Study of Fallout Metrics for Contamination Analysis

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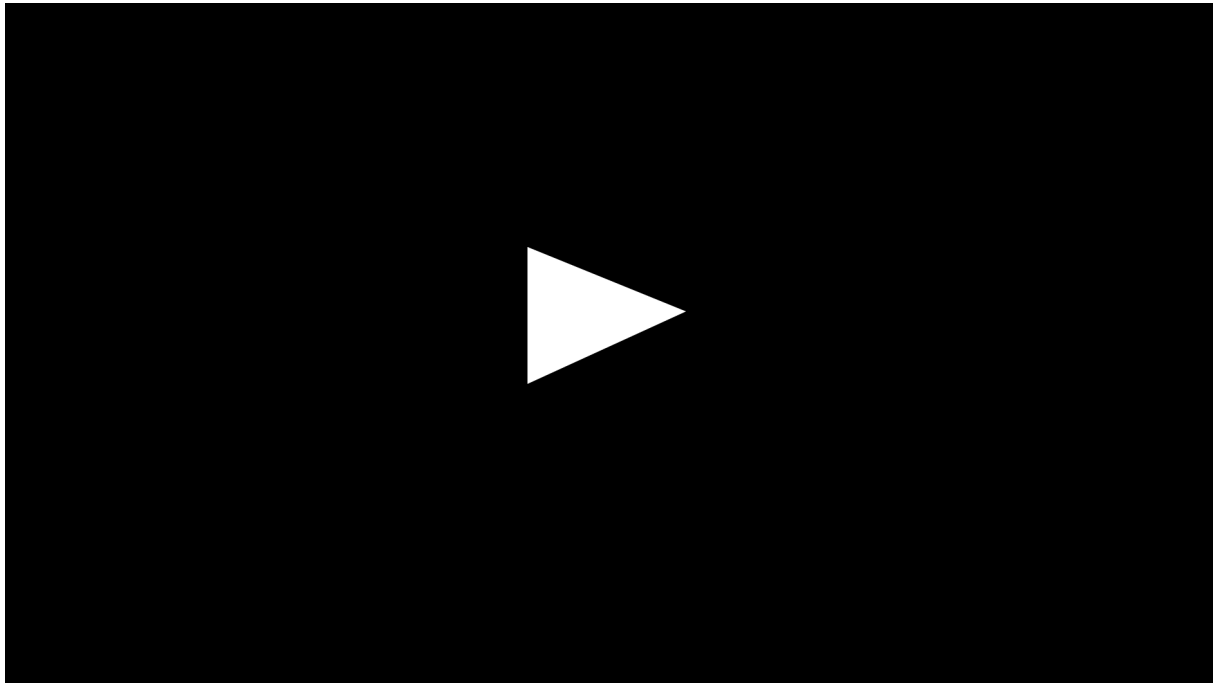
Definition of the Problem

A challenge present for many projects, including James Webb Space Telescope (JWST), is predicting contamination fallout for the various orientations possible for surfaces such as optics and instruments.



Relevance: The vertical to horizontal fallout ratio is critical for contamination requirements and allocations to identify money and resources necessary for project mission objectives. This has been an ongoing issue in contamination engineering for years.

Goal: determine an accurate ratio or method for vertical to horizontal fallout that can be applied in future contamination analytics

Definition of the Problem

Currently, vertical particle build up is quantified as approximately 1/10 of horizontal surfaces (Tribble, A., et al. "Contamination Control Engineering Design Guidelines for the Aerospace Community - Results." *Space Programs and Technologies Conference*, 1996, doi:10.2514/6.1996-4375). ***There is not sufficient data with accuracy to support this assumption.***

Previous studies:

1) Limited fallout studies in Spacecraft Systems Development and Integration Facility (SSDIF)
   - 4 studies prior to 2005 that did not properly account for:
     Integration and testing (I&T) levels, duration of exposure, percent area coverage (PAC) levels lower than typical literature values

2) SSDIF Fallout Study for JWST in 2005-2006
   - Inconclusive results for the effect of orientation on fallout

Location	WFC3	Lower Mezzanine	South Wall	HFMS
Exposure (Days)	217	256	234	346
Horizontal (PAC/day)	0.00024	0.000088	0.000057	0.000054
Vertical (PAC/day)	1.11E-05	2.68E-07	1.69E-06	1.97E-06
Inverted (PAC/day)	8.01E-07	1.36E-06	1.15E-06	1.87E-06
Relative Rate Percentages				
Horizontal	100%	100%	100%	100%
Vertical	4.53%	0.30%	2.95%	3.62%
Inverted	0.33%	1.54%	2.01%	3.43%

3) Verifying rule of thumb predictions for Integrated Science Instrument Module (ISIM) sensitive surfaces (varying orientations) for JWST

In all cases, results were not reproducible

Hasegawa, Mark. "Applying SSDIF Particle Fallout Rates to the JWST Program". 2007

Scope of Effort

1. Vertical to horizontal fallout study (short and long term exposure)
2. Camera imaging of sensitive surfaces

- Issues to address:
  - Investigate effect of orientation on spacecraft fallout
  - Imaging sensitive hardware surfaces directly

- Restrictions:
  - Timeline: 6 months-1 year
  - Minimal funding

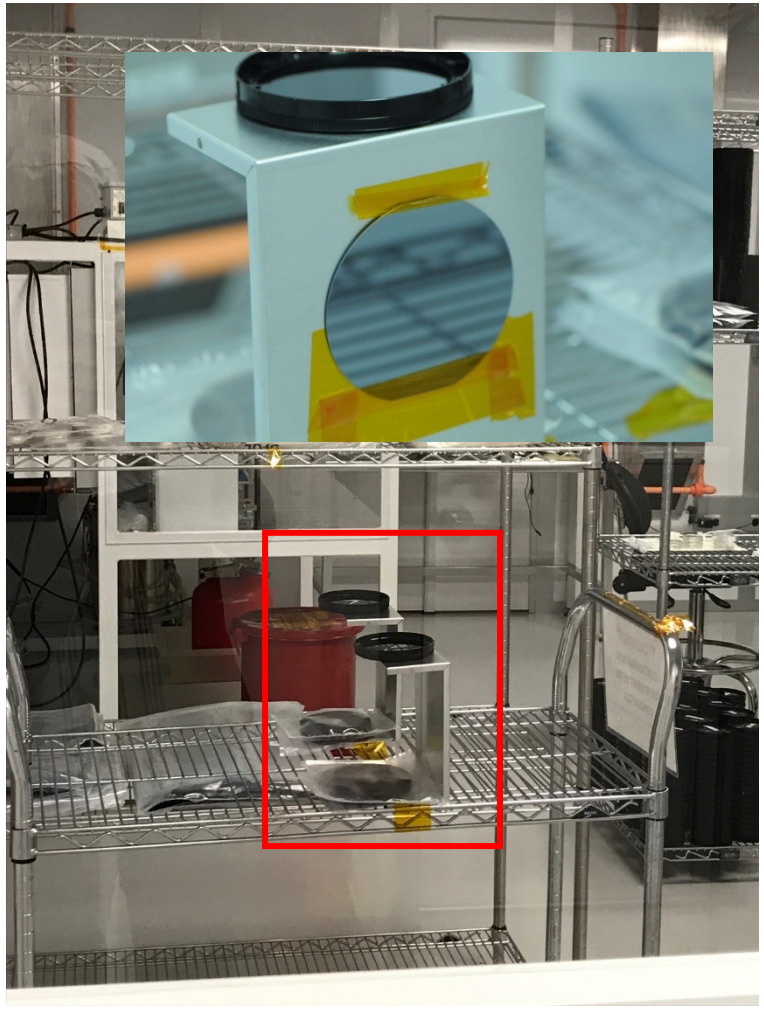
- Goals:
  - Vertical to horizontal ratio and tolerance
  - Photography capabilities to use in conjunction with Image Analysis (IA)

Vertical-Horizontal Study Setup

Silicon wafers are used to determine fallout and represent sensitive surfaces of flight hardware

After being deployed for a determined amount of time, the wafers are read on an Image analysis (IA) system to determine the percent area coverage (PAC) and counts of particles and fibers

4 wafers: 2 vertical and 2 horizontal set up in three low activity locations:
BATCAVE (BC)
SSDIF
SCA

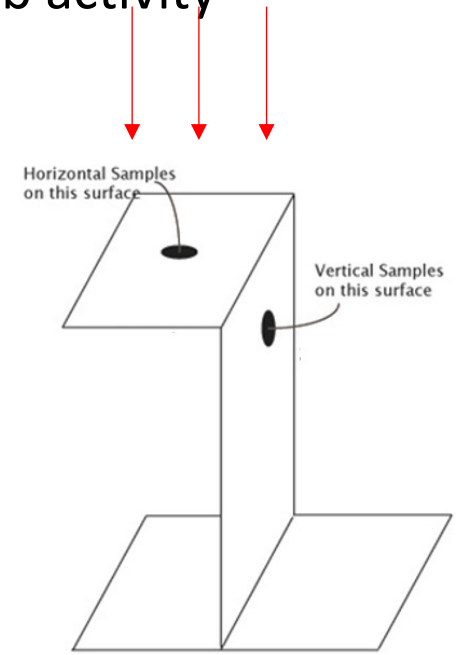


Bldg 7 BC facility setup

GSFC Facilities

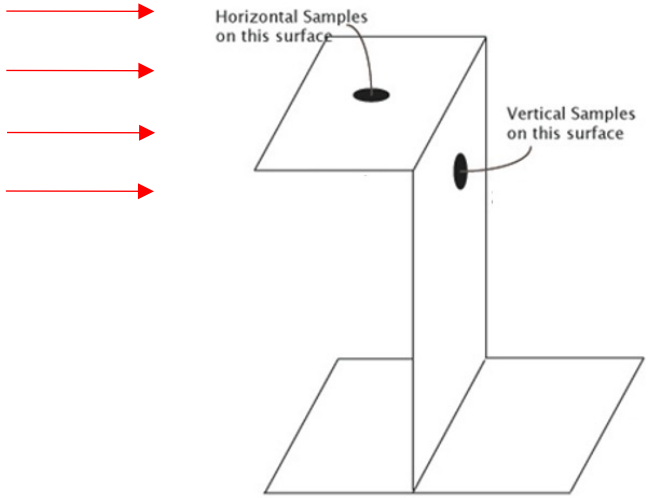
BC

- Classification: 10 K, ISO7
- Flow: Top Down
- Activity Level: Very low, Lab activity



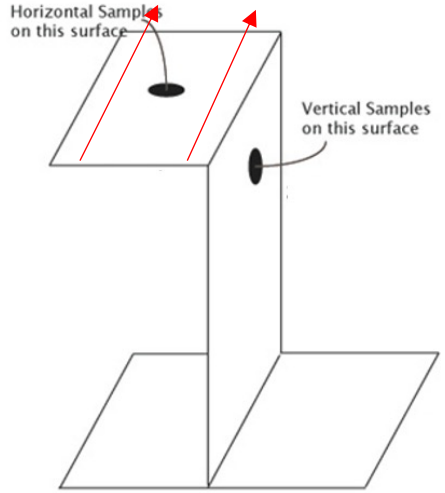
SSDIF

- Classification: 10 K, ISO7
- Flow: Horizontal Laminar unidirectional
- Activity Level: Low

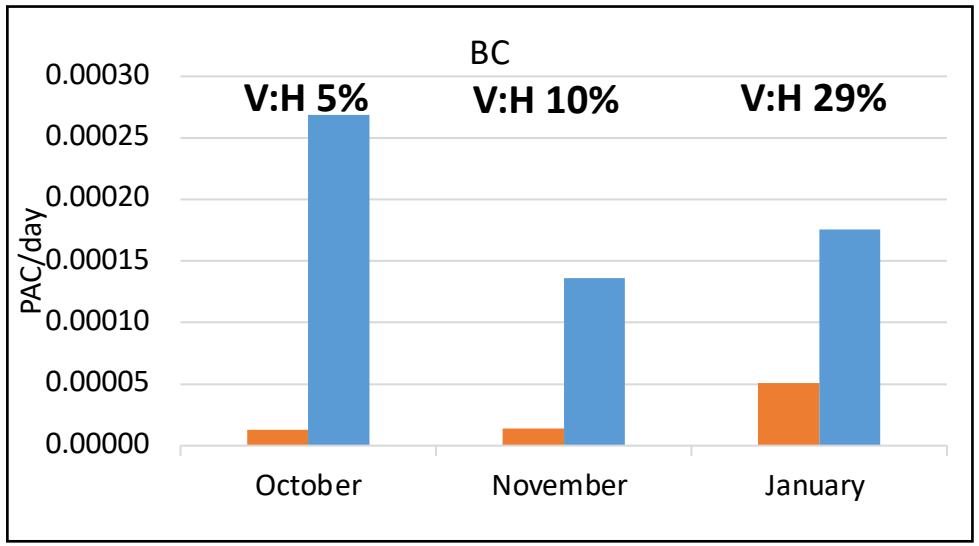


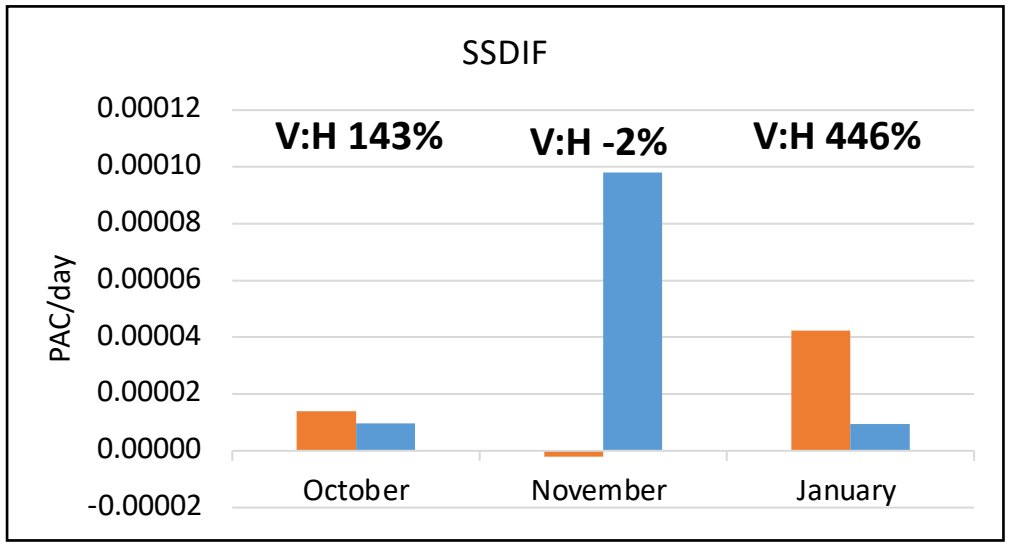
SCA

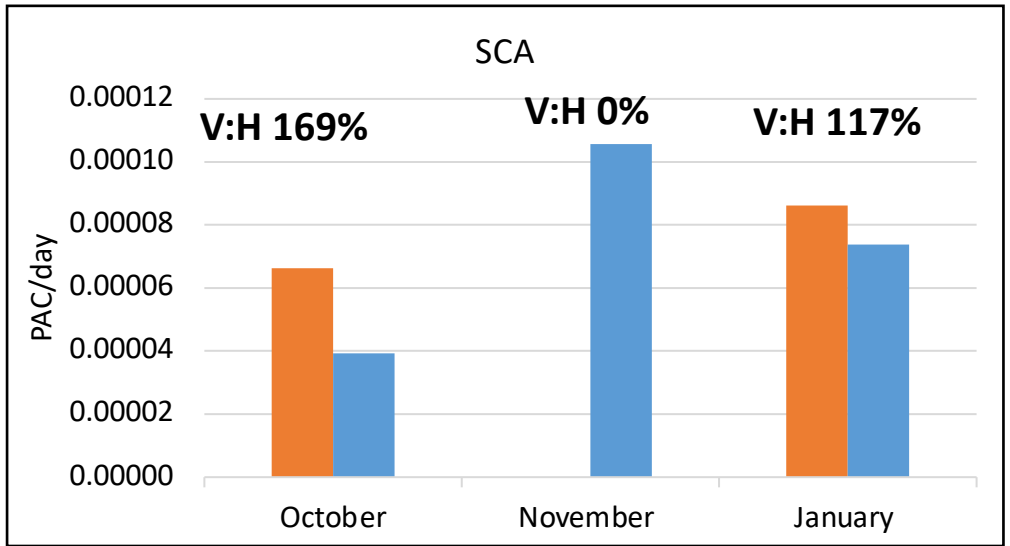
- Classification: 10 K, ISO7
- Flow: Horizontal Laminar unidirectional
- Activity level: Low

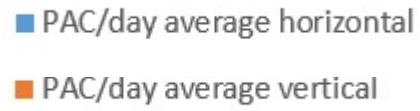


GSFC Facilities PAC/day each month







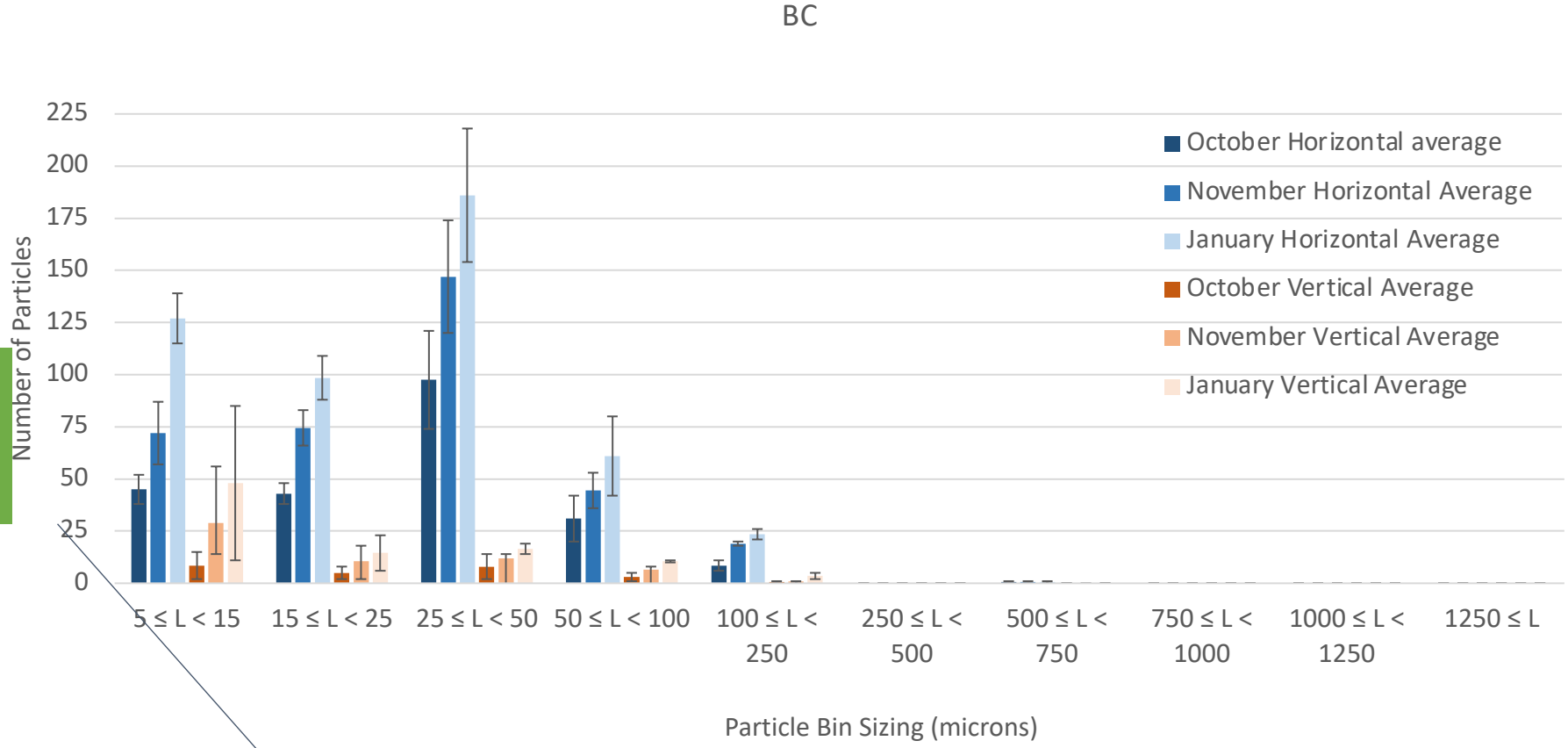


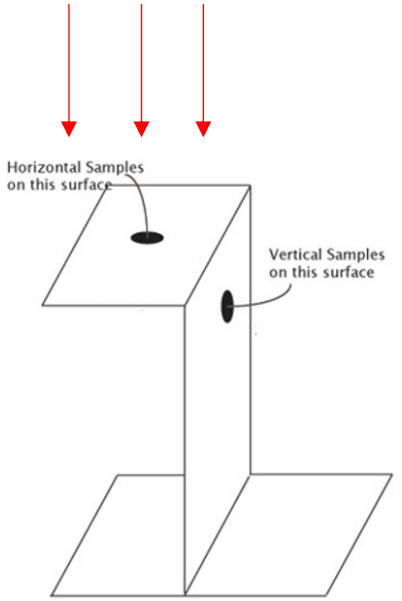
Reproducible vertical to horizontal ratios NOT observed after 3 months of deployment for each PAC/day read. This could be due to the low work activity load.

Examine particle size distributions to identify vertical to horizontal fallout per bin size.

*Note: wafers deployed in September 2019. Cumulative wafers were redeployed after each read. No **wafers** replaced.

Particle Size Distribution, BC



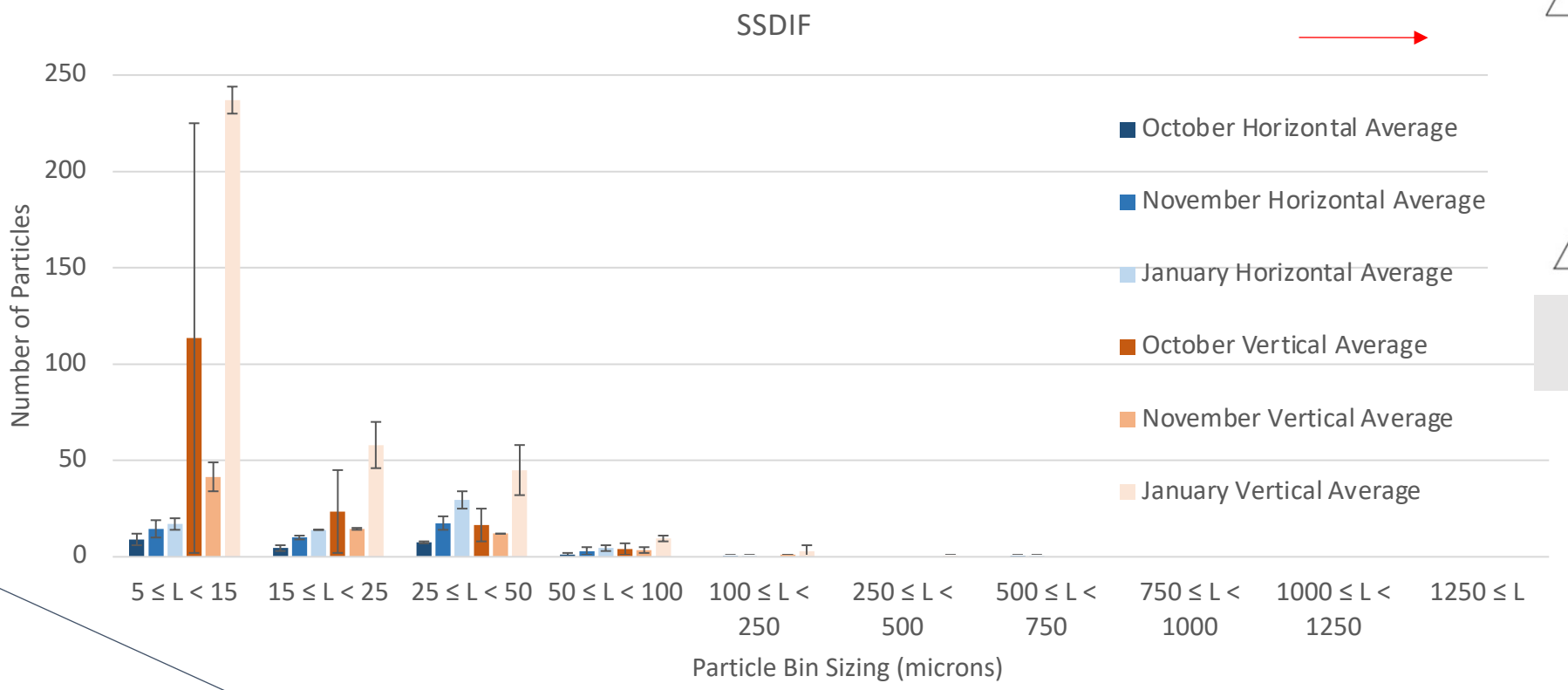


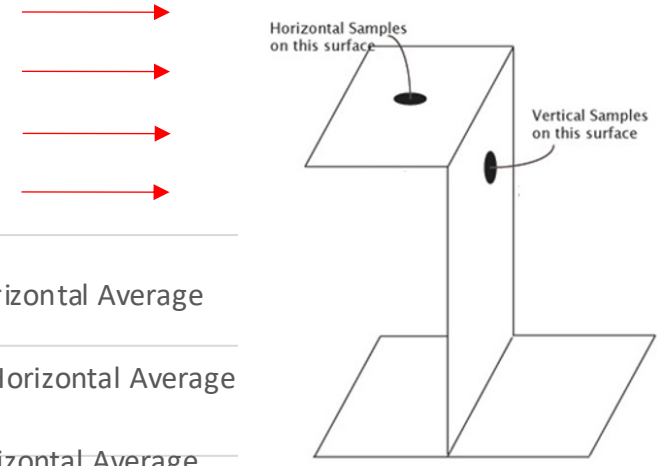
Activity level:
very low, lab activity

Ratio of vertical to horizontal not consistent among bin sizes

	5 ≤ L < 15	15 ≤ L < 25	25 ≤ L < 50	50 ≤ L < 100	100 ≤ L < 250	250 ≤ L < 500	500 ≤ L < 750	750 ≤ L < 1000
October Vertical: Horizontal %	19	12	8	10	6	0	0	0
November Vertical: Horizontal %	40	14	8	15	5	0	0	0
January Vertical: Horizontal %	38	15	9	17	15	0	0	0
Standard Error	7	1	0	2	3	0	0	0

Particle Size Distribution, SSDIF





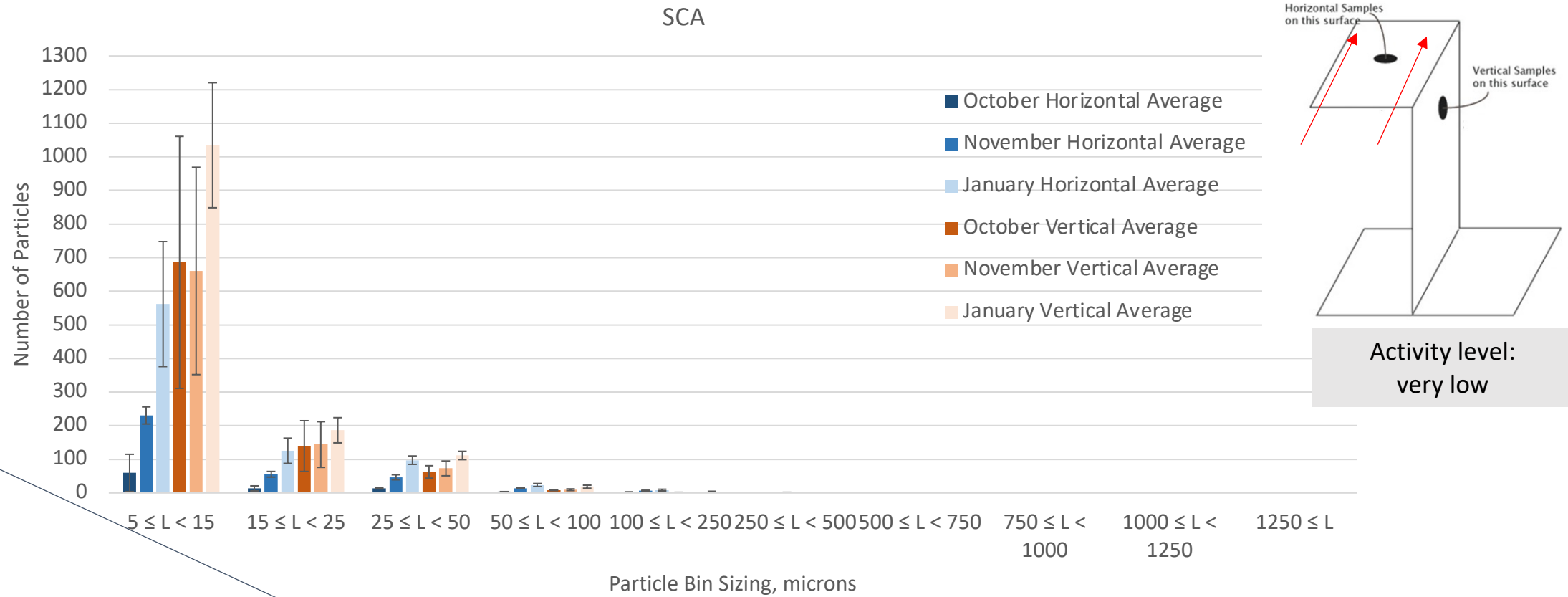
Activity level: very low

Ratio of vertical to horizontal not consistent among bin sizes. Vertical samples appear to have higher fallout due to turbulence caused by being in the wake of airflow.

	5 ≤ L < 15	15 ≤ L < 25	25 ≤ L < 50	50 ≤ L < 100	100 ≤ L < 250	250 ≤ L < 500	500 ≤ L < 750	750 ≤ L < 1000
October Vertical: Horizontal %	1261	522	220	400	0	0	0	0
November Vertical: Horizontal %	286	145	69	117	200	0	0	0
January Vertical: Horizontal %	1394	414	153	211	600	N/A	0	N/A
Standard Error	349	112	44	83	176	0	0	0

Particle Size Distribution, SCA

Ratio of vertical to horizontal not consistent among bin sizes.
Vertical samples appear to have higher fallout.



Activity level: very low

	5 ≤ L < 15	15 ≤ L < 25	25 ≤ L < 50	50 ≤ L < 100	100 ≤ L < 250	250 ≤ L < 500	500 ≤ L < 750	750 ≤ L < 1000
October Vertical: Horizontal %	1153	1033	446	243	40	0	0	0
November Vertical: Horizontal %	287	259	157	68	7	0	0	0
January Vertical: Horizontal %	184	149	114	79	29	0	0	0
Standard Error	307	278	104	57	10	0	0	0

Note: these samples have been moved due to project work

GSFC Study Findings

- For short duration exposures (~3 months), particle build up on vertical surfaces can NOT be approximated as 1/10 of horizontal surfaces.
  - PAC/day each month vertical to horizontal ratios were variable
  - Vertical to horizontal fallout not consistent among bin sizes

What other factors could be affecting this vertical to horizontal ratio besides wafer orientation to gravity?

Minitab Statistical Analysis of GSFC Study

Using Minitab software, the statistical significance of each variable on PAC/day was investigated.

Facility	Orientation wrt to airflow	Orientation with airflow degrees	PAC/day
1	0	90	0.0000029
1	0	90	0.0000229
1	1	0	0.0002200
1	1	0	0.0003171
2	0	180	0.0000250
2	0	180	0.0000028
2	1	90	0.0000111
2	1	90	0.0000083
3	0	90	0.0000946
3	0	90	0.0000378
3	1	90	0.0000108
3	1	90	0.0000676
1	0	90	0.0000280
1	0	90	0.0000000
1	1	0	0.0000240
1	1	0	0.0002480
2	0	180	-0.0000160
2	0	180	0.0000120
2	1	90	0.0001800
2	1	90	0.0000160
3	0	90	-0.0000077
3	0	90	0.0000077
3	1	90	0.0001038
3	1	90	0.0001077
1	0	90	0.0000361
1	0	90	0.0000653
1	1	0	0.0001342
1	1	0	0.0002175
2	0	180	0.0000188
2	0	180	0.0000677
2	1	90	0.0000130
2	1	90	0.0000064
3	0	90	0.0001607
3	0	90	0.0000116
3	1	90	0.0000627
3	1	90	0.0000849

Variables:

1) Facility

1 BC
2 SSDIF
3 SCA

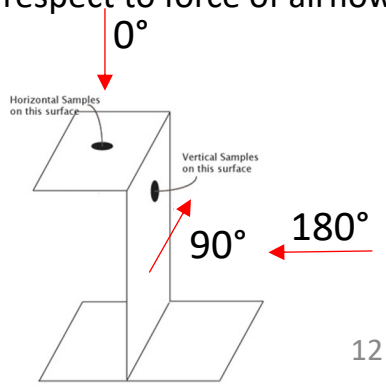
2) Orientation with respect to gravity

0 Vertical
1 Horizontal

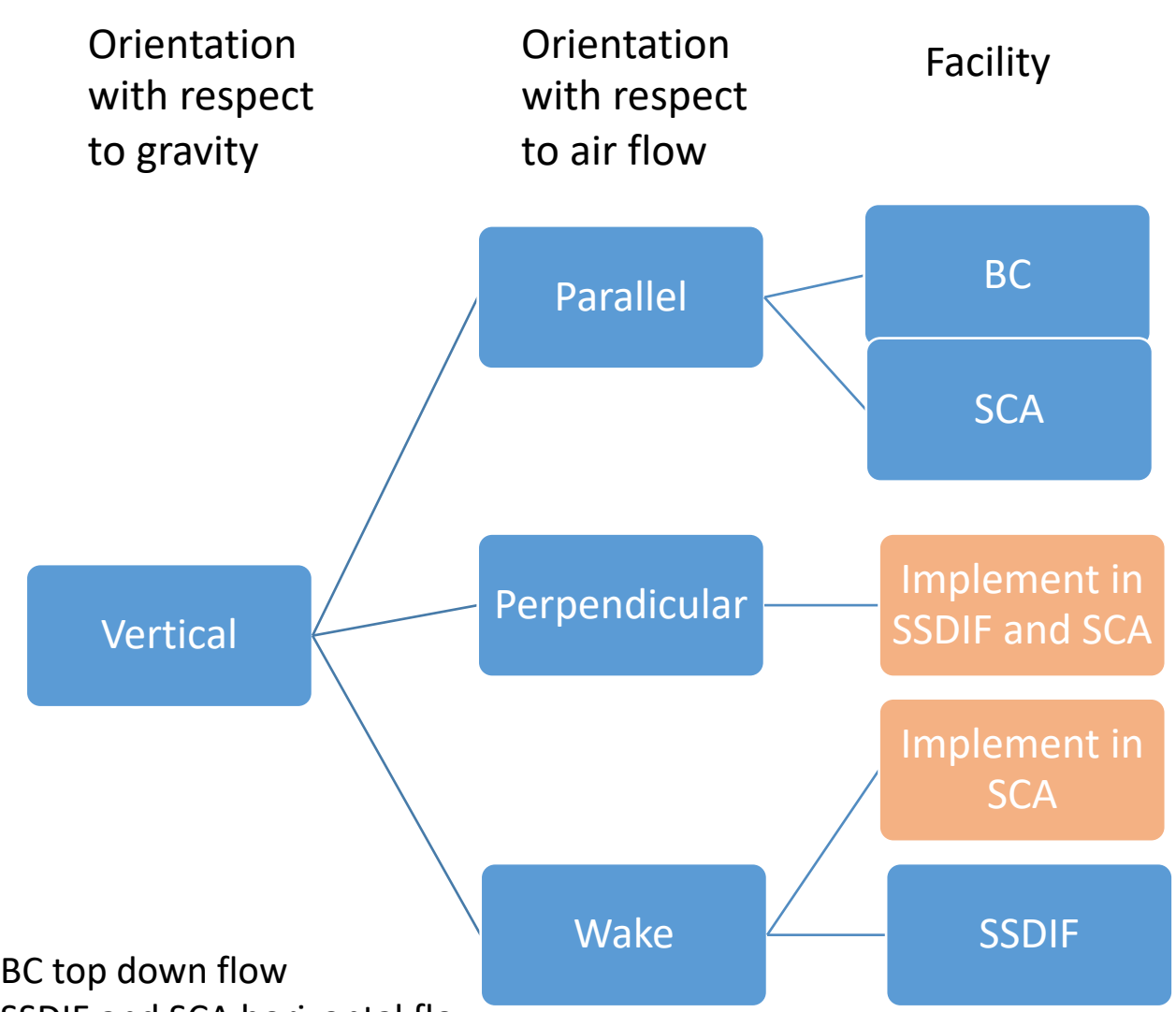
3) Orientation with respect to airflow

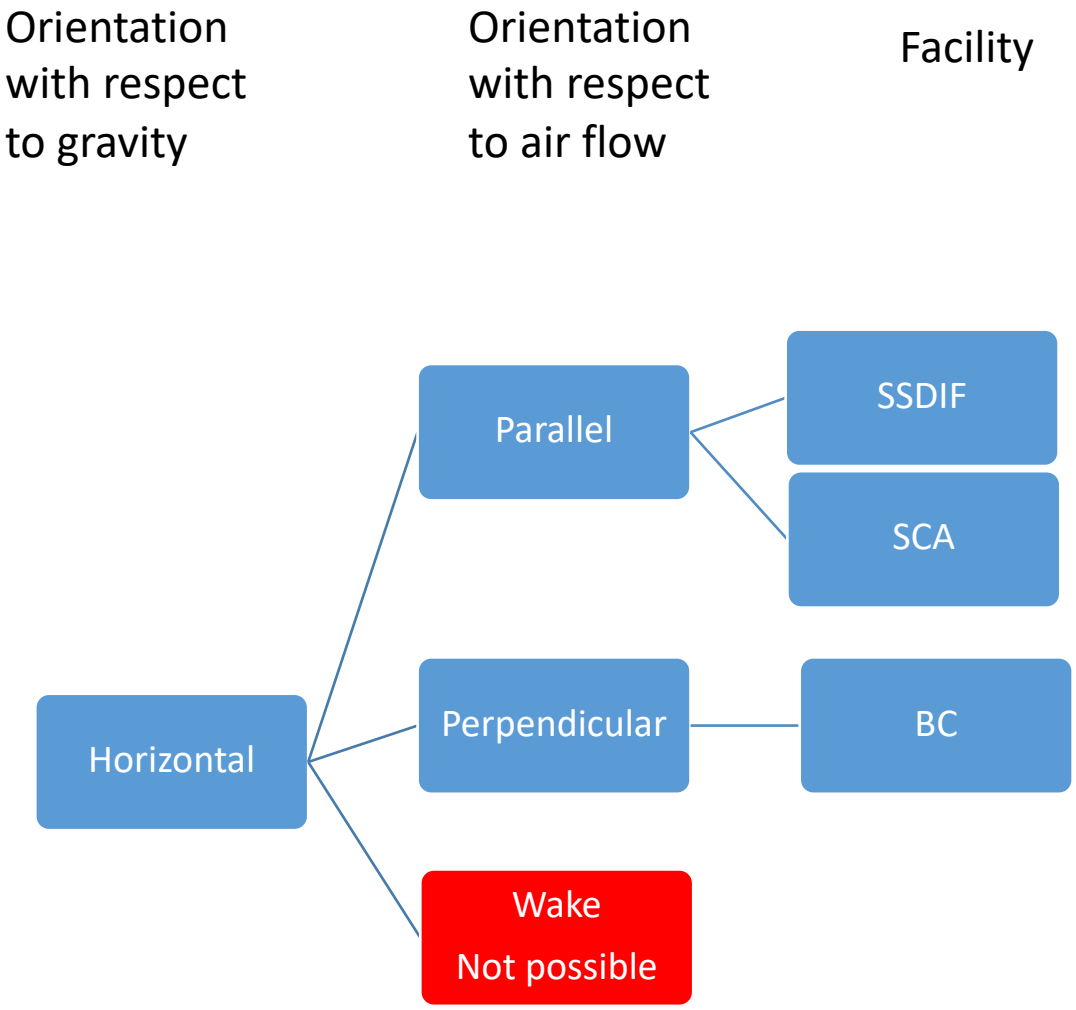
180 degrees	Wake
90 degrees	Parallel
0 degrees	Perpendicular

using the angle with respect to force of airflow



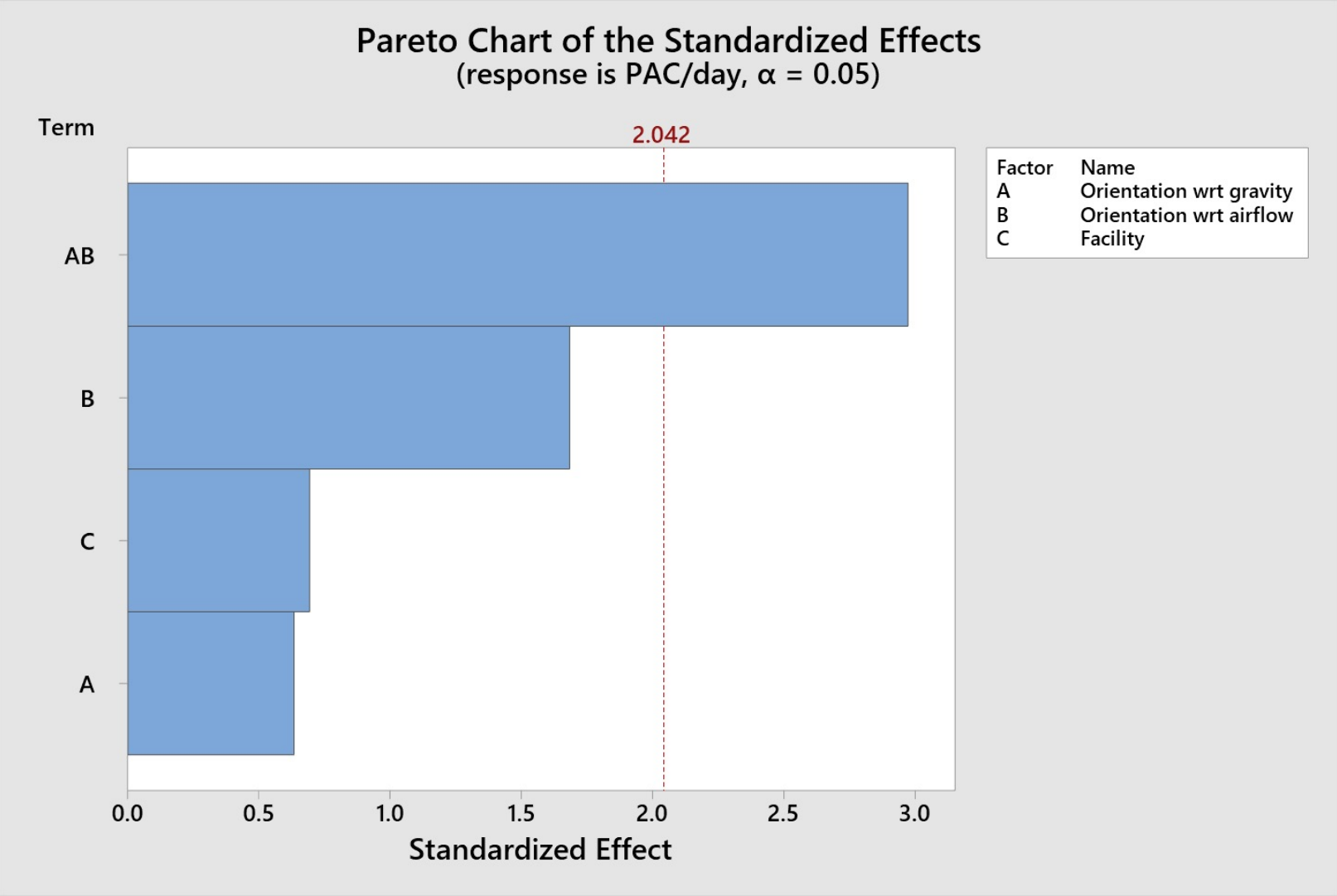
Samples with respect to airflow and gravity





BC top down flow
SSDIF and SCA horizontal flow

Pareto Chart for GSFC Study



- Full response factorial run with a 95% confidence interval
- Orientation wrt to gravity interaction with orientation wrt to airflow is statistically significant

Analysis of Variance for GSFC Study

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	0.000000	0.000000	6.93	0.000
Linear	4	0.000000	0.000000	6.78	0.001
Orientation wrt gravity	1	0.000000	0.000000	0.40	0.531
Orientation wrt airflow	1	0.000000	0.000000	2.84	0.102
Facility	2	0.000000	0.000000	0.72	0.494
2-Way Interaction	1	0.000000	0.000000	8.84	0.006
Orientation wrt gravity*Orientation wrt airflow	1	0.000000	0.000000	8.84	0.006
Error	30	0.000000	0.000000		
Total	35	0.000000			

Orientation wrt to airflow has a larger effect than the facility.
The orientation with respect to gravity is *the least significant factor*.

Particle Adhesion

- Typically, molecular and electrostatic interactions adhere particles to a surface
  - These interactions include forces such as: capillary, van der Waals, electrical double layer, ionic attraction, gravity
    - van der Waals forces likely dominate for small particles
- Material, size and shape of the particles directly influence the adhesion
- Humidity can also influence adhesion greatly

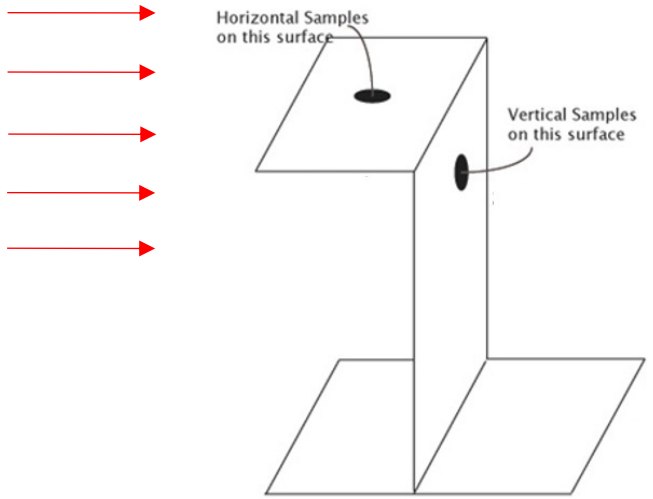
Micron size particle adhesion is not well understood for cleanrooms

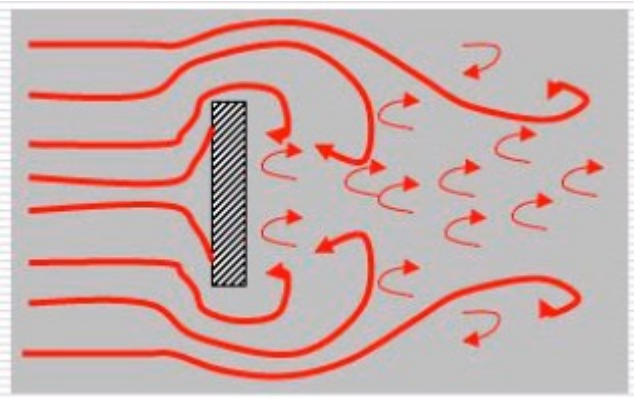
M. B. Ranade (1987) Adhesion and Removal of Fine Particles on Surfaces, Aerosol Science and Technology, 7:2, 161-176, DOI: 10.1080/02786828708959155
https://www.rdworldonline.com/microelectronics-cleaning-the-cleanroom-qa/

Object in the wake of airflow

- An object obstructing air streamlines results in a pressure gradient
- Upstream: higher pressure
- Downstream: lower pressure

- *What affect could this turbulent flow have on particulate adhered to vertical samples?*





Buch, J.D. and Barsh, M.K., "Analysis of particulate contamination buildup on surfaces", *Optical SystemContamination: Effects, Measurement, Control*, SPIE Vol. 777, (1987), pp. 43-54
https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19690024397.pdf
https://slideplayer.com/slide/4569109/

Vertical and Horizontal Fallout Findings

- 2 sets of vertical and horizontal wafers, analyzed monthly, have been deployed in the BC, SSDIF, and SCA at GSFC
- **Assumption of 1/10 vertical to horizontal fallout that has been used for many years as common practice IS NOT APPLICABLE to all cases**
  - For short term exposure, one value for a vertical to horizontal ratio cannot be identified.
  - Vertical to horizontal ratio to apply for future contamination predictions is still being investigated.
- New issue identified: the orientation with respect to airflow for samples needs to be considered

1/10 vertical to horizontal fallout assumption can not be applied as a universal factor
Ability to accurately predict saves project funds and schedule
Project success depends on understanding these concepts

Recommendations

- Projects can NOT rely on the 1/10 approximation for vertical to horizontal fallout
- For sensitive hardware, do not keep the surface in the wake of airflow. Instead, the surface should be parallel or perpendicular to airflow
- These wafer set ups should be used to monitor the facility where hardware will be for a time period prior to the start of sensitive hardware arriving
  - These are easy and cost effective to implement and can inform the effect of orientation on fallout

Future Studies

- Samples need to be deployed in all orientations with respect to airflow in each facility
- Facility variable needs to be further specified by air changes, air velocity, and work activity levels

- Goal: a handbook value for vertical vs horizontal fallout

Camera ImageJ Analysis (CIJA)

Predictions for contamination are limited, as shown in the vertical horizontal study.

For samples that cannot be sampled directly(tape lift or rinse), a direct measurement of the surface would be ideal.

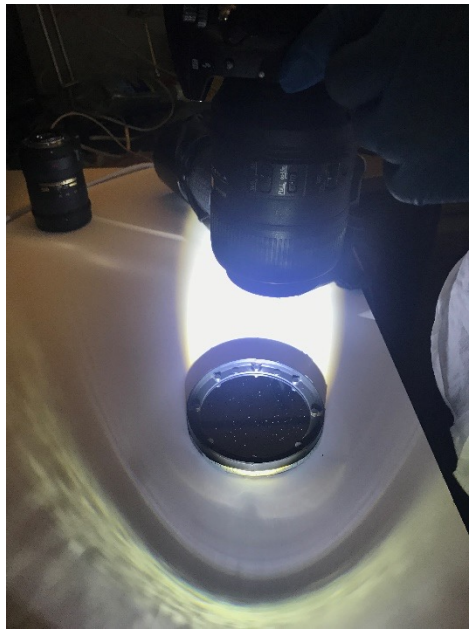
A more accurate representation of a surface of interest could be a picture that is processed through ImageJ software to verify contamination requirements.

Thesis: CIJA can be used as an alternative to IA with an associated error.

Goal: Determine a setup and processing procedure that is comparable to the current IA process.

Initial Efforts

Chris Gunn(NASA Photographer Code 443) assisted with an initial experiment for particulate resolution through cameras.



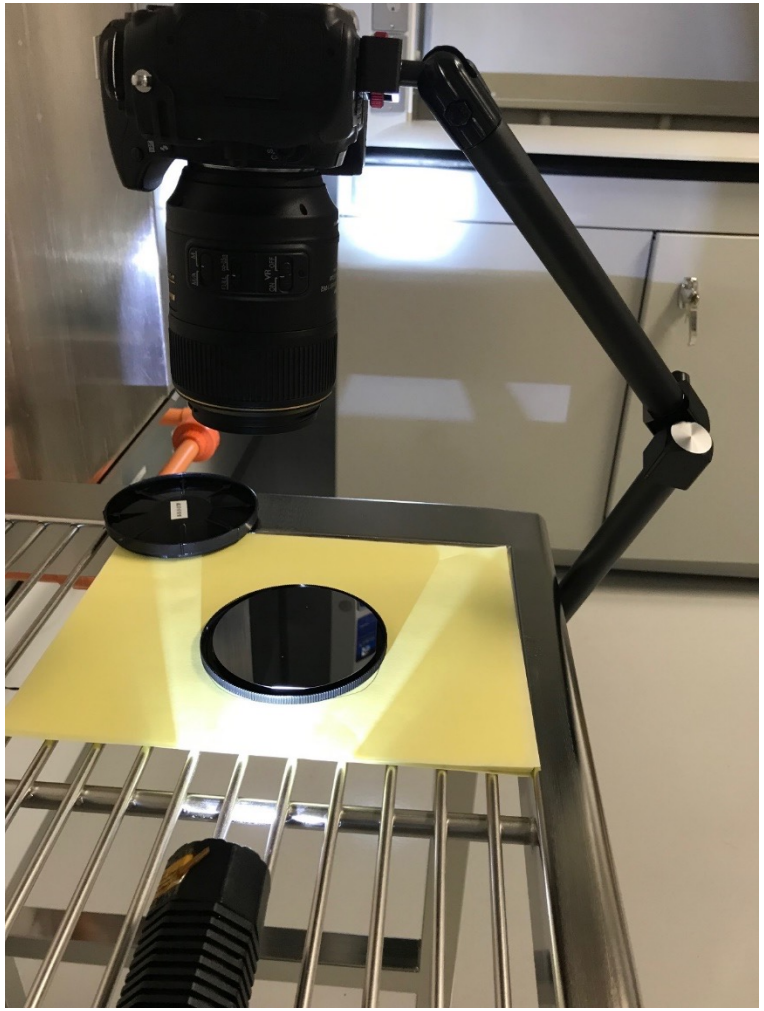
Nikon D700 Camera
Nikon f/2.8 105mm lens
PAC(ImageJ): 0.004

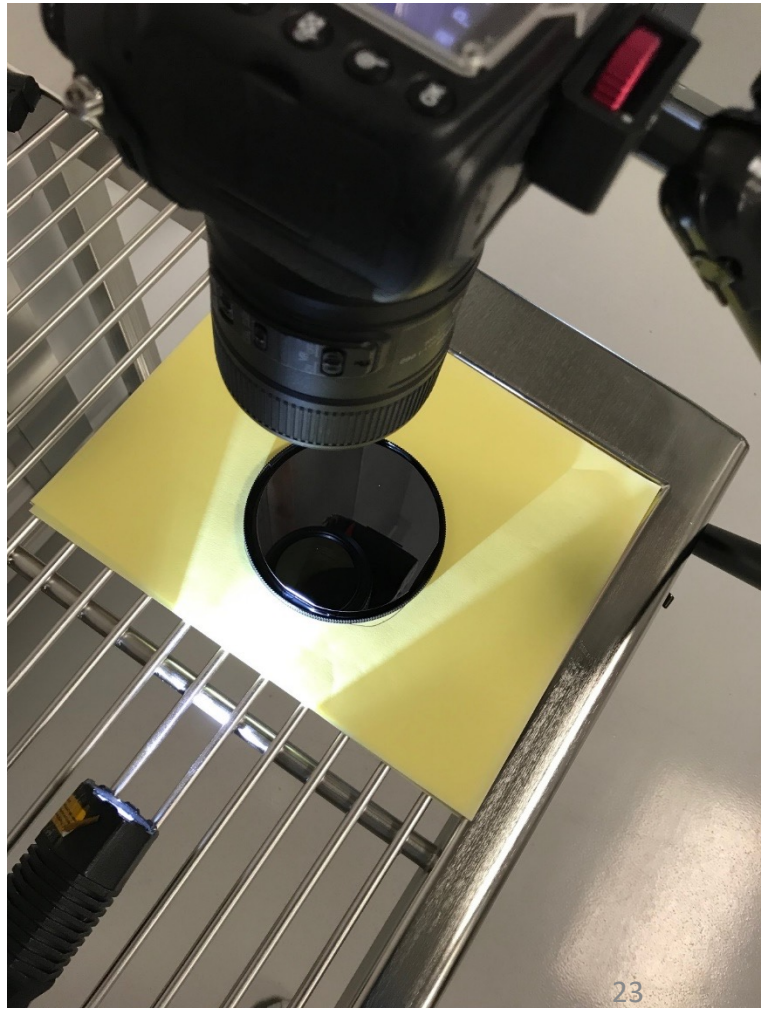
Hasselblad camera, 50 megapixels
PAC(ImageJ): 0.004

Determined 1:1 ft best setting for capturing particulate
To minimize shaking from human factor with handheld camera, a camera stand should be acquired

CIJA Set up

- Tripod purchased that has capability to take orthogonal images of wafers
- Camera: Nikon D300
- Nikon f/2.8 105mm lens
- 1:1 ft magnification
- ~ 6 in focus distance
- 23.5x15.6 mm image size
- Oblique angle light source





Issues addressed to date and future work

- Setup:
  - Tripod: While more stable than just a human holding, minimal movements can affect the image taken.
  - Image: I am not able to track well where I am on the wafer. I have looked for laser grids but have not found a product suitable yet.
  - Lighting: Ring light shows reflection into wafer. Variable lighting can affect particle size in wafer images
    - Develop a stand for two lights at oblique angles across the wafer?

- Processing:
  - Image taken 1:1 is 366.6 mm
  - IA area is 4.71E09 mm
  - Can I scale the CIJA image PAC? I assumed that PAC could be comparable even though the areas between CIJA and IA varies.
  - Need to further work on the output to Excel from ImageJ
  - Ability to get the size distribution of particles through ImageJ software. Will it be comparable to IA output?

Acronym List

JWST	James Webb Space Telescope
SSDIF	Space Systems Development and Integration Facility
SCA	Spacecraft Checkout Area
I&T	Integration and Testing
IA	Image Analysis
PAC	Percent Area Coverage
ISIM	Integrated science instrument module
CIJA	Camera ImageJ Analysis
BITSE	Balloon-borne Investigation of Temperature and Speed of Electrons
CODEX	COronal Diagnostic Experiment

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Craig Jones

Drew Uhl

Christopher Gunn

Jolearra Tshiteya

Jerron Jackson

Jim Loughlin

Code 546

Code 551

Code 443

JWST

BITSE

CODEX