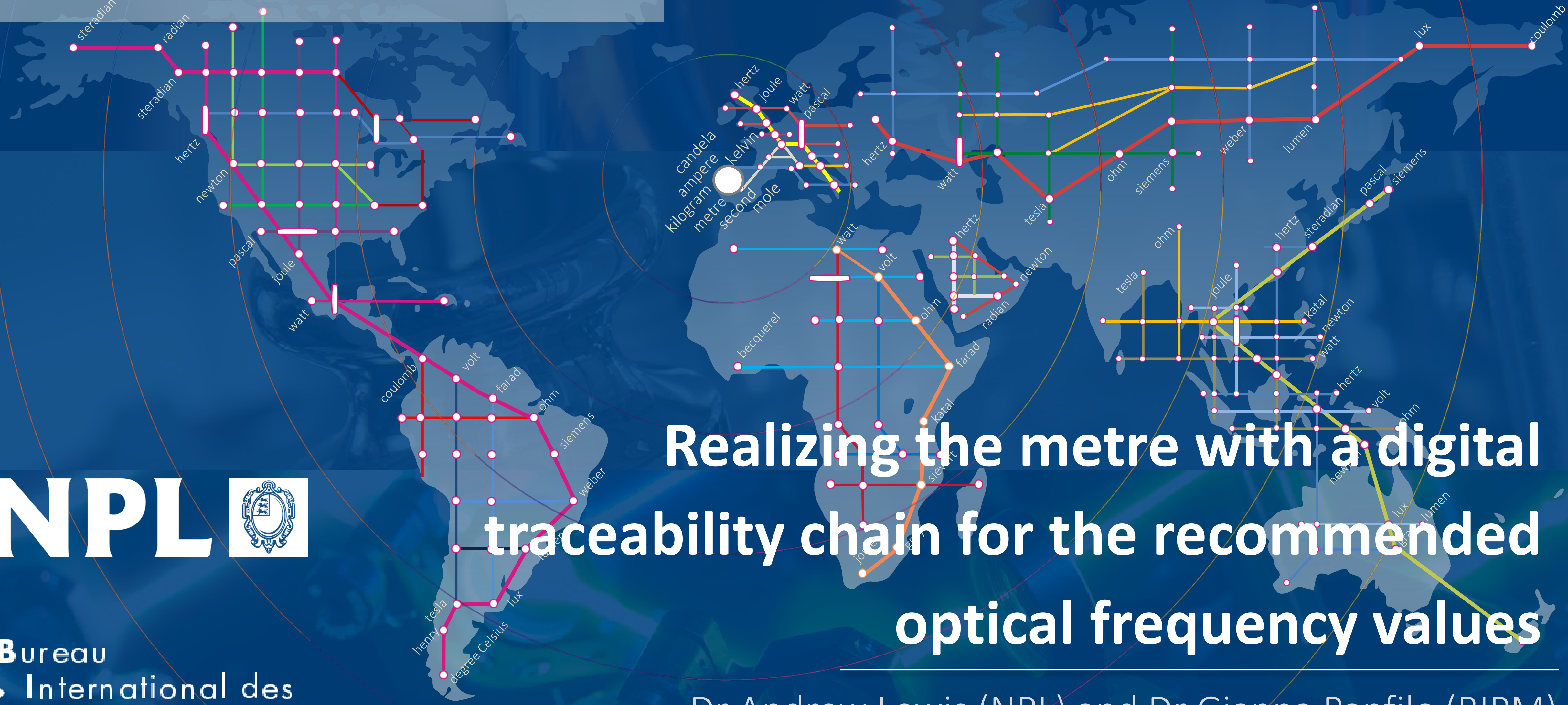
SciDataCon 2022 – 22 June 2022



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Realizing the metre with a digital traceability chain for the recommended optical frequency values

Dr Andrew Lewis (NPL) and Dr Gianna Panfilo (BIPM)

Outline

- The CIPM Consultative Committee for Length
- The SI unit of length, the metre – definition, realisations
- Digitalising the SI metre at the highest level
  - "Unique SI Reference Point"
  - CCL-CCTF database of recommended frequencies
  - Digitalisation of *Mise en Pratique* data
- Outcomes
  - Digital metadata traceability
  - Benefits for end users
  - Benefits for metrology providers (including CCL, CIPM, BIPM)
- Summary

The CIPM Consultative Committee for Length (CCL)

- The Consultative Committee for the Definition of the Metre (CCDM) was set up in 1952, becoming the Consultative Committee for Length (CCL) in 1997.
- Present activities concern matters related to the **definition and realization** of the metre, practical length and angle measurement, and advice to the CIPM in the field of length metrology.
- CCL has joint responsibility (with CC Time and Frequency) for the list of ***Recommended values of standard frequencies***, for the **realisation of the metre** and secondary representations of the **second.**
- CCL has a **Task Group on Digitalization**.

The metre

- The **SI Brochure** gives high-level details of the International System of units (SI), including the definition of the metre:

  The metre, symbol m, is the SI unit of length. It is defined by taking the fixed numerical value of the speed of light in vacuum, c, to be 299 792 458 when expressed in the unit m s^{-1} , where the second is defined in terms of the caesium frequency $\Delta\nu_{Cs}$.

- The ***Mise en Pratique*** (MeP, ‘putting into practice’) for the metre describes practical aspects of realizing the metre as a physical standard, based on the definition.

Mise en Pratique for the metre

- The most popular way of realising the metre, especially at the macroscale, is through the use of optical interferometry, but this requires knowledge of the **optical frequency** of the light wave.

- Two options exist:
  - Measure the frequency, *e.g.* using a frequency comb, traceable to the second
  - Use one of the **standard frequencies in the list maintained by the CCL and the CCTF**

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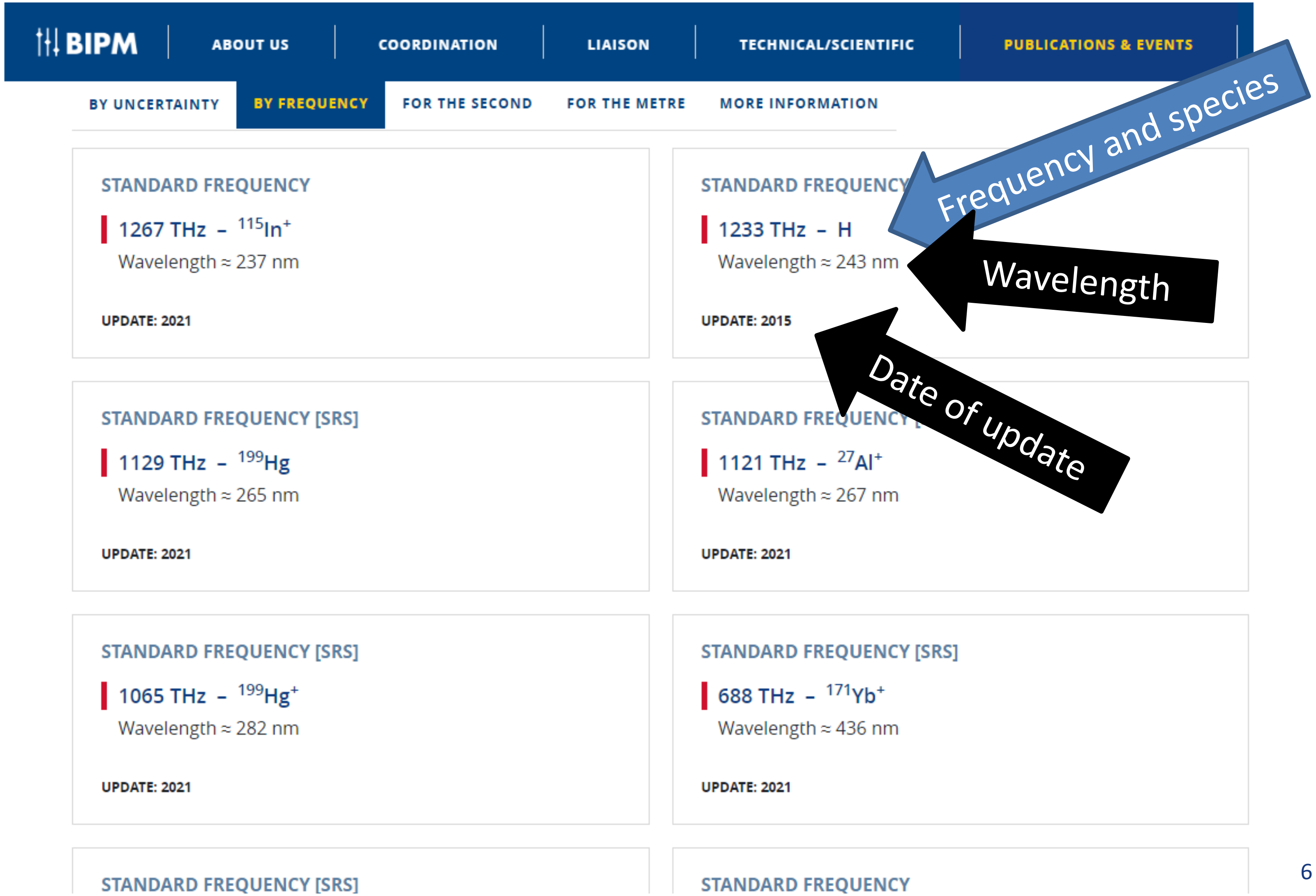
List of Recommended values of standard frequencies

https://www.bipm.org/en/publications/mises-en-pratique/standard-frequencies



<u>Frequency coverage</u>

29.1 THz to 1267 THz

also 6.835 GHz (Rb)

<u>Wavelength coverage</u>

237 nm to 10.3 µm

also spectral lamps 467 nm to 646 nm

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474 THz, 633 nm He-Ne laser (I_2 stabilised)

MEP 2003

IODINE ($\lambda \approx 633$ nm)

Absorbing molecule $^{127}I_2$, a_{16} or f component, R(127) 11-5 transition (1)

1. CIPM recommended values

The values $f = 473\ 612\ 353\ 604$ kHz
$\lambda = 632\ 991\ 212.58$ fm
with a relative standard uncertainty of 2.1×10^{-11} apply to the radiation of a He-Ne laser with an internal iodine cell, stabilized using the third harmonic detection technique, subject to the conditions:

- cell-wall temperature (25 ± 5) °C (2);
- cold-finger temperature (15.0 ± 0.2) °C;
- frequency modulation width, peak-to-peak, (6.0 ± 0.3) MHz;
- one-way intracavity beam power (i.e. the output power divided by the transmittance of the output mirror) (10 ± 5) mW for an absolute value of the power shift coefficient ≤ 1.0 kHz/mW.

These conditions are by themselves insufficient to ensure that the stated standard uncertainty will be achieved. It is also necessary for the optical and electronic control systems to be operating with the appropriate technical performance. The iodine cell may also be operated under relaxed conditions, leading to the larger uncertainty specified in section 2 below.

2. Source data

Adopted value: $f = 473\ 612\ 353\ 604\ (10)$ kHz $u_c/y = 2.1 \times 10^{-11}$

for which:

$\lambda = 632\ 991\ 212.579\ (13)$ fm $u_c/y = 2.1 \times 10^{-11}$

Atom/molecule, transition specification, selected component

Values for frequency, (vacuum) wavelength and uncertainty, basic stabilisation technique

Requirements to achieve specified uncertainty level:

- Cell wall temperature
- Cold finger temperature
- Frequency modulation
- Intra-cavity power

474 THz, 633 nm He-Ne laser (I_2 stabilised) ...continued

Table 1

$\lambda \approx 633$ nm $^{127}I_2$ R(127) 11-5

a_n	x	$[f(a_n)-f(a_{16})]$ /MHz	...]/MHz	u_c/MHz
a_2	t	−721.8		
a_3	s	−697.8		
a_4	r	−459.62		
a_5	q	−431.58		
a_6	p	−429.18		
a_7	o	−402.09		
a_8	n	−301.706		
a_9	m	−292.693		
a_{10}	l	−276.886		
a_{11}	k	−268.842		

Frequency referenced to

Ref. [18–29]

Other components, same transition

Table 2

$\lambda \approx 633$ nm $^{127}I_2$ P(33) 6-3

b_n	x	$[f(b_n)-f(b_{21})]$/MHz	u_c/MHz	b_n	x	$[f(b_n)-f(b_{21})]$ /MHz	u_c /MHz
b_1	u	−922.571	0.008	b_{12}	j	−347.354	0.007
b_2	t	−895.064	0.008	b_{13}	i	−310.30	0.01
b_3	s	−869.67	0.0				
b_4	r	−660.50	0.0				
b_5	q	−610.697	0.0				
b_6	p	−593.996	0.0				
b_7	o	−547.40	0.0				
b_8	n	−487.074	0.0				
b_9	m	−461.30	0.0				
b_{10}	l	−453.21	0.0				
b_{11}	k	−439.01	0.0				

Frequency referenced to a_{16} (f), R(127) 11-5, ...
f (b_{21}, P(33) 6-3) − f (...

Ref. [25, 30–34]

Components of a different transition

Table 3

$\lambda \approx 633$ nm $^{129}I_2$ P(54) 8-4

a_n	x	$[f(a_n)-f(a_{28})]$ /MHz	u_c/MHz	a_n	x	$[f(a_n)-f(a_{28})]$/MHz	u_c /MHz
a_2	z′	−449	2	a_{16}	i′	−197.73	0.08
a_3	y′	−443	2	a_{17}	h′	−193.23	0.08
a_4	x′	−434	2	a_{18}	g′	−182.74	0.03
a_5	w′	−429	2	a_{19}	f′	−162.61	0.05
a_6	v′	−360.9	1	a_{20}	e′	−155.72	0.05
a_7	u′	−345.1	1	a_{21}	d′	−138.66	0.05
a_8	t′	−340.8	1	a_{22}	c′	−130.46	0.05
a_9	s′	−325.4	1	a_{23}	a′	−98.22	0.03
a_{10}	r′	−307.0	1	a_{24}	n_2	−55.6 see m_8 table 7	0.5
a_{11}	q′	−298.2	1	a_{25}	n_1	−55.6 see m_8 table 7	0.5
a_{12}	p′	−293.1	1	a_{26}	m_2	−43.08	0.03
a_{13}	o′	−289.7	1	a_{27}	m_1	−41.24	0.05
a_{14}	n′	−282.7	1	a_{28}	k	0	—
a_{15}	j′	−206.1	0.2				

Frequency referenced to a_{16} (f), R(127) 11-5, $^{127}I_2$: f = 473 612 353 604 kHz [17]
f (a_{28}, P(54) 8-4) − f (a_{16}, R(127) 11-5 {$^{127}I_2$}) = −42.99 (4) MHz [35–36]

Ref. [35–43]

Components of a third transition

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The situation until now

- To make a realisation of the metre (for macro-scale metrology)
  - Read the **SI Brochure** to understand the definition of the metre
  - Select a transition from the **List of Recommended frequencies**
  - Build a **laser/experiment** that follows the **MeP** guidance
  - Operate the laser, perform **beat frequency** measurements, enter data from the frequencies list
  - Remember to **check laser parameters** are within specification
  - Remember to look for **updates to laser parameters/frequency values/uncertainties…**

- These are all **analogue** processes, based on documents that a human needs to find, read, and understand – the documents could be updated at any time…

- How to **digitalize** this approach? – there are 3 tasks to perform…

TASK 1 - Digitalisation of the metre – "Unique SI Reference Point"

The "Unique SI Reference Point" – a digital implementation of the SI Brochure (J. Miles Presentation) – Example of the metre

Digital SI Units Browse the system API

UNIT: meter API Back to Index

- **PID**: si:unit:meter
- **Definition**: The metre, symbol m, is the SI unit of length. It is defined by taking the fixed numerical value of the speed of light in vacuum, *c*, to be 299 792 458 when expressed in the unit m s^{-1}, where the second is defined in terms of the caesium frequency $\Delta\nu_{Cs}$.
- **Source**: SI Brochure 9th Ed. 2019, p 131
- **Reference**: CGPM Resolution 1 of the 26th CGPM (2018) "On the revision of the International System of Units (SI)" https://www.bipm.org/en/committees/cg/cgpm/26-2018/resolution-1
- **Status**: Valid
- **Valid**: 2019-05-20 -
- **Notes**
  1. This definition implies the exact relation $c = 299\ 792\ 458\ \mathrm{m\ s^{-1}}$. Inverting this relation gives an exact expression for the metre in terms of the defining constants c and $\Delta\nu_{Cs}$:

     $$1\ \mathrm{m} = \left(\frac{c}{299\ 792\ 458}\right)\mathrm{s} = \frac{9\ 192\ 631\ 770}{299\ 792\ 458}\frac{c}{\Delta\nu_{Cs}} \approx 30.663\ 319\frac{c}{\Delta\nu_{Cs}}$$

  2. The effect of this definition is that one metre is the length of the path travelled by light in vacuum during a time interval with duration of $1/299\ 792\ 458$ of a second.
- **Related Definitions**
  - isBaseUnitOf -> length
  - hasUnitSymbol -> m
  - hasDefiningEquation -> equation for the meter

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(prototype for discussion)

TASK 2 - Digitalisation of the metre – CCL-CCTF database of recommended frequencies

Development of the CCL-CCTF database is ongoing at the BIPM. Here are some excerpts.

Welcome on CCL-CCTF database consultation

See Reference frequencies " For the meter"

See Reference frequencies "For the second"

Reference frequencies + source data: (by transition)

127I2 612 nm | View

Source data by year of approval

2021 | View

Table 3 related transitions (by MeP -- specie+lambda)

MeP_I2_612nm | View

Infos from Specie 127I2 with lambda = 612 nm

target	wavelength	transition	meter	second	frequency	freq unit	freq uncertainty	wavelength	wave. unit	authority	validity start	validity end	uncertainty calculation	frequency calculation	references
127I2	612 nm	R(47) 9-2	x		489880354.9	MHz	3e-10	611970770.0	fm	CIPM	2003-10-10			Other available values having relative uncertainties higher than 3.0 x 10-10 have not been used. The relative standard uncertainty calculated from the dispersion of the six values is 2.8 x 10-10 , which the CCL preferred to round up to 3.0 x 10-10.	CIPM Recommendation 1 (CI-2003): Revision of the Mise en pratique list of recommended radiations

Measurements used for calculations (source data) : 127I2 612 nm

Meas.Frequency	Year	Measurement Reference	Uncertainty
489880354979	2003	CCDM/82-34 , NPL, Laser wavelength Measurements, May 1982	1e-10
489880354728	2003	CCDM/82-19a, BIPM, Réponse au questionnaire CCDM/82-3	2.1e-10
489880355026	2003	Bönsch G., Gläser M., Spieweck F., Bestimmung der Wellenlangenverhältnisse von drei 127I2-stabilisierten Lasern bei 515 nm, 612 nm und 633 nm, PTB Jahresbericht, 1986, 161	8.3e-11
489880355062	2003	Vitushkin L. F., Zakharenko Yu. G., Yvanov I. V., Leibengardt G. I., Shur V. L., Measurements of Wavelength of High-Stabilized He-Ne/I2 Laser at 612 nm, Opt. Spectr., 1990, 68, 705-707	3e-10
489880358850	2003	Himbert M., Bouchareine P., Hachour A., Juncar P., Millerioux Y., Razet A., Measurements of Optical Wavelength Ratios Using a Compensated Field Sigmameter, IEEE Trans. Instrum. Meas., 1991, 40, 200-203	8.5e-11

Related transitions from MeP_I2_612nm

component	transition	operation	aref	transition_ref	diff	diff_unit	unc	unc_unit
a1	R(47) 9-2	minus	a7	R(47) 9-2	-357.16	3	0.02	3
a2	R(47) 9-2	minus	a7	R(47) 9-2	-333.97	3	0.01	3
a3	R(47) 9-2	minus	a7	R(47) 9-2	-312.46	3	0.02	3
a4	R(47) 9-2	minus	a7	R(47) 9-2	-86.168	3	0.007	3
a5	R(47) 9-2	minus	a7	R(47) 9-2	-47.274	3	0.004	3
a6	R(47) 9-2	minus	a7	R(47) 9-2	-36.773	3	0.003	3
a8	R(47) 9-2	minus	a7	R(47) 9-2	81.452	3	0.003	3
a9	R(47) 9-2	minus	a7	R(47) 9-2	99.103	3	0.003	3

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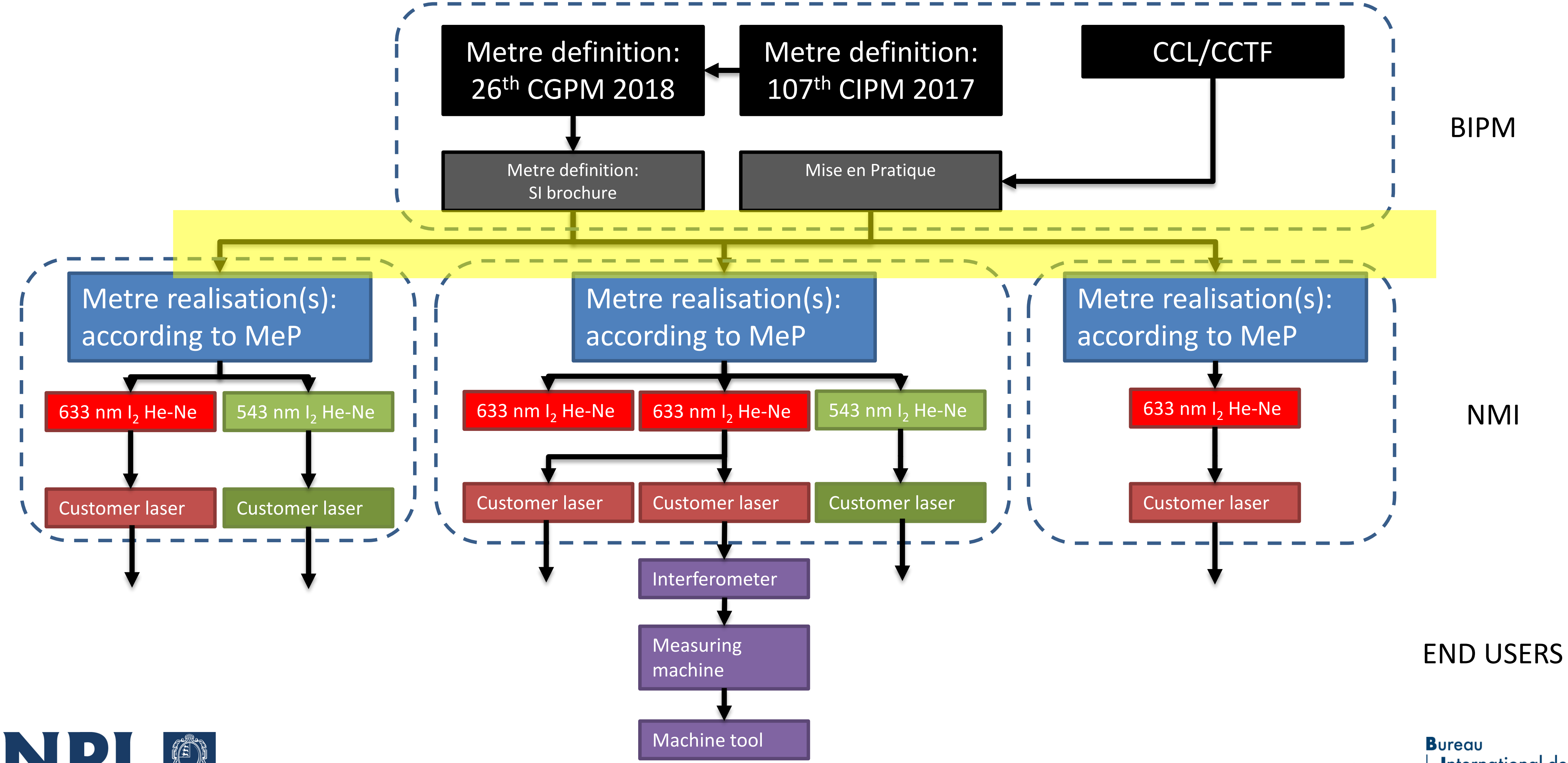
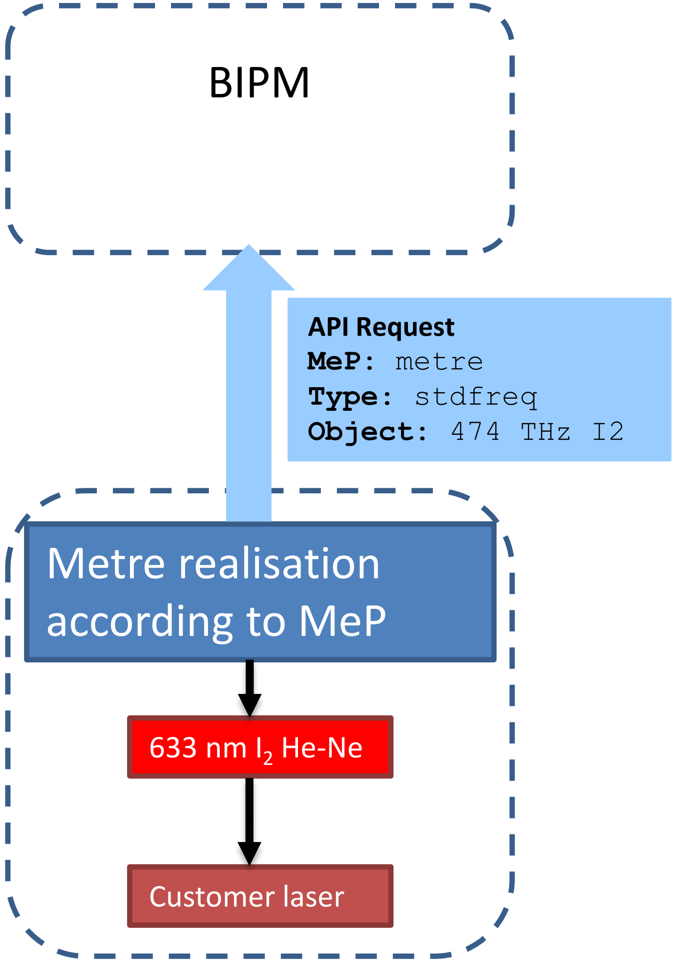
TASK 3 - Digitalisation of *MeP* data – for machine access

- *Mise en Pratique* contains lots of meta data critical to both the approval/authority process and for the implementation. This is understood by the scientists in the field, and probably encoded into the operating procedures of their lasers built to be *MeP* compliant.
- What happens if things change?
    - Does any change to the text in the *Mise en Pratique* automatically trigger review/update of laser calibrations?
    - Are the local assumed conditions still valid?
    - Is the latest data used?
    - Are there any typos?
    - Are the latest values implemented in my software?
    - Who approved the latest update? (CCL? CIPM?)
- => Make all the critical meta data digitally accessible, *e.g*. as XML encoded data

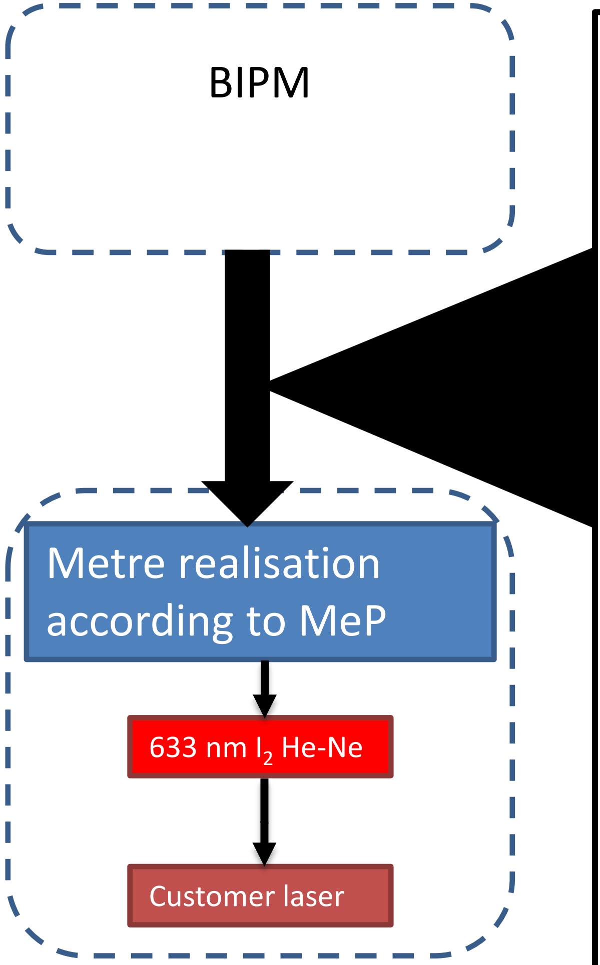
Length traceability chain at the highest level, through the primary realisations of the metre



Meta data download during a laser calibration



NMI laser system queries the BIPM server using a structured API call



BIPM server responds with structured data based on agreed scheme


```
<?xml version="1.0" encoding="UTF-8"?>

<freq:stdfreq
   xmlns:freq="NPL_MeP_Schema“
   xmlns:xs=http://www.w3.org/2001/XMLSchema
   xmlns:si="https://ptb.de/si"
   >
   <freq:label>474 THz – I2</freq:label>
   <freq:freqlabel>474 THz</freq:freqlabel>
   <freq:target>127I2</freq:target>
   <freq:validfrom>2003-09-12</freq:validfrom>
   <freq:srs>false</freq:srs>

   <freq:transitionname>R(127) 11-5</freq:transitionname>
   <freq:compname>a16</freq:compname>
   <freq:altcompname>f</freq:altcompname>
   <freq:value>
      <si:real>
         <si:value>473612353604</si:value>
         <si:unit>\kilo\hertz</si:unit>
         <si:expandedUnc>
            <si:uncertainty>10</si:uncertainty>
            <si:coverageFactor>1</si:coverageFactor>
            <si:coverageProbability>0.68</si:coverageProbability>
            <si:distribution>normal</si:distribution>
         </si:expandedUnc>
      </si:real>
   </freq:value>
...
```

Proposed MeP standard frequencies XML schema

The XML schema defines five elements:

`stdfreq`	- standard frequencies – values of reference frequency, administrative information *e.g.* validity
`funcc`	- fixed uncertainty contributions – *e.g.* iodine purity
`rule`	- implementation rules – constraint information, *e.g.* cold-well temperature (min, max, nominal, sensitivity)
`transition`	- optical transitions – target atom/molecule/ion, name, offset from nominal frequency
`component`	- optical components – names & offsets from the transition reference

Using XML makes the data clear, robust, machine readable, searchable, parsable, standardised

Draft Schema and example data files

A. J. Lancaster and A. J. Lewis, "NPL MeP standard frequencies XML schema," 07 April 2022. https://doi.org/10.5281/zenodo.6412020.

Example use of schema – 474 THz (633 nm)

```xml
<?xml version="1.0" encoding="UTF-8"?>

<freq:stdfreq
    xmlns:freq="NPL_MeP_Schema"
    xmlns:xs="http://www.w3.org/2001/XMLSchema"
    xmlns:si="https://ptb.de/si"
    >
    <freq:label>474 THz – I2</freq:label>
    <freq:freqlabel>474 THz</freq:freqlabel>
    <freq:target>127I2</freq:target>
    <freq:validfrom>2002-10-11</freq:validfrom>
    <freq:srs>false</freq:srs>

    <freq:transitionname>R(127) 11-5</freq:transitionname>
    <freq:compname>a16</freq:compname>
    <freq:altcompname>f</freq:altcompname>
    <freq:value>
        <si:real>
            <si:value>473612353604</si:value>
            <si:unit>\kilo\hertz</si:unit>
            <si:expandedUnc>
                <si:uncertainty>10</si:uncertainty>
                <si:coverageFactor>1</si:coverageFactor>
                <si:coverageProbability>0.68</si:coverageProbability>
                <si:distribution>normal</si:distribution>
            </si:expandedUnc>
        </si:real>
    </freq:value>

    <freq:numberofrules>5</freq:numberofrules>
    <freq:rule>
        <freq:description>Iodine cell: cell-wall temperature</freq:description>
        <freq:nominal>
            <si:real>
                <si:value>25</si:value>
                <si:unit>\degreecelsius</si:unit>
            </si:real>
```

MEP 2003

IODINE ($\lambda \approx 633$ nm)

Absorbing molecule $^{127}I_2$, a_{16} or f component, R(127) 11-5 transition (1)

1. CIPM recommended values

The values f = 473 612 353 604 kHz
λ = 632 991 212.58 fm
with a relative standard uncertainty of 2.1×10^{-11} apply to the radiation of a He-Ne laser with an internal iodine cell, stabilized using the third harmonic detection technique, subject to the conditions:

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- cold-finger temperature (15.0 ± 0.2) °C;
- frequency modulation width, peak-to-peak, (6.0 ± 0.3) MHz;
- one-way intracavity beam power (i.e. the output power divided by the transmittance of the output mirror) (10 ± 5) mW for an absolute value of the power shift coefficient ≤ 1.0 kHz/mW.

These conditions are by themselves insufficient to ensure that the stated standard uncertainty will be achieved. It is also necessary for the optical and electronic control systems to be operating with the appropriate technical performance. The iodine cell may also be operated under relaxed conditions, leading to the larger uncertainty specified in section 2 below.

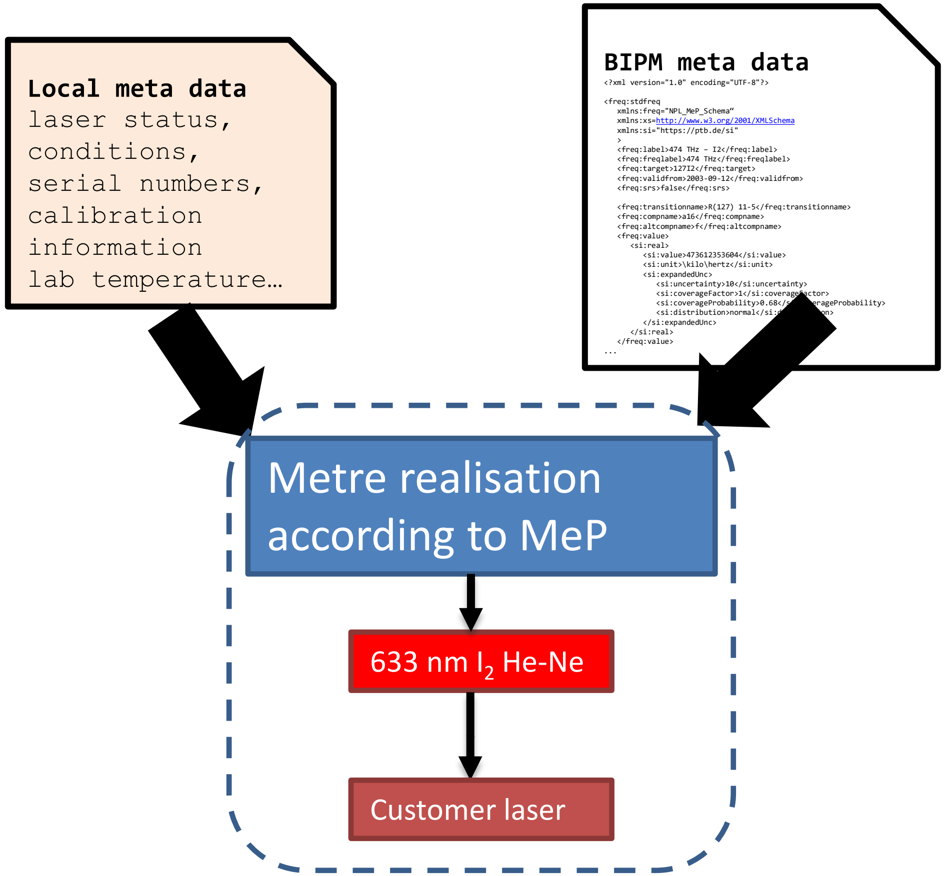
2. Source data

Adopted value:	f = 473 612 353 604 (10) kHz	$u_c/y = 2.1 \times 10^{-11}$
	for which:	
	λ = 632 991 212.579 (13) fm	$u_c/y = 2.1 \times 10^{-11}$

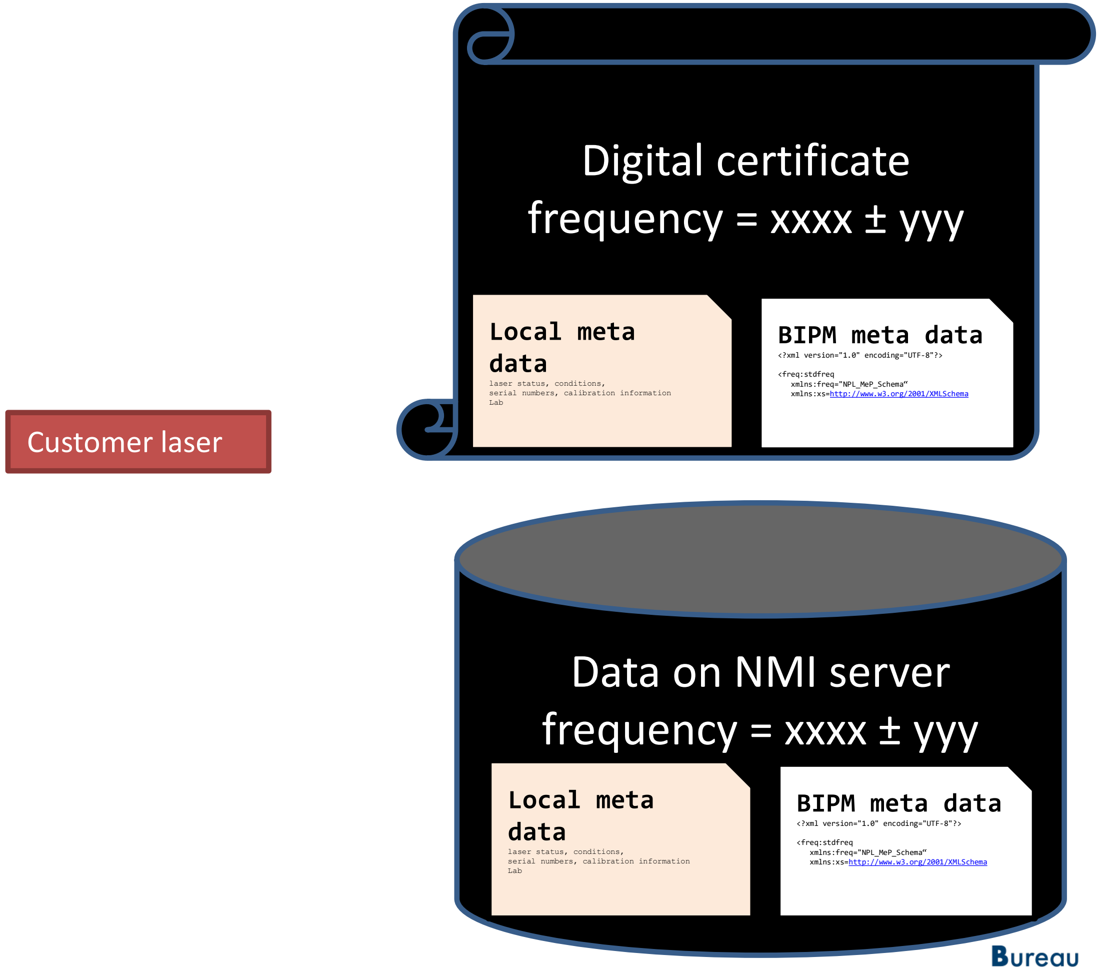

```xml
<si:value>473612353604</si:value>
            <si:unit>\kilo\hertz</si:unit>
            <si:expandedUnc>
                <si:uncertainty>10</si:uncertainty>
                <si:coverageFactor>1</si:coverageFactor>
                <si:coverageProbability>0.68</si:coverageProbability>
                <si:distribution>normal</si:distribution>
            </si:expandedUnc>
```

Meta data exchange during a laser calibration

Laser calibration system performs the physical calibration, storing the XML meta data from the BIPM and additional meta data from the local system *e.g.* lab temperature, laser power



Laser is returned to customer, NMI makes the calibration data (including meta data) available from its server (or supplied on digital certificate)



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Outcomes

- Digital certificate (or data on NMI server) now holds both parts of the traceability of the calibration: the physical data AND the authority and validity meta data
- No transcription errors, latest values automatically used
- Fully transparent, traceable (data & authority) to SI/CIPM/CGPM via NMI
- BIPM/CIPM/SI ‘cited’ as top level in the chain
- NMI adds own meta data (adding value)
- Customer can then integrate all or some of this meta data into their own process e.g. to demonstrate the traceability link to accreditors, or to place validity limits on their use of the laser

Summary

- Digitalisation of the SI metre is underway:
  - digital definition (Unique SI Reference Point)
  - digital database of MeP frequencies
  - **additional work starting on making MeP data available via XML**

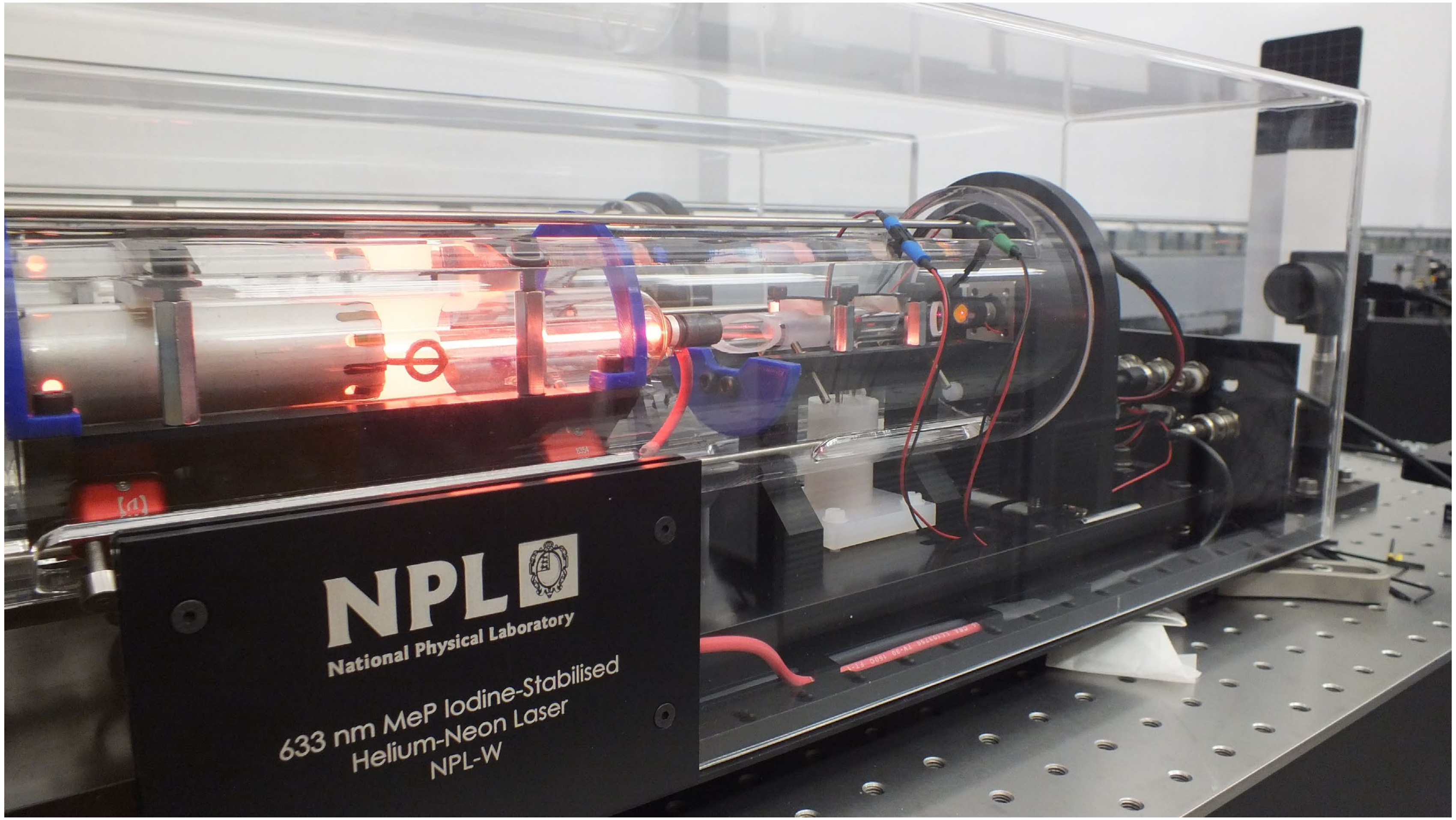
- XML schema described
  - how it relates to analogue documentation
  - how it captures the critical practitioner information

- Benefits for
  - BIPM/CIPM in the increased visibility
  - NMI/DI – fewer errors, ability to have better automation
  - end user – more information, greater confidence

Acknowledgements

- CCL President, CCL WG-Strategy, CCL Digitalisation Task Group : instigation of work
- Andrew Lancaster, NPL : detailed design of the XML schema
- Aurélie Harmegnies, BIPM : software development of the CCL-CCTF database

New NPL MeP laser – ‘digital ready’



- Computer control of laser using embedded min-computer (Raspberry Pi)
- Digital readout of operational parameters
- API calls to obtain/query MeP data from the BIPM
- Turnkey from switch-on to calibration certificate

Thank you!

Dr Andrew Lewis

NPL

Dr Gianna Panfilo

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