Center of Excellence for Aerospace Particulate Emissions Reduction Research

PM Line Loss Correction without Direct Size Measurement

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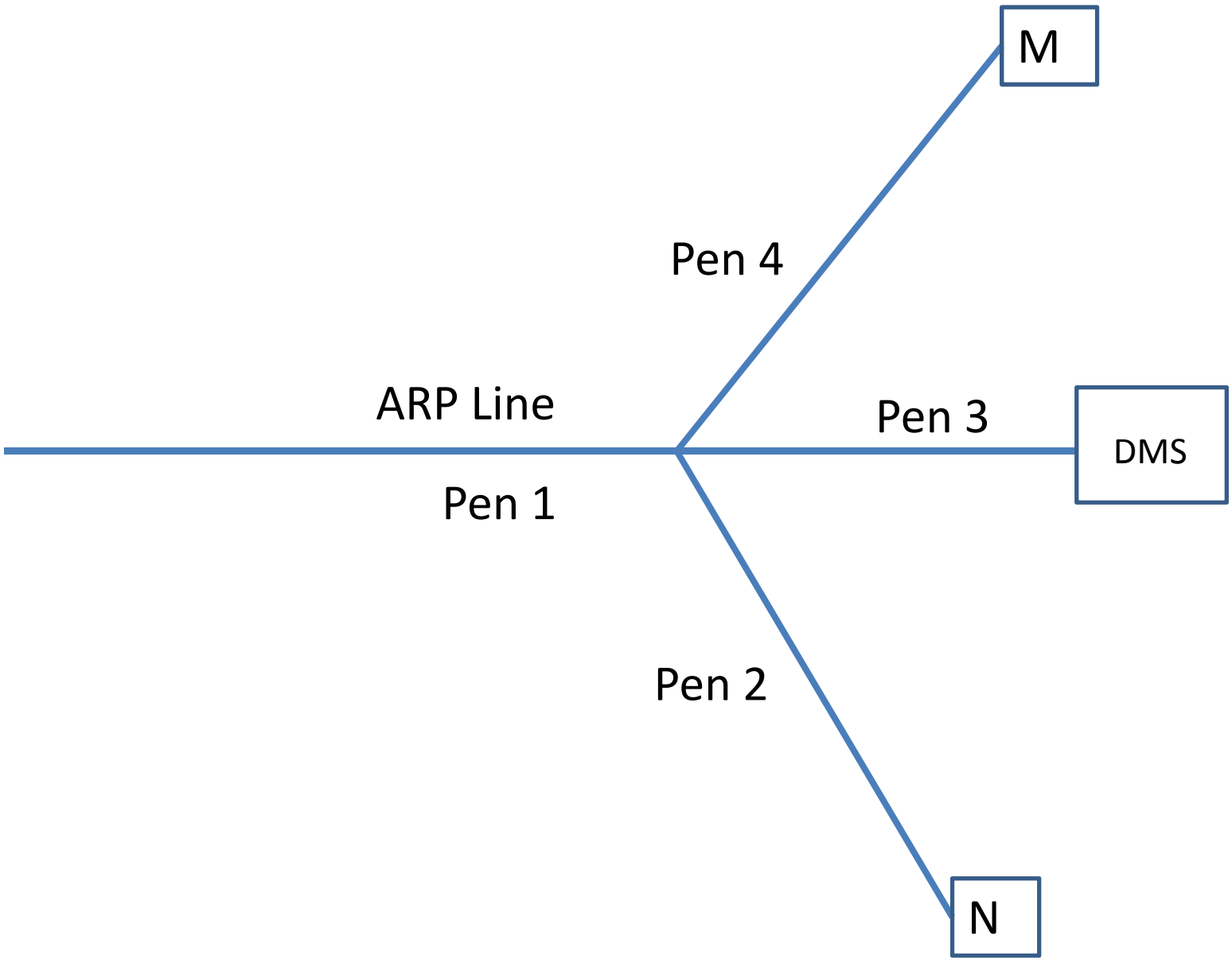
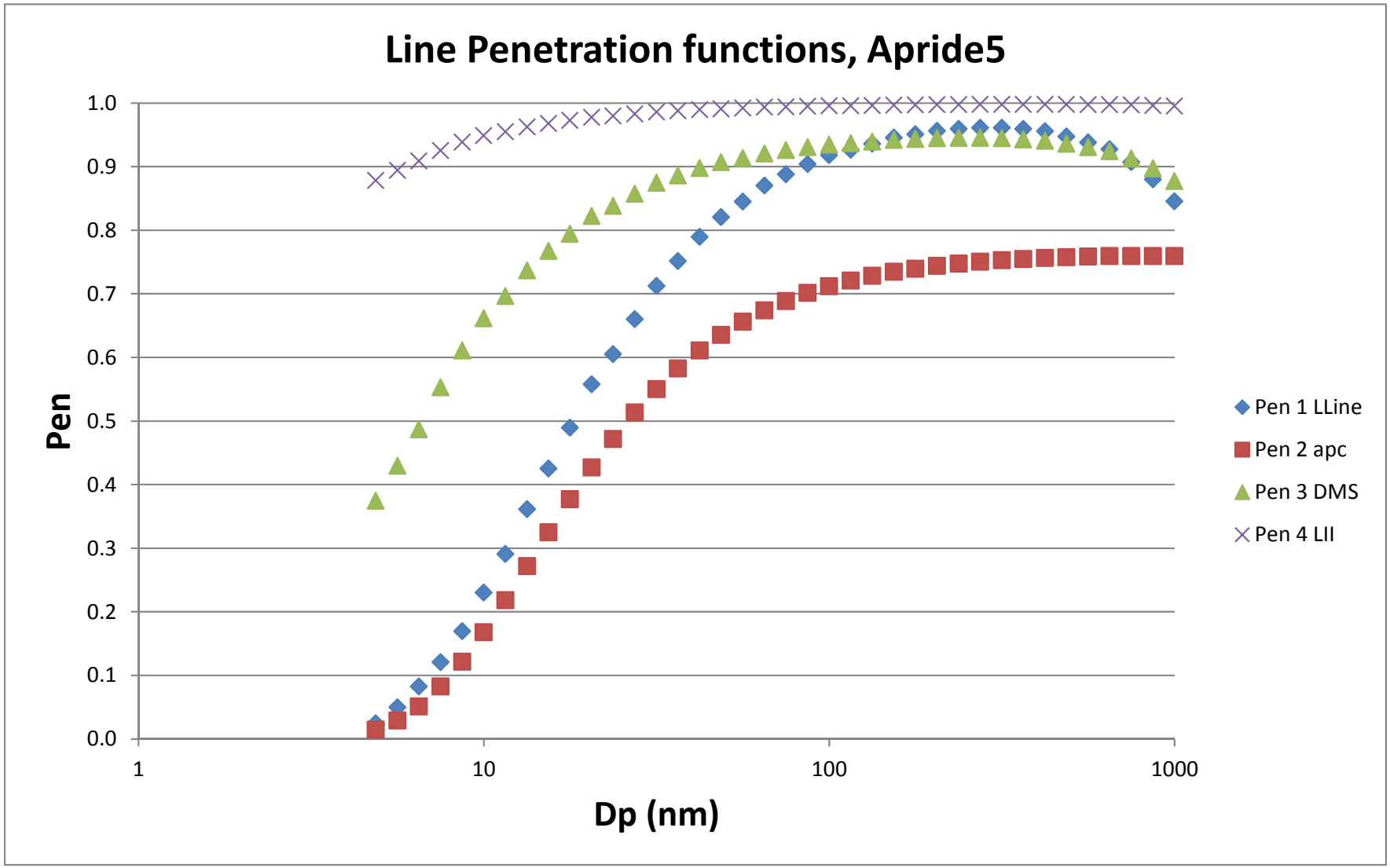
ETH Conf. on Combustion Generated Nanoparticles
Zurich, CH
June 2014


M
Pen 4
ARP Line
Pen 3
DMS
Pen 1
Pen 2
N

Line Penetration Functions



Line Loss Correction

- Measurement data: {M_d, N_d, pen1, pen2, pen4}
- N_u = FacN(M_d, N_d,pen)*N_d
- M_u = FacM(M_d, N_d,pen)*M_d

Engine Test Campaigns

- APRIDE 2
  - SR Technics, Zurich CH, Dec 2011
  - 3 engine types
  - Wide range of engine conditions
  - 56 test points
- APRIDE 5
  - SR Technics, Zurich CH, Aug 2013
  - 2 engine types
  - Wide range of engine conditions
  - 39 test points
  - Catalytic stripper

Results

	FacN_dms			FacM_dms	
	Apride2	Apride5		Apride2	Apride5
	Dec 2011	Aug 2013		Dec 2011	Aug 2013
Min	1.39	2.31		1.18	1.06
Max	2.25	6.01		1.35	1.19
Avg	1.70	4.15		1.26	1.12
σ	0.26	1.44		0.04	0.04

Upstream Lognormal: N_u, GMD_u, GSD_u

Measurement Data: {M_d, N_d, pen1, pen2, pen4}

Pen2 includes leg 2 line loss, loss in the CS,
and accounts for the APC size dependent counting efficiency.

Goal: Find facN (=N_u/N_d) and facM (=M_u/M_d)

First find a ballpark conc & size

- Treat the aerosol as being monodisperse
- Number conc N_u, diameter GMD_u
- $N_d = N_u * pen1(GMD_u) * pen2(GMD_u)$
- $M_d = M_u * pen1(GMD_u) * pen4(GMD_u)$
- $M_u = (\pi\rho/6) GMD_u^3 N_u$
- $X = (6M_d/\pi\rho N_d)^{1/3}$
  $= GMD_u * [pen4(GMD_u)/pen2(GMD_u)]^{1/3}$
- $GMD_{u0}(nm) = \Sigma_{i=0}^{3} \alpha_i (X)^i$
- $N_{u0} = N_d/[pen1(GMD_{u0}) * pen2(GMD_{u0})]$

1st Lognormal Upstr Aerosol

- Increase the width to a finite known value
- Same upstream number and mass
- $N_{u1}=N_{u0}$, $GMD_1=GMD_{u0}/\exp(1.5su^2)$
- $su = \ln(GSD_u)$
- $Note$: $M = \left(\frac{\pi}{6}\right)\rho N * GMD^3 * \exp(4.5s^2)$
- Downstream N and M for this lognormal won't match N_d and M_d due to size dep pen.

For 1st Lognormal

- Generate size distributions upstream, at M instr, and at N instr.
- Calc massM_{d1} at mass instr, number N_{d1} at number instr.

2^{nd} iteration Lognormal

- $N_{u2}=N_{u1}*(N_d/N_{d1})$
- $GMD_2 = GMD_1*(M_dN_{d1}/M_{d1}N_d)^{1/3}$,
- Same GSD_u
- Generate size distributions upstream, at M instr, and at N instr.
- Calc mass upstream (M_{u2}) and at mass instr (M_{d2}), number upstream (N_{u2}) and at number instr. (N_{d2}).
- Calc facN=N_{u2}/N_{d2} and facM=M_{u2}/M_{d2}

Soot Density

- $X = (6M_d/\pi\rho N_d)^{1/3}$
- $\rho = M/Vol = (6M/\pi)/ \Sigma x_i^3 \Delta_i snm_i$

  $= (6M/\pi)/ (\Sigma x_i^3 \Delta_i\ sn_i * pen4_i/pen3_i)$

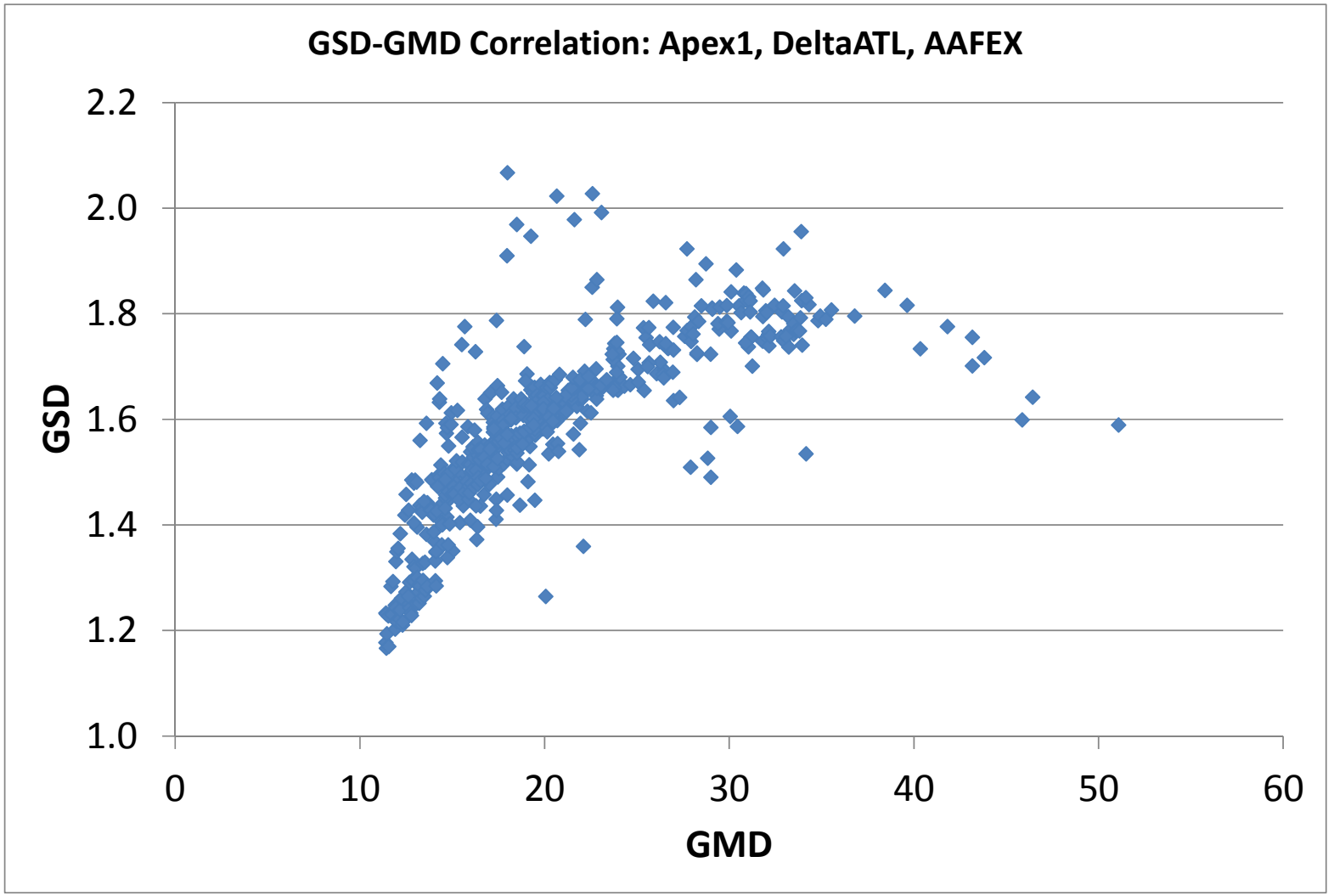
  $= (6M/\pi)/sum$ $\quad sum = \Sigma x_i^3 \Delta_i\ sn_i * pen4_i/pen3_i$
- $\delta\rho/\rho = sqrt\{ (\delta M/M)^2 + (\delta sum/sum)^2\}$

  $\delta sum = sqrt\{\Sigma(x_i^3 \Delta_i\ \delta sn_i * pen4_i/pen3_i)^2\}$

  $\delta M/M = sqrt\{ (\delta M_{ran})^2 + max(0.002\ mg/m^3, M*\delta Msys\%)^2\}$

  $\delta Msys = 0.16$ $\quad 16\%$
- $Weight = 1/\delta\rho^2$
- $< \rho > = 0.55 \pm 0.03$

GSD Downstream

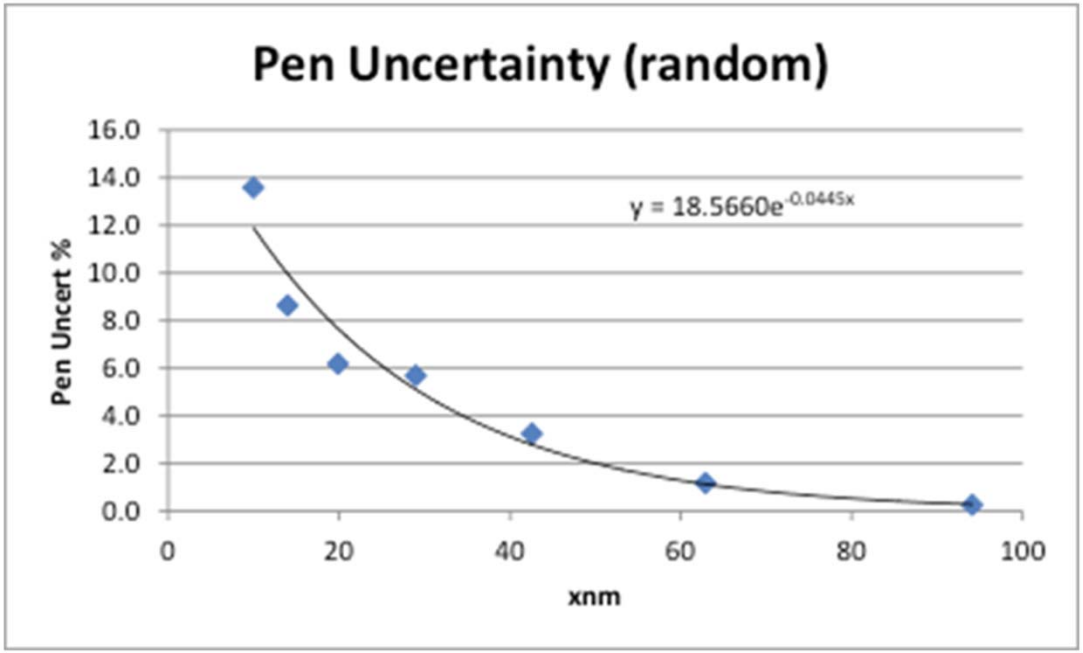


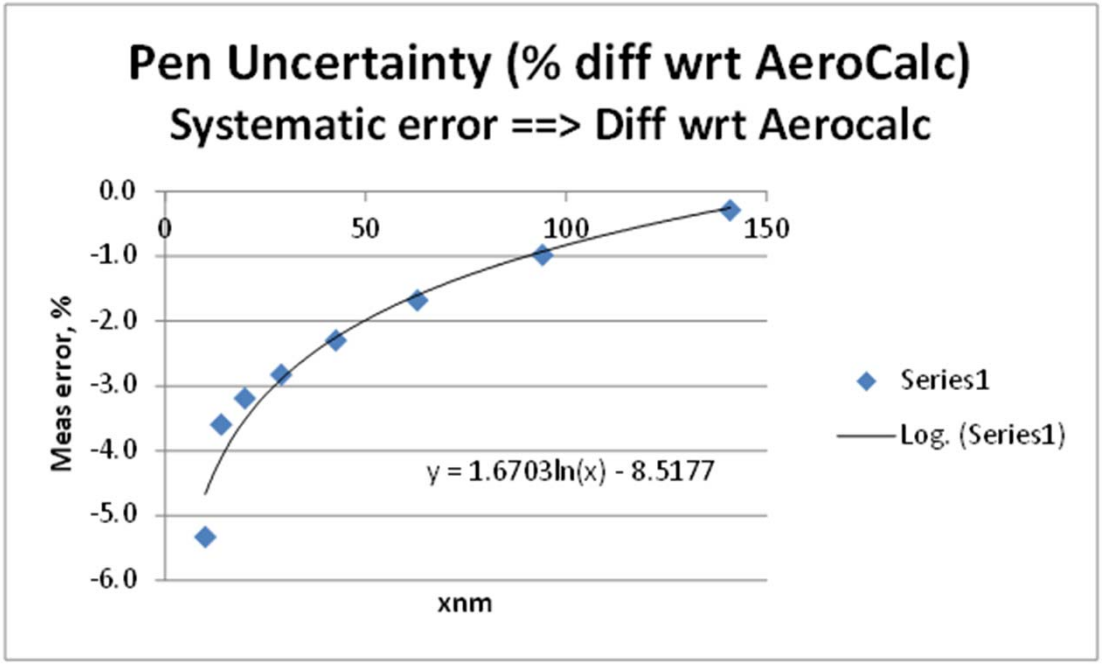
GSD Upstream

- Use downstream GMD_d, GSD_d to generate upstream GSD_u.
  - GSD (data) = 1.72 ± 0.23
  - GSD (smooth) = 1.81 ± 0.19
- GSD (E31 LLC) = 1.8

δfacN – Monodisperse model

- facN = N_u/N_d = 1/pen12(GMD_u)
  = rpen12(GMD_u)
- δpen1 and δpen2
  - Random (AAFEX2)
  - Systematic (AAFEX2)
- δfacN1% = sqrt[$δpen1\%^2$+ $δpen2\%^2$]
- $δfacN_2$ = (∂ facN /∂GMD)* $δGMD_u$
- = (∂ rpen12(GMD) /∂GMD)* $δGMD_u$
- = slope12(GMD_u) * $δGMD_u$


Pen Uncertainty (random)
Pen Uncert %
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
20
40
60
80
100
xnm
y = 18.5660e-0.0445x


Pen Uncertainty (% diff wrt AeroCalc)
Systematic error ==> Diff wrt Aerocalc
Meas error, %
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
0
50
100
150
xnm
y = 1.6703ln(x) - 8.5177
Series1
Log. (Series1)

$$GMD_u(nm) = \Sigma_{i=0}^{3} \alpha_i (X)^i$$

$$X = (6M_d/\pi\rho N_d)^{1/3}$$

$$\delta X/X = (1/3)\mathrm{sqrt}\{(\delta M_d/M_d)^2 + (\delta N_d/N_d)^2\}$$

$$\delta X = (X/3)\mathrm{sqrt}\{(\delta M_d/M_d)^2 + (\delta N_d/N_d)^2\}$$

$$\delta GMD_u = (\partial GMD/\partial X) * \delta X = \Sigma_{i=1}^{3} \alpha_i * i(X)^{i-1}\, \delta X$$

$$\delta facN_2 = slope12(GMD_u) * \delta GMD_u$$

$$\delta facN = \mathrm{sqrt}\{ (facN * \delta\%facN_1)^2 + \delta facN_2^{\,2} \}$$

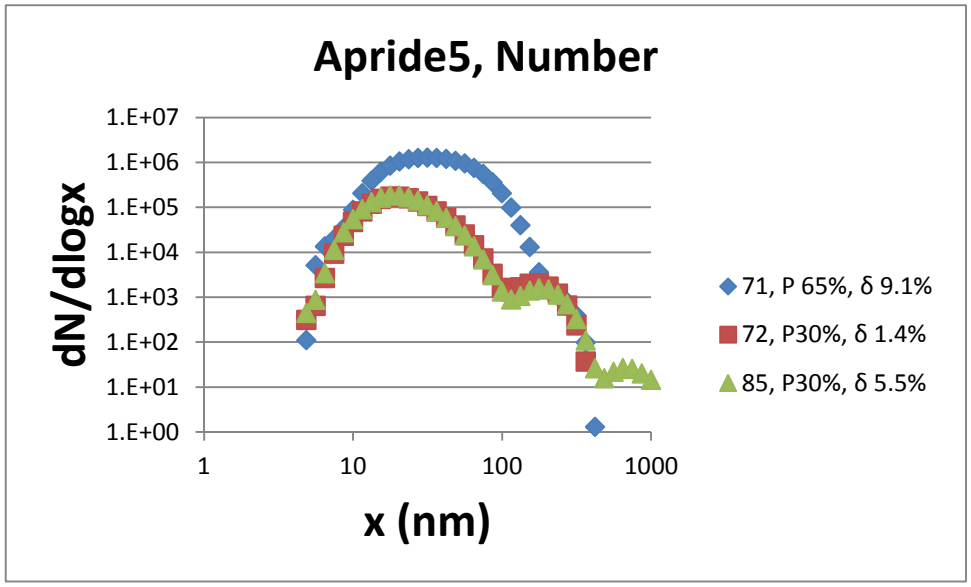
δfacM

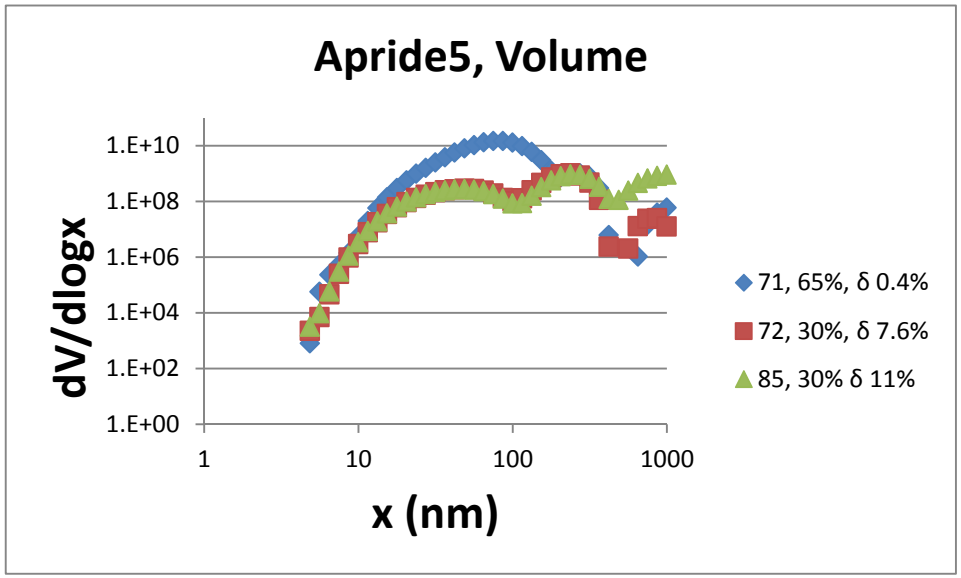
- facM = $M_u/M = 1/pen14(GMD_u)$)
- Same as facN, but pen2 → pen4

Results_Apride5

ρ	GSD	Weighted RMS % error facN	Weighted RMS % error facM	Total weighted RMS % error
0.55	1.72	10.2	7.1	17.3
0.55	1.82	6.0	6.9	12.9
1	1.80	14.5	4.8	19.3
1	1.63	5.5	12.8	18.3
0.34	1.96	7.2	4.8	12.0

Size distributions





Conclusions

- Reasonable line loss corrections can be made for number and mass without size data.
- Require size dependent line penetration functions and downstream number and mass concentration measurements.
- For Apride5 data set weighted RMS errors in correction factors were 6.0% for number and 6.9% for mass using model parameters: ρ=0.55 g/cm^3 and GSD=1.82.