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D-SI

The machine-readable SI format for the exchange of metrological data – version 1.3

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SmartCom WP 1 aims

D-SI*

D-SI = Digital System of Units

=

Universal data model for transfer of metrological data via digital communication

- Format must be
- unambiguous
- universal
- safe
- uniform

Metrology Standards

IT Standards

* European figurative mark and word mark proposed

Overview

1. Real quantity
2. Structure for SI units
3. Coverage regions
4. Complex quantity
5. List Data Model (general)
6. List of real quantities
7. List of complex quantities
8. Structure for non-SI units (hybrid)
9. Further application examples

Overview

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Uniform data format

Minimum requirement — Maximum information

$$\mathrm{Y} = y\ [\mathrm{SI}] \quad U_{95}(k)\ \text{distribution UTC}$$

Coordinated Universal Time

type of distribution normal, uniform, …

coverage factor

measurement uncertainty + confidence interval

Si-unit

measurement value

SmartCom Real format: Atomic

Y = *y* [SI] $U_{95}(k)$ distribution UTC

real *quantity type* *atomic*	**components** (of the real quantity type)			
	label	value	unit	dateTime
basic real quantity (atomic)				

mandatory | optional

- SI unit format
- VIM
- ISO 80000
- CODATA
- IEEE 754
- RFC 362 (UTF-8)
- ISO 8601

- value and unit are the minimum requirement
- optional label and dateTime information

(details on data types on the next slides)

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Definition of data-types I

component	data type	Description
value	decimal number format	**numerical value** of the real quantity (details outlined on following slides)
unit	SI-unit format	String of characters providing **the unit** of the quantity (details outlined in section 3)
label	String of characters	An unregulated text field for the **identification of the real element**. A label may for example provide the name of the underlying quantity. Specific vocabularies (and/or ontologies) of the application for which the data format is used may be defined by users.
dateTime	ISO 8601 UTC time	**local time** with an information about the **offset to UTC time** (details outlined on following slides)

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Decimal number format

Basic number format:

- decimal numbers only with the dot as separator

  3.14 +67. -0.0 .678 -0.978

- integer exponent in scientific form allowed

  9.e3 0.2E-5 -3E10 -4.17e+4

- also representation of integer numbers allowed

  0 12 7689 -23

- recommendation to be conform with IEEE 754 double precision

- no NaN, INF, null

dateTime (ISO 8601)

ISO 8601(2004) format for time stamp

2019-06-03T11:30:01.04+02:00

local time with offset to UTC time (Coordinated Universal Time)

decimal value for second part

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UTF-8 encoding (RFC 362)

Background:

- All data in IT is encoded binary.
- There exist different code tables that describe how to encode human-readable letters in binary form.
- Well known code tables are ASCII, Unicode, UTF-8, UTF-16,…
- If for example the encoding is Unicode but the decoding in human-readable form is ASCII, then one may get gibberish output.

Resulting requirement

- Make sure to use UTF-8 encoding and decoding to always have the correct interpretation of character data
- UTF-8 = Universal Code Character Set Transformation Format 8-bit
- ASCII encoding is a subset of UTF-8 encoding
- UTF-8 is supported by many software tools, browsers, …

SmartCom — Real format: Extended

Y = y [SI] $U_{95}(k)$ distribution UTC

real *quantity type* *extended*	**components** (of the real quantity type): label	value	unit	dateTime	expandedUnc (S)	coverageInterval (S)
Basic real with expanded measurement uncertainty	optional	mandatory	mandatory	optional	mandatory	
Basic real with coverage interval (probabilistic-symmetric)	optional	mandatory	mandatory	optional		mandatory

(S) sub type — mandatory — optional

- GUM
- SI unit format
- VIM
- ISO 80000
- CODATA
- IEEE 754
- RFC 362 (UTF-8)
- ISO 8601

- uncertainty information now encapsulated by the elements „expandedUnc“ and „coverageInterval“
- details on the elements on the following slides.

SmartCom Expanded measurement uncertainty

Y = y [SI] $U_{95}(k)$ distribution UTC

sub type - expandedUnc *expanded measurement uncertainty for real quantity*	**components** (of the expandedUnc type)			
	uncertainty	**coverageFactor**	**coverageProbability**	**distribution**
expanded measurement uncertainty				

mandatory	**optional**

GUM

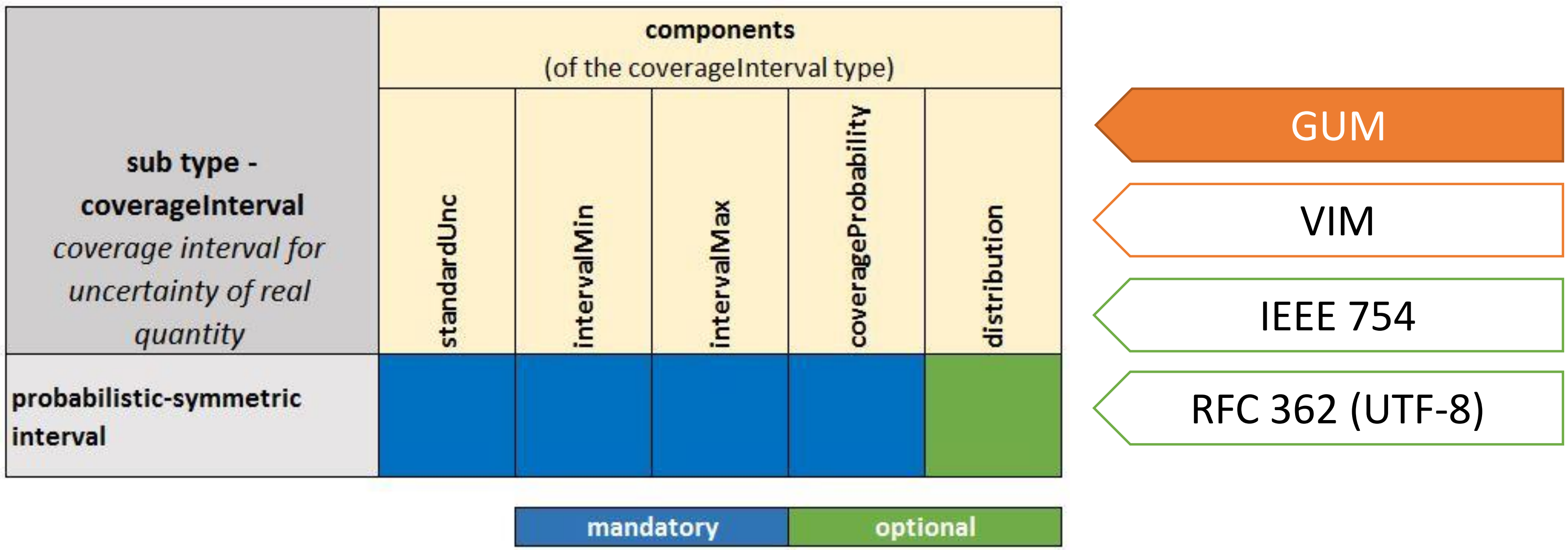
VIM

IEEE 754

RFC 362 (UTF-8)

- mandatory and optional components for statement of uncertainty as before but all is encapsulated in the element „expandedUnc“
- „uncertainty“ is half width of coverage interval

Coverage interval



- Probabilistic-symmetric coverage interval encapsulated in type „coverageInterval“.
- The coverage interval can be provided with the additional component „standardUnc“ for the standard uncertainty (propagation of uncertainty).
- The standard uncertainty is needed for application of GUM’s Law of Propagation of Uncertainty.

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Definition of data-types II

Data types in „expandedUnc“ and „coverageInterval“ elements:

component	data type	description
uncertainty	constraint decimal number format	Value of the expanded measurement uncertainty (half length of coverage interval) – positive decimal number
coverageFactor	constraint decimal number format	positive decimal number greater or equal to „1“ – no scientific exponent
coverageProbability	constraint decimal number format	positive decimal number within the interval [0,1] – no scientific exponent
intervalMin	decimal number format	upper bound of probabilistic symmetric coverage interval
intervalMax	decimal number format	lower bound of probabilistic-symmetric coverage interval
distribution	String of characters	textual definition of the distribution of the measured quantity value

Examples: real extended

Example: XML implementation of real with expanded uncertainty

```
<si:real>
    <si:label>temperature</si:label>
    <si:value>20.10</si:value>
    <si:unit>\degreecelsius</si:unit>
    <si:expandedUnc>
        <si:uncertainty>0.50</si:uncertainty>
        <si:coverageFactor>2</si:coverageFactor>
        <si:coverageProbability>0.95</si:coverageProbability>
        <si:distribution>normal</si:distribution>
    </si:expandedUnc>
</si:real>
```

Example: XML implementation of real with coverage interval

```
<si:real>
    <si:label>temperature</si:label>
    <si:value>20.10</si:value>
    <si:unit>\degreecelsius</si:unit>
    <si:coverageInterval>
        <si:standardUnc>0.25</si:standardUnc>
        <si:intervalMin>19.60</si:intervalMin>
        <si:intervalMax>20.60</si:intervalMax>
        <si:coverageProbability>0.95</si:coverageProbability>
        <si:distribution>normal</si:distribution>
    </si:coverageInterval>
</si:real>
```

basic real

expanded uncertainty

coverage interval

Units of uncertainty values

unit of real

```
<si:real>
    <si:label>temperature</si:label>
    <si:value>20.10</si:value>
    <si:unit>\degreecelsius</si:unit>
    <si:coverageInterval>
        <si:standardUnc>0.25</si:standardUnc>
        <si:intervalMin>19.60</si:intervalMin>
        <si:intervalMax>20.60</si:intervalMax>
        <si:coverageProbability>0.95</si:coverageProbability>
        <si:distribution>normal</si:distribution>
    </si:coverageInterval>
</si:real>
```

- the local unit in „real“ is also applied to the numerical values that give the uncertainty.
- In the example above, these numerical values are „standardUnc“, „intervalMin“ and „intervalMax“.
- In the case of the expanded uncertainty, the component „uncertainty“ must have a numerical value in the unit of „real“.

Real constants

Mathematical constants and **fundamental physical constants** (CODATA)

constant *quantity type*	components (of the constant quantity type)					
	label	value	unit	dateTime	uncertainty	distribution
constant quantity with an exact value	optional	mandatory	mandatory	optional		
constant quantity with an uncertainty	optional	mandatory	mandatory	optional	mandatory	optional

(S) sub type | mandatory | optional

(examples on next slide)

Values of fundamental physical constants:

- component „uncertainty“ is the standard deviation of an experimentally defined constant.
- For constants from CODATA, „uncertainty“ is the uncertainty reported in the CODATA list.

Values of mathematical constants that must be rounded (i.e. PI):

- „uncertainty“ is the standard deviation of a rectangular distribution that contains the exact value of the constant with 100% probability

Constant: examples

Example: XML representation of math. constant pi:

```
<si:constant>
    <si:label>pi</si:label>
    <si:value>3.140</si:value>
    <si:unit>\one</si:unit>
    <si:uncertainty>0.003</si:uncertainty>
    <si:didtribution>rectangular</si:didtribution>
</si:constant>
```

„uncertainty“ of rounded value (≈0.005/sqrt(3))

Example: XML representation of Planck constant before 2019-05-20:

```
<si:constant>
    <si:label>planck constant</si:label>
    <si:value>6.626070040e-34</si:value>
    <si:unit>\kilogram\metre\tothe{2}\second\tothe{-1}</si:unit>
    <si:dateTime>2018-11-16T12:30:01.67-01:00</si:dateTime>
    <si:uncertainty>8.1e-42</si:uncertainty>
    <si:distribution>normal</si:distribution>
</si:constant>
```

CODATA 2014 value

Example: XML representation of Planck constant since 2019-05-20:

```
<si:constant>
    <si:label>planck constant</si:label>
    <si:value>6.62607015e-34</si:value>
    <si:unit>\kilogram\metre\tothe{2}\second\tothe{-1}</si:unit>
    <si:dateTime>2019-05-21T02:00:00.10-01:00</si:dateTime>
</si:constant>
```

new SI value

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SI units – unit identifiers

Unit type	Unit example	Symbol	SmartCom identifiers
SI base units	metre kilogram	m kg	\metre \kilogram
SI derived units with own symbol	radian dimension number newton degree Celsius gram	rad N °C g	\radian \one \newton \degreecelsius \gram
non-SI units allowed with the SI	degree hour arcminute	° h ‘	\degree \hour \arcminute
SI prefix	micro	µ	\micro
Exponent operator	metre squared	m^2	\metre\tothe{2}

- All identifiers are lower case
- Unit „one“ is the unit for dimension number (i.e. for counts and for ratios of quantities of the same unit)

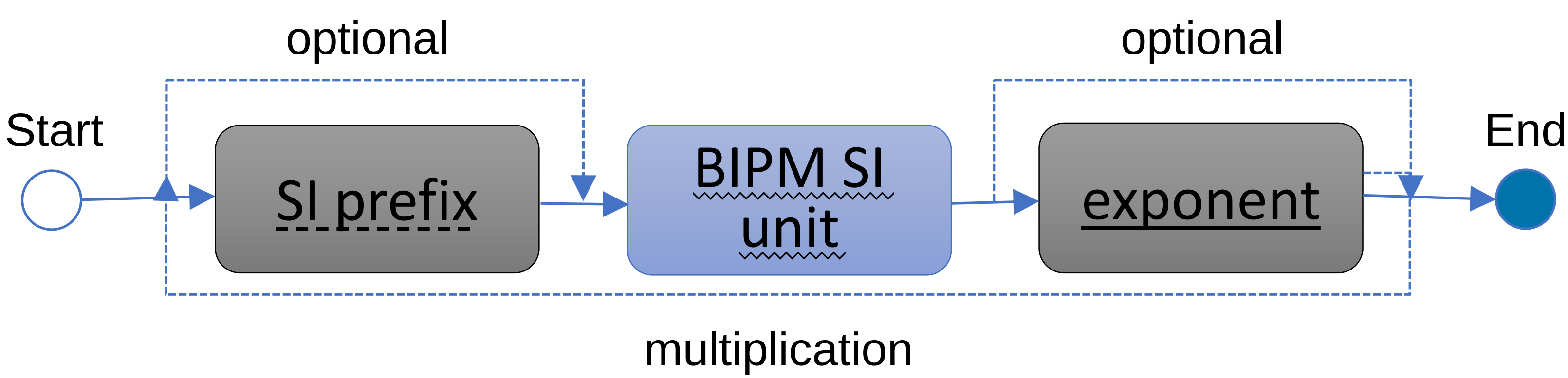
SI unit syntax

Changes:

- Syntax reduced to combination of prefix, unit, exponent and multiplication
- Deprecated „\per“ operator for division of units
- No blank spaces, tabs or carriage returns before, within or after the unit expression.

Unit language for BIPM SI brochure

$\frac{\mathrm{km}}{\mathrm{h}}$ → \kilo\metre\hour\tothe{-1}



SI-units syntax rules

Further syntax rules adapted to IEC/TS 62720 that extend the rules from BIPM SI brochure:

- Each unit shall have only one prefix (i.e. no „\milli\kilo\metre“)
- Decimal multiples of the mass unit are build with a SI prefix and the unit identifier „\gram“ (i.e. „\milli\gram“)
- The SI base unit for mass shall not be combined with a prefix (i.e. no „\nano\kilogram“)
- The unit for quantities of dimension number shall not be combined with a prefix (i.e. no „\kilo\one“)
- Furthermore, a prefix is not permitted for the following units: \degree, \degreecelsius, \kilogram, \mmhg, \minute, \hour, \day,
  \second\tothe{-1} (rotation), \minute\tothe{-1} (rotation)
- If a unit is assigned with an exponent, then the exponent is applied to the unit and the prefix that is defined for the unit (i.e. „\kilo\metre\tothe{3}“ is equivalent to 10^9 m^3)

SI-units syntax rules

Further syntax rules adapted to IEC/TS 62720 that extend the rules from BIPM SI brochure (continued from previous slide):

- Unit of dimension number shall not have an exponent (i.e. no „\one\tothe{3}“
- If a unit is combined by two or more units that build a ratio of units, then it is allowed to have either one prefix in the nominator, one prefix in the denominator or one prefix in each of the both components of the ratio (i.e. allowed „\millli\metre\nano\second\tothe{-1}“). To have two ore more prefixes in either the nominator of the unit or in the denominator of the unit is forbidden.

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D-SI implementation requirements

The D-SI data model is a unique structure for the exchange of metrological data.

The implementation of the D-SI data model is the realization of this structure in a data format like XML, JSON, CSV and many more.

The implementation may have additional requirements such as:

- Canonic and unique representation of units
- Enumeration of allowed units with fixed identifiers
- Enumeration of allowed distributions with fixed values
- Considerations on application specific requirements (i.e. strict rules for application of some cryptographic algorithms)

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SI-units syntax examples

- The International System of Units (SI) (and the here presented unit format derived from the SI) allows to express several units in different forms as outlined in the examples below.

$\frac{\mathrm{m}}{\mathrm{m}}$ → \metre\metre\tothe{-1} or \radian or \one

m^2 → \metre\tothe{2} or \metre\metre

$\frac{\mathrm{m}^3}{\mathrm{m}}$ → \metre\tothe{3}\metre\tothe{-1} or \metre\tothe{2}

- **For helping to decide which expression should be used in the D-SI, the following recommendations are made:**
    1. Choose expressions with SI-base units above other unit symbols.
    2. Choose expressions using exponents above multiple alignment of one and the same unit term.
    3. Use algebraical reduction according to requirements of the underlying metrological area.

SmartCom SI-units syntax examples (cont.)

- When using the SI unit format and converting units from different formats into the SI unit format, special regards should be taken into account on the correct interpretation of the unit.
- The interpretation of existing (human-readable) formats can be ambiguous like:

cd	→	\candela	or	\centi\day ?
mm	→	\milli\metre	or	\metre\metre ?

- In many cases documentation on the unit format is missing. Furthermore, different separators for multiplication of units and powers are in use like:

m · m	→	\metre\metre
m m	→	\metre\metre
m2	→	\metre\tothe{2}
m^2	→	\metre\tothe{2}

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Overview

SmartCom Application of coverage regions

<u>Coverage regions for multivariate quantities</u>

Application of the coverage regions:

- provide bivariate uncertainty for complex quantities
- provide multivariate uncertainty for vectors of real & complex quantities

Coverage regions in our metadata format and wording:

- GUM S2: elliptical coverage region & hyper-ellipsoidal coverage region
  -> D-SI: ellipsoidalRegion
- GUM S2: rectangular coverage region & hyper-rectangular coverage region
  -> D-SI: rectangularRegion

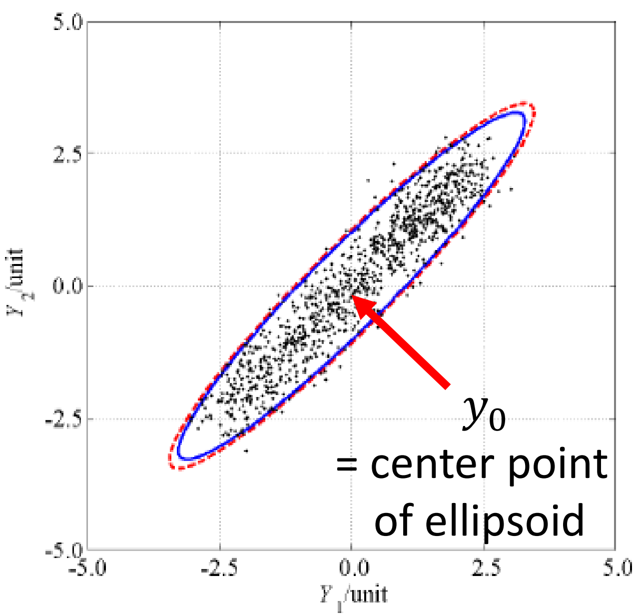
Not considered in our format:

- GUM: smallest coverage region
  -> D-SI: subject to modeling using fundamental components and lists from the metadata format

GUM S2 requirements

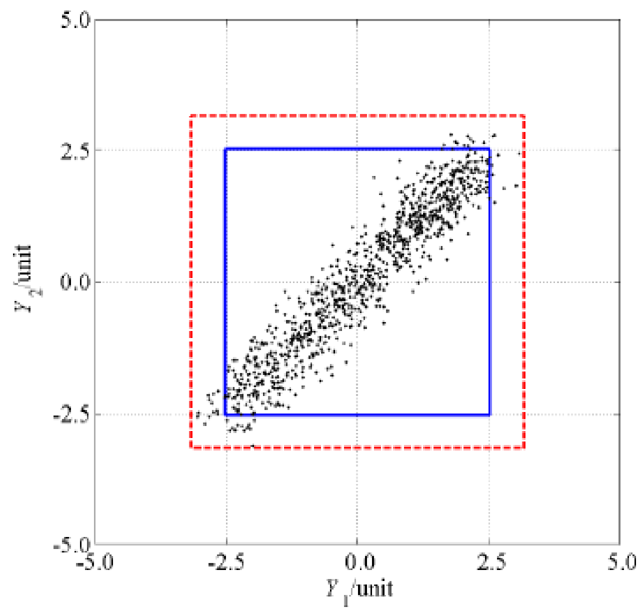
Hyper-ellipsoidal region

- $(y - y_0)^T \boldsymbol{U}_y^{-1} (y - y_0) = k_p$
- $\boldsymbol{U}_y$ (covariance matrix)
- p (coverage probability)
- k_p (coverage factor / ellipsoid size scale factor)



Hyper-rectangular region

- $y_j \pm k_q u(y_j)$
- $u(y_j)$ $(j = 1, .., m)$ (std. uncert.)
- k_q (coverage factor)
- $q = 1 - (1 - p)/m$
- p (coverage probability)



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Hyper-ellipsoidal region

sub type - ellipsoidalRegion *hyper-ellipsoidal coverage region*	**components** (of the ellipsoidalRegion type)			
	covarianceMatrix (S)	coverageFactor	coverageProbability	distribution
n-dimensional ellipsoidal region	**dimension n x n**			

(s) sub-type	**mandatory**	**optional**

- In the revised definition of the hyper-ellipsoidal coverage region, the covariance information is encapsulated within a „covarianceMatrix“ element.
- The covariance information can be used to apply the law of propagation of uncertainty according to GUM supplement 2 on the data.
- The components that define the covariance matrix have been completely changed in comparison to older versions of the data model (see the slide after the next slide).

Hyper-rectangular region

sub type - **rectangularRegion** *hyper-rectangular coverage region*	components (of the rectangularRegion type)			
	covarianceMatrix (S)	coverageFactor	coverageProbability	distribution
n-dimensional rectangular region	dimension n x n			

(s) sub-type	mandatory	optional

- The revised definition of the hyper-rectangular coverage region does also allow to apply the law for the propagation of uncertainty from GUM supplement 2.
- Therefore, the covariance matrix was introduced as a component of the coverage region (see definition on the next slides).
- The bounds of the coverage region are calculated from the variance values within the covariance matrix.

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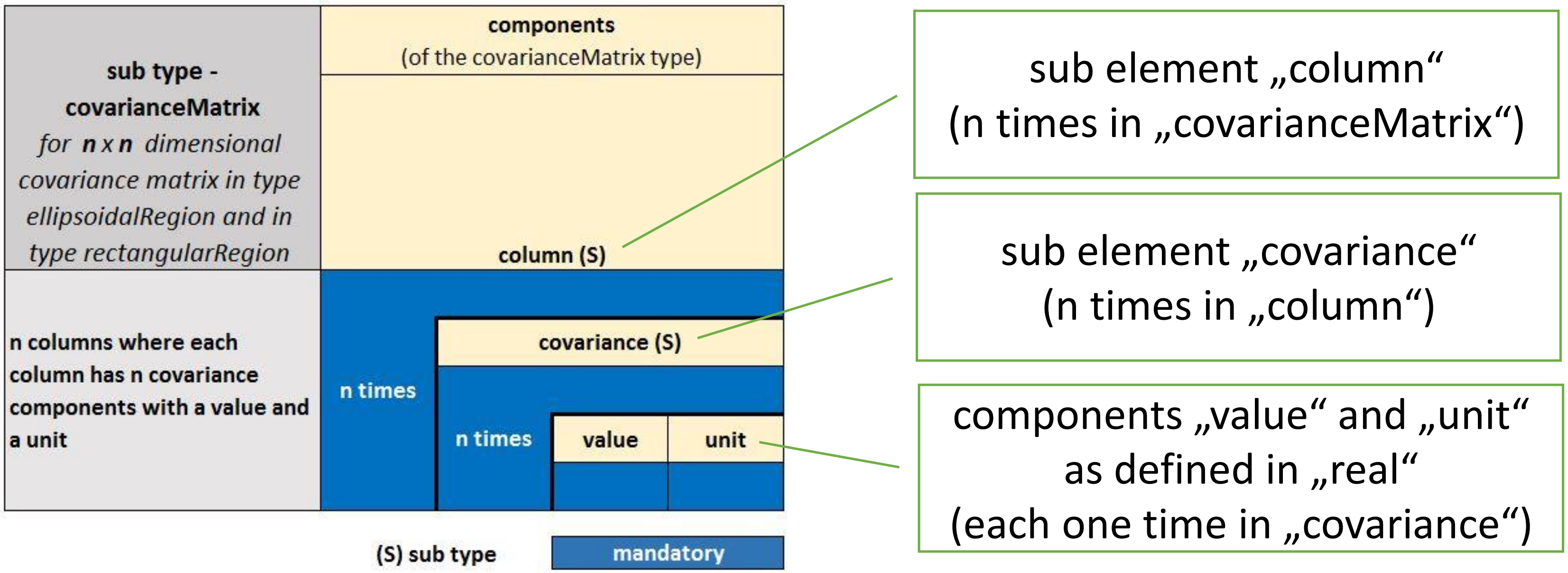
Covariance matrix

- The covariance matrix is a fundamental part of information on uncertainty of multivariate quantities according to GUM supplement 2.
- Hence, the covariance matrix was defined as independent data type.
- The hyper-ellipsoidal and hyper-rectangular coverage region are both deduced from the values in the covariance matrix.

Covariance matrix



- The originally proposed definition of the covariance matrix (in the ellipsoidal coverage region) was simplified to a column-wise representation of the data in the covariance matrix.
- Each covariance (and variance) value must provide a numerical value an a unit (data types as for components in definition of “real”).
- how to write the data from a covariance matrix into the sub type “covarianceMatrix” is explained on the next slide

Covariance matrix

Serialization of a 2x2 covariance matrix into an XML structure

XML serialization of covariance matrix

```xml
<si:covarianceMatrix>
    <!-- first (left) column of matrix -->
    <si:column>
        <si:covariance>
            <si:value>0.212</si:value>
            <si:unit>\metre\metre</si:unit>
        </si:covariance>
        <si:covariance>
            <si:value>0.051</si:value>
            <si:unit>\second\metre</si:unit>
        </si:covariance>
    </si:column>
    <!-- second (right) column of matrix -->
    <si:column>
        <si:covariance>
            <si:value>0.051</si:value>
            <si:unit>\metre\second</si:unit>
        </si:covariance>
        <si:covariance>
            <si:value>0.101</si:value>
            <si:unit>\second\second</si:unit>
        </si:covariance>
    </si:column>
</si:covarianceMatrix>
```

$$\begin{pmatrix} u_1^2 \\ c_{21} \end{pmatrix}$$ first column

covariance matrix

$$\boldsymbol{U}_y = \begin{pmatrix} u_1^2 & c_{12} \\ c_{21} & u_2^2 \end{pmatrix} = \begin{pmatrix} 0.212\ \mathrm{m}^2 & 0.051\ \mathrm{ms} \\ 0.051\ \mathrm{sm} & 0.101\ \mathrm{s}^2 \end{pmatrix}$$

$$\begin{pmatrix} c_{12} \\ u_2^2 \end{pmatrix}$$ second column

(u_1^2, u_2^2 are variance values where u_1, u_2 are std. uncertainty values; c_{21}, c_{12} are covariance values)

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Definition of data types III

component	data type	description
value (in covarianceMatrix)	constrained decimal number format	Must be a positive value in case of a variance. Else, the absolute value of correlation associated with the covariance value must be lesser or equal to 1.
unit (in covarianceMatrix)	SI-unit format	Product of the units that are associated by the covariance value
coverageFactor (in coverage region types)	constraint decimal number format	positive decimal number (for "rectangularRegion" the value of k_q with $q = 1 - (1 - p)/m$, coverage probability p and dimension of quantity m.
coverageProbability (in coverage region types)	constraint decimal number format	positive decimal number within the interval [0,1] – no scientific exponent
distribution (in coverage region types)	String of characters	textual definition of the distribution of the measured quantity value

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Overview

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Atomic complex

complex *quantity type* *atomic*	components (of the complex quantity type)							
	label	valueReal	valueImag	valueMagnitude	valuePhase	unit	unitPhase	dateTime
Cartesian coordinate form (atomic)	optional	mandatory	mandatory			mandatory		optional
Polar coordinate form (atomic)	optional			mandatory	mandatory	mandatory	mandatory	optional

mandatory	optional

Math:
a (real part)
b (imaginary part)
i (imaginary number)
Cartesian: $z = a + ib$

r (magnitude)
φ (phase angle)
Polar: $z = re^{i\varphi}$
$(r = \sqrt{a^2 + b^2})$

- A Cartesian coordinate form and a polar coordinate form are allowed
- The Cartesian coordinate form is recommended to be used
- Cartesian form with numerical values “valueReal” for the real part and “valueImag” for the imaginary part of the complex quantity
- Polar coordinate form with components “valueMagnitude” for the amplitude value and “valuePhase” for the phase angle value
- Each complex quantity has only one physical unit which is set by the component “unit”. This unit applies for the real and imaginary part as well as for the magnitude value.

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Definition of data types IV

component	data type	description
valueReal, valueImag, valueMagnitude, valuePhase	decimal number format	**numerical values** of the components of a complex quantity
unit (in complex)	SI-unit format	String of characters providing **the unit** of the quantity (details outlined in section 3)
unitPhase (in complex)	constrained SI-unit format	String of characters providing **the unit** of the phase angle of the complex quantity in polar coordinate form. The unit must represent an angular unit. Unit "\one" is not allowed. (details next slide)
label	String of characters	An unregulated text field for the **identification of the complex element**. A label may for example provide the name of the underlying quantity.
dateTime	ISO 8601 UTC time	**local time** with an information about the **offset to UTC time**

Angular units in complex

Angular units in the SI format that can be used for „unitPhase“:

- **Units for angle in radian unit:**
  - „\radian“ or „\metre\tothe{0}“ or „\metre\metre\tothe{-1}“
  - combinations of the unit „\radian“ with a SI prefix
- **Units for angle in degree and associated units**
  - „\degree“, „\arcminute“, „\arcsecond“

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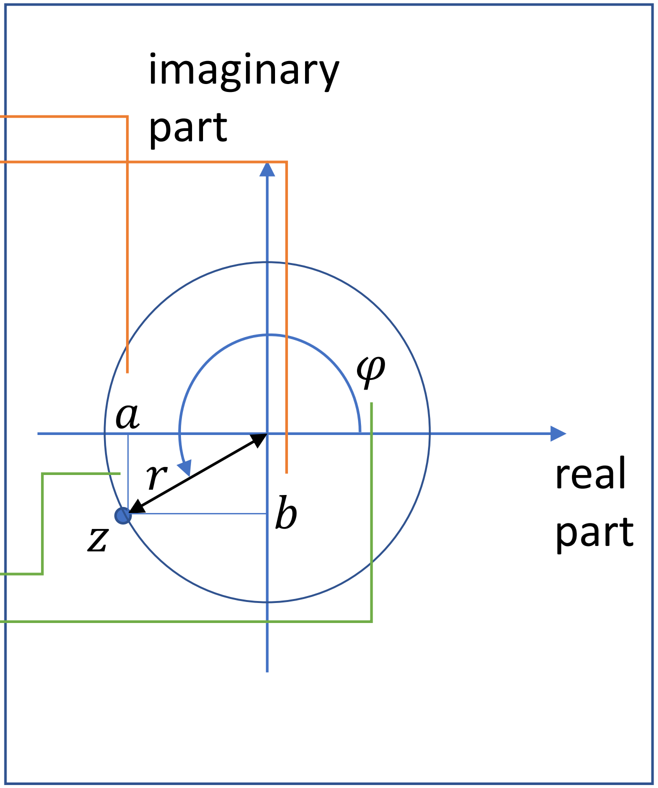
Examples complex I

Example: XML implementation of Cartesian complex quantity

```
<si:complex>
    <si:label>amplifier signal</si:label>
    <si:valueReal>-10.310</si:valueReal>
    <si:valueImag>5.010</si:valueImag>
    <si:unit>\volt</si:unit>
</si:complex>
```

Example: XML implementation of polar coordinate complex quantity

```
<si:complex>
    <si:label>amplifier signal</si:label>
    <si:valueMagnitude>11.463</si:valueMagnitude>
    <si:valuePhase>2.689</si:valuePhase>
    <si:unit>\volt</si:unit>
    <si:unitPhase>\radian</si:unitPhase>
</si:complex>
```



Complex value z in 2D complex space

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Extended complex

complex *quantity type* *extended*	**components** (of the complex quantity type)									
	label	valueReal	valueImag	valueMagnitude	valuePhase	unit	unitPhase	dateTime	ellipsoidalRegion (S)	rectangularRegion (S)
Cartesian coordinate form with hyper-ellipsoidal coverage region	optional	mandatory	mandatory			mandatory		optional	dimension 2 x 2	
Cartesian coordinate form with hyper-rectangular coverage region	optional	mandatory	mandatory			mandatory		optional		dimension 2 x 2
Polar coordinate form with hyper-ellipsoidal coverage region	optional			mandatory	mandatory	mandatory	mandatory	optional	dimension 2 x 2	
Polar coordinate form with hyper-rectangular coverage region	optional			mandatory	mandatory	mandatory	mandatory	optional		dimension 2 x 2

(S) sub type | mandatory | optional

- Similar to the case of real quantities the uncertainties are encapsulated within the „ellipsoidalRegion“ and „rectangularRegion“ sub type (definition in section 4).
- The “ellipsoidalRegion” component must provide a bivariate uncertainty with a covariance matrix of dimension 2x2
- The “rectangularRegion” component must provide a bivariate uncertainty with a covariance matrix of dimension 2x2

Examples complex II

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Example: XML implementation of complex with ellipsoidal coverage region

```
<si:complex>
    <si:valueReal>-10.310</si:valueReal>
    <si:valueImag>5.010</si:valueImag>
    <si:unit>\volt</si:unit>
    <si:ellipsoidalRegion>
        <si:covarianceMatrix>
            <si:column>
                <si:covariance>
                    <si:value>0.050</si:value>
                    <si:unit>\volt\volt</si:unit>
                </si:covariance>
                <si:covariance>
                    <si:value>-0.003</si:value>
                    <si:unit>\volt\volt</si:unit>
                </si:covariance>
            </si:column>
            <si:column>
                <si:covariance>
                    <si:value>-0.003</si:value>
                    <si:unit>\volt\volt</si:unit>
                </si:covariance>
                <si:covariance>
                    <si:value>0.105</si:value>
                    <si:unit>\volt\volt</si:unit>
                </si:covariance>
            </si:column>
        </si:covarianceMatrix>
        <si:coverageFactor>2.45</si:coverageFactor>
        <si:coverageProbability>0.95</si:coverageProbability>
        <si:distribution>normal-bivariate</si:distribution>
    </si:ellipsoidalRegion>
</si:complex>
```

atomic complex
Cartesian form

ellipsoidal
coverage region

covariance matrix

additional data of
coverage region

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Overview

1. Real quantity
2. Structure for SI units
3. Coverage regions
4. Complex quantity
5. List Data Model (general)
6. List of real quantities
7. List of complex quantities
8. Structure for non-SI units (hybrid)
9. Further application examples

Application of lists

Vector quantities from GUM Supplement 2:

- vector quantity of real components
  → D-SI: implementation as list of real quantities
- vector quantity of complex components
  → D-SI: implementation as list of complex quantities

Further features of vector quantities according to GUM supplement 2:

- optional multivariate uncertainty statements by using hyper-ellipsoidal and hyper-rectangular coverage regions (definition in draft part 2/3)
- optional global statement of measurement units that are valid for all components in the list
- optional global statement of a univariate uncertainty for lists of real quantities and a global bivariate uncertainty for lists of complex quantities

Recursive list (composite design: "a list of lists"):

- for implementation of data models with dimension two and higher (e.g. a matrix or a tensor)
- for implementation of individual data models (e.g. data of a Monte Carlo simulation or data representing a smallest coverage region)

List: atomic data model

list *of quantities type* atomic	components (of the list type)				
	label	real (S)	complex (S)	list (S)	dateTime
basic list of real (atomic)		**n times**			
basic list of complex (atomic)			**n times**		
recursive list of lists				**n times**	

(S) sub type	**mandatory**	**optional**

- „real“ from section 2
- „complex“ from section 5
- „label“ and „dateTime“ data types as defined for „real“

- Either a list of only „real“ quantities, only „complex“ quantities or only „list“ components.
- Optional „label“ of list and „dateTime“ component for a time stamp that may state the data when the list was recorded.
- The list of real and complex can be extended with additional uncertainty statements (see sections 7 & 8).

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Examples: atomic list

Example: list of two real quantities

```
<si:list>
    <si:real>
        <si:value>1.00</si:value>
        <si:unit>\metre</si:unit>
    </si:real>
    <si:real>
        <si:value>1.00</si:value>
        <si:unit>\second</si:unit>
    </si:real>
</si:list>
```

Example: list of two complex quantities

```
<si:list>
    <si:complex>
        <si:valueReal>-10.310</si:valueReal>
        <si:valueImag>5.010</si:valueImag>
        <si:unit>\volt</si:unit>
    </si:complex>
    <si:complex>
        <si:valueReal>-10.510</si:valueReal>
        <si:valueImag>5.510</si:valueImag>
        <si:unit>\volt</si:unit>
    </si:complex>
</si:list>
```

Example: list of two lists with real quantities

```
<si:list>
    <si:list>
        <si:real>
            <si:value>2.34</si:value>
            <si:unit>\metre</si:unit>
        </si:real>
        <si:real>
            <si:value>3.34</si:value>
            <si:unit>\metre</si:unit>
        </si:real>
    </si:list>
    <si:list>
        <si:real>
            <si:value>4.34</si:value>
            <si:unit>\metre</si:unit>
        </si:real>
        <si:real>
            <si:value>5.34</si:value>
            <si:unit>\metre</si:unit>
        </si:real>
    </si:list>
</si:list>
```

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General aspects of lists

1. Data overhead reduction: global statement of units and uncertainties for real and complex quantities that are provided in a list (must have two or more real or complex components)
2. Global statements of univariate uncertainty (real) or bivariate uncertainty (complex) only in combination with global units allowed
3. If global unit or uncertainty is provided, then no local unit and/or uncertainty within real and respectively complex are allowed.
4. Global multivariate uncertainty statements are allowed for lists of real and complex elements
5. Local and global label and dateTime elements are both allowed to be used.
6. No global units and/or uncertainty for list of lists
7. Unlimited depth of list nesting (recursive nesting)

more details in section 7 & 8

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Overview

1. Real quantity
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3. Coverage regions
4. Complex quantity
5. List Data Model (general)
6. **List of real quantities**
7. List of complex quantities
8. Structure for non-SI units (hybrid)
9. Further application examples

SmartCom

Extended list of real

list *of real quantities type extended*	components (of the list of real quantities type)						
	label	dateTime	listUnit	listUnivariateUnc (S)	real (S)	ellipsoidalRegion (S)	rectangularRegion (S)
real quantities with an optional list unit			replaces unit in real		n times		
independent real quantities with a list uncertainty (univariate)			replaces unit in real	replaces uncert. in real	n times		
multivariate vector of real quantities with a hyper-ellipsoidal coverage region			replaces unit in real		n times	dimension n x n	
multivariate vector of real quantities with a hyper-rectangular coverage region			replaces unit in real		n times		dimension n x n

(S) sub type — mandatory (blue) — optional (green)

Additional components in „list“ that can only be used with „real“:

- listUnit
- listUnivariateUnc

Additional components in „list“ that provide a global multivariate uncertainty:

- ellipsoidalRegion
- rectangularRegion

SmartCom

Features of list of real

- Is a list of real quantities (at least one real quantity must be contained)
- Allows the specification of a **global unit** („listUnit")
  - only if two ore more real quantities are contained in the list
  - if a global unit is specified, then the local units in the „real" components must not be provided
- Allows the definition of a **global univariate uncertainty**
  - only if two or more real quantities that are also independent
  - only in combination with a global unit
  - only if the uncertainty of all real quantities in the list can either be expressed by the expanded measurement uncertainty or by the coverage interval
- Allows to state a **multivariate uncertainty** that is valid for all real quantities and that expresses correlation between the real quantities in the list. Requires at least two real quantities in the list.

Details on these aspects are outlined on the next slides.

Global unit

- The unit in the component „listUnit“ is the reference unit of all „real“ quantities in the „list“.
- It is not allowed to provide a „unit“ component in the „real“ components in the „list“, if the „list“ provides a „listUnit“.
- A global unit can be combined with a global univariate uncertainty statement (described under global univariate uncertainty)
- A global unit can also be combined with a global multivariate uncertainty statement for a list of real quantities (described under global multivariate uncertainty)
- The difference between using the global unit and local units is outlined on the next slide.
- It is recommended to use a global unit if the data allow it.

Examples: list of real I

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Difference between global and local unit

Example: XML implementation of the list data model with three real components.

```
<si:list>
    <si:real>
        <si:value>2.34</si:value>
        <si:unit>\metre</si:unit>
    </si:real>
    <si:real>
        <si:value>3.34</si:value>
        <si:unit>\metre</si:unit>
    </si:real>
    <si:real>
        <si:value>4.34</si:value>
        <si:unit>\metre</si:unit>
    </si:real>
</si:list>
```

local units

Example: XML implementation of the list data model with three real components. A global unit is stated.

```
<si:list>
    <si:listUnit>\metre</si:listUnit>
    <si:real>
        <si:value>2.34</si:value>
    </si:real>
    <si:real>
        <si:value>3.34</si:value>
    </si:real>
    <si:real>
        <si:value>4.34</si:value>
    </si:real>
</si:list>
```

global unit

SmartCom Global univariate uncertainty (1/2)

list *of real quantities type extended*	components (of the list of real quantities type)						
	label	dateTime	listUnit	listUnivariateUnc (S)	real (S)	ellipsoidalRegion (S)	rectangularRegion (S)
real quantities with an optional list unit	optional	optional	replaces unit in real (optional)		n times (mandatory)		
independent real quantities with a list uncertainty (univariate)	optional	optional	replaces unit in real (mandatory)	replaces uncert. in real (mandatory)	n times (mandatory)		
multivariate vector of real quantities with a hyper-ellipsoidal coverage region	optional	optional	replaces unit in real (optional)		n times (mandatory)	dimension n x n (mandatory)	
multivariate vector of real quantities with a hyper-rectangular coverage region	optional	optional	replaces unit in real (optional)		n times (mandatory)		dimension n x n (mandatory)

(S) sub type — mandatory — optional

- global uncertainties encapsulated in the component „listUnivariateUnc“ in a list of real quantities
- global uncertainty must be stated together with global unit
- definition of type “listUnivariateUnc” on next slide

SmartCom Global univariate uncertainty (2/2)

sub type - **globalUnivariateUnc** *for global univariate uncertainty in list of real quantities*	**components** (of global univariate uncertainty type): **expandedUnc (S)**	**components** (of global univariate uncertainty type): **coverageInterval (S)**
Basic real with expanded measurement uncertainty	mandatory	
Basic real with coverage interval (probabilistic-symmetric)		mandatory

(s) sub-type — **mandatory**

- Selection of either expanded measurement uncertainty („expandedUnc“) or coverage interval („coverageInterval“) for global uncertainty of a list of real quantities.
- The data types of the uncertainty data models are those defined in section 2 for „real“ quantities.
- The global unit is also the reference unit for “uncertainty” in the “expandedUnc” type.
- The global unit is also the reference unit for „standardUnc“, “intervalMin” and “intervalMax” in the „coverageInterval“ type.

Example: list of real II

Example 4:

XML implementation of the list data model with local univariate uncertainty components

```
<si:list>
    <si:real>
        <si:value>2.34</si:value>
        <si:unit>\metre</si:unit>
        <si:expandedUnc>
            <si:uncertainty>0.01</si:uncertainty>
            <si:coverageFactor>2</si:coverageFactor>
            <si:coverageProbability>0.95</si:coverageProbability>
            <si:distribution>normal</si:distribution>
        </si:expandedUnc>
    </si:real>
    <si:real>
        <si:value>3.34</si:value>
        <si:unit>\metre</si:unit>
        <si:expandedUnc>
            <si:uncertainty>0.01</si:uncertainty>
            <si:coverageFactor>2</si:coverageFactor>
            <si:coverageProbability>0.95</si:coverageProbability>
            <si:distribution>normal</si:distribution>
        </si:expandedUnc>
    </si:real>
</si:list>
```

local unit

local expanded uncertainty

SmartCom Example: list of real III

Example 5:

Example from previous slide simplified by global unit and uncertainty statement.

```
<si:list>
    <si:listUnit>\metre</si:listUnit>
    <si:listUnivariateUnc>
        <si:expandedUnc>
            <si:uncertainty>0.01</si:uncertainty>
            <si:coverageFactor>2</si:coverageFactor>
            <si:coverageProbability>0.95</si:coverageProbability>
            <si:distribution>normal</si:distribution>
        </si:expandedUnc>
    </si:listUnivariateUnc>
    <si:real>
        <si:value>2.34</si:value>
    </si:real>
    <si:real>
        <si:value>3.34</si:value>
    </si:real>
</si:list>
```

global unit

global expanded uncertainty

Real list with multivariate uncertainty

list *of real quantities type extended*	components (of the list of real quantities type)						
	label	dateTime	listUnit	listUnivariateUnc (S)	real (S)	ellipsoidalRegion (S)	rectangularRegion (S)
real quantities with an optional list unit			replaces unit in real		n times		
independent real quantities with a list uncertainty (univariate)			replaces unit in real	replaces uncert. in real	n times		
multivariate vector of real quantities with a hyper-ellipsoidal coverage region			replaces unit in real		n times	dimension n x n	
multivariate vector of real quantities with a hyper-rectangular coverage region			replaces unit in real		n times		dimension n x n

(S) sub type | mandatory | optional

- Representation of a vector quantity with "real" components and an multivariate uncertainty statement by a hyper-ellipsoidal coverage region or a hyper-rectangular coverage region.

- The uncertainty components "ellipsoidalRegion" and "rectangularRegion" refer to the data models for coverage regions in section 4

Examples: list of real IV

Example: XML implementation of the list data model with two real components and a global ellipsoidal coverage region.

multivariate uncertainty

```xml
<si:list>
    <si:real>
        <si:value>2.340</si:value>
        <si:unit>\metre</si:unit>
    </si:real>
    <si:real>
        <si:value>3.340</si:value>
        <si:unit>\second</si:unit>
    </si:real>
    <si:ellipsoidalRegion>
        <si:covarianceMatrix>
            <si:column>
                <si:covariance>
                    <si:value>0.212</si:value>
                    <si:unit>\metre\metre</si:unit>
                </si:covariance>
                <si:covariance>
                    <si:value>0.051</si:value>
                    <si:unit>\second\metre</si:unit>
                </si:covariance>
            </si:column>
            <si:column>
                <si:covariance>
                    <si:value>0.051</si:value>
                    <si:unit>\metre\second</si:unit>
                </si:covariance>
                <si:covariance>
                    <si:value>0.101</si:value>
                    <si:unit>\second\second</si:unit>
                </si:covariance>
            </si:column>
        </si:covarianceMatrix>
        <si:coverageFactor>2.45</si:coverageFactor>
        <si:coverageProbability>0.95</si:coverageProbability>
        <si:distribution>normal-multivariate</si:distribution>
    </si:ellipsoidalRegion>
</si:list>
```

Example: XML implementation of the list data model with two real quantities and a global rectangular coverage region.

multivariate uncertainty

```xml
<si:list>
    <si:real>
        <si:value>2.340</si:value>
        <si:unit>\metre</si:unit>
    </si:real>
    <si:real>
        <si:value>3.340</si:value>
        <si:unit>\second</si:unit>
    </si:real>
    <si:rectangularRegion>
        <si:covarianceMatrix>
            <si:column>
                <si:covariance>
                    <si:value>0.212</si:value>
                    <si:unit>\metre\metre</si:unit>
                </si:covariance>
                <si:covariance>
                    <si:value>0.051</si:value>
                    <si:unit>\second\metre</si:unit>
                </si:covariance>
            </si:column>
            <si:column>
                <si:covariance>
                    <si:value>0.051</si:value>
                    <si:unit>\metre\second</si:unit>
                </si:covariance>
                <si:covariance>
                    <si:value>0.101</si:value>
                    <si:unit>\second\second</si:unit>
                </si:covariance>
            </si:column>
        </si:covarianceMatrix>
        <si:coverageFactor>2.24</si:coverageFactor>
        <si:coverageProbability>0.95</si:coverageProbability>
        <si:distribution>normal-multivariate</si:distribution>
    </si:rectangularRegion>
</si:list>
```

Example: units of multivariate regions

Example: “list” with two real quantities and a multivariate ellipsoidal coverage region

```
<si:list>
    <si:real>
        <si:value>2.340</si:value>
        <si:unit>\metre</si:unit>
    </si:real>
    <si:real>
        <si:value>3.340</si:value>
        <si:unit>\second</si:unit>
    </si:real>
    <si:ellipsoidalRegion>
        <si:covarianceMatrix>
            <si:column>
                <si:covariance>
                    <si:value>0.212</si:value>
                    <si:unit>\metre\metre</si:unit>
                </si:covariance>
                <si:covariance>
                    <si:value>0.051</si:value>
                    <si:unit>\second\metre</si:unit>
                </si:covariance>
            </si:column>
            <si:column>
                <si:covariance>
                    <si:value>0.051</si:value>
                    <si:unit>\metre\second</si:unit>
                </si:covariance>
                <si:covariance>
                    <si:value>0.101</si:value>
                    <si:unit>\second\second</si:unit>
                </si:covariance>
            </si:column>
        </si:covarianceMatrix>
        <si:coverageFactor>2.45</si:coverageFactor>
        <si:coverageProbability>0.95</si:coverageProbability>
        <si:distribution>normal-multivariate</si:distribution>
    </si:ellipsoidalRegion>
</si:list>
```

unit A

unit B

units of real components

units of covariance matrix values

unit A*A

unit B*A

unit A*B

unit B*B

Overview

1. Real quantity
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3. Coverage regions
4. Complex quantity
5. List Data Model (general)
6. List of real quantities
7. **List of complex quantities**
8. Structure for non-SI units (hybrid)
9. Further application examples

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Extended list of complex quantities

list *of complex quantities in Cartesian coordinate form type extended*	**components** (of the list of complex quantities type)						
	label	dateTime	listUnit	listBivariateUnc (S)	complex (S)	ellipsoidalRegion (S)	rectangularRegion (S)
complex quantities in Cartesian coordinate form with an optional list unit	optional	optional	replaces unit in complex (optional)		n times (mandatory)		
independent complex quantities in Cartesian coordinate form with a list uncertainty (bivariate)	optional	optional	replaces unit in complex (mandatory)	replaces uncert. in complex (mandatory)	n times (mandatory)		
multivariate vector of complex quantities in Cartesian coordinate form with a hyper-ellipsoidal coverage region	optional	optional	replaces unit in complex (optional)		n times (mandatory)	dimension 2n x 2n (mandatory)	
multivariate vector of complex quantities in Cartesian coordinate form with a hyper-rectangular coverage region	optional	optional	replaces unit in complex (optional)		n times (mandatory)		dimension 2n x 2n (mandatory)

(S) sub type — mandatory (blue) — optional (green)

For the Cartesian coordinate form

- Most aspects of the definition of a list of complex quantities are the same as for the list of “real” quantities (section7).
- Components “label” and “dateTime” can both be provided global and local.
- The extended list allows a global unit “listUnit”, a global bivariate uncertainty or a multivariate uncertainty.
- All „complex“ components must be in the Cartesian coordinate form!

Extended list of complex quantities

list *of complex quantities in polar coordinate form type - extended -*	**components** (of the list of complex quantities type)							
	label	dateTime	listUnit	listUnitPhase	listBivariateUnc (S)	complex (S)	ellipsoidalRegion (S)	rectangularRegion (S)
complex quantities in polar coordinate form with an optional list unit			both components replaces unit in complex			n times		
independent complex quantities in polar coordinate form with a list uncertainty (bivariate)			both components replaces unit in complex		replaces uncert. in complex	n times		
multivariate vector of complex quantities in polar coordinate form with a hyper-ellipsoidal coverage region			both components replaces unit in complex			n times	dimension 2n x 2n	
multivariate vector of complex quantities in polar coordinate form with a hyper-rectangular coverage region			both components replaces unit in complex			n times		dimension 2n x 2n

(S) sub type — mandatory — optional

For the polar coordinate form

- Most aspects of the definition of a list of complex quantities are the same as for the list of "real" quantities (section7).
- Components "label" and "dateTime" can both be provided global and local.
- The extended list allows the global units "listUnit" & "listUnitPhase, a global bivariate uncertainty or a multivariate uncertainty.
- All „complex" components must be in the polar coordinate form!

Features of list of complex

- Is a list of complex quantities (at least one complex quantity must be contained)
- Allows the specification of **global unit(s)** („listUnit“ & “listUnitPhase”)
  - only if two ore more complex quantities are contained in the list
  - if global units are specified, then the local units in the „complex“ components must not be provided
- Allows the definition of a **global bivariate uncertainty**
  - only if two or more complex quantities that are also independent
  - only in combination with a global unit(s)
  - only if the uncertainty of all complex quantities in the list can either be expressed by the ellipsoidal region or by the rectangular region (Sect. 4)
- Allows to state a **multivariate uncertainty** that is valid for all complex quantities and that expresses correlation between the real quantities in the list. Requires at least two real quantities in the list.

Details on these aspects are outlined on the next slides.

Examples: list of complex I

difference between global and local units for list of complex

Example: XML implementation of the list data model with two complex components (polar form).

```
<si:list>
    <si:complex>
        <si:valueMagnitude>-10.30</si:valueMagnitude>
        <si:valuePhase>1.50</si:valuePhase>
        <si:unit>\ampere</si:unit>
        <si:unitPhase>\radian</si:unitPhase>
    </si:complex>
    <si:complex>
        <si:valueMagnitude>-12.30</si:valueMagnitude>
        <si:valuePhase>1.80</si:valuePhase>
        <si:unit>\ampere</si:unit>
        <si:unitPhase>\radian</si:unitPhase>
    </si:complex>
</si:list>
```

Example: XML implementation of the list data model with two complex components (polar form) and global units are stated

```
<si:list>
    <si:listUnit>\ampere</si:listUnit>
    <si:listUnitPhase>\radian</si:listUnitPhase>
    <si:complex>
        <si:valueMagnitude>-10.0</si:valueMagnitude>
        <si:valuePhase>1.50</si:valuePhase>
    </si:complex>
    <si:complex>
        <si:valueMagnitude>-12.30</si:valueMagnitude>
        <si:valuePhase>1.80</si:valuePhase>
    </si:complex>
</si:list>
```

local units

global units

SmartCom — Global bivariate uncertainty (1/2)

list *of complex quantities in Cartesian coordinate form type extended*	**components** (of the list of complex quantities type)						
	label	dateTime	listUnit	listBivariateUnc (S)	complex (S)	ellipsoidalRegion (S)	rectangularRegion (S)
complex quantities in Cartesian coordinate form with an optional list unit	optional	optional	replaces unit in complex (optional)		n times (mandatory)		
independent complex quantities in Cartesian coordinate form with a list uncertainty (bivariate)	optional	optional	replaces unit in complex (mandatory)	replaces uncert. in complex (mandatory)	n times (mandatory)		
multivariate vector of complex quantities in Cartesian coordinate form with a hyper-ellipsoidal coverage region	optional	optional	replaces unit in complex (optional)		n times (mandatory)	dimension 2n x 2n (mandatory)	
multivariate vector of complex quantities in Cartesian coordinate form with a hyper-rectangular coverage region	optional	optional	replaces unit in complex (optional)		n times (mandatory)		dimension 2n x 2n (mandatory)

(S) sub type — mandatory (blue) — optional (green)

- Global units and global bivariate uncertainty are mandatory.
- All complex components must be independent.
- All „complex“ components must be of the same type (either Cartesian or polar coordinate form).
- Structure of sub type „listlBivaraiteUnc“ explained on next slide.

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Global bivariate uncertainty (2/2)

sub type - globalBivariateUnc *for global bivariate uncertainty in list of complex quantities*	**components** (of global bivariate uncertainty type)	
	ellipsoidalRegion (S)	**rectangularRegion (S)**
hyper-ellipsoidal coverage region	**dimension 2 x 2**	
hyper-rectangular coverage region		**dimension 2 x 2**

(s) sub-type — **mandatory**

- The sub types „ellipsoidalRegion" and „rectangularRegion" are those defined in section 4.
- Both „ellipsoidalRegion" and „rectangularRegions" must have a covariance matrix of dimension 2 x 2 (bivariate quantity).
- The global units that are stated together with the global bivariate uncertainties must also be the units for the components of the covariance matrix inside „ellipsoidalRegion" and repsectively inside „rectagularRegion".

Examples: list of complex II

Example: XML implementation of the list data model with local bivariate uncertainty

```xml
<si:list>
    <si:complex>
        <si:valueReal>-10.310</si:valueReal>
        <si:valueImag>5.010</si:valueImag>
        <si:unit>\volt</si:unit>
        <si:ellipsoidalRegion>
            <si:covarianceMatrix>
                <si:column>
                    <si:covariance>
                        <si:value>0.050</si:value>
                        <si:unit>\volt\volt</si:unit>
                    </si:covariance>
                    <si:covariance>
                        <si:value>-0.003</si:value>
                        <si:unit>\volt\volt</si:unit>
                    </si:covariance>
                </si:column>
                <si:column>
                    <si:covariance>
                        <si:value>-0.003</si:value>
                        <si:unit>\volt\volt</si:unit>
                    </si:covariance>
                    <si:covariance>
                        <si:value>0.105</si:value>
                        <si:unit>\volt\volt</si:unit>
                    </si:covariance>
                </si:column>
            </si:covarianceMatrix>
            <si:coverageFactor>2.45</si:coverageFactor>
            <si:coverageProbability>0.95</si:coverageProbability>
            <si:distribution>normal-bivariate</si:distribution>
        </si:ellipsoidalRegion>
    </si:complex>
```

```xml
    <si:complex>
        <si:valueReal>-10.510</si:valueReal>
        <si:valueImag>5.510</si:valueImag>
        <si:unit>\volt</si:unit>
        <si:ellipsoidalRegion>
            <si:covarianceMatrix>
                <si:column>
                    <si:covariance>
                        <si:value>0.050</si:value>
                        <si:unit>\volt\volt</si:unit>
                    </si:covariance>
                    <si:covariance>
                        <si:value>-0.003</si:value>
                        <si:unit>\volt\volt</si:unit>
                    </si:covariance>
                </si:column>
                <si:column>
                    <si:covariance>
                        <si:value>-0.003</si:value>
                        <si:unit>\volt\volt</si:unit>
                    </si:covariance>
                    <si:covariance>
                        <si:value>0.105</si:value>
                        <si:unit>\volt\volt</si:unit>
                    </si:covariance>
                </si:column>
            </si:covarianceMatrix>
            <si:coverageFactor>2.45</si:coverageFactor>
            <si:coverageProbability>0.95</si:coverageProbability>
            <si:distribution>normal-bivariate</si:distribution>
        </si:ellipsoidalRegion>
    </si:complex>
</si:list>
```

local bivariate uncertainty

Examples: list of complex III

```
<si:list>
    <si:listUnit>\volt</si:listUnit>
    <si:listBivariateUnc>
        <si:ellipsoidalRegion>
            <si:covarianceMatrix>
                <si:column>
                    <si:covariance>
                        <si:value>0.050</si:value>
                        <si:unit>\volt\volt</si:unit>
                    </si:covariance>
                    <si:covariance>
                        <si:value>-0.003</si:value>
                        <si:unit>\volt\volt</si:unit>
                    </si:covariance>
                </si:column>
                <si:column>
                    <si:covariance>
                        <si:value>-0.003</si:value>
                        <si:unit>\volt\volt</si:unit>
                    </si:covariance>
                    <si:covariance>
                        <si:value>0.105</si:value>
                        <si:unit>\volt\volt</si:unit>
                    </si:covariance>
                </si:column>
            </si:covarianceMatrix>
            <si:coverageFactor>2.45</si:coverageFactor>
            <si:coverageProbability>0.95</si:coverageProbability>
            <si:distribution>normal-bivariate</si:distribution>
        </si:ellipsoidalRegion>
    </si:listBivariateUnc>
    <si:complex>
        <si:valueReal>-10.310</si:valueReal>
        <si:valueImag>5.010</si:valueImag>
        <si:unit>\metre</si:unit>
    </si:complex>
    <si:complex>
        <si:valueReal>-10.510</si:valueReal>
        <si:valueImag>5.510</si:valueImag>
        <si:unit>\metre</si:unit>
    </si:complex>
</si:list>
```

Example: XML implementation of the list data model with global bivariate uncertainty

global unit

global bivariate uncertainty

SmartCom

Examples: list of complex IV

```
<si:list>
    <si:listUnit>\volt</si:listUnit>
    <si:listUnitPhase>\radian</si:listUnitPhase>
    <si:listBivariateUnc>
        <si:ellipsoidalRegion>
            <si:covarianceMatrix>
                <si:column>
                    <si:covariance>
                        <si:value>0.050</si:value>
                        <si:unit>\volt\volt</si:unit>
                    </si:covariance>
                    <si:covariance>
                        <si:value>-0.003</si:value>
                        <si:unit>\radian\volt</si:unit>
                    </si:covariance>
                </si:column>
                <si:column>
                    <si:covariance>
                        <si:value>-0.003</si:value>
                        <si:unit>\volt\radian</si:unit>
                    </si:covariance>
                    <si:covariance>
                        <si:value>0.105</si:value>
                        <si:unit>\radian\radian</si:unit>
                    </si:covariance>
                </si:column>
            </si:covarianceMatrix>
            <si:coverageFactor>2.45</si:coverageFactor>
            <si:coverageProbability>0.95</si:coverageProbability>
            <si:distribution>normal-bivariate</si:distribution>
        </si:ellipsoidalRegion>
    </si:listBivariateUnc>
    <si:complex>
        <si:valueMagnitude>11.463</si:valueMagnitude>
        <si:valuePhase>2.689</si:valuePhase>
    </si:complex>
    <si:complex>
        <si:valueMagnitude>10.543</si:valueMagnitude>
        <si:valuePhase>1.937</si:valuePhase>
    </si:complex>
</si:list>
```

global unit A

global unit B

unit A*A

unit B*A

unit A*B

unit B*B

Example: units in the global bivariate uncertainty statement

(polar coordinate form)

(for Cartesian coordinate form trivial units in covariance matrix – always A*A)

units of complex components

units of covariance matrix values

SmartCom Complex list with multivariate uncertainty

list *of complex quantities in Cartesian coordinate form type extended*	components (of the list of complex quantities type)						
	label	dateTime	listUnit	listBivariateUnc (S)	complex (S)	ellipsoidalRegion (S)	rectangularRegion (S)
complex quantities in Cartesian coordinate form with an optional list unit			replaces unit in complex		n times		
independent complex quantities in Cartesian coordinate form with a list uncertainty (bivariate)			replaces unit in complex	replaces uncert. in complex	n times		
multivariate vector of complex quantities in Cartesian coordinate form with a hyper-ellipsoidal coverage region			replaces unit in complex		n times	dimension 2n x 2n	
multivariate vector of complex quantities in Cartesian coordinate form with a hyper-rectangular coverage region			replaces unit in complex		n times		dimension 2n x 2n

(S) sub type | mandatory | optional

- Amount of **2** to **n** „complex“ components required.
- All „complex“ components must be of the same type (either Cartesian or polar coordinate form)
- A global unit is optional.
- The elements “ellipsoidalRegion” and “rectangularRegion” (definition in section 4) must have a covariance matrix of dimension **2n** x **2n**.
- No global bivariate uncertainty allowed with multivariate uncertainty.

Examples: list of complex V

Example: XML implementation of a list with two complex components an a multivariate hyper-ellipsoidal uncertainty.

```
<si:list>
    <si:complex>
        <si:valueMagnitude>11.463</si:valueMagnitude>
        <si:valuePhase>2.689</si:valuePhase>
        <si:unit>\ampere</si:unit>
        <si:unitPhase>\radian</si:unitPhase>
    </si:complex>
    <si:complex>
        <si:valueMagnitude>10.543</si:valueMagnitude>
        <si:valuePhase>1.937</si:valuePhase>
        <si:unit>\volt</si:unit>
        <si:unitPhase>\degree</si:unitPhase>
    </si:complex>
    <si:ellipsoidalRegion>
            <si:covarianceMatrix>
                <si:column>
                    <si:covariance>
                        <si:value>0.050</si:value>
                        <si:unit>\ampere\ampere</si:unit>
                    </si:covariance>
                    <si:covariance>
                        <si:value>0.244</si:value>
                        <si:unit>\radian\ampere</si:unit>
                    </si:covariance>
                    <si:covariance>
                        <si:value>0.007</si:value>
                        <si:unit>\volt\ampere</si:unit>
                    </si:covariance>
                    <si:covariance>
                        <si:value>0.000</si:value>
                        <si:unit>\degree\ampere</si:unit>
                    </si:covariance>
                </si:column>
```

unit A

unit B

unit C

unit D

multivariate uncertainty

(continued on next slide)

column 1 of covariance matrix

$$\begin{pmatrix} 0.050 & 0.244 & 0.007 & 0.000 \\ 0.244 & 0.105 & 0.051 & 0.109 \\ 0.007 & 0.051 & 0.076 & 0.002 \\ 0.000 & 0.109 & 0.002 & 0.602 \end{pmatrix}$$

units in the covariance matrix

$$\begin{pmatrix} A*A & A*B & A*C & A*D \\ B*A & B*B & B*C & B*D \\ C*A & C*B & C*C & C*D \\ D*A & D*B & D*C & D*D \end{pmatrix}$$

SmartCom Examples: list of complex V (continued)

```xml
<si:column>
    <si:covariance>
        <si:value>0.244</si:value>
        <si:unit>\ampere\radian</si:unit>
    </si:covariance>
    <si:covariance>
        <si:value>0.105</si:value>
        <si:unit>\radian\radian</si:unit>
    </si:covariance>
    <si:covariance>
        <si:value>0.051</si:value>
        <si:unit>\volt\radian</si:unit>
    </si:covariance>
    <si:covariance>
        <si:value>0.109</si:value>
        <si:unit>\degree\radian</si:unit>
    </si:covariance>
</si:column>
<si:column>
    <si:covariance>
        <si:value>0.007</si:value>
        <si:unit>\ampere\volt</si:unit>
    </si:covariance>
    <si:covariance>
        <si:value>0.051</si:value>
        <si:unit>\radian\volt</si:unit>
    </si:covariance>
    <si:covariance>
        <si:value>0.076</si:value>
        <si:unit>\volt\volt</si:unit>
    </si:covariance>
    <si:covariance>
        <si:value>0.002</si:value>
        <si:unit>\degree\volt</si:unit>
    </si:covariance>
</si:column>
```

```xml
                <si:column>
                    <si:covariance>
                        <si:value>0.000</si:value>
                        <si:unit>\ampere\degree</si:unit>
                    </si:covariance>
                    <si:covariance>
                        <si:value>0.109</si:value>
                        <si:unit>\radian\degree</si:unit>
                    </si:covariance>
                    <si:covariance>
                        <si:value>0.002</si:value>
                        <si:unit>\volt\degree</si:unit>
                    </si:covariance>
                    <si:covariance>
                        <si:value>0.602</si:value>
                        <si:unit>\degree\degree</si:unit>
                    </si:covariance>
                </si:column>
            </si:covarianceMatrix>
            <si:coverageFactor>3.08</si:coverageFactor>
            <si:coverageProbability>0.95</si:coverageProbability>
            <si:distribution>normal-multivariate</si:distribution>
        </si:ellipsoidalRegion>

</si:list>
```

column two of covariance matrix
column three of covariance matrix
column four of covariance matrix

Overview

1. Real quantity
2. Structure for SI units
3. Coverage regions
4. Complex quantity
5. List Data Model (general)
6. List of real quantities
7. List of complex quantities
8. **Structure for non-SI units (hybrid)**
9. Further application examples

Units in D-SI data model

Recommended units in the D-SI data model (listed in BIPM brochure):

- seven SI base units
- units derived from SI base units
- non-SI units that are allowed to be used together with the SI

Unrecommended units in the D-SI data model

- Units that are not listed in the SI brochure „The International System of Units“
- An exception to this recommendation is recognized for internationally accepted systems of units and scales in the area of reference materials and in the area of reference procedures

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Hybrid data model

- While the recommended units can be directly used as reference for real and complex quantities in the D-SI data model, this is not allowed for the unrecommended units.
- An adapter is offered for those quantities with an unrecommended unit in order to integrate them into the machine-readable D-SI data model. This adapter is denoted as the hybrid data model or in short “hybrid”.
- The application of the hybrid data model requires a conversion of the quantity with the non-SI unit into a quantity with an adequate SI unit.
- Both quantities are then put together into one data element – the hybrid element.
- The hybrid data element must contain at least one quantity with an SI unit. The amount of additional quantities with other units can be one or more.

SmartCom Components of the hybrid data model

hybrid *adapter for non-SI quantities based on real, complex, list and constant*	**components** (of the hybrid type)			
	real (S)	complex (S)	list (S)	constant (S)
hybrid adapter for real quantities	**1 .. n times**			
hybrid adapter for complex quantities		**1 .. n times**		
hybrid adapter for list quantities			**1 .. n times**	
hybrid adapter for constants				**1 .. n times**

(S) sub type **mandatory**

Real quantity in hybrid

- A real quantity in hybrid comprises one real component that must state the quantity value in a SI-base unit.
- Furthermore, it can provide additional real quantities with SI derived units or non-SI units that convert to the real quantity with the SI-base unit.

Example: XML implementation of a real quantity in hybrid

```
<si:hybrid>
    <!-- A: length from B converted to SI -->
    <si:real>
        <si:value>0.3048006</si:value>
        <si:unit>\metre</si:unit>
    </si:real>
    <!-- B: length with imperial unit foot -->
    <si:real>
        <si:value>1</si:value>
        <si:unit>ft(U.S. survey)</si:unit>
    </si:real>
</si:hybrid>
```

SmartCom

Measurement uncertainty in hybrid

- For all quantities in an hybrid element, the model of measurement uncertainty must be identical.
- In the case of a real quantity it is not allowed to mix the expanded measurement uncertainty statement with the statement of a probabilistic symmetric coverage interval.
- In the case of complex quantities, the Cartesian coordinate form must not be mixed with the polar coordinate form.
- The mixture of coverage region types is also forbidden for complex quantities and lists of quantities.

SmartCom

Example: hybrid adapter for lists

List A: quantities with SI units (converted from List B)

List B: quantities with non-SI units

```
<si:hybrid>
    <!-- A: list from B converted to SI -->
    <si:list>
        <si:real>
            <si:value>0.00454609</si:value>
            <si:unit>\metre\tothe{3}</si:unit>
        </si:real>
        <si:real>
            <si:label>hardness Rockwell C scale</si:label>
            <si:value>63.00</si:value>
            <si:unit>\metre\metre\tothe{-1}</si:unit>
            <si:expandedUnc></si:expandedUnc>
                <si:uncertainty>1.56</si:uncertainty>
                <si:coverageFactor>2</si:coverageFactor>
                <si:coverageProbability>0.95</si:coverageProbability>
            </si:expandedUnc>
        </si:real>
    </si:list>
    <!-- B: list with non-SI units -->
    <si:list>
        <si:real>
            <si:value>1</si:value>
            <si:unit>gallon(U.K.)</si:unit>
        </si:real>
        <si:real>
            <si:label>hardness Rockwell C scale</si:label>
            <si:value>63.00</si:value>
            <si:unit>HRC</si:unit>
            <si:expandedUnc>
                <si:uncertainty>1.56</si:uncertainty>
                <si:coverageFactor>2</si:coverageFactor>
                <si:coverageProbability>0.95</si:coverageProbability>
            </si:expandedUnc>
        </si:real>
    </si:list>
</si:hybrid>
```

List A shall contain the same amount of quantities as list B

Unit „gallon“ form list B, converted to SI-unit

Unit „HRC“ form list B, converted to SI-unit

Measurement uncertainty (same unit as the respective quantity; converted from list B to list A)

Overview

1. Outline of previous review and changes
2. Real quantity
3. Structure for SI units
4. Coverage regions
5. Complex quantity
6. List Data Model (general)
7. List of real quantities
8. List of complex quantities
9. Further application examples

SmartCom

Future perspective

- **Development of design guides for commonly used data structures** like

    - shortest coverage interval for real quantity
    - smallest coverage region for vector quantity (list)
    - different types of Monte Carlo Simulation Data
    - mapping to formats that are established in particular areas (i.e. METAS UncLib / VNA Tool format)
    - scales, intervals and value ranges
    - …

- These data structures exceed the minimum required „real“ and „complex“ data models from SmartCom but they can be expressed by using the „list“ structure in the D-SI data model.

- Examples are provided here for a Tensor and simple Monte Carlo Simulation data. These examples are presented on the next two slides.

SmartCom

Recursive usage of lists

Example: XML implementation of a 2x2 matrix (tensor) using recursive lists and real components.

```
<si:list>
    <!-- list with column one -->
    <si:list>
        <si:real>
            <si:value>2.34</si:value>
            <si:unit>\metre</si:unit>
        </si:real>
        <si:real>
            <si:value>3.34</si:value>
            <si:unit>\metre</si:unit>
        </si:real>
    <si:list>
    <!-- list with column two -->
    <si:list>
        <si:real>
            <si:value>4.34</si:value>
            <si:unit>\metre</si:unit>
        </si:real>
        <si:real>
            <si:value>5.34</si:value>
            <si:unit>\metre</si:unit>
        </si:real>
    <si:list>
<si:list>
```

interpretation of values

	column 1	column 2
row 1	2.34 m	4.34 m
row 2	3.34 m	5.34 m

Example: Monte Carlo Data

Example:

XML implementation of Monte Carlo simulation data in the generic list data model. The data comprises Monte Carlo Samples and a Monte Carlo result that was calculated from arithmetic mean and standard deviation of the samples.

```
<si:list>
        <si:label>Monte Carlo Simulation Data</si:label>
        <si:list>
                <si:label>Simulation Result</si:label>
                <si:real>
                        <si:value>0.998714286</si:value>
                        <si:unit>\metre</si:unit>
                        <si:coverageInterval>
                                <si:standardUnc>0.003450328</si:standardUnc>
                                <si:intervalMin>0.997</si:intervalMin>
                                <si:intervalMax>1.002</si:intervalMax>
                                <si:coverageProbability>0.95</si:coverageProbability>
                        </si:coverageInterval>
                </si:real>
        </si:list>
```

```
    <si:list>
        <si:label>Monte Carlo Samples</si:label>
        <si:real>
            <si:value>1.002</si:value>
            <si:unit>\metre</si:unit>
        </si:real>
        <si:real>
            <si:value>1.001</si:value>
            <si:unit>\metre</si:unit>
        </si:real>
        <si:real>
            <si:value>0.998</si:value>
            <si:unit>\metre</si:unit>
        </si:real>
        <si:real>
            <si:value>1.001</si:value>
            <si:unit>\metre</si:unit>
        </si:real>
        <si:real>
            <si:value>0.997</si:value>
            <si:unit>\metre</si:unit>
        </si:real>
        <si:real>
            <si:value>0.992</si:value>
            <si:unit>\metre</si:unit>
        </si:real>
        <si:real>
            <si:value>1.000</si:value>
            <si:unit>\metre</si:unit>
        </si:real>
    </si:list>
</si:list>
```

This document is an outcome of the project Work Package 1

Project:

Start	June 2018
Duration	3 Years
Partners	PTB, NPL, CMI, UM, Aalto, TalTech, UNICAS, NIM, KRISS, Ostfalia, Hexagon, Mitutoyo, Sartorius, Zeiss
Collaborators	ITRI, Mettler-Toledo
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