EURADOS Training course

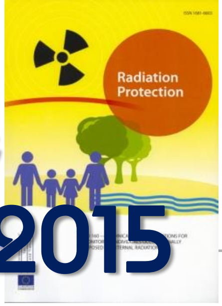
Evaluating uncertainty

Monte Carlo evaluation in a spreadsheet

Janwillem van Dijk

Eurados Training Course

Lisbon, Portugal, 18-22 May 2015



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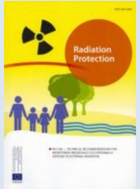

Evaluating uncertainty

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mcm_example.xlsm,
mcm_example.ods

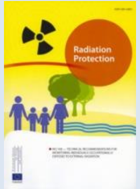
$$x = f_{\mathrm{R}} f_{\mathrm{Det}} \left(f_{E,\alpha} H_{\mathrm{True}} + f_{\mathrm{Bg}} h_{\mathrm{Bg}} \right) + z$$

$$y = \frac{x - Z}{F_R F_{E,\alpha} F_{Det}} - \frac{F_{Bg}}{F_{E,\alpha}} Y_{Bg}$$

***x*: the signal you will see from the reader**

***y*: the dose you will report**

Symbols in capital are expectations



Evaluating uncertainty

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mcm_example.xlsm - Microsoft Excel non-commercial use

Monte Carlo uncertainty evaluation of TNO C-detector, LiF:Mg,Ti + 1mm Al

					Bayesian	
H_{true}	1000	μSv	H_{mcm}	1000.0 μSv	1000.0 μSv	
H_{nat}	100	μSv	stdev	164.9 16%	164.9 16%	
			Low 95%	688.9	689.0 μSv	
			High 95%	1333.3	1334.4 μSv	
N	10000					

$f_{E,\alpha}$	min	0.393
	max	1.257
$u_{Bg,rel}$		0.1

$$x = f_R f_{Det}(f_{E,\alpha} H_{True} + f_{Bg} h_{Bg}) + z$$

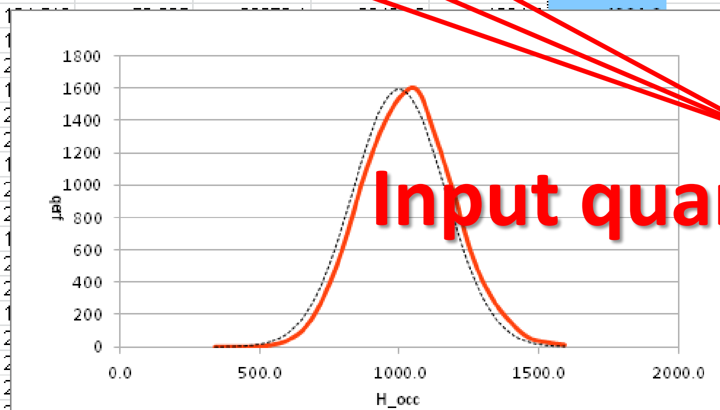
$$y = \frac{x - Z}{F_R F_{E,\alpha} F_{Det}} - \frac{F_{Bg}}{F_{E,\alpha}} Y_{Bg}$$

measurement equations

Count	10000
First >0	0

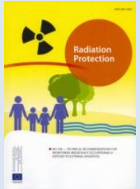
		Detector				Reader				Dose (μSv)			95% coverage	
	H_{nat}	f_{Bg}	$f_{E,\alpha}$	f_{Det}	x_{blank}	f_{reader}	x	$u_{x,rel}$		H_{occ}				
mean	100	1	1	1	200	50	μSv	1		1000.03	1000.0	Low	688.9	689.0
stdev	10	0.05	0.144	0.050	10	2.5	μSv	0.02		164.91	164.9	High	1333.3	1334.4

	Natural	Bg resp,	Response	Detector	Blank	Sensitivity	Signal	Signal	H_{gross}	H_{occ}	Sorted		Frequency	Bayesian Frequency	Normal
0	96.770	0.926	1.007	0.953	203.230	50.877	53585.6	52454.4	1045.1	945.1	375.7	340.4	0	0	1
1	107.384	0.990	1.171	1.032	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	450.6	406.3	1	1	2
2	96.975	0.998	1.145	0.984	[illegible]						475.1	472.3	1	1	10
3	109.846	1.133	1.096	1.043	[illegible]						478.0	538.3	10	10	32
4	100.042	1.014	0.933	1.025	[illegible]						497.9	604.2	44	44	90
5	100.244	0.988	0.961	0.958	[illegible]						502.4	670.2	132	132	216
6	95.384	0.942	0.801	0.978	[illegible]						503.7	736.2	332	332	444
7	117.429	1.027	1.082	0.912	[illegible]						506.9	802.1	630	630	777
8	89.112	0.966	0.963	0.991	[illegible]						[illegible]	[illegible]	[illegible]	[illegible]	1159
9	94.357	0.980	0.902	0.896	[illegible]						[illegible]	[illegible]	[illegible]	[illegible]	1473
10	87.161	0.956	0.863	1.014	[illegible]						524.7	1000.0	1538	1538	1596
11	100.148	0.901	0.889	1.014	[illegible]						527.8	1066.0	1590	1590	1473
12	91.912	1.018	1.097	1.000	[illegible]						540.4	1132.0	1295	1295	1159
13	110.290	0.960	0.851	0.999	[illegible]						541.4	1197.9	943	943	777
14	101.760	1.019	0.863	0.959	[illegible]						543.9	1263.9	556	556	444
15	89.983	1.058	0.798	0.900	[illegible]						547.2	1329.9	311	311	216
16	103.119	0.960	0.964	1.026	[illegible]						547.5	1395.8	161	161	90
17	106.017	1.138	1.081	0.989	[illegible]						550.6	1461.8	60	60	32



Input quantities in red

Monte-Carlo



Evaluating uncertainty

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mcm_example.xlsm - Microsoft Excel non-commercial use

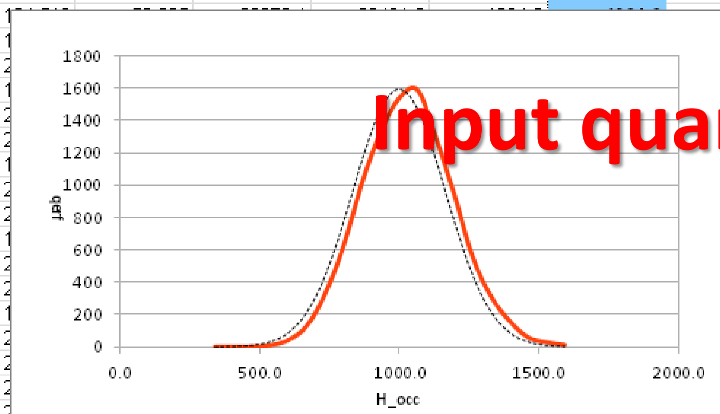
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	Monte Carlo uncertainty evaluation of TNO C-detector, LiF:Mg,Ti + 1mm Al															
2									Bayesian							
3	H_{true}	1000	μSv			H_{mcm}	1000.0	μSv	1000.0	μSv						
4	H_{nat}	100	μSv			stdev	164.9	16%	164.9	16%						
5																
6							Low 95%	688.9	689.0	μSv						
7	N	10000					High 95%	1333.3	1334.4	μSv						
8																
9	$f_{E,\alpha}$	min		0.[illegible]93												
10		max		1.[illegible]57												
11	$u_{Bg,rel}$		0.1									Count	10000			
12												First >0	0			
13			Detector					Reader			Dose (μSv)					
14		H_{nat}	f_{Bg}	$f_{E,\alpha}$	f_{Det}	x_{blank}	f_{read}	x	$u_{x,rel}$		H_{occ}			95% coverage		
15	mean	100	1	1	1	200	50	μSv	1		1000.03	1000.0	Low	688.9	689.0	
16	stdev	10	0.[illegible]5	0.[illegible]44	0.050	10	[illegible].5	μSv	0.02		164.91	164.9	High	1333.3	1334.4	
17																
18															Bayesian	
19		Natural	Bg resp,	Response	Detector	Blank	Sensitivity	Signal	Signal	H_{gross}	H_{occ}	Sorted		Frequency	Frequency	Normal
20	0	96.770	0.926	1.007	0.953	203.230	50.877	53585.6	52454.4	1045.1	945.1	375.7	340.4	0	0	1
21	1	107.384	0.990	1.171	1.032							450.6	406.3	1	1	2
22	2	96.975	0.998	1.145	0.984							475.1	472.3	1	1	10
23	3	109.846	1.133	1.096	1.043							478.0	538.3	10	10	32
24	4	100.042	1.014	0.933	1.025							497.9	604.2	44	44	90
25	5	100.244	0.988	0.961	0.958							[illegible]	[illegible]	[illegible]	[illegible]	216
26	6	95.384	0.942	0.801	0.978							[illegible]	[illegible]	[illegible]	[illegible]	444
27	7	117.429	1.027	1.082	0.912							506.9	802.1	630	630	777
28	8	89.112	0.966	0.963	0.991							511.4	868.1	1019	1019	1159
29	9	94.357	0.980	0.902	0.896							524.3	934.1	1333	1333	1473
30	10	87.161	0.956	0.863	1.014							524.7	1000.0	1538	1538	1596
31	11	100.148	0.901	0.889	1.014							527.8	1066.0	1590	1590	1473
32	12	91.912	1.018	1.097	1.000							540.4	1132.0	1295	1295	1159
33	13	110.290	0.960	0.851	0.999							541.4	1197.9	943	943	777
34	14	101.760	1.019	0.863	0.959							543.9	1263.9	556	556	444
35	15	89.983	1.058	0.798	0.900							547.2	1329.9	311	311	216
36	16	103.119	0.960	0.964	1.026							547.5	1395.8	161	161	90
37	17	106.017	1.138	1.081	0.989							550.6	1461.8	60	60	32

Monte-Carlo

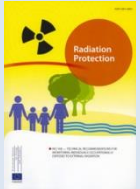
$$x = f_{\mathrm{R}} f_{\mathrm{Det}}(f_{E,\alpha} H_{\mathrm{True}} + f_{\mathrm{Bg}} h_{\mathrm{Bg}}) + z$$

$$y = \frac{x - Z}{F_R F_{E,\alpha} F_{Det}} - \frac{F_{Bg}}{F_{E,\alpha}} Y_{Bg}$$

h_{Bg} f_{Bg} $f_{E\alpha}$ f_{Det} Z f_R



Input quantities in red



Evaluating uncertainty

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mcm_example.xlsm - Microsoft Excel non-commercial use

Monte Carlo uncertainty evaluation of TNO C-detector, LiF:Mg,Ti + 1mm Al

H_{true}	1000	μSv	H_{mcm}	1000.0 μSv	Bayesian 1000.0 μSv
H_{nat}	100	μSv	stdev	164.9 16%	164.9 16%
			Low 95%	688.9	689.0 μSv
			High 95%	1333.3	1334.4 μSv
N	10000				
$f_{E,\alpha}$	min	0.393			
	max	1.257			
$u_{Bg,rel}$	0.1				

$$x = f_R f_{Det}(f_{E,\alpha} H_{True} + f_{Bg} h_{Bg}) + z$$

$$y = \frac{x - Z}{F_R F_{E,\alpha} F_{Det}} - \frac{F_{Bg}}{F_{E,\alpha}} Y_{Bg}$$

The signal from the reader

Gross dose

Net dose

Count 10000

First >0 0

	Detector				Reader				Dose (μSv)			
	H_{nat}	f_{Bg}	$f_{E,\alpha}$	f_{Det}	x_{blank}	f_{reader}	x	$u_{x,rel}$		H_{occ}		95% coverage
mean	100	1	1	1	200	50	μSv	1		1000.03	1000.0	Low 688.9 689.0
stdev	10	0.05	0.144	0.050	10	2.5	μSv	0.02		164.91	164.9	High 1333.3 1334.4

	Natural	Bg resp,	Response	Detector	Blank	Sensitivity	Signal	Signal	H_{gross}	H_{occ}	Sorted		Frequency	Bayesian Frequency	Normal
0	96.770	0.926	1.007	0.953	203.230	50.877	53585.6	52454.4	1045.1	945.1	375.7	340.4	0	0	1
1	107.384	0.990	1.171	1.032							450.6	406.3	1	1	2
2	96.975	0.998	1.145	0.984							475.1	472.3	1	1	10
3	109.846	1.133	1.096	1.043							478.0	538.3	10	10	32
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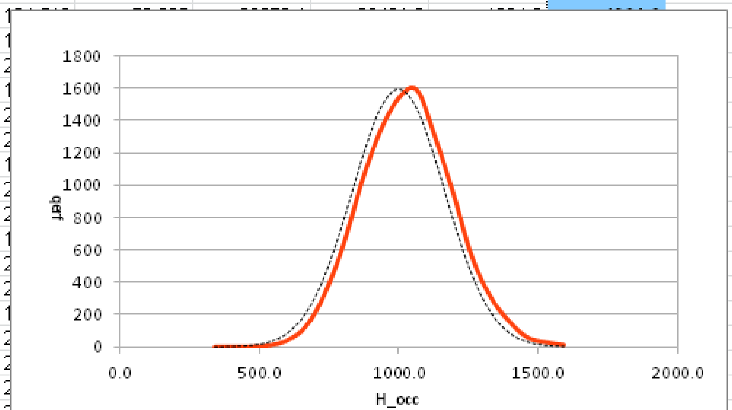
15	89.983	1.058	0.798	0.900							547.2	1329.9	311	311	216
16	103.119	0.960	0.964	1.026							547.5	1395.8	161	161	90
17	106.017	1.138	1.081	0.989							550.6	1461.8	60	60	32



Monte-Carlo

Evaluating uncertainty

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mcm_example.xlsm - Microsoft Excel non-commercial use

Monte Carlo uncertainty evaluation of TNO C-detector, LiF:Mg,Ti + 1mm Al

H_{true}	1000	μSv	H_{mcm}	1000.0 μSv	Bayesian 1000.0 μSv
H_{nat}	100	μSv	stdev	164.9 16%	
			Low 95%	688.9	689.0 μSv
N	10000		High 95%	1333.3	1334.4 μSv

Statistics

$f_{E,\alpha}$	min	0.393
	max	1.257
$u_{Bg,rel}$		0.1

$$x = f_R f_{Det}(f_{E,\alpha} H_{True} + f_{Bg} h_{Bg}) + z$$

$$y = \frac{x - Z}{F_R F_{E,\alpha} F_{Det}} - \frac{F_{Bg}}{F_{E,\alpha}} Y_{Bg}$$

Data sorted with macro
Statistics at end of column

Count 10000
First >0 0

	H_{nat}	f_{Bg}	$f_{E,\alpha}$	f_{Det}	x_{blank}	f_{reader}	x	$u_{x,rel}$	Dose (μSv) H_{occ}			95% coverage	
		Detector				Reader							
mean	100	1	1	1	200	50	μSv	1	1000.03	1000.0	Low	688.9	689.0
stdev	10	0.05	0.144	0.050	10	2.5	μSv	0.02	164.91	164.9	High	1333.3	1334.4

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9	[illegible]	[illegible]	[illegible]	[illegible]							524.3	934.1	1333	1333	1473
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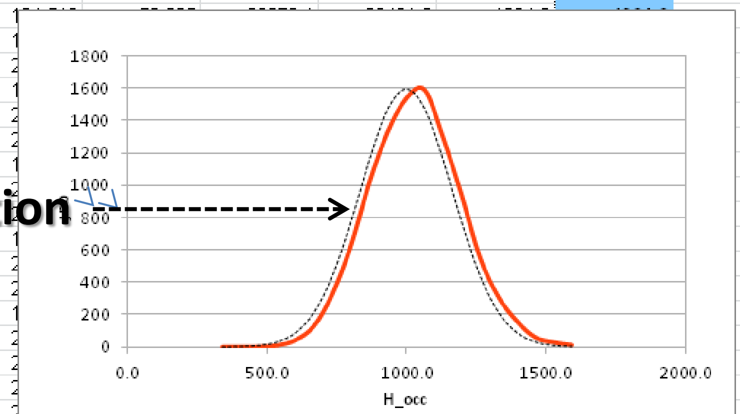
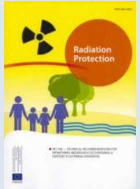
Normal distribution



Monte-Carlo



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H_{nat}	100	µSv	stdev	164.9 16%		164.9 16%
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Bayesian statistics

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Count	10000
First >0	0

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
		Detector				Reader				Dose (µSv)					
	H_{nat}	f_{Bg}	$f_{E,\alpha}$	f_{Det}	x_{blank}	f_{reader}	x	$u_{x,rel}$		H_{occ}			95% coverage		
mean	100	1	1	1	200	50	µSv	1		1000.03	1000.0	Low	688.9	689.0	
stdev	10	0.05	0.144	0.050	10	2.5	µSv	0.02		164.91	164.9	High	1333.3	1334.4	
														Bayesian	
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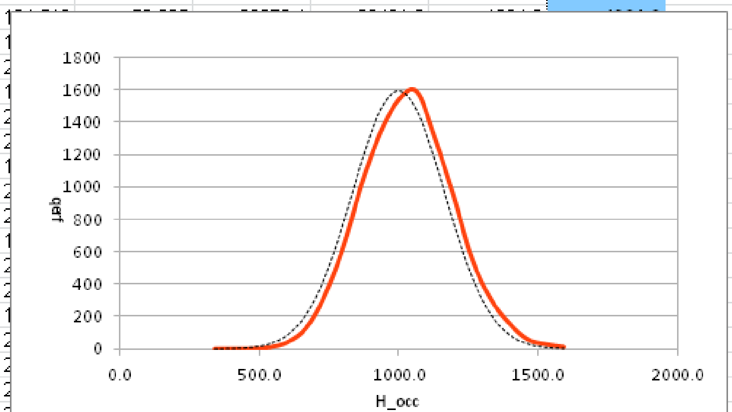
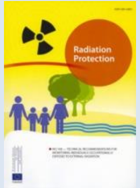


Monte-Carlo



MCM number of samples needed

The sheet works with 10,000 samples

Recalculation (Press F9) will show different results

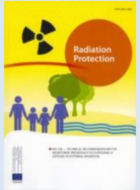
The figure changes shape

10,000 samples is in general far to few

IEC TR 62461:2015 recommends 1,000,000

The JCGM gives an adaptive procedure

van Dijk, J.W.E. *Measurement models for passive dosemeters in view of uncertainty evaluation using Monte Carlo method*, Radiat. Prot. Dosim. 162(4), 438-445 (2014)

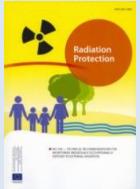


EURADOS

MCM number of samples needed

My experience for the current type of problems:

300,000-500,000 will do
except where the measurand distribution is very skewed



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Characteristic limits

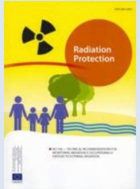
Decision threshold

- The value above which you can decide that a dose above background level is observed

Detection limit

- The smallest true value of the dose that can be detected with the dosemeter

ISO 11929:2010, *Determination of the detection limit and decision threshold for ionizing radiation measurements*



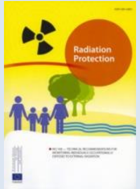
Characteristic limits

Rule of thumb:

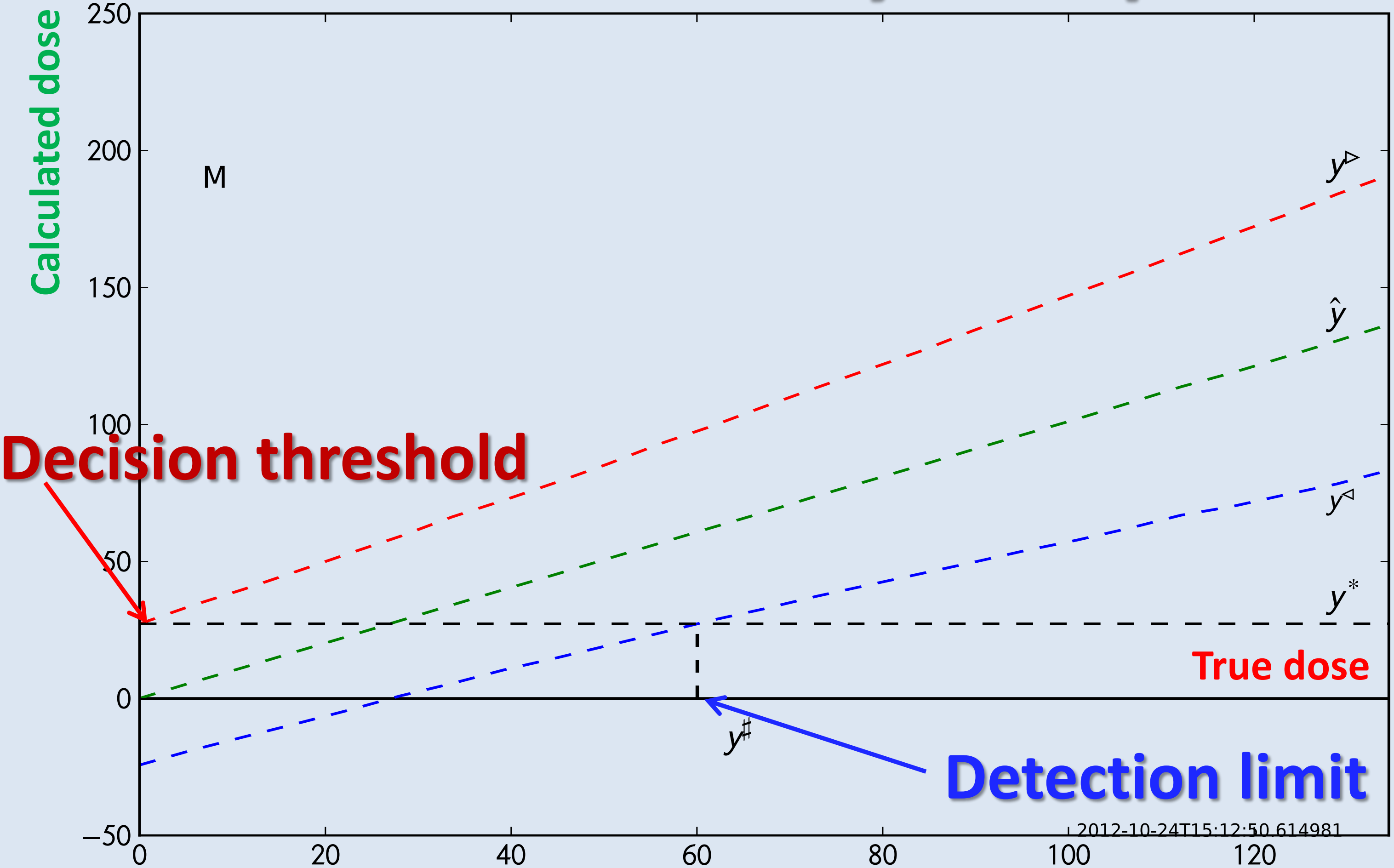
$$y^{*} \quad \simeq 1.7u_y \,|\, y = 0.0$$

$$y^{\#} \quad \simeq 3.3u_y \,|\, y = 0.0$$

L.A. Curry, *Uncertainties in measurements close to the detection limit: Detection and quantification capabilities* in IAEA Tecdoc 1401 (9-34)



Characteristic limits by interpolation



Evaluating uncertainty

EURADOS

mcm_example.xlsm - Microsoft Excel non-commercial use

Monte Carlo uncertainty evaluation of TNO C-detector, LiF:Mg,Ti + 1mm Al

H_{true}	10	µSv	H_{mcm}	9.9	µSv		**Bayesian** 14.6	µSv
H_{nat}	100	µSv	stdev	12.8	129%		10.0	68%
				Low 95%		-13.8	0.8	µSv
				High 95%		36.1	37.5	µSv
N	10000							

$f_{E,\alpha}$	min	0.393
	max	1.257
$u_{Bg,rel}$	0.1	

$$x = f_R f_{Det} (f_{E,\alpha} H_{True} + f_{Bg} h_{Bg}) + z$$

$$y = \frac{x - Z}{F_R F_{E,\alpha} F_{Det}} - \frac{F_{Bg}}{F_{E,\alpha}} Y_{Bg}$$

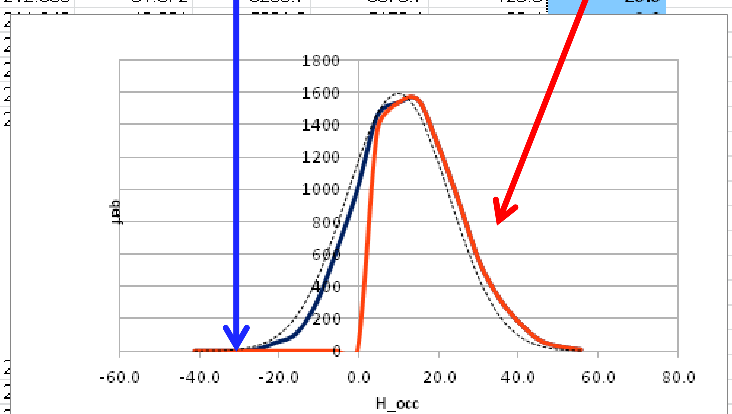
Count 10000

	H_{nat}	f_{Bg} (Detector)	$f_{E,\alpha}$	f_{Det}	x_{blank}
mean	100	1	1	1	200
stdev	10	0.05	0.144	0.050	10

95% coverage	Bayesian
-13.8	0.8
36.1	37.5

	Natural	Bg resp.	Response	Detector	Blank	Sensitivity	Signal	Signal	H_{gross}	H_{occ}	Sorted		Frequency	Bayesian Frequency	Normal
0	107.788	0.991	0.953	1.030	212.838	51.872	6260.7	6375.7	123.5	23.5	-31.6	-41.2	0	0	1
1	91.585	1.001	1.129	0.931							-30.0	-36.1	0	0	2
2	90.274	0.979	1.031	1.035							-29.9	-31.0	1	0	10
3	101.671	0.968	1.079	1.037							-29.2	-25.8	10	0	32
4	97.289	1.037	0.966	0.982							-28.8	-20.7	54	0	90
5	120.313	0.966	1.035	1.109							-28.7	-15.6	110	0	216
											-27.8	-10.5	303	0	444
											-27.4	-5.4	629	0	777
											-26.5	-0.3	1001	0	1159
											-26.3	4.8	1460	1377	1473
											-26.0	9.9	1536	1536	1596
											-25.8	15.0	1553	1553	1473
											-25.5	20.1	1263	1263	1159
											-25.3	25.2	922	922	777
											-25.1	30.3	554	554	444
15	97.116	1.079	0.964	1.122							-25.1	35.4	323	323	216
16	103.194	1.043	1.044	1.061							-25.0	40.5	172	172	90
17	112.907	1.041	0.978	1.044							-24.9	45.6	66	66	32

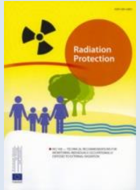
Monte-Carlo



Bayesian statistics

Negative doses!

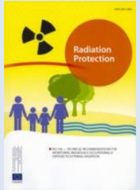
Change H_{true} into 10 µSv



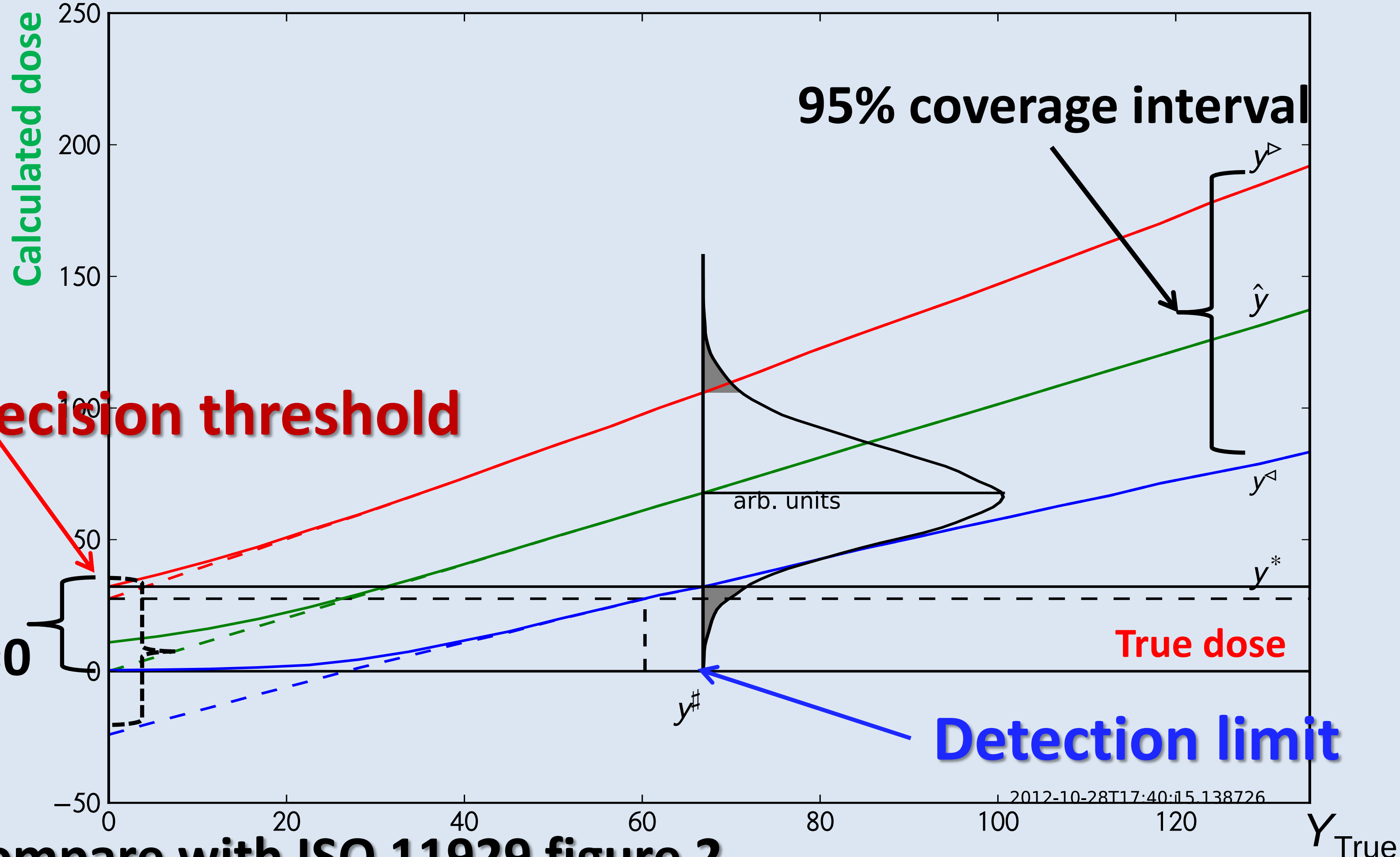
MCM and Bayes

Using Mont Carlo Bayesian statistics for prior: $$P\left(y<0\right)=0$$ **is achieved by rejecting all negative samples**

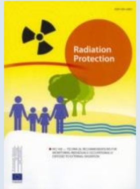
C. Elster, *Calculation of uncertainty in the presence of prior knowledge*. Metrologia <u>44</u> 111-116 (2007)



Characteristic limits by interpolation

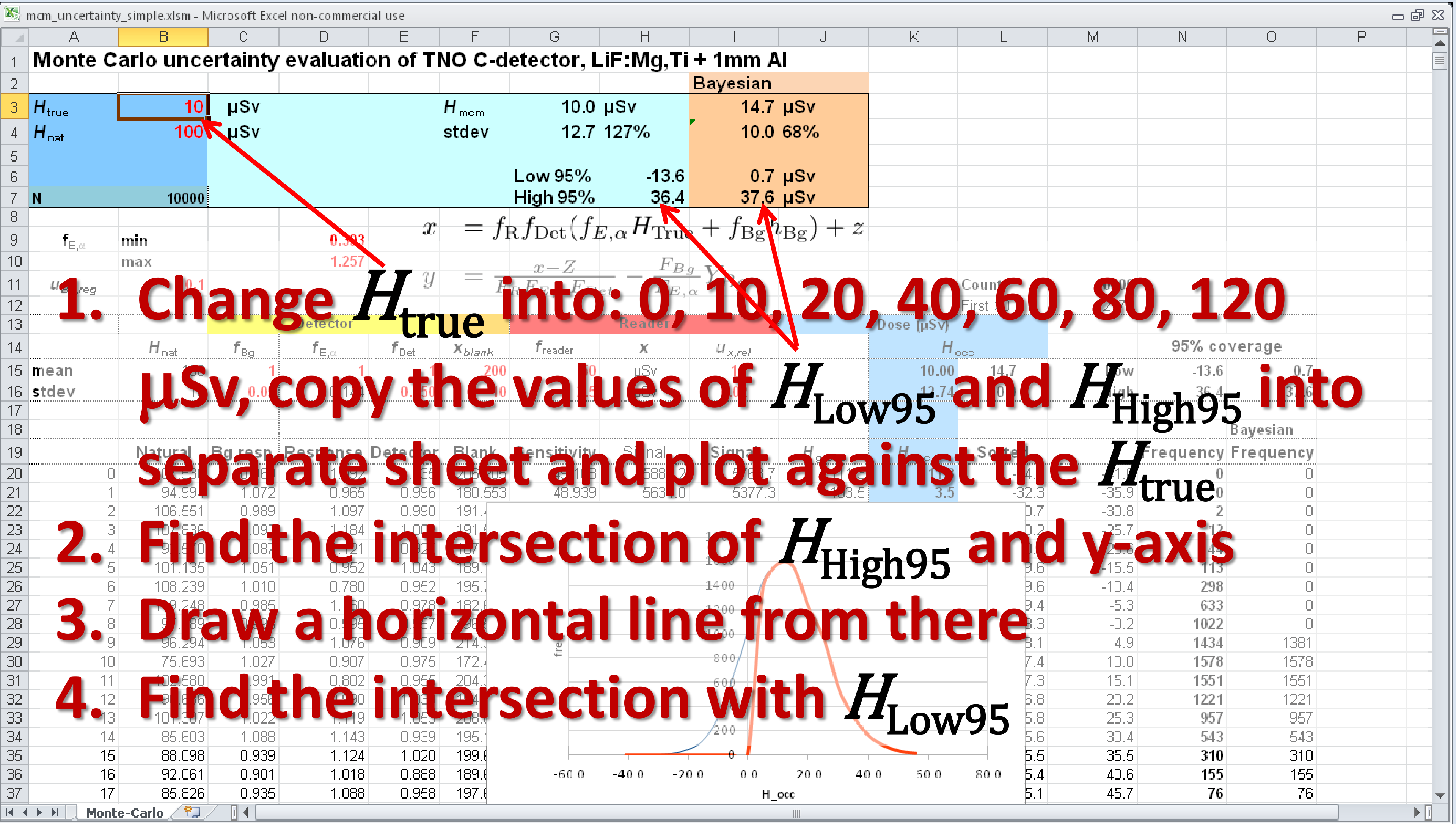


Compare with ISO 11929 figure 2



Evaluating uncertainty

EURADOS



1. Change H_{true} into: 0, 10, 20, 40, 60, 80, 120 µSv, copy the values of H_{Low95} and H_{High95} into separate sheet and plot against the H_{true}
2. Find the intersection of H_{High95} and y-axis
3. Draw a horizontal line from there
4. Find the intersection with H_{Low95}

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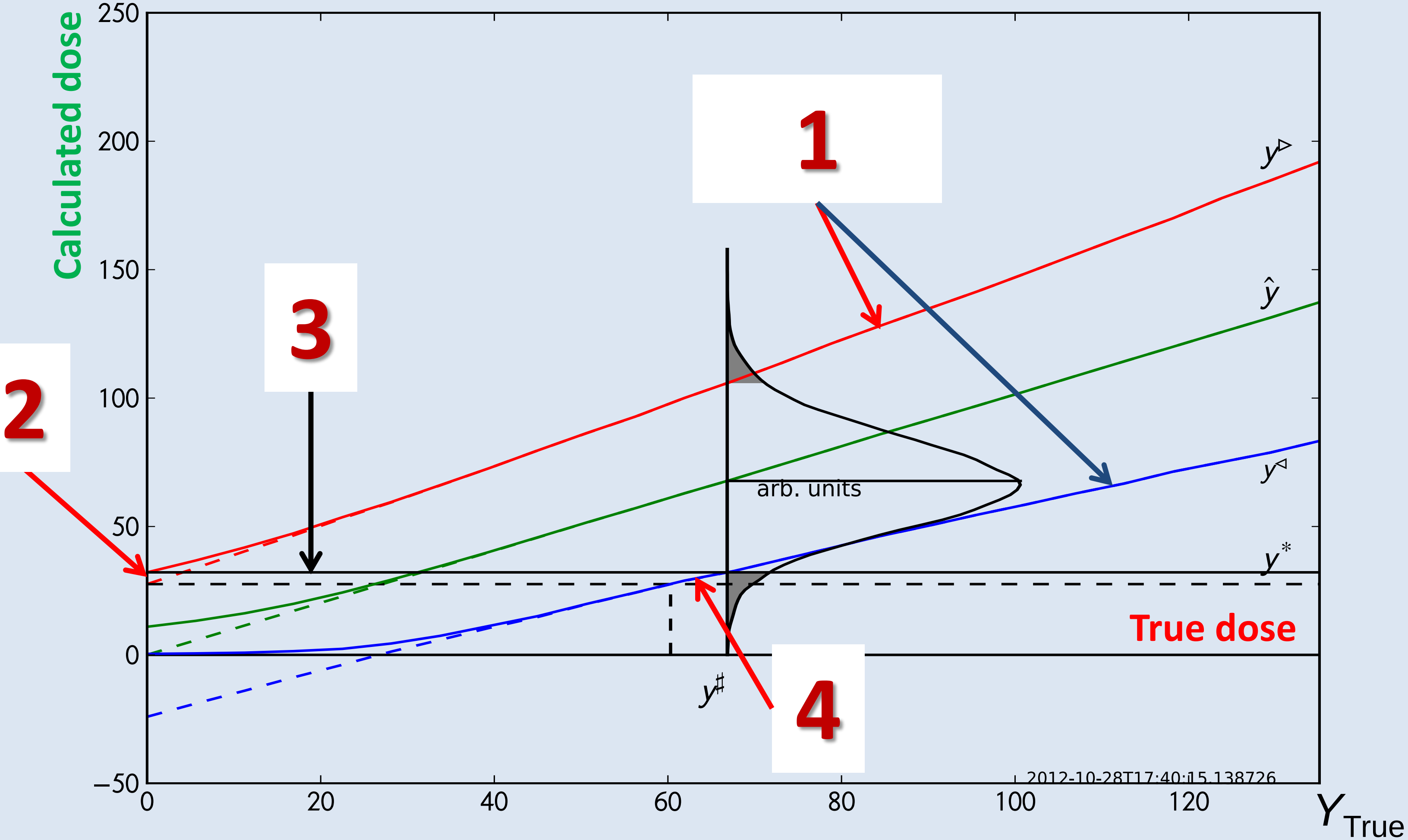
Characteristic limits by interpolation



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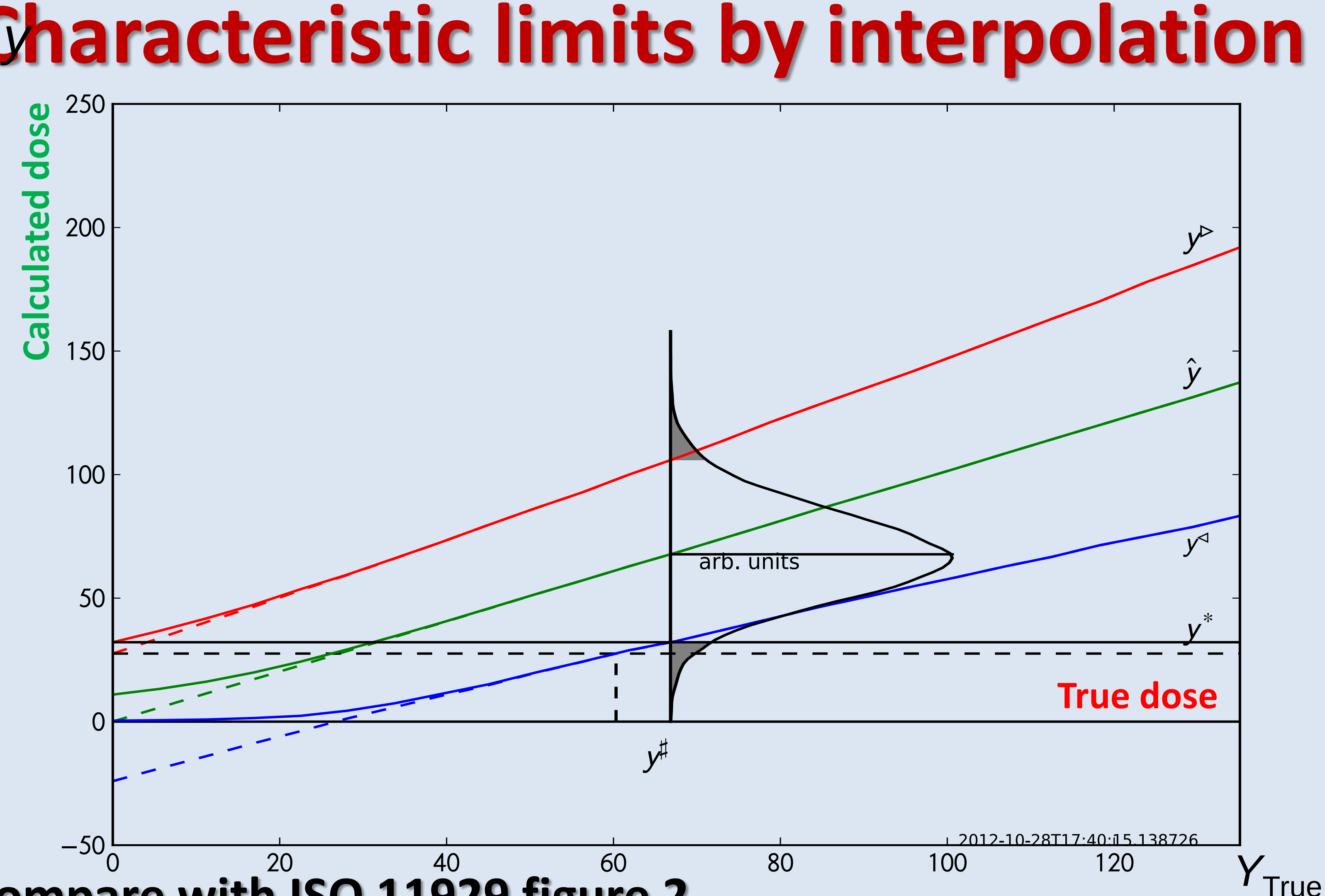
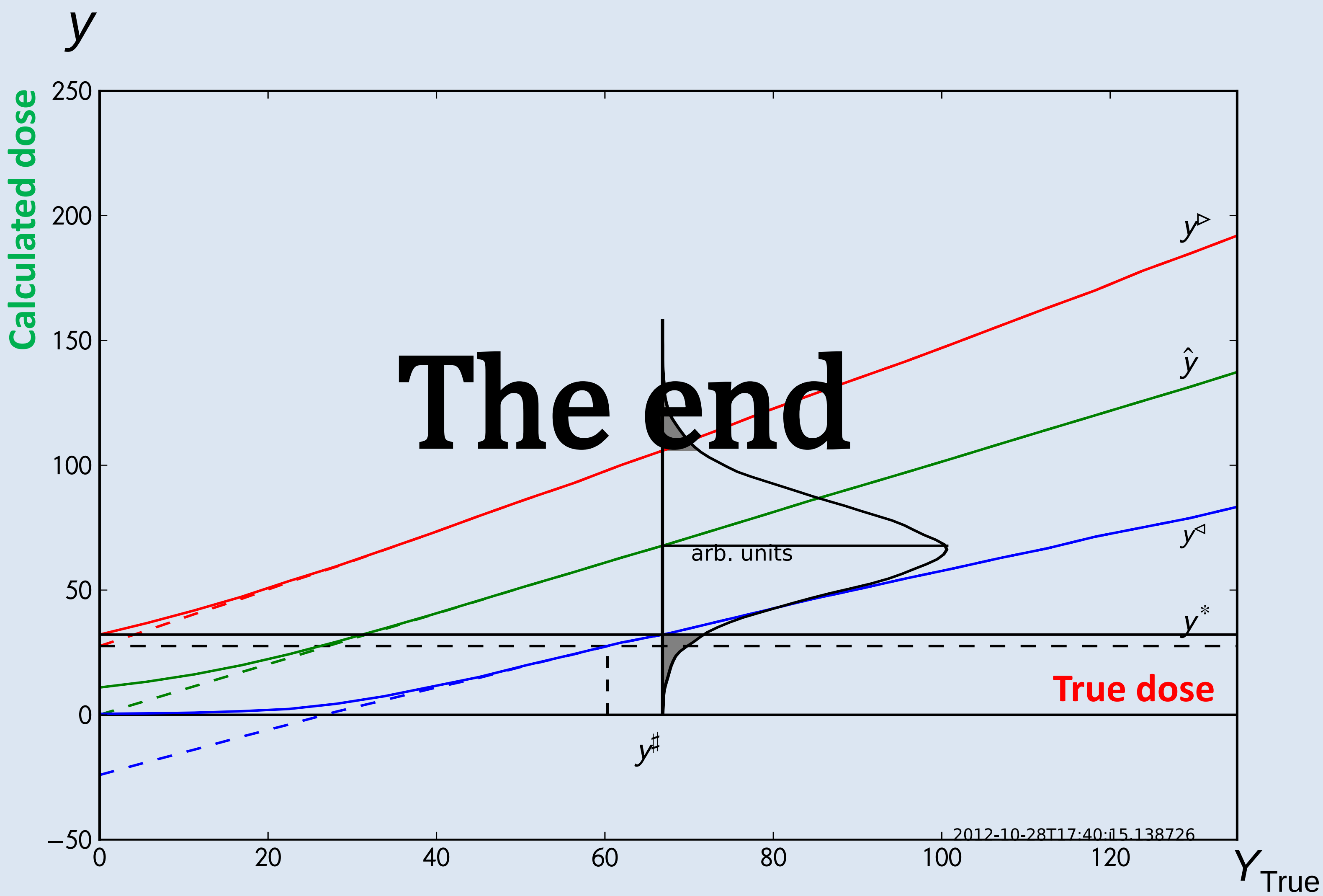
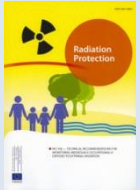
Characteristic limits by interpolation



Compare with ISO 11929 figure 2

Evaluating uncertainty





Important guiding documents

Joint Committee on Guides in Metrology

- **Guide to the expression of uncertainties in measurement and supplements**
- ***http://www.bipm.org/en/publications/guides/gum.html*** ***)**

European Commission

- **Technical Recommendations for Monitoring Individuals Occupationally Exposed to Ionizing Radiation**
- ***http://ec.europa.eu/energy/sites/ener/files/documents/160.pdf*** ***)**

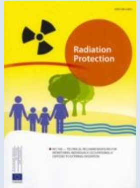
ICRU Report 76

- **Measurement quality assurance for ionizing radiation dosimetry**
- ***http://www.icru.org***

IEC TR 62461

- **Radiation Protection Instrumentation – Determination of uncertainty**
- ***http://webstore.iec.ch/preview/info_iec62461%7Bed2.0%7Den.pdf***

***) Document can be downloaded for free**



Some Monte Carlo literature

J. W. E. van Dijk , *Measurement models for passive dosemeters in view of uncertainty evaluation using the Monte Carlo method.* Radiat Prot Dosimetry (2014) 162 (4): 438-445

H. Stadtmann and C. Hranitzky, *Uncertainty assessment of a two element LiF:Mg,Ti TL personal dosemeter using Monte-Carlo techniques*. Radiat Prot Dosimetry (2011) 144 (1-4): 67-71

R. Behrens, *Uncertainties in external dosimetry: analytical vs. Monte Carlo method.* Radiat Prot Dosimetry (2010) 138 (4): 346-352

J. W. E. van Dijk, *Developments in uncertainty analysis for individual monitoring.* Radiat Prot Dosimetry (2011) 144 (1-4): 56-61

J. W. E. van Dijk , *Evaluating the uncertainty in measurement of occupational exposure with personal dosemeters*. Radiat Prot Dosimetry (2007) 125 (1-4): 387-394

J. W. E. van Dijk, *Uncertainties in personal dosimetry for external radiation: a Monte Carlo approach.* Radiat Prot Dosimetry (2006) 121 (1): 31-38

Maurice Cox, Peter Harris, Gyeonghee Nam, and David Thomas, *The use of a Monte Carlo method for uncertainty calculation, with an application to the measurement of neutron ambient dose equivalent rate.* Radiat Prot Dosimetry (2006) 121 (1): 12-23

Evaluating uncertainty

EURADOS

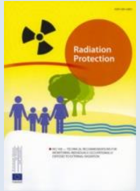
IEC TR 62461 Table B1

IEC TR 62461*)

Table B.1 – Example of an uncertainty budget for a photon dose measurement with a passive dosimetry system according to IEC 62387-1:2007 and low level of consideration of the workplace conditions, see text for details

Quantity	Best estimate	Absolute standard uncertainty	Distribution; mean value, x; half-width, a	Sensitivity coefficient	Uncertainty contribution to output quantity
N_0	1,00	$0.05\sqrt{6}$ = 0,020 4	Triangular; x = 1,0; a = 0,05	10 mSv	0,20 mSv
K_n	1,00	$0.10\sqrt{3}$ = 0,057 7	Rectangular; x = 1,0; a = 0,1	10 mSv	0,58 mSv
$K_{E,\square\varphi}$	1,00	0,40/3 = 0,133	Gaussian; x = 1,0; a = 0,4	10 mSv	1,33 mSv
K_{add}	1,00	0	Rectangular; x = 1,0; a = 0,0	10 mSv	0,0 mSv
K_{temp}	1,00	0,20/3 = 0,066 7	Gaussian; x = 1,0; a = 0,20	10 mSv	0,67 mSv
K_{light}	1,00	0,1/3 = 0,033 3	Gaussian; x = 1,0; a = 0,10	10 mSv	0,33 mSv
K_{bup}	1,00	0,1/3 = 0,033 3	Gaussian; x = 1,0; a = 0,10	10 mSv	0,33 mSv
K_{stab}	1,00	0,1/3 = 0,033 3	Gaussian; x = 1,0; a = 0,10	10 mSv	0,33 mSv
K_{tempR}	1,00	0,1/3 = 0,033 3	Gaussian; x = 1,0; a = 0,10	10 mSv	0,33 mSv
K_{lightR}	1,00	0,1/3 = 0,033 3	Gaussian; x = 1,0; a = 0,10	10 mSv	0,33 mSv
K_{pow}	1,00	0,1/3 = 0,033 3	Gaussian; x = 1,0; a = 0,10	10 mSv	0,33 mSv
G	10 mSv	0,05 × 10 mSv = 0,50 mSv	Gaussian with one reading; x = 10,0 mSv; a = 1,50 mSv	1,00	0,50 mSv
$D_{EMC,1}$	0 mSv	0,7 x 0,1 mSv/3 = 0,023 3 mSv	Gaussian; x = 0,0 mSv; a = 0,07 mSv	−1,00	0,023 mSv
$D_{EMC,2}$	0 mSv	0,7 x 0,1 mSv/3 = 0,023 3 mSv	Gaussian; x = 0,0 mSv; a = 0,07 mSv	−1,00	0,023 mSv
$D_{EMC,3}$	0 mSv	0,7 x 0,1 mSv/3 = 0,023 3 mSv	Gaussian; x = 0,0 mSv; a = 0,07 mSv	−1,00	0,023 mSv
$D_{EMC,4}$	0 mSv	0,7 x 0,1 mSv/3 = 0,023 3 mSv	Gaussian; x = 0,0 mSv; a = 0,07 mSv	−1,00	0,023 mSv
$D_{EMC,5}$	0 mSv	0,7 x 0,1 mSv/3 = 0,023 3 mSv	Gaussian; x = 0,0 mSv; a = 0,07 mSv	−1,00	0,023 mSv
$D_{EMC,6}$	0 mSv	0,7 x 0,1 mSv/3 = 0,023 3 mSv	Gaussian; x = 0,0 mSv; a = 0,07 mSv	−1,00	0,023 mSv
$D_{EMC,7}$	0 mSv	0,7 x 0,1 mSv/3 = 0,023 3 mSv	Gaussian; x = 0,0 mSv; a = 0,07 mSv	−1,00	0,023 mSv
D_{drpo}	0 mSv	0,7 x 0,1 mSv/3 = 0,023 3 mSv	Gaussian; x = 0,0 mSv; a = 0,07 mSv	−1,00	0,023 mSv
$H_p(10)$	10,0 mSv	1,9 mSv (19 %)	(Analytical method)		

***) Taken with permission from TR 62461 IEC:2014-08 45B final draft. Not to be used for reference purposes.**

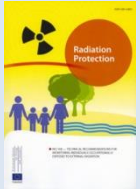


Evaluating uncertainty

EURADOS

The law of propagation of uncertainty, LPU, is based on the Taylor series development.
The measurand is for a value of the input quantity that slightly varies from the true value, approximated by a first degree Taylor series truncated after the 1^{st} degree.

See NPL document ***dem_es11.pdf*** Chapter 6



Evaluating uncertainty

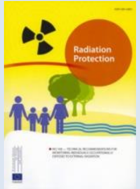
EURADOS

True value — **Small deviation due to uncertainty**

$$
\begin{aligned}
y &= f(x) \\
y_\Delta &= f(x+\Delta) \\
&= f(x) + \frac{\partial f(x)}{\partial x}\Delta + \frac{\frac{\partial^2 f(x)}{\partial x^2}}{2!}\Delta^2 + \ldots
\end{aligned}
$$

Negligible: $+ \frac{\frac{\partial^2 f(x)}{\partial x^2}}{2!}\Delta^2 + \ldots$

Sensitivity coefficient: $\frac{\partial f(x)}{\partial x}$



Evaluating uncertainty

The variance of the joint distribution of a series of normal distributions is the sum of the variances of the individual distributions.

Adding the squares of the product of sensitivity coefficient and standard uncertainty gives the variance in the measurand.

$$v_x = \left(\frac{\partial f(x)}{\partial x} u_x \right)^2$$

Assumptions:

The higher degree terms of the Taylor series can be neglected (~LPU)

The distribution of the measurand is approximately normal (~ CLT)