Digitalisation in CCL-CCTF

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CONSULTATIVE COMMITTEE FOR LENGTH

CONSULTATIVE COMMITTEE FOR TIME AND FREQUENCY

22 May 2023

CCL digitalisation survey results (CCL 2021)

General responses to digitalising the SI

92 % were aware of the digital SI initiative

79 % were planning to use digital calibration certificates

66 % were planning web services/portals

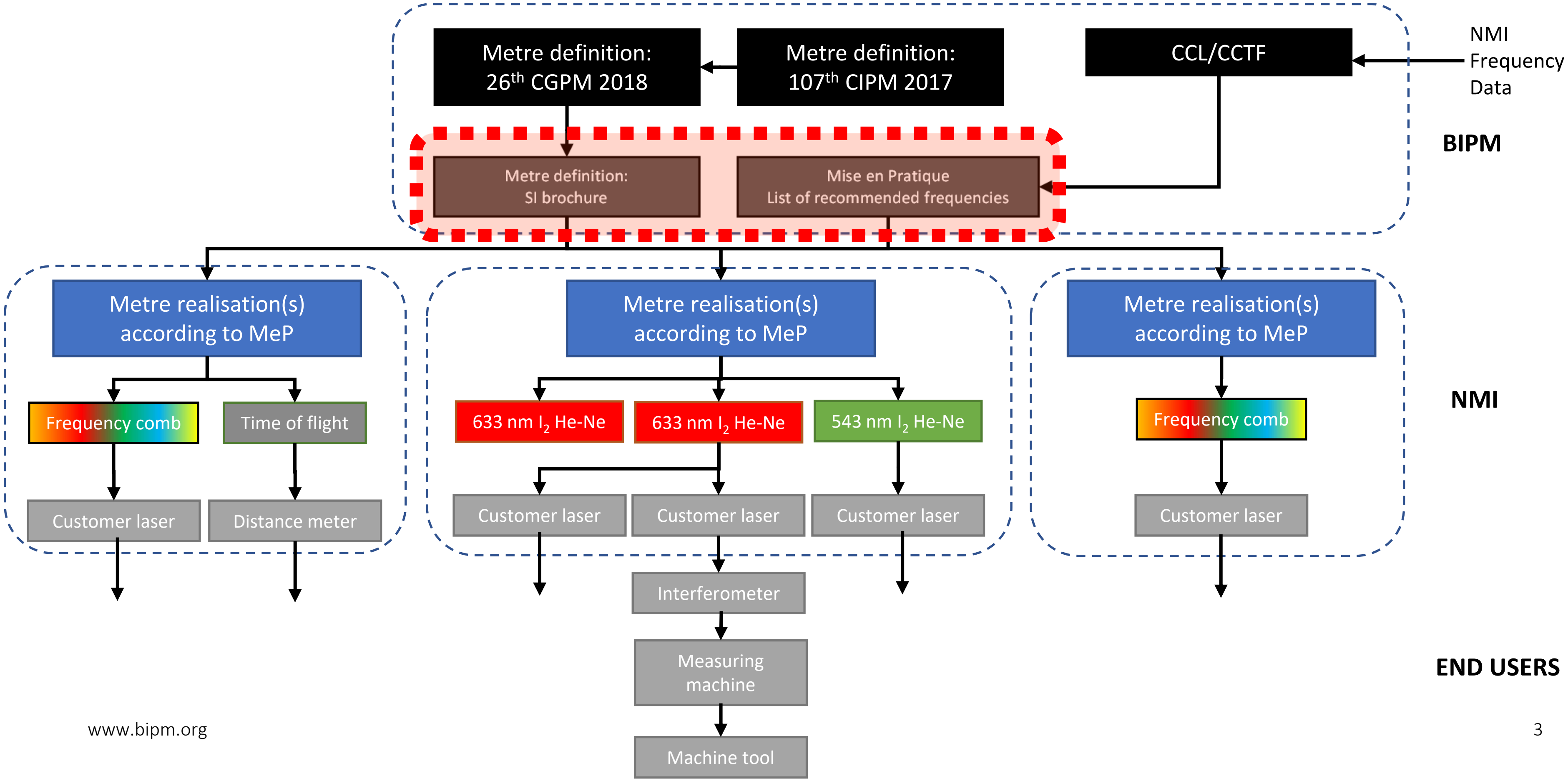
50 % had already started digitalisation projects, 29 % were planning to

Responses to questions on digitalising the metre realisations

100 % would access wavelength values and uncertainties

72 % would want to check approval dates , 68 % to check approval authority

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

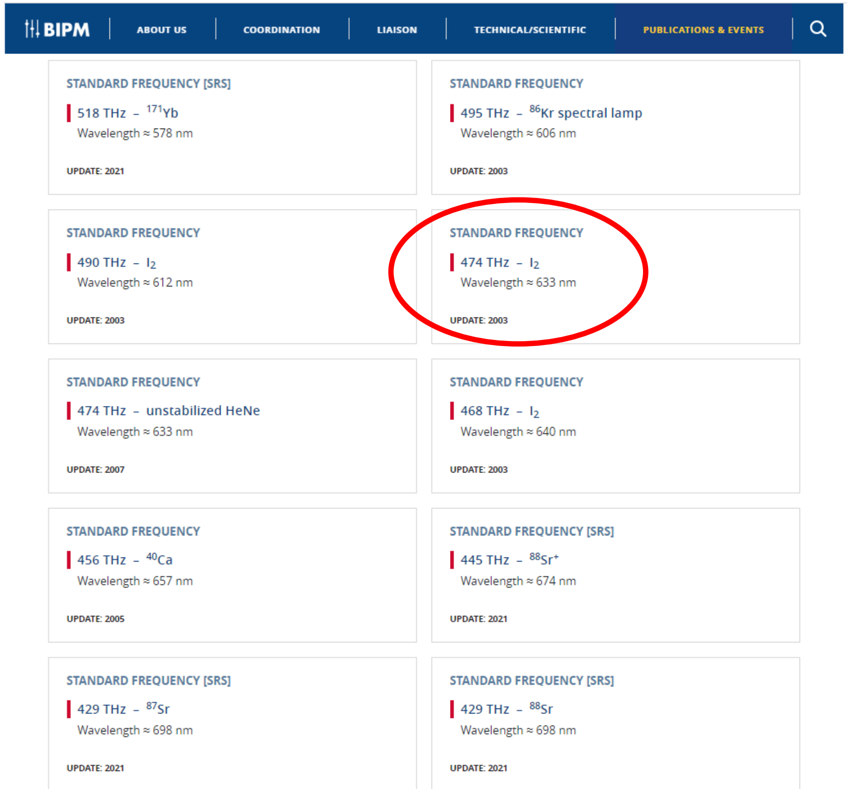


Situation on metre realisation data

- The information about the SI metre definition and realisation are both available electronically as PDF documents. They are intended for human interaction/interpretation. The ***Mise en Pratique*** and the ***List of Recommended values of Standard Frequencies*** are only available in PDF – they require **human** download, reading, selection and extraction of key data.
- The ***List of Recommended values of Standard Frequencies*** 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.
- What happens if things change?
  - Does any **change** to the text in the ***List of Frequencies*** automatically trigger review/update of laser calibrations?
  - Are the **local assumed conditions** still valid?
  - Is the **latest** data used?
  - Are the latest values implemented in **my software**?
  - Who **approved** the latest update? (CCL? CIPM?)
  - Can I **guarantee** perfect **transcription** of the data into my operational system?

⇨ Make the critical metre realisation data available digitally

What does the data look like?



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

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 $\quad u_c/y = 2.1 \times 10^{-11}$

for which:

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

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.(				
b_4	r	−660.50	0.(				
b_5	q	−610.697	0.(				
b_6	p	−593.996	0.(				
b_7	o	−547.40	0.(				
b_8	n	−487.074	0.(				
b_9	m	−461.30	0.(				
b_{10}	l	−453.21	0.(				
b_{11}	k	−439.01	0.(				

Frequency referenced to a_{16} (f), R(127) 11-5, ¹…
$f(b_{21}$, 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				

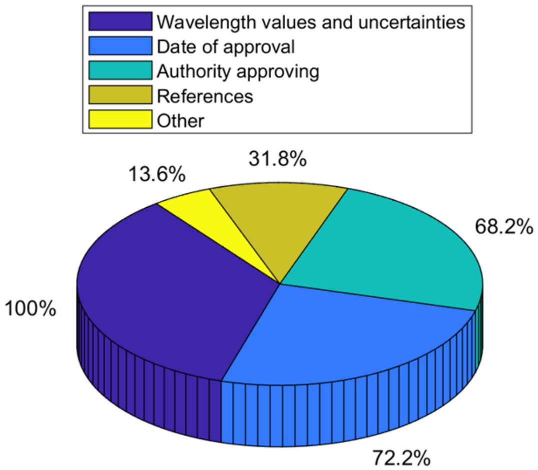
Frequency referenced to a_{16} (f), R(127) 11-5, $^{127}I_2$: f = 473 612 353 604 kHz [17]
$f(a_{28}$, P(54) 8-4) − $f(a_{16}$, R(127) 11-5 {$^{127}I_2$}) = −42.99 (4) MHz [35–36]

Ref. [35–43]

Components of a third transition

Lots of information, paper format

User needs



- DATA: Wavelength values and uncertainties
- METADATA: Date of approval
- METADATA: Authority approving
- DATA: References

- Other:
  - Guidelines on how to ensure traceability from MeP down to end users.
  - The detailed description of the set-up used to achieve the stated wavelength value and uncertainty, as in the actual MeP on the BIPM website.
  - Associated parameters required to achieve accuracy, e.g. cell wall temperature tolerance, intracavity power.

Technical suggestions:

- Harmonized data structure (FAIR data principles)
- The data structure accessible via a unique ID, comparable to the DOI for publications

Digitalisation tasks

Task 1: The “Unique SI Reference Point” – a digital implementation of the **SI Brochure** — BIPM

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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Task 2: CCL-CCTF **database** of recommended **frequencies with API access** — BIPM

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

Task 3: Agreed **XML schema** for data download — CCL-CCTF + NPL

NPL–proposed XML schema
Based on Digital-SI XML schema
from SmartCOM project

CCL-CCTF database of recommended frequencies

Welcome on CCL-CCTF database consultation

[Last update 26/01/2023 : see changes log]
>> This page is only for data content checking <<
- On request to the BIPM Time Department, a dump of the database can be provided.
- Database scheme can be accessed here
- Example of call to get XML file result : **curl -k -u ccl-cctf --url 'https://webtai.bipm.org/ccl-cctf/xml_auto.html?target=127I2|552+THz&date=2022-11-15'**

CCL+CCTF mixed informations

XML files generator

114Cd 641 THz | View

Reference frequencies + source data: (by transition) [CCL&CCTF]

all | View

Global content view for final XML input data check

all | View

CCL informations

See Reference frequencies list " For the meter"

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

MeP_C2H2_1.54µm | View

CCTF informations

See Reference frequencies list "For the second"

annual calculation source data (CCTF use)

all | View

Any comment to report ? Contact us


```xml
<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 - 127I2</freq:label>
  <freq:freqlabel>474 THz</freq:freqlabel>
  <freq:target>127I2</freq:target>
  <freq:validfrom>2003-10-10</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>9</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>6</freq:numberofrules>
  <freq:rule>
    <freq:description>cell wall temperature</freq:description>
```

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annual calculation source data (CCTF use)

`all` `View`

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Infos from Specie 127I2 with lambda = 633 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	633 nm	R(127) 11-5	x		473612353604	kilo hertz	9	632991212.58	fm	CIPM	2003-10-10			The source data are all given with respect to the BIPM4 laser standard frequency. The relative standard uncertainty includes the uncertainty in the absolute frequency measurement and the uncertainty obtained by comparing the different frequency standards with the BIPM4 standard. The CCL proposed that the recommended radiation for the R(127) 11-5 transition, using 633 nm He-Ne lasers, no longer correspond to the a13 or i component, but is replaced by the a16 or f component, which was decided by the CIPM 2001.	CIPM Recommendation 1 (CI-2003): Revision of the Mise en pratique list of recommended radiations

Measurements used for calculations (source data) : 127I2 633 nm

Meas.Frequency	Year	Measurement Reference	Uncertainty	uncertainty factor	calculation info
8.2	2003	Yoon T. H., Ye J., Hall J. L., Chartier J.-M., Absolute frequency measurement of the iodine-stabilized He-Ne laser at 633 nm, Appl. Phys. B., 2001, 72, 221-226 Ye J., Yoon T. H., Hall J. L., Madej A. A., Bernard J. E., Siemsen K. J., Marmet L., Chartier J.-M., Chartier A., Accuracy Comparison of Absolute Optical Frequency Measurement between Harmonic-Generation Synthesis and a Frequency-Division Femtosecond Comb, Phys. Rev. Lett., 2000, 85, 3797-3800	4e-12		
7.4	2003	Bernard J. E., Madej A. A., Siemsen K. J., Marmet L., Absolute frequency measurement of the HeNe I2 standard at 633 nm, Opt. Commun., 2001, 187, 211-218 Ye J., Yoon T. H., Hall J. L., Madej A. A., Bernard J. E., Siemsen K. J., Marmet L., Chartier J.-M., Chartier A., Accuracy Comparison of Absolute Optical Frequency Measurement between Harmonic-Generation Synthesis and a Frequency-Division Femtosecond Comb, Phys. Rev. Lett., 2000, 85, 3797-3800	3e-12		
4.2	2003	Sugiyama K., Onae A., Hong F.-L., Inaba H., Slyusarev S. N., Ikegami T., Ishikawa J., Minoshima K., Matsumoto H., Knight J. C., Wadsworth W. J., Russel P. St. J., Optical frequency measurement using an ultrafast mode-locked laser at NMIJ/AIST, 6th Symposium on Frequency Standards and Metrology, Ed. Gill P, World Scientific (Singapore), 2002, 427-434	1.4e-11		
8.2	2003	Lea S. N., Margolis H. S., Huang G., Rowley W. R. C., Henderson D., Barwood G. P., Klein H. A., Webster S. A., Blythe P., Gill P., Windeler R. S., Femtosecond Optical Frequency Comb Measurements of Lasers Stabilised to Transitions in 88Sr+, 171Yb+, and I2 at NPL, 6th Symposium on Frequency Standards and Metrology, Ed. Gill P, World Scientific (Singapore), 2002, 144-151	5.3e-12		

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CCL+CCTF mixed informations

XML files generator

[114Cd 641 THz] [View]

Reference frequencies + source data: (by transition) [CCL&CCTF]

[all] [View]

Global content view for final XML input data check

[all] [View]

CCL informations

See Reference frequencies list " For the meter"

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

[MeP_C2H2_1.54µm] [View]

CCTF informations

See Reference frequencies list "For the second"

annual calculation source data (CCTF use)

[all] [View]

Any comment to report ? Contact us

MeP_I2_633nm (for URI encoding issue check...)

Check for parsed elements from database , for XML content

View Frequency elements

label	freqlabel	target	mep	validfrom	validto	SRS	transitionname	compname	altcompname	frequency	uncertainty	unit	numberofrules	numberoffunces
474 THz - 127I2	474 THz	127I2	MeP_I2_633nm	2003-10-10			R(127) 11-5	a16	f	473612353604	9	\kilo\hertz	6	6

View rules

label	freqlabel	target	mep	description	nominal_value	nominal_unit	min_value	min_unit	max_value	max_unit
474 THz - 127I2	474 THz	127I2	MeP_I2_633nm	Frequency modulation width peak-to-peak	6	\mega\hertz	5.7	\mega\hertz	6.3	\mega\hertz
474 THz - 127I2	474 THz	127I2	MeP_I2_633nm	Power shift coefficient	0	\kilo\hertz\per\milli\watt	-1	\kilo\hertz\per\milli\watt	1	\kilo\hertz\per\milli\watt
474 THz - 127I2	474 THz	127I2	MeP_I2_633nm	cold finger temperature	15	\degreecelsius	14.8	\degreecelsius	15.2	\degreecelsius
474 THz - 127I2	474 THz	127I2	MeP_I2_633nm	One-way intracavity beam power	10	\milli\watt	5	\milli\watt	15	\milli\watt
474 THz - 127I2	474 THz	127I2	MeP_I2_633nm	cell wall temperature	25	\degreecelsius	20	\degreecelsius	30	\degreecelsius
474 THz - 127I2	474 THz	127I2	MeP_I2_633nm	detection case	3	\f				

View funces

label	freqlabel	target	mep	description	value	unit
474 THz - 127I2	474 THz	127I2	MeP_I2_633nm	cold finger temperature	3	\kilo\hertz
474 THz - 127I2	474 THz	127I2	MeP_I2_633nm	Frequency modulation width peak-to-peak	3	\kilo\hertz
474 THz - 127I2	474 THz	127I2	MeP_I2_633nm	beat-frequency measurements between two lasers	5	\kilo\hertz
474 THz - 127I2	474 THz	127I2	MeP_I2_633nm	cell wall temperature	2.5	\kilo\hertz
474 THz - 127I2	474 THz	127I2	MeP_I2_633nm	iodine purity	5	\kilo\hertz
474 THz - 127I2	474 THz	127I2	MeP_I2_633nm	One-way intracavity beam power	5	\kilo\hertz

CCL-CCTF database of recommended frequencies

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CCL+CCTF mixed informations

XML files generator

114Cd 641 THz [View]

Reference frequencies + source data: (by transition) [CCL&CCTF]

all [View]

Global content view for final XML input data check

all [View]

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See Reference frequencies list " For the meter"

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

MeP_C2H2_1.54µm [View]

CCTF informations

See Reference frequencies list "For the second"

annual calculation source data (CCTF use)

all [View]

Any comment to report ? Contact us

Related transitions from MeP_I2_633nm

component	x component	transition	operation	aref	transition_ref	diff	diff_unit	unc
a10	r'	P(54) 8-4	minus	a28	P(54) 8-4	-307.0	3	1
a10	l	R(127) 11-5	minus	a16	R(127) 11-5	-276.886	3	0.005
a11	q'	P(54) 8-4	minus	a28	P(54) 8-4	-298.2	3	1
a11	k	R(127) 11-5	minus	a16	R(127) 11-5	-268.842	3	0.005
a12	p'	P(54) 8-4	minus	a28	P(54) 8-4	-293.1	3	1
a12	j	R(127) 11-5	minus	a16	R(127) 11-5	-160.457	3	0.005
a13	o'	P(54) 8-4	minus	a28	P(54) 8-4	-289.7	3	1
a13	i	R(127) 11-5	minus	a16	R(127) 11-5	-138.892	3	0.005
a14	n'	P(54) 8-4	minus	a28	P(54) 8-4	-282.7	3	1
a14	h	R(127) 11-5	minus	a16	R(127) 11-5	-116.953	3	0.005
a15	j'	P(54) 8-4	minus	a28	P(54) 8-4	-206.1	3	0.2
a15	g	R(127) 11-5	minus	a16	R(127) 11-5	-13.198	3	0.005
a16	i'	P(54) 8-4	minus	a28	P(54) 8-4	-197.73	3	0.08
a16	f	R(127) 11-5	minus	a16	R(127) 11-5	0	3	0
a17	h'	P(54) 8-4	minus	a28	P(54) 8-4	-193.23	3	0.08
a17	e	R(127) 11-5	minus	a16	R(127) 11-5	13.363	3	0.005
a18	[illegible]	P(54) 8-4	minus	a28	P(54) 8-4	[illegible]	[illegible]	[illegible]

Example use of schema – 474 THz (633 nm)

```
curl -k -u ccl-cctf --url 'https://webtai.bipm.org/ccl-cctf/xml_auto.html?target=127I2|474+THz&date=2023-05-22'
```


```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
$\lambda = 632\ 991\ 212.58$ 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

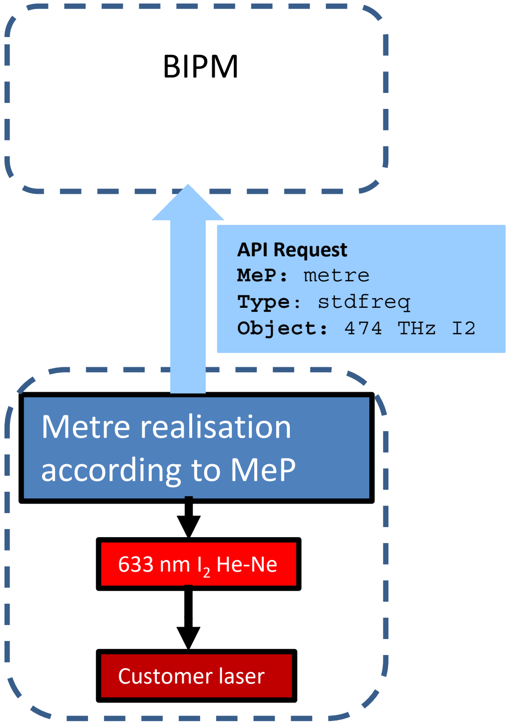
Adopted value: $f = 473\ 612\ 353\ 604\ (10)$ kHz $u_c/y = 2.1 \times 10^{-11}$

for which:

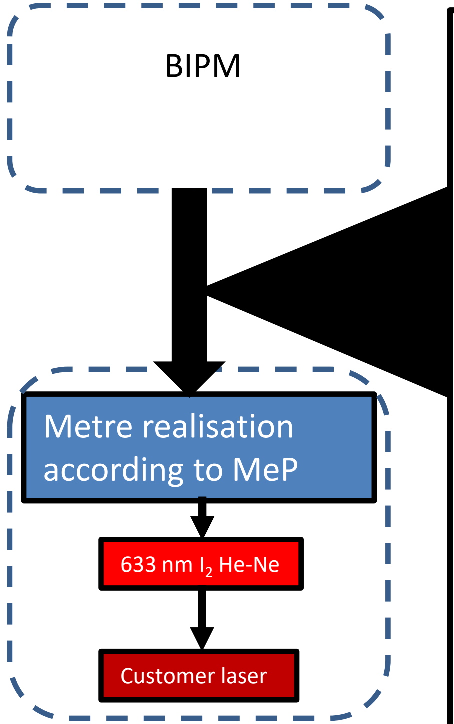
$\lambda = 632\ 991\ 212.579\ (13)$ fm $u_c/y = 2.1 \times 10^{-11}$


```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 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>

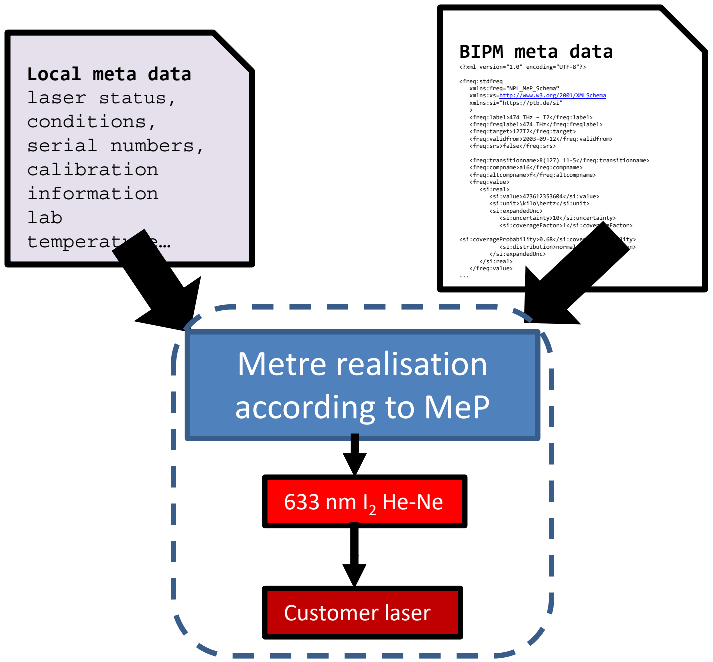
   <freq:transitionname>R(127) 11-5</freq:transitionname>
   <freq:compname>a16</freq:compname>
   <freq:altcompname>f</freq:altcompname>
   <freq:value>
      <si:real>
         <si:value>473612353604</si:value>
         <si:unit>\kilo\hertz</si:unit>
         <si:expandedUnc>
            <si:uncertainty>10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

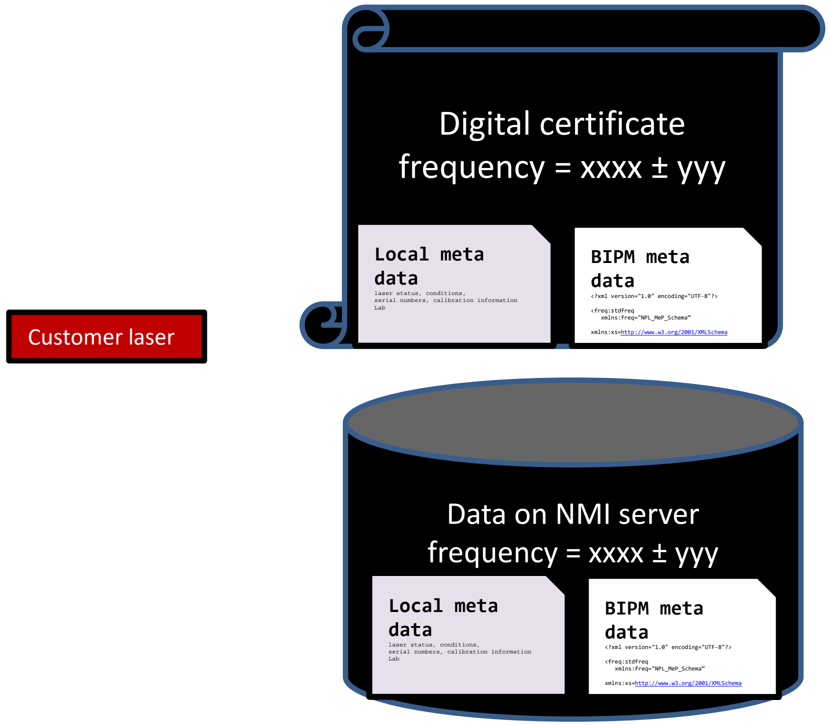
<si:coverageProbability>0.68</si:coverageProbability>
            <si:distribution>normal</si:distribution>
         </si:expandedUnc>
      </si:real>
   </freq:value>
...
```

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)





Outcomes

- Digital certificate (or data on NMI server) can hold 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

Publication and XML schemas

A digital framework for realising the SI—a proposal for the metre

A J Lewis *et al.* 2022 *Metrologia* **59** (4) 044004

https://doi.org/10.1088/1681-7575/ac7fce

NPL MeP standard frequencies XML schema

A J Lancaster *et al.* (2022)

https://doi.org/10.5281/zenodo.6412020

SmartCom Digital-SI (D-SI) XML exchange format for metrological data version 1.3.1

D Hutzschenreuter *et al.* (2020)

https://doi.org/10.5281/zenodo.3826517

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Metrologia 59 (2022) 044004 (9pp) https://doi.org/10.1088/1681-7575/ac7fce

A digital framework for realising the SI—a proposal for the metre

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Abstract
A current focus of the international metrology community is the digitalisation of documents, certificates and services in response to initiatives underway throughout industry and to the requirement to follow the principles of data being Findable, Accessible, Interoperable, and Reusable. We propose the key elements of a digital framework for the SI metre, at the point of realisation, showing how it may be implemented in practice. We give examples of direct benefits of this approach, which may be extended to other SI units.

Keywords: SI, metre, digitalisation, FAIR, XML, traceability, metadata

(Some figures may appear in colour only in the online journal)

1. Introduction: digitalisation in manufacturing and metrology

The process of digitalisation is revolutionising how products are designed, produced, used, and maintained throughout their lifecycle [1], transforming factory operations and processes and their supply chains. The drivers for digitalisation are varied, being largely focussed on improving: efficiency, productivity, accuracy, or responsiveness; and through these improvements, deriving a reduction in cost. Digitalised manufacturing also has a key part to play in design for recyclability and product end of life management [2].

Metrology lies at the heart of manufacturing, and the international system of units, the SI, lies at the heart of metrology. There are two main drivers for the digitalisation of metrology. Firstly, the need for metrology to assume the same digital status as other technologies underpinning the Industry 4.0 [3] and Factory of the Future [4] paradigms; and secondly the requirements for metrology data produced though calibration to fulfil as many Findable, Accessible, Interoperable, and Reusable (FAIR) data principles as possible, especially where a publicly-funded National Metrology Institute (NMI) is the provider [5] and they are re-using high-level information on SI unit definitions and realisations.

The digitalisation of metrology is being encouraged by the International Committee for Weights and Measures (CIPM) which has tabled a Draft Resolution for the General Conference on Weights and Measures (CGPM) which will meet for its 27th meeting in November 2022. The draft resolution, 'On the global digital transformation and the International System of Units' states:

> *'The General Conference on Weights and Measures… (anticipates)… creation of a fully digital representation of the SI, including robust, unambiguous, and machine-actionable representations of measurement units, values and uncertainties; … encourages … the CIPM to undertake the development and promotion of an SI digital framework, that will include the following features: a globally accepted digital representation of the SI … facilitating use of digital certificates in the existing robust infrastructure for the world-wide recognition and acceptance of calibration and measurement capabilities; the adoption of the FAIR principles (Findable, Accessible, Interoperable, and Reusable) for digital metrological data and metadata, …'*

The majority of members of the CIPM Consultative Committee for Length (CCL) plan to offer digital calibration certificates and digitalisation work is already underway at the

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88888888888 888                        888
    888     888                        888
    888     888                        888
    888     88888b.   8888b.  88888b.  888  888      888  888  .d88b.  888  888
    888     888 "88b     "88b 888 "88b 888 .88P      888  888 d88""88b 888  888
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    888     888  888 888  888 888  888 888 "88b      Y88b 888 Y88..88P Y88b 888
    888     888  888 "Y888888 888  888 888  888       "Y88888  "Y88P"   "Y88888
                                                          888
                                                     Y8b d88P
                                                      "Y88P"
```