Calculating the uncertainty due to matrix corrections in electron probe microanalysis

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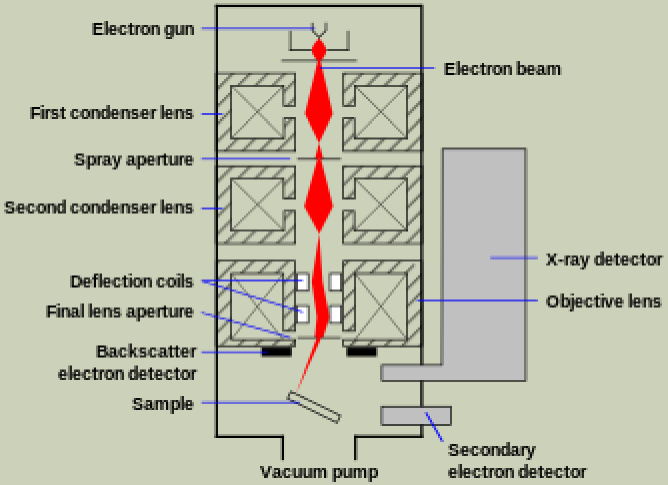
We can calculate uncertainties,

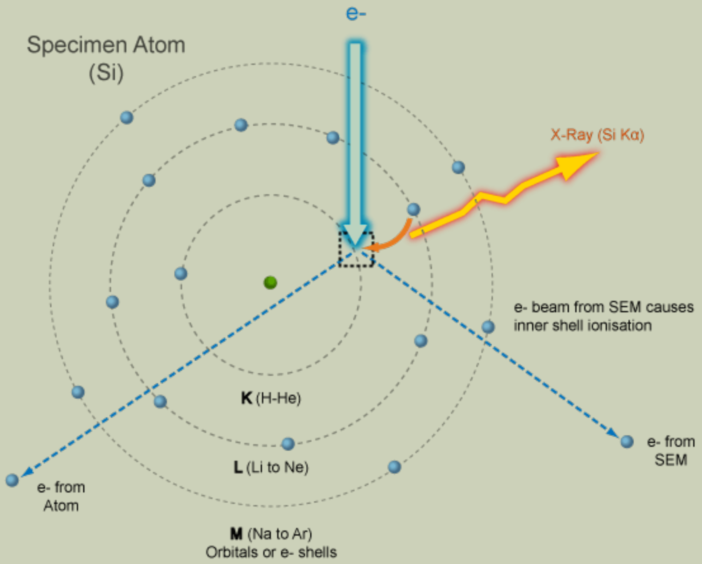
so what?

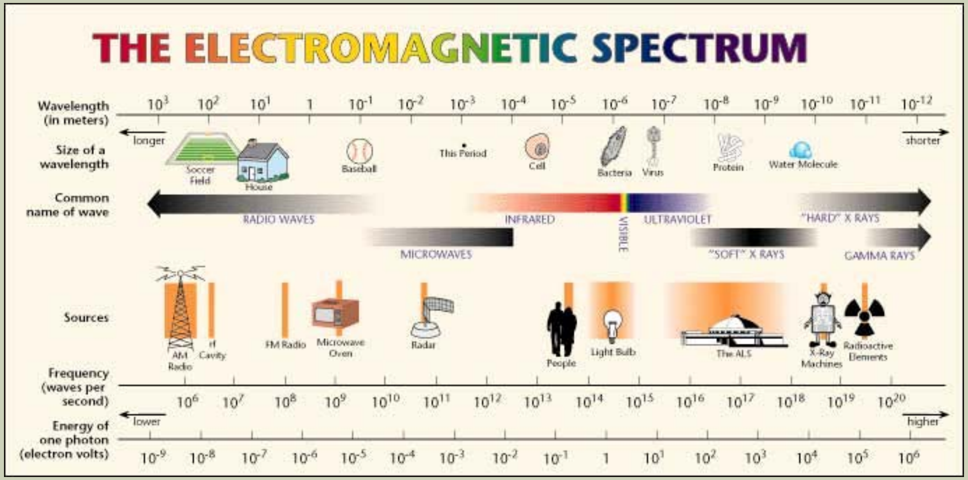
That and $6 will get you an beer at Dogfish Head…

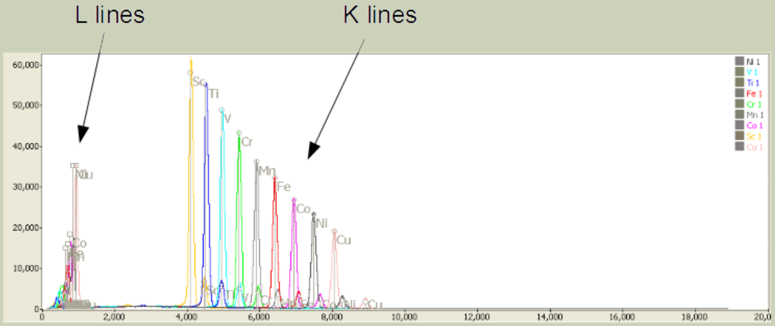
SEM


Electron gun
Electron beam
First condenser lens
Spray aperture
Second condenser lens
X-ray detector
Deflection coils
Objective lens
Final lens aperture
Backscatter electron detector
Sample
Vacuum pump
Secondary electron detector

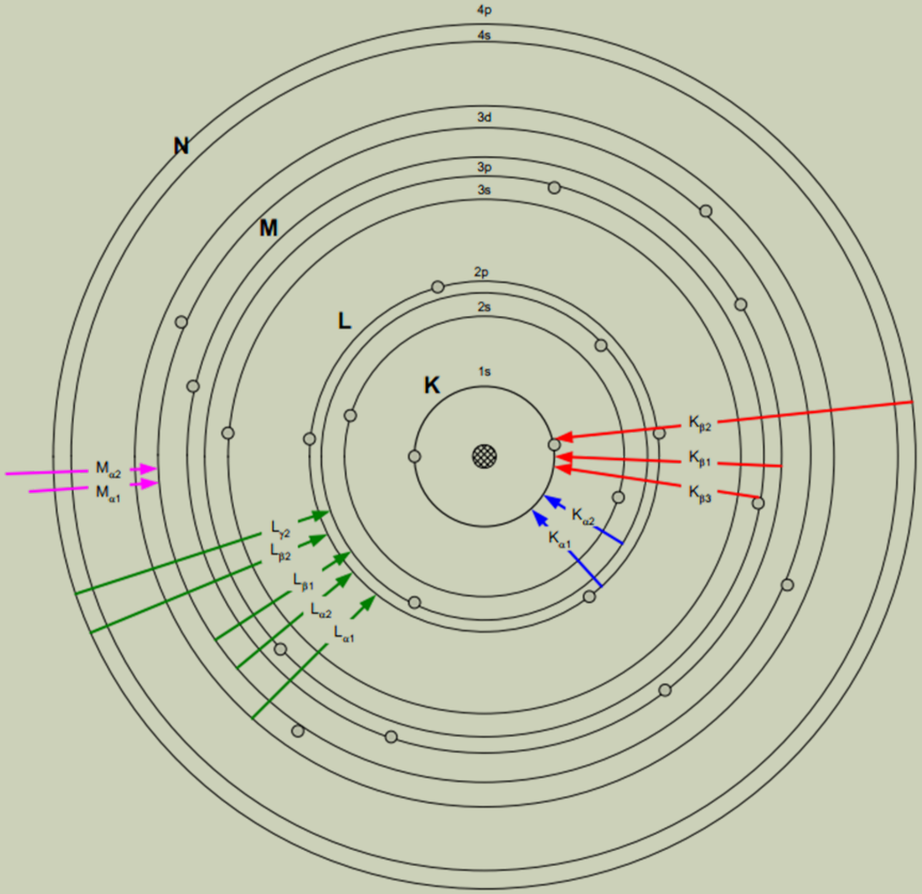
Characteristic X-Ray Production

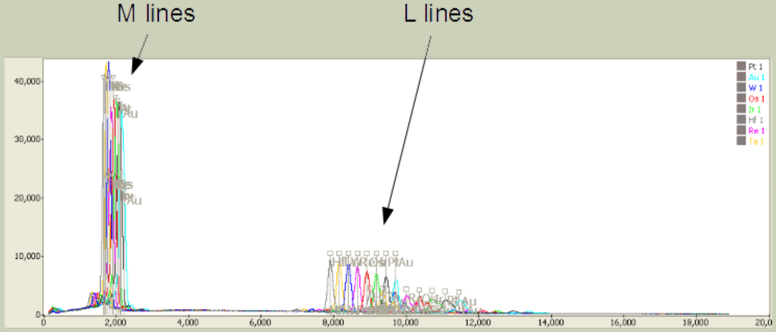






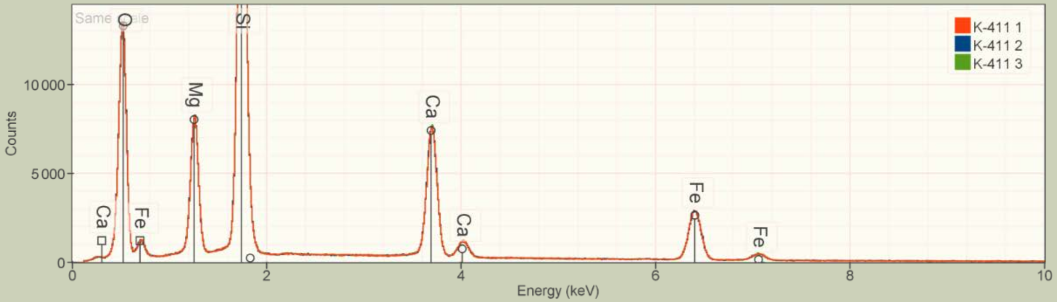
Z = 21 (Sc) to 29 (Cu)





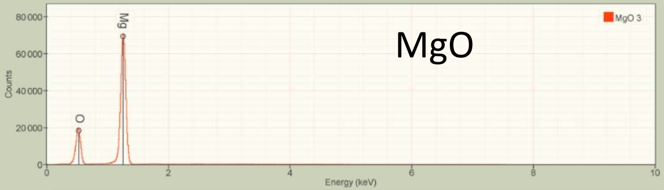
Z = 72 (Hf) to 79 (Au)

k-ratios



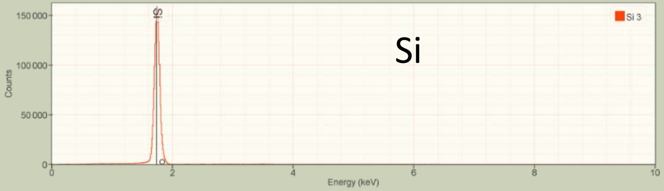
=

⇨ 0.1076



+

⇨ 0.1792



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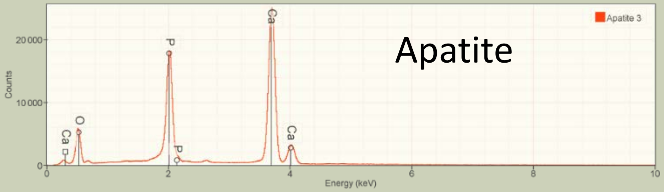
⇨ 0.2947



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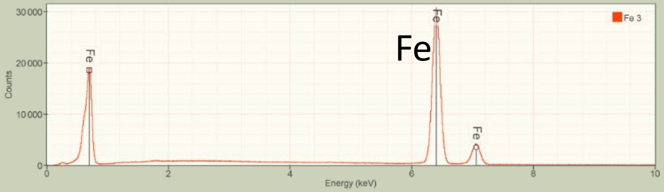
⇨ 0.0921



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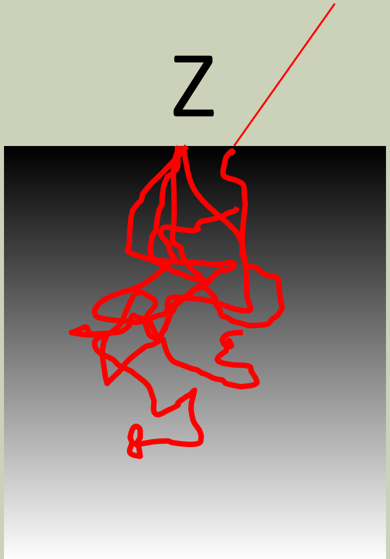
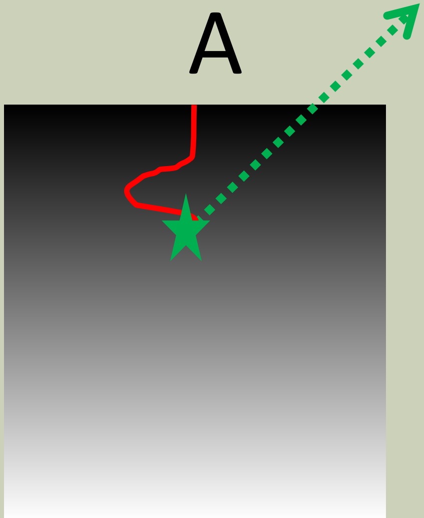
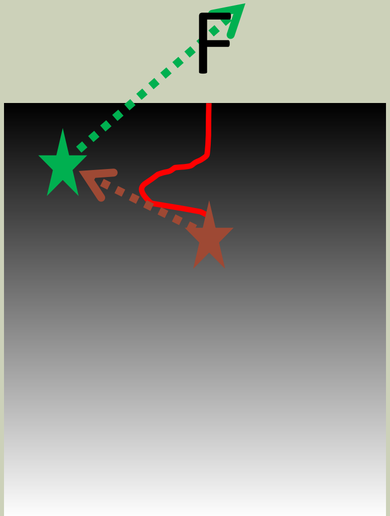
Matrix correction



Stopping / backscatter



X-ray absorption

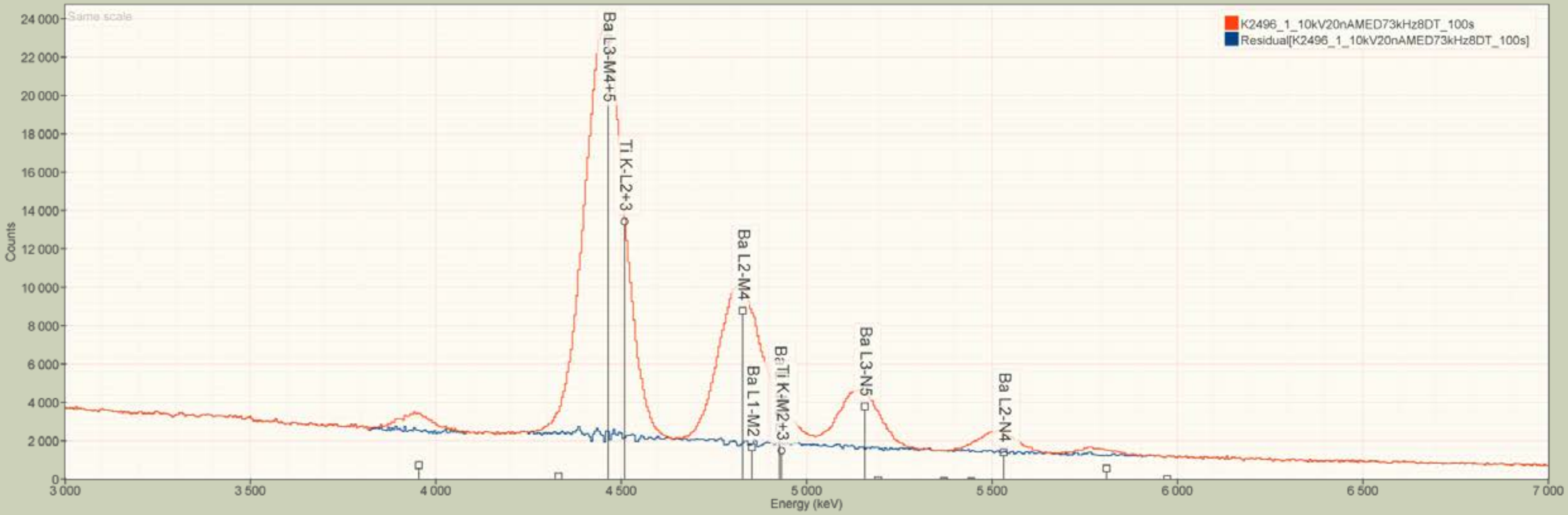


Secondary fluorescence

$$k_A = \frac{\{Z \cdot A \cdot F\}_{Unk,A}}{\{Z \cdot A \cdot F\}_{Std,A}} C_A$$

```
IUPAC      Seigbahn   Standard   Energy     ZAF        Z          A          F          k-ratio
O K-L3     O Kα1      MgO        0.5249     0.5777     1.0240     0.5650     0.9985     0.616525
Mg K-L3    Mg Kα1     MgO        1.2536     0.7593     1.0240     0.7365     1.0069     0.111390
Si K-L3    Si Kα1     Pure Si    1.7397     0.7039     0.9817     0.7157     1.0018     0.178651
Si K-M3    Si Kβ1     Pure Si    1.8290     0.7302     0.9817     0.7424     1.0019     0.185337
Ca K-L3    Ca Kα1     CaF2       3.6917     0.9169     0.9637     0.9460     1.0057     0.197481
Ca K-M3    Ca Kβ1     CaF2       4.0127     0.9275     0.9637     0.9565     1.0063     0.199775
Fe K-L3    Fe Kα1     Pure Fe    6.4039     0.8348     0.8422     0.9912     1.0000     0.093572
Fe K-M3    Fe Kβ1     Pure Fe    7.0580     0.8367     0.8422     0.9934     1.0000     0.093780
Fe L3-M5   Fe Lα1     Pure Fe    0.7045     0.2557     0.8574     0.2980     1.0009     0.028659
```

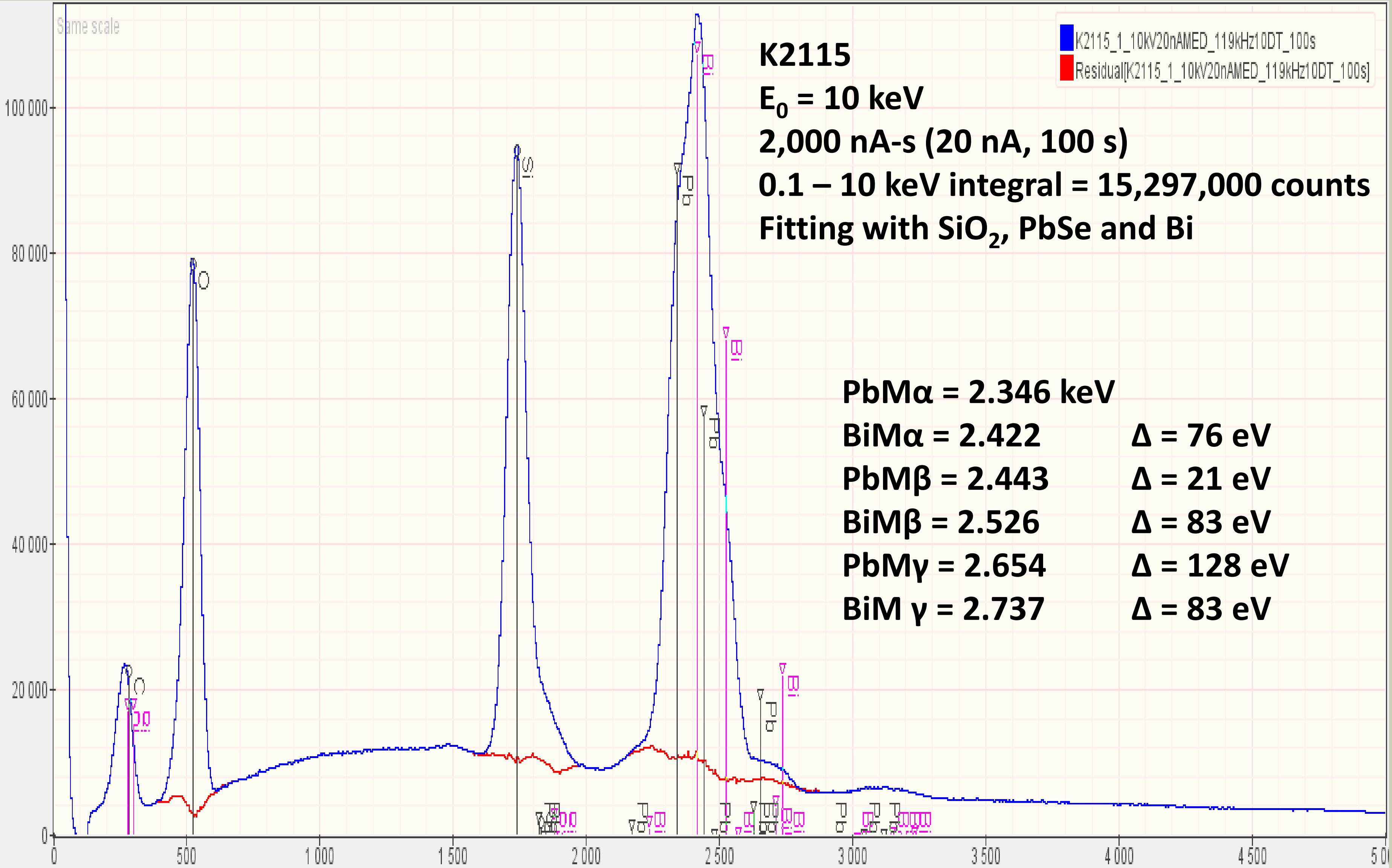
Minor element quantification with major element overlap



K2496 glass

- E_0 = 10 keV
- 1000 nA-s
- 0.1-10keV integral = 12,175,000 counts
- Standards:
  - SiO_2
  - $BaSi_2O_5$ (Sanbornite) for Ba
  - Ti

Raw total (mass fraction)	O, mass conc (stoichiometry)	Si, mass conc	Ti, mass conc	Ba, mass conc
0.9836±0.0011	0.3195±0.0004	0.2251±0.0004	0.0180±0.0003	0.4374±0.0012
0.9824±0.0011	0.3202±0.0004	0.2260±0.0004	0.0178±0.0003	0.4360±0.0012
0.9828±0.0011	0.3197±0.0004	0.2259±0.0004	0.0170±0.0003	0.4374±0.0012
0.9828±0.0011	0.3196±0.0004	0.2255±0.0004	0.0176±0.0003	0.4374±0.0012
0.9814±0.0011	0.3197±0.0004	0.2256±0.0004	0.0175±0.0003	0.4372±0.0012
0.9811±0.0011	0.3199±0.0004	0.2257±0.0004	0.0178±0.0003	0.4366±0.0012
0.9819±0.0011	0.3194±0.0004	0.2254±0.0004	0.0173±0.0003	0.4379±0.0012
average	0.3197	0.2256	0.0176	0.4371
s		0.00028	0.00031	0.00058
s (relative)		0.13%	1.8%	0.13%
synthesized		0.2291	0.0180	0.4299
Relative error		-1.5%	-2.4%	1.7%
Error in k (counts)		0.0001 (0.044% relative)	0.0003 (1.7% relative)	0.0007 (0.16% relative)
Error in Z (estimate)		1.1E-5 (0.0049% rel)	2.5E-7 (0.0014% relative)	2.1E-7 (4.8E-5% relative)
Error in A (estimate)		0.0015 (0.66% relative)	3.9E-6 (0.022% relative)	1.9E-5 (0.0044% relative)



K2115

E_0 = 10 keV

2,000 nA-s (20 nA, 100 s)

0.1 – 10 keV integral = 15,297,000 counts

Fitting with SiO_2, PbSe and Bi

PbMα = 2.346 keV
BiMα = 2.422 Δ = 76 eV
PbMβ = 2.443 Δ = 21 eV
BiMβ = 2.526 Δ = 83 eV
PbMγ = 2.654 Δ = 128 eV
BiM γ = 2.737 Δ = 83 eV

Unknown: NIST Glass K2115

Raw total	O, atom conc	Si, atom conc	Pb, atom conc	Bi, atom conc
0.9979±0.0013	0.6159±0.0009	0.1828±0.0004	0.1035±0.0003	0.0979±0.0003
0.9977±0.0013	0.6159±0.0009	0.1828±0.0004	0.1032±0.0003	0.0981±0.0003
0.9960±0.0013	0.6159±0.0009	0.1829±0.0004	0.1033±0.0003	0.0979±0.0003
0.9965±0.0013	0.6160±0.0009	0.1830±0.0004	0.1029±0.0003	0.0981±0.0003
0.9963±0.0013	0.6159±0.0009	0.1829±0.0004	0.1032±0.0003	0.0979±0.0003
0.9969±0.0013	0.6158±0.0009	0.1826±0.0004	0.1036±0.0003	0.0981±0.0003
0.9975±0.0013	0.6158±0.0009	0.1825±0.0004	0.1036±0.0003	0.0981±0.0003

Measurement
- E_0 = 10 keV
- Standards:
  - SiO_2
  - PbSe
  - Bi

Silicon
- Average = 0.1828
- σ = 0.00016
- σ_{rel} = 0.090%
- Synthesis = 0.1863
- Rel error = -1.9%

Bismuth
- Average = 0.0980
- σ = 0.00009
- σ_{rel} = 0.10%
- Synthesis = 0.0961
- Rel error = 2.0%

Lead
- Average = 0.1033
- σ = 0.00024
- σ_{rel} = 0.23%
- Synthesis = 0.1003
- Rel error = 3.0%

The Big Question

Given that EDS with an SDD can produce such amazingly good results *when applied correctly**, how do we encourage people to do the right thing?

* Standards-based analysis with carefully prepared standards and unknowns under well-controlled and well-selected conditions.

My Answer:

Make doing the right thing as easy as possible.

What did we gloss over?

- ✓ Selection of beam energy
- ✓ Selection of standards
- ✓ Necessity for references
- ✓ Selection of transition (K vs. L, L vs. M)
- ✓ Selection of probe dose (for the unknown, the standards and the references)

No wonder people are intimidated by the prospect of performing a standards-based EDS measurement.

What is wrong with this picture?

Development of copper-based metal matrix composites: An analysis by SEM, EDS and XRD

Syed Nasimul Alam and Harshpreet Singh

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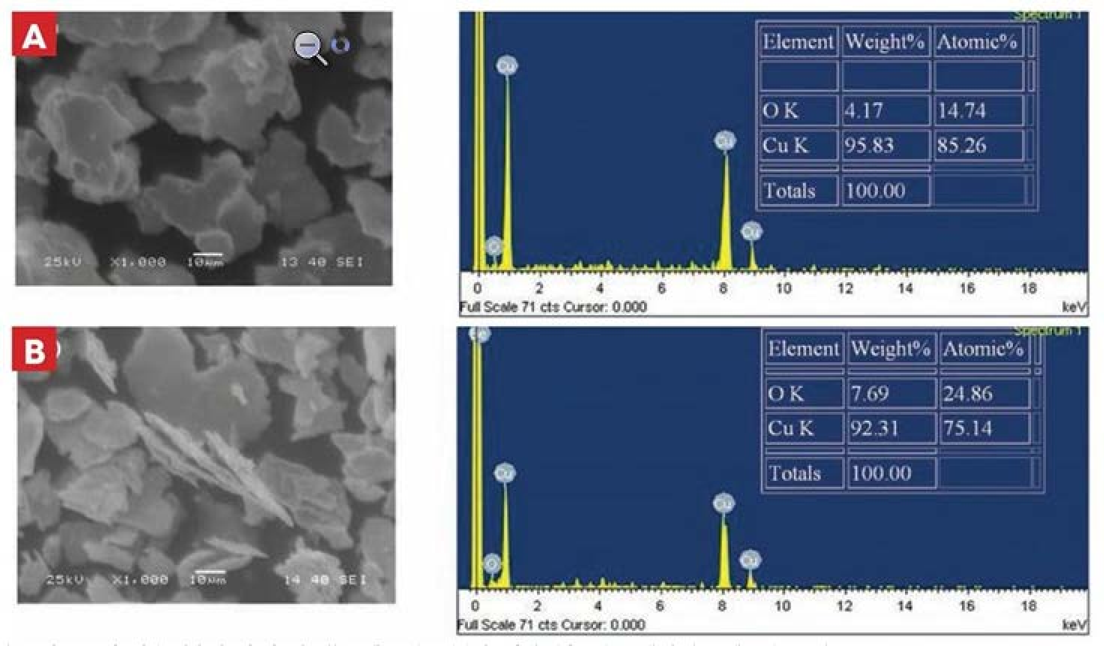


Element	Weight%	Atomic%
O K	4.17	14.74
Cu K	95.83	85.26
Totals	100.00	

Element	Weight%	Atomic%
O K	7.69	24.86
Cu K	92.31	75.14
Totals	100.00	

What is wrong with this picture?

Really? Exactly 100%

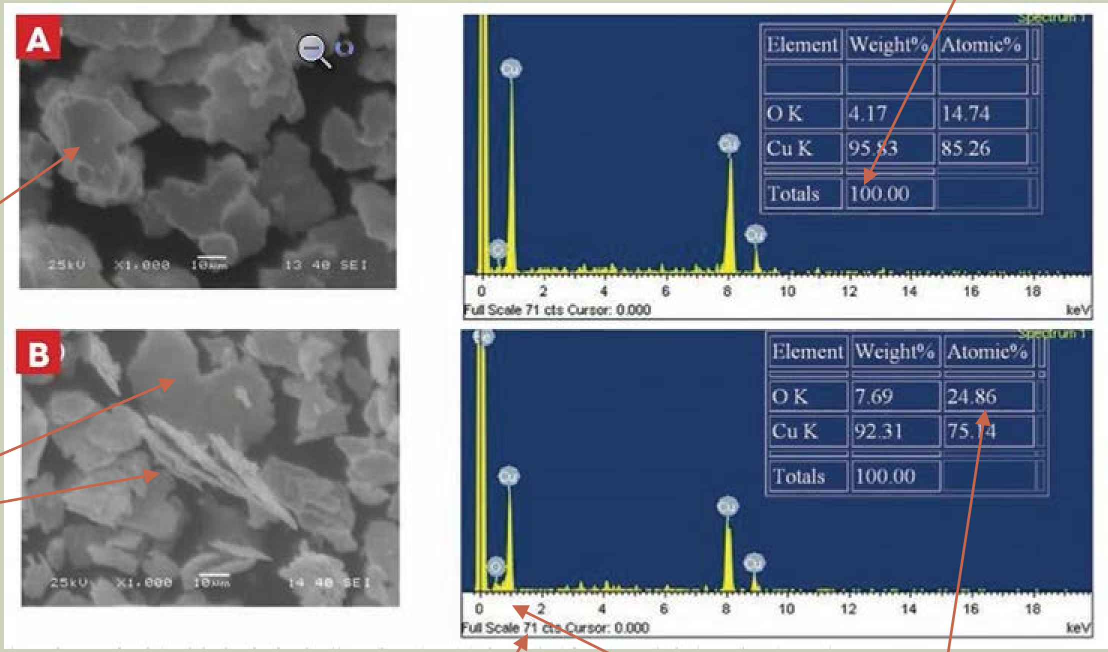
What about this peak

Development of copper-based metal matrix composites: An analysis by SEM, EDS and XRD

Syed Nasimul Alam and Harshpreet Singh

Doesn't look flat, polished, bulk to me…

Doesn't look homogeneous



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Element	Weight%	Atomic%
O K	7.69	24.86
Cu K	92.31	75.14
Totals	100.00	

71 counts full scale!

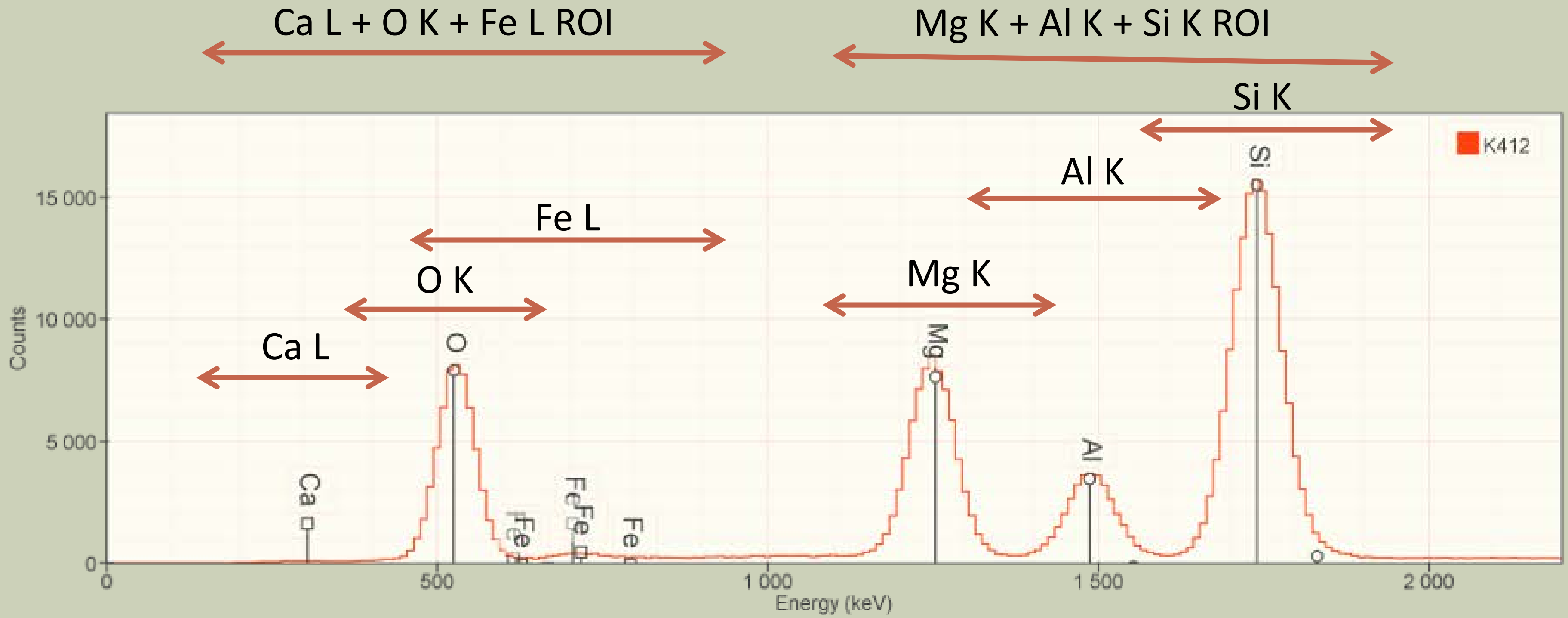
10 counts for how many digits of precision?

Crisis in microanalysis

- EPMA is only one of many techniques for which the typical technician is responsible
- Many labs fail to provide adequate training
- Instrument vendors are not motivated to ensure that their instruments produce reliable results in the field
- EPMA is conceptually simple but the devil is in the details

The literature is awash with poor quality EPMA measurements

K412



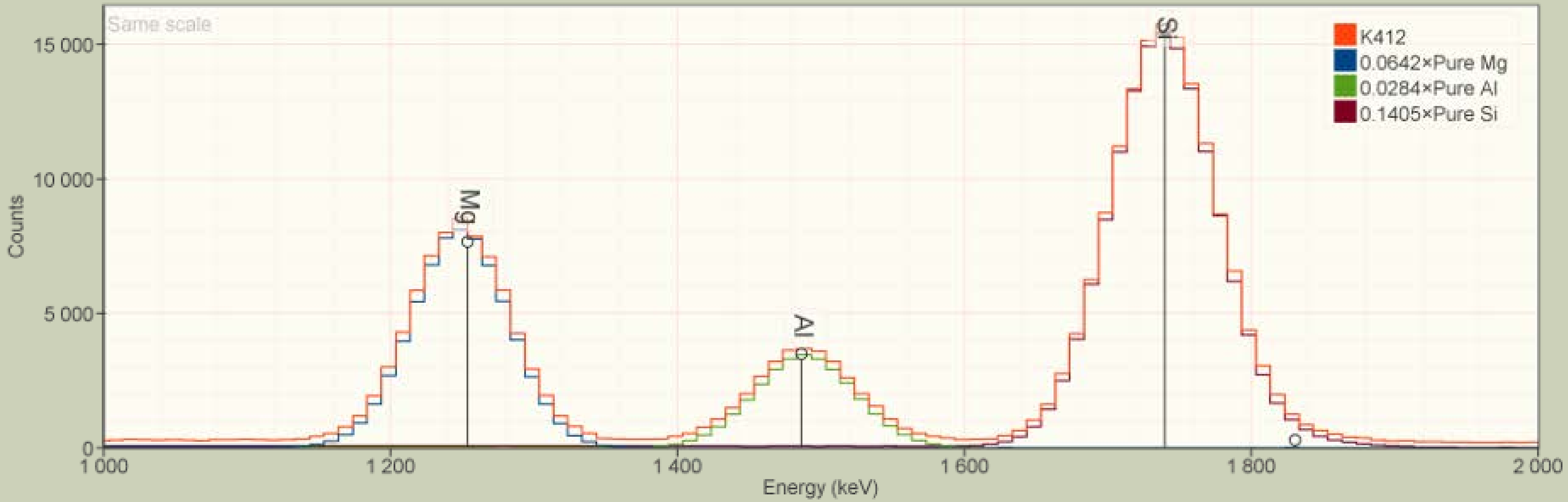
An accurate fit requires both peak and background

To extract the O K intensity we need references for Ca L, O K and Fe L → CaF_2, Al_20_3 and Fe
Mg K intensity we need references for Mg K, Al K and Si K → Mg, Al_20_3 and Si

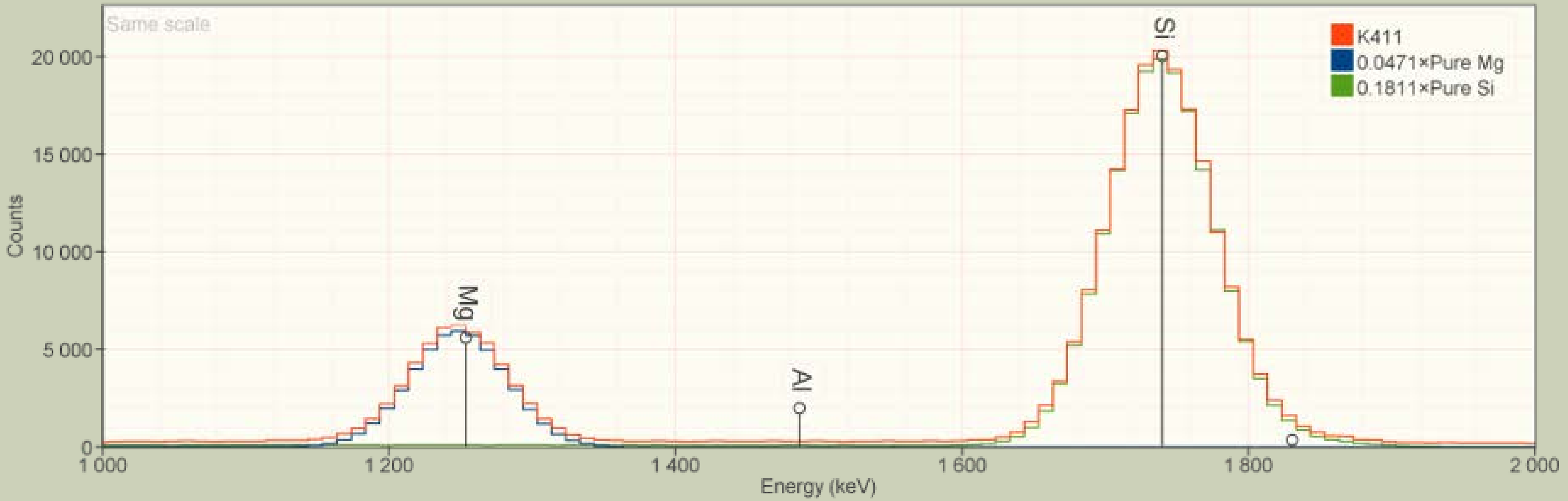
Standards and References

- Standards provide **intensity** information
- References provided **peak shape** information
- Sometimes the standard can provide both intensity and shape information (in which case the standard can act as reference too.)
- You may need references for elements that **aren't even in the unknown** (but are in the standard.)
- Using standards **similar in composition** to the unknown typically produces more accurate measurements.

Fit the references to the standard



Fit the references to the unknown



k (Mg in K411 vs K412) = 0.0471 / 0.0642 = 0.7344 k (Si in K411 vs K412) = 0.1405 / 0.1811 = 1.2889

Why like standards?

IUPAC	*Seigbahn*	*Standard*	*ZAF*	*Standard*	*ZAF*
O K-L3	O Kα1	K412	0.9973	Al_2O_3	0.652
Mg K-L3	Mg Kα1	K412	0.9543	Mg	0.5259
Si K-L3	Si Kα1	K412	1.0676	Si	0.7039
Si K-M3	Si Kβ1	K412	1.0614	Si	0.7302
Ca K-L3	Ca Kα1	K412	1.0058	CaF_2	0.9169
Ca K-M3	Ca Kβ1	K412	1.0061	CaF_2	0.9275
Fe K-L3	Fe Kα1	K412	1.0045	Fe	0.8348
Fe K-M3	Fe Kβ1	K412	1.0046	Fe	0.8367
Fe L3-M5	Fe Lα1	K412	1.011	Fe	0.2557

Small corrections (ZAF ~ 1) typically lead to accurate measurements.

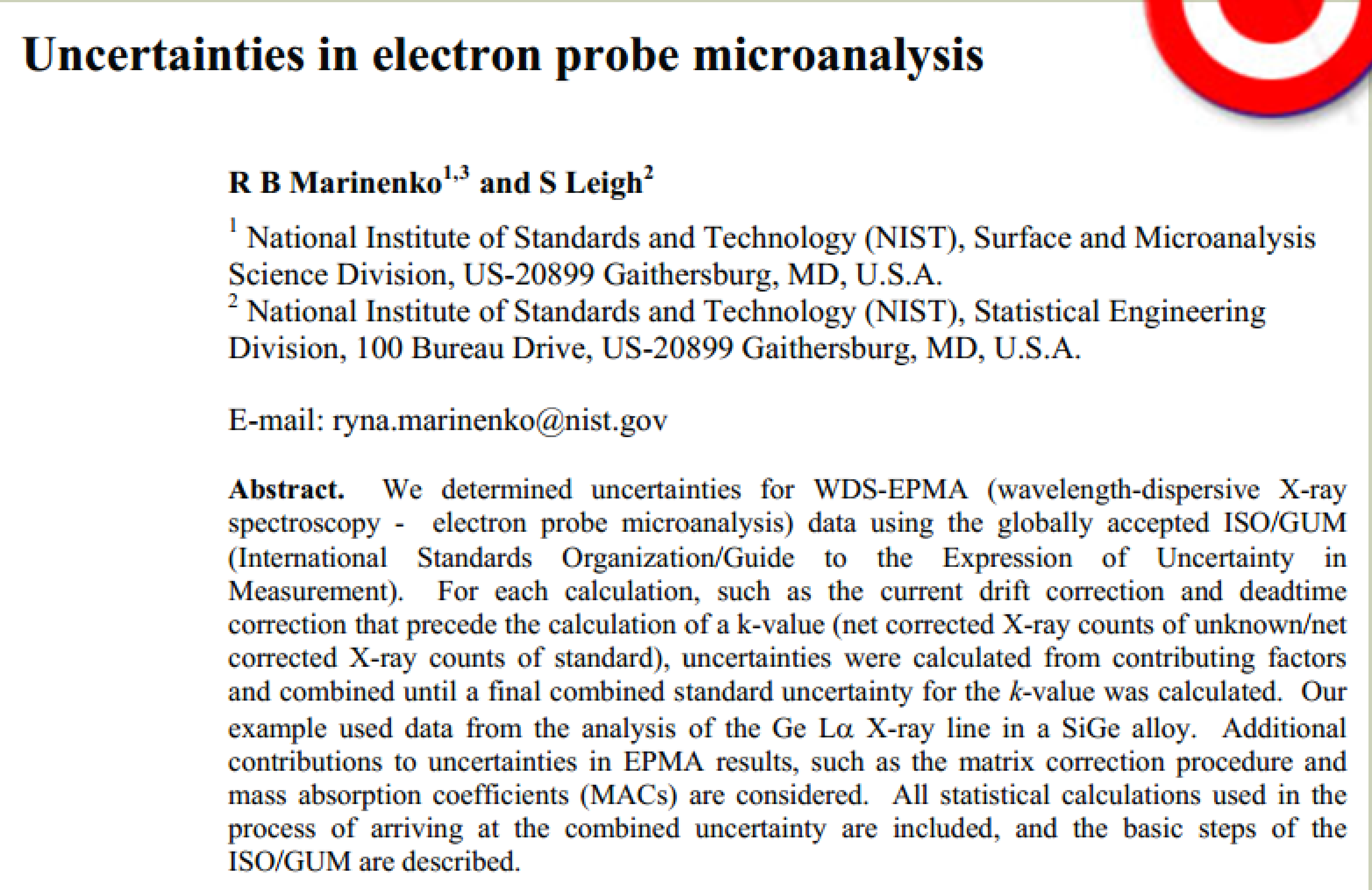
What can we do?

- Education
  - Works but up to a point…
- More helpful tools
  - Help the user to a select a suitable beam energy
  - Help to select good standards
  - Inform the user about reference requirements
  - Help to determine suitable probe doses
  - Warn about potential pitfalls
- Better tools
  - Eliminate the need for references

Measurement Uncertainties

- Precision
  - Count statistics in the standard, the reference and the unknown
  - Instrument stability
  - Sample stability
- Accuracy
  - Suitability of the matrix correction
  - Accuracy of the physical parameters ([μ/ρ] & η)
  - Sample preparation (Coatings, surface roughness…)

Precision



Uncertainties in electron probe microanalysis

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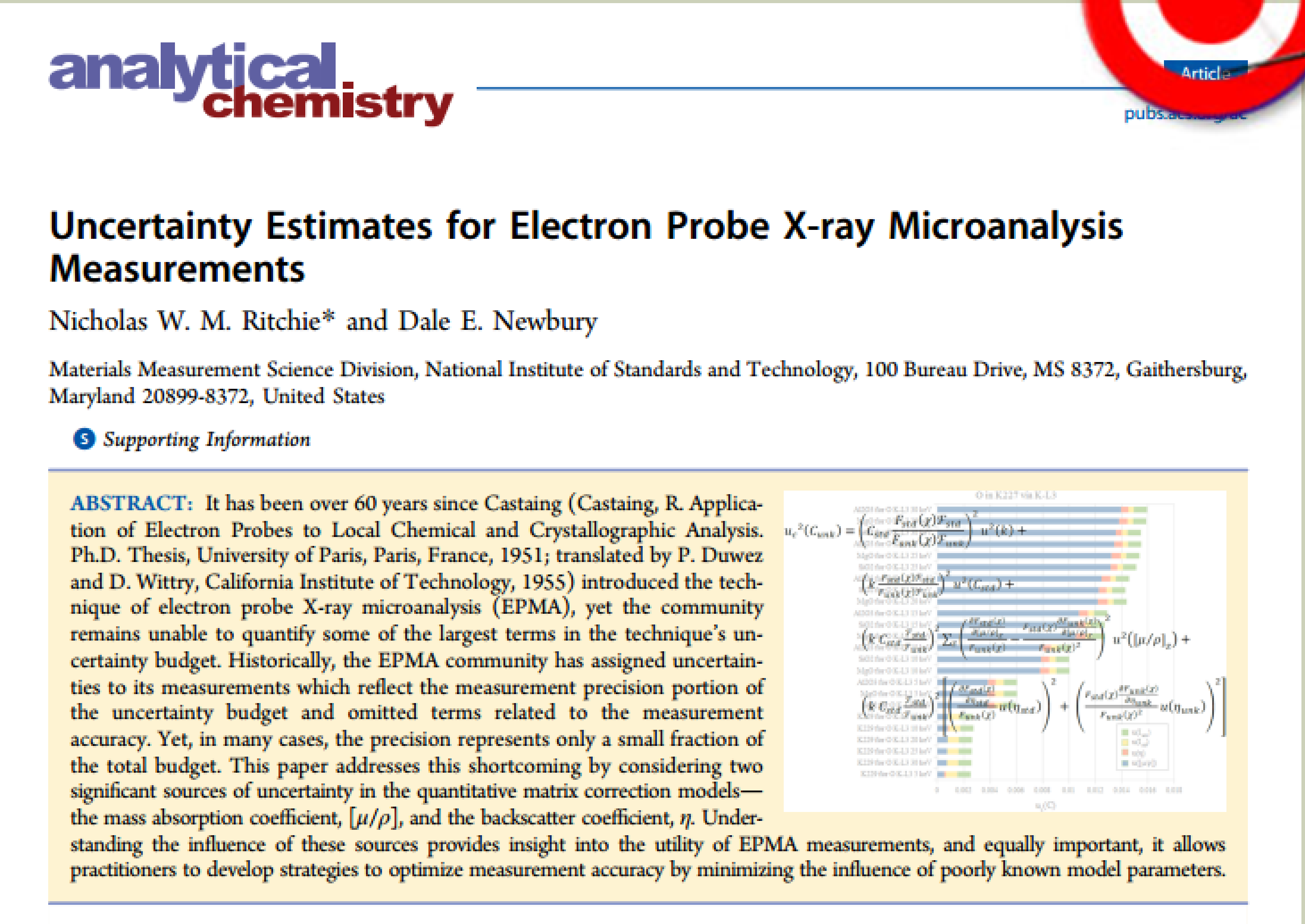
Abstract. We determined uncertainties for WDS-EPMA (wavelength-dispersive X-ray spectroscopy - electron probe microanalysis) data using the globally accepted ISO/GUM (International Standards Organization/Guide to the Expression of Uncertainty in Measurement). For each calculation, such as the current drift correction and deadtime correction that precede the calculation of a k-value (net corrected X-ray counts of unknown/net corrected X-ray counts of standard), uncertainties were calculated from contributing factors and combined until a final combined standard uncertainty for the *k*-value was calculated. Our example used data from the analysis of the Ge Lα X-ray line in a SiGe alloy. Additional contributions to uncertainties in EPMA results, such as the matrix correction procedure and mass absorption coefficients (MACs) are considered. All statistical calculations used in the process of arriving at the combined uncertainty are included, and the basic steps of the ISO/GUM are described.

Accuracy



analytical chemistry

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Uncertainty Estimates for Electron Probe X-ray Microanalysis Measurements

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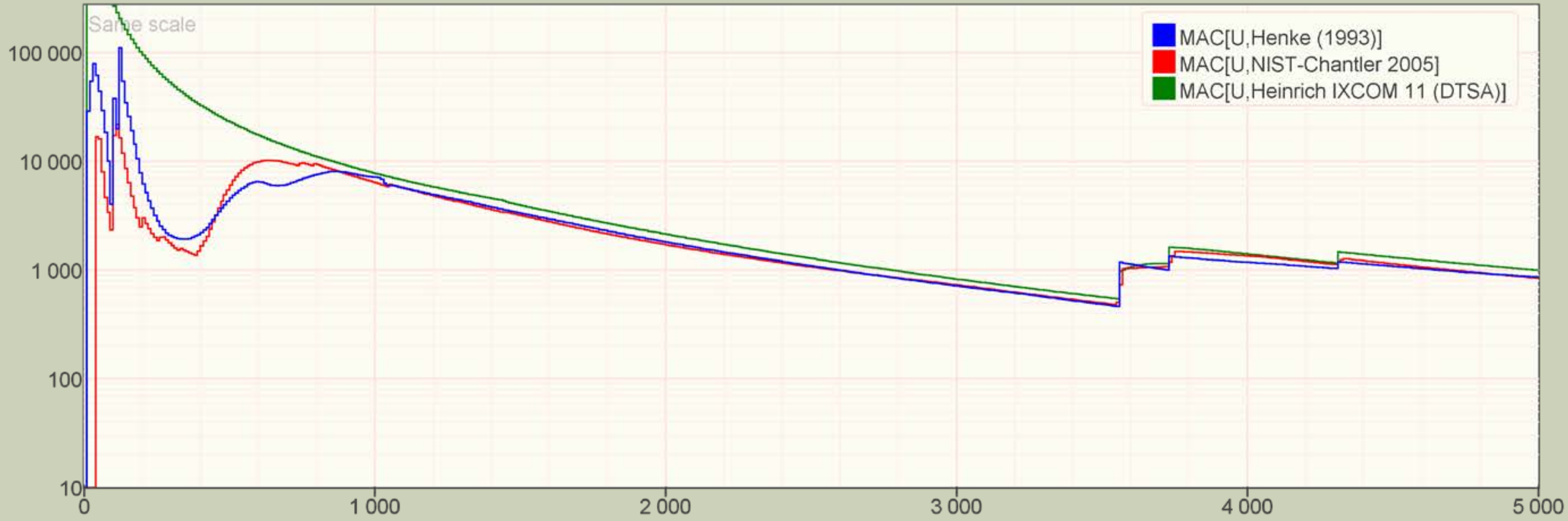
Supporting Information

ABSTRACT: It has been over 60 years since Castaing (Castaing, R. Application of Electron Probes to Local Chemical and Crystallographic Analysis. Ph.D. Thesis, University of Paris, Paris, France, 1951; translated by P. Duwez and D. Wittry, California Institute of Technology, 1955) introduced the technique of electron probe X-ray microanalysis (EPMA), yet the community remains unable to quantify some of the largest terms in the technique's uncertainty budget. Historically, the EPMA community has assigned uncertainties to its measurements which reflect the measurement precision portion of the uncertainty budget and omitted terms related to the measurement accuracy. Yet, in many cases, the precision represents only a small fraction of the total budget. This paper addresses this shortcoming by considering two significant sources of uncertainty in the quantitative matrix correction models—the mass absorption coefficient, $[\mu/\rho]$, and the backscatter coefficient, η. Understanding the influence of these sources provides insight into the utility of EPMA measurements, and equally important, it allows practitioners to develop strategies to optimize measurement accuracy by minimizing the influence of poorly known model parameters.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🟥 MAC[U,NIST-Chantler 2005]
🟩 MAC[U,Heinrich IXCOM 11 (DTSA)]
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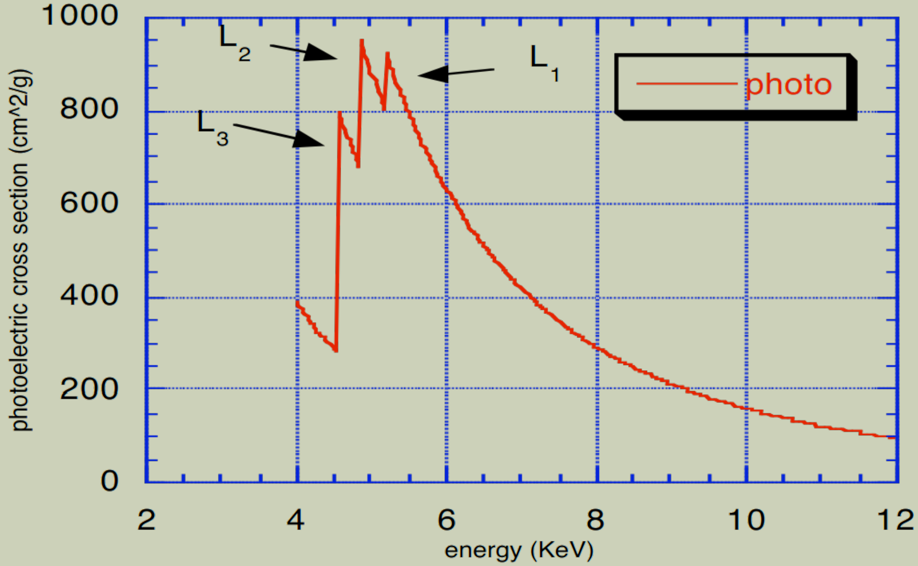
L2
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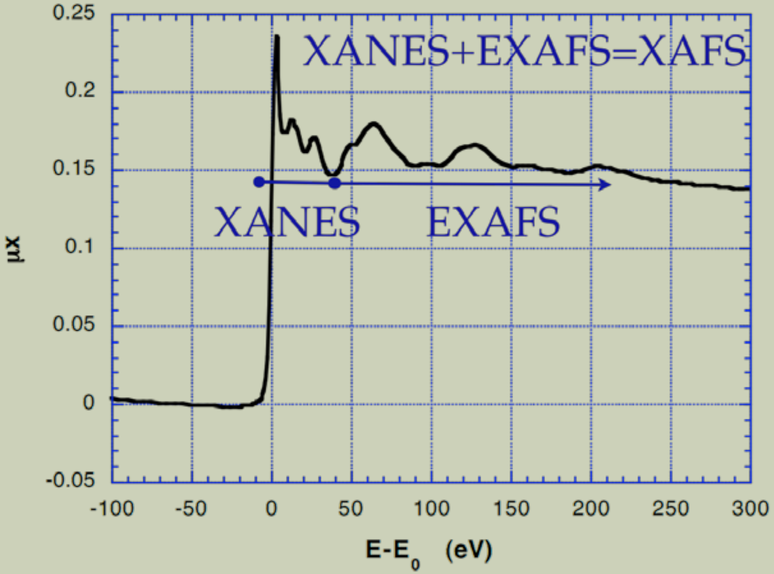
energy (KeV)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XANES
EXAFS
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0.2
0.15
0.1
0.05
0
-0.05
μx
-100
-50
0
50
100
150
200
250
300
E-E0 (eV)

Gauss’ Formula

$$u(y(x_{i,j,\dots})^2 = \sum_{i=1,n} {c_i}^2 \; u(x_i)^2 + \sum_{\substack{i,k=1,n \\ i \neq k}} c_i \, c_k u(x_i, x_k)$$

$c_i = \frac{\partial y}{\partial x_i}$	Sensitivity coefficient with respect to x_i
$u(x_i)$	Uncertainty in y arising from uncertainty in x_i
$u(x_i, x_k) = u(x_i)\, u(x_k)\, r_{i,k}$	The covariance between x_i and x_k
$-1 \leq r_{i,k} \leq 1$	The correlation between x_i and x_k

BIPM – JCGM 100:2008 Guide to the expression of uncertainty in measurement
EURACHEM-CITAC Guide C64 – Quantifying Uncertainty in Analytical Measurement

$$u(a+b) = \sqrt{u(a)^2 + u(b)^2}$$

If the source of uncertainty
in a and b are uncorrelated

$$u(a+b) = u(a) + u(b)$$

If the source of uncertainty
in a and b are 100% correlated.

Applying Gauss’ Formula

Applying Gauss’ Formula to XPP

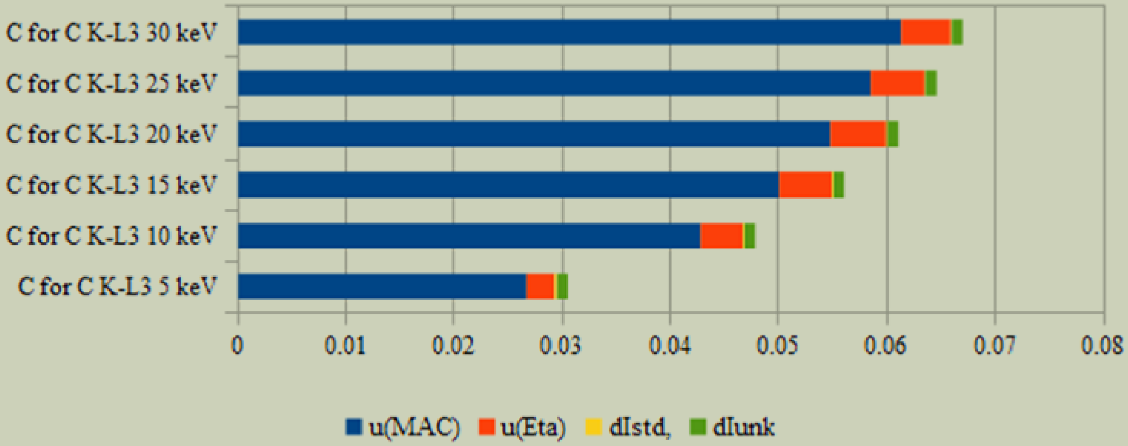
This is the sensitivity of XPP to uncertainty in $[\mu/\rho]_z$.

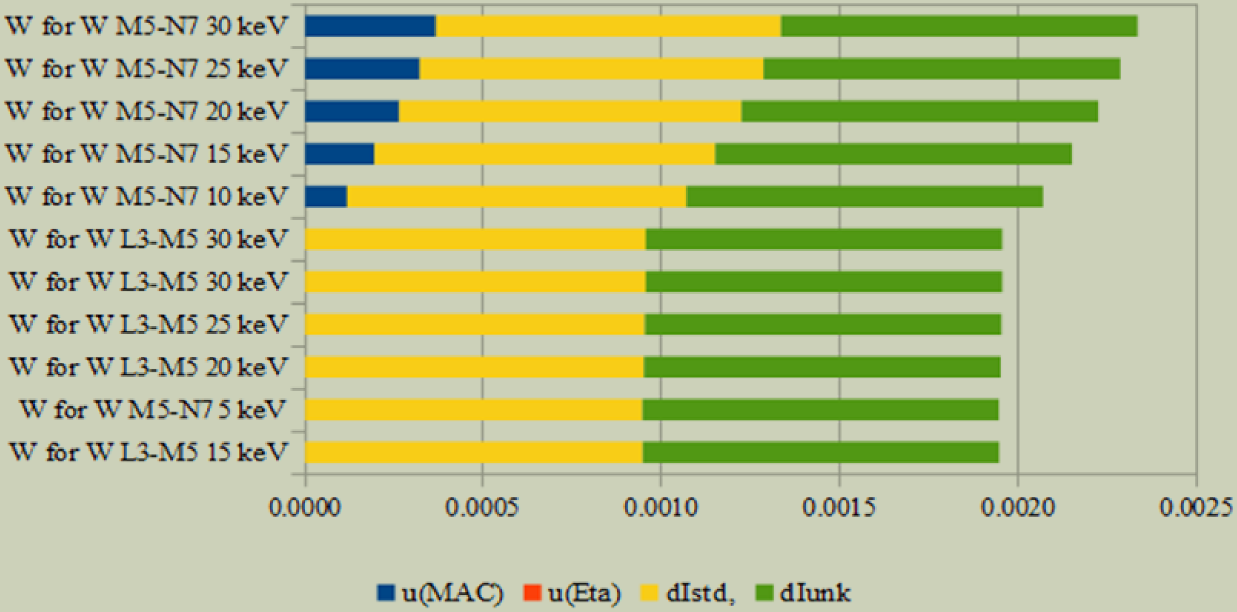
Measurement Optimization

$$M = \{ C_i \pm \Delta C_i \}$$

C_i	Mass fraction of element *i*
ΔC_i	Measurement uncertainty in the mass fraction of element *i*
$\min(f(\{ \Delta C_i \}; P))$	Select the measurement parameters P such that a function f of the measurement uncertainties is minimized.

Example: Tungsten Carbide





Optimizing Precision

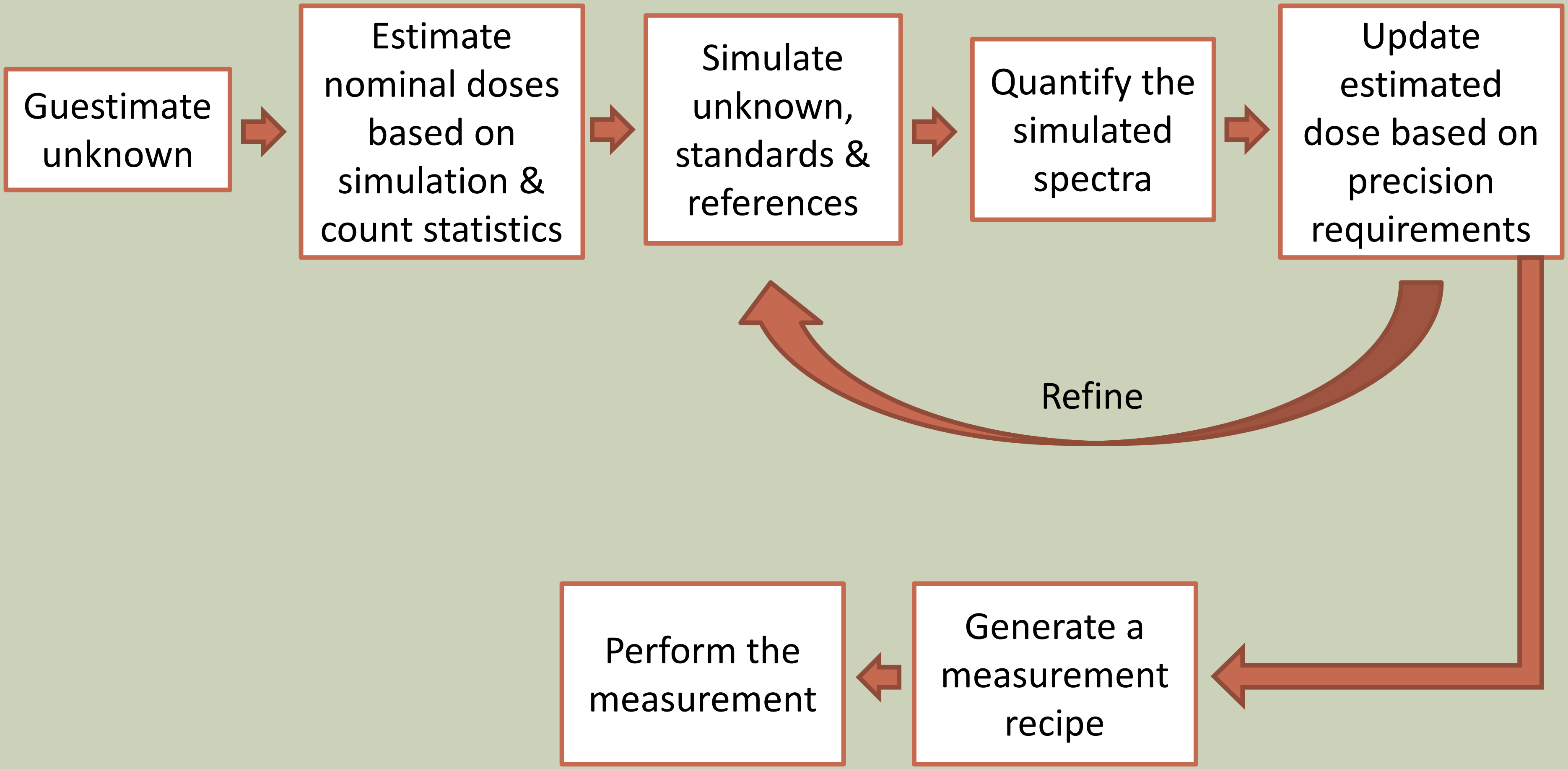
How do I pick the probe doses
(live time × probe current)
to produce the desired measurement precision?

- Not all elements need to be measured with the same precision
- We probably want to optimize the choices to minimize the total measurement time
- Dose correct spectrum simulation can help

Rules of Thumb:

✓ Precision scales with the square root of counts / probe dose.
✓ Precision depends on the standard, the unknown and any references.
✓ The references (if any) contribute to the error budget twice.

Estimating Dose Requirements



Guestimate unknown

Estimate nominal doses based on simulation & count statistics

Simulate unknown, standards & references

Quantify the simulated spectra

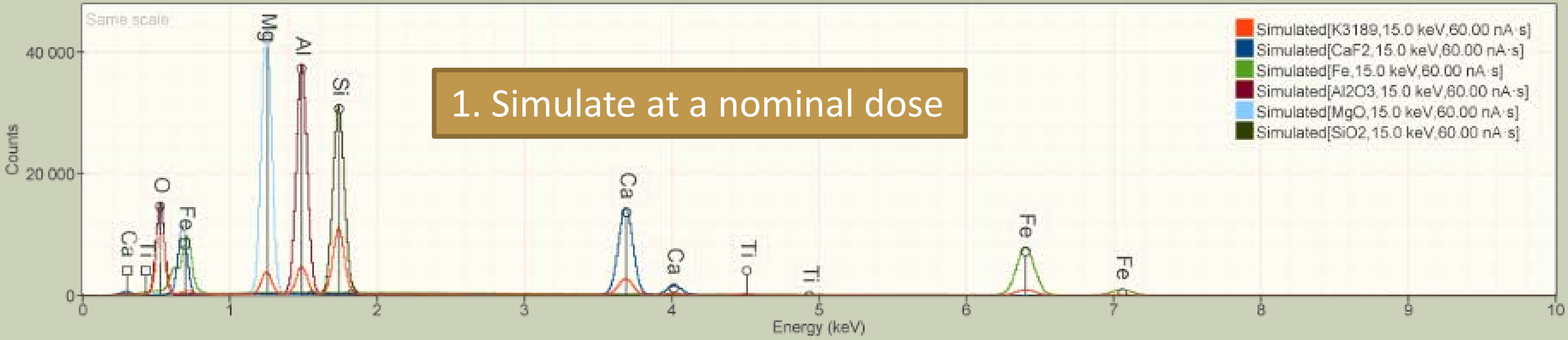
Update estimated dose based on precision requirements

Refine

Generate a measurement recipe

Perform the measurement

Estimating dose requirements

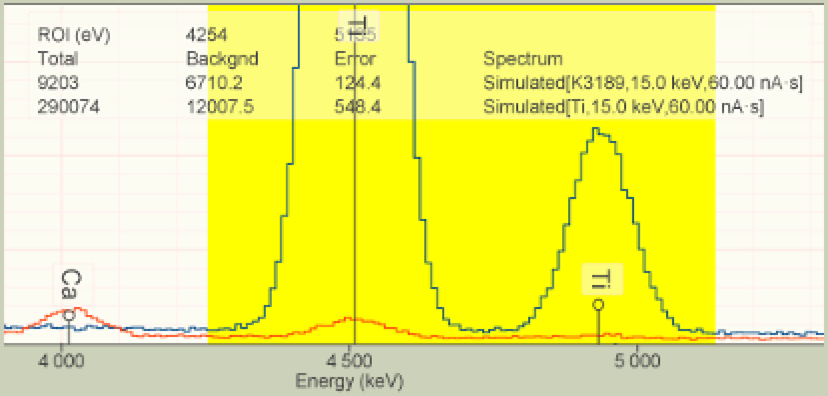


1. Simulate at a nominal dose

2. Perform the simulated quant.

3. Combine with data from the simulated spectra

Name	*k*	*dk*	*dk/k (%)*	*Dose (tot)*
O All	0.65978	0.0018	0.3%	4.87
Mg All	0.08065	0.0004	0.5%	14.75
Al All	0.11902	0.0005	0.5%	12.81
Si All	0.35037	0.0008	0.2%	3.699
Ca K-family	0.18338	0.0009	0.5%	14.77
Ca L-family	0.22206	0.0120	5.4%	
Ti Kα	0.00976	0.0002	2.8%	459.1
Ti Kβ	0.01142	0.0018	15.8%	
Ti L-family	0.04432	0.0056	12.7%	
Fe Kα	0.11745	0.0011	1.0%	54.5
Fe Kβ	0.10297	0.0043	4.2%	
Fe L-family	0.05958	0.0017	2.9%	



```
ROI (eV)   4254      5135
Total      Backgnd   Error   Spectrum
9203       6710.2    124.4   Simulated[K3189,15.0 keV,60.00 nA·s]
290074     12007.5   548.4   Simulated[Ti,15.0 keV,60.00 nA·s]
```

3. Estimate the standard & unknown doses

$D_{Ti,unk}$ = 441 s $D_{Ti,std}$ = 19 s → k/dk = 99.2

Acquisition Optimization

- Minimize total acquisition time

$$T_{Total} = T_{unk} + \sum_{z} T_{std,z} + \sum_{j} T_{ref,j}$$

- Constrained by precision requirements $\frac{U(k_z)}{k_z} < p_z$ where p_z is the desired fraction precision for element z.
- The precision scales with $\sqrt{T}$ and the individual contributions can be determined from simulated spectra by fitting a noise-free simulated reference to the unknown, standard and references.

Output

- Sample preparation requirements
- Instrument settings
- Standard spectrum requirements
- Reference spectrum requirements
- Recommendations on the number of unknown spectra to collect
- Suggestion on which lines to use for the quantification

What does the analyst need to know?

- What elements are in the unknown
  - Collect a quick qual spectrum
- The approximate composition of the unknown
  - Quick standardless analysis
- Which standard materials are available
  - Labs can distribute this to users as a DTSA-II standard database

Why not standardless?

Compound	Metal	Analysis	Relative Error(%)	Sulfur	Analysis	Relative Error (%)
FeS	0.635	0.629	-1	0.365	0.371	1.8
FeS_2	0.466	0.642	38	0.534	0.358	-33
CuS	0.665	0.764	15	0.335	0.236	-30
ZnS	0.671	0.762	14	0.329	0.239	-28
SrS	0.732	0.758	3.6	0.268	0.242	-10
CdS	0.778	0.808	3.8	0.222	0.192	-13
Sb_2S_3	0.717	0.739	3.1	0.283	0.261	-7.8
PbS	0.866	0.914	5.5	0.134	0.086	-36

Occasionally brilliant

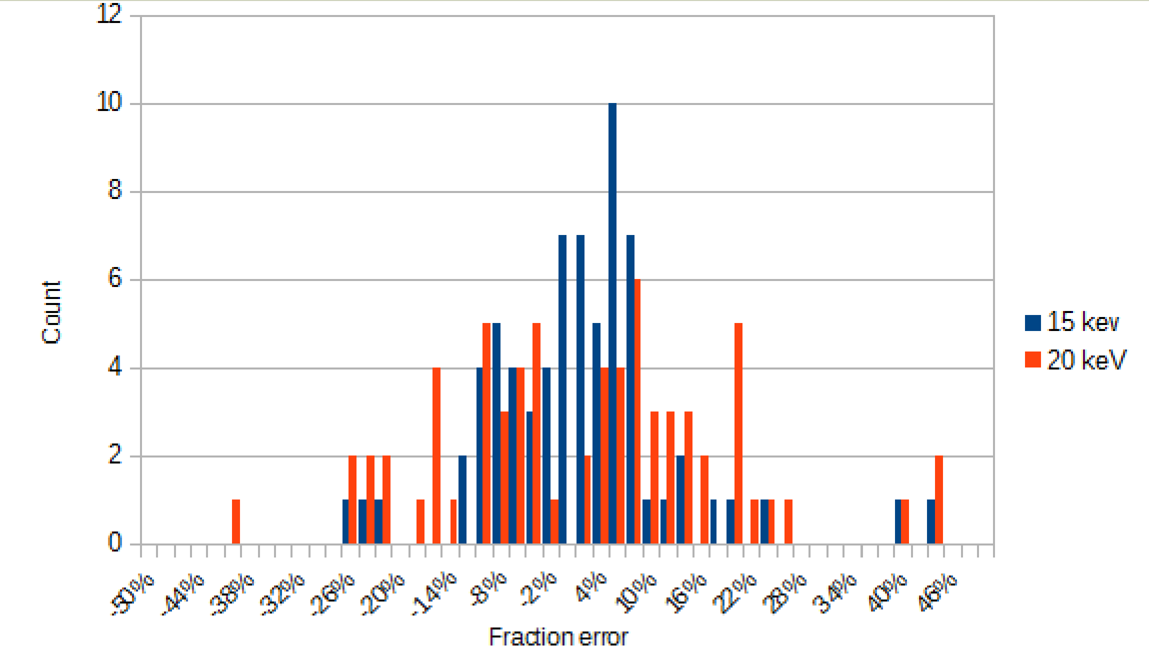
Vendor “A” standardless analysis

Thanks Dale.

Vendor A

Measure O directly

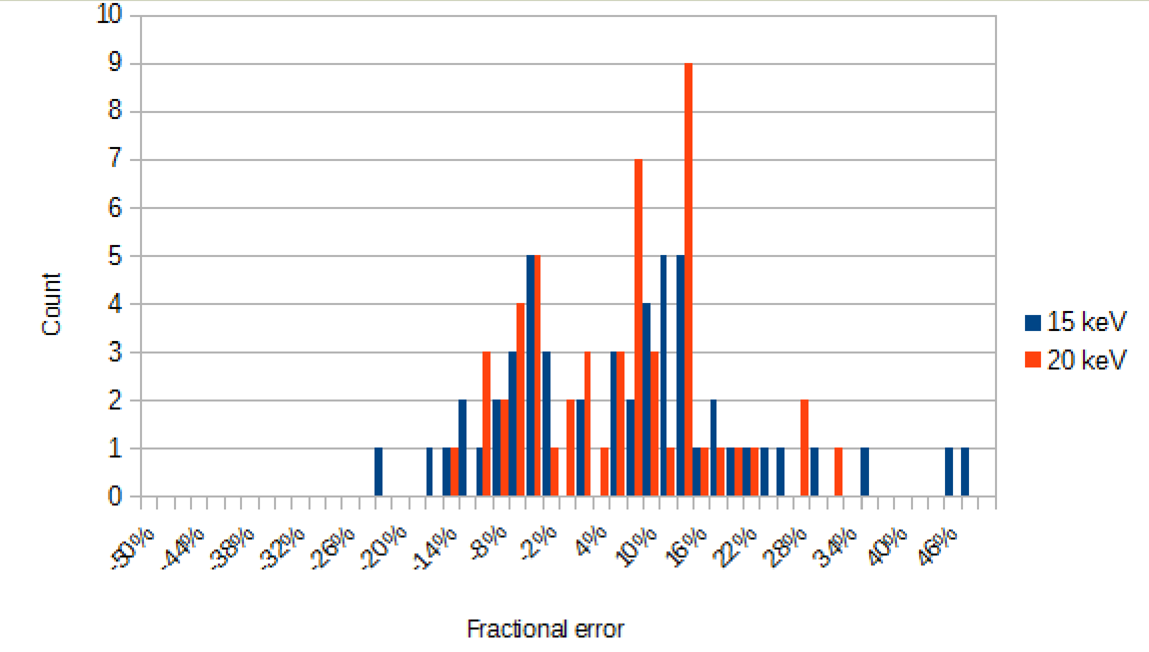
142 measurements



Vendor B

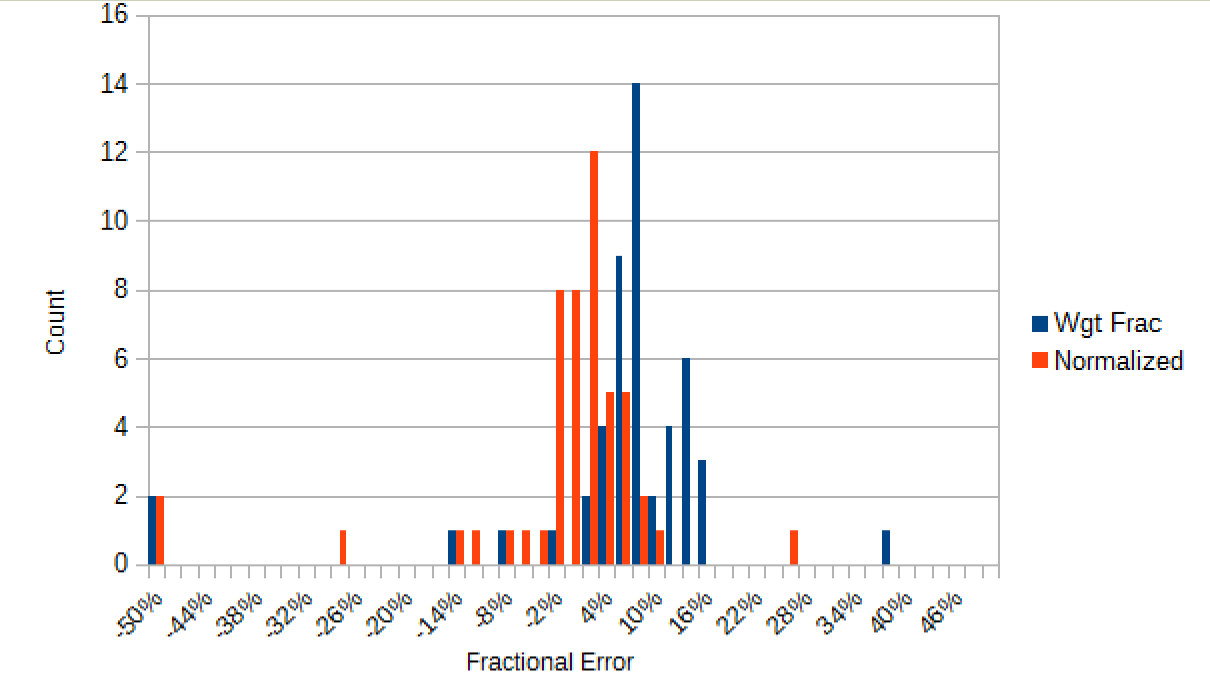
Measure O directly

104 measurements



Vendor C

15 keV – Unnormalized vs normalized



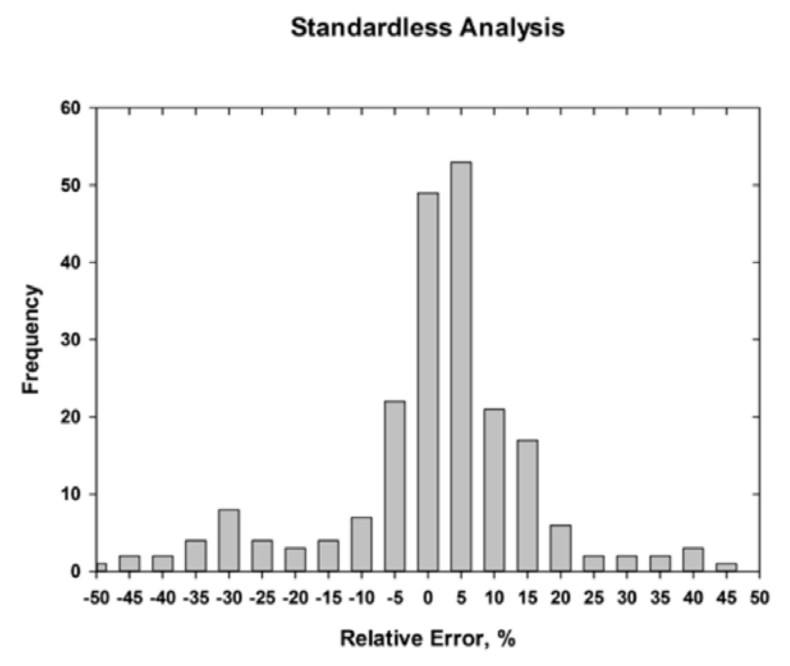
Why standards-based?

Compound	Metal	Analysis	Relative Error(%)	Sulfur	Analysis	Relative Error (%)
FeS	0.635	0.635	0	0.365	0.365	0
FeS_2	0.466	0.463	-0.6	0.534	0.537	0.6
CuS	0.665	0.667	0.3	0.335	0.333	-0.6
ZnS	0.671	0.674	0.4	0.329	0.326	-0.9
SrS	0.732	0.737	0.7	0.268	0.263	-1.9
CdS	0.778	0.786	1	0.222	0.214	-3.6
Sb_2S_3	0.717	0.727	1.4	0.283	0.273	-3.5
PbS	0.866	0.87	0.5	0.134	0.13	-3

Predictably reliable

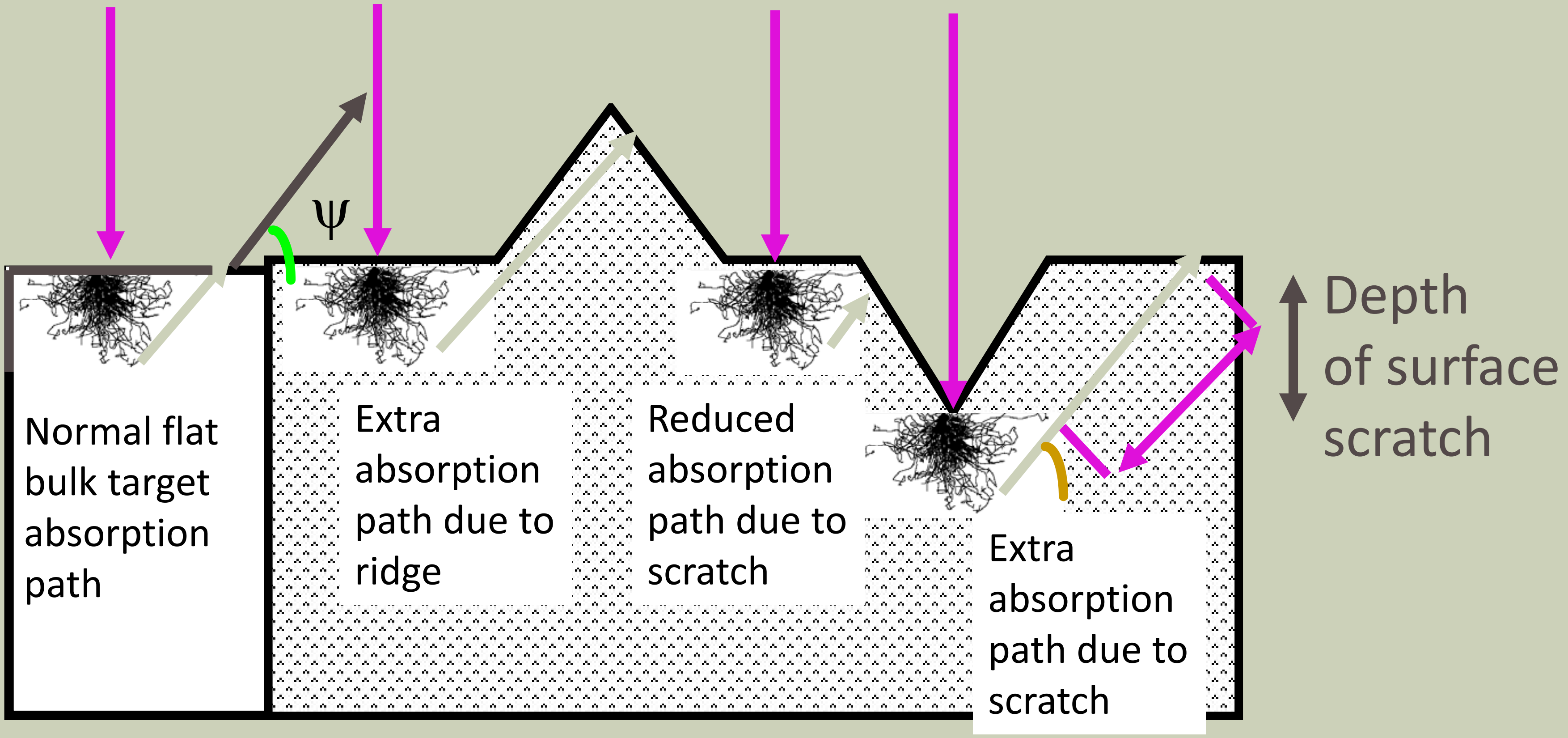
NIST DTSA-II standards-based analysis

Thanks Dale.


Standardless Analysis
Frequency
60
50
40
30
20
10
0
-50
-45
-40
-35
-30
-25
-20
-15
-10
-5
0
5
10
15
20
25
30
35
40
45
50
Relative Error, %

Geometric Effects

Common, practical examples: surface roughness, scratches



Normal flat bulk target absorption path

Extra absorption path due to ridge

Reduced absorption path due to scratch

Extra absorption path due to scratch

Depth of surface scratch

FeS_2

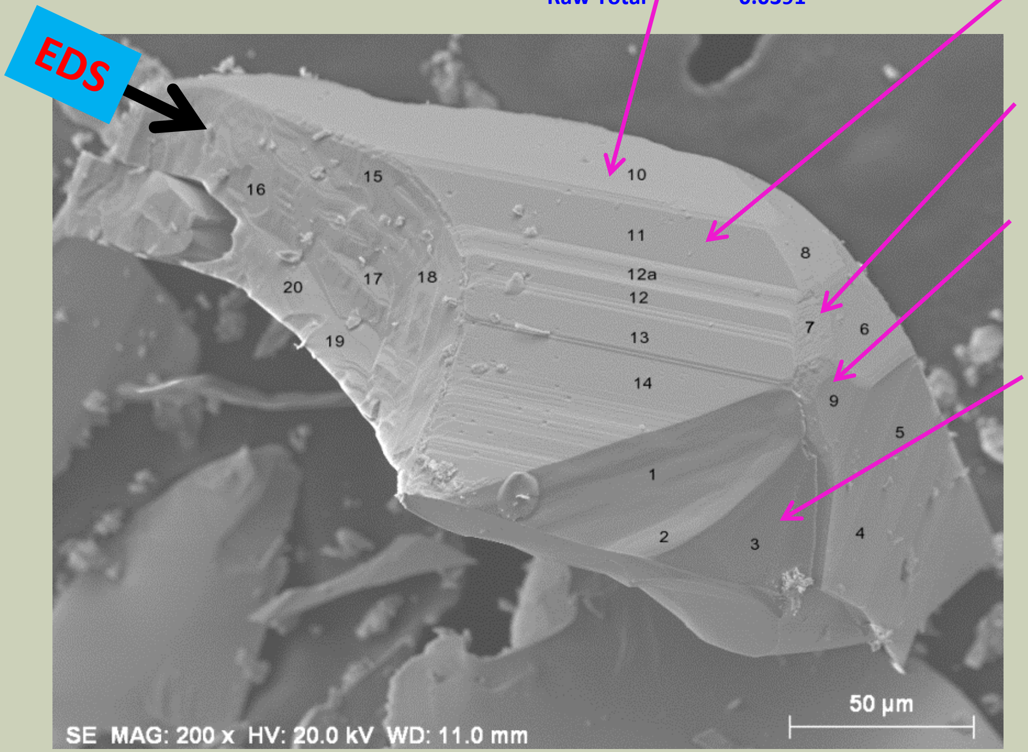
Element	Ideal mass concentration
S	0.5345
Fe	0.4655

Errors in Normalized Analysis

(k-ratio protocol with CuS and Fe, DTSA-II)

Location 10	Norm conc	relative error
S	0.2727	-49%
Fe	0.7273	56%
Raw Total	0.0391	

Location 11	Norm conc	relative error
S	0.5015	-6%
Fe	0.4985	7%
Raw Total	0.8773	

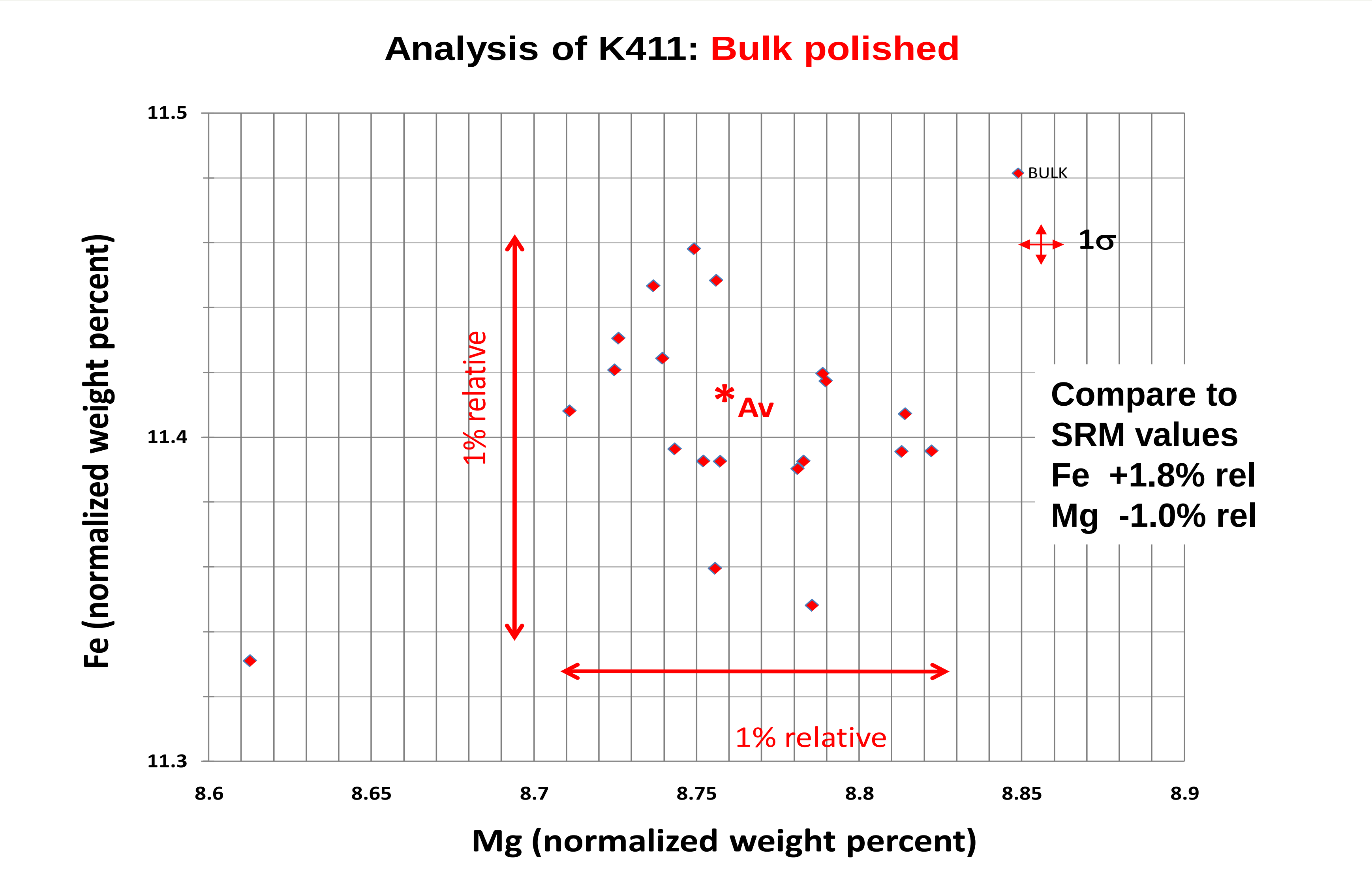


Location 7	Norm conc	relative error
S	0.0381	-93%
Fe	0.9619	107%
Raw Total	0.1121	

Location 9	Norm conc	relative error
S	0.3654	-32%
Fe	0.6346	36%
Raw Total	0.5244	

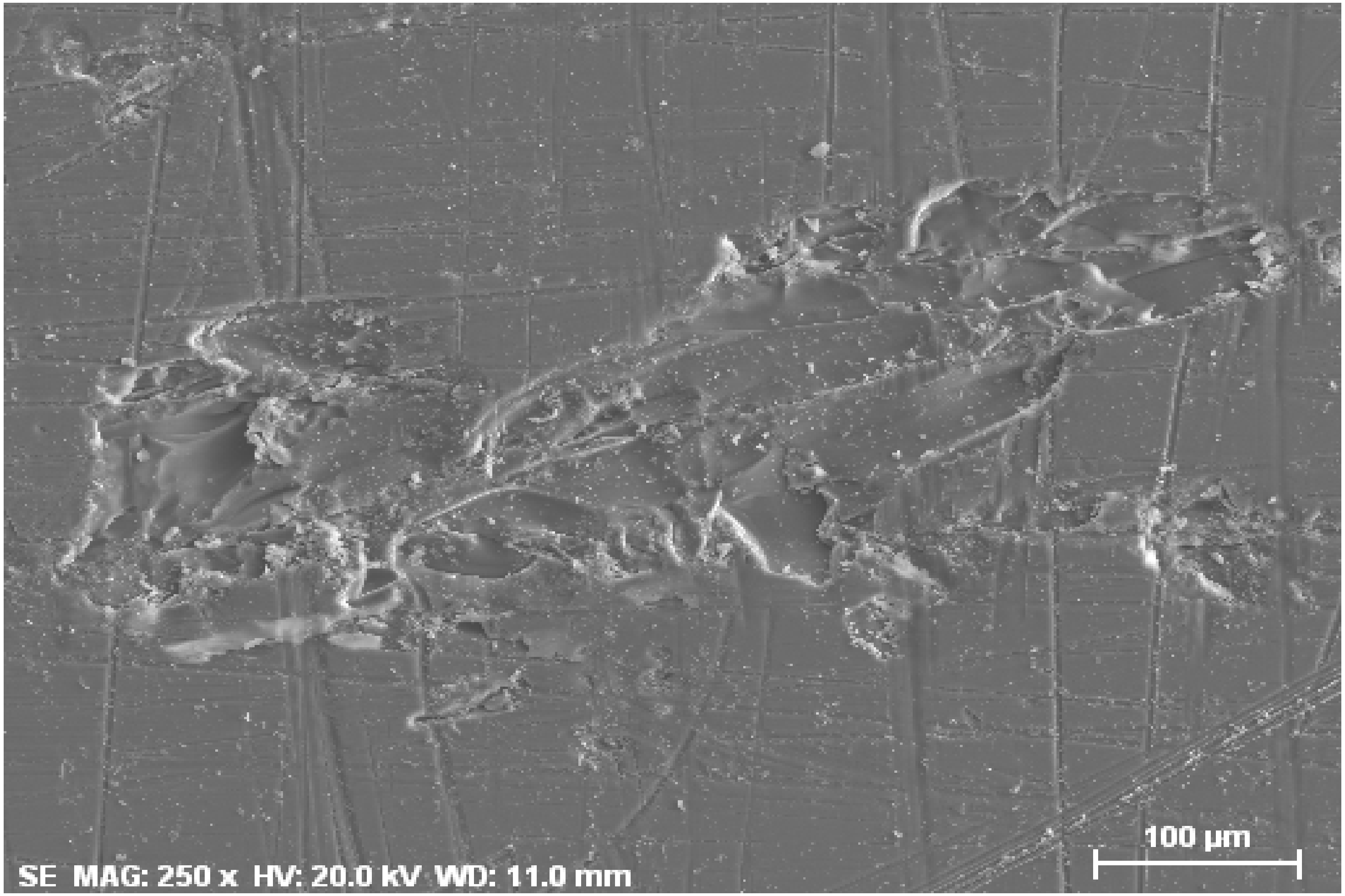
Location 3	Norm conc	relative error
S	0.5352	0.13%
Fe	0.4648	-0.15%
Raw Total	0.9892	

Analysis with the ideal flat polished sample shape

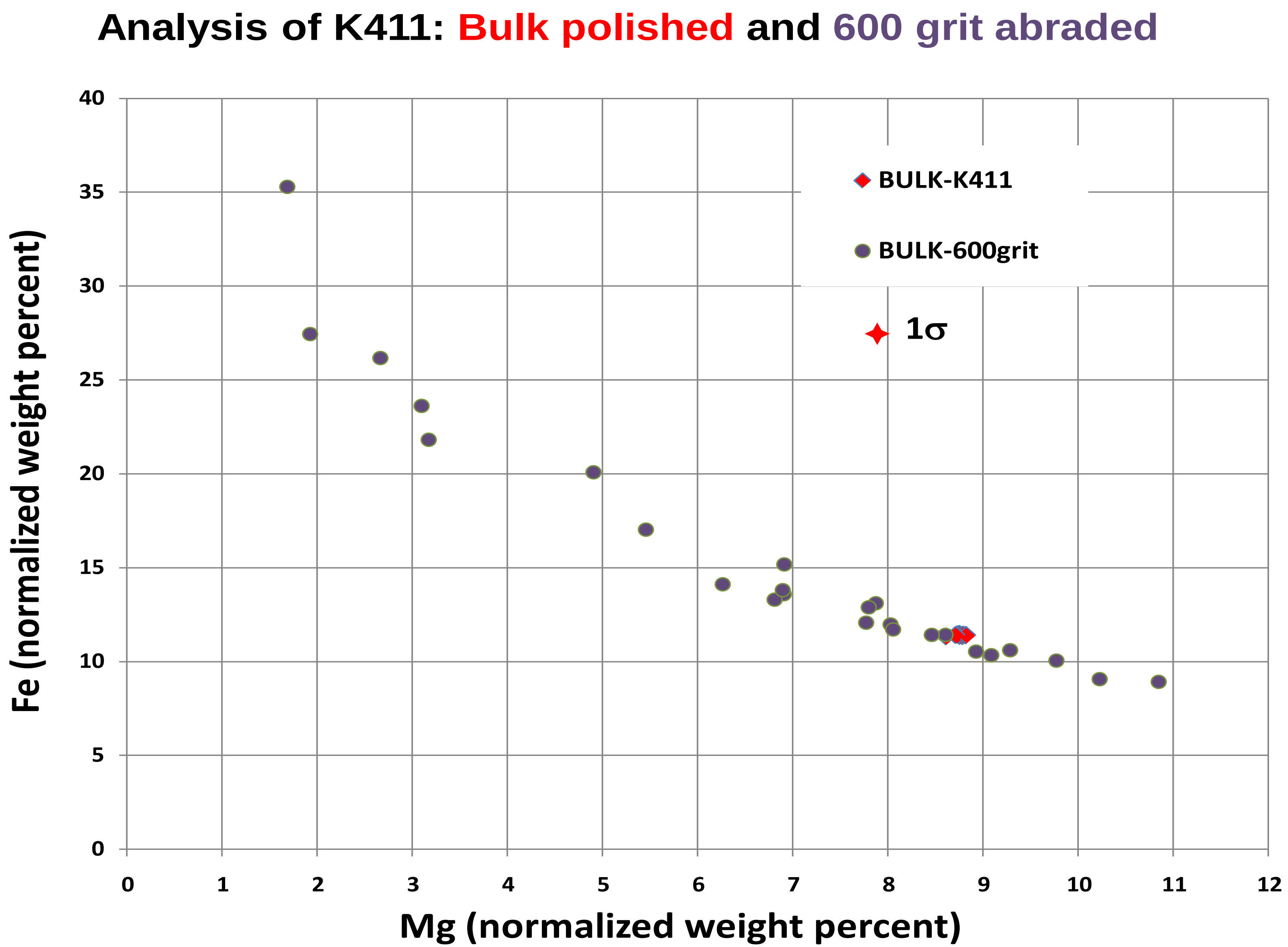


Compare to
SRM values
Fe +1.8% rel
Mg -1.0% rel

Analysis with a compromised sample shape: surface abrasion



Analysis with a compromised sample shape: surface abrasion



Only the beginning

- Better estimates of uncertainty for sub-optimal samples
- Better estimates of uncertainty for standardless analysis
- Make better use of redundant data
- Make better use of simulation to identify

Is there a better way?

Assume the ideal

- Assume that the user will make the optimal choices
- Don’t provide information about consequences
- Don’t present alternatives or consequences
- Let the user sink or swim

A Better Way

Assume the ideal

- Assume that the user will make the optimal choices
- Don't provide information about consequences
- Don't present alternatives or consequences
- Let the user sink or swim

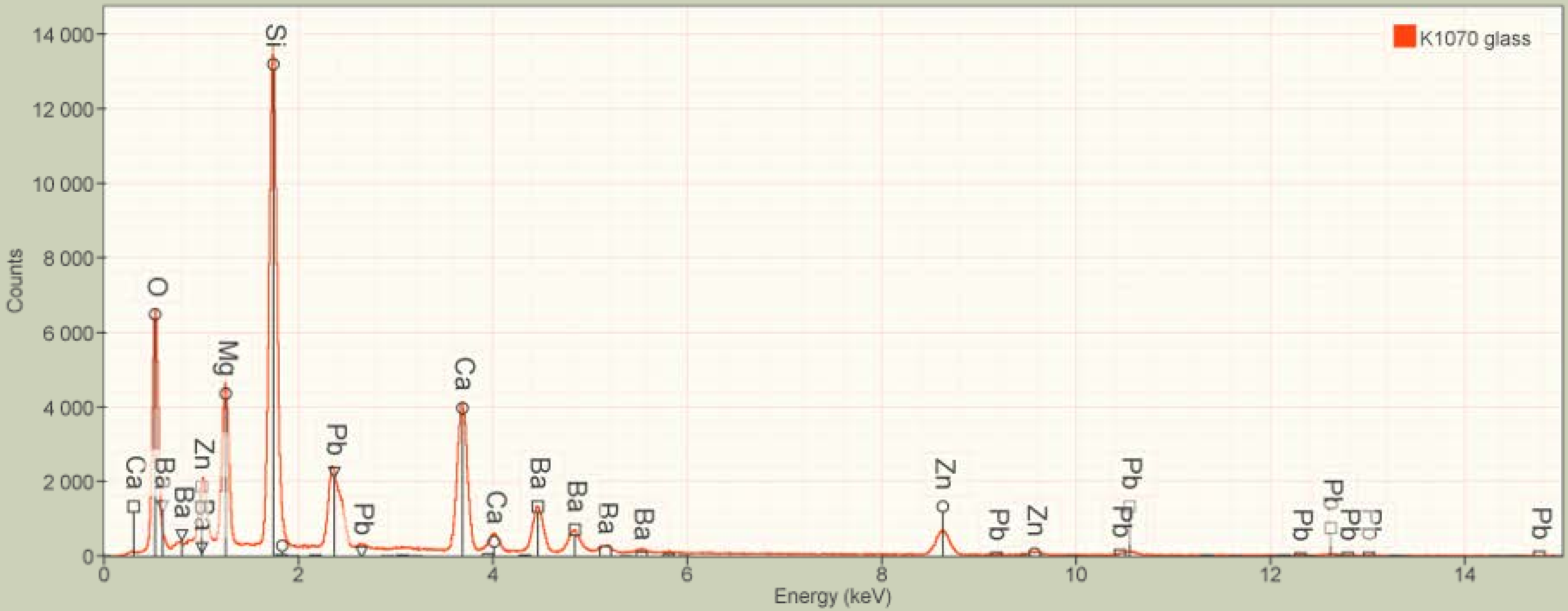
Work towards ideal

- Assume that the user will make sub-optimal choices
- Present the consequences of those choices
- Present alternative choices and the consequences
- Allow the user to make the choices suited to their application – expeditious to optimal

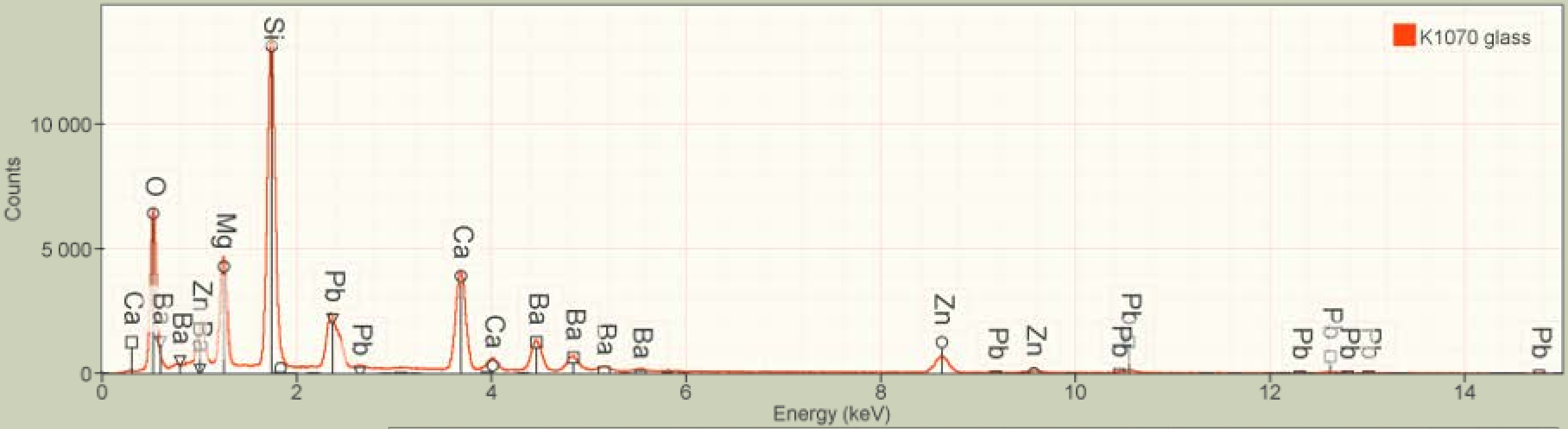
Conclusion

- Being able to calculate uncertainties is all very well and good
  - How we use the uncertainties is critical
- Being able to calculate realistic uncertainties will help users to:
  - Identify bad measurement practices
  - Avoid bad measurement practices
  - Be more realistic about measurement tradeoffs
  - Be more realistic about the utility of the measurement
  - Plan better measurements
- Better designed tools can help
  - Simply being able to produce good results isn't enough

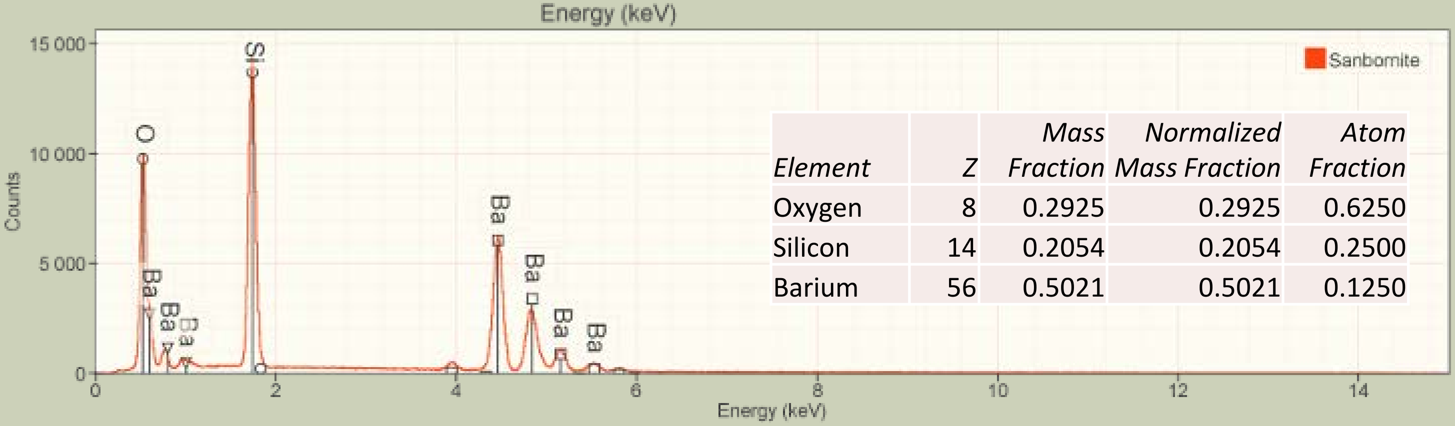
Extra slides



Element	*Z*	*Mass Fraction*	*Normalized Mass Fraction*	*Atom Fraction*
Oxygen	8	0.3431	0.3431	0.5919
Magnesium	12	0.0754	0.0754	0.0856
Silicon	14	0.1870	0.1870	0.1838
Calcium	20	0.0893	0.0893	0.0615
Zinc	30	0.1004	0.1004	0.0424
Barium	56	0.1120	0.1120	0.0225
Lead	82	0.0928	0.0928	0.0124

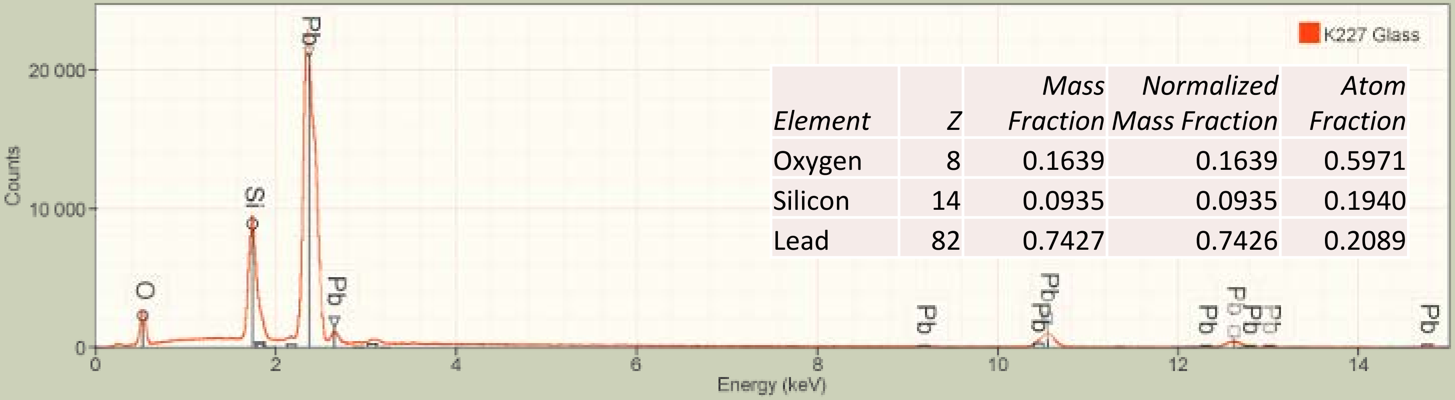


Ba, Si, O



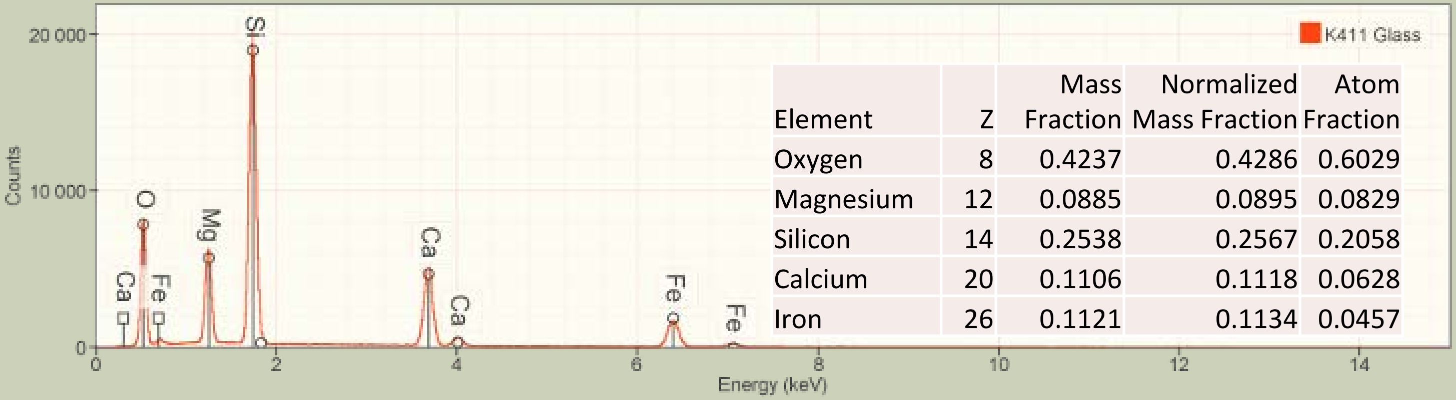
Element	*Z*	*Mass Fraction*	*Normalized Mass Fraction*	*Atom Fraction*
Oxygen	8	0.2925	0.2925	0.6250
Silicon	14	0.2054	0.2054	0.2500
Barium	56	0.5021	0.5021	0.1250

Pb



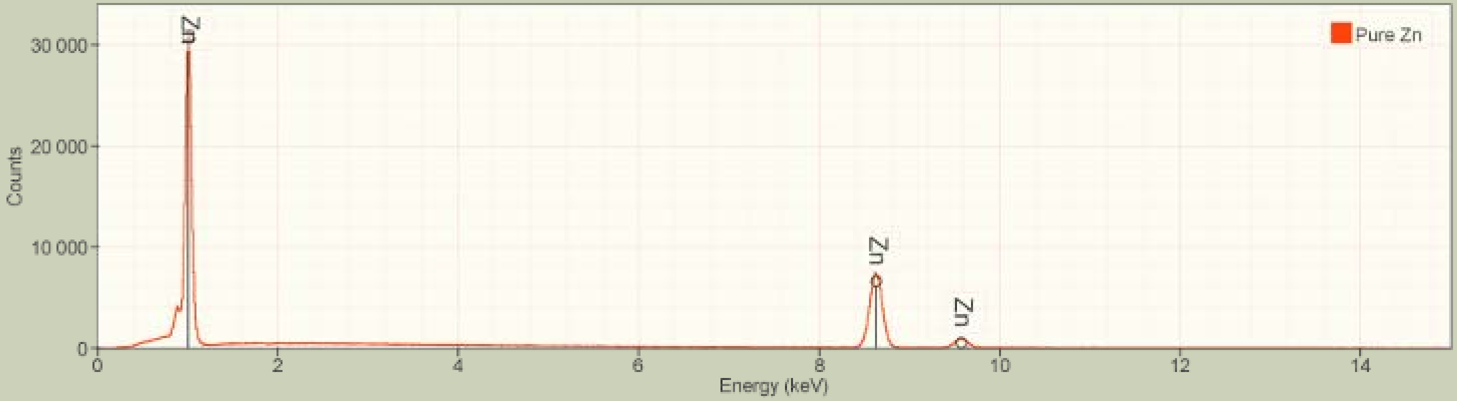
Element	*Z*	*Mass Fraction*	*Normalized Mass Fraction*	*Atom Fraction*
Oxygen	8	0.1639	0.1639	0.5971
Silicon	14	0.0935	0.0935	0.1940
Lead	82	0.7427	0.7426	0.2089

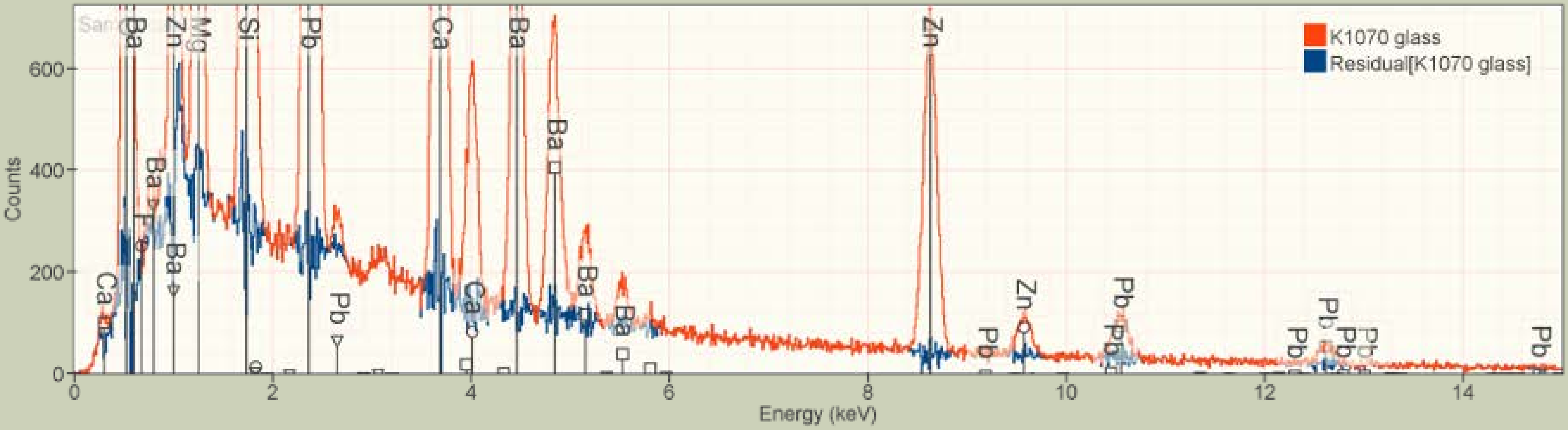
Mg, Ca



Element	Z	Mass Fraction	Normalized Mass Fraction	Atom Fraction
Oxygen	8	0.4237	0.4286	0.6029
Magnesium	12	0.0885	0.0895	0.0829
Silicon	14	0.2538	0.2567	0.2058
Calcium	20	0.1106	0.1118	0.0628
Iron	26	0.1121	0.1134	0.0457

Zn





Name	*K1070 glass*	*Relative to*
Mg All	0.7108	Mg in K411
Si All	0.9502	Si in Sanbornite
Ca K-family	0.8156	Ca in K411
Ca L-family	1.0031	Ca in K411
Zn Kα	0.0889	Zn in Pure Zn
Zn Kβ	0.0891	Zn in Pure Zn
Zn L3-M5 + 6 others	0.0581	Zn in Pure Zn
Ba L3-M5 + 5 others	0.2012	Ba in Sanbornite
Ba L2-N4 + 2 others	0.2389	Ba in Sanbornite
Ba L3-M1	0.2118	Ba in Sanbornite
Ba M-family	0.1533	Ba in Sanbornite
Pb L2-M4 + 13 others	0.0963	Pb in K227
Pb L2-N4 + 1 others	0.0849	Pb in K227
Pb L3-M1	0.0245	Pb in K227
Pb Lα	0.0878	Pb in K227
Pb M5-N7 + 6 others	0.0964	Pb in K227
Pb M4-N2 + 1 others	0.1056	Pb in K227

The peak in the unknown has k times the number of counts (per nA·s) as the peak in the standard.

IUPAC	*Seigbahn*	*Standard*	*Energy*	*ZAF*	*Z*	*A*	*F*	*k-ratio*
O K-L3	O Kα1	Sanbornite	0.5249	0.5823	0.9339	0.6234	1.0004	0.6831
Mg K-L3	Mg Kα1	K411	1.2536	0.865	1.0665	0.8134	0.9972	0.7373
Si K-L3	Si Kα1	Sanbornite	1.7397	1.0532	0.9327	1.1298	0.9994	0.959
Si K-M3	Si Kβ1	Sanbornite	1.829	1.0459	0.9327	1.122	0.9994	0.9523
Ca K-L3	Ca Kα1	K411	3.6917	1.0168	1.0727	0.9444	1.0036	0.8213
Ca K-M3	Ca Kβ1	K411	4.0127	1.0242	1.0727	0.9513	1.0036	0.8272
Zn K-L3	Zn Kα1	Pure Zn	8.6389	0.8746	0.8753	0.9882	1.011	0.0878
Zn K-M3	Zn Kβ1	Pure Zn	9.572	0.8779	0.8753	0.9909	1.0121	0.0881
Zn L3-M5	Zn Lα1	Pure Zn	1.0116	0.4637	0.8886	0.5205	1.0026	0.0466
Ba L3-M5	Ba Lα1	Sanbornite	4.4663	0.8983	0.927	0.968	1.001	0.2004
Pb L3-M5	Pb Lα1	K227	10.5512	0.7611	0.7547	1.0099	0.9986	0.0951
Pb M5-N7	Pb Mα1	K227	2.3459	0.7699	0.8213	0.9375	0.9999	0.0962

Element	*Standard*	*Measured*	*Difference*	*% Difference*
Si	18.7	18.39	-0.31	-1.7
Pb	9.28	8.57	-0.71	-7.6
O	34.31	33.67	-0.64	-1.9
Ba	11.2	11.18	-0.02	-0.1
Zn	10.04	10.18	0.14	1.4
Ca	8.93	8.82	-0.11	-1.3
Mg	7.54	7.21	-0.33	-4.4