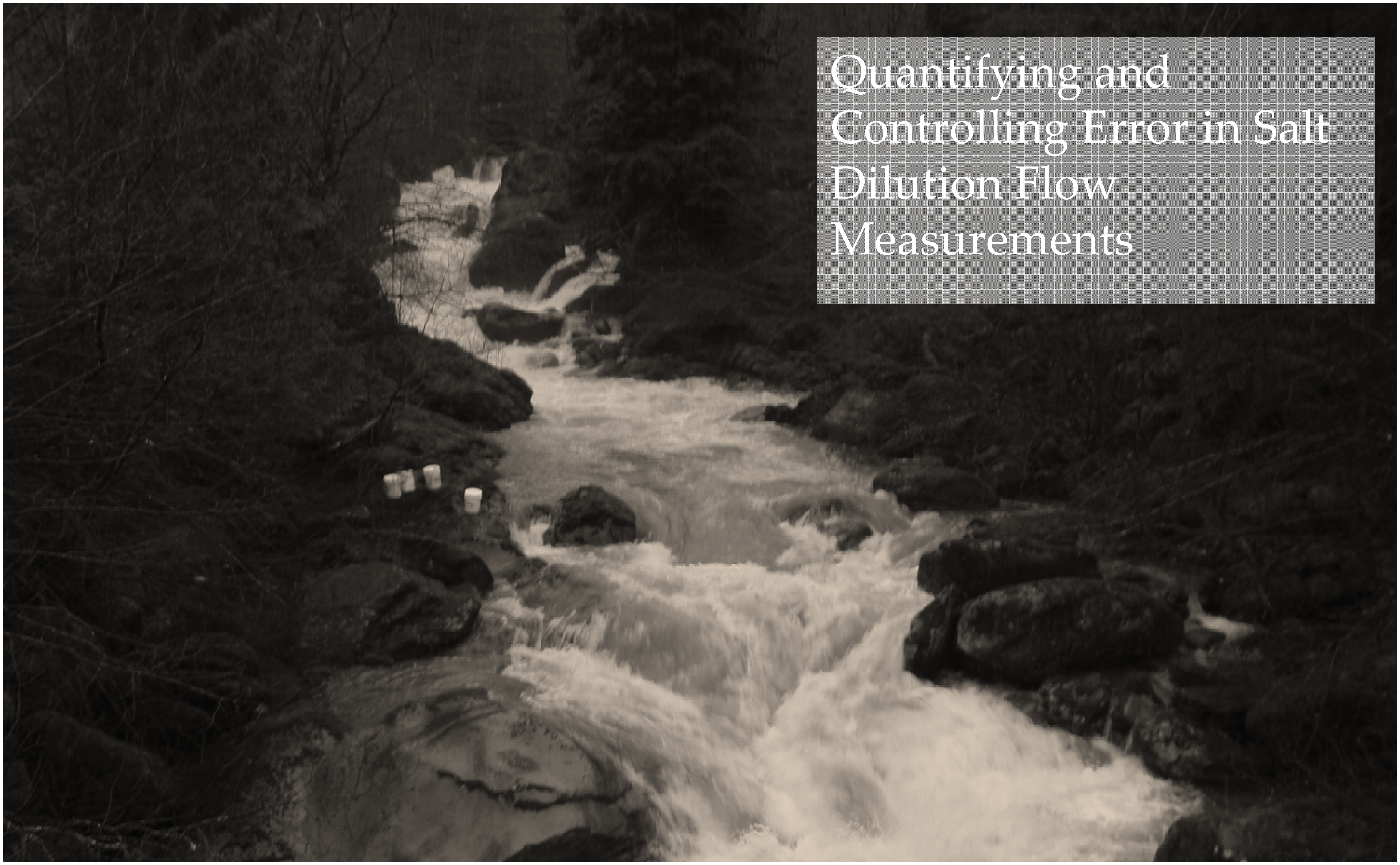
Quantifying and Controlling Error in Salt Dilution Flow Measurements



Gabe Sentlinger (ARD), Andre Zimmermann (nhc), Mark Richardson (UBC), John Fraser (ARD)

$$Q = \frac{Mass}{\sum \left(Ec(t) - EC(bg) \right) * dt * CF.T}$$

$$\frac{\delta Q}{Q} = \frac{\delta M}{M} + \frac{\delta \sum \left(EC(t) - EC(bg) \right)}{\sum \left(EC(t) - EC(bg) \right)} + \frac{\delta dt}{dt} + \frac{\delta CF.T}{CF.T}$$

-We want to identify sources of error/uncertainty and control for them.
-Ensure calibration, repeatability, linearity of method.

Components of Error	Lower Range	Upper Range	Notes
Mixing	0%	>200%	Can be eliminated with long mixing length
Salt Mass	<1%	10%	Can be nearly eliminated with careful procedures
CF.T	<1%	10%	Temperature Compensation
BG EC.T	<1%	>40%	Depending on SNR and EC.T Drift
Sensor Resolution	<1%	>40%	Baseline and SNR
Summary	<4%	>300%	

EC.T Uncertainty

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Quantifying Uncertainty

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Measurement of liquid flow in open channels — Tracer dilution methods for the measurement of steady flow —

Part 3:
Chemical tracers

4.4 Chloride

The conductivity method owes its popularity to the relative simplicity and low cost of conductivity meters that can be used in the field, and to the properties of the tracer (sodium chloride) which is characterized by a high degree of electrolytic dissociation when dissolved in water, easy availability and low price, and a moderate solubility, with little dependence of solubility on temperature. Furthermore, sodium chloride is relatively harmless to animal and plant life in the concentrations used, and shows little adsorption by vegetation and the materials of the streambed.

10.3 Chloride

The World Health Organization's Guidelines for Drinking Water Quality regard excessive concentrations of chloride in potable waters as unacceptable on the grounds of taste:

"High concentration of chloride give an undesirable taste to water and beverages. Taste thresholds for chloride (as sodium, potassium or calcium chloride) are in the range of chloride ion concentrations of 200-300 mg per litre."

Chloride can also have effects on freshwater organisms: Benthic fauna affected by saline runoff have been observed to drift at chloride concentrations of around 800 mg/l. While it is unlikely that concentrations of this magnitude will persist in the stream during dilution gauging, high concentrations can occur close to the injection point during the injection.

INTERNATIONAL STANDARD ISO 9555-3:1992(E)

(from Moore, 2005)

Goals:
1-Quantify Uncertainty
2-Reduce Uncertainty and/or Dosage

Table 1. Volumes/masses of injected salt used in different studies

Author	Mass of salt injected per m³/s streamflow (kg)	Equivalent volume (L) of 20% salt solution (1 kg salt in 5 L water)
Østrem (1964)	0.5	2.5
Church and Kellerhals (1970)	0.2	1
Day (1976)	0.3	1.5
Elder *et al.* (1990)	5	25
Hudson and Fraser (2002)	2	10

Measurement of liquid flow in open channels — Tracer dilution methods for the measurement of steady flow —

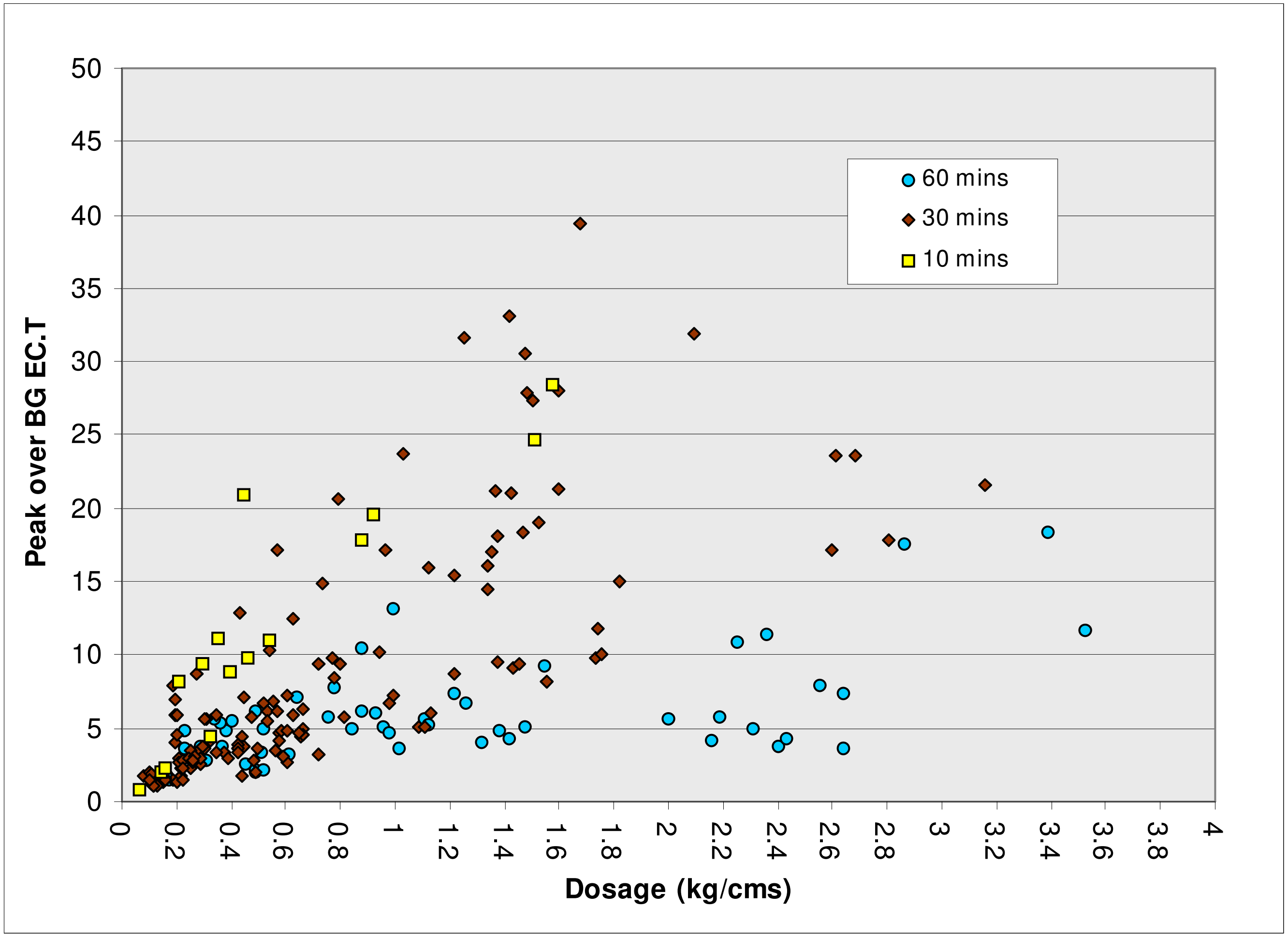
Part 3:
Chemical tracers

-Previous studies have suggested a multiplier over background (ie 50% - 500%).
-We recommend a SNR approach instead.
-For Inst. Resolution of 0.1 uS/cm and low BG noise, a rise of 10 uS/cm is a SNR of 100. This introduces only 1% uncertainty into measurement.
-Avoid Overdosing!

ISO9555-3			
Criteria	[Cl] mg/l	[NaCl] (mg/l)	Peak over BG
Taste	200	330	687
Benthic	800	1319	2747

Area/Dose s*mg/l	Peak mg/l for Transit Time (mins)			Peak EC.T over BG EC.T for Transit Time (mins)		
	10	30	60	10	30	60
200	5	2	1	10	3	2
500	13	4	2	26	9	4
1,000	25	8	4	52	17	9
2,000	50	17	8	104	35	17
4,000	100	33	17	208	69	35

NOTES
A) Peak : Average Factor *15*



-Typically we are aiming for a Peak over BG EC.T of 10-30 uS/cm, with at least a sensor resolution of 0.1uS/cm. If 1uS/cm resolution, then larger peak over BG EC.T is needed (larger dose). Larger dose needed for longer transit time. Inject large doses slooooowwwwwllllyyy.

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Peak over BG EC.T

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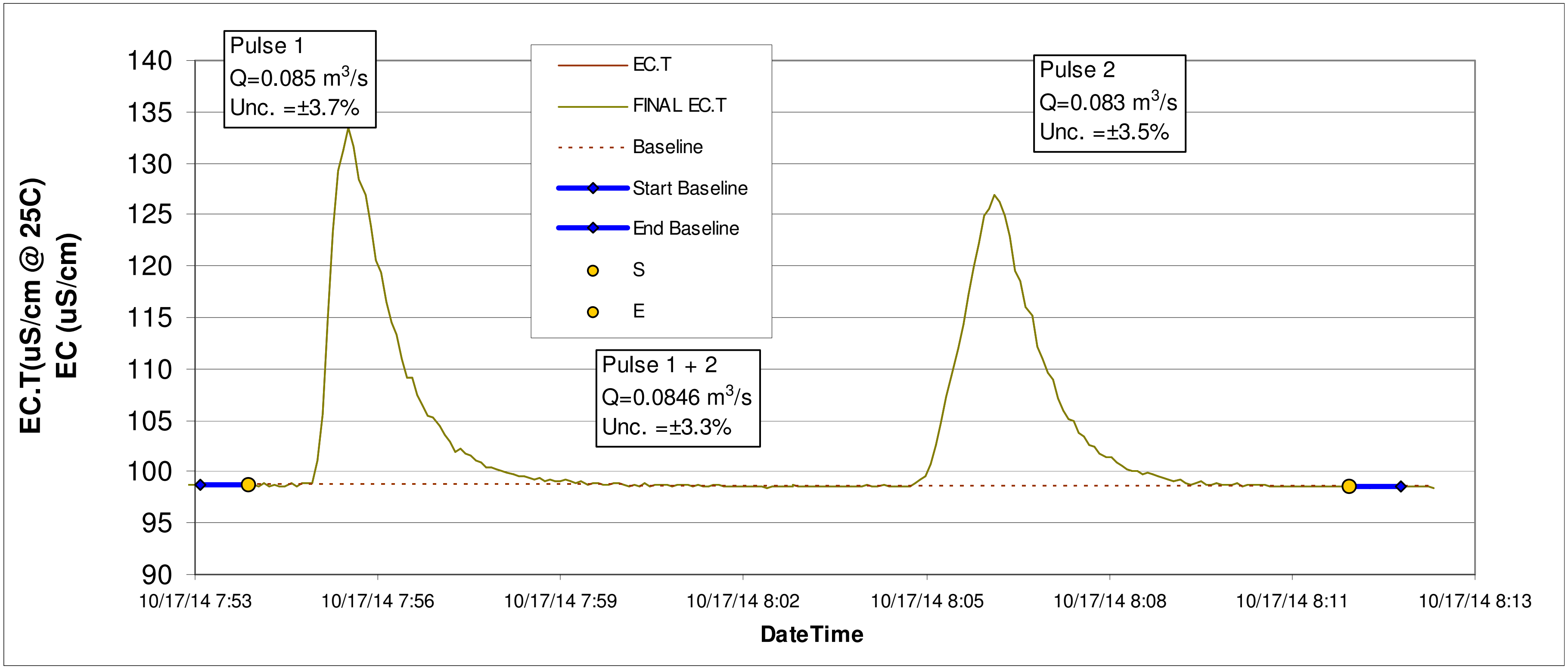

- -Injection rate not important. Better to ensure it doesn't sink to bottom and avoid WQ guideline problems at point of injection. Better to spread injection out.
- -There is no significant difference between Pulse 1 (instantaneous) and Pulse 2 (slowly over 1min) or Pulse 1+Pulse 2 (sum of both masses).

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Duration of Injection not important

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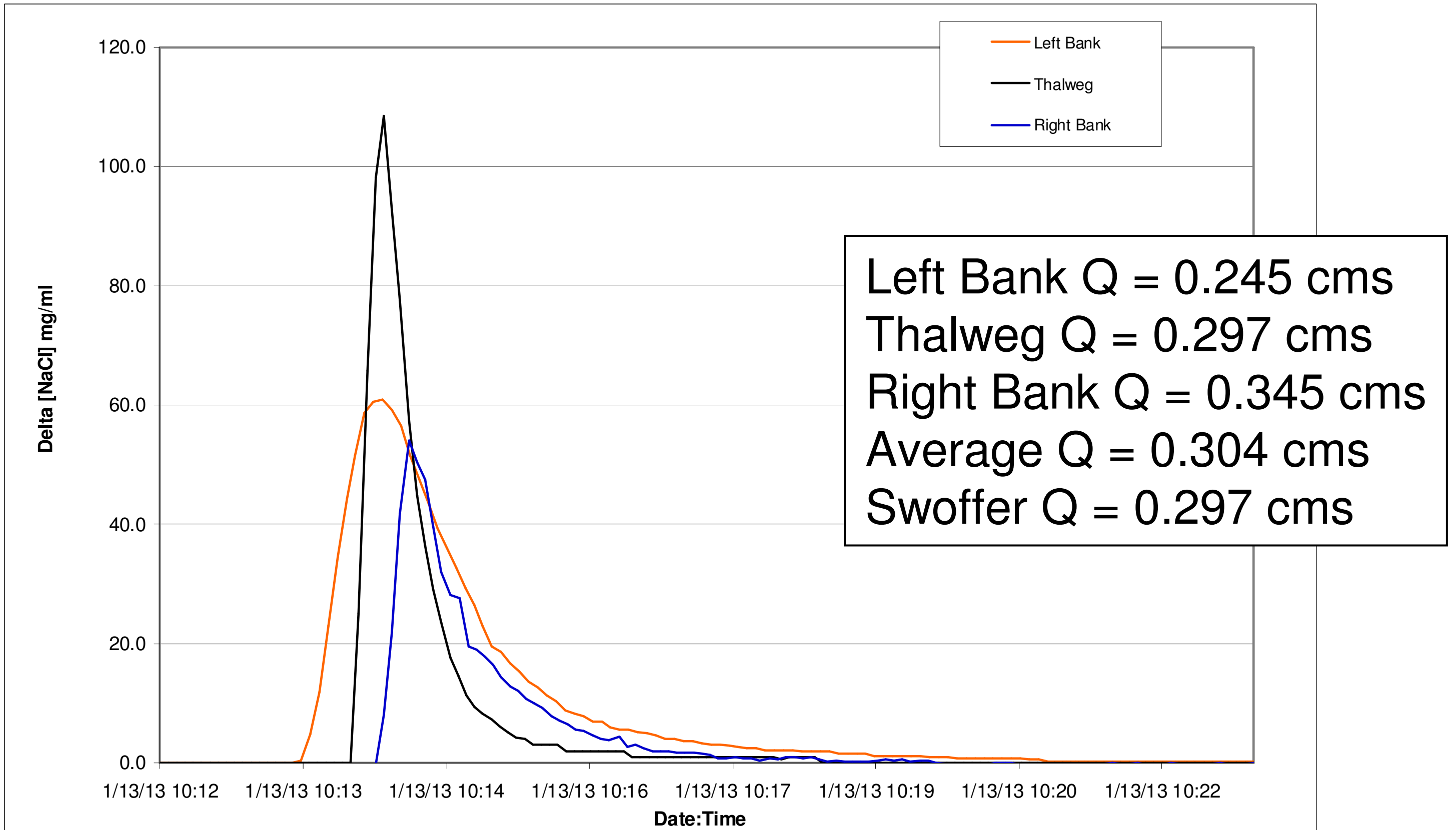

(from Carnation Creek, B.C. Courtesy of Robin Pike, MOE)

- Difficult to quantify missing error. Multiple probes, or injections, can help determine appropriate mixing reach for given Q
- This is a single pulse measured on left and right bank, and thalweg. Standard Deviation ±21%.

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Lowest Fruit: Mixing Error

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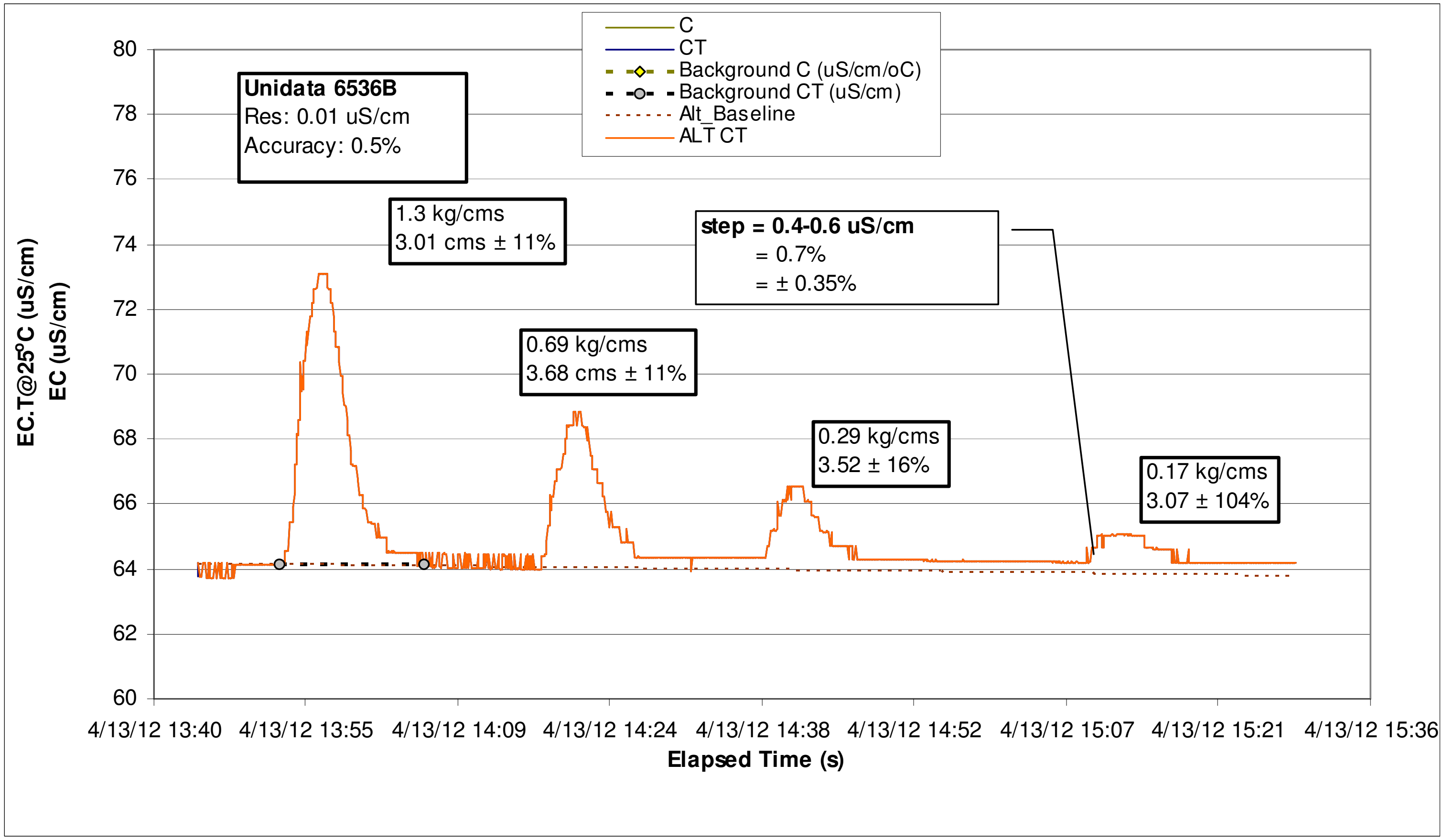
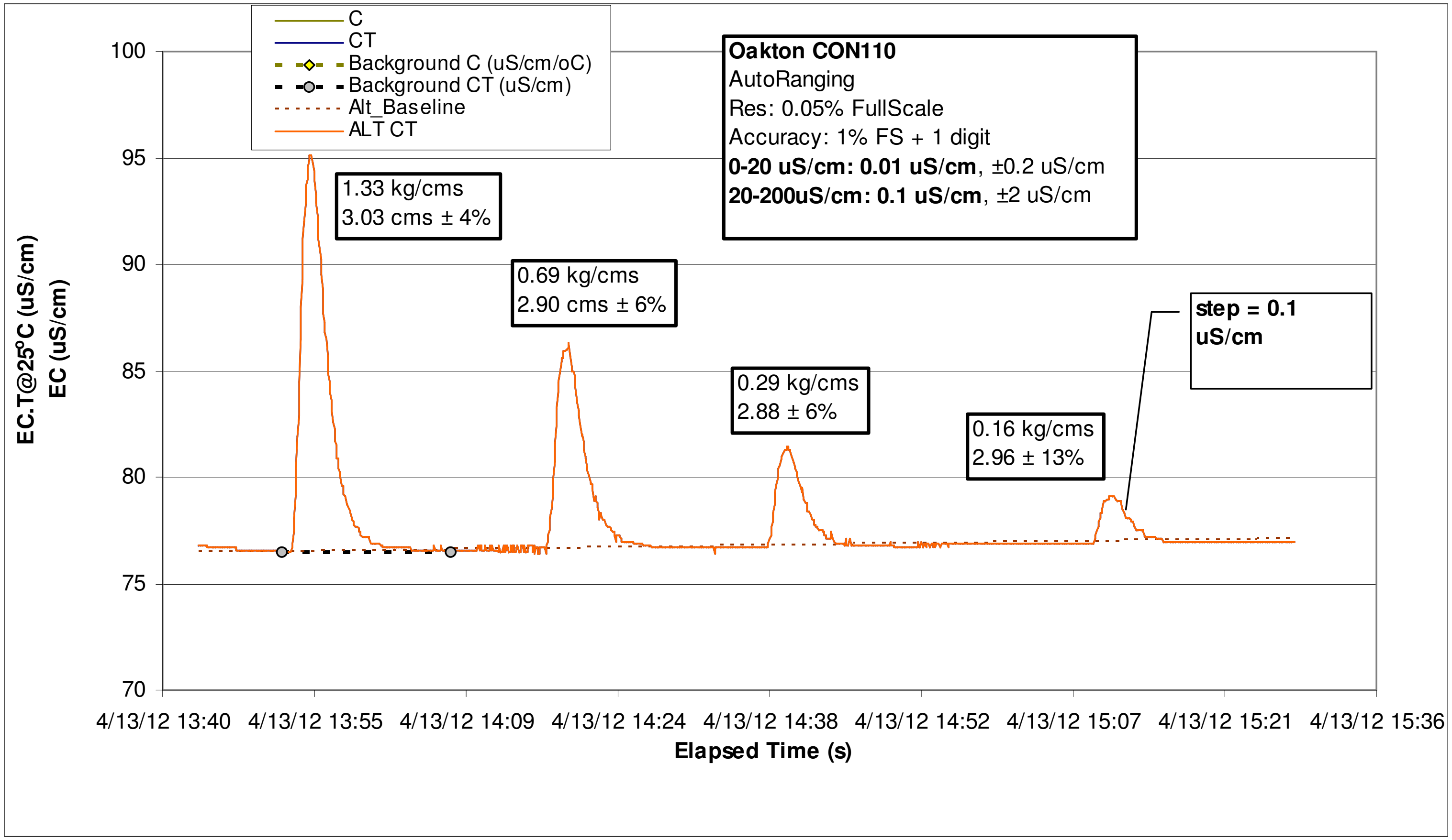
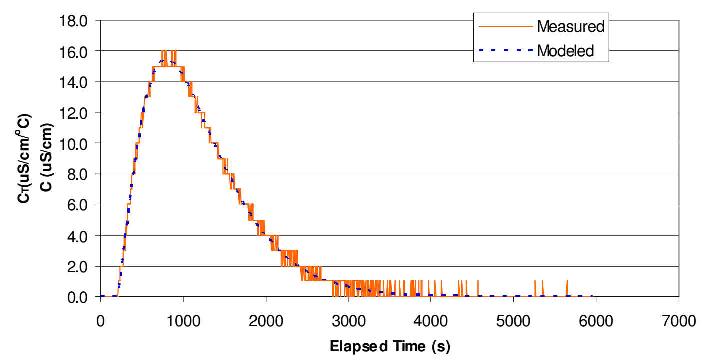


- What is the limit of the instrument?
- This is a Unidata 6536B with resolution of 0.01 uS/cm but accuracy of 0.5% of the reading. We found quanta of 0.4-0.6 uS/cm (+/-0.35%)

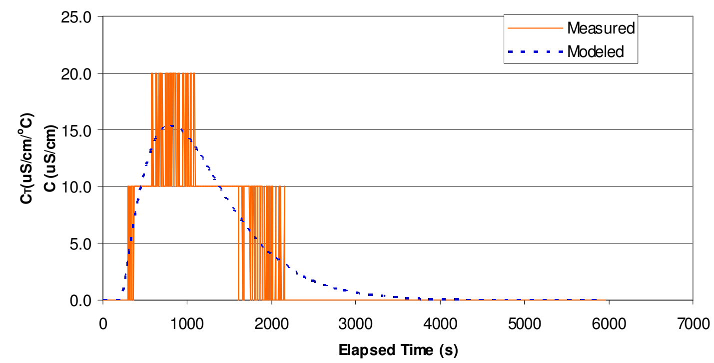


– Oakton Con110 has better accuracy and resolution at lower ranges, higher SNR, therefore less uncertainty in Q.

Noise = 1, Res = 1, SNR≈40, MaxE≈1.5%



Noise = 5, Res = 10, SNR = ~2, MaxE≈15%



Noise < Resolution = Bad

- Difficult to assess true error without knowing Q.
- Built an Instrument Model to model SNR. Random noise and Sensor Resolution. Random noise is not divided between real and sensor. Modeled is simple chi-squared function.
- Noise in SNR includes quantization noise.
- When Noise < Resolution, bias is likely, depending on background EC.T
- Max Error is worst out of 20 simulations (α≈0.05)

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Initial study examined SNR

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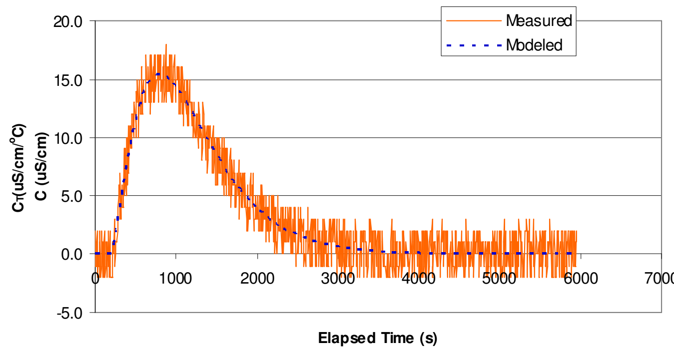
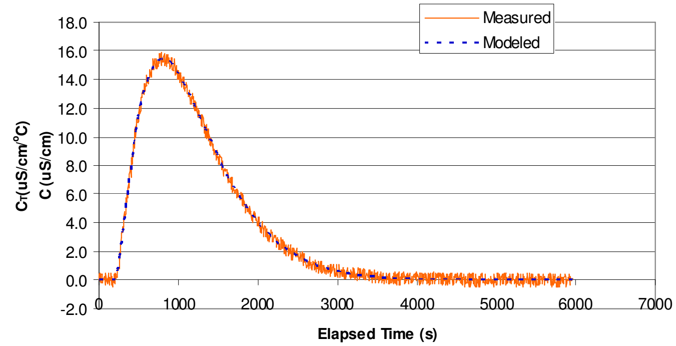
Noise = 5, Res = 1, SNR ≈ 4, MaxE ≈ 13%



Noise > Resolution = Good

Noise = 1, Res = .1, SNR ≈ 90, MaxE ≈ 3%



Noise > Resolution = Good

- Best Instrument for SD is
  - High Resolution and Quanta (0.1 uS/cm or better for EC.T <200uS/cm)
  - Repeatable, Linear, Stable (these are different than accuracy).
  - Absolute calibration not necessary if insitu CF.T derivation carried out for each site.
  - Benefit of absolute calibration is that it gives expected CF.T values for QA/QC.

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Initial study examined SNR

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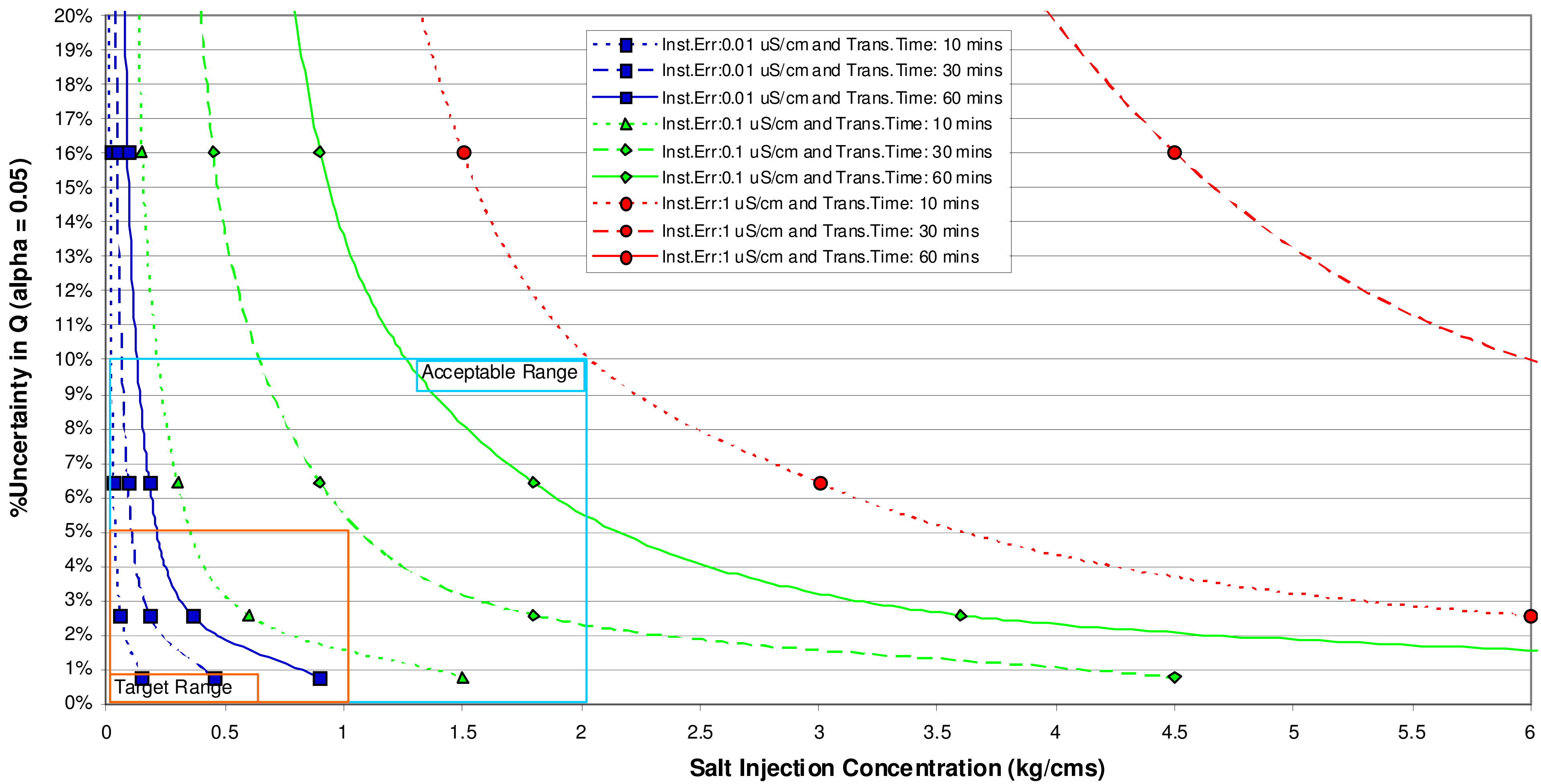

- Reduce the amount of salt required for a given flow/ reduce uncertainty associated with salt dilution measurement.
- Establish SOP to ensure data quality and traceability, quantify uncertainty, and protect sensitive habitat.

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Need for fast, accurate, reproducible method

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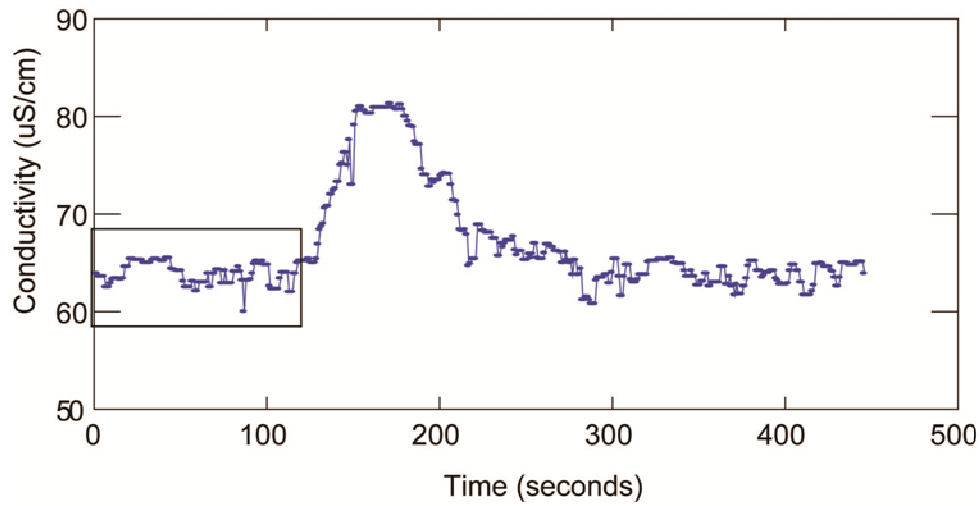
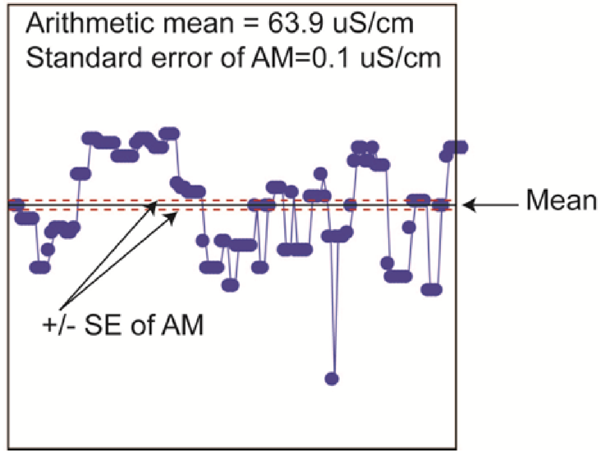
- Determine Standard Error (SE) of mean for pre- and post-.
- Assume SE is representative of signal and background error

$$SE_{BGEC.T} = \frac{s_{BGEC.T}}{\sqrt{n}}$$

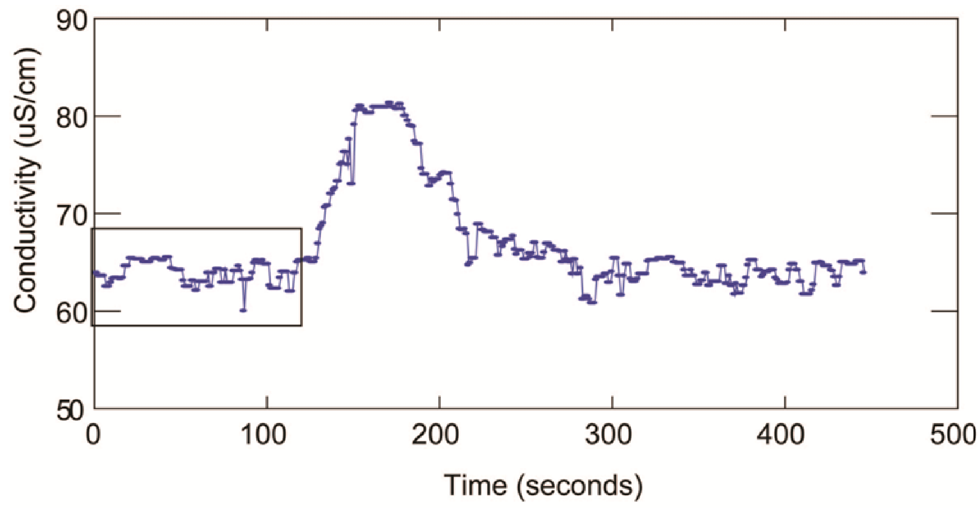
- I generally use 10 points pre and 10 points post. I use SE of entire 20 point sample. This takes into account changing BG or incomplete trace.
- EC.T Unc. is larger of SE and ½ Sensor Resolution

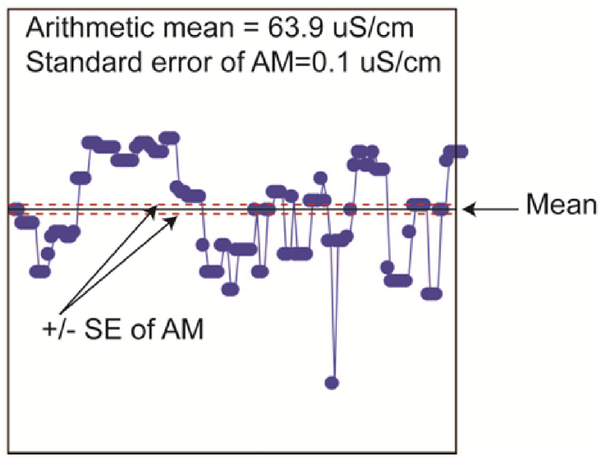
$$EC.TUnc = \max\left(SE_{BGEC.T}, \frac{1}{2}R\right)$$



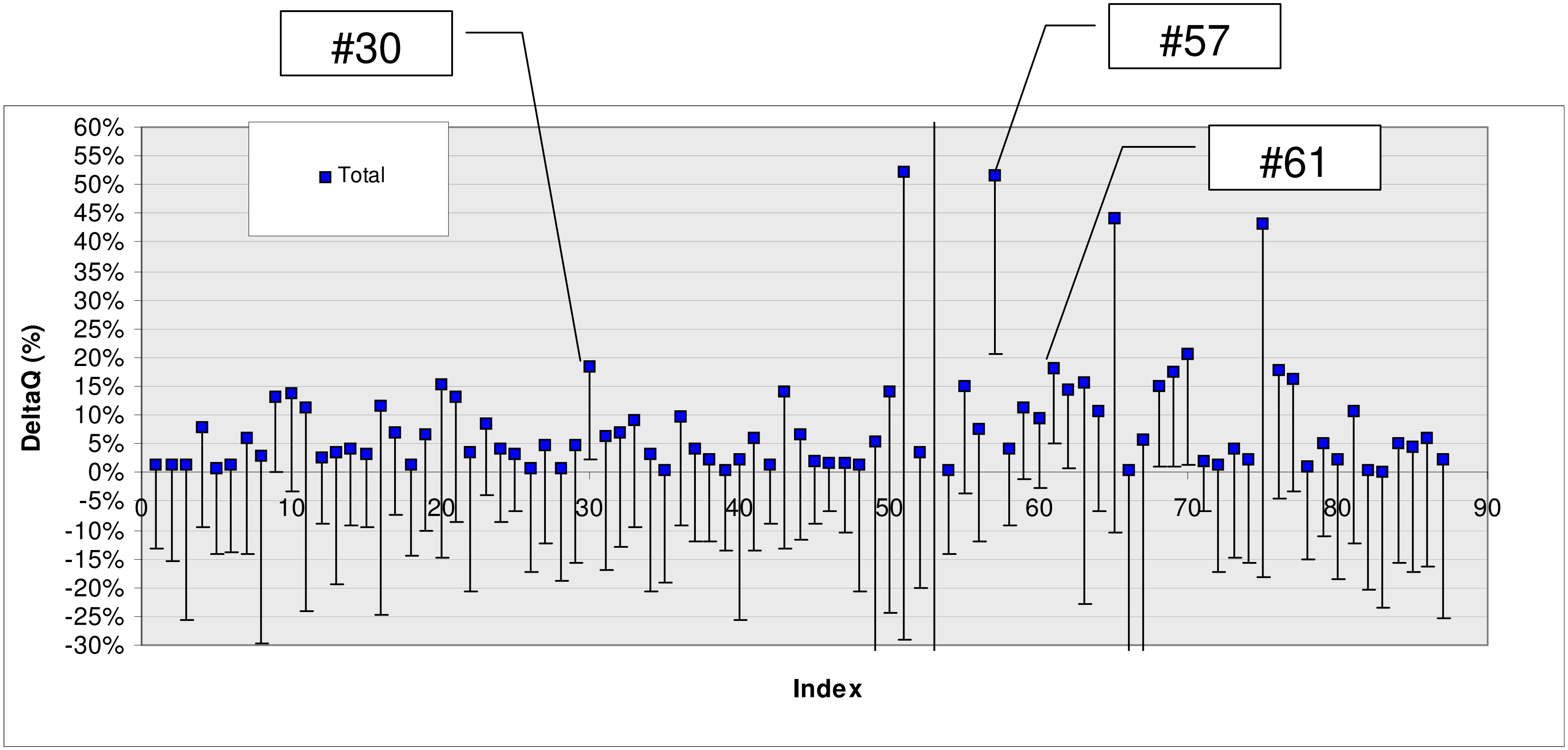


- Noise = EC.TUnc*Trans.Time
- Signal=Area under curve
  =AverageEC.T*Trans.Time
- SNR=AverageEC.T/ECTUnc.
- AreaUnc. = 1/SNR
- Example:
- Area under curve =1228 sec.uS/cm
- Noise = 89.2 sec.uS/cm
- SNR= 1228/89
  =13.8 or 7.3%
  or 14.6% uncertainty at α=0.05
- *In most figures, ± 1σ is reported although most people think of error as ± 2σ.





Uncertainty in Area under Pulse



-This figure shows the result of ~343 recent measurements.

-87 Concurrent measurements.

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Delta Q vs Sqrt(Unc.1^2 + Unc.2^2)

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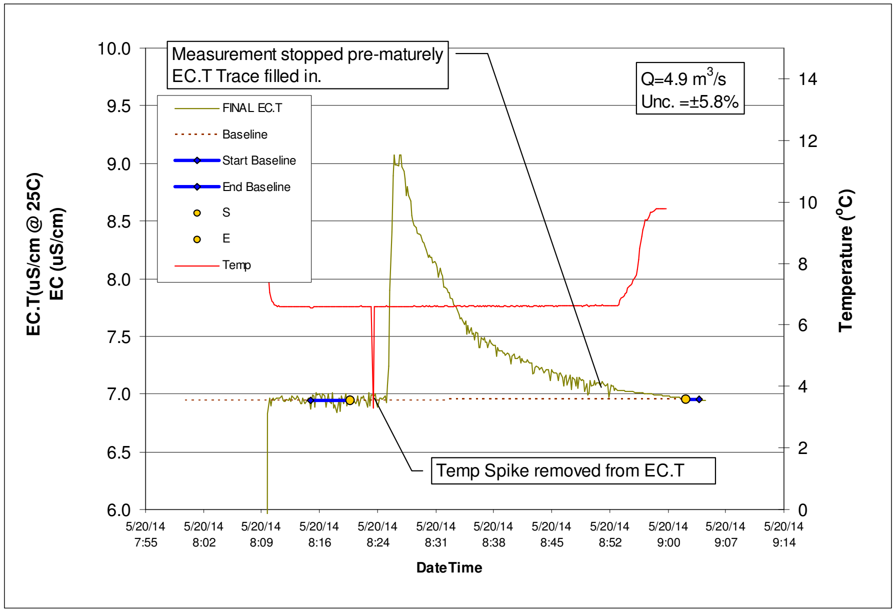

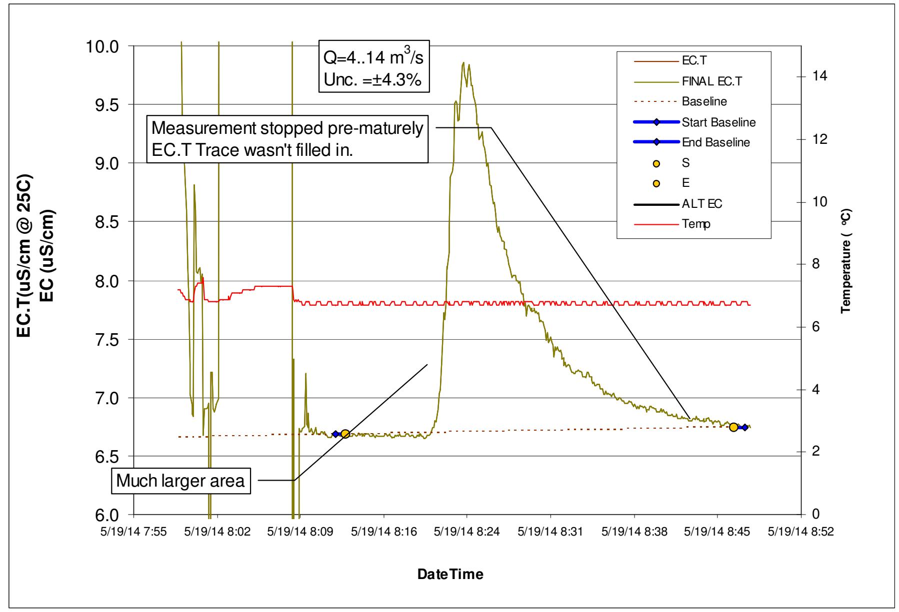

- #30 Mixing length too short.
- DQ = 18.5%
- Indicators: Shape of pulse not smooth.
- DQ is larger than Unc1 + Unc2.
- CM measurement was 3.3 m³/s.

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Discrepancy in #30

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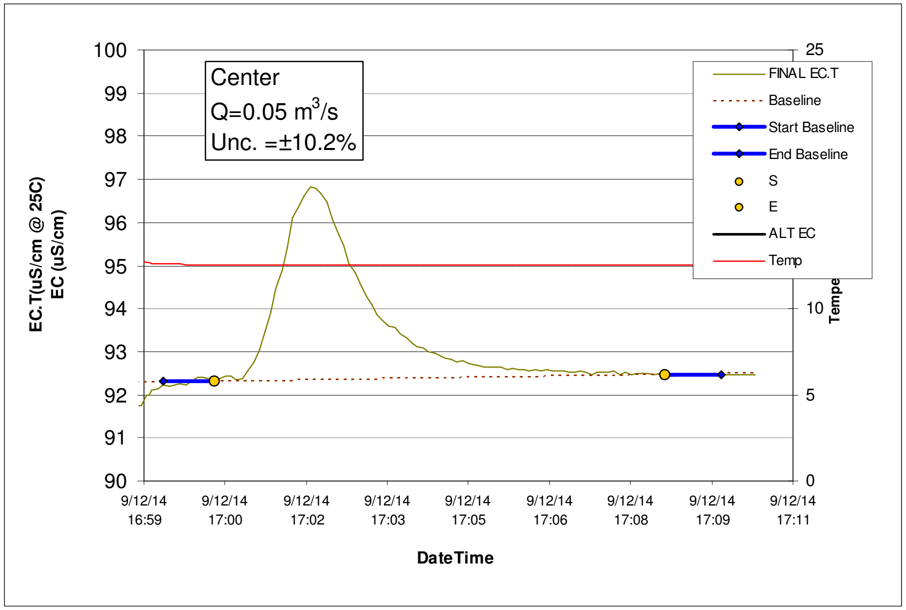

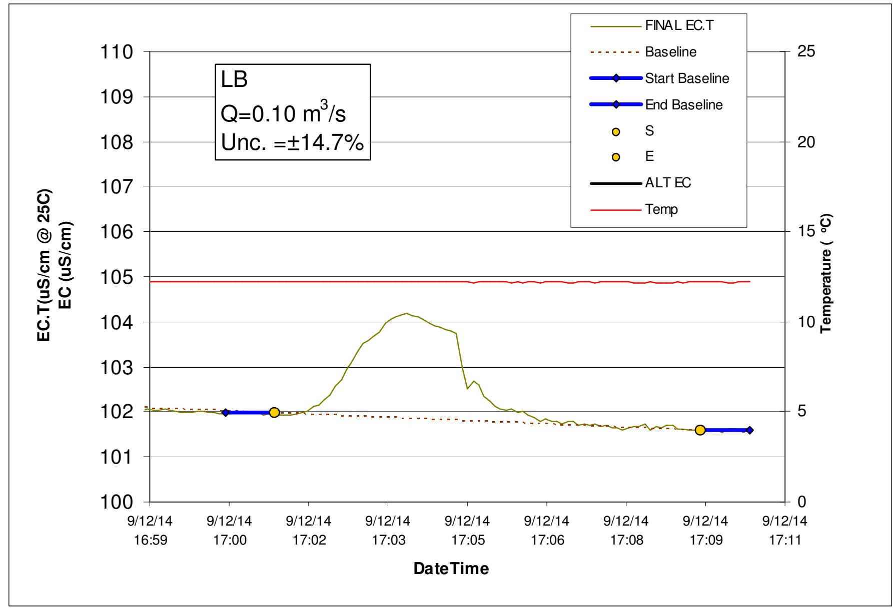

-#57 Mixing length too short.

-DQ = 52%

-Indicators: Shape of LB pulse and

-DQ is larger than Unc1 + Unc2.

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Discrepancy in #57

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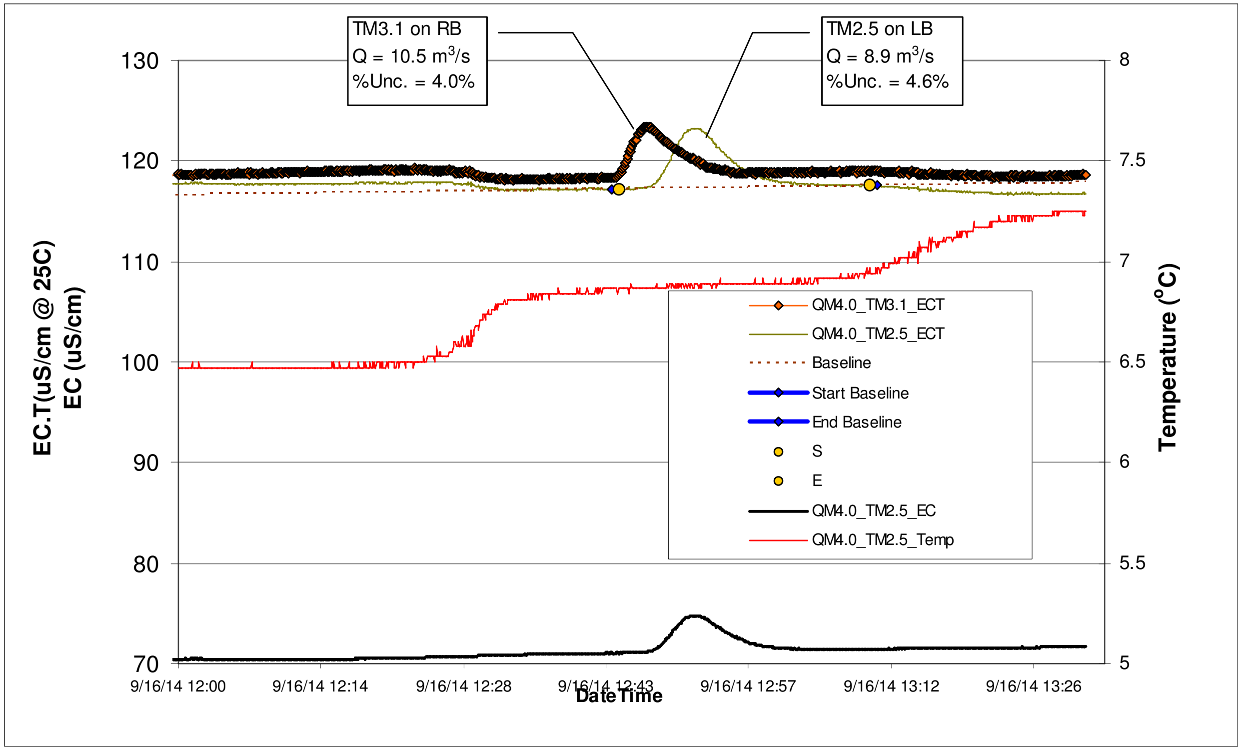

-#61 Large temperature compensation, temperature change, dosage too low.

-DQ = 18%, 1.1 kg/m^3/s.

-Indicators: BG ECT not steady

-CM measurement was 10.2 m^3/s.

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Discrepancy in #61

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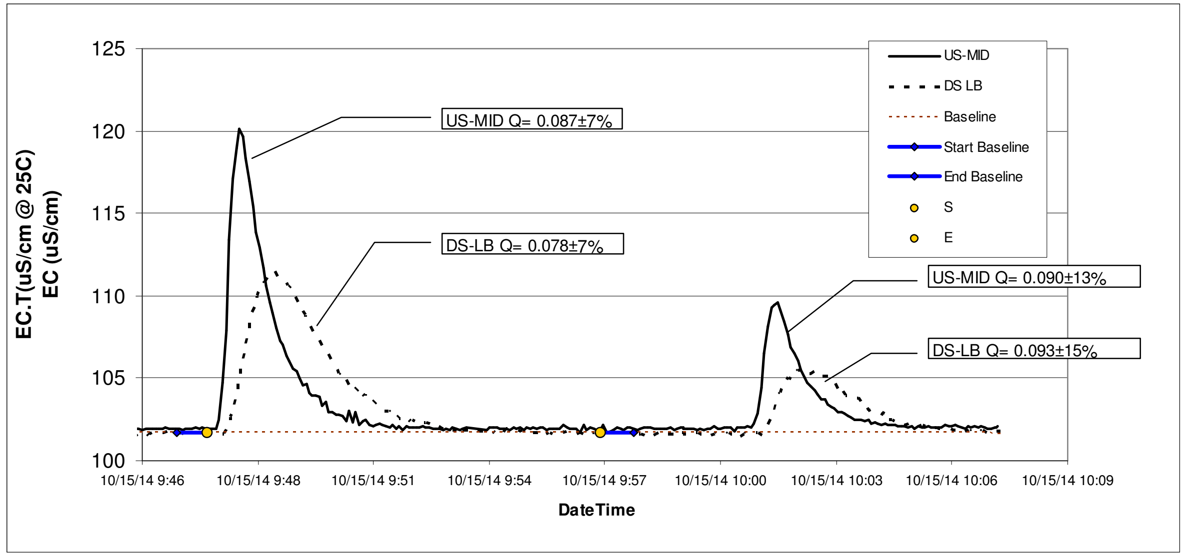

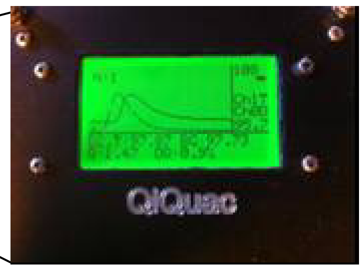

-US-MID higher peak, earlier, but approximately the same area (no significant difference between derived Q at 95% confidence)

-Typical setup with one probe mid-channel upstream, second probe left bank downstream.

-DQ and %Unc. Calculated in realtime to aid in decision making.

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Experimental Setup

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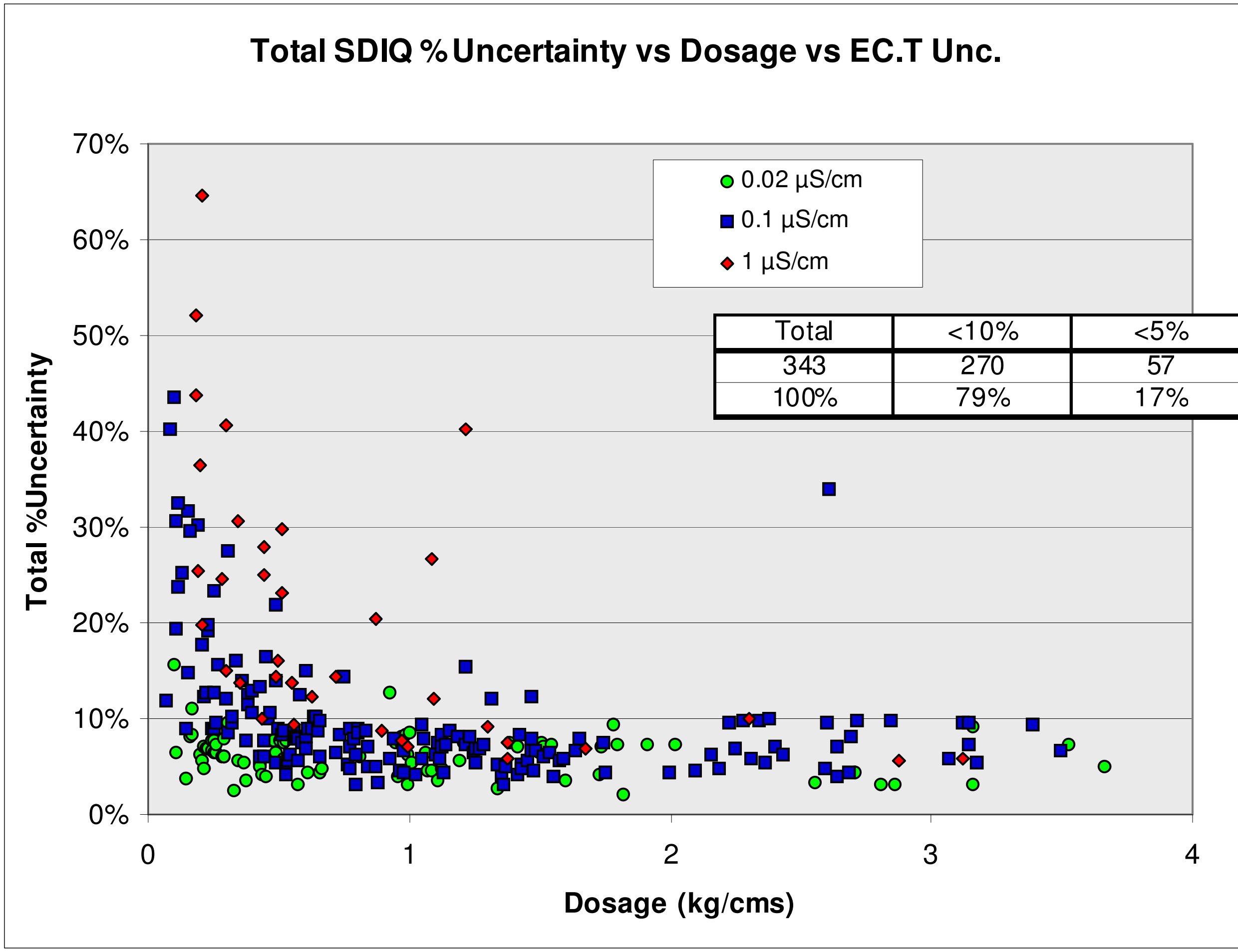

Total	<10%	<5%	<3%
343	270	57	4
100%	79%	17%	1%

-This figure shows the result of 343 recent measurements (2013-2014).

-Lowest Uncertainty when EC.T Unc. is smallest.

-Baseline of ~3% Uncertainty from CF.T and NaCl Mass.

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Total % Uncertainty

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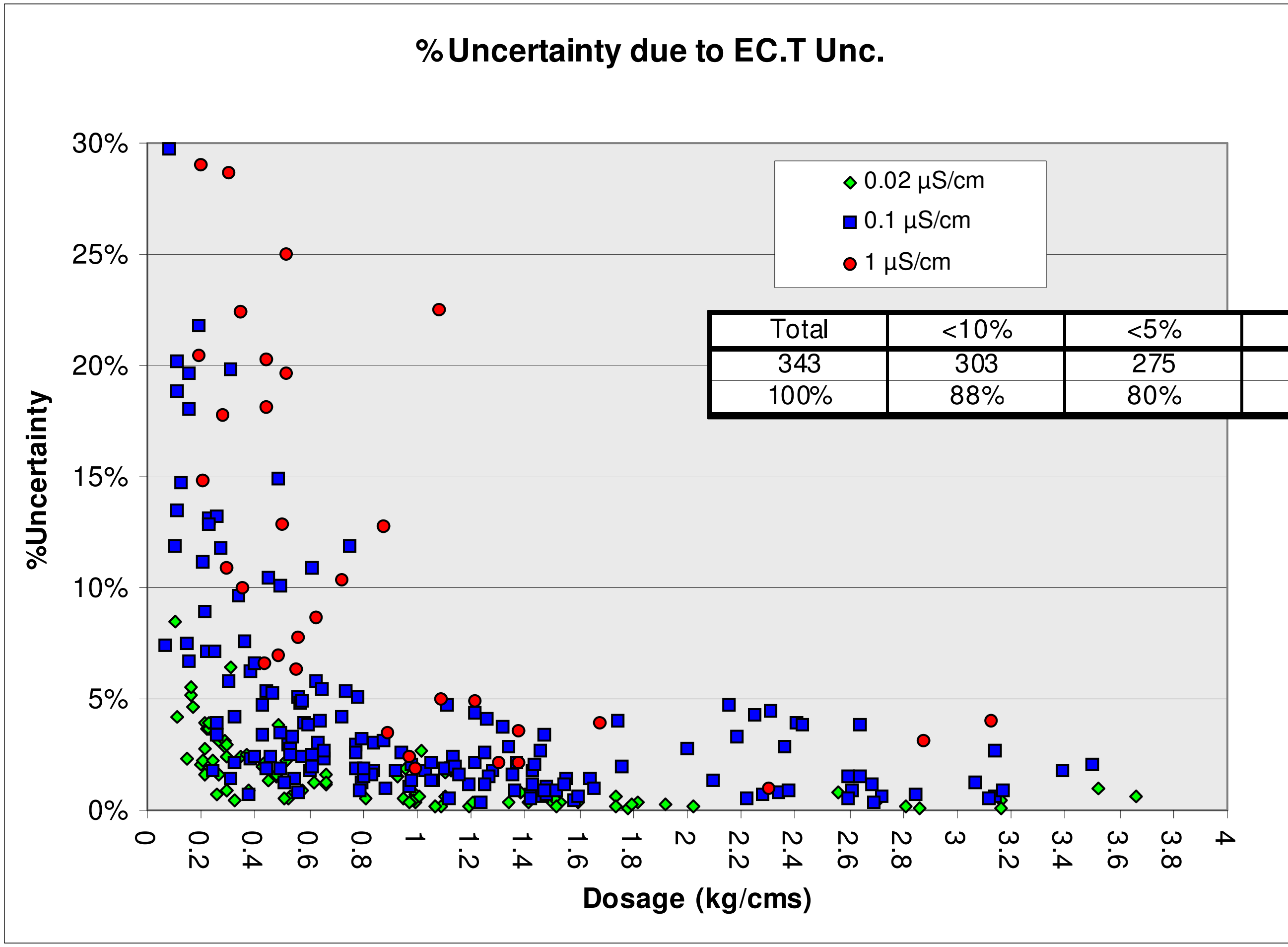
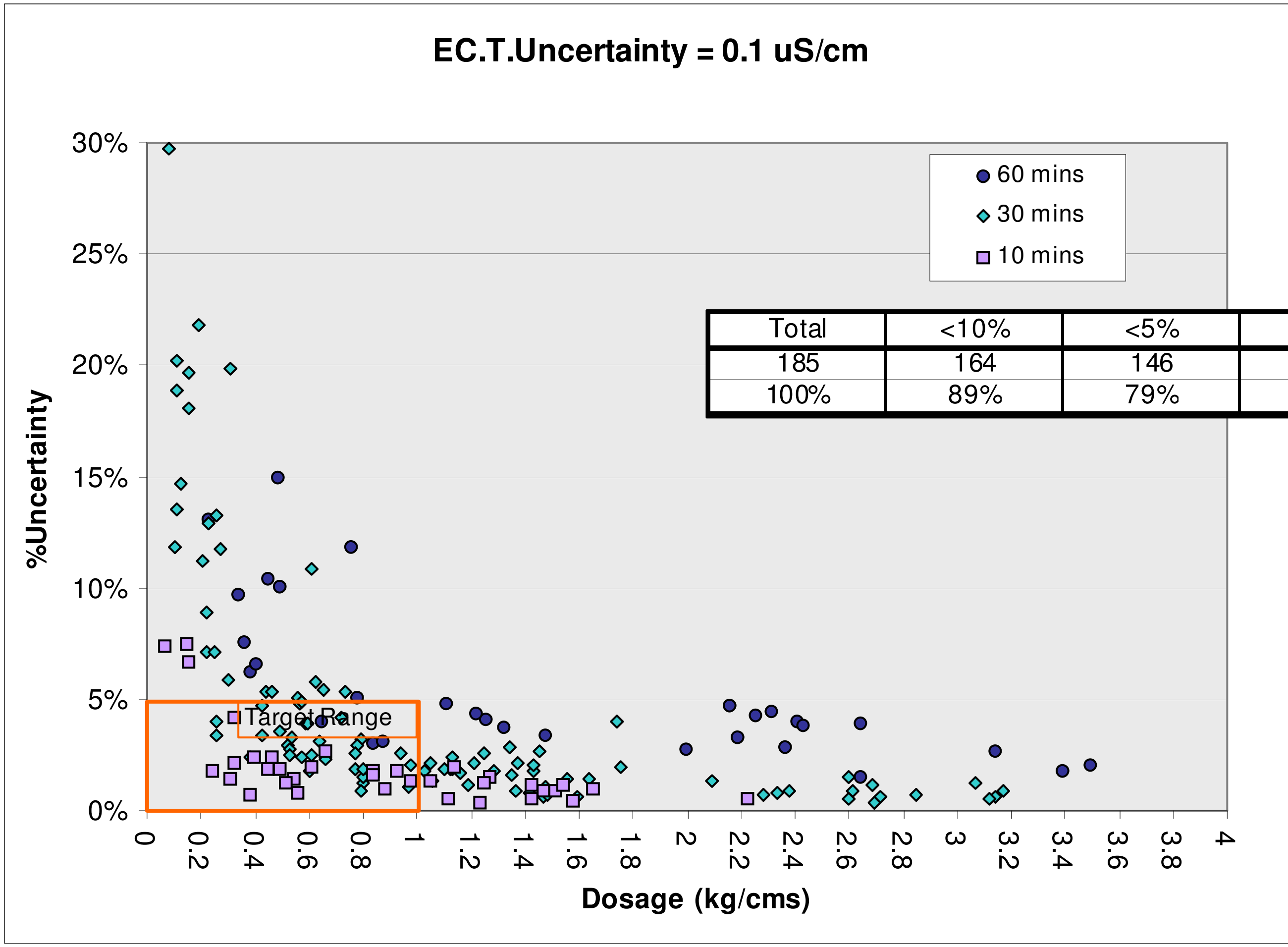


Total	<10%	<5%	<3%
343	303	275	225
100%	88%	80%	66%

-Remove Unc. Due to CF.T and Mass.

-Unc. Due to SNR steady at 5% until ~0.7 kg/cms

% Uncertainty due to EC.T Unc.



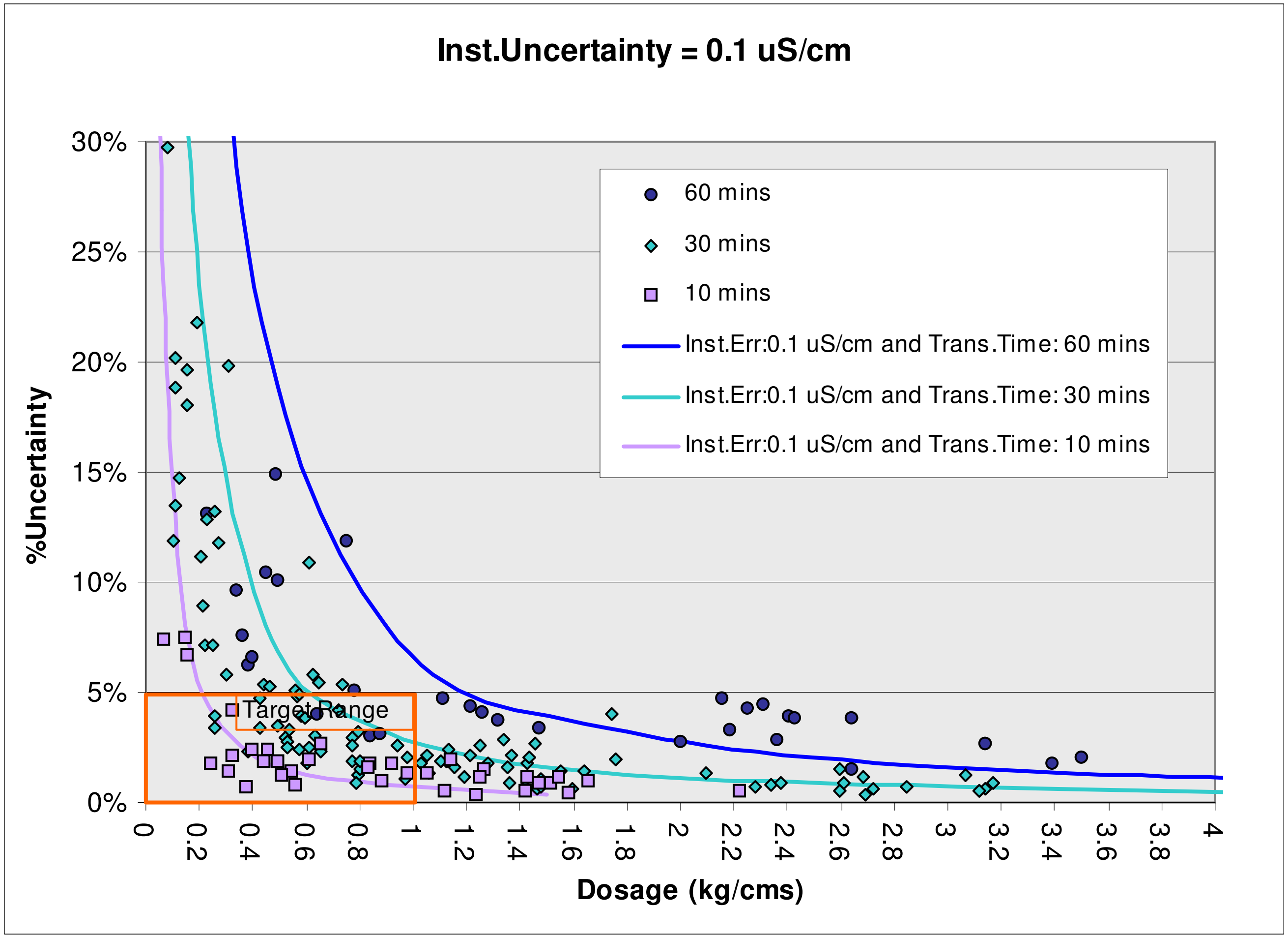
Total	<10%	<5%	<3%
185	164	146	115
100%	89%	79%	62%

-We can further explain variance by transit time of pulse.

-The faster the transit time, assuming completely mixed, the lower the uncertainty.

-0.1 µS/cm typical of many commercial sensors for EC.T < 200 µS/cm.

% Uncertainty due to EC.T Unc.:0.1µS/cm



I compared to my 2012 estimates of Uncertainty (x0.5 to get 1σ). Good agreement with 0.1 μS/cm above 1 kg/cms, but overestimated for less than 1 kg/cms.

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% Uncertainty due to EC.T Unc.:0.1μS/cm

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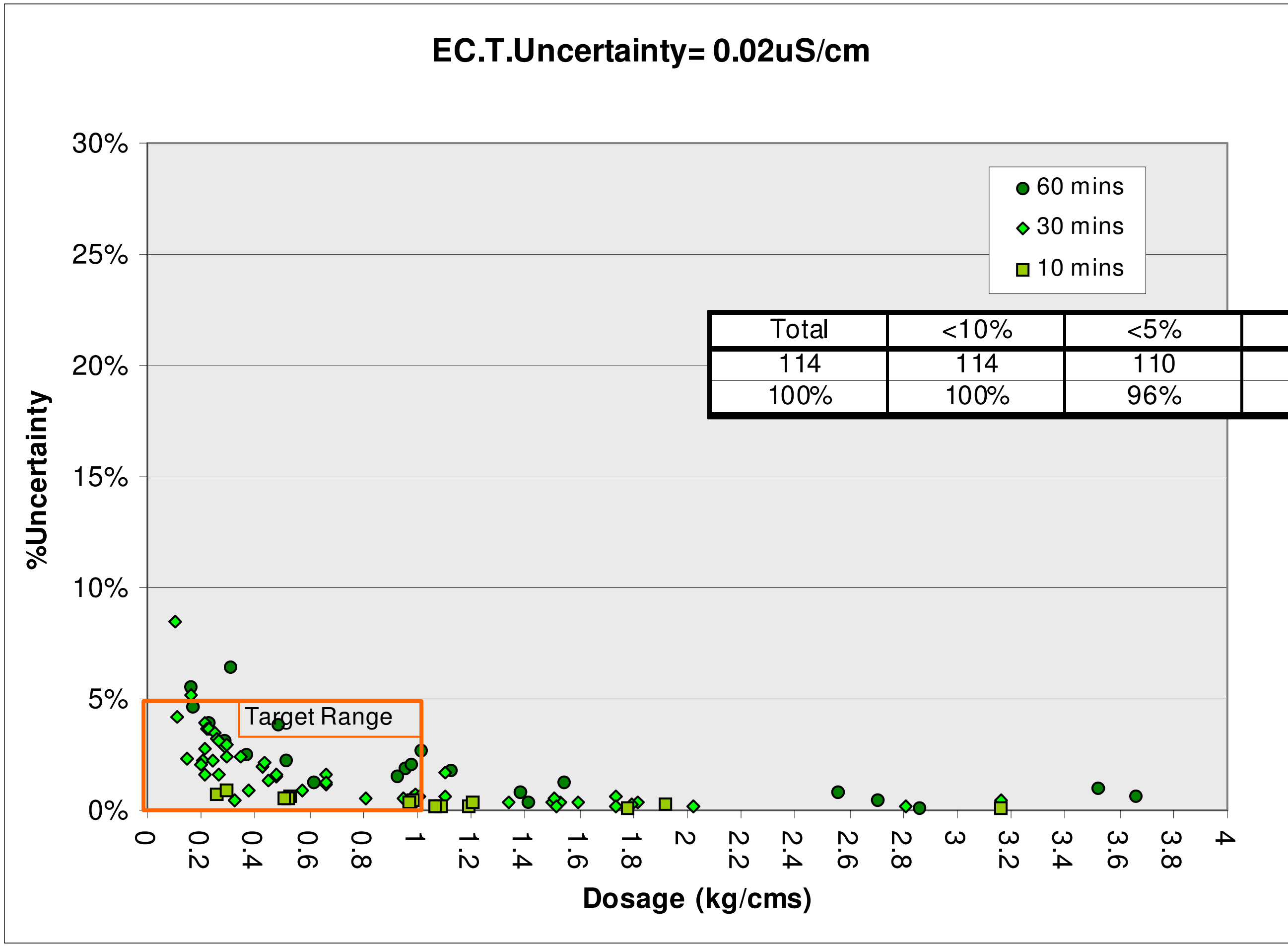

Total	<10%	<5%	<3%
114	114	110	99
100%	100%	96%	87%

-If we can attain EC.T Unc. of 0.02 µS/cm (requires finer than 0.02 µS/cm resolution), then we can reduce the dose to 0.2 kg/cms and remain below 5% Uncertainty.

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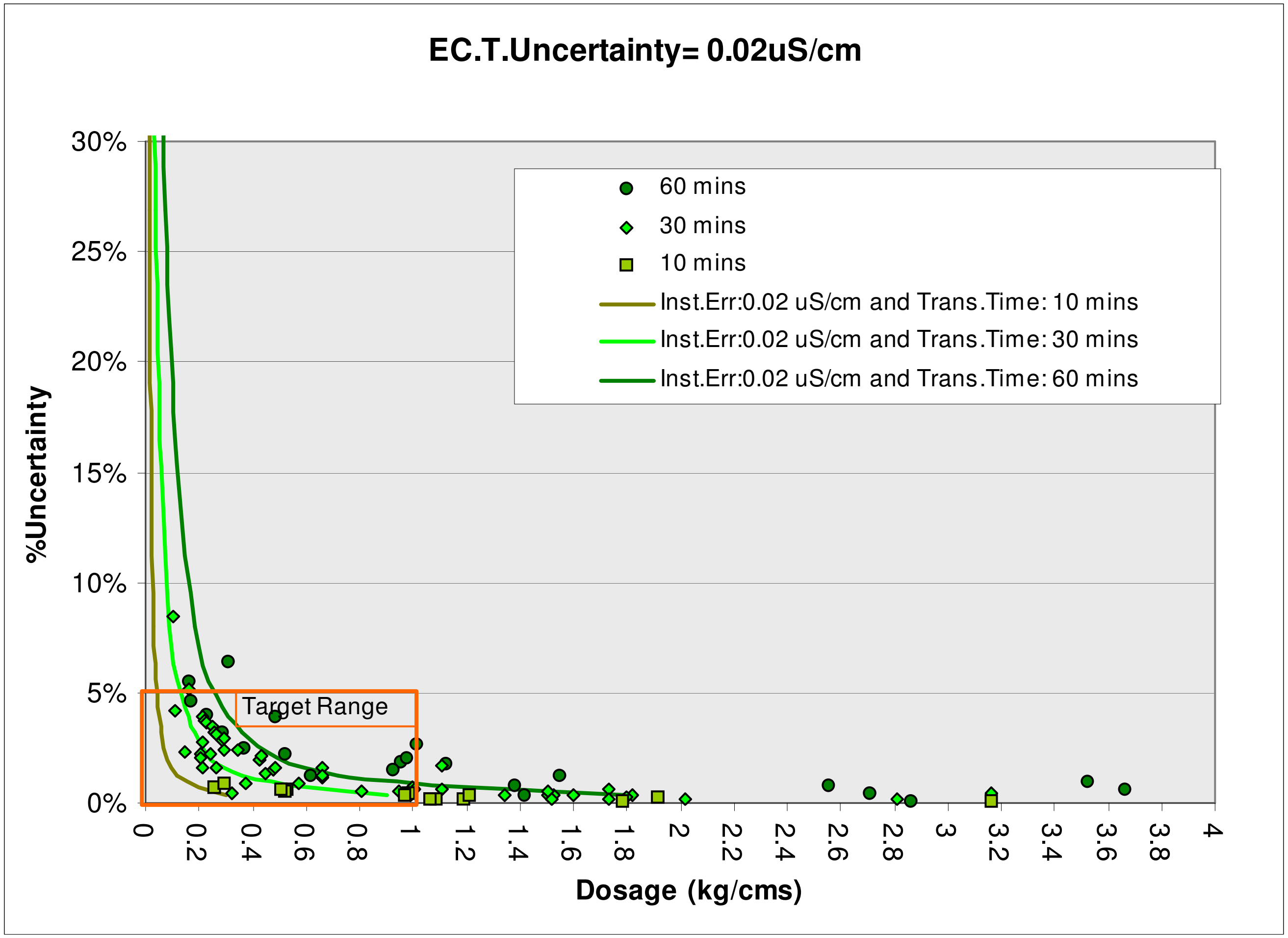
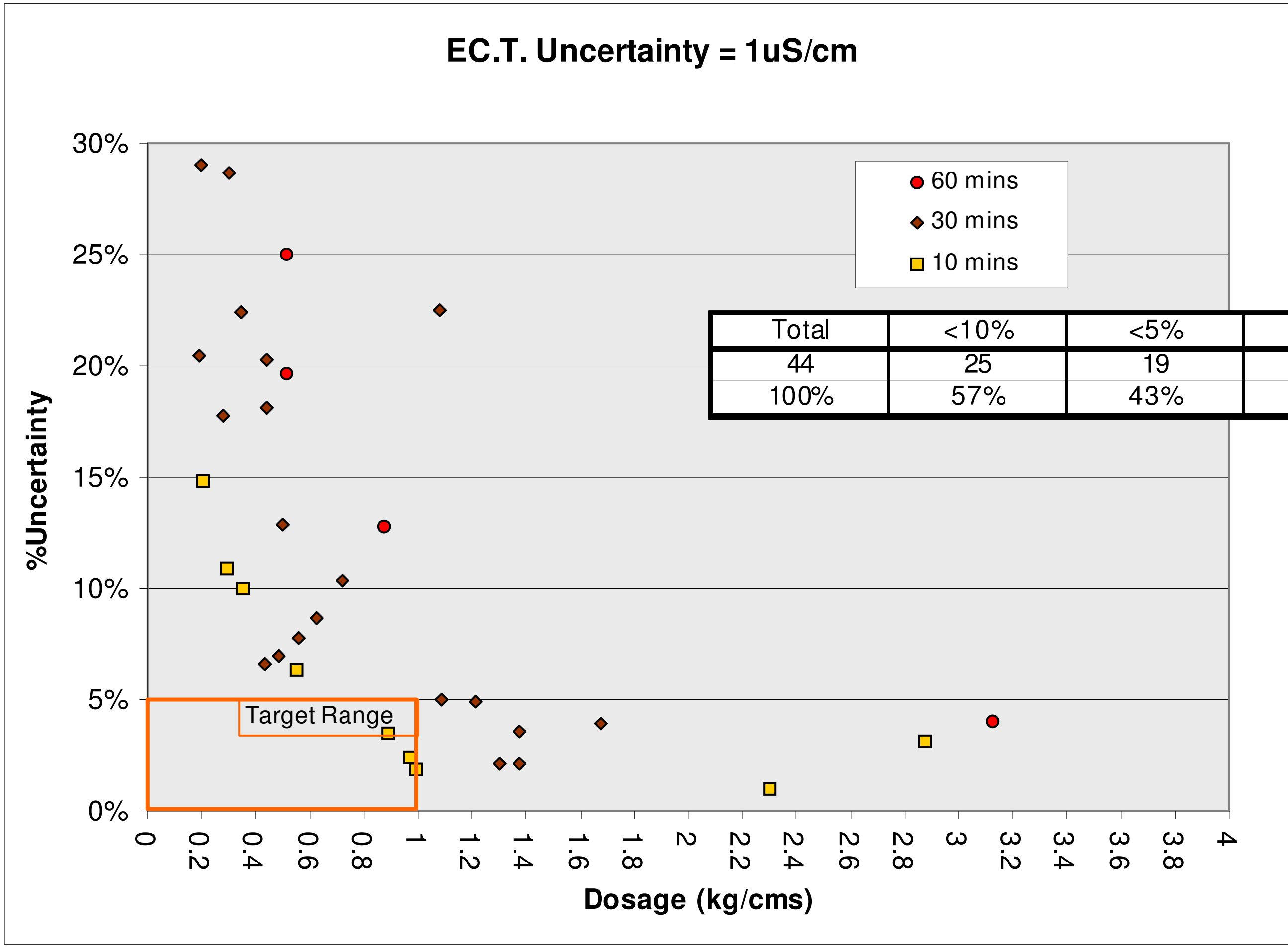


- Good agreement with 0.02 μS/cm.
- Used 0.02 μS/cm because Inst.Res 0.01 μS/cm but still shows noise, partly due to temperature.

AQUARIUS Research & Development Inc. UBC % Uncertainty due to EC.T Unc.: 0.02 μS/cm nhc northwest hydraulic consultants



Total	<10%	<5%	<3%
44	25	19	11
100%	57%	43%	25%

-EC.T Unc. Ceiling 1 μS/cm or greater. Combined sensor resolution, background noise, and return to background EC.T.

-Only two measurements in target range.

-Possible to get high quality measurement, but requires larger dose.

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% Uncertainty due to EC.T Unc.: 1μS/cm

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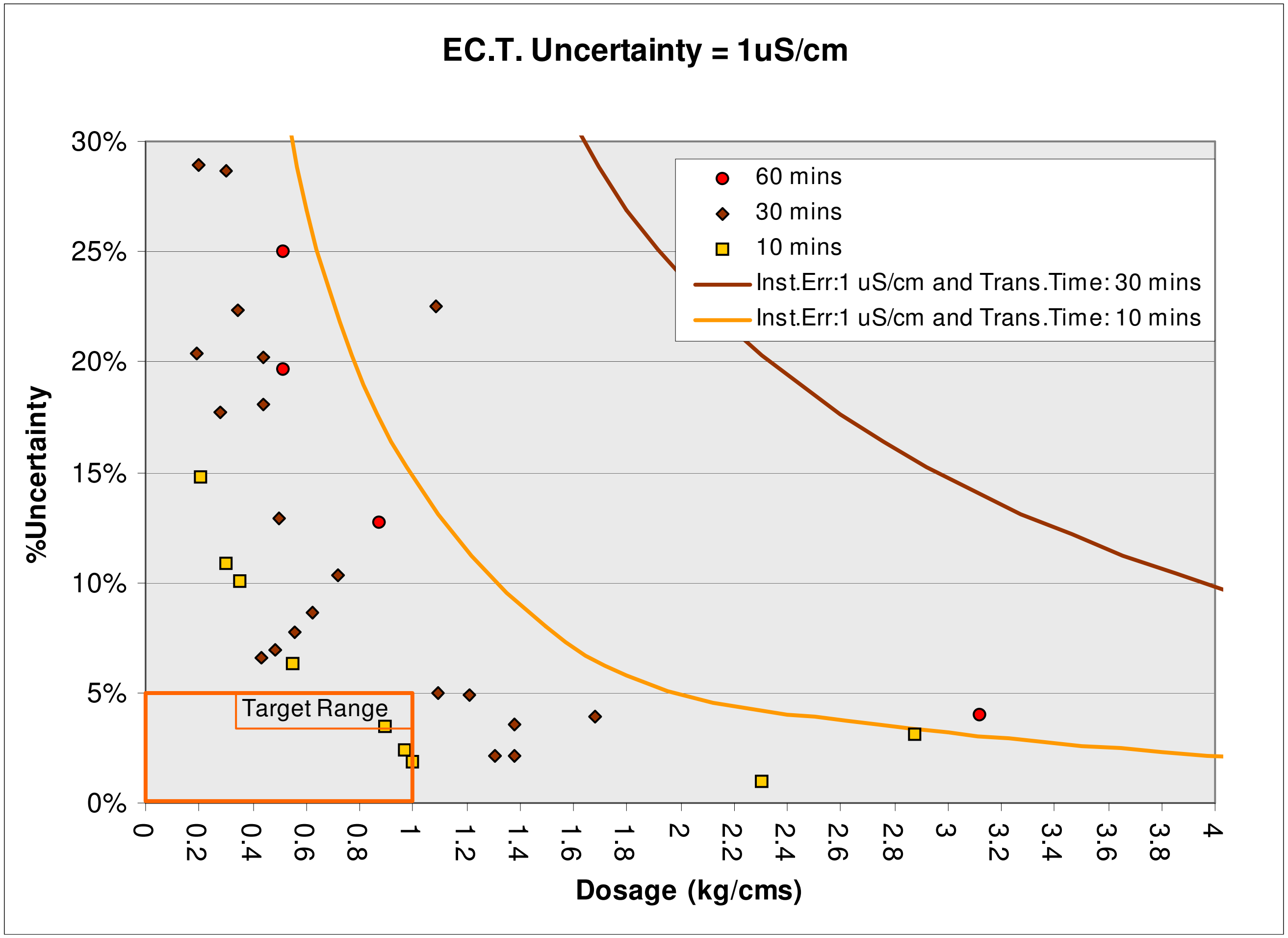

- Unc. Overestimated for EC.T Unc. = 1 us/cm. Not sure why yet

% Uncertainty due to EC.T Unc.: 1μS/cm

C:\Users\gsentlin\AQUARIUS_R&D\BUSINESS\Research&Development\Conferences\AWRA_Virginia\CF.T Calcs\[Raffuse_SD-CM_Apr 13 2012_InstrumentNoise Model_v0.9.xls]SNR_%Error 10/31/14

Dose (kg/cms) Required for 5% Uncertainty at 95%				Dose (kg/cms) Required for 10% Uncertainty at 95%			
(2.5% SE)	Transit Time (mins)			**(5.0% SE)**	Transit Time (mins)		
EC.T Unc. (μS/cm)	10	30	60	EC.T Unc. (μS/cm)	10	30	60
0.01	0.04	0.11	0.21	0.01	0.02	0.06	0.13
0.02	0.07	0.21	0.42	0.02	0.04	0.13	0.25
0.1	0.35	**1.1**	2.1	0.1	0.2	**0.6**	1.3
1	*1.2*	*2*	*5*	1	*0.8*	*1.2*	*6*

NOTES

A) EC.T Unc. Is the total uncertainty in the measurement due to Instrument Resolution, BG Noise, drifting background (due to temperature or EC).

B) Dose estimates from the EC.T Unc. = 1 uS/cm are estimated visually from scatter plots.

VER 0.6

- The relationship shown in previous figures is tabulated here for two data classes. NaCl dose depends on EC.T Unc. and transit time.
- Most common EC.T Unc. and transit time (0.1 uS/cm and 30 mins) requires 1.1 kg/cms to attain ±5% at 95%confidence.
- Shorter transit time or lower EC.T Unc. results in lower dose required.
- Rule of Thumb:
  - 10x the EC.T Unc. at 30 mins. Except at 1uS/cm use 2kg/cms.
  - Half the dose for 10 mins, double for 60 mins.
- Best Practice: Pre-dissolve or inject slowly (>30 second).

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Recommendations

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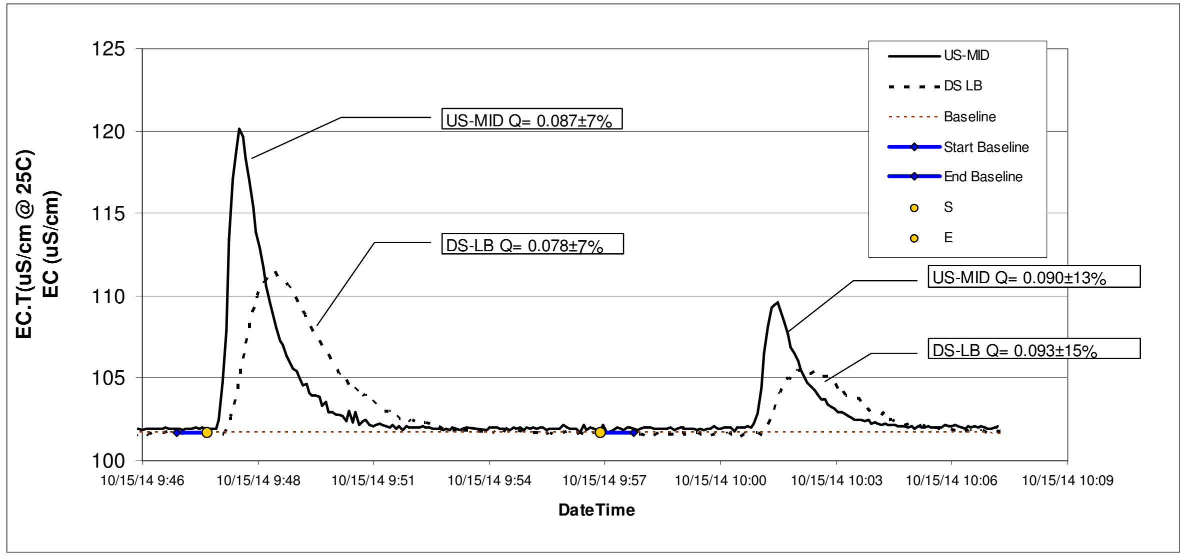

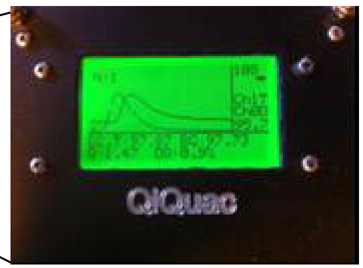

Thank you

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Dan Moore, UBC

Questions?

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