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**Memo CP-D/564 (Rev.)**

**Date:** 21 May 2009  
**To:** Distribution  
**From:** N. Otsuka

**Subject:      **Compilation of covariance matrix given in the AGS format****

Compilation of experimental covariance matrix for transmission and reaction yield will be proposed in the NRDC 2009 meeting by Drs. Stefan Kopecky and Peter Schillebeeckx (EC-JRC-IRMM, Geel). By using their expression of covariance matrix - AGS (Analysis of Geel Spectra) - total size covariance matrix is reduced from  $n^2$  to  $n(k+1)$ , where  $n$  is the total number of TOF (time of flight) channel ( $\sim 10^4$ ). A note for this formalism in Appendix 3 might be helpful for discussion.

They propose compilation of matrices  $D$  and  $S$  defined in Eqs.10 and 11 in the note as a function of TOF. I prepared a coding sample (Appendix 2) according to their template for EXFOR compilation (Appendix 1). Some possible technical questions are summarized below:

- Can we add TOF (in second) as an independent variable instead of incident energy?
- Can we allow negative values under ERR- $n$ ? Sensitivity coefficient in Eq. 12 ( $\partial\sigma_i/\partial x^l$ ) can be negative.
- We do not need new headings for uncertainties in the coding sample because the size of covariance matrices of systematic effect sources (defined in matrices  $W$  in Eq. 7) is 1 x 1 for all 4 sources, and the matrix  $S$  then gives usual partial uncertainty (See Eq.12). **But the situation is not simple if the matrix is larger than 1 x 1.**

**Example of 2 x 2 matrix:**

If the background correction is given in linear function like  $B = a + b*TOF$ ,  $W_{qr}^l$  is a 2 x 2 symmetric matrices ( $q, r = 1$  or  $2$ ) for each  $l$ , and we will compile 2 elements of  $S_{ip}^l$  ( $p = 1$  or  $2$ ) under two columns in EXFOR. They are however not usual partial uncertainties ERR- $n$ .

## Appendix 1: EXFOR template from Geel

### 1. EXPERIMENT DESCRIPTION

<b>Main Reference</b>		1
<b>Facility</b>	GELINA	2,3
<b>Neutron production</b>		4
Primary neutron production target	Uranium	
Time resolution primary beam (ns)	1 ns	
Moderator material	H <sub>2</sub> O	
Surface Dimensions (mm x mm or diameter in mm)	2 containers 100 x 100 mm	
Thickness (mm)	40 mm	
<b>Experimental details</b>		
Measurement type	Transmission	
Flight path length (m) (moderator – target (detector): face to face distance)	26.444 +/- 0.006 m	
Angle (with respect to cp beam)	99 deg	
Beam dimensions (mm x mm or diameter in mm)	Diameter 40 mm	
<b>Detector</b>		
Type	Scintillator	
Material	Li-glass (NE 905)	
Surface Dimensions (mm x mm or diameter in mm)	120 mm diameter	
Thickness (mm)	12.7 mm	
<b>Sample</b>		
Type (metal, powder)	Metal	
Chemical composition	Cd	
Atomic abundance of main element	100 %	
Weight	2.0993 +/- 0.0001 g	
Weight per unit area (g/cm <sup>2</sup> )	0.04172 g/cm <sup>2</sup>	
Geometry		
Surface dimensions (mm x mm or diameter in mm)	Diameter 80.04 +/- 0.03 mm	
Thickness (mm)	0.050 mm (nominal)	
Thickness of main element (at/b)	$2.2352 \cdot 10^{-4}$ at/b	
Containment description	No container	
<b>Uncertainties (at 1 sigma level)</b>		
Normalization (relative )		
Other sources creating correlated uncertainty components (see data format)	Dead Time correction sample in [1] Background correction sample in parameter one [2] Dead Time correction sample out [3] Background correction sample out parameter one [4]	

### References

- [1] S. Kopecky et al., submitted to NIMB  
 [2] J.M. Salome and R. Cools, Nucl. Instrum. Methods Phys. Res. A **179** (1981), 13  
 [3] D. Tronc, J.M. Salome, K.H. Böckhoff, Nucl. Instrum. Methods Phys. Res. A **228** (1985), 217  
 [4] M. Flaska et al. Nucl. Instrum. Methods Phys. Res. A **531** (2004), 392

## 2. DATA FORMAT

According to AGS format

Time-of-Flight [ns]		Observable Transmission	Uncertainty					
Low	High		Total $\sigma$	Uncorrelated $\sigma^2$	Correlated Components			
					[1]	[2]	[3]	[4]
3.1188E+06	3.1444E+06	9.1309E-01	5.2664E-03	2.7570E-05	6.5601E-06	-1.0072E-04	-7.4295E-06	9.3673E-05
3.1444E+06	3.1700E+06	9.0347E-01	5.2812E-03	2.7719E-05	6.3922E-06	-1.0226E-04	-7.2767E-06	9.4143E-05
3.1700E+06	3.1956E+06	9.0134E-01	5.2989E-03	2.7902E-05	6.3386E-06	-1.0281E-04	-7.2228E-06	9.4387E-05
3.1956E+06	3.2212E+06	8.8804E-01	5.2316E-03	2.7195E-05	6.2074E-06	-1.0196E-04	-7.1256E-06	9.2229E-05
3.2212E+06	3.2468E+06	8.8347E-01	5.2576E-03	2.7461E-05	6.1074E-06	-1.0321E-04	-7.0280E-06	9.2872E-05
...	...	...	...	...	...	...	...	...
6.5116E+06	6.6140E+06	5.1049E-01	1.7897E-03	3.0786E-06	2.7113E-06	-5.1153E-05	-4.0677E-06	2.6553E-05
6.6140E+06	6.7164E+06	5.1780E-01	1.8092E-03	3.1479E-06	2.7654E-06	-5.0203E-05	-4.1206E-06	2.6437E-05
6.7164E+06	6.8188E+06	5.2519E-01	1.8266E-03	3.2107E-06	2.8231E-06	-4.9156E-05	-4.1785E-06	2.6257E-05
6.8188E+06	6.9212E+06	5.3394E-01	1.8541E-03	3.3090E-06	2.8821E-06	-4.8495E-05	-4.2320E-06	2.6329E-05
6.9212E+06	7.0236E+06	5.4117E-01	1.8762E-03	3.3897E-06	2.9320E-06	-4.7730E-05	-4.2778E-06	2.6267E-05
7.0236E+06	7.0246E+06	5.6613E-01	1.9202E-02	3.6855E-04	3.0999E-06	-4.8282E-05	-4.4270E-06	2.7783E-05

### Appendix 2: Coding sample

```

ENTRY          00001  20090507          0000100000001
SUBENT        00001001  20090507          0000100100001
BIB           14      66                  0000100100002
TITLE         The total cross section and resonance parameters for 0000100100003
              the 0.178 eV resonance of 113Cd                    0000100100004
AUTHOR        (S.Kopecky, I.Ivanov, M.Moxon, P.Schillebeeckx, 0000100100005
              P.Siegler, I.Sirakov)                               0000100100006
INSTITUTE     (2ZZZGEL)                                           0000100100007
REFERENCE     (J,NIM/B,,2009) Submitted to NIM/B                 0000100100008
              #doi: 10.1016/j.nimb.2009.04.010                  0000100100009
REL-REF       (N,,J,NIM/A,179,13,1981)                            0000100100010
              J.M.Salome+, Details of GELINA facility           0000100100011
              (N,,J,NIM/A,228,217,1985)                          0000100100012
              D.Tronc+, Details of GELINA facility              0000100100013
              (N,,J,NIM/A,531,392,2004)                          0000100100014
              M.Flaska+, Details of neutron production         0000100100015
FACILITY      (LINAC,2ZZZGEL) GELINA                               0000100100016
INC-SOURCE    Diameter of neutron beam = 40 mm                   0000100100017
              (PHOTO) (g,n) on uranium target                   0000100100018
              (2 containers, 100 x 100 mm, 40 mm thick)         0000100100019
              (THCOL) Water moderator                            0000100100020
METHOD        (TRN,TOF) Flight path (moderator - target (detector) 0000100100021
              face to face distance) = 26.444 +/- 0.006 m      0000100100022
DETECTOR      (SCIN,GLASD) Li-glass scintillator (NE 905)       0000100100023
              120 mm diameter, 12.7 mm thick                    0000100100024
SAMPLE        Physical type: Metal                                0000100100025
              Chemical composition: Element (Cd)                 0000100100026
              Purity of main element: 100%                       0000100100027
              Weight per area: 0.04172 g/cm2                     0000100100028
              Diameter: 80.04 +/- 0.03 mm                        0000100100029
              Thickness: 0.050 mm (nominal)                       0000100100030
              Thickness of main element: 2.2352E-04 atom/b      0000100100031
CORRECTION    Data are corrected for                               0000100100032
              - dead time at sample-in detector (din);           0000100100033
              - background at sample-in detector (Bin);          0000100100034
              - dead time at sample-out detector (dout);          0000100100035
              - background at sample-out detector (Bout),         0000100100036
              as follows:                                         0000100100037
              T=(din*Cin-Bin)/(dout*Cout-Bout)                   0000100100038
              , where                                             0000100100039
              T: Transmission;                                    0000100100040
              Cin: Count at sample-in detector;                  0000100100041
              Cout: Count at sample-out detector.                 0000100100042
ERR-ANALYS    (ERR-T) Total uncertainty                           0000100100043
              (ERR-S) Sum of uncorrelated uncertainties          0000100100044
              due to counting statistics                           0000100100045

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(sample-in and sample-out) 0000100100046
(ERR-1) Uncertainty due to dead-time correction (sample-in) 0000100100047
(sample-in) 0000100100048
(ERR-2) Uncertainty due to background correction (sample-in) 0000100100049
(sample-in) 0000100100050
(ERR-3) Uncertainty due to dead-time correction (sample-out) 0000100100051
(sample-out) 0000100100052
(ERR-4) Uncertainty due to background correction (sample-out) 0000100100053
(sample-out) 0000100100054
COVARIANCE If i=j, 0000100100055
cov(T_i,T_j) = (ERR-S)i**2 +(ERR-1)i**2+(ERR-2)i**2 0000100100056
+(ERR-3)i**2+(ERR-4)i**2 0000100100057
,else 0000100100058
cov(T_i,T_j) = (ERR-1)i*(ERR-1)j 0000100100059
+(ERR-2)i*(ERR-2)j 0000100100060
+(ERR-3)i*(ERR-3)j 0000100100061
+(ERR-4)i*(ERR-4)j 0000100100062
. 0000100100063
HISTORY (20090403R) On. Received by e-mail from S.Kopecky 0000100100064
(20090423C) On. 0000100100065
(20090507A) On. ERR-ANALYSIS updated, 0000100100066
CORRECTION and COVARIANCE added. 0000100100067
(20090520A) On. TITLE added, AUTHOR corrected 0000100100068
ENDBIB 66 0 0000100100069
NOCOMMON 0 0 0000100100070
ENDSUBENT 69 0 0000100199999
SUBENT 00001002 20090507 0000100200001
BIB 3 3 0000100200002
REACTION (48-CD-0(N,TOT),TRN) 0000100200003
STATUS (TABLE) Data on MS word file 0000100200004
ENDBIB 3 0 0000100200006
COMMON 2 3 0000100200007
TOF-L TOF-L-ERR 0000100200008
M M 0000100200009
26.444 0.006 0000100200010
ENDCOMMON 3 0 0000100200011
DATA 9 101 0000100200012
TOF-MIN TOF-MAX DATA ERR-T ERR-S ERR-1 0000100200013
ERR-2 ERR-3 ERR-4 0000100200014
NS NS NO-DIM NO-DIM NO-DIM NO-DIM 0000100200015
NO-DIM NO-DIM NO-DIM 0000100200016
3.1188E+06 3.1444E+06 9.1309E-01 5.2664E-03 5.2507E-03 6.5601E-06 0000100200017
-1.0072E-04-7.4295E-06 9.3673E-05 0000100200018
3.1444E+06 3.1700E+06 9.0347E-01 5.2812E-03 5.2649E-03 6.3922E-06 0000100200019
-1.0226E-04-7.2767E-06 9.4143E-05 0000100200020
3.1700E+06 3.1956E+06 9.0134E-01 5.2989E-03 5.2822E-03 6.3386E-06 0000100200021
-1.0281E-04-7.2228E-06 9.4387E-05 0000100200022
3.1956E+06 3.2212E+06 8.8804E-01 5.2316E-03 5.2149E-03 6.2074E-06 0000100200023
-1.0196E-04-7.1256E-06 9.2229E-05 0000100200024
...
6.7164E+06 6.8188E+06 5.2519E-01 1.8266E-03 1.7918E-03 2.8231E-06 0000100200211
-4.9156E-05-4.1785E-06 2.6257E-05 0000100200212
6.8188E+06 6.9212E+06 5.3394E-01 1.8541E-03 1.8191E-03 2.8821E-06 0000100200213
-4.8495E-05-4.2320E-06 2.6329E-05 0000100200214
6.9212E+06 7.0236E+06 5.4117E-01 1.8762E-03 1.8411E-03 2.9320E-06 0000100200215
-4.7730E-05-4.2778E-06 2.6267E-05 0000100200216
7.0236E+06 7.0246E+06 5.6613E-01 1.9202E-02 1.9198E-02 3.0999E-06 0000100200217
-4.8282E-05-4.4270E-06 2.7783E-05 0000100200218
ENDDATA 206 0 0000100200219
ENDSUBENT 218 0 0000100299999
ENDENTRY 2 0 0000199999999
ENDTRANS 1 0 Z999999999999

```

# Note: A compact expression of experimental covariance

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This is a note for compact expression of experimental covariance (AGS format)[1, 2].

## Formalism

Let us consider a quantity at  $i$ -th incident energy bin  $\sigma_i$  ( $1 \leq i \leq n$ ) as a function of  $M$  uncorrelated quantities  $y_i^m$  ( $1 \leq m \leq M$ ) and  $K \times L$  correlated quantities  $x_r^l$  ( $1 \leq l \leq L, 1 \leq r \leq K_l, K = K_1 + K_2 + \dots + K_L$ ):

$$\sigma_i \equiv \sigma(\{y_i^m\}, \{x_r^l\}). \quad (1)$$

The total uncertainty of  $\sigma_i$  is decomposed to uncorrelated and correlated terms

$$(\Delta\sigma_i)_{\text{tot}}^2 = \sum_{m=1}^M (\Delta\sigma_i)_m^2 + \sum_{l=1}^L (\Delta\sigma_i)_l^2 \quad (2)$$

$$= \sum_{m=1}^M \left( \frac{\partial\sigma_i}{\partial y_i^m} \Delta y_i^m \right)^2 + \sum_{l=1}^L \sum_{q,r=1}^{K_l} \left( \frac{\partial\sigma_i}{\partial x_q^l} \Delta x_q^l \right) \left( \frac{\partial\sigma_i}{\partial x_r^l} \Delta x_r^l \right) c_{qr}^l \quad (3)$$

where  $c_{qr}^l$  is the correlation matrix of the quantity  $x^l$ . We assume that there is no correlation between  $x_q^k$  and  $x_r^l$  if  $k \neq l$ .

The covariance matrix of  $\sigma_i$  is then

$$V_{ij} = \sum_{m=1}^M (\Delta\sigma_i)_m (\Delta\sigma_j)_m \delta_{ij} + \sum_{l=1}^L (\Delta\sigma_i)_l (\Delta\sigma_j)_l C_{ij}^l \quad (4)$$

$$= \sum_{m=1}^M \frac{\partial\sigma_i}{\partial y_i^m} \frac{\partial\sigma_j}{\partial y_j^m} U_{ij}^m + \sum_{l=1}^L \sum_{q,r=1}^{K_l} \frac{\partial\sigma_i}{\partial x_q^l} \frac{\partial\sigma_j}{\partial x_r^l} W_{qr}^l \quad (V, U \in R^{n \times n}, W \in R^{K_l \times K_l}) \quad (5)$$

, where two covariance matrices

$$U_{ij}^m \equiv (\Delta y_i^m)^2 \delta_{ij}, \quad (6)$$

$$W_{qr}^l \equiv \Delta x_q^l \Delta x_r^l c_{qr}^l \quad (7)$$

are introduced ( $\delta_{ij}$ : Kronecker's delta).

The matrix  $W^l$  is positive definite and symmetric and, therefore, can be decomposed to an upper triangle matrix  $R$  ( $R \in R^{K_l \times K_l}$ ) and its transposed matrix  $R^T$  as  $W^l = R^l R^{lT}$  (Cholesky decomposition). Then

$$V_{ij} = \sum_{m=1}^M \frac{\partial\sigma_i}{\partial y_i^m} \frac{\partial\sigma_j}{\partial y_j^m} U_{ij}^m + \sum_{l=1}^L \sum_{p,q,r=1}^{K_l} \frac{\partial\sigma_i}{\partial x_q^l} \frac{\partial\sigma_j}{\partial x_r^l} R_{qp}^l R_{pr}^l \quad (8)$$

$$= D_{ij} + \sum_{l=1}^L \sum_{p=1}^{K_l} S_{ip}^l S_{jp}^l \quad (9)$$

, where

$$D_{ij} \equiv \sum_{m=1}^M \frac{\partial \sigma_i}{\partial y_i^m} \frac{\partial \sigma_j}{\partial y_j^m} U_{ij}^m = \delta_{ij} \sum_{m=1}^M (\Delta \sigma_i)_m^2 \quad (D \in R^{n \times n}, \text{diagonal}), \quad (10)$$

$$S_{ip}^l \equiv \sum_{q=1}^{K_l} \frac{\partial \sigma_i}{\partial x_q^l} R_{qp}^l \quad (S^l \in R^{n \times K_l}) \quad (11)$$

. The covariance matrix  $V$  is now expressed by the  $n$  elements of the diagonal matrix  $D$  and  $n \times K$  elements of the matrices  $S^l$  ( $1 \leq l \leq L$ ). This reduces total number of elements from  $n \times n$  to  $n \times (1 + K)$

If  $K_l=1$  for all  $l$ ,  $W_{qr}^l \rightarrow W^l = (\Delta x^l)^2$ ,  $c_{qr}^l \rightarrow c^l = 1$ ,  $R_{qp}^l \rightarrow R^l = \sqrt{W^l} = \Delta x^l$ , and

$$S_{ip}^l \rightarrow S_i^l = \frac{\partial \sigma_i}{\partial x^l} \Delta x^l \equiv (\Delta \sigma_i)_l, \quad (12)$$

which signature is positive or negative. Therefore the covariance matrix and its diagonal component are

$$V_{ij} = \delta_{ij} \sum_{m=1}^M (\Delta \sigma_i)_m^2 + \sum_{l=1}^L (\Delta \sigma_i)_l (\Delta \sigma_j)_l \quad (13)$$

$$(\Delta \sigma)_{\text{tot}}^2 = V_{ii} = \sum_{m=1}^M (\Delta \sigma_i)_m^2 + \sum_{l=1}^L (\Delta \sigma_i)_l^2 \quad (14)$$

## EXFOR

We need one column for  $D_{ii}$  ( $1 \leq i \leq n$ ) and  $K = K_1 + \dots + K_L$  columns for  $S_{ip}^l$  ( $1 \leq l \leq L, 1 \leq p \leq K_l, 1 \leq i \leq n$ ).

If  $K_l = 1$  for all  $L$  and the incident energy  $E_i$  is known, we can use the current EXFOR format:

EN	ERR-S	ERR-1	...	ERR-L
	$D_{ii}$	$S_i^1$	...	$S_i^L$
$E_1$	$(\Delta \sigma_1)_0$	$(\Delta \sigma_1)_1$	...	$(\Delta \sigma_1)_L$
$E_2$	$(\Delta \sigma_2)_0$	$(\Delta \sigma_2)_1$	...	$(\Delta \sigma_2)_L$
...	...	...	...	...
$E_i$	$(\Delta \sigma_i)_0$	$(\Delta \sigma_i)_1$	...	$(\Delta \sigma_i)_L$
...	...	...	...	...
$E_n$	$(\Delta \sigma_n)_0$	$(\Delta \sigma_n)_1$	...	$(\Delta \sigma_n)_L$

, where we allow to use the heading ERR-S for total uncorrelated uncertainty

$$(\Delta \sigma_i)_0^2 = \sum_{m=1}^M (\Delta \sigma_i)_m^2 \quad (15)$$

### Example - Transmission

Transmission  $T$  (, TRN in EXFOR) is related to total cross section  $\sigma_T$  as follows:

$$T(E) = \exp(-L\rho\sigma_T(E)) \quad (16)$$

( $L$ : target thickness,  $\rho$ : target density), and expressed in terms of the 6 observables

- $C_i^{\text{in}}$  : Count at sample-in detector (uncorrelated)

- $C_i^{\text{out}}$ : Count at sample-out detector (uncorrelated)
- $d^{\text{in}}$ : Dead time correction for sample-in detector (correlated)
- $d^{\text{out}}$ : Dead time correction for sample-out detector (correlated)
- $B^{\text{in}}$ : Background correction for sample-in detector (correlated)
- $B^{\text{out}}$ : Background correction for sample-out detector (correlated)

as follows:

$$T_i = T_i(C_i^{\text{in}}, C_i^{\text{out}}, d^{\text{in}}, d^{\text{out}}, B^{\text{in}}, B^{\text{out}}) = \frac{d^{\text{in}}C_i^{\text{in}} - B^{\text{in}}}{d^{\text{out}}C_i^{\text{out}} - B^{\text{out}}} \quad (17)$$

This is the case of  $M = 2$ ,  $L = 4$  and  $K_l = 1$  ( $1 \leq l \leq 4$ ) in the formalism. Covariance matrices for uncorrelated quantities are

$$U_{ij}^{\text{Cin}} = (\Delta C_i^{\text{in}})^2 \delta_{ij}, U_{ij}^{\text{Cout}} = (\Delta C_i^{\text{out}})^2 \delta_{ij}, \quad (18)$$

while covariance matrices for correlated quantities and these Cholesky decompositions are

$$W^{\text{din}} = (\Delta d_i^{\text{in}})^2, W^{\text{dout}} = (\Delta d_i^{\text{out}})^2, W^{\text{Bin}} = (\Delta B_i^{\text{in}})^2, W^{\text{Bout}} = (\Delta B_i^{\text{out}})^2 \quad (19)$$

and

$$R^{\text{din}} = \Delta d^{\text{in}}, R^{\text{dout}} = \Delta d^{\text{out}}, R^{\text{Bin}} = \Delta B^{\text{in}}, R^{\text{Bout}} = \Delta B^{\text{out}}. \quad (20)$$

Therefore the covariance matrix  $V$  is expressed by  $n$  elements of the matrix  $D$

$$D_{ij} = \frac{\partial T_i}{\partial C_i^{\text{in}}} \frac{\partial T_j}{\partial C_j^{\text{in}}} U_{ij}^{\text{Cin}} + \frac{\partial T_i}{\partial C_i^{\text{out}}} \frac{\partial T_j}{\partial C_j^{\text{out}}} U_{ij}^{\text{Cout}} \quad (21)$$

$$= (\Delta T_i)_{\text{Cin}}^2 \delta_{ij} + (\Delta T_i)_{\text{Cout}}^2 \delta_{ij} \quad (22)$$

and  $n \times 4$  elements of  $S$  matrices:

$$S_i^{\text{din}} = \frac{\partial T_i}{\partial d^{\text{in}}} R^{\text{din}} = \frac{\partial T_i}{\partial d^{\text{in}}} \Delta d^{\text{in}} \equiv (\Delta T_i)_{\text{din}} \quad (23)$$

$$S_i^{\text{dout}} = \frac{\partial T_i}{\partial d^{\text{out}}} R^{\text{dout}} = \frac{\partial T_i}{\partial d^{\text{out}}} \Delta d^{\text{out}} \equiv (\Delta T_i)_{\text{dout}} \quad (24)$$

$$S_i^{\text{Bin}} = \frac{\partial T_i}{\partial B^{\text{in}}} R^{\text{Bin}} = \frac{\partial T_i}{\partial B^{\text{in}}} \Delta B^{\text{in}} \equiv (\Delta T_i)_{\text{Bin}} \quad (25)$$

$$S_i^{\text{Bout}} = \frac{\partial T_i}{\partial B^{\text{out}}} R^{\text{Bout}} = \frac{\partial T_i}{\partial B^{\text{out}}} \Delta B^{\text{out}} \equiv (\Delta T_i)_{\text{Bout}} \quad (26)$$

Covariance matrix can be reconstructed from these elements as follows:

$$V_{ij} = D_{ij} S_i^{\text{din}} S_j^{\text{din}} + S_i^{\text{dout}} S_j^{\text{dout}} + S_i^{\text{Bin}} S_j^{\text{Bin}} + S_i^{\text{Bout}} S_j^{\text{Bout}} \quad (27)$$

$$= (\Delta T_i)_{\text{Cin}}^2 \delta_{ij} + (\Delta T_i)_{\text{Cout}}^2 \delta_{ij} + (\Delta T_i)_{\text{din}} (\Delta T_j)_{\text{din}} + (\Delta T_i)_{\text{dout}} (\Delta T_j)_{\text{dout}} + (\Delta T_i)_{\text{Bin}} (\Delta T_j)_{\text{Bin}} + (\Delta T_i)_{\text{Bout}} (\Delta T_j)_{\text{Bout}} \quad (28)$$

. The diagonal element  $V_{ii}$  gives the total uncertainty of  $T^i$

$$(\Delta T_i)_{\text{tot}}^2 = (\Delta T_i)_{\text{Cin}}^2 + (\Delta T_i)_{\text{Cout}}^2 + (\Delta T_i)_{\text{din}}^2 + (\Delta T_i)_{\text{dout}}^2 + (\Delta T_i)_{\text{Bin}}^2 + (\Delta T_i)_{\text{Bout}}^2 \quad (29)$$

This can be compiled as follows

EN	ERR-S	ERR-1	...	ERR-4
$E_1$	$(\Delta T_1)_C$	$(\Delta T_1)_{\text{din}}$	...	$(\Delta T_1)_{\text{Bout}}$
$E_2$	$(\Delta T_2)_C$	$(\Delta T_2)_{\text{din}}$	...	$(\Delta T_2)_{\text{Bout}}$
...	...	...	...	...
$E_i$	$(\Delta T_i)_C$	$(\Delta T_i)_{\text{din}}$	...	$(\Delta T_i)_{\text{Bout}}$
...	...	...	...	...
$E_n$	$(\Delta T_n)_C$	$(\Delta T_n)_{\text{din}}$	...	$(\Delta T_n)_{\text{Bout}}$

, where

$$(\Delta T_i)_C^2 = (\Delta T_i)_{\text{Cin}}^2 + (\Delta T_i)_{\text{Cout}}^2 \quad (30)$$

## References

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