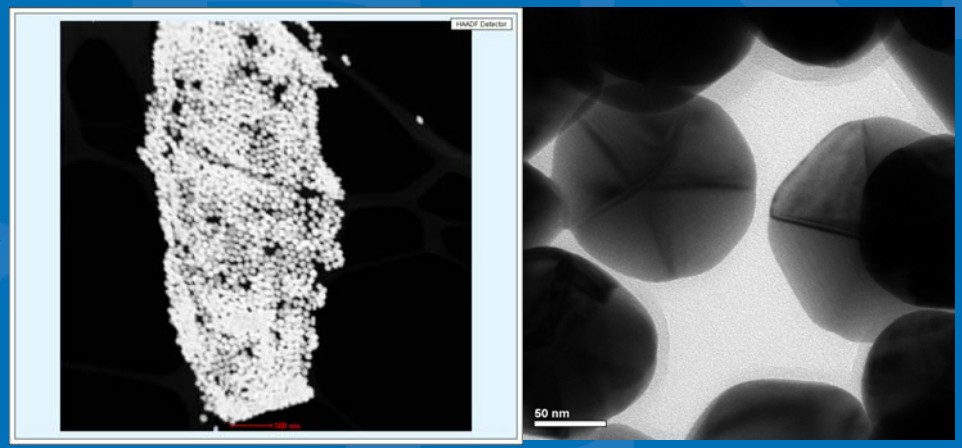
EPA
United States
Environmental Protection
Agency

Single-particle ICPMS for characterizing metal-based nanoparticles in the environment – advances and challenges

E. M. Heithmar



EPA United States Environmental Protection Agency

Presentation Overview

- Metal-based nanoparticles in the environment
- Methods for metal-based ENMs
- Fundamentals of single-particle ICPMS
- Analytical figures of merit – effects of operational and physical parameters
- Conclusions
- Future work

EPA United States Environmental Protection Agency

Metal-Based Nanoparticles in the Environment - Applications

- Metal-based nanoparticles comprise the largest volume of engineered nanomaterials.
- Production is increasing.
- Uses are expanding:
  - TiO_2 for water treatment, catalysis, UV blocking.
  - Ag as antimicrobial.
  - CeO_2 as fuel additive, catalyst.
  - Quantum dots for power/lighting.
  - Fe (NZVI) for pollution abatement.

EPA United States Environmental Protection Agency

Metal-Based Nanoparticles in the Environment - Implications

- "Nano" aspect of metal-based nanoparticles leads to unique physical-chemical properties:
  - Neither dissolved nor bulk.
  - Current models for estimating release, transformations, transanport, fate, bioavailability, and effects don't apply.
- Scientific community recognizes the greatly expanding use and resulting potential environmental impact.
- Regulatory agencies taking more precautionary approach.

EPA United States Environmental Protection Agency

Measuring Metal-Containing ENMs in the Environment

- Single-particle imaging and spectroscopic methods are often definitive for detection, but:
  - These methods are not quantitative nor representative.
- Ensemble methods – in particluar hyphenated techniques – allow representative samples, provide good particle size resolution, high elemental sensitivity.
  - flow-field flow fractionation coupled with ICPMS most common.
- Hyphenated methods provide total metal concentration associated with a size fraction of nanoparticles.
- Hyphenated methods are only a screening tool:
  - cannot provide metal content of individual particles, i.e., cannot definitively identify nanoparticles.

EPA United States Environmental Protection Agency

Single-Particle ICPMS - an alternative to hyphenated methods

- Provides particle concentration of metal-containing nanoparticles & mass of metal in each particle.
- Advantages - does not require separation, i.e., fast and limits interaction with nanoparticles (potentially fewer artifacts).
- Fast.
- Minimal potential for artifacts from particle-surface interactions.
- Only a screening tool:
  - Cannot provide size of particles it measures, i.e., cannot definitively identify nanoparticles.

EPA United States Environmental Protection Agency

SP-ICPMS - complementary to hyphenated methods

SP-ICPMS

- Provides concentration of metal-based nanoparticles, and mass of metal in each particle.
- No information on particle diameters.

Hyphenated Methods

- Provide separation of particles according to hydrodynamic diameter, and determines total metal concentration associated with each particle size.
- No information on number or characteristics of metal-based particles.

EPA United States Environmental Protection Agency

Potential Applications of SP-ICPMS

- Rapid screening of environmental (water) samples for metal-containing ENMs.
  - Sample throughput >10 times that of hyphenated methods.
- Monitoring rapid transformation processes.
  - Transformations with half-lifes much less than an hour cannot be monitored by hyphenated methods.
- Coupled with size separation or measurement, provides selective detection and quantitation of metal-based ENMs.
  - Combination gives analyte density of particle.

Previous Work in SP-ICPMS

- C. Degueldre, P.-Y. Favarger. 2003 Coll. Surf. A. 217, 137-142.
- C. Degueldre, P.-Y. Favarger, C. Bitea. 2004. Analytica Chimica Acta 518, 137–142.
- C. Degueldre, P.-Y. Favarger. 2004. Talanta 62, 1051–1054.
- C. Degueldre, P.-Y. Favarger , S. Wold. 2006. Analytica Chimica Acta 555, 263–268.
- M. Hassellöv. 1st International Workshop on Aquatic Nanoscience & Nanotechnology. Vienna, 2007.
- M. Hassellöv. 2nd Conference on Environmental Effects of Nanoparticles and Nanomaterials. London, 2007.
- E. K. Lesher, S. Lee, and J. F. Ranville. American Chemical Society, 42nd Western Regional Meeting. Las Vegas, 2008.
- E. K. Lesher, S. Lee, and J. F. Ranville. International Environmental Nanotechnology Conference. Chicago, 2208.

United States Environmental Protection Agency

Fundamentals of SP-ICPMS

- Conventional ICPMS measures the metal ions dissolved in millions of sample droplets introduced to the plasma each second.
  - The signal is constant on the experimental time scale.
- SP-ICPMS measures the metal ions in plumes produced by tens of particles vaporized in the plasma each second.
  - These are episodic on the experimental time scale.

United States Environmental Protection Agency

ICPMS Signal - Dissolved Analyte

Analyte ion flux in plasma

$q_i = c_a\ f_s\ \varepsilon_n\ \varepsilon_{v,a,i}\ N_A / 60\ A_r$

q_i = metal ion flux in plasma (s^{-1})
c_a = analyte metal concentration in sample (g/mL)
f_s = sample flow rate (mL/min)
ε_n = nebulization efficiency
$\varepsilon_{v,a,i}$ = vaporization, atomization, and ionization efficiency
N_A = Avagadro's number
A_r = atomic weight of analyte metal
(note: ions are distributed in about 10^6 aerosol droplets reaching the plasma)

Analyte Signal Intensity

$I_a = q_i\ A_i\ \varepsilon_d$

I_a = analyte signal intensity (s^{-1})
A_i = relative abundance of monitored analyte isotope
ε_d = MS detection efficiency

United States Environmental Protection Agency

ICPMS Signal – Analyte in Nanoparticles

Analyte ion flux in plasma

Analyte ion flux is contained in ion plumes from individual nanoparticles vaporized by the plasma. The flux of nanoparticles in the plasma is

$$q_p = c_p f_s \varepsilon_n / 60$$

c_p = nanoparticle concentration in sample (mL^{-1})

$c_p = c_a / m_{a,p}$

$m_{a,p}$ = average analyte mass in nanoparticle (g)]

$$q_{i,avg} = q_p m_{a,p} N_A (A_i/A_r) \varepsilon_d$$

United States Environmental Protection Agency

ICPMS Signal – Analyte in Nanoparticles (cont'd.)

Analyte Signal Intensity

- Analyte ions are detected only during time ($\tau_p \approx 10^{-4}$ s) an ion plume transits to the detector; otherwise, intensity at the detector, I_b, is due to background. The key to SP-ICPMS is to measure the signal with high temporal resolution (i.e., measurement windows >>1 second) so the number of background ions detected in each data point is much less than the number of ions produced by a nanoparticle ion cloud.

- Number of particles counted per second, is equal to the particle flux (i.e., every particle entering the plasma is counted).

$$q_p = c_p f_s \varepsilon_n / 60$$

- The number of ions detected for each plume transit is proportional to the analyte mass in the particle.

$$n_{i,p} = m_{a,p} N_A (A_i / A_r) \; n_{i,p} = m_{a,p} N_A (A_i / A_r) \varepsilon_{v,a,i} \varepsilon_d$$

Example – Gold at 100 pg/mL

Dissolved

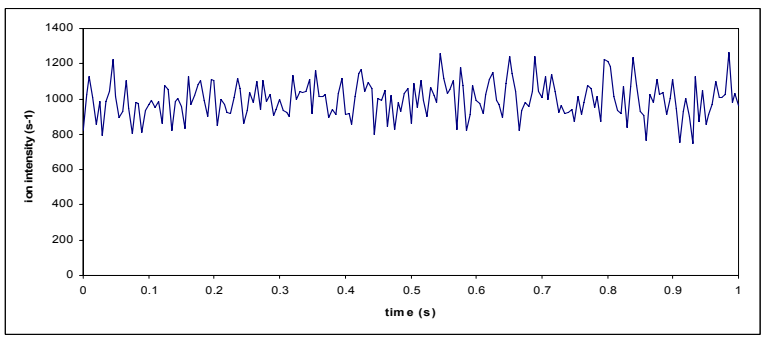
Assume:

- f_s = 1 mL/min,
- ε_n = 0.02
- $\varepsilon_{v,a,l}$ = 1
- ε_d = 1 x 10^{-5}

Then: q_i = 1 x 10^8 s^{-1}

These are distributed among the >10^6 aerosol droplets, so analyte signal intensity is constant at

I_a = 1 x 10^3 s^{-1}



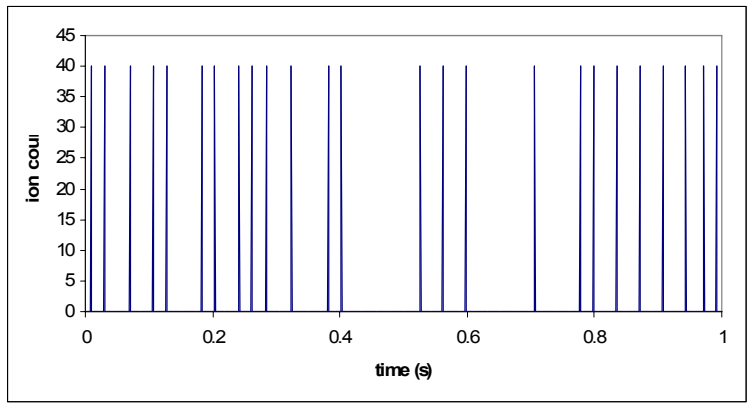
50 nm nanoparticles

$m_{a,p}$ = 1.3 x 10^{-15} g

c_p = 7.6 x 10^4 mL^{-1}

Assume: same conditions as for dissolved.

Then: q_p = 25 s^{-1}; $n_{a,p}$ = 40



United States Environmental Protection Agency

SP-ICPMS Figures of Merit

- Nanoparticle concentration metrics and single particle metrics (particle analyte mass) are controlled by different factors. For both, the following should be considered:
  - precision
  - accuracy
  - dynamic range
    - detection limit
    - upper linear range

United States Environmental Protection Agency

Nanoparticle Concentration

- Precision controlled by counting statistics
  - $\sigma \geq p^{0.5}$
  - $\sigma \geq (q_p T_s)^{0.5}$
    - p = total particles counted
    - T_s = total counting time
- Accuracy controlled by nebulization efficiency
  - Changes in viscosity, surface tension affect accuracy.

United States Environmental Protection Agency

Nanoparticle Concentration Dynamic Range

Detection limit is ultimately determined by background nanoparticle concentration. When this is negligible, detection limit is only limited by reasonable signal acquisition time. Assuming 1 nanoparticle can be counted in 30 seconds, with parameter values as in previous example:

$$C_{p,\,DL} = 60\, q_p / f_s\, \varepsilon_n = 100\ mL^{-1}$$

However, a ***practical quantitation limit*** (PQL) is often defined as the concentration giving less that 1% false negatives (~3 standard deviations below the mean total particle count, p_m). Using counting statistics:

$$0 = p_m - 3\sqrt{p_m}$$
$$p_m = 9$$

So, the practical quantitation limit for q_p is about 0.3 s^{-1} (30 second maximum acquisition time), and, assuming the conditions for the detection limit:

$$C_{p,\,PQL} = 60\, q_p / f_s\, \varepsilon_n = 900\ mL^{-1}$$

Alternatively, PQL can be defined by the maximum acceptable relative standard deviation (RSD). If an RSD ≤ 15% is specified, the minimum q_p is 1.5 s^{-1} and $C_{p,\,PQL} = 4500\ mL^{-1}$.

United States Environmental Protection Agency

Nanoparticle Concentration Upper Linear Range

- Upper linear range is determined by the need to avoid multiple ion plumes transiting the detector during a detector dwell time t_d (the sampling time per data point in seconds). To avoid unacceptable numbers of these events (~10% of total counts):

$$q_p \leq 0.1 / t_d$$

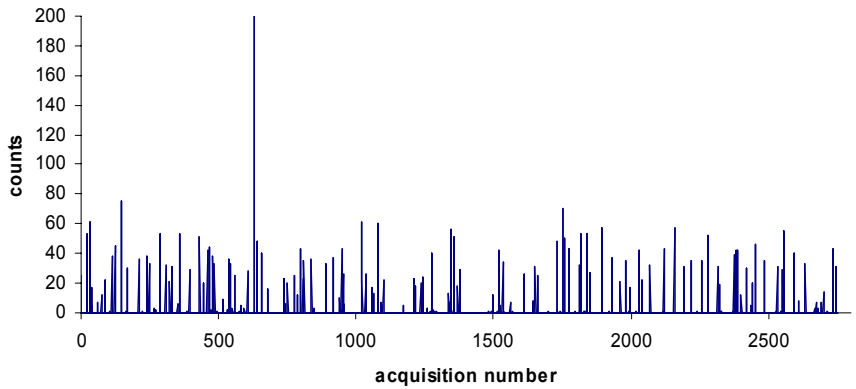
- SP-ICPMS to date has used dwell times of ≥10 ms, so the plasma particle flux should be less than about 10 s^{-1}.
  - For 25 nm diameter silver nanoparticles, SP-ICPMS is limited to samples less than about 2.5 ng/L Ag. [Note: 1 ng/L in handouts is incorrect]
  - Practical dynamic range ($c_{p,max}$/ $c_{p,min}$) is 30 or less.

United States Environmental Protection Agency

Experimental Conditions for SP-ICPMS

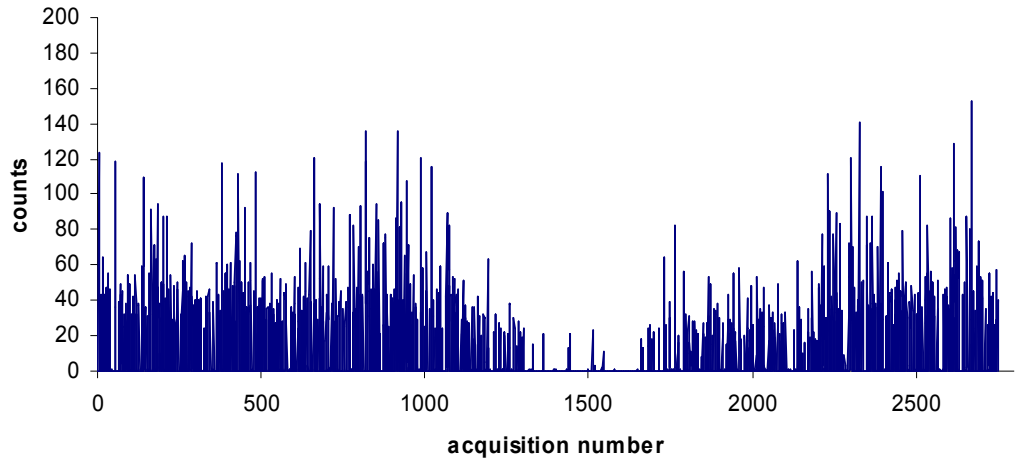
- Perkin Elmer DRC-e
- Plasma conditions and lens settings optimized for 5 ppb dissolved gold
- Dwell time 10 ms, 3 ms, 1 ms, 0.3 ms, or 0.1 ms
- 550 dwell periods per repetition, either 550, 2750, or 11,000 total acquisitions per experiment

Effect of Dwell Time on Upper Linear Range



50 nm Au, 1.25 x 10^5 mL^{-1}, 1 ms dwell time

1 ms dwell time produces baseline separation of particle ion plume signals and minimizes multiple-particle detections. The particle flux to the plasma is approximately 40-50 s^{-1} at this particle concentration.



50 nm Au, 1.25 x 10^5 mL^{-1}, 10 ms dwell time

EPA United States Environmental Protection Agency

Deviation of Linearity of Particle Count[a]

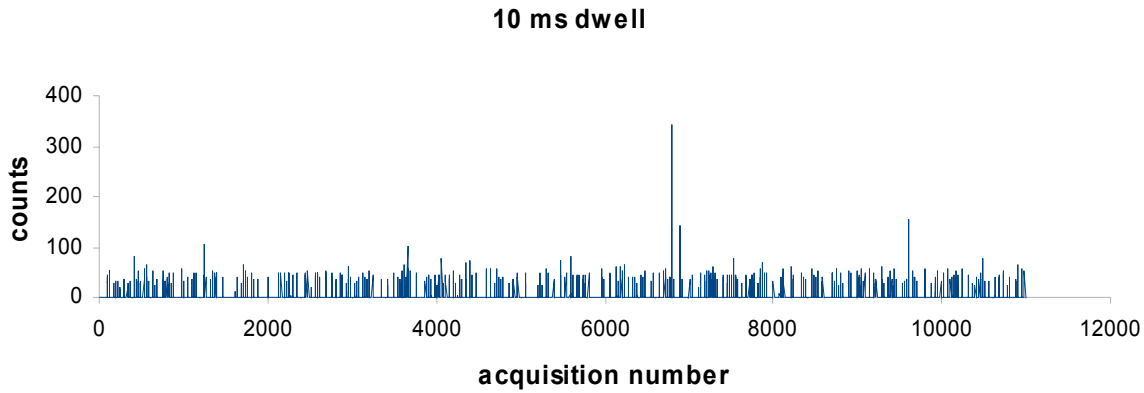
Dwell Time (ms)	% deviation 1.25×10^5 mL^{-1}	% deviation 1.25×10^6 mL^{-1}	% deviation 5.0×10^6 mL^{-1}
10	-30	NA[b]	NA
3	1.0	-65	NA
1	-4.8	-25	NA
0.3	-1.3	-9.3	-39
0.1	-7.3	-12	-32

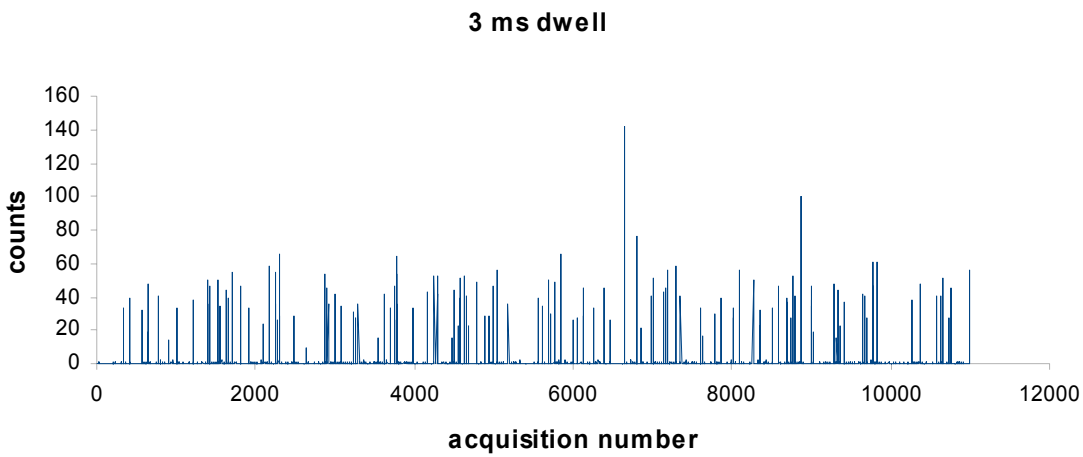
[a] Relative to particle count at 1.25×10^{-4} mL^{-1}

[b] Not analyzed. Particle pulses merged into continuum.

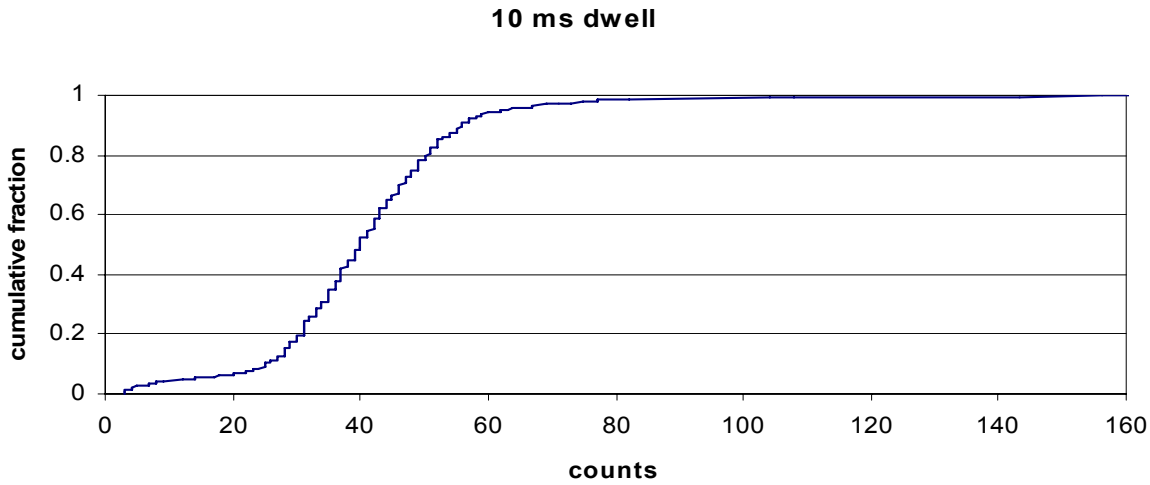
United States Environmental Protection Agency

Particle Analyte Mass – $n_{i,p}$ vs. time at 1.25 x 10^4 mL^{-1}

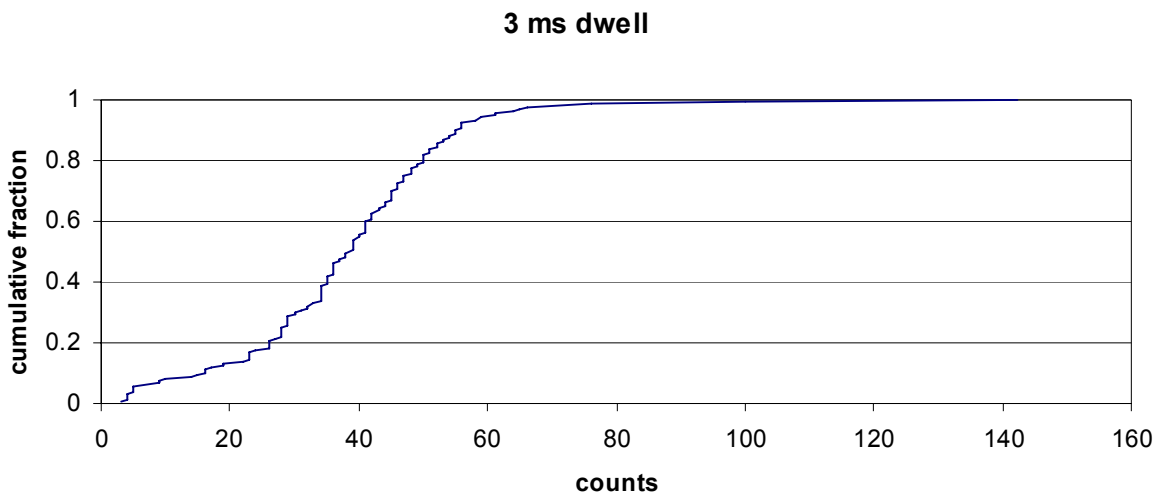




Particle Analyte Mass – $n_{i,p}$ distributions at 1.25×10^4 mL^{-1}

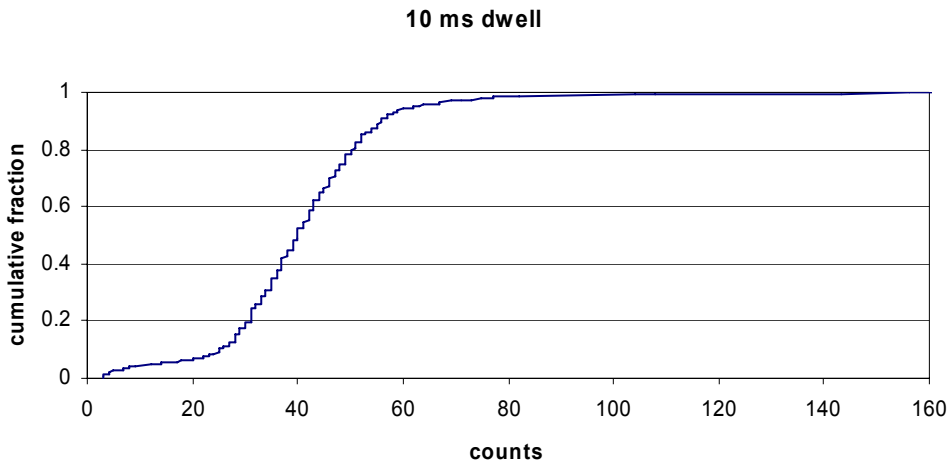


rsd diam.
15.8%

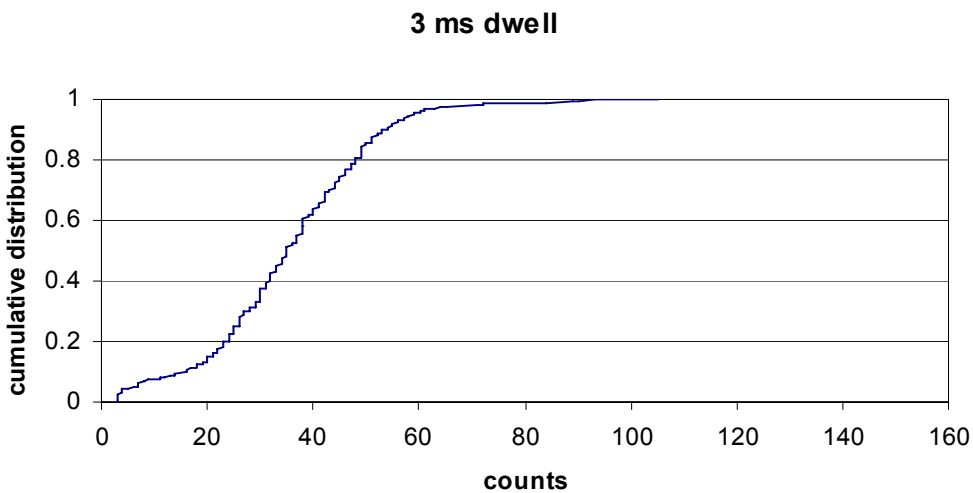


rsd diam.
18.3%

Particle Analyte Mass – $n_{i,p}$ distributions at 1.25 x 10^5 mL^{-1}

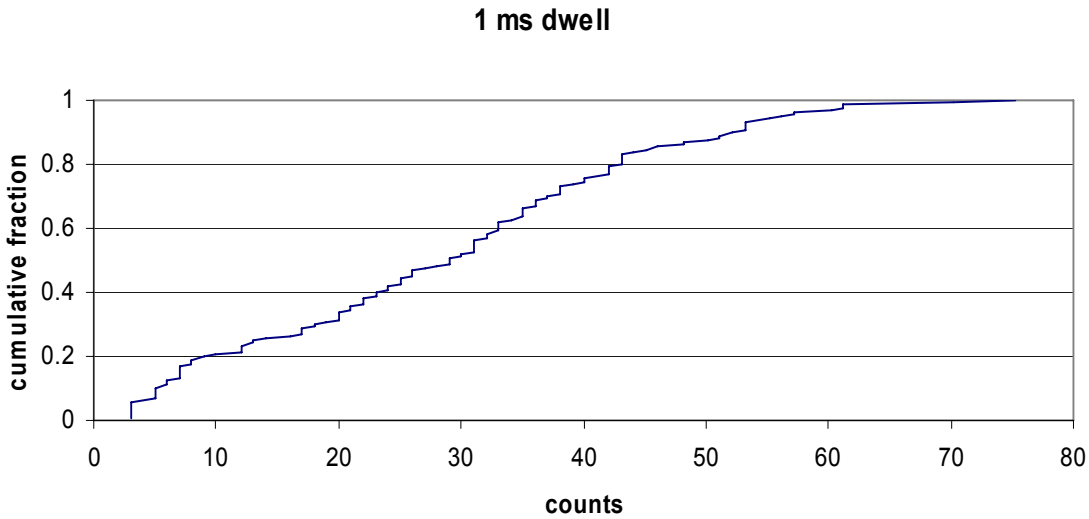


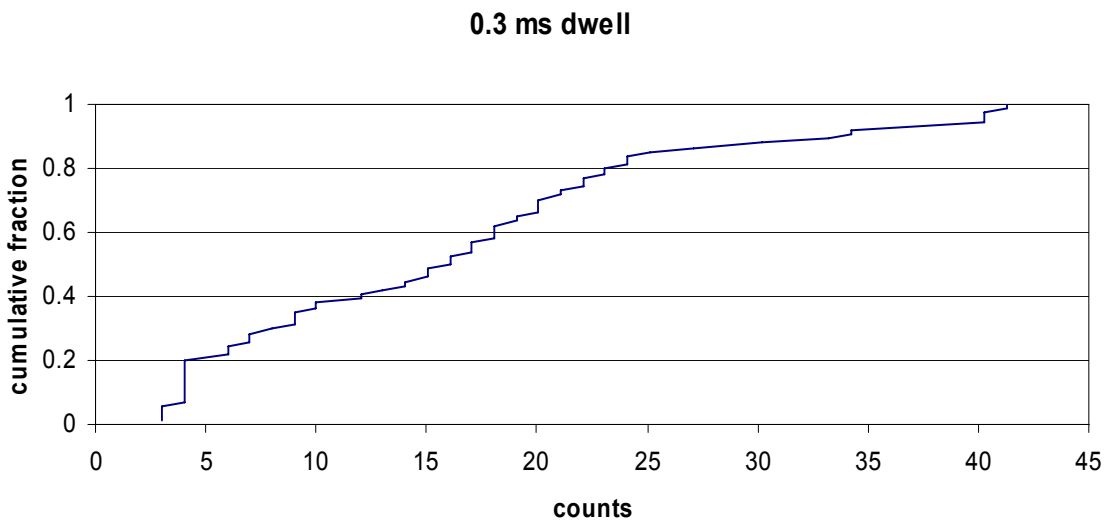
rsd diam.
15.9%



rsd diam.
18.2%

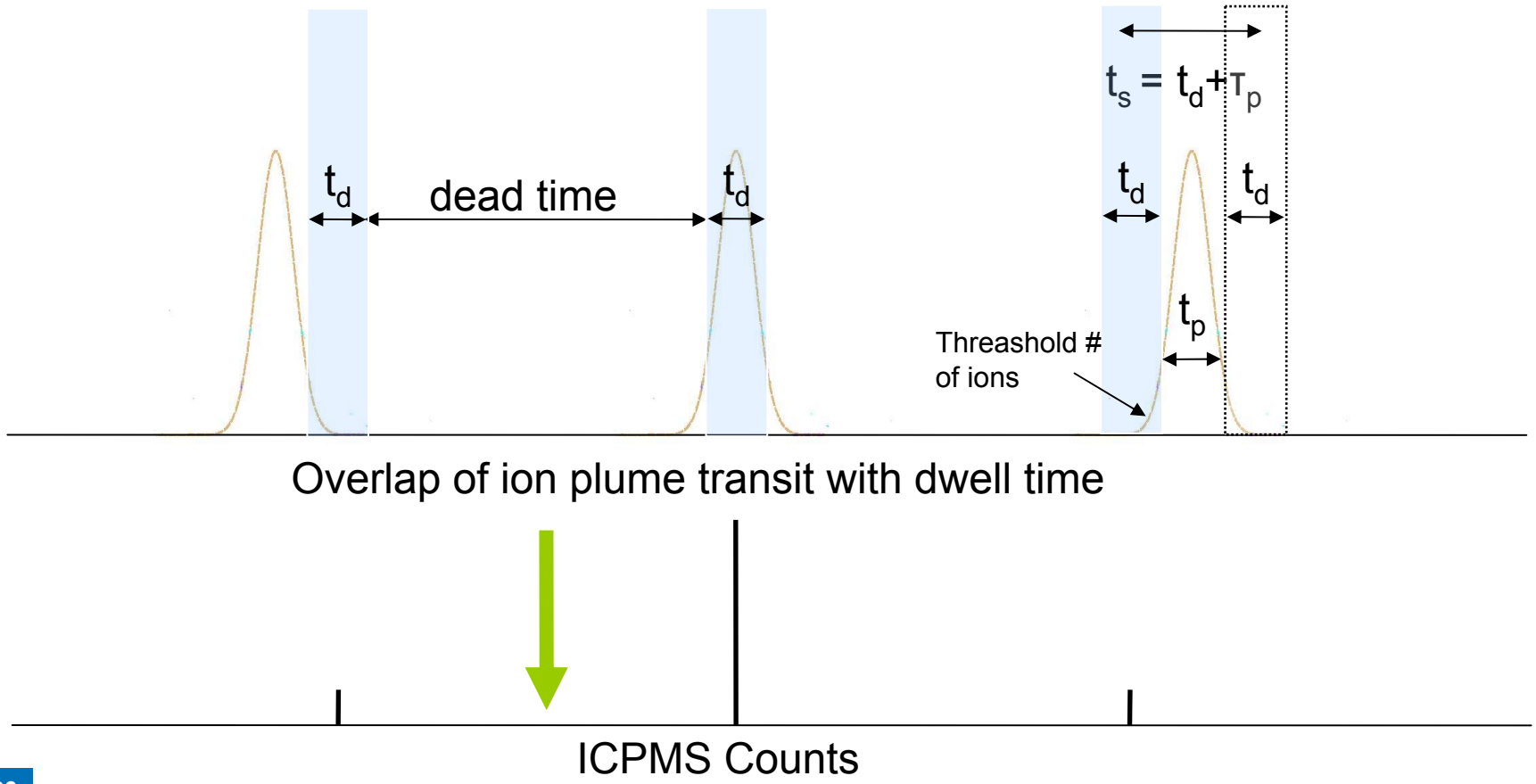
Particle Analyte Mass – $n_{i,p}$ distributions at 1.25×10^4 mL^{-1}





United States Environmental Protection Agency

Effect of Discontinuous Sampling on Signal Dispersion and Sampling Time



EPA United States Environmental Protection Agency

Estimation of τ_p from Data Regression

- For each data point, the effective measurement time is:

$$t_s = t_d + \tau_p$$

- For the 11000 data points acquired for a 1.25×10^4 mL^{-1} 50 nm gold nanoparticle suspension at each dwell time:

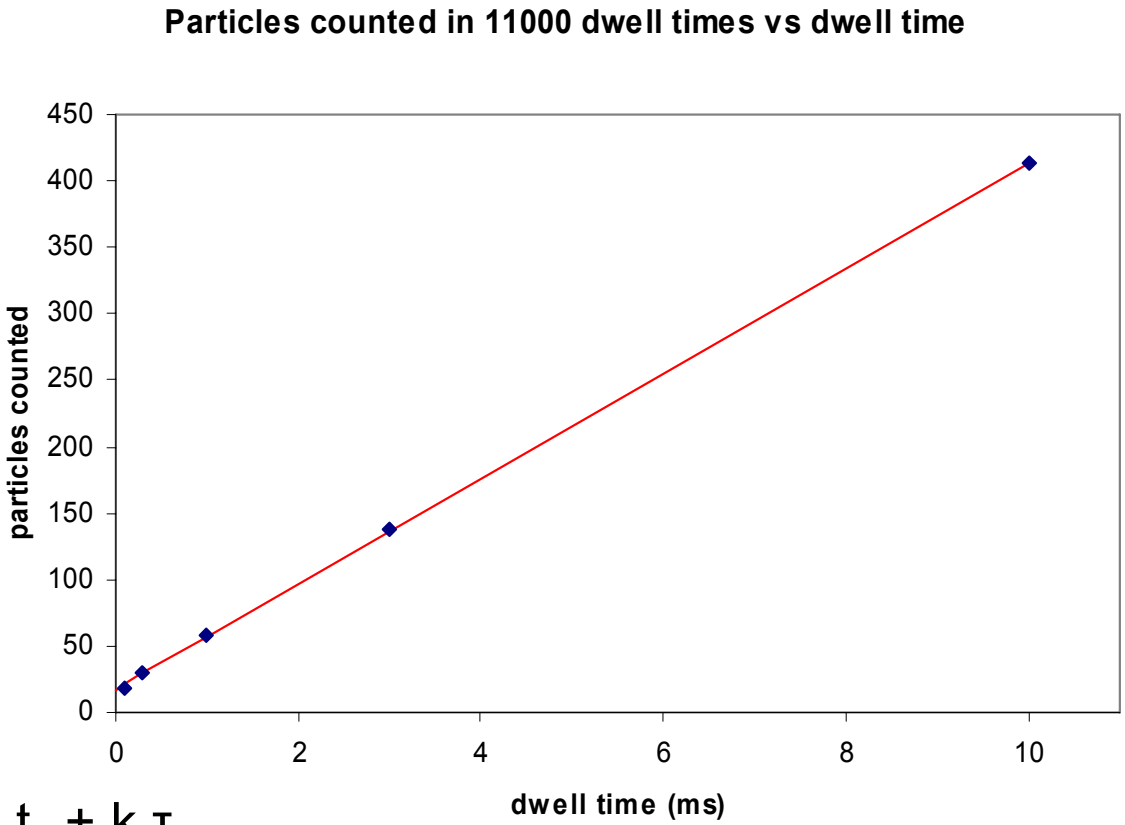
$$p = k\, t_s$$

  - p = total particles counted
  - k = proportionality factor including the number of acquisitions and the nebulization efficiency.

  Distributing k:

$$p = k\, t_d + k\, \tau_p$$

United States Environmental Protection Agency



$p = k\, t_d + k\, \tau_p$

$p = 39.7 t_d + 17.25$

$\tau_p = 17.25/39.7 = 0.434$ ms

United States Environmental Protection Agency

Ion Plume Transit Time Discussion

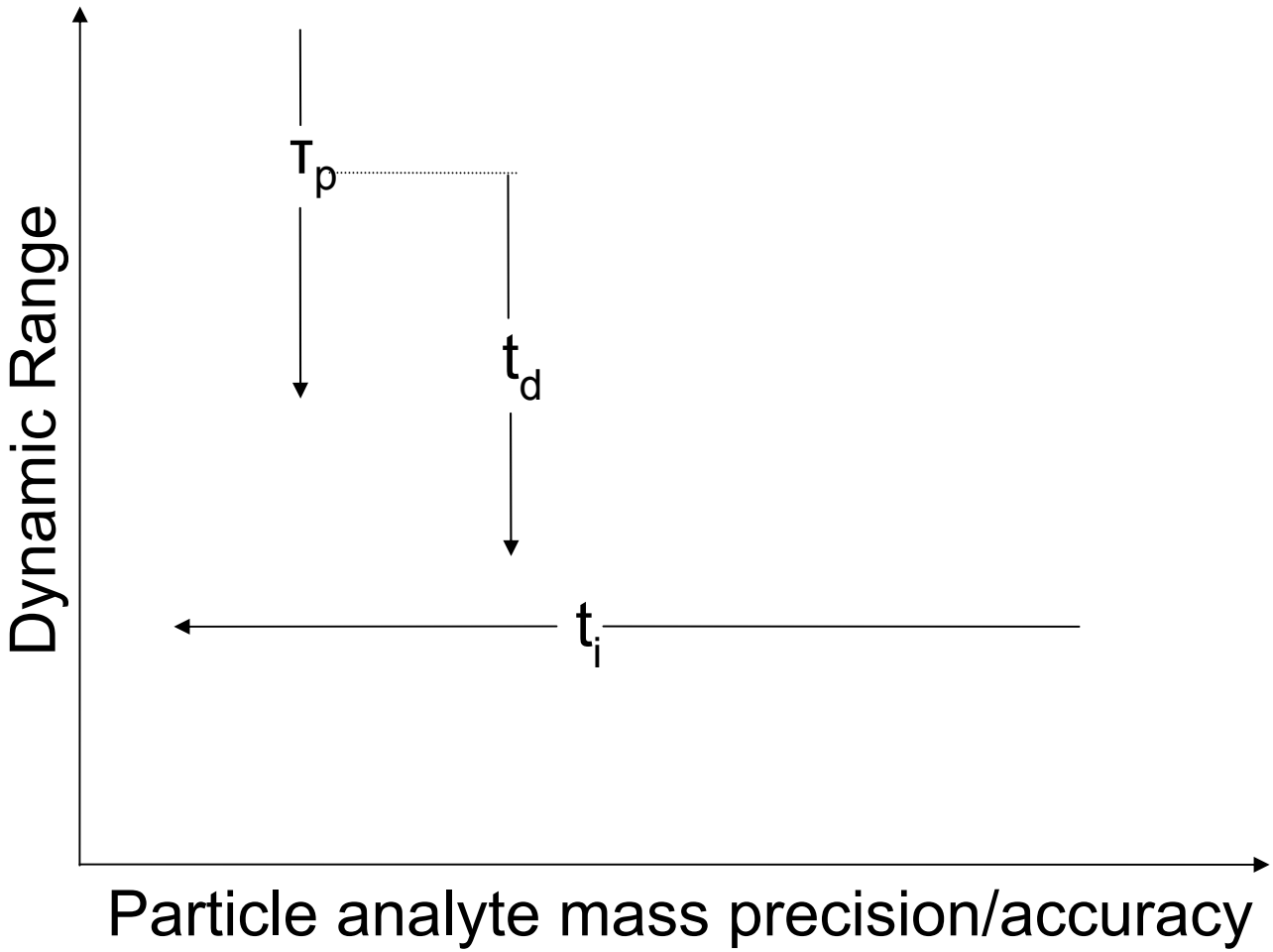
- A 430 μs transit time limits the available improvement of particle concentration upper linear range to about a factor of 20 compared to previous studies. It also degrades the particle analyte mass precision and accuracy for short dwell times.

- This ion plume transit time is unusually long compared to published values, and compared to the expected range that can be estimated using normal plasma temperatures and gas flows.

- The plasma sampling depth was fixed at 11 mm for these experiments, and plasma conditions were optimized using dissolved analyte. These conditions may have contributed to the long transit time.

United States Environmental Protection Agency

Effect of timing on SP-ICPMS metrics



EPA United States Environmental Protection Agency

Particle Analyte Mass Accuracy

- Calculate ε_n from particle count data at 1.25×10^4 mL^{-1}
  - $\varepsilon_n = 60\ q_p / c_p\ f_s = 0.018$
- Calculate ε_d from dissolved gold standard
  - $\varepsilon_d = I_a / q_i\ A_i = I_a\ 60\ A_r / c_a\ f_s\ \varepsilon_n\ \varepsilon_{v,a,l}\ N_A\ A_i = 1.1 \times 10^{-5}$
- Calculate particle analyte mass from average $n_{i,p}$ of 40
  - $m_{a,p} = n_{i,p} / [N_A\ (A_i / A_r\ )\ \varepsilon_d] = 1.2 \times 10^{-15}$ g
- This analyte mass corresponds to a gold nanoparticle of 49 nm diameter, compared to 50 nm by LLS.

EPA United States Environmental Protection Agency

Particle Analyte Mass Detection Limit

- For background << 1 per dwell time, minimum particle analyte mass corresponds to mass giving $n_{i,p}$ = 2 ions detected per ion plume.
- For this study:
  - $m_{a,p,min} = 1.2 \times 10^{-15} \times 2 / 40 = 6 \times 10^{-17}$ g = 60 attograms
  - This corresponds to a gold nanoparticle diameter of 18 nm.

- For signifigant background:
  - $m_{a,p,min}$ is proportional to $\sqrt{t_d}$
  - 100 μs dwell time would yield a particle mass detection limit 10 times lower than 10 ms dwell.

EPA United States Environmental Protection Agency

Particle Analyte Mass Upper Linear Range

- Upper linear range is limited by upper linear limit of pulse counting rate (ca. 2 x 10^6 s^{-1}) during the ion plume transit. For 100 μs τ_p, the upper limit is ca. 200 counts.
- This is a mass dynamic range of 100, or a particle size equivalent dynamic range of only about ca. 5.
- Upper particle analyte mass dynamic range can be extended by
  - increasing τ_p
  - decreasing sensitivity (e.g., reducing bandpass)

EPA United States Environmental Protection Agency

Conclusions

- Shorter dwell times significantly increase the upper dynamic range of SP-ICPMS nanoparticle concentration determinations.
- Discontinuous sampling of current commercial ICPMS instruments at short dwell times increases the dispersion of measurement of analyte mass in nanoparticles.
- Dwell times less than 3 ms with current instrumentation and operating conditions used in this study are not suitable for particle analyte mass measurement.
- Dwell time of 0.3 ms, in conjunction with a size-selective separation technique, could be useful to distinguish analyte nanoparticles from analyte sorbed to other particles.
- Data are consistent with an ion plume transit time of about 400 μs.

EPA United States Environmental Protection Agency

Future Work

- **Develop instrumentation for continuous sampling by ICPMS at dwell times less than 0.3 ms.**
- Decrease ion plume transit time τ_p by optimizing experimental parameters.
- Develop techniques for increasing dynamic range of particle analyte mass measurement.
- Evaluate SP-ICPMS for transformation studies.
- Couple SP-ICPMS with size-selective techniques.
- Evaluate applicability of SP-ICPMS to Ag, CeO_2 and TiO_2.

EPA
United States
Environmental Protection
Agency

Acknowledgements

I am indebted to Steve Beres and Ken Neubauer of Perkin Elmer Instruments for the use of the DRC-e to conduct these experiments and for their patient instruction on the basic operation of the instrument. I also thank David Armstrong and Donna Sellman of Perkin Elmer for facilitating my work.