiotherapy dosemeters, radiodiagnostics dosemeters, dosemeters), **Absorbed dose rate to water** (radiotherapy dosemeters), **ambient dose equivalent rate** (radioprotection on dosemeters), **directional dose equivalent rate** (radioprotection on dosemeters), **personal dose equivalent at 10 mm depth** (personal dosemeters), **personal dose equivalent at 0.07 mm depth** (personal dosemeters) traceability from BIPM;
- •E: **Air Kerma rate** (radiodiagnostics dosemeters) traceability from PTB;
- •F: **Absorbed dose rate to tissue** (dosemeters) traceability from NPLl;
- •G: **Absorbed dose rate to tissue** (Calibration of ionisation chambers) traceability from PTB;

- H: **Activity** (single nuclide solution) traceability from NPL;
- I: **Activity per unit mass** (single nuclide solution), Activity (gas source in glass bulb) traceability from NIST;
- J: **Activity per unit mass** (reference material) traceability from OMH;
- K: **Air Kerma** (radiotherapy dosemeters, radiodiagnostics dosemeters), **reference air Kerma rate** (radiotherapy well ionisation chambers, brachytherapy sources), **absorbed dose to water** (radiotherapy dosimeters), **absorbed dose to air inside the chamber** (plane parallel ionisation chambers) traceability from BIPM;
- L: **Air Kerma** (non-specific targets), **ambient dose equivalent rate** (radioprotection dosemeters), **directional dose equivalent rate** (radioprotection dosemeters), **personal dose equivalent at 0.07 mm depth** (personal dosemeters), **personal dose equivalent at 10 mm depth** (personal dosemeters traceability from PTB;
- M: **Ambient dose equivalent rate** (radioprotection dosemeters) traceability from NPL;
- N: **Activity** (reference material), **activity per unit mass** (reference material), **activity per unit volume** (reference material) traceability from NIST;
- O: **Fluence rate** (neutron sensitive device), **ambient dose equivalent rate** (neutron dosemeter), **personal dose equivalent rate** (neutron personal dosimeter) traceability from NPL.

Notes and observations: This category is characterised by the fact that NMIs are only able to declare uncertainties at around the 1% level due to the difficulty of the measurements. For example, the primary standard for air kerma is a free-air ionisation chamber, which requires the measurement of currents as low as 3 pA. Overall, Germany is the leading NMI in this activity with the UK placed in second position, offering slightly less coverage. The UK leads in 'neutron measurements' offering SoA services and widest coverage. In 'dosimetry' and 'radioactivity' the UK provides near SoA uncertainty but with other laboratories offering greater coverage. 'Dosimetry' is led by Germany whilst 'radioactivity' is led by both Germany and France. The UK NMI does not declare any CMCs in 'dosimetry' for 'ambient dose equivalent' and 'directional dose equivalent'. These factors are derived from the 'air kerma' primary standards by applying the conversion coefficients given in the appendix of ICRU Report 47 "Measurement of Dose Equivalents from External Photon and Electron Radiations". In the UK this conversion is done in the calibration laboratory. This is an illustration of the care that must be taken when using the benchmarking data conclusions. Although the CMCs vocabulary is arrived at by international consensus, not all countries provide solutions to their users' needs in the same way.

Quantity Graph:

Quantity Graph: Ionising Radiation, Uncertainty level vs Range of services offered

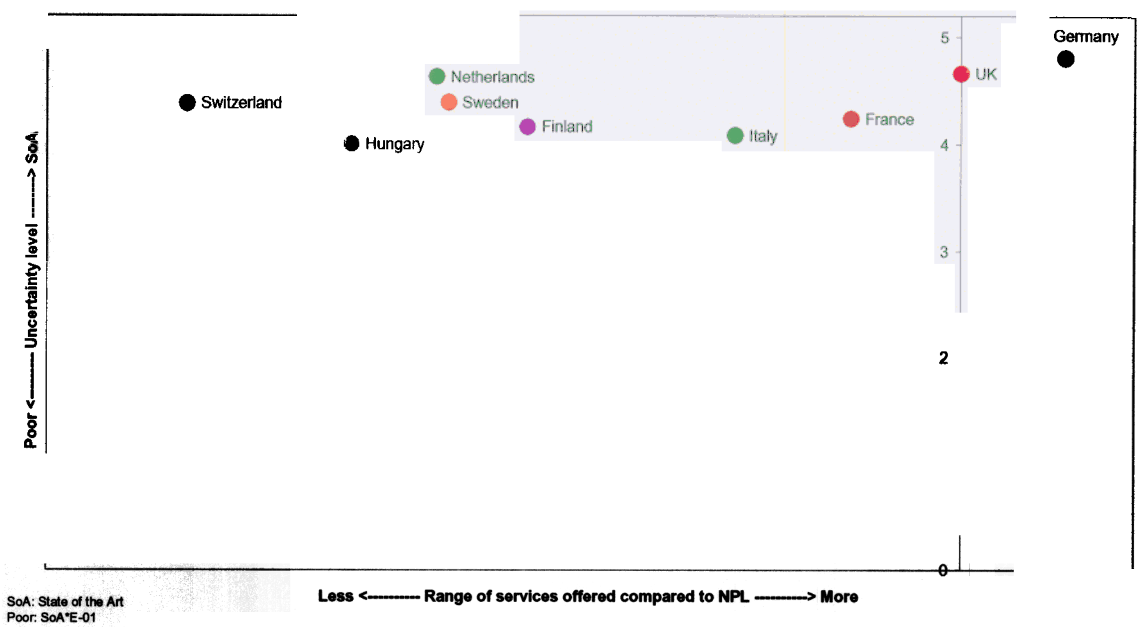


Figure 26: Quantity graph, Ionising Radiation

Sub-quantity Graphs:

Dosimetry: Uncertainty level vs Range of services offered

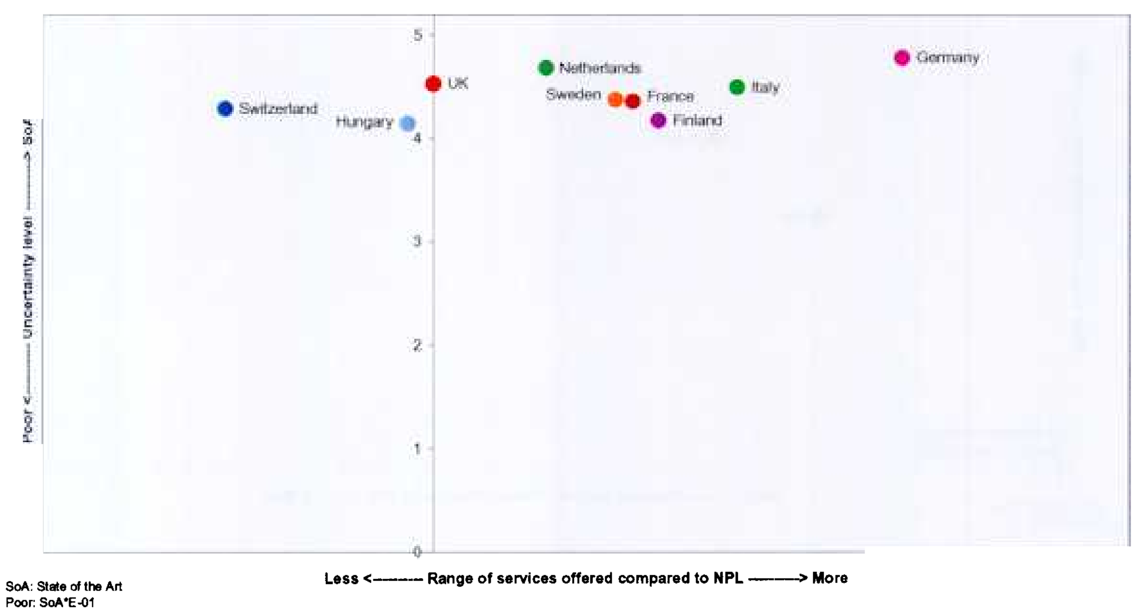


Figure 27: Sub-quantity graph, 'dosimetry'

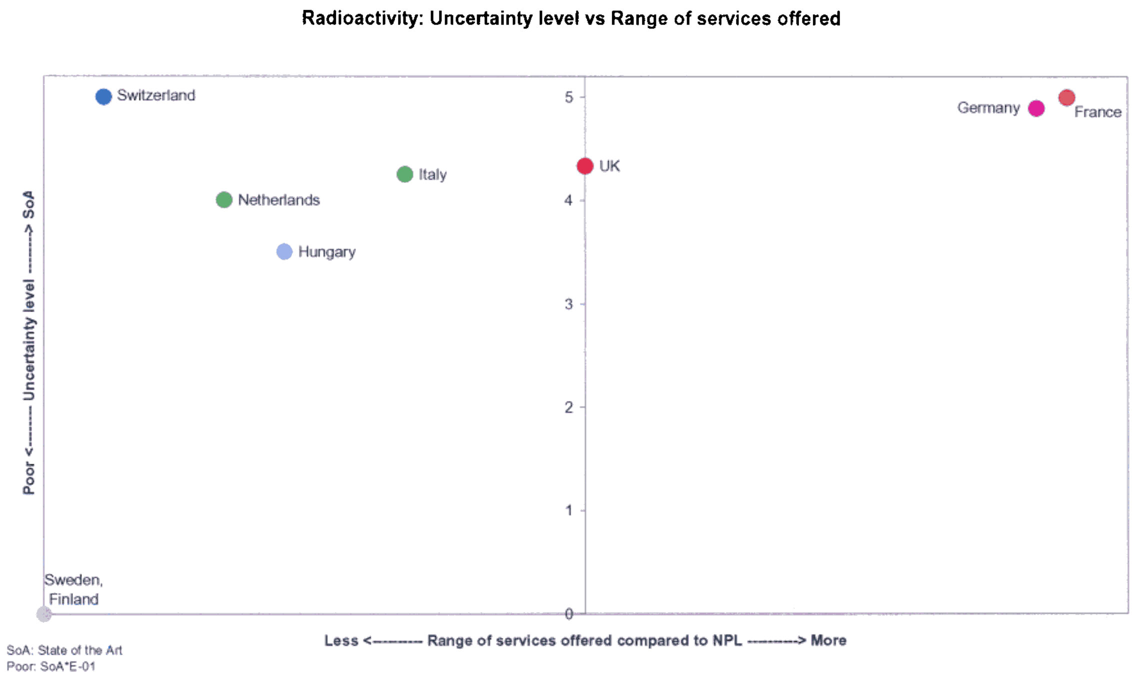


Figure 28: Sub-quantity graph, 'radioactivity'

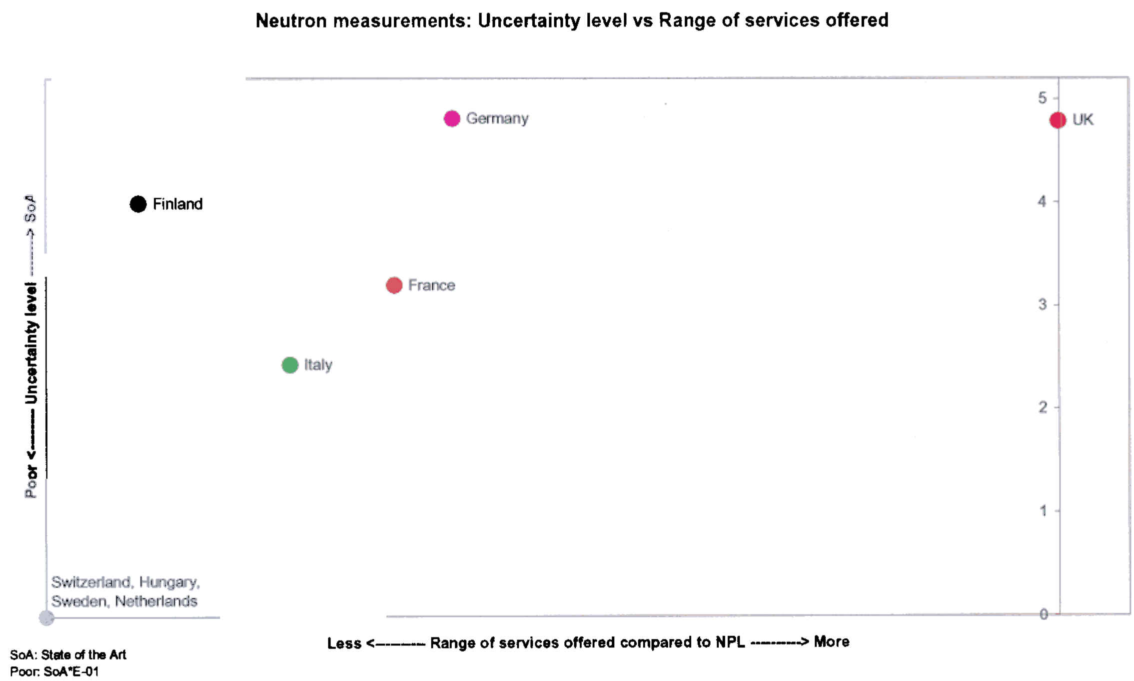


Figure 29: Sub-quantity graph, 'neutron measurements'

3.6 Length

CMCs benchmarked for the following countries: UK, Denmark, Finland, France, Germany, Italy, Netherlands, Spain, Switzerland, USA.

Status of the data: The data from the European NMIs have been agreed by the JCRB and are now on the BIPM database. The data from NIST have been agreed by SIM and some of them are still under discussion by other RMOs.

Traceability as declared in CMCs:

Table 8: Traceability arrangements for Length.

Provides Traceability \ Takes traceability	UK	Denmark	Finland	France	Germany	Italy	Netherlands	Spain	Switzerland	USA
UK										
Denmark										
Finland										
France										
Germany		**E**	**A**					**B**		
Italy										
Netherlands										
Spain										
Switzerland										
USA								**C**		
ZEISS		**D**								

- A: **Surface texture** (depth standard, roughness standard) traceability from PTB;
- B: **Roundness standards** (external cylinder, hemisphere, magnification standards), **Straightness standards** (cylindrical straightness standard, internal cylinder, external cylinder) traceability from PTB;
- C: **Surface texture** (groove or step height standard) traceability from NIST;
- D: **CMM artefacts** (ball/hole plate, CMM) traceability from ZEISS;
- E: **Surface texture** (depth standard, roughness standard) traceability from PTB.

Notes and observations: Length is an example of a mature or 'well established', 'classical' measurement field. This is illustrated on the quantity graph where all the benchmarked laboratories are able to offer a similar level of performance. For measurement of dimensions of material artefacts, improvement of the performance level is limited by the temperature control facilities available at the laboratories (the closer the temperature is to 20°C, the better the uncertainty) and by the quality of the artefact under test. There is also a limitation due to imprecise knowledge of coefficients of thermal expansion of customer-supplied artefacts, which has a large impact on the achievable uncertainty. The spread in the coverage is mainly due to the fact that there are different needs in the different countries, for example NMIs in countries with few accredited laboratories will offer a wide range of services, on the other hand the UK NMI only offers top-level services, having devolved the lower level, routine services to UKAS accredited laboratories. The UK offers the widest coverage in 'radiation of the mise en pratique' with a number of NMIs offering similar levels of uncertainty. For 'various dimensional' the UK, USA, Germany and Finland all offer SoA services. In other sub-quantities, the UK offers SoA or near SoA services but usually with other NMIs providing a wider range of services. In many cases, the UK is able to offer the same services as listed in the CMC tables of other laboratories, but because the demand for such services is low (it being satisfied by the UKAS accredited laboratories), the services are not classed as 'routine' and so do not feature in CMC tables or lists of routine services.

Quantity Graph:

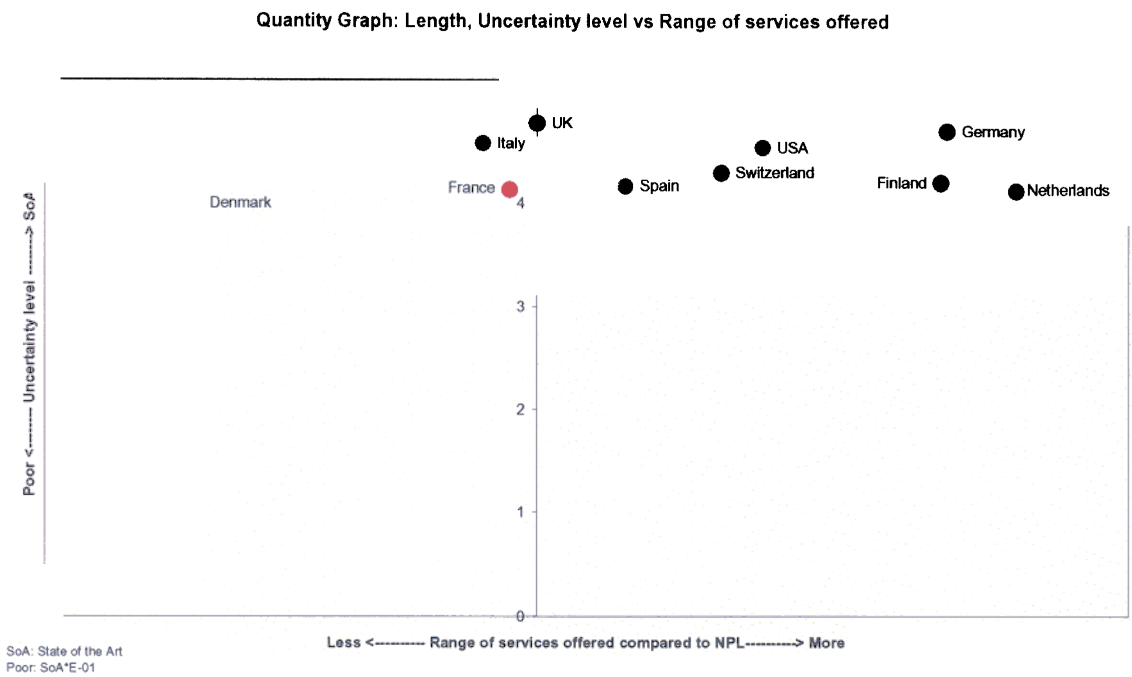


Figure 30: Quantity graph, Length

Sub-quantity Graphs:

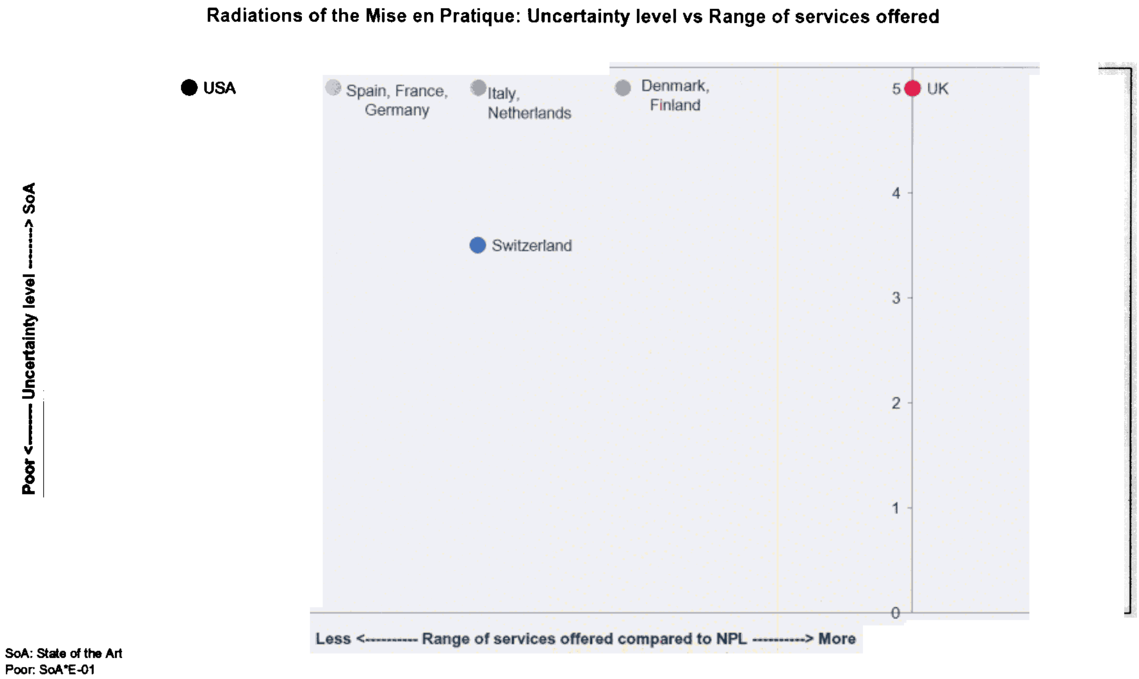


Figure 31: Sub-quantity graph, 'radiations of the Mise en Pratique'

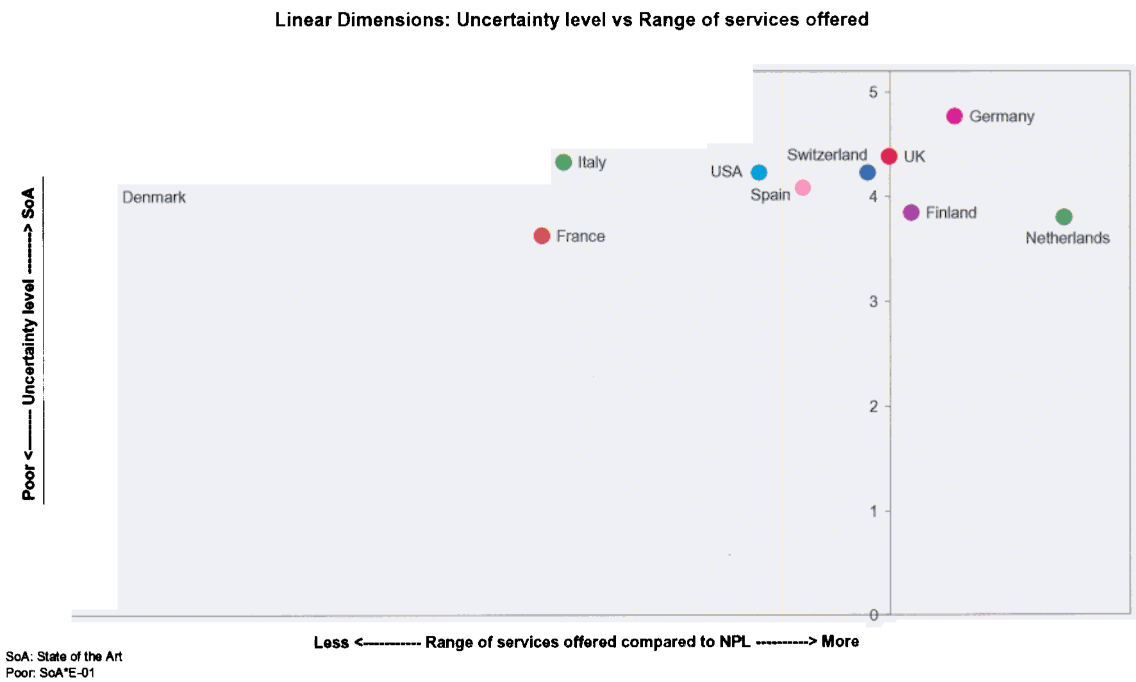


Figure 32: Sub-quantity graph: 'linear dimensions'

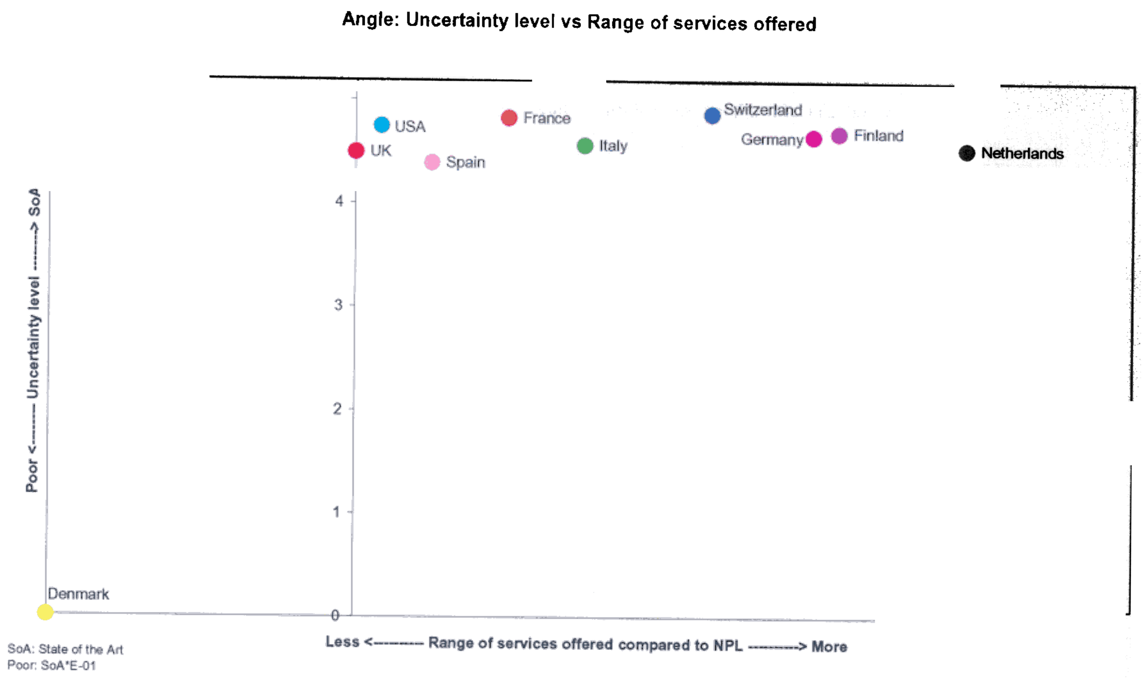


Figure 33: Sub-quantity graph, 'angle'

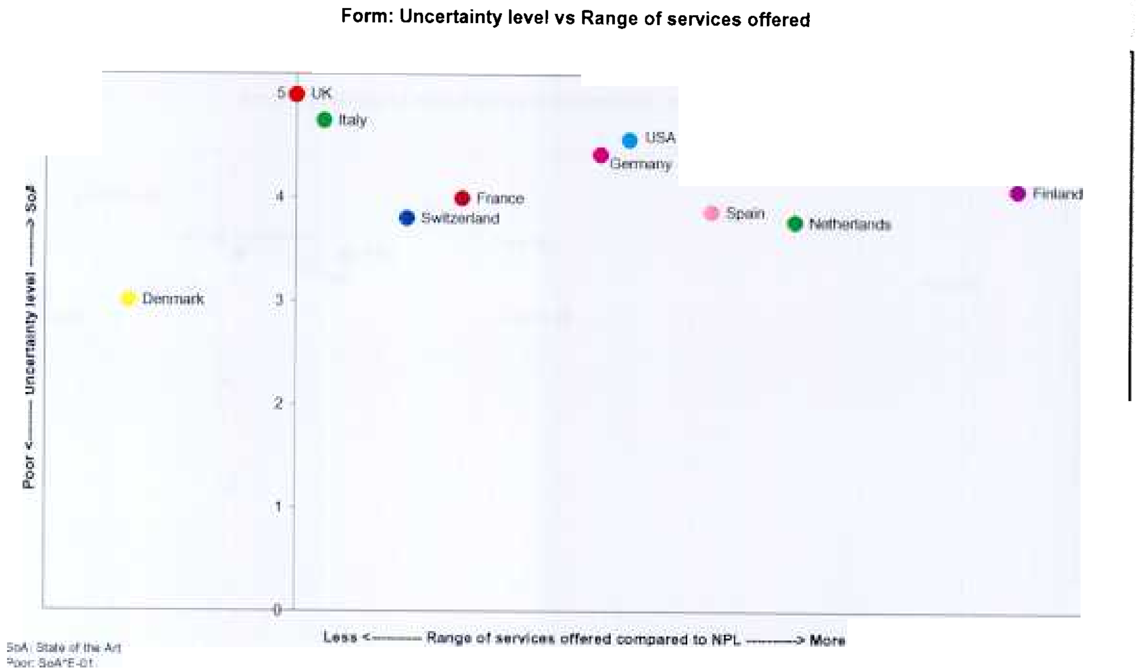


Figure 34: Sub-quantity graph, 'form'

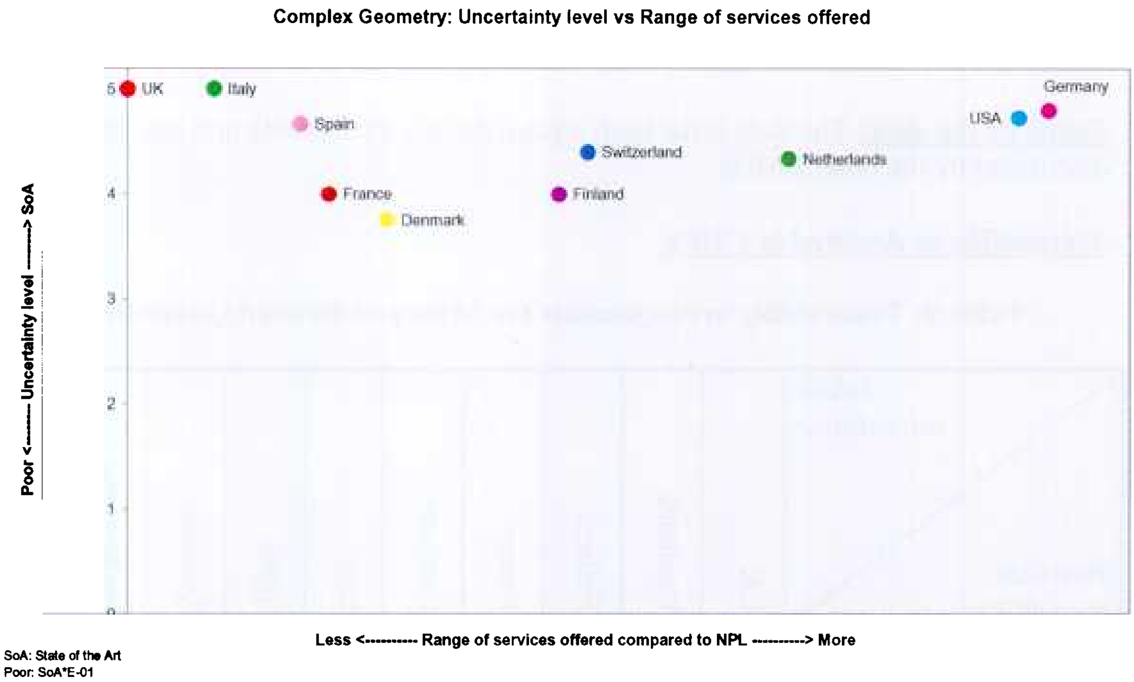


Figure 35: Sub-quantity graph, 'complex geometry'

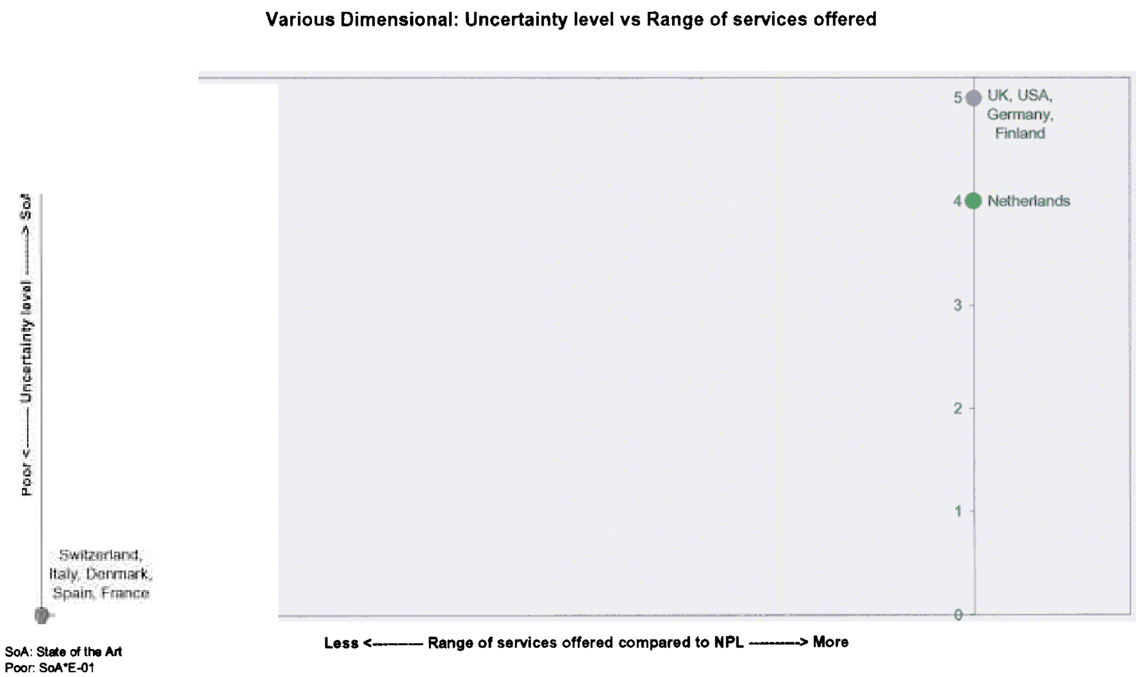


Figure 36: Sub-quantity graph, 'various dimensional'

3.7 Mass and Related Quantities

CMCs benchmarked for the following countries: UK, Denmark, Finland, France, Germany, Italy, Spain, Sweden, Switzerland, USA.

Status of the data: The data have been agreed by the local RMO and are still under discussion by the other RMOs.

Traceability as declared in CMCs:

Table 9: Traceability arrangements for Mass and Related Quantities.

Provides traceability \ Takes traceability	UK	Denmark	Finland	France	Germany	Italy	Spain	Sweden	Switzerland	USA
UK							L	A		
Denmark										
Finland										
France			B				M	C	D	
Germany		E	F			G	K	H		N
Italy									I	
Spain										
Sweden										
Switzerland										
USA										
MKS			P							

- A: **Pressure** (absolute pressure) traceability from NPL;
- B: **Pressure** (absolute pressure, gauge pressure) traceability from BNM-LNE;
- C: **Pressure** (gauge pressure) traceability from BNM;
- D: **Pressure** (absolute pressure, gauge pressure, differential pressure) traceability from BNM-LNE;
- E: **Force** (compression, tension), **pressure** (absolute pressure, gauge pressure, differential pressure) traceability from PTB;
- F: **Force** (tension and compression, Force measuring device), **torque** traceability from PTB;
- G: **Force** (compression) traceability from PTB;
- H: **Force** (tension & compression, compression) traceability from PTB;
- I: **Volume (solid), density** (solid) traceability from IMGC;
- K: **Volume** (solid), **force** (tension & compression), **pressure** (gauge pressure) traceability from PTB;
- L: **Pressure** (absolute pressure, gauge pressure) traceability from NPL;
- M: **Pressure** (absolute pressure, gauge pressure) traceability from BNM-LNE;
- N: **Hardness** traceability from PTB;

•P: **Pressure** (absolute pressure) traceability from MKS.

Notes and observations: Overall a cluster of 4 countries, Germany, France, Italy and USA (in this order) are the leading NMIs in this quantity in terms of coverage and uncertainty. The UK offers SoA uncertainty but less coverage. One explanation for the overall score for remaining countries is that the group takes traceability for at least some of the services from the leading NMIs and therefore their uncertainty budgets include additional transfer uncertainties. In addition, the inherent performance of equipment used for primary realisations is generally better than the performance of the standards used for secondary realisations. The UK NMI does not offer 'viscosity' (led by Germany, with France offering slightly less coverage), and 'gravity' (led by Switzerland) but is amongst the leaders (France, USA, Germany) in 'pressure'. The UK does not offer 'torque' (led by Germany) and 'hardness' (led by the USA), but is in the process of setting up some capabilities in these two areas. The UK and Germany are in second position in terms of coverage for 'mass' where USA is the leading NMI. In the case of 'force', some services can be entered a single line or as two different lines (depending on the uncertainty) and this can lead to a minor anomaly in the benchmarking coverage, which includes a factor related to the number of lines.

Quantity Graph:

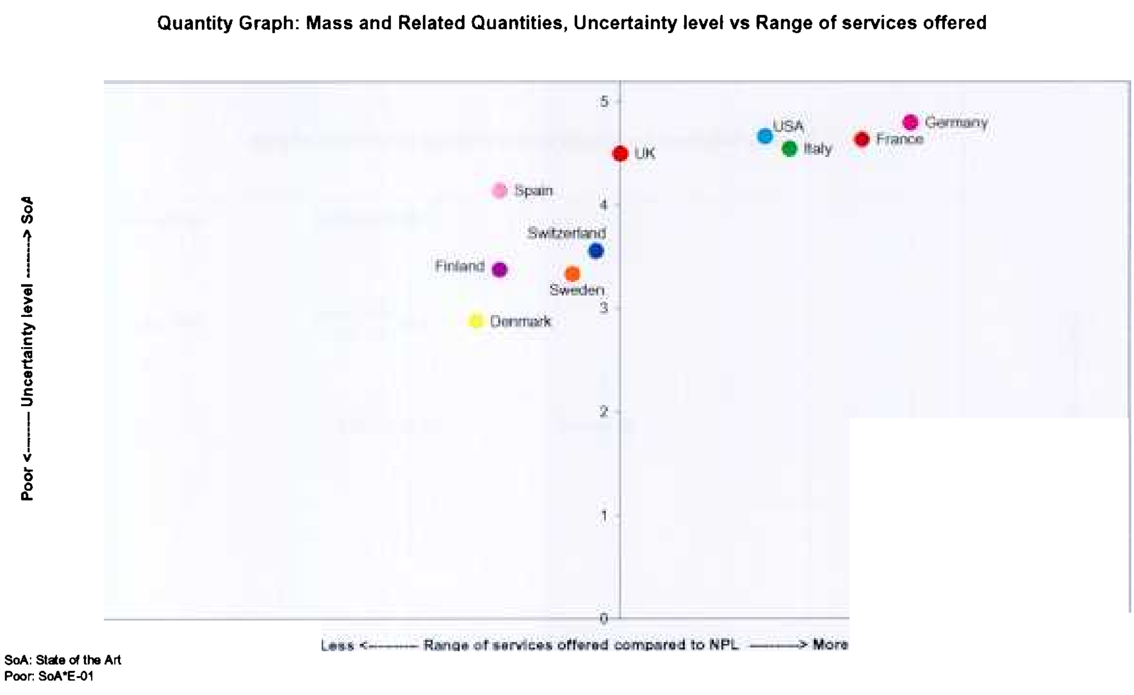


Figure 37: Quantity graph, Mass and Related Quantities

Sub-quantity Graphs:

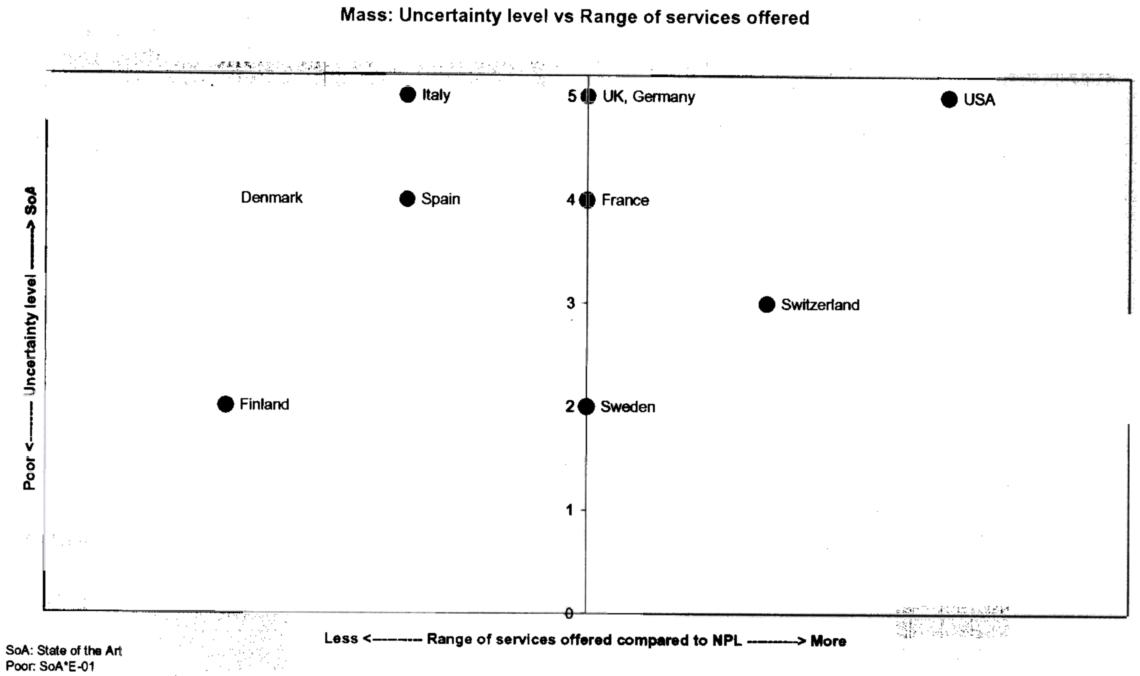


Figure 38: Sub-quantity graph, 'mass'

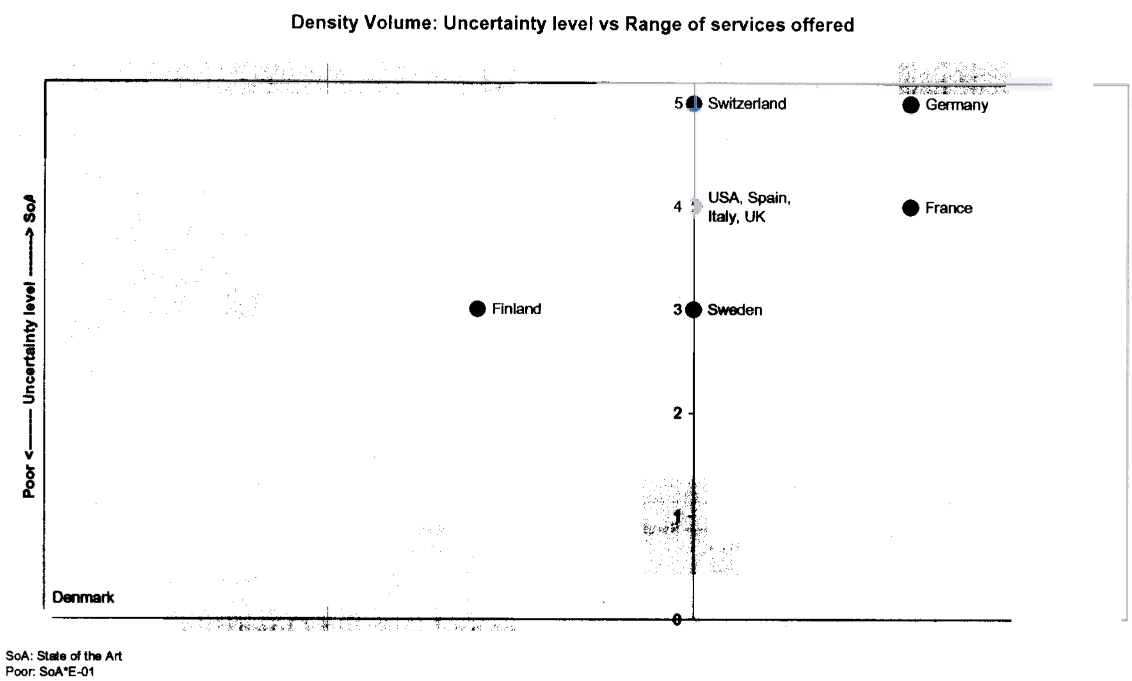


Figure 39: Sub-quantity graph, 'density volume'

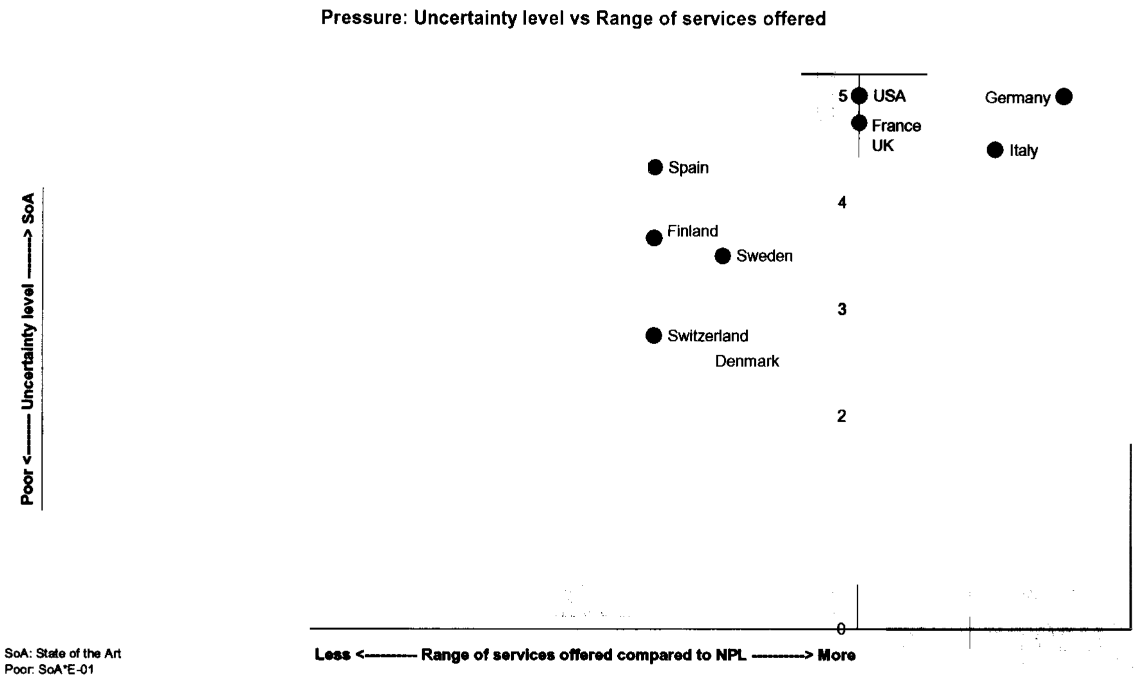


Figure 40: Sub-quantity graph, 'pressure'

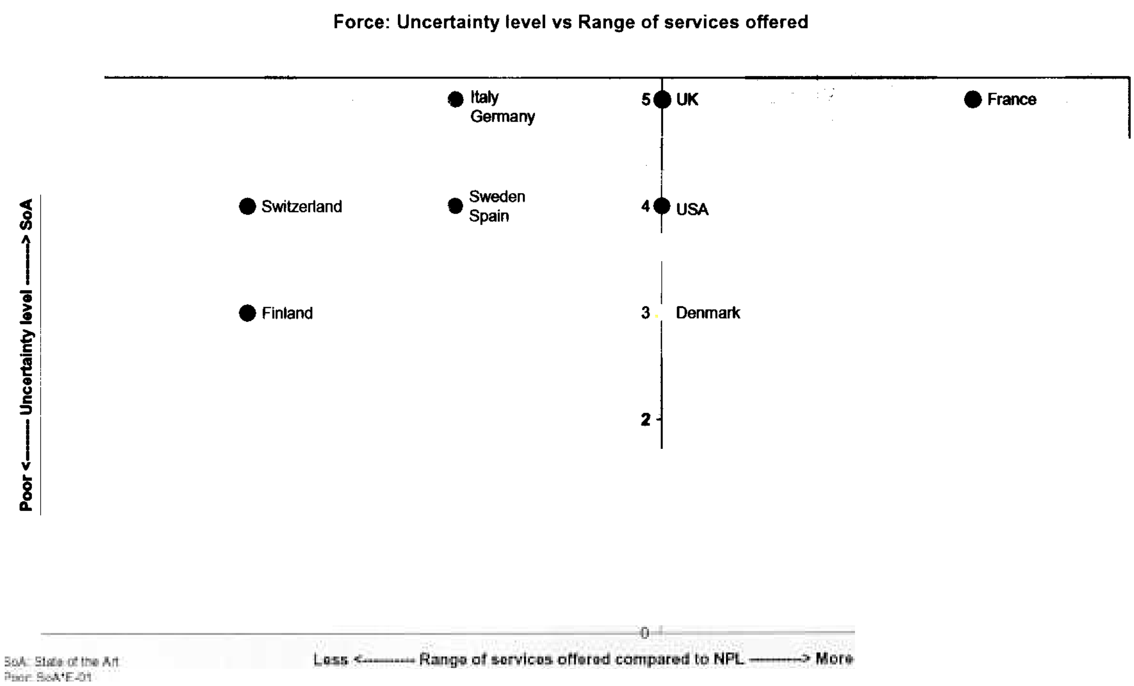


Figure 41: Sub-quantity graph, 'force'

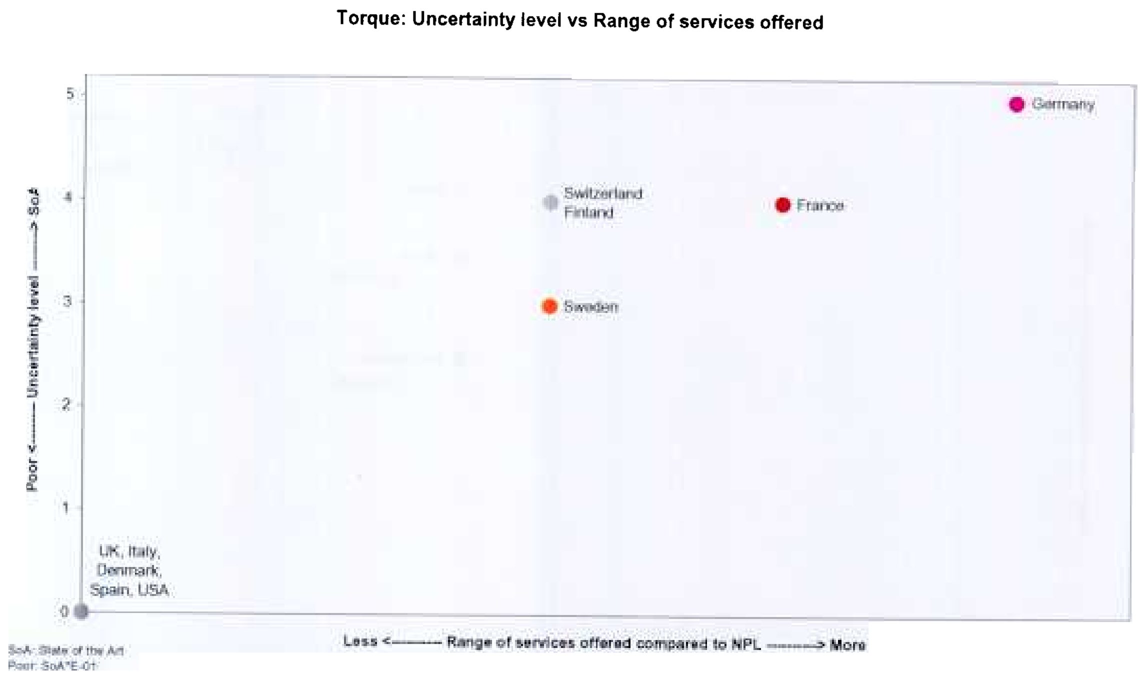


Figure 42: Sub-quantity graph, 'torque'

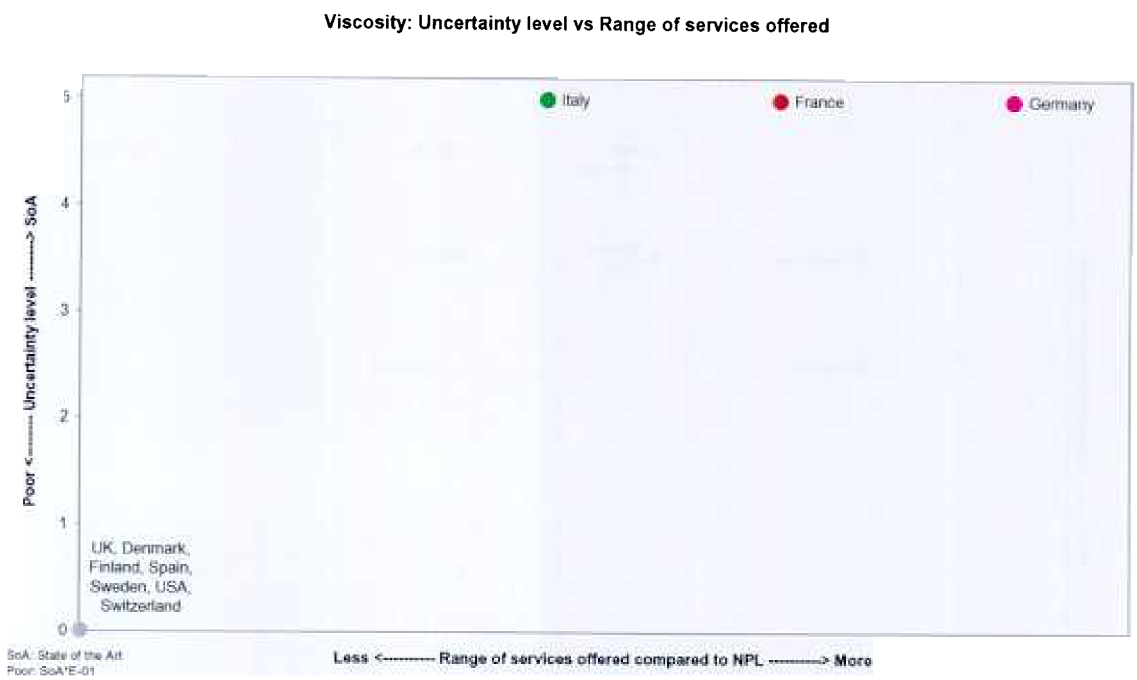


Figure 43: Sub-quantity graph, 'viscosity'

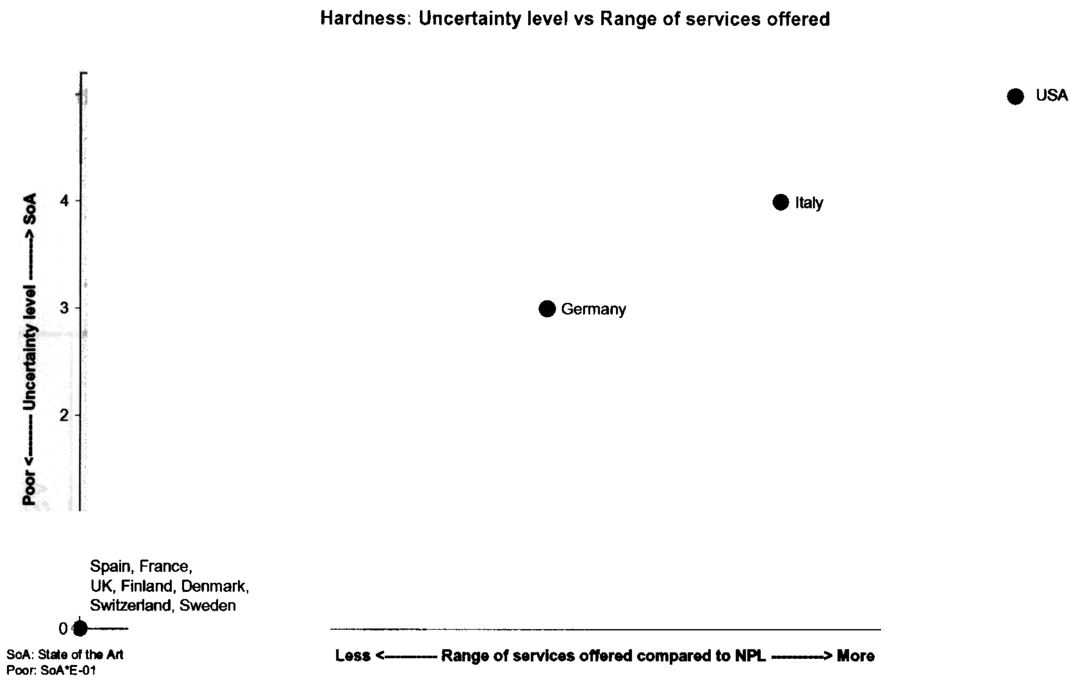


Figure 44: Sub-quantity graph, 'hardness'

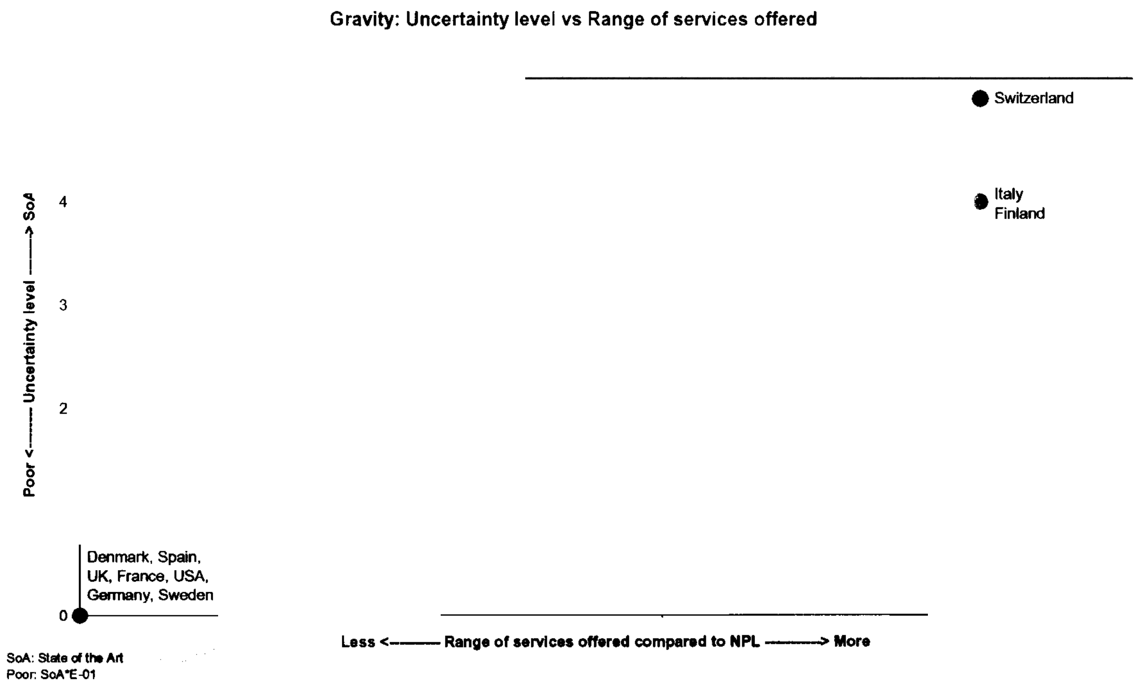


Figure 45: Sub-quantity graph, 'gravity'

3.8 Photometry and Radiometry

CMCs benchmarked for the following countries: UK, Denmark, Finland, France, Germany, Hungary, Italy, Spain, Sweden, Switzerland, USA.

Status of the data: The data have been agreed by the RMOs and the JCRB and are now available on the KCDB.

Traceability as declared in CMCs:

Table 10: Traceability arrangements for Photometry and Radiometry.

Provides Traceability \ Takes traceability	UK	Denmark	Finland	France	Germany	Hungary	Italy	Spain	Sweden	Switzerland	USA
UK										**C**	
Denmark											
Finland											
France											
Germany	**G**		**A**				**I**				
Hungary											
Italy											
Spain											
Sweden											
Switzerland											
USA						**E**					
Canada	**H**		**B**								
BIPM						**F**			**D**		

- A: **Spectral Properties of Materials** (Reflectance, diffuse, spectral) traceability from PTB;
- B: **Spectral Properties of Materials** (Reflectance, diffuse, spectral) traceability from NRC;
- C: **Properties of detectors** (Responsivity, laser, power; Responsivity, spectral, power), **spectral emission properties of sources** (Irradiance, spectral), **fibre optics** (Responsivity) traceability from NPL;
- D: **Photometry** (luminous intensity; luminous flux; luminance; illuminance responsivity) traceability from BIPM;
- E: **Properties of detectors** (responsivity, laser, power); **spectral emission properties of sources** (irradiance spectral) traceability from NIST;
- F: Photometry (luminous flux) traceability from BIPM;
- G: **Colour and other spectrally-integrated measurements of materials** (Colour, surface, x,y,Y; Colour , surface, lab) traceability from PTB;

- H: **Colour and other spectrally-integrated measurements of materials** (Colour, surface, x,y,Y; Colour , surface, lab) traceability from NRC;
- I: **Spectral properties of materials** (reflectance, diffuse, spectral) traceability from PTB.

Notes and observations: This quantity shows a spread in the uncertainty level with some laboratories offering a significantly lower performance level than the leading NMIs. Several of these laboratories are setting up their own independent scales and, with time, their performance level should get nearer to SoA although the coverage might remain broadly unchanged, as these laboratories would tend to focus on a limited range of services. Measurements in this area are technically challenging and it takes significant length of time to build up expertise. Overall, the UK offers SoA services and the widest coverage, and is the leading NMI for 'properties of detectors and sources' and 'properties of materials'. USA and Germany are the leading NMIs in terms of range of services and performance level in 'fibre optics' and 'photometry' respectively. However it should be noted that for this quantity it has been agreed that data will be submitted in several phases, concentrating on services closely linked to key comparisons in the early phases. This means that only around 50% of the total number of services have so far been entered into the database and consequently, particularly in areas such as fibre optics which are well removed from key comparison quantities, it is probable that there will be some small changes in the relative positions between NMIs into the future. Furthermore, some countries have only submitted data to cover the most important ranges within a given service, whereas some others have declared data for all possible ranges for each service. This means that the coverage for certain countries (including the UK) might appear lower than it really is.

In addition, differences in the approach to establishing acceptable uncertainties within the MRA have been identified at inter-regional level. Within EUROMET the approach has been that measurement uncertainties for base scales must be supported by comparison data and that capabilities for other services must be compatible with the base scale uncertainties. Thus, although several EUROMET NMIs, including NPL, have been working to improve base scale uncertainties, these will not be entered into the database until key comparisons currently underway have been completed. The other regions have taken a different approach and SIM in particular have argued that improved uncertainties do not need such supporting evidence a priori. The result is that some EUROMET NMIs, are actually closer to SoA for some services than is currently indicated. Discussions are underway with the aim of agreeing a more uniform approach between regions, which, it is hoped, will remove such anomalies.

Quantity Graph:

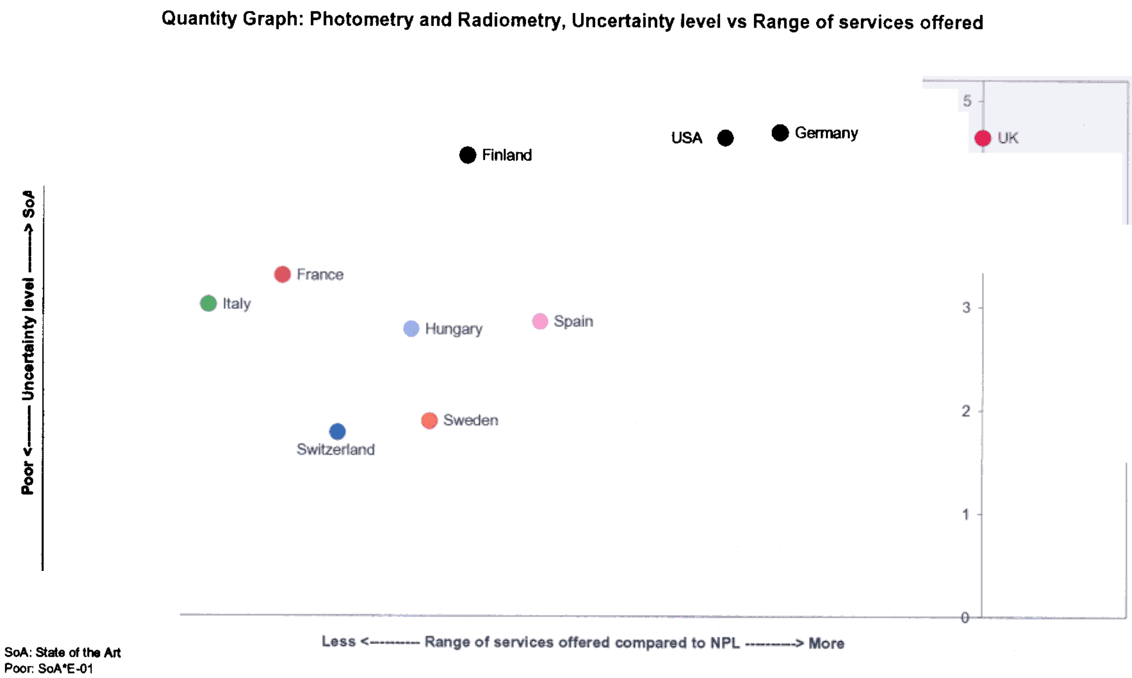


Figure 46: Quantity graph, Photometry and Radiometry

Sub-quantity Graphs:

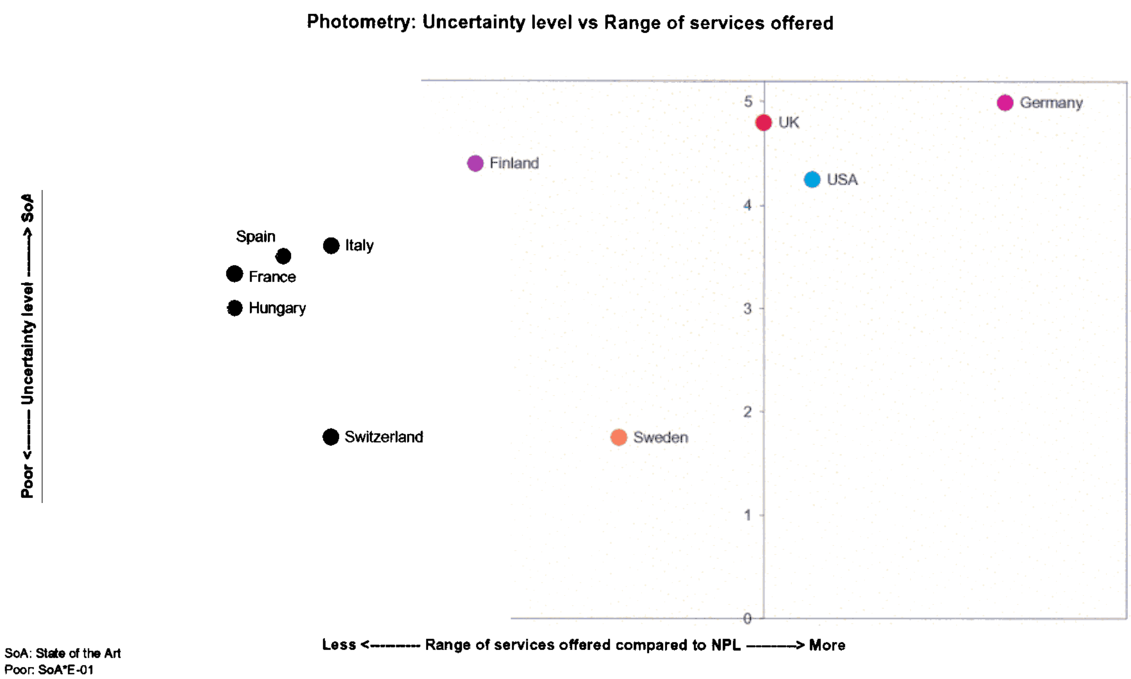


Figure 47: Sub-quantity graph, 'photometry'

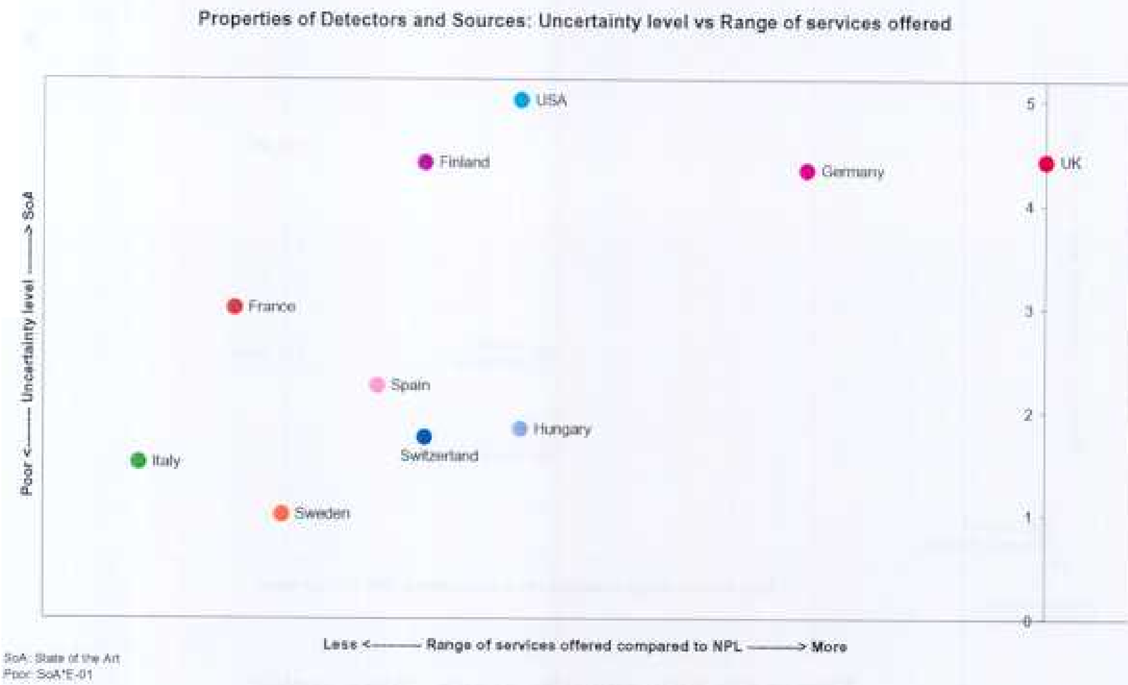


Figure 48: Sub-quantity graph, 'properties of detectors and sources'

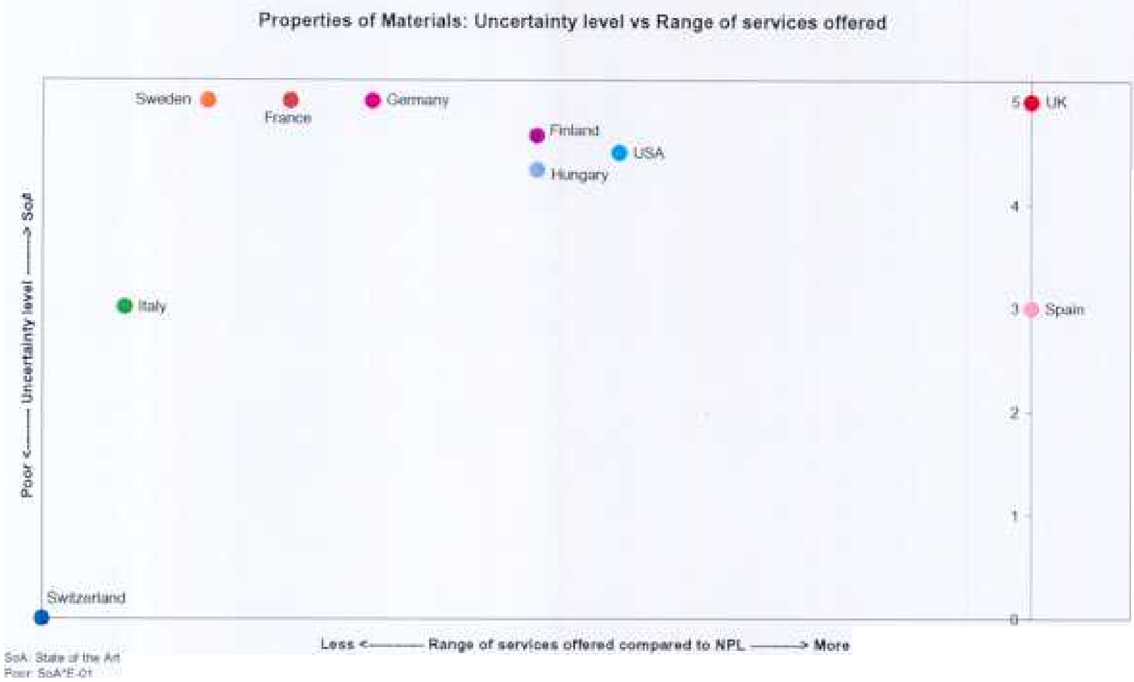


Figure 49: Sub-quantity graph, 'properties of materials'

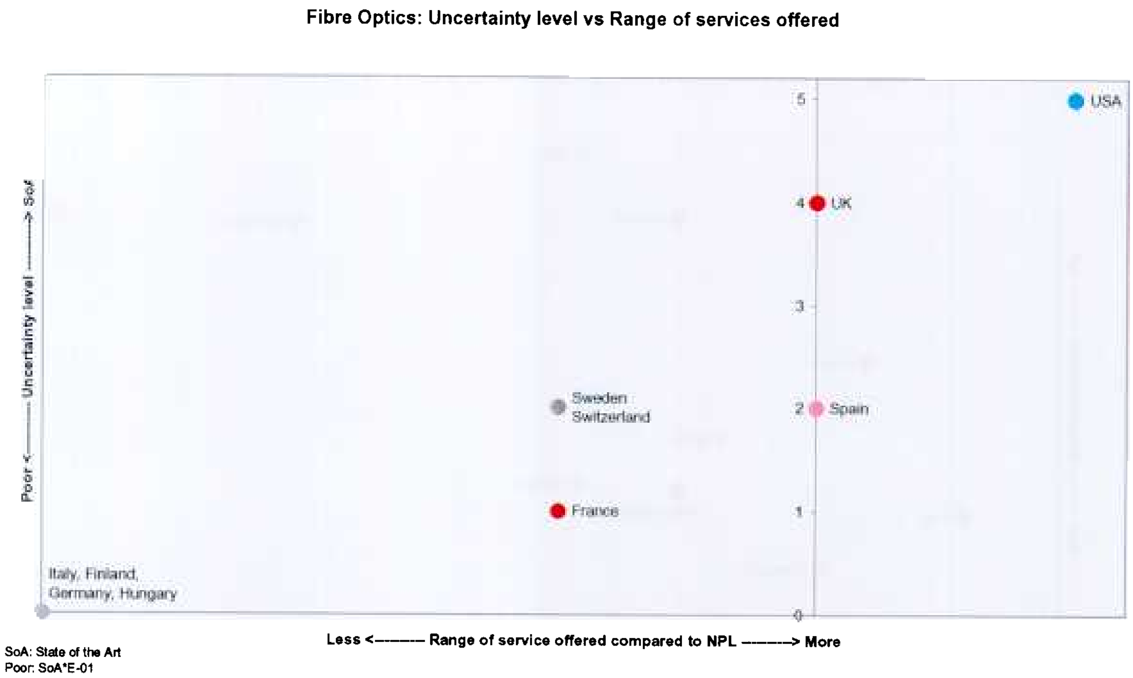


Figure 50: Sub-quantity graph, 'fibre optics'

3.9 Thermometry

CMCs benchmarked for the following countries: UK, Finland, France, Germany, Italy, Netherlands, Poland, Sweden, Switzerland, USA.

Status of the data: The data have been agreed by the local RMOs and are now undergoing a review by other RMOs.

Traceability as declared in CMCs:

Table 11: Traceability arrangements for Thermometry.

Takes traceability → / Provides traceability ↓	UK	Finland	France	Germany	Italy	Netherlands	Poland	Sweden	Switzerland	USA
UK			C						A	
Finland										
France										
Germany									B	
Italy										
Netherlands										
Poland										
Sweden		D								
Switzerland										
USA										

- A: **Thermocouples** (Noble-metal thermocouples) traceability from NPL;
- B: **Thermocouples** (Noble-metal thermocouples) traceability from PTB;
- C: **Standard platinum resistance thermometers** (Capsule-type SPRTs) traceability from NPL;
- D: **Thermocouples** (Noble-metal thermocouples) traceability from SP.

Notes and observations: In this quantity CMCs are still under review within the RMOs, and the plots should be treated with caution. In addition, the CMCs have not been developed for the full range of services within EUROMET and this leads to some distortion when comparisons are made with the USA which has declared a broader scope of CMCs, especially with respect to 'ITS-90 approximations', or secondary-level services. However, some services are missing in the USA list, for example in humidity, although NIST is known to provide the services. Generally, the USA CMCs carry smaller uncertainties than other countries, and consequently it is placed in the top right of the overall summary. Within Europe those laboratories, which have taken part in CCT key comparisons, are able to quote smaller uncertainties than those which have not. Together with Germany, the UK offers near SoA and widest coverage in 'ITS-90 realisation'.

Quantity Graph:

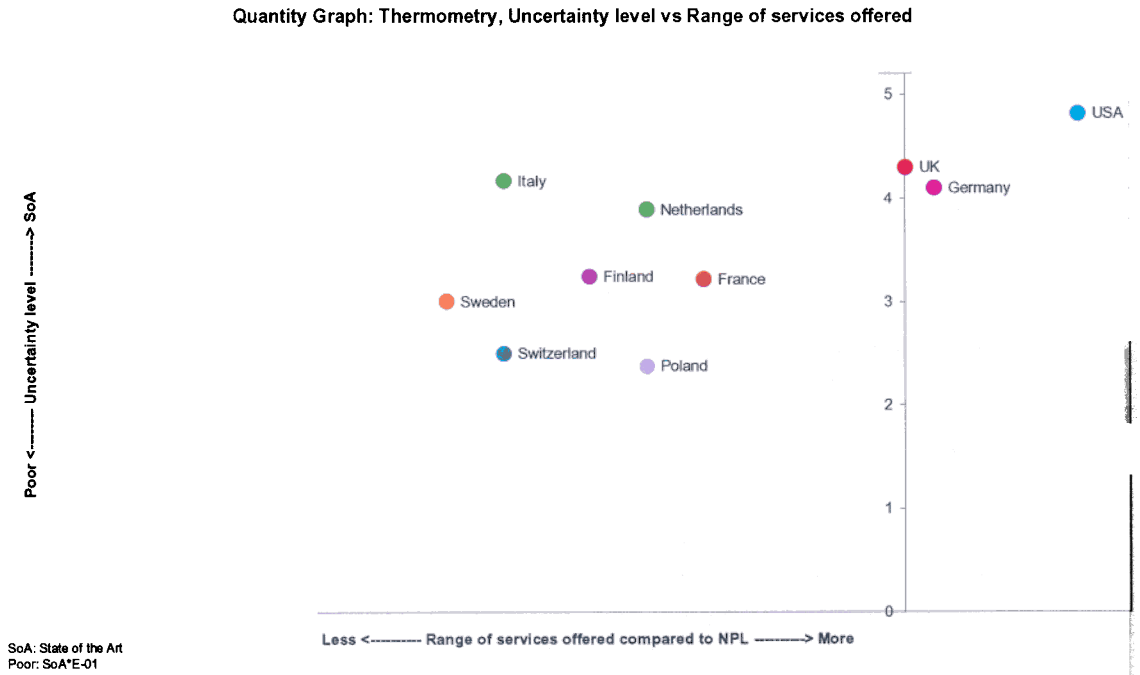


Figure 51: Quantity graph, Thermometry

Sub-quantity Graphs

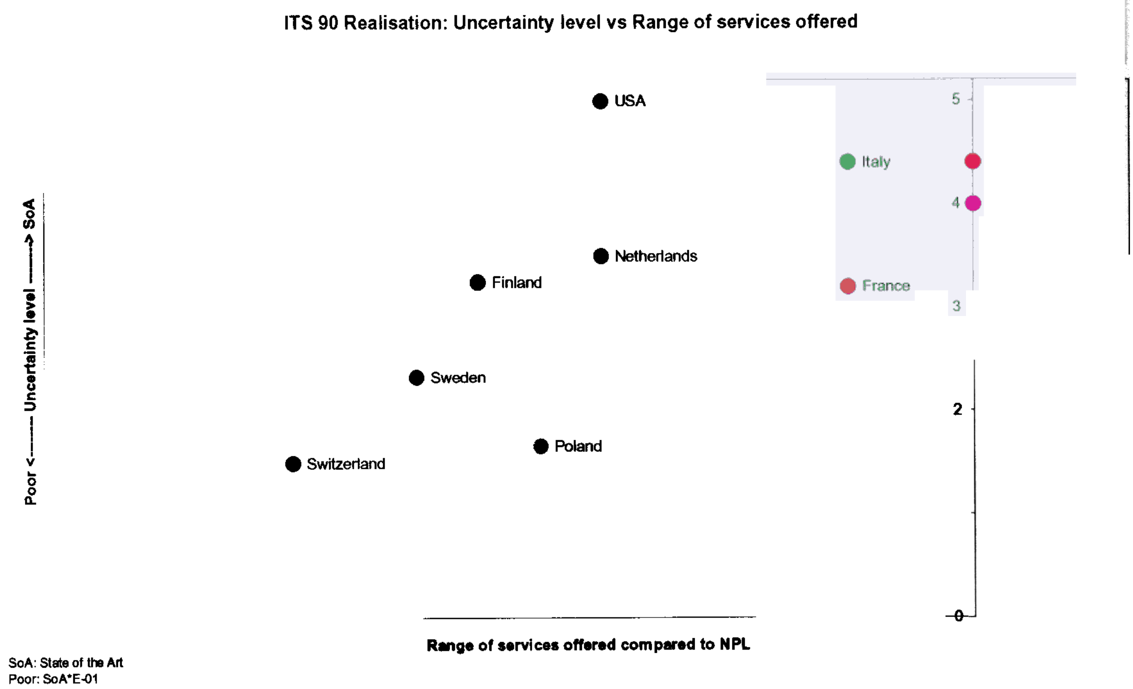


Figure 52: Sub-quantity graph, 'ITS 90 realisation'

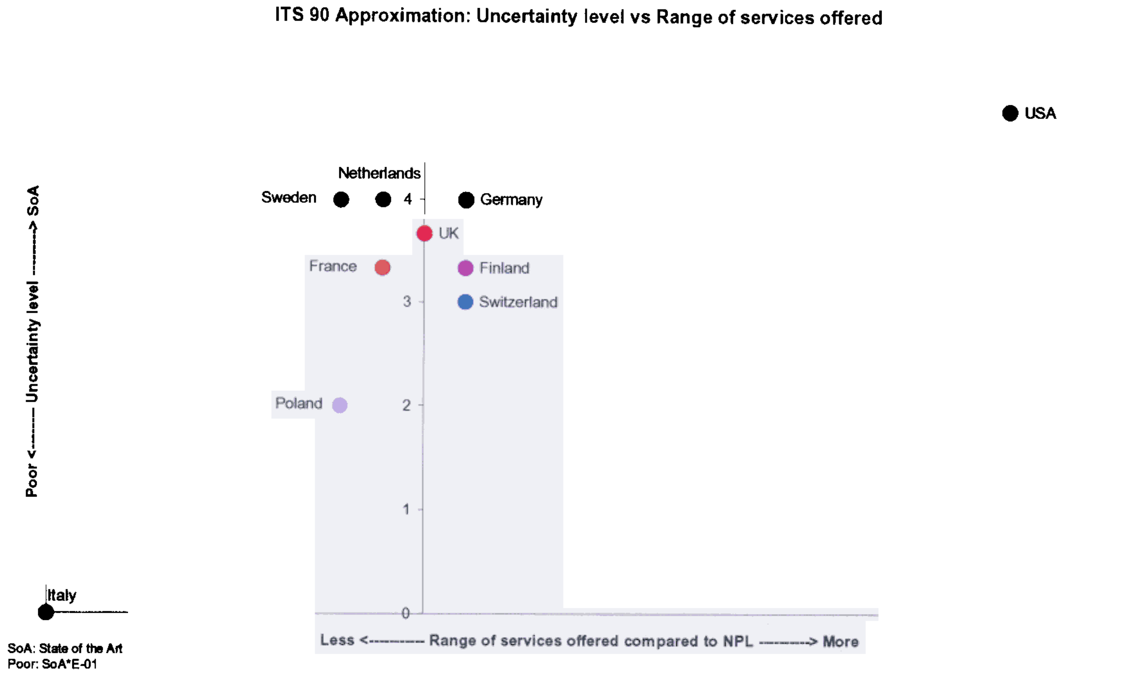


Figure 53: Sub-quantity graph, 'ITS 90 approximation'

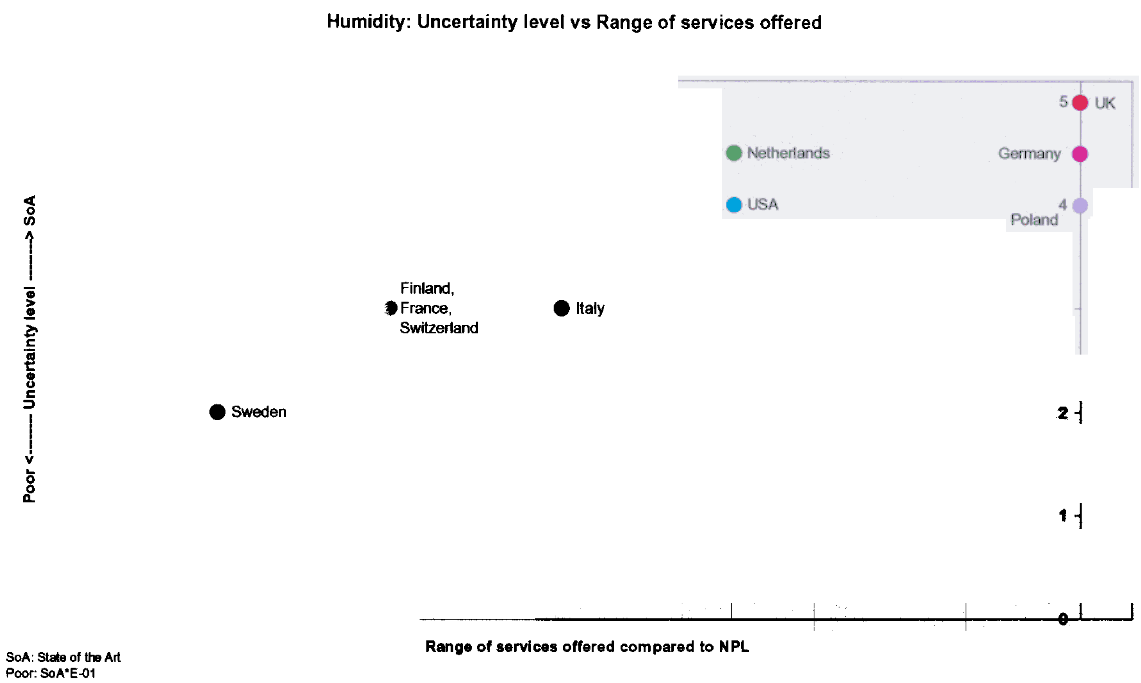


Figure 54: Sub-quantity graph, 'humidity'

3.10 Time and Frequency

Status of the data: The data for Time and Frequency have not yet been agreed and are still under review by the RMOs, they were therefore not benchmarked.

4 Summary and Conclusions

The advent of the MRA makes available for the first time data described in a harmonised way that can be readily benchmarked. The data from the KCDB were used for the benchmarking where they were available, supplemented by data that had completed the local RMO review. The progress on the evolution of the CMCs differs from one quantity to another one. For example, at the time of the benchmarking exercise, data for Length, Electricity and Magnetism were available on the BIPM database. On the other hand, data for Time and Frequency and Flow had not passed the local RMO review and were not benchmarked in this project.

As resources were limited only eight NMIs from the EUROMET membership were benchmarked in each quantity representing about one third of EUROMET, thus the majority of European NMIs do not appear in the study. The countries chosen were generally those most active in terms of declaring CMCs, however for some quantities many NMIs are active at a similar level and those selected for benchmarking were a representative sample.

A number of issues identified in the study warrant discussion:

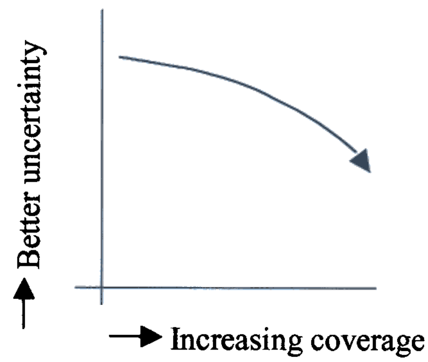
- The CMCs as described in the MRA are those that are *'ordinarily available to customers of an institute through its calibration and measurement services'*. The EUROMET Contact Persons who were responsible for assigning the scores in the benchmarking and who had overseen the CMCs review were of the opinion the NMIs have interpreted this definition in different ways. This is more likely to be an issue when the frequency of a given service tails off in an NMI. That is: what is an 'ordinarily available' service when the calibration is carried out at infrequent intervals and the details may be dominated by the customer's requirements.
- Services may be devolved to accredited laboratories, therefore they will not appear in the CMCs statements (and therefore do not contribute to the benchmarking score) although the services are still available in the country. Indeed the question of where is the boundary of an NMI may be asked. In many European countries (including the UK) the National Measurement System is supported by more than one laboratory. The advent of the MRA and the CMCs has resulted in additional laboratories being identified as contributing to the MRA process (therefore included in the CMCs) and for this reason the benchmarking study was carried out on a country-by-country basis rather than for individual laboratories.

These two points are not apparent to users of the database who may draw incorrect conclusions from casual examinations of the data and benchmarking scores.

The number of traceability arrangements identified in the study (nearly 80) caused some surprise in the UK, where traditionally the primary realisation has been available domestically. The study clearly shows that international traceability is quite a common solution to meeting peripheral needs. However closer examination also revealed differences in the definition of traceability, whilst most institutes appear to follow the 'EUROMET guide 6' definition [4], it seems that some countries consider "participation in an international comparison and use of an associated reference value" constitutes traceability. The authors had not previously been aware of this approach.

The study has generated a wealth of data that is suitable for 'data mining' in many ways. It enables the key players and their relative performance to be identified by quantity and sub-quantity. The representations at the sub-quantity level give information that is more appropriate for detailed analysis, whereas the representations at the quantity level are to give an overview only. Due to the lack of homogeneity within quantities, caution should be exercised when drawing conclusions from the quantity graphs. The exercise confirms that the UK is amongst the leading NMIs. It also illustrates a number of examples where smaller NMIs are able to offer SoA services in their areas of specialisation, with many of them taking traceability from other NMIs in other areas.

Prior to analysis of the data, the options open to an NMI about to declare CMCs were considered. For any given area an NMI might declare its best services (in terms of uncertainty) only, or alternatively a wide range of services with the result that the average performance (in terms of uncertainty) would reduce. This is shown in graphical form below:



It was postulated that the results of amalgamating output from a number of NMIs with different ranges of 'coverage' would follow the same broad profile. However examination of the graphs clearly shows the hypothesis was flawed. The trend varies from 'flat' to 'improving uncertainty with increasing service coverage'. It is interesting to speculate whether this is an argument of "critical mass" i.e. laboratories with sufficient staff, experience, equipment etc will produce overall improved results (individual exceptions notwithstanding). If this argument is correct then it is an important lesson for European Metrology regarding the amassing and maintaining of appropriate critical mass, whether in a single laboratory, or in some *'virtual laboratories'* or in networks of excellence.

As the UK EUROMET Contact Persons carried out all marking, there was an identified risk of national bias in the benchmarking. However the blind check carried out independently by another leading NMI in Europe demonstrated a high level of consistency between the scores within the general accuracy of the exercise.

5 Acknowledgements

The authors would like to thank David Nettleton for the review of the benchmarking model, Dr. Andrew Lewis for testing the benchmarking model, the UK Contact Persons for scoring the CMCs and PTB for carrying out the blind check.

6 References

The CIPM Mutual recognition of national measurement standards and of calibration and measurement certificates issued by national metrology institutes, edited by the BIPM, October 1999. See BIPM web site www.bipm.fr.

The Key Comparison Database, see BIPM web site.

Technical supplement to the arrangement T.7, Mutual recognition of national measurement standards and of calibration and measurement certificates certificates issued by national metrology institutes, edited by BIPM, October 1999, 39.

EUROMET Guide n°: 6, 'EUROMET Traceability', May 2001 (revised version), see EUROMET web site www.euromet.ch.

7 Appendix A

CLASSIFICATION OF SERVICES IN LENGTH

BRANCH: LASER

1. Radiations of the mise en pratique

1.1 Laser radiations

1.1.1 Stabilized laser of the mise en pratique1: *vacuum wavelength, absolute frequency*

1.1.2 Other stabilized lasers: *vacuum wavelength, absolute frequency*

1.2 Lamp radiations

1.2.1 Spectral lamp: *vacuum wavelength, absolute frequency*

BRANCH: DIMENSIONAL METROLOGY

2. Linear dimensions

2.1 Length instruments

2.1.1 Laser or length interferometer (system, optics, refractometer): *error of indicated displacement, wavelength compensation*

2.1.2 Electronic Distance Measurement (EDM) instrument: *error of indicated distance*

2.1.3 One-dimension measuring machine: *error of indicated size, error of indicated displacement*

2.1.4 Height measuring instrument: *error of indicated vertical size, error of indicated displacement*

2.1.5 One-dimension displacement transducer or actuator (LVDT, PZT, etc.): *error of indicated displacement*

2.1.6 Gauge block comparator: *error of indicated displacement*

2.1.7 Dial-indicator tester: *error of indicated displacement*

2.2 End standards

2.2.1 Gauge block: *central length, variation in length, thermal expansivity*

2.2.2 Length bar, long gauge block: *central length, variation in length, thermal expansivity*

2.2.3 Micrometer setting rod: *length*

2.2.4 Step gauge: *face spacing*

2.2.5 Gap gauge: *face spacing*

2.2.6 Feeler (thickness) gauge: *thickness*

2.3 Line standards

2.3.1 Precision line scale: *line spacing*

2.3.2 Stage micrometer: *line spacing*

2.3.3 Grid plate: *grid point coordinates*

2.3.4 One-dimension grating: *pitch*

2.3.5 Two-dimension grating: *pitch, orthogonality*

2.3.6 Linewidth standard: *linewidth*

2.3.7 Surveyor or engineer tape, (geodetic) wire: *line spacing*

2.3.8 Surveyor levelling rod: *line spacing*

2.3.9 Engineer or machinist scale, steel: *line spacing*

2.4 Diameter standards

2.4.1 External cylinder (plug, piston, pin, wire): *diameter*

2.4.2 Internal cylinder (ring): *diameter*
2.4.3 Sphere (ball): *diameter*

3. Angle

3.1 Angle by circle dividers

3.1.1 Optical polygon: *face angle, pyramid error, face flatness*
3.1.2 Index table: *index angle*
3.1.3 Rotary table, rotary encoder scale: *position angle*

3.2 Small-angle generators

3.2.1 Sine bar or table: *cylinder spacing, angle*

3.3 Angle instruments

3.3.1 Autocollimator: *error of indicated angle, axes orthogonality*
3.3.2 Electronic level: *error of indicated inclination angle*
3.3.3 Clinometer: *error of indicated inclination angle*
3.3.4 Spirit (bubble) level: *error of indicated inclination angle*
3.3.5 Theodolite: *error of indicated angle, axes orthogonality*
3.3.6 Bevel, protractor: *error of indicated angle*
3.3.7 Squareness tester: *error of indicated squareness, error of indicated straightness*

3.4 Angle artefacts

3.4.1 Angle block: *included angle, pyramid error, face flatness*
3.4.2 90° steel, granite or try square: *squareness*
3.4.3 90° cylinder square: *squareness*
3.4.4 Cone (taper) gauge: *cone angle, diameter*

3.5 Angle prisms

3.5.1 Optical square (pentaprism): *deviation angle*
3.5.2 Retroreflection (cube-corner, cat-eye) prism: *deviation angle*

4. Form

4.1 Flatness standards

4.1.1 Optical flat: *flatness*
4.1.2 Optical parallel or wedge: *parallelism, wedge angle*
4.1.3 Surface plate: *flatness*

4.2 Roundness standards

4.2.1 External cylinder: *roundness*
4.2.2 Internal cylinder: *roundness*
4.2.3 Sphere or hemisphere: *roundness*
4.2.4 Magnification standard (e.g. flick standard): *roundness, amplitude and phase harmoniccontent*

4.3 Straightness standards

4.3.1 Straight edge: *straightness*
4.3.2 Cylindrical straightness standard: *straightness*
4.3.3 Straightness of guideway: *straightness*

4.4 Cylindricity standards

4.4.1 External cylinder: *cylindricity*
4.4.2 Internal cylinder: *cylindricity*

4.5 Optical standards

4.5.1 Lens, radius standards: *focal length, radius of curvature*

5. Complex geometry

5.1 Surface texture

5.1.1 Depth standard, groove depth standard, step height standard (e.g. ISO 5436-1 Type A):*(groove) depth, step height*

5.1.2 Tip-condition standard (e.g. ISO 5436-1 Type B): *radii, angle*

5.1.3 Spacing standard (e.g. ISO 5436-1 Type C): *amplitude parameters, wavelength parameters*

5.1.4 Roughness standard (e.g. ISO 5436-1 Type D): *ISO roughness parameters*

5.1.5 Profile coordinate standard (e.g. ISO 5436-1 Type E): *profile coordinates*

5.1.6 Soft gauge standard (reference software data set): *error in calculated dimensions, error in calculated parameters*

5.2 Screw standards

5.2.1 Thread plug, plain: *pitch diameter, pitch, flank angle*

5.2.2 Thread plug, tapered: *pitch diameter, pitch, flank angle, taper angle*

5.2.3 Thread ring, plain: *pitch diameter, pitch, flank angle*

5.2.4 Thread ring, tapered: *pitch diameter, pitch, flank angle, taper angle*

5.2.5 Internal API (American Petroleum Institute) screw thread gauge: *API thread parameters*

5.2.6 External API (American Petroleum Institute) screw thread gauge: *API thread parameters*

5.3 Gear standards

5.3.1 Spur gear: *pitch, involute*

5.3.2 Bevel gear: *pitch, involute, bevel angle*

5.3.3 Gear pitch master: *total cumulative pitch deviation*

5.3.4 Gear lead master: *total cumulative pitch deviation, single pitch deviation*

5.3.5 Gear involute master: *involute profile (slope, form) deviation*

5.4 Coordinate Measuring Machine (CMM) artefacts

5.4.1 Ball (hole, bore) plate: *ball center coordinates, hole center coordinates*

5.4.2 Ball bar: *ball spacing*

5.4.3 Large CMM artefact: *interval distances*

5.4.4 Reference software: *error in calculated dimensions, parameters or features*

5.5 Two-dimension and three-dimension instruments

5.5.1 Measuring projector: *error of indicated size, location or shape*

5.5.2 Measuring microscope: *error of indicated size, location or shape*

5.5.3 Coordinate Measuring Machine (CMM): *error of indicated size, location or shape*

5.5.4 Laser tracking measuring system: *error of indicated size, location or shape*

5.5.5 Motion (translation, angle) stage: *error in prescribed translation or angular motion*

5.6 Hardness artefacts

5.6.1 Hardness indenter (Rockwell, Vickers): *tip (size or shape)*

6. Various dimensional

6.1 Hand instruments

6.1.1 External micrometer: *error of indicated size*

6.1.2 Micrometer head: *error of indicated displacement*

6.1.3 Depth micrometer: *error of indicated depth*

6.1.4 Calliper: *error of indicated size*

6.1.5 Depth gauge: *error of indicated depth*
6.1.6 Internal two-point (bore) micrometer: *error of indicated diameter*
6.1.7 Internal three-point (bore) micrometer: *error of indicated diameter*
6.1.8 Dial gauge: *error of indicated displacement*

6.2 Pressure artefacts

6.2.1 Piston/cylinder assembly: *three-dimension size, shape*

6.3 Thermal expansivity

6.3.1 Thermal expansion artefact: *thermal expansion coefficient*

6.4 Long distance

6.4.1 Geodetic baseline: *interval distances*

6.5 Reference materials

6.5.1 Standard particle: *particle size, particle shape*
6.5.2 Sieve or mesh opening: *size or shape of the aperture*

6.6 Layer thickness

6.6.1 Layer thickness standard: *layer thickness*

Length, United Kingdom, NPL (National Physical Laboratory)

Calibration or Measurement Service			Measurand Level or Range			Measurement Conditions/Independent Variable		Expanded Uncertainty					
Class	Instrument or Artifact	Instrument Type or Method	Minimum value	Maximum value	Units	Parameter	Specifications	Value	Units	Coverage factor	Level of Confidence	Is the expanded uncertainty a relative one?	NMI Service Identifier
Laser radiations	Stabilized laser of the mise en pratique: vacuum wavelength	Optical beat frequency	633	633	nm			0.04	fm	2	95%	No	1a
Laser radiations	Stabilized laser of the mise en pratique: absolute frequency	Optical beat frequency	474	474	THz			24	kHz	2	95%	No	1b
Laser radiations	Stabilized laser of the mise en pratique: vacuum wavelength	Optical beat frequency	543	543	nm			0.28	fm	2	95%	No	2a
Laser radiations	Stabilized laser of the mise en pratique: absolute frequency	Optical beat frequency	551	551	THz			0.28	MHz	2	95%	No	2b
Laser radiations	Stabilized laser of the mise en pratique: vacuum wavelength	Optical beat frequency	612	612	nm			0.36	fm	2	95%	No	3a
Laser radiations	Stabilized laser of the mise en pratique: absolute frequency	Optical beat frequency	490	490	THz			0.3	MHz	2	95%	No	3b
Laser radiations	Other stabilized laser: vacuum wavelength	Optical beat frequency	633	633	nm			0.15	fm	2	95%	No	4
Laser radiations	Other stabilized laser: vacuum wavelength	Optical beat frequency	543	543	nm			0.35	fm	2	95%	No	5
Laser radiations	Other stabilized laser: vacuum wavelength	Optical beat frequency	612	612	nm			0.52	fm	2	95%	No	6
Length instruments	Laser interferometer: displacement L	Comparison of two interferometers	0	30	m			Q[0.8, 0.12L], L in m	µm	2	95%	No	7