Air Quality Monitoring and Sensor Technologies

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Key Take Home Training Topics

- Features of continuous monitoring study designs
- An examination of use of continuous monitors and their application
- Examples of continuous monitors, especially low cost sensors
- Data quality features one must consider
- Resources available to you on sensor selection
- Monitoring decision making

Your Instructor-Ron Williams

- 35 year veteran of academic, private institution, and government-based environmental or associated research programs
- Currently, the Project Lead for EPA-ORD's Air, Climate, and Energy's Emerging Technology research area
- Has designed and executed studies involving the collection in excess of 10K participant days of environmental measures involving both continuous and time integrated monitoring (personal, indoor, outdoor, ambient)
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Disclaimer

- Mention of trade names or commercial products does not constitute endorsement or recommendation for use and are provided here solely for informational purposes

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Be Careful of What You Ask For....

Anyone who has ever conducted extensive continuous monitoring and then had to deal with making sense out of it

Value of Continuous Measures

- Provides greater understanding of time and location changes of environmental conditions
- Has the potential of defining critical episodic events that would otherwise not be discovered
- Helps to define the validity of the data measurement itself
- Needed anytime a mobile measurement is required

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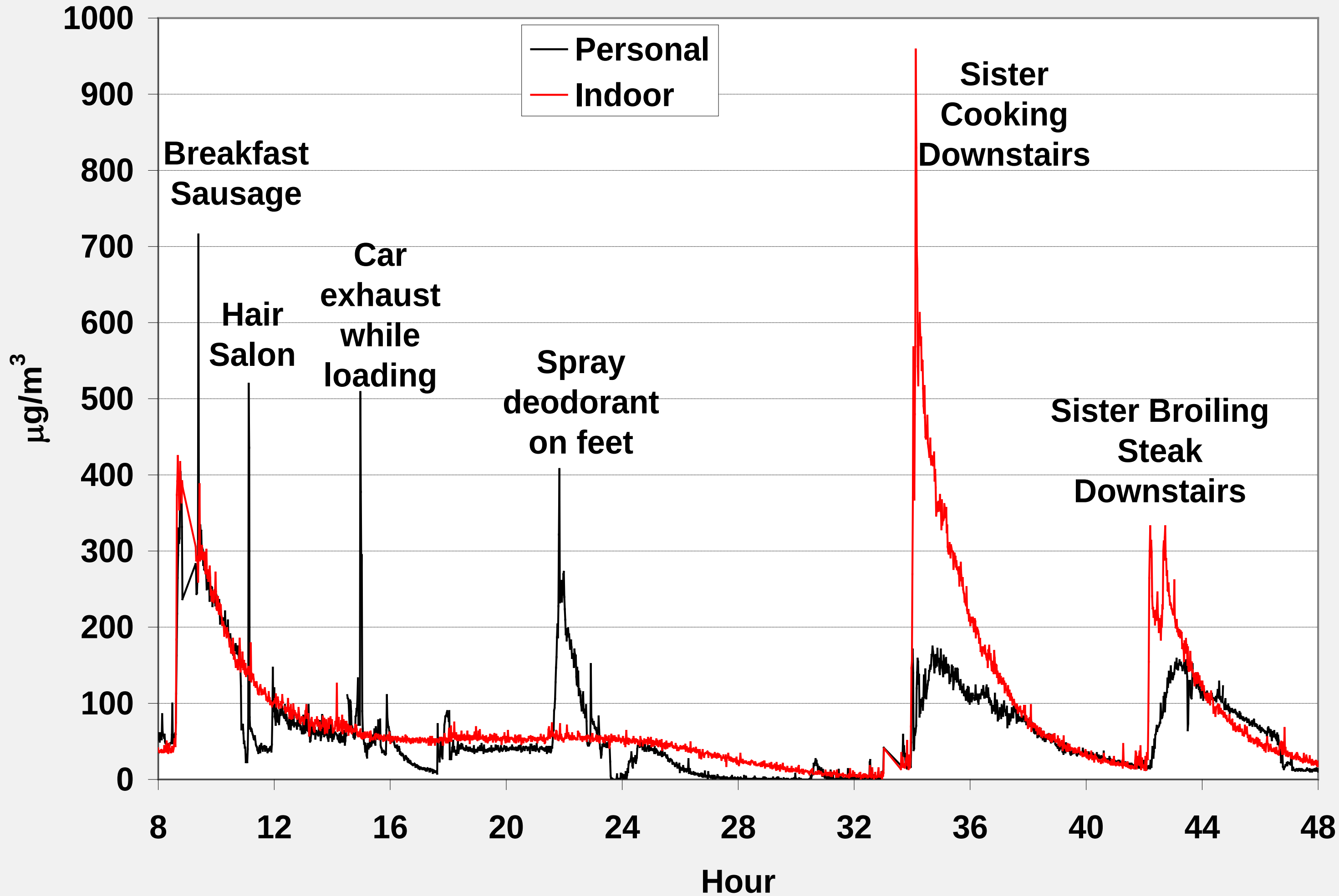
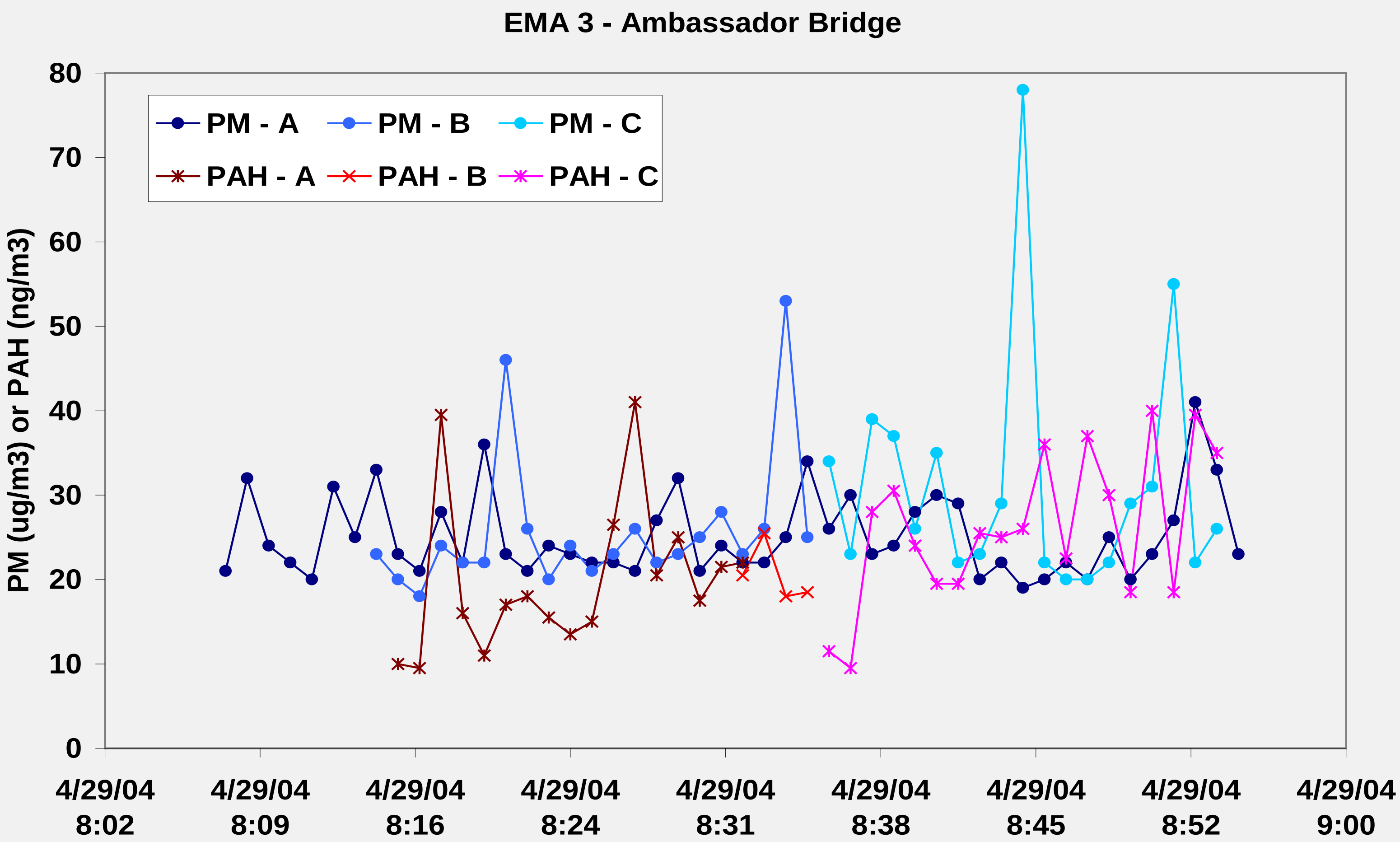
Continuous $PM_{2.5}$ Monitoring

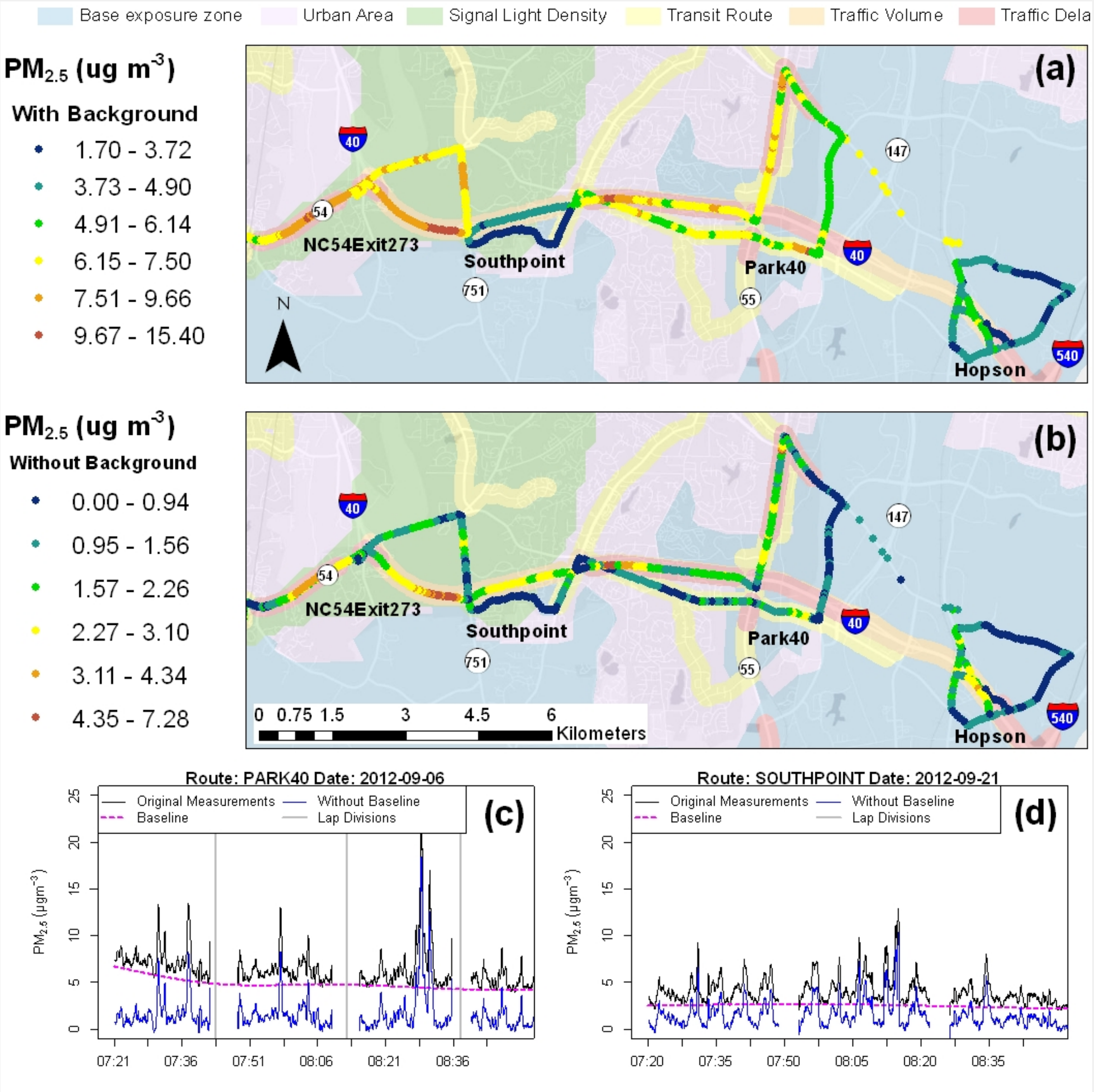


Indoor versus Personal $PM_{2.5}$ Concentrations

Changing Conditions and Site Comparisons



Continuous Mobile Monitoring



Brantley et al., AMT 2014

Key Negative Considerations

- The amount of data being produced can become staggering. As an example:
  - A single monitor operating 24 hrs/day @ 1 second time resolution for 1 week would produce >600K one second data points!
- Need for more sophisticated data recovery and manipulation software. Excel normally does not meet this need. Often earth mapping software is required to make sense of the data (visual representation)
- Monitors are not without bias and noise. Some pre-determined plan should exist for reducing this effect (either during or following data collections). The basic bias and noise features of the monitor should be known before sampling is initiated

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Examination of Continuous Monitoring Applications

A Typical Regulatory Monitor

- Produces data of known value and highly reliable
- Stationary- cannot be easily relocated
- Instruments are often large and require a building to support their operation
- Expensive to purchase and operate (typically > $20K each)
- Requires frequent visits by highly trained staff to check on their operation
- Often operate for 10+ years before needing to be replaced

A Typical Low Cost Monitor

- Inexpensive ($100 to $5000) to purchase
- Highly portable and easy to operate (often mobile)
- Requires little or no training to start collecting data
- Inexpensive to operate (replace or recharge batteries)
- Lifetime of service not expected to exceed 1-2 years

Metal Oxide (MOS), Electrochemical and Light Scattering Sensors

- The most widely available of all sensor types
- Inexpensive ($15-$300)
- Available in a wide array of pollutants
- Often not specific to any one pollutant
- Co-factors often influence their output
- Response relational to some given parameter

- Light scattering sensors dominate market
- Cost varies ($50-6000)
- Sensitive to RH and stray light
- Size definition varies widely
- Unit output definition varies widely
- Aerosol composition influences response
- Not true mass measurement

Photo credit: http://www.alpha-sense.com/

Typical Pollutants of Interest

Air Pollutant of Interest	Type	Source Example	Useful Detection Limits	Range to Expect	Level
Ozone (O_3)	Secondary	Formed via UV (sunlight) and pressure of other key pollutants	10 ppb	0-150 ppb	75 ppb (8 hr)
Carbon monoxide (CO)	Primary	Fuel combustion – mobile sources, industrial processes	0.1 ppm	0-0.3 ppm	9 ppm (8 hr) 35 ppm (1 hr)
Sulfur dioxide (SO_2)	Primary	Fuel combustion – electric utilities, industrial processes	10 ppb	0-100 ppb	75 ppb (1 hr) 0.5 ppm (3 hr)
Nitrogen dioxide (NO_2)	Primary and Secondary	Fuel combustion – mobile sources, electric utilities, off-road equipment	10 ppb	0-50 ppb	100 ppb (1 hr) 53 ppb (1 yr)
Carbon dioxide (CO_2)	Primary	Fuel combustion – electric utilities, mobile sources	100 ppm	350-600 ppm	None
Volatile organic compounds (VOCs)	Primary and Secondary	Fuel combustion (mobile sources, industries) gasoline evaporation; solvents	1 µg/m^3	5-100 µg/m^3 (total VOCs)	None
Benzene (an example of a VOC and air toxic)	Primary	Gasoline, evaporative losses from above ground storage tanks	0.01 – 10 µg/m^3	0-3 µg/m^3	None
Fine particulate matter ($PM_{2.5}$)	Primary and Secondary	Fuel combustion (mobile sources, electric utilities, industrial processes), dust, agriculture, fires	5 µg/m^3 (24-hr)	0-40 µg/m^3 (24-hr)	35 µg/m^3 (24 hr) 12 µg/m^3 (1 yr)
Particulate matter (PM_{10})	Primary and Secondary	Dust, fuel combustion (mobile sources, industrial processes), agriculture, fires	10 µg/m^3 (24-hr)	0-100 µg/m^3 (24-hr)	150 µg/m^3 (24 hr)
Black carbon (BC)	Primary	Biomass burning, diesel engines	0.05 µg/m^3	0-15 µg/m^3	None

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Possible Sensor Tiers

Tier	Application Area	Pollutants	Precision and Bias Error	Data Completeness*	Rationale (Tier I-IV)
I	Education and Information	All	<50%	≥ 50%	Measurement error is not as important as simply demonstrating that the pollutant exists in some wide range of concentration.
II	Hotspot Identification and Characterization	All	<30%	≥ 75%	Higher data quality is needed here to ensure that not only does the pollutant of interest exist in the local atmosphere, but also at a concentration that is close to its true value.
III	Supplemental Monitoring	Criteria pollutants, Air Toxics (incl. VOCs)	<20%	≥ 80%	Supplemental monitoring might have value in potentially providing additional air quality data to complement existing monitors. To be useful in providing such complementary data, it must be of sufficient quality to ensure that the additional information is helping to "fill in" monitoring gaps rather than making the situation less understood.
IV	Personal Exposure	All	<30%	≥ 80%	Many factors can influence personal exposures to air pollutants. Precision and bias errors suggested here are representative of those reported in the scientific literature under a variety of circumstances. Error rates higher than these make it difficult to understand how, when, and why personal exposures have occurred.

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Example - PM Sensors

DYLOS

SPECK

MET ONE

SHINYEI

AIRBEAM

TZOA

Example- Gas Sensors

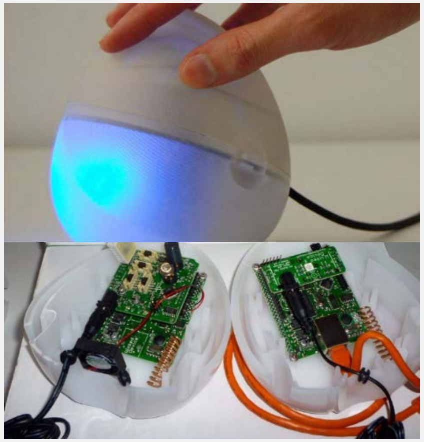
SENSARIS

AIR CASTING

CAIRCLIP

AEROQUAL

AQ EGG



NODE

Example- MultiPollutant Stations

ELM

HAZ-SCANNER

AQ MESH

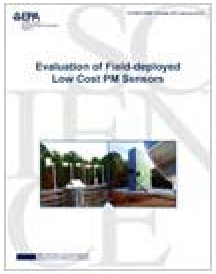
Resources Developed for Citizens

Air Sensor Guidebook

CSAM Operating Procedures

Mobile Sensors & Applications for Air Pollutants

Citizen Science Air Monitor (CSAM): Quality Assurance Guidelines



Evaluation of Field-deployed Low Cost PM Sensors

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Select Quality Assurance Parameters

- Bias - is it routinely high or low with respect to the true value
- Precision - how repeatable is the measurement
- Calibration - does it respond in a systematic fashion as conc changes
- Detection limit - how low and high will it measure successfully
- Response time - how fast does the response vary with conc change
- Linearity of sensor response - what is the linear or multilinear range
- Measurement duration - how much data do you need to collect
- Measurement frequency - how many collection periods are needed
- Data aggregation - value in aggregating data (1 sec, 1 min, 1 hr, etc)
- Selectivity/specificity - does it respond to anything else
- Interferences - how does heat, cold, effect response
- Sensor poisoning and expiration - how long will the sensor be useful
- Concentration range - will the device cover expected highs and lows
- Drift - how stable is the response
- Accuracy of timestamp - what response output relates to the event
- Climate susceptibility - does RH, temp, direct sun, etc impact data
- Data completeness - what is the uptime of the sensor
- Response to loss of power - what happens when it shuts down

Sensor Considerations

- Weather. Many devices are temperature and/or relative humidity (RH) sensitive
- Most sensors are not weather protected
- Battery life. Wide range in operational ranges exist
- Orientation. Some devices require a very specific orientation
- Data storage/transmission. WiFi, data card, cellular, tablet, PC. Lots of variants and often problematic
- Lack of sensitivity. Failure to measure at ambient levels
- Interferences. Gas sensors often respond to “other” pollutants

Resources for Decision Making

Continuous Measurement Decision Tree

- Define the pollutant or exposure variable(s) of interest
- What is the hypothesis that needs to be tested?
- Are continuous measurements truly needed. Are simple time integrated options (e.g., y/n) as valuable?
- What parameters need to be co-measured to facilitate the testing?
- Do they all lend themselves to continuous monitoring or only some of them? Does it matter?
- What analytical methods are available to collect the raw data?

Continuous Measurement Decision Tree

- Are these methods readily available?
- Are they within your financial budget and timeline relative to acquisition (number of sensors)? Would you need to make the devices “field worthy”?
- Based on relevant statistical tests, what population size of data need be collected? What assumptions are you having to make to develop those statistical tests?
- Can you successfully execute a study design once you have defined the data size population (with respect to study resources)?

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Continuous Measurement Decision Tree

- What do you need to do to “validate” or prepare the continuous monitor before its use? Is this feasible with your resources and expertise. Are there others who could do this for you if you lack the expertise?
- Do you have software that will reduce the labor of recovering big data for the purpose at hand? If not, can you handle the labor to more laboriously recover/organize/validate data?
- Data validation is paramount to your success. Will you be able to use collocation or other QA schemes to ensure data is and peer acceptable?

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Continuous Measurement Decision Tree

- What is the shortest duration of measurement that is feasible, reasonable, and logical with respect to the study design and hypothesis. Do you collect “it all” and then decide if aggregation is profitable as part of your post-processing effort?
- How do you plan to handle monitor refurbishment, calibration, repair and upkeep as part of the day to day operation of the equipment? Are there any “off days” where such work can occur with no impact on the data collection schedule?

Thank You. Questions?