The Impacts of Airborne Cloud Microphysical Instrumentation Mounting Location on Measurements Made During Observations of Aerosols Above Clouds and Their Interactions (ORACLES)

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Dissertation Defense

Friday, 23 June 2023

Grand Forks, North Dakota

Outline

- ORACLES Project Description
- NASA P-3 Pylon Designs
- Computational Fluid Dynamics with OpenFOAM
- Simulations of ORACLES Cloud Sampling Profiles
- Recommendations and Future Work

NASA ORACLES

ObseRvations of Aerosols above Clouds and their Interactions

- A five-year NASA investigation into the climate impacts of Southern Africa's biomass burning aerosols (Redemann et al. 2021).
- Three separate field experiments were conducted off the coast of Africa.
  - September 2016 – Walvis Bay, Namibia
  - August 2017 - São Tomé and Príncipe
  - October 2018 - São Tomé and Príncipe
- Primary platform:
  - NASA P-3 Orion - Wallops Flight Facility
  - NASA ER-2

Photo from NASA ORACLES: https://espo.nasa.gov/ORACLES/content/ORACLES

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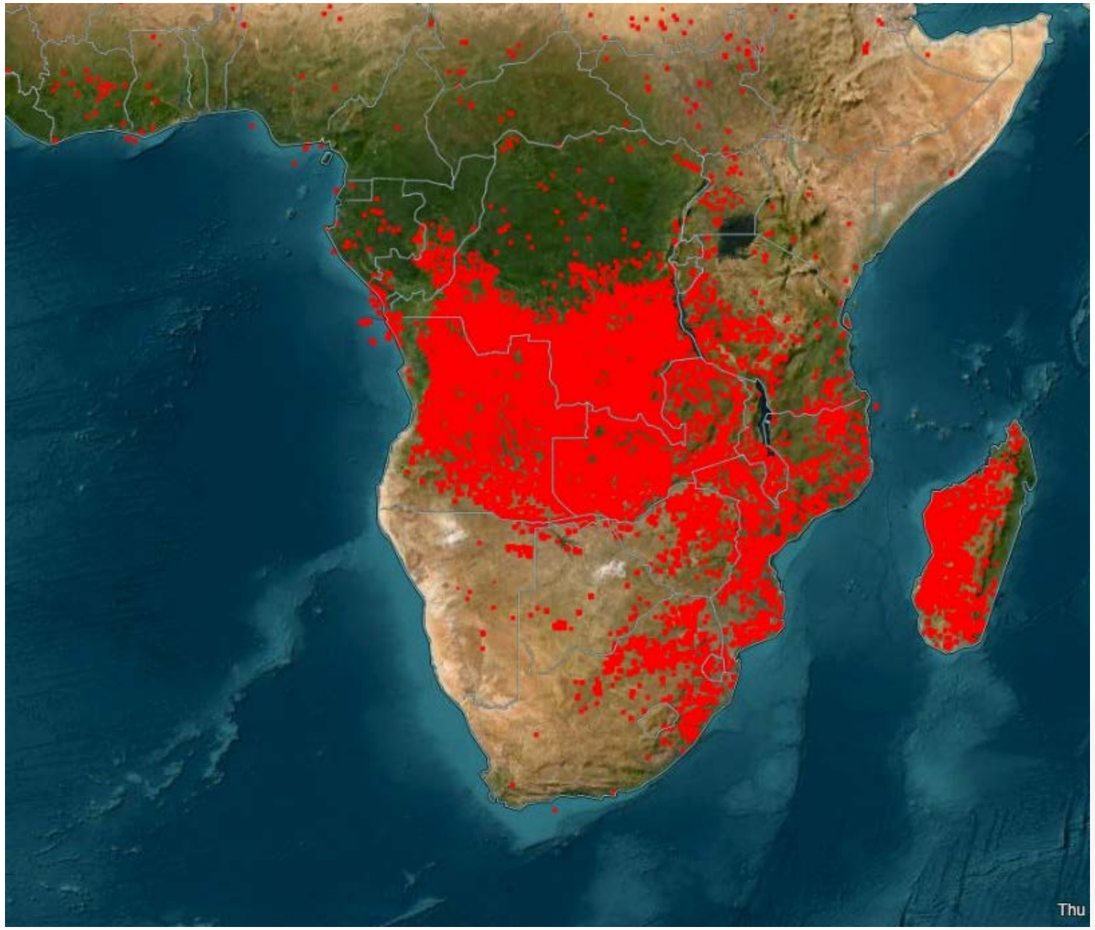
Biomass Burning Aerosols

- Southern Africa accounts for almost one third of the Earth's total biomass burning emissions.
- With burned areas in southern Africa increasing even with the decreasing trend in global biomass burning (Andela et al. 2017; Redemann et al. 2021).
- Biomass burning aerosol emissions from southern Africa are routinely transported west off the continent and over one of the world's three semi-permanent marine stratocumulus cloud decks.



NASA's Fire Information for Resource Management System (FIRMS) (https://earthdata.nasa.gov/firms), part of NASA's Earth Observing System Data and Information System (EOSDIS); 15 June 2023

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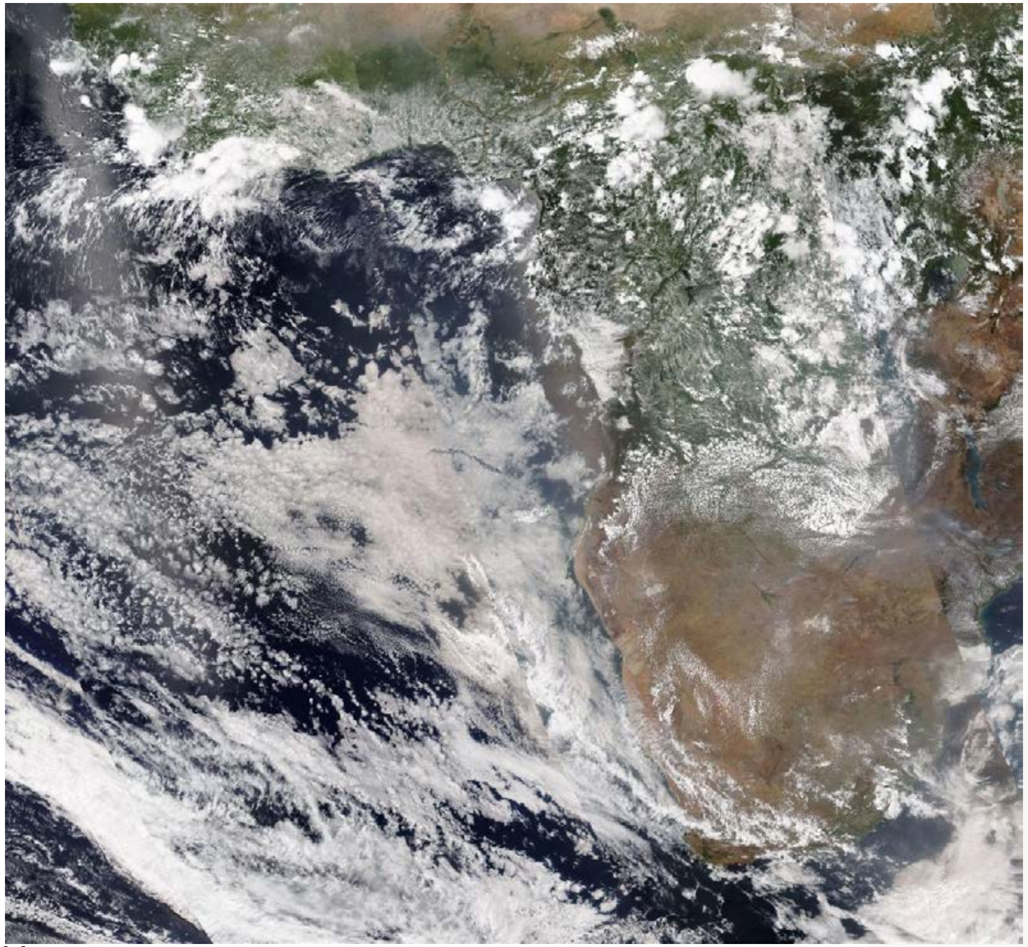
Southern Atlantic Marine Stratocumulus

- Stratocumulus (Wood 2012)
  - Class of low clouds composed of an ensemble of individual convective elements .
  - Earth's most common cloud type.
  - Susceptible to perturbations in atmospheric aerosols.
- Southern Atlantic Ocean
  - 40-60% annual cloud coverage within this region (Wood 2012).
  - Profound impact on Earth's radiation budget.



We acknowledge the use of imagery provided by services from NASA's Global Imagery Browse Services (GIBS), part of NASA's Earth Observing System Data and Information System (EOSDIS).

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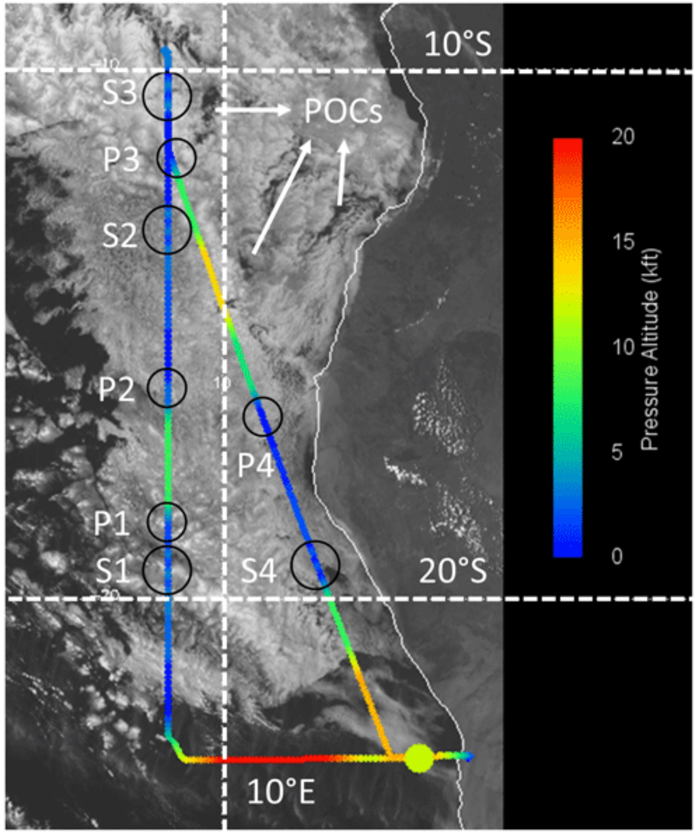
Aerosol Indirect Effect

- Twomey (1977) found that with increasing cloud condensation nuclei, smaller, more numerous cloud droplets were formed.
- Albrecht (1989) argued that the result of the Twomey effect is a decrease in the variability of the cloud droplet distribution, with results in the reduction of collision-coalescence and precipitation efficiency.
- Series of papers by Dr. Sid Gupta investigates aerosol indirect effects for ORACLES.



Gupta, S et al. (2021) Impact of the variability in vertical separation between biomass burning aerosols and marine stratocumulus on cloud microphysical properties over the Southeast Atlantic, Atmos. Chem. Phys., 21, 4615–4635, https://doi.org/10.5194/acp-21-4615-2021

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`Cloud Probes` Team

- UND, CIWRO, OU, and UIUC investigated cloud microphysical properties within the African Marine Stratocumulus.
- Operated a suite of microphysical instrumentation to observe aerosol and cloud distributions from 0.1µm to 19.2 cm.
- Primary focus is the Aerosol Indirect Effect.

Instrument	Main Parameter	Sampling Frequency	Measurement Range
Cloud Droplet Probe (CDP)	Cloud Droplet Number Distribution *n*(D)	10 Hz	2 – 50 µm
Cloud and Aerosol Spectrometer	Droplet Images, Cloud Droplet Number Distribution *n*(D)	10 Hz *n*(D); Asynchronous images	0.5 – 50 µm 25-1600 µm
Two-Dimensional Stereo Probe	Droplet Images, Droplet Number Distribution *n*(D)	Asynchronous images; 1 Hz *n*(D)	10 – 1280 µm
High Volume Precipitation Spectrometer	Droplet Images, Droplet Number Distribution *n*(D)	Asynchrones images; 1 Hz n(D)	150 – 19200 µm
Passive Cavity Aerosol Spectrometer	Aerosol Number Distribution *n*(D)	10 Hz	0.1 – 3 µm
CSIRO King Hotwire	Bulk Liquid Water Content	25 Hz	0.05 – 3 g m^{-3}

Cloud Profiles – ‘Sawtooths’

- Cloud and aerosol in-situ sampling were separated into two distinct maneuvers:
  - ‘Sawtooth’ profiles
  - Constant altitude in-cloud legs
- In total, the NASA P-3 Orion aircraft flew 350.6 flight hours in 44 science operations flights between ORACLES-2016 and ORACLES-2018.
  - 329 cloud profiles transecting the vertical distribution of marine stratocumulus (Redemann et al. 2021; Gupta et al. 2022)

Photo Courtesy of Sid Gupta

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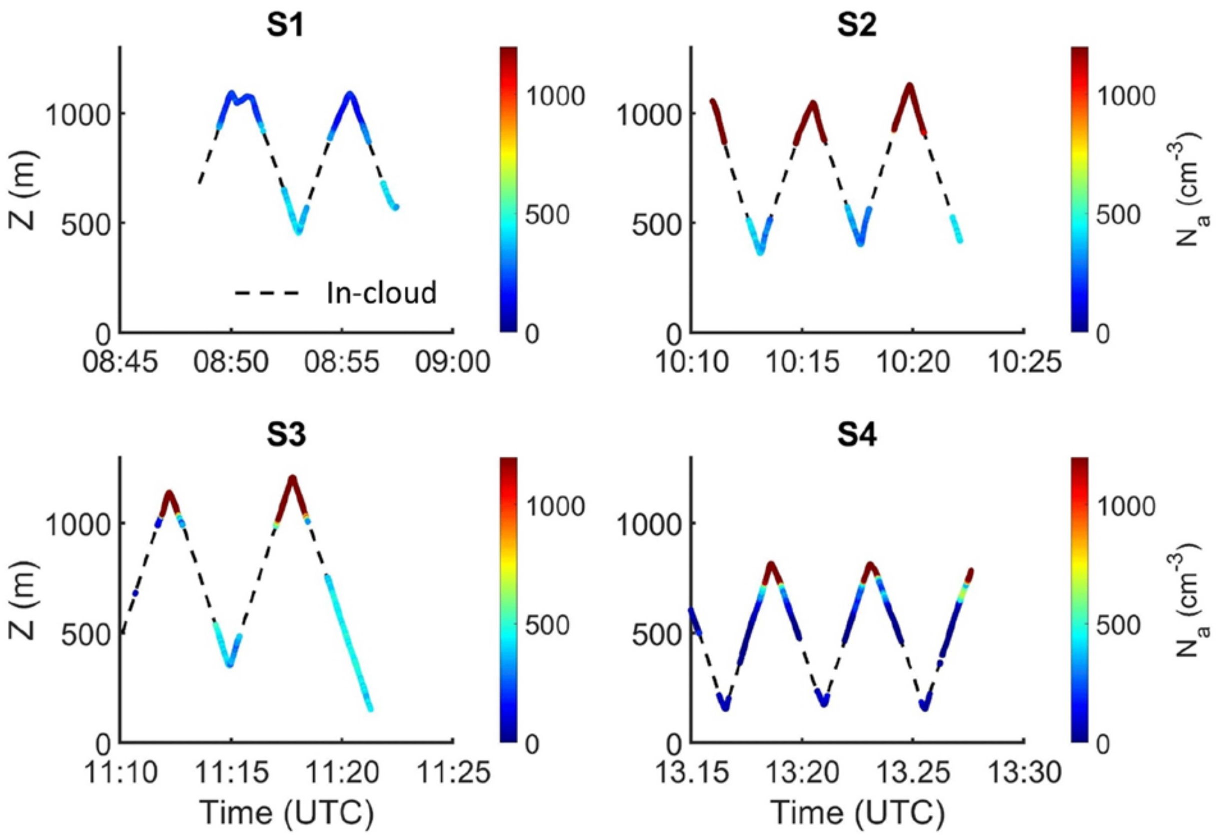

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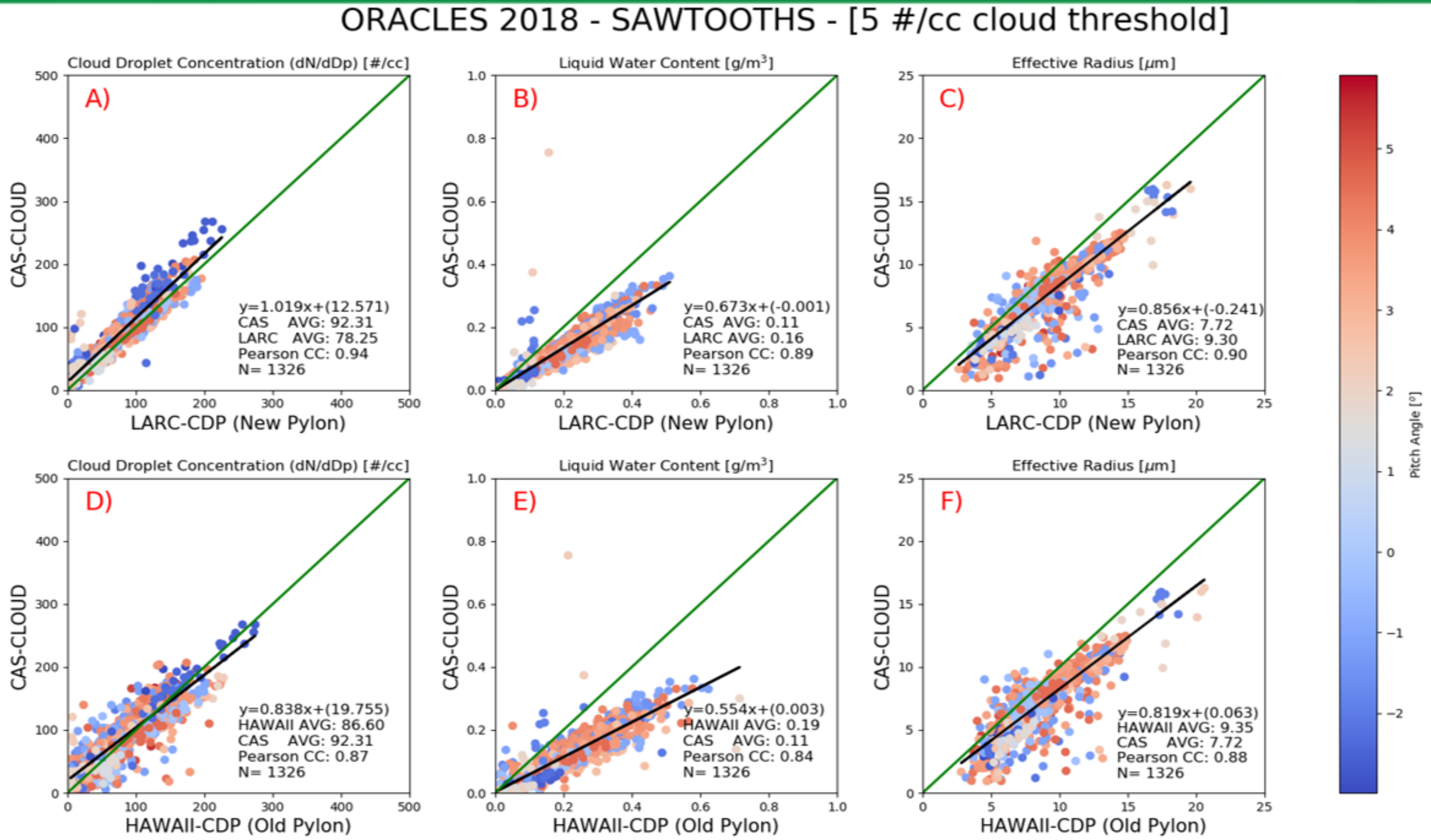
Cloud Droplet Instrument Intercomparisons

- Following ORACLES-2016, we had concerns that the mounting location of the instruments was influencing the observations.
    - The intercomparison showed the relationship between Nd between the CAS and PDI were dependent on the pitch angle of the aircraft during sawtooth maneuvers.
- Concern was that particle trajectories may be altered by the Navy pylon



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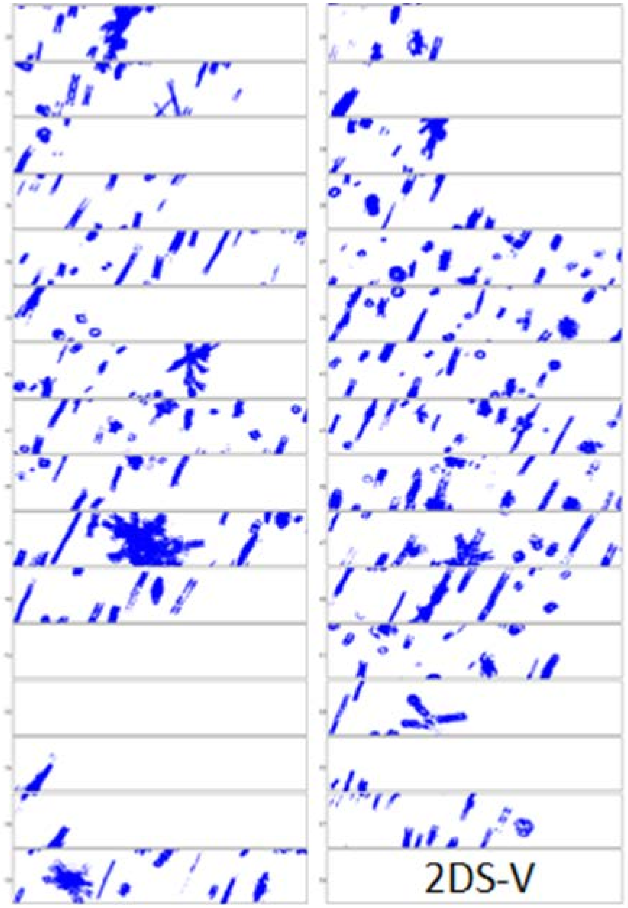
Aircraft Instrument Placement

- Beard (1983) studied the orientation of OAP images due to the tilting of images in the direction of flight.
- Norment (1988) found that the PMS FSSP under-sampled cloud droplets (5-50 microns diameter) between 10-13% at 0 degrees angle of attack, and 18-24% at 4 degrees angle of attack.
  - Angle of attack:
    - The angle at which the chord of an aircraft's wing meets the relative wind.
- MacPherson and Baumgardner (1988) conducted extensive wind tunnel tests of the King Air pylon assembly with chalk and oil.



O'Brien, J.R., "Sensitivity Of Two-Dimensional Stereo (2DS) Probe Derived Parameters To Particle Orientation" (2016). Theses and Dissertations. 2056. https://commons.und.edu/theses/2056

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Angle of Attack Dependence

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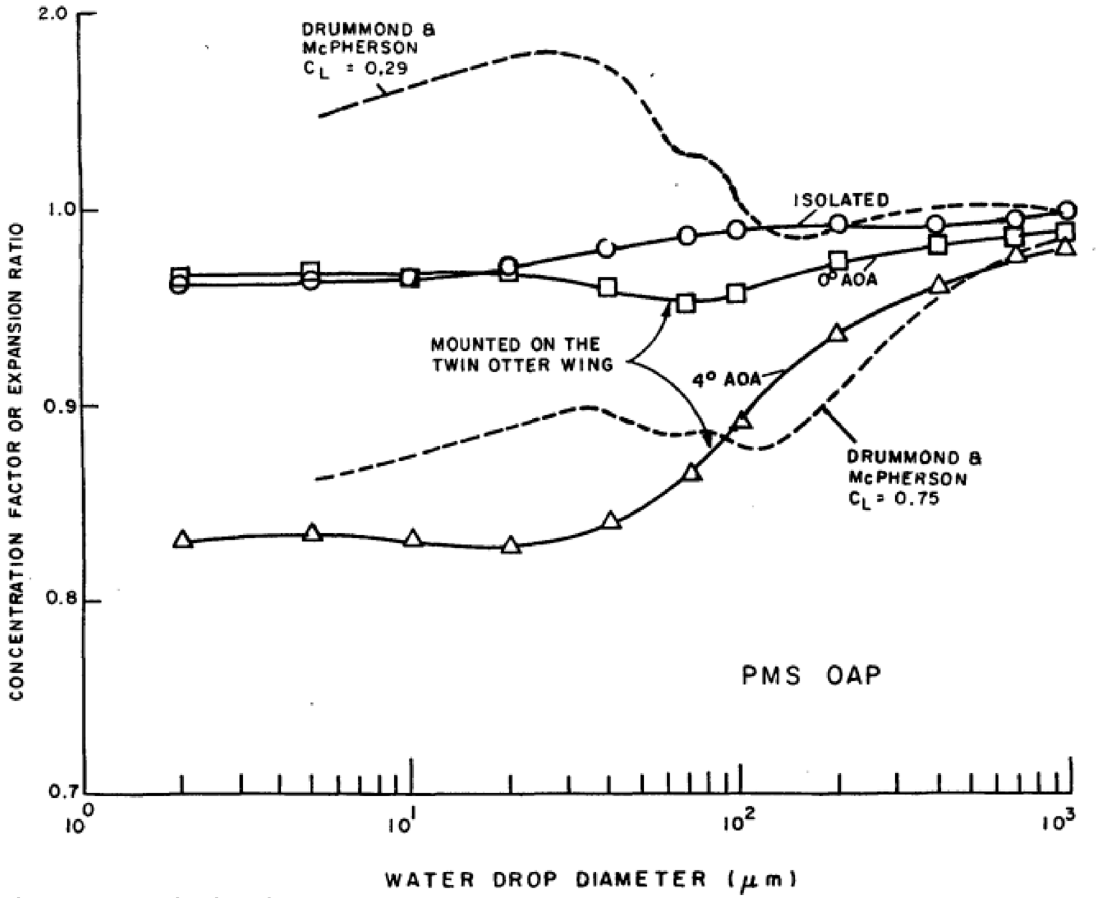

*Norment, H. G., 1988: Three-Dimensional Trajectory Analysis of Two Drop Sizing instruments: PMS*OAP and PMS* FSSP. J. Atmos. Oceanic Technol.,* ***5****, 743–756, https://doi.org/10.1175/1520-0426(1988)005<0743:TDTAOT>2.0.CO;2.*

Recent Advancements

- Bennett et al. (2019) conducted numerical simulations to understand the aerodynamics around their pylon assembly.
  - Only considered the effect of longitudinal and lateral velocity components on the sizing of hydrometeors within the DMT Cloud Imaging Probe (CIP-100).
- Spanu et al. (2020) conducted numerical simulations investigate flow around wing-mounted instruments on board the DSR Dassault Falcon 20E.
  - Determined the sampling efficiency (i.e. concentration of particles within the sample volume compared to free steam concentrations).
  - Cloud droplets less than 100 microns in diameter were shown to have a sampling efficiency of 77%.

UK Met Office – BAe FAAM Research Aircraft

Barrett, P. A., and Coauthors, 2022: Intercomparison of airborne and surface-based measurements during the CLARIFY, ORACLES and LASIC field experiments. *Atmospheric Meas. Tech.*, **15**, 6329–6371, https://doi.org/10.5194/amt-15-6329-2022.

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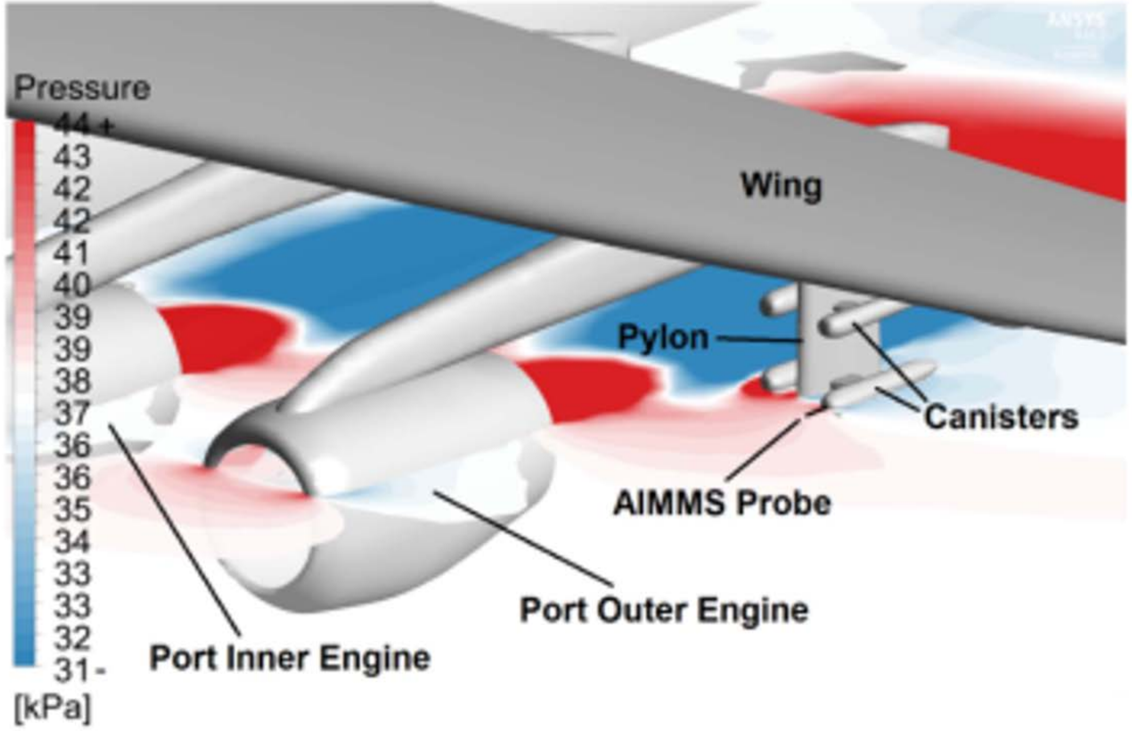

UK Met Office – BAe FAAM Research Aircraft

Bennett, C. J., G. J. Nott, A. Wellpott, N. Lawson, M. Delise, B. Woodcock, and G. B. Gratton, 2019: Characterizing Instrumentation Canister Aerodynamics of FAAM BAe-146-301 Atmospheric Research Aircraft. J. Aerosp. Eng., ***32****, 04019047, https://doi.org/10.1061/(ASCE)AS.1943-5525.0001044.*

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Recent Advancements – DSR Falcon

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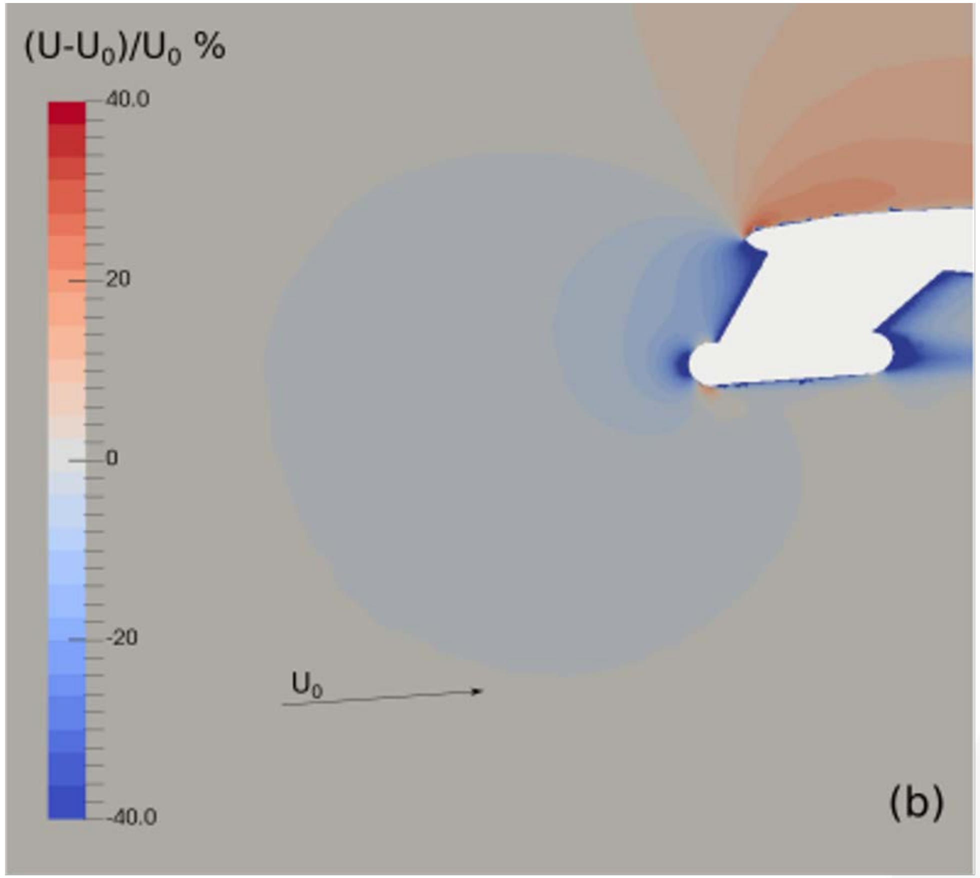

DSR Dassault Falcon 20E

Spanu, A., M. Dollner, J. Gasteiger, T. P. Bui, and B. Weinzierl, 2020: Flow-induced errors in airborne in situ measurements of aerosols and clouds. Atmospheric Meas. Tech., ***13****, 1963–1987, https://doi.org/10.5194/amt-13-1963-2020.*

Instrument Placement – NASA P-3

- Typically assumed that the sampling locations are approximately freestream.
  - Freestream: air far upstream of an aerodynamic body, before the body has a chance to deflect, slow down, or compress the air.
- Recommended new pylon configuration place instruments as far ahead and beneath the wing as possible.
- **Should wing-mounted instruments sample ahead or behind of the leading edge of the aircraft wing?**

Navy - NASA P-3 Original Pylon Configuration
Extended - NASA P-3 New Pylon Configuration

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ORACLES CDP Comparison

- Determine CDP placement through comparison of simultaneous observations.
- ORACLES-2017:
  - UND CDP failure due to optical misalignment.
- ORACLES-2018:
  - Brought three separate CDPs to Sao Tome.
  - Results did not provide evaluation of freestream conditions.

Navy - NASA P-3 Original Pylon Configuration
Extended - NASA P-3 New Pylon Configuration

Computational Fluid Dynamics

- A computer aided engineering tool designed around the Navier-Stokes equations to accurately model physical phenomena.
- Robust solutions with numerous applications:
  - Stress tests
  - Aerodynamics
  - Combustion
- Open Source Field Operation and Manipulation (OpenFOAM) package.

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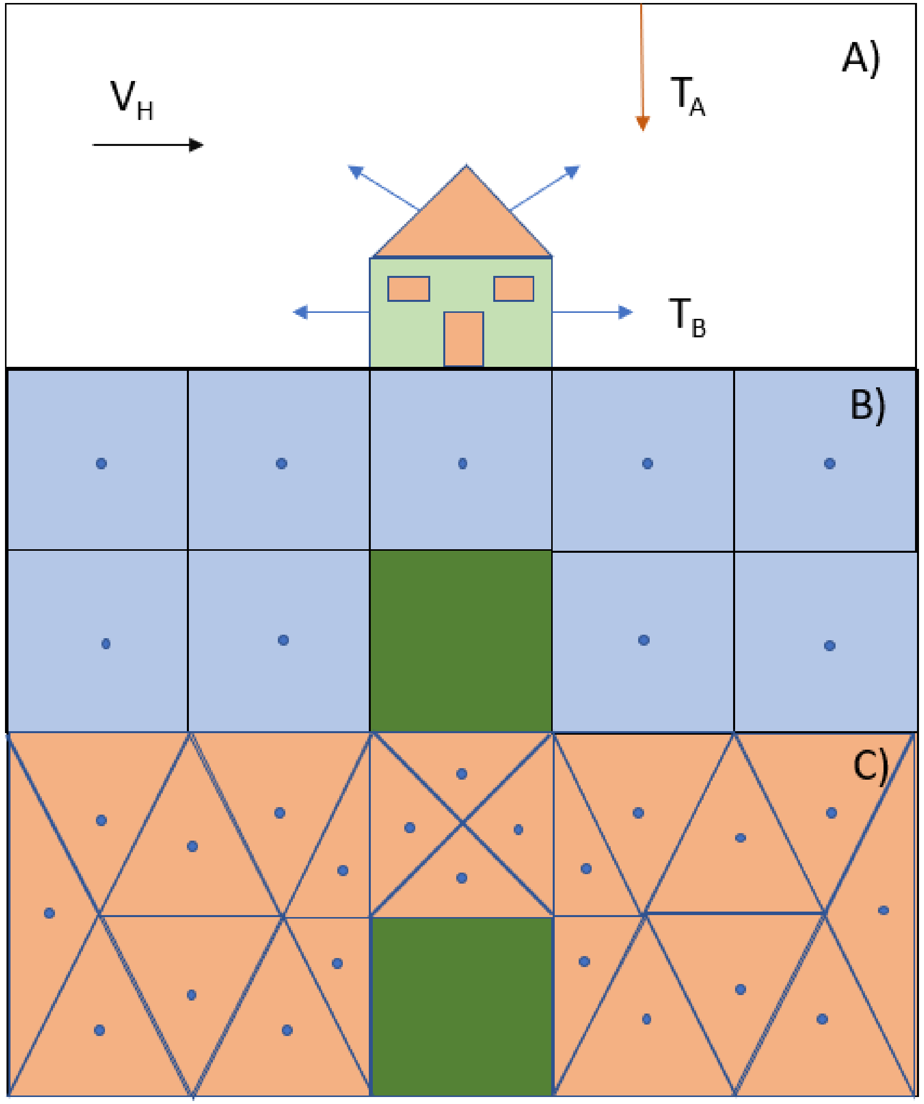
Software - OpenFoam

- OpenFOAM is open source CFD software owned by the OpenFOAM foundation, distributed under a General Public license and was created in the C++ programming language with an object-oriented coding approach (Jasak et al. 2007).
- The open-source nature of OpenFOAM allows for the development of community code and tutorials for researchers starting out with CFD analysis and removes the cost barrier of commercial software fees for many university researchers.
  - *Thank you CFD-Online.com!*
- Core numerical method used is the finite volume method.
  - A technique to transform physical properties represented as partial differential equations over a domain into discrete algebraic equations over finite volumes (Moukalled et al. 2016a)

Procedure Outline

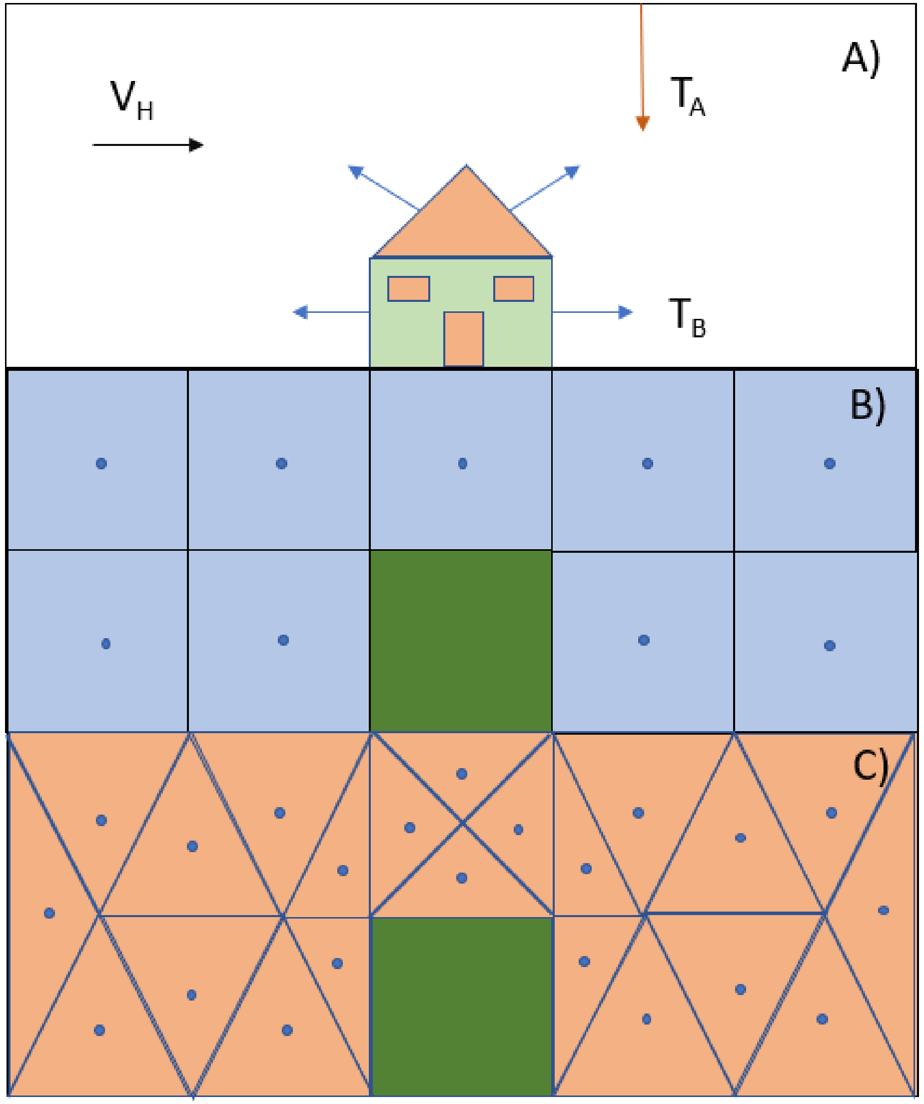
- Define all physical parameters that influence what you are modeling.
- Domain Discretization
  - The domain is subdivided into discrete non-overlapping elements that yield a grid or mesh system, which is defined by a set of vertices and bounded by faces.
  - Structured grids:
    - Ease in computation of gradients and the flux due to implicit mapping between elements.
  - Unstructured grids:
    - Flexibility in type of element used.



Governing Equations

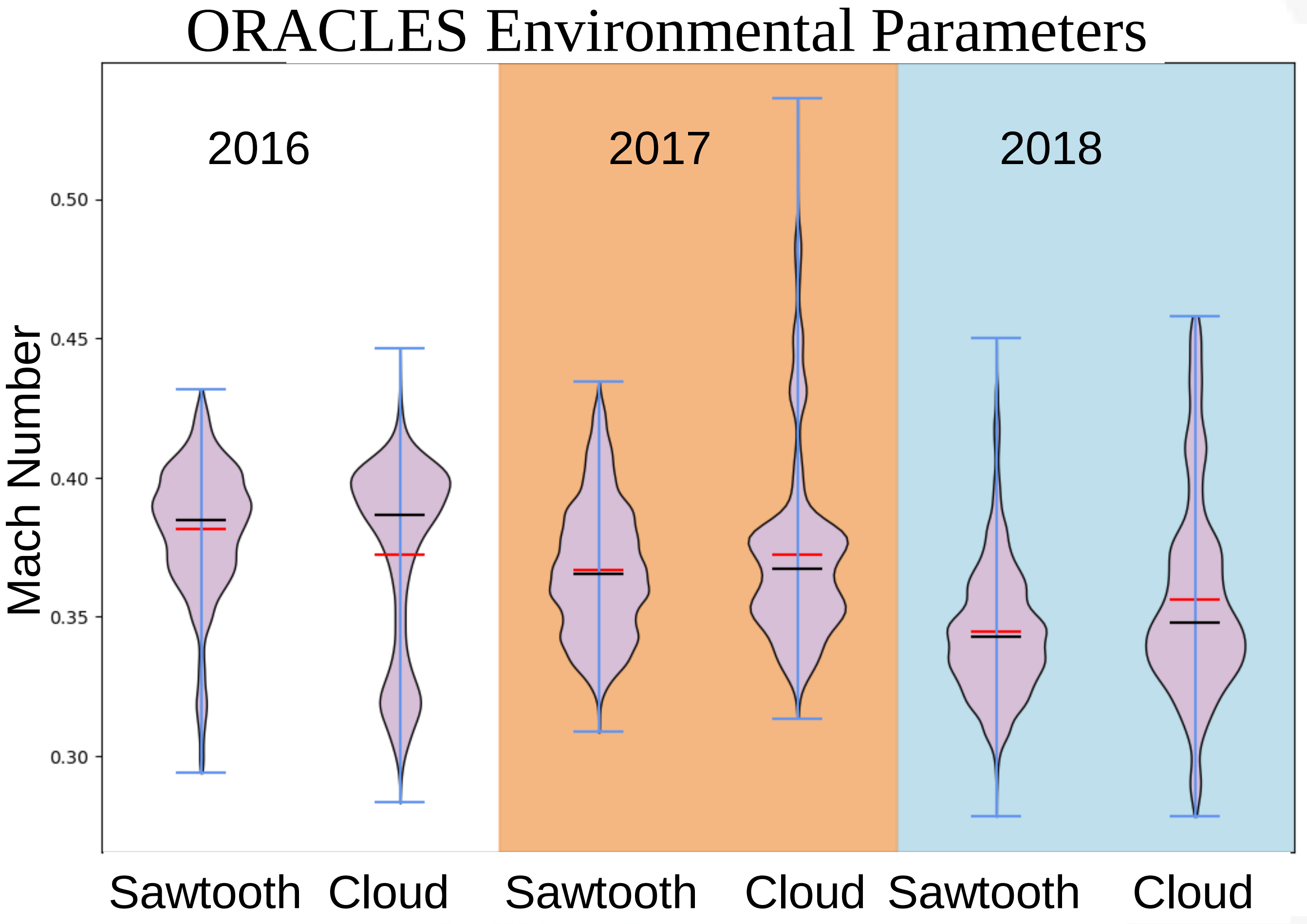
- Transform Navier Stokes equations into algebraic equations that can be solved numerically
- Numerical solutions to the finite volume method employ an iterative method, which repeatedly solves the discrete system of equations across the domain by:

    1. Initial guess of discrete values of ϕ across the domain at each grid element
    2. At each grid element C, update discrete value utilizing
    3. Iterate across the domain, with updated values of C influencing F
    4. Check if appropriate convergence criterion has been met. Otherwise, repeat.



What Are We Solving? Equations

- Incompressible flow
  - Assumes density of the fluid is constant
- Compressible flow
  - Density requires explicit calculation
  - Need to know thermodynamics of the flow fluid (i.e. Energy Equation)
- When can does the density of the fluid become variable?
  - ~0.3 Mach Number
- Subsonic aerodynamic flow
  - Disturbances propagate both upstream and downstream through domain



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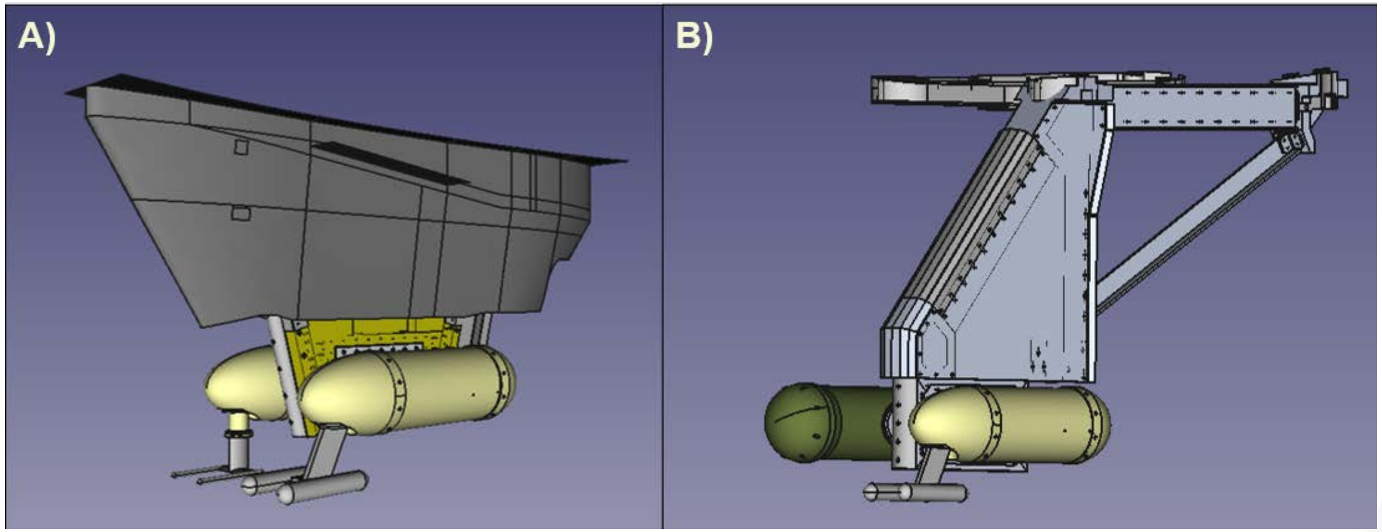
How Are We Defining the Domain?

- A simplistic three-dimensional cubic domain is first created with the OpenFoam *blockMesh* utility
  - 300m x 300m x 300m domain
- Three-dimensional computer-aided design (CAD) models of the NASA P-3 pylon configurations, with associated instrument canisters and instruments, were provided by the NASA Wallops Island Flight Facility
- the OpenFOAM utility *snappyHexMesh* is used to conform the volume mesh to the CAD model surface

Computer Aided Design Models



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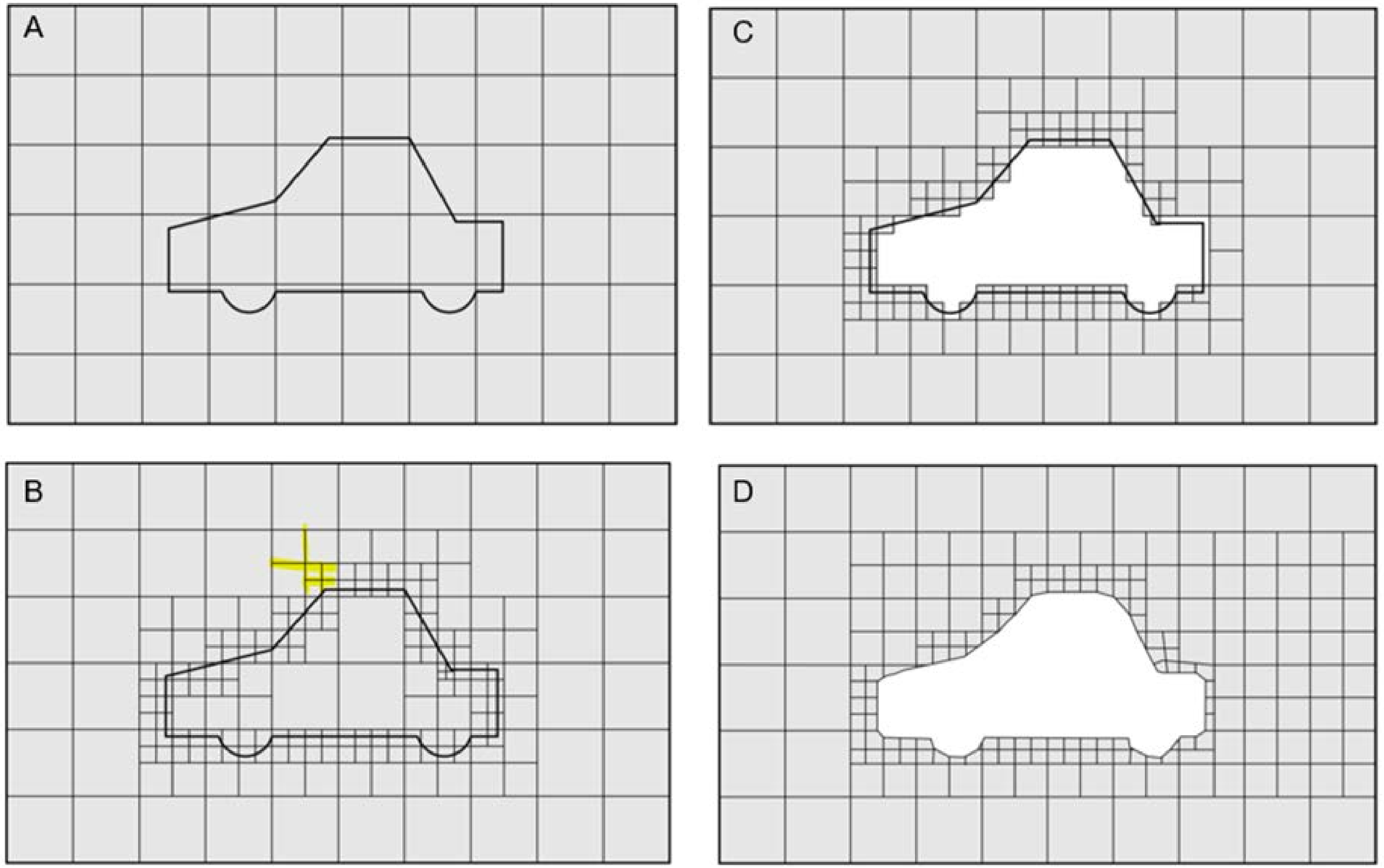
Mesh Geometry

- *snappyHexMesh* chisels the volume mesh to the geometry surface.
- A) The edges of the CAD object are first defined with the *surfaceFeatureExtract* utility.
- B) Cell splitting is performed on the edges specified by this utility and then across the surface of the geometry.
- C) Removal of volume mesh cells that are contained within the CAD object.
- D) 'Snap' CAD features into the volume mesh.



Greenshields, C., 2017: OpenFOAM User Guide: CFD Direct, Architects of OpenFOAM. CFD Direct,. https://cfd.direct/openfoam/user-guide/ (Accessed March 16, 2021)

Simulations Freestream Configuration

- Simulations of both pylon configurations at multiple initial conditions are performed.
- Initial conditions are determined from observational values during ORACLES cloud profiles.
- `Sawtooth` profiles are simulated through the altering of angle of attack of the aircraft.

Pylon Type	Velocity [m/s]	Temperature [K]	Pressure [mb]	Angle of Attack [°]
Extended	120 140	303 293	900 800	-4, 0, +4 -4, 0, +4
Navy	120 140	303 293	900 800	-4, 0, +4 -4, 0, +4

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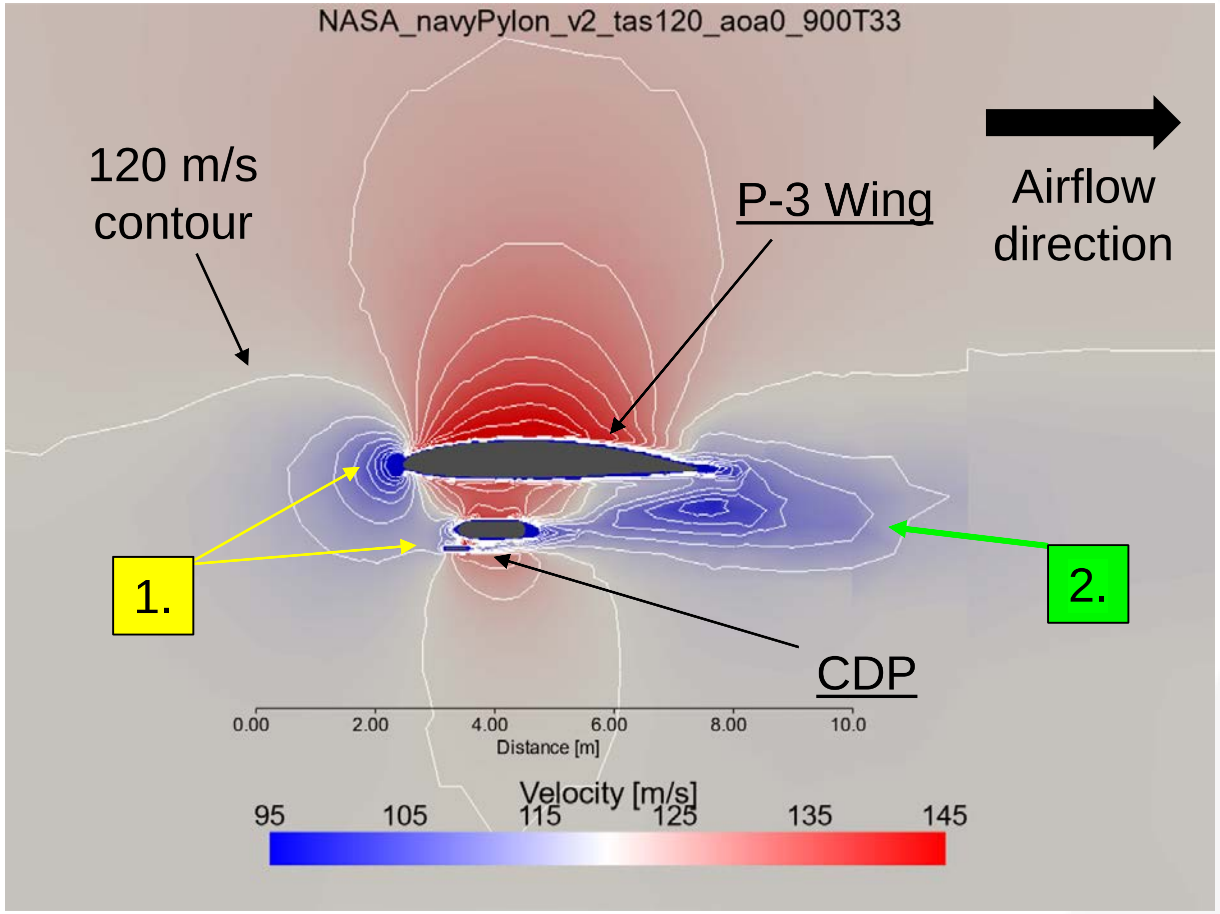
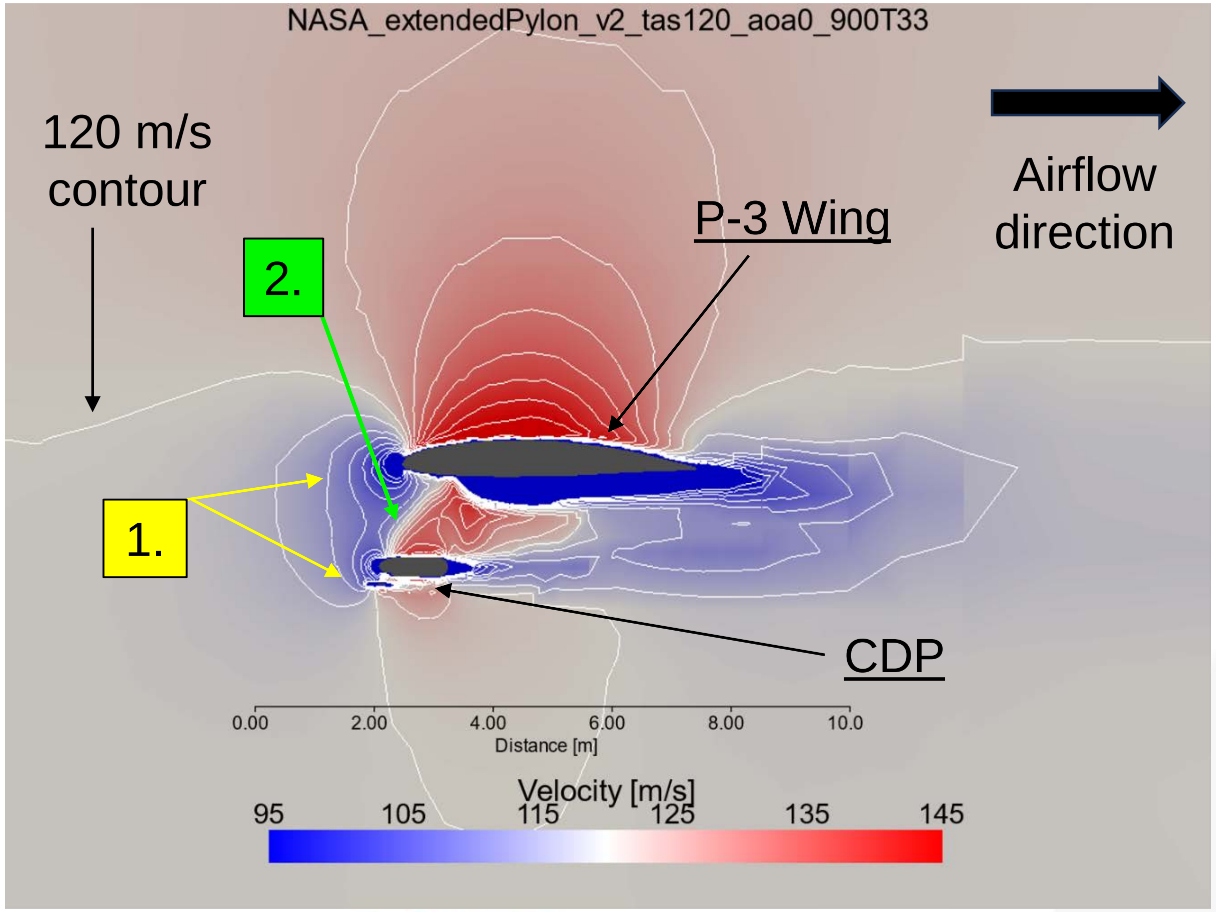
Navy Pylon

- Initialized with 120 ms^{-1} freestream velocities (white within figure).
- 1. Deceleration ahead of pylon assembly primarily due to leading edge of wing.
  - CDP is near freestream
- 2. Wake extends well behind (and ahead of) the pylon assembly.
  - Expected for subsonic aerodynamic flow

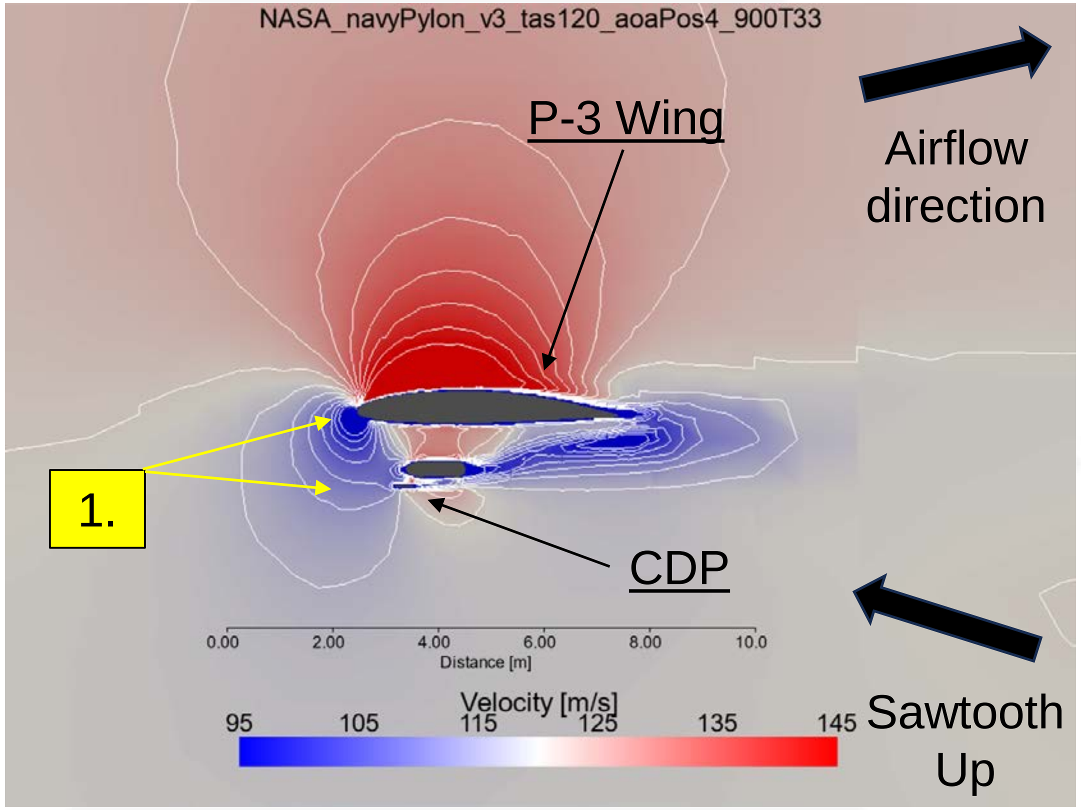


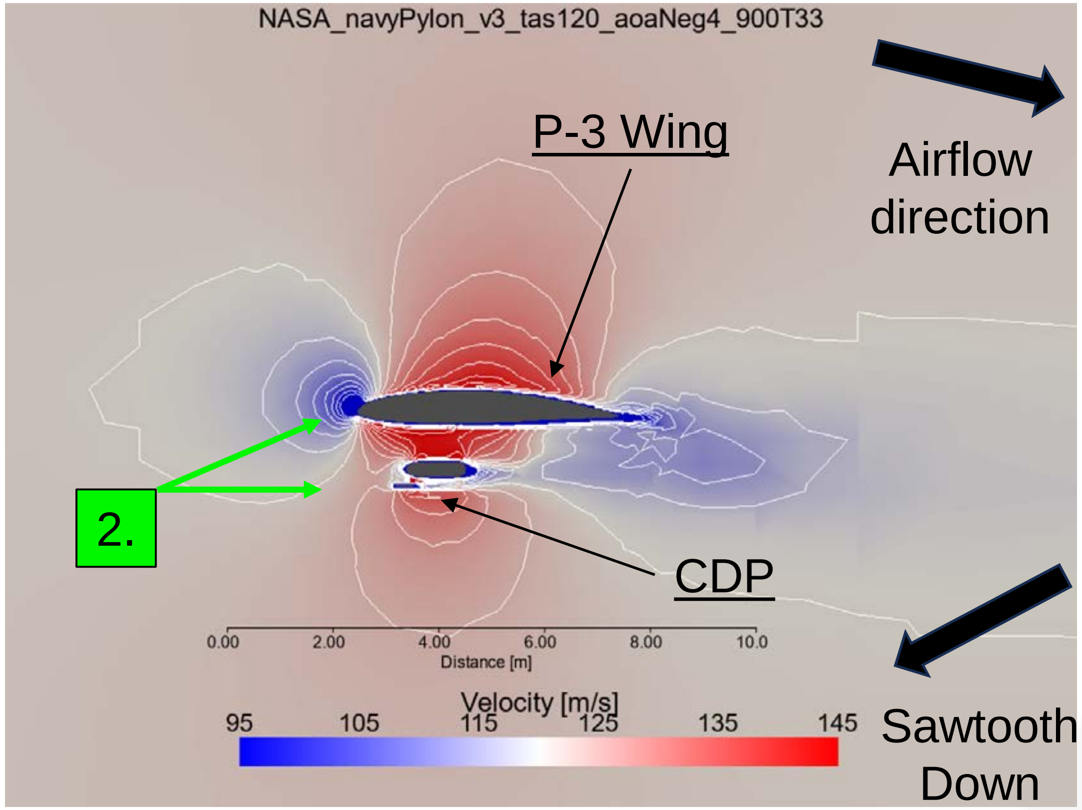
Extended Pylon

- Initialized with 120 ms^{-1} freestream velocities (white within figure).
- 1. Extent of deceleration ahead of pylon assembly is similar to the Navy Pylon.
    - Greater departure from freestream conditions at the CDP location than Navy Pylon
- 2. Tight gradient is associated with larger, longer, and wider Extended Pylon mount.



Navy Pylon – Varying Angle of Attack





1. Larger Departure from Freestream at the CDP location compared to level flight.

2. Near freestream conditions sampled at the CDP location.

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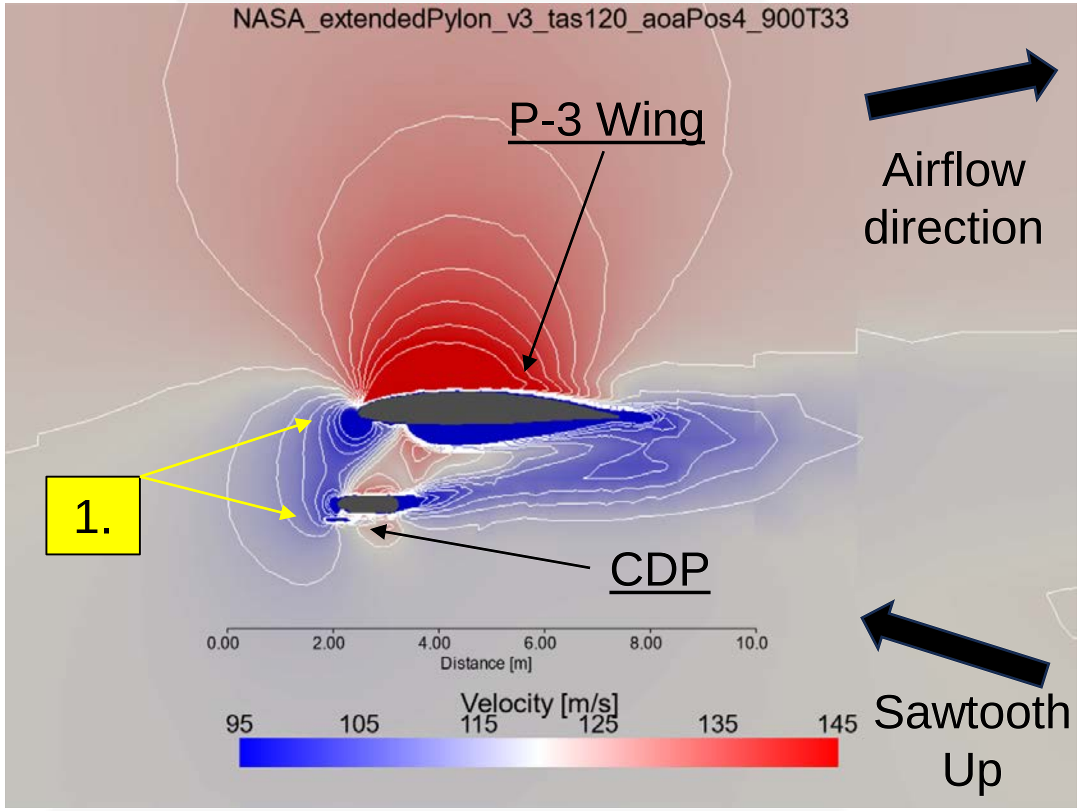
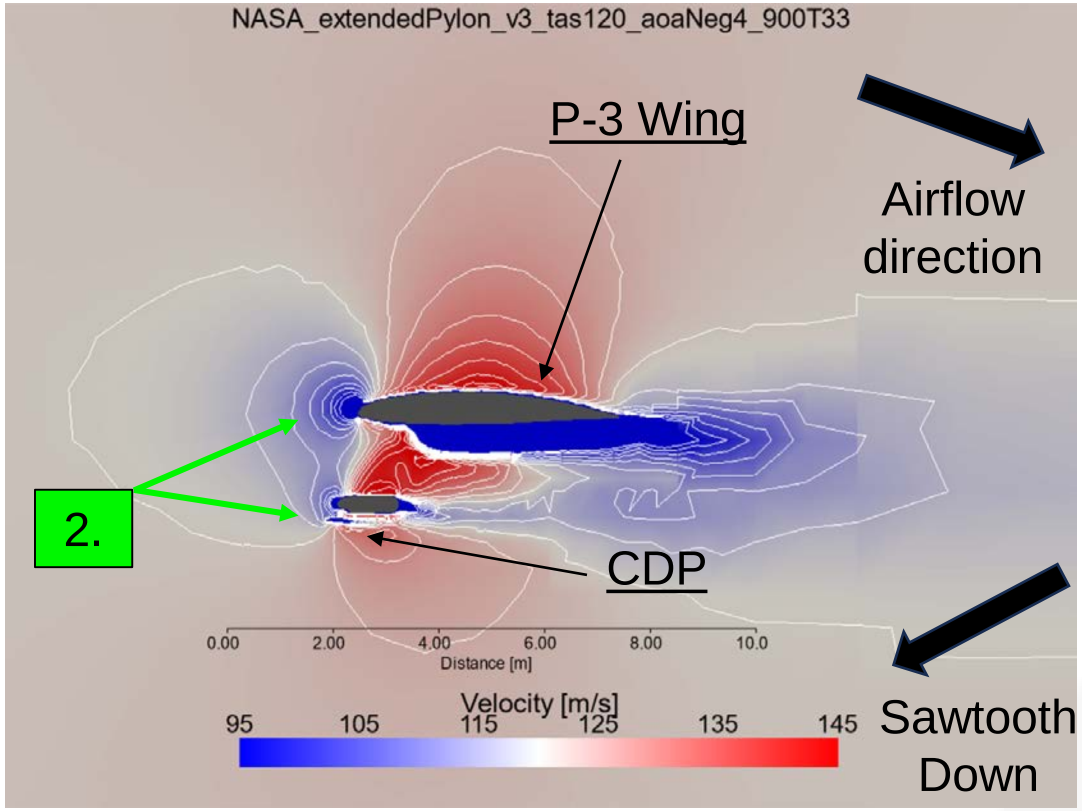
Extended Pylon – Varying Angle of Attack



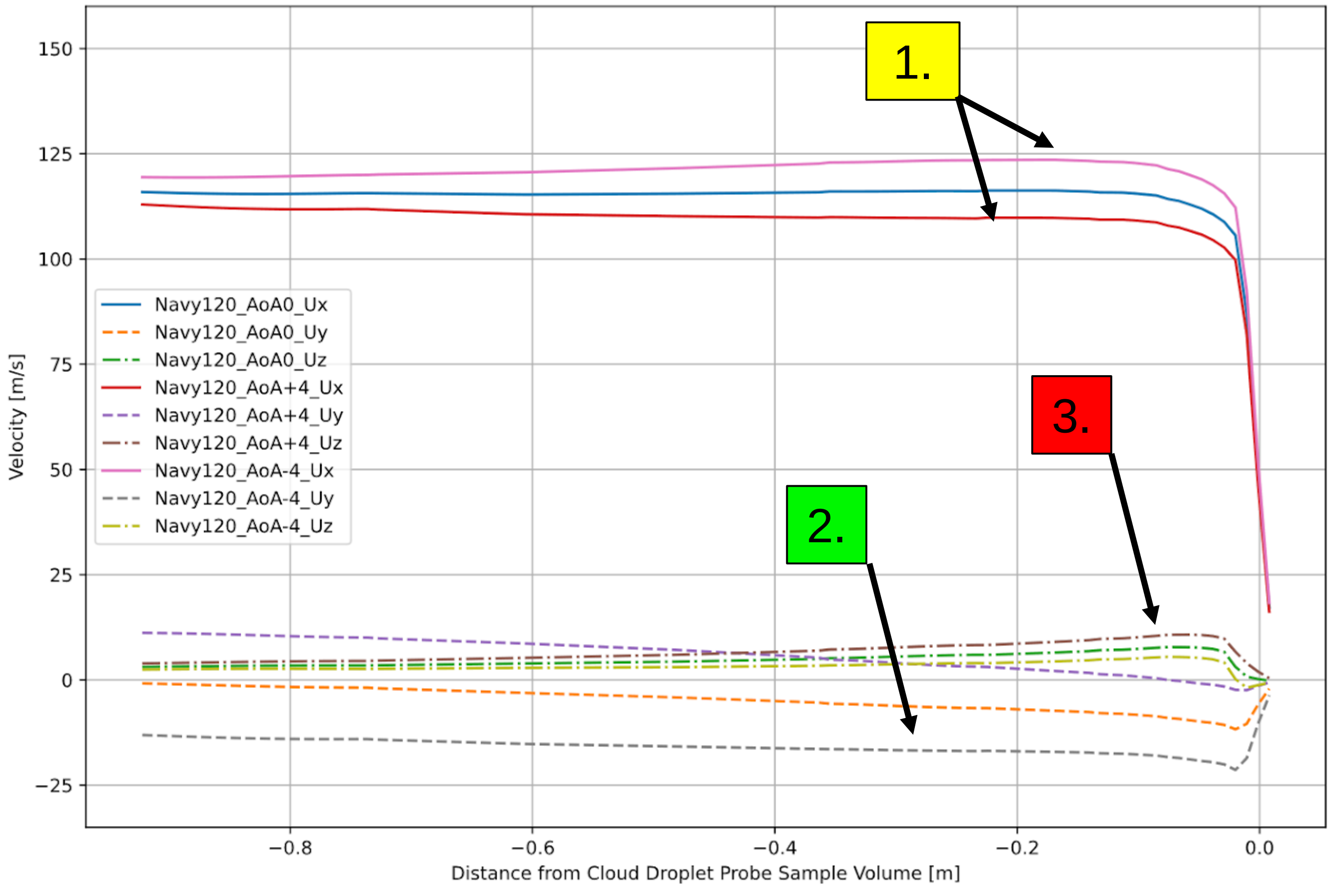


1. Velocity departure from freestream ahead of pylon similar to level flight.

2. Extent of airflow deceleration ahead of pylon increased compared to level flight.

Navy Pylon – Velocity Ahead of CDP

- Subset of 3D velocity field from cells through the CDP sample volume.
- Flow deceleration contained to within a meter ahead of the instrument.
- 1. Spread with flow deceleration due to angle of attack.
- 2. Downward velocity component at the probe location.
- 3. Outboard velocity component.



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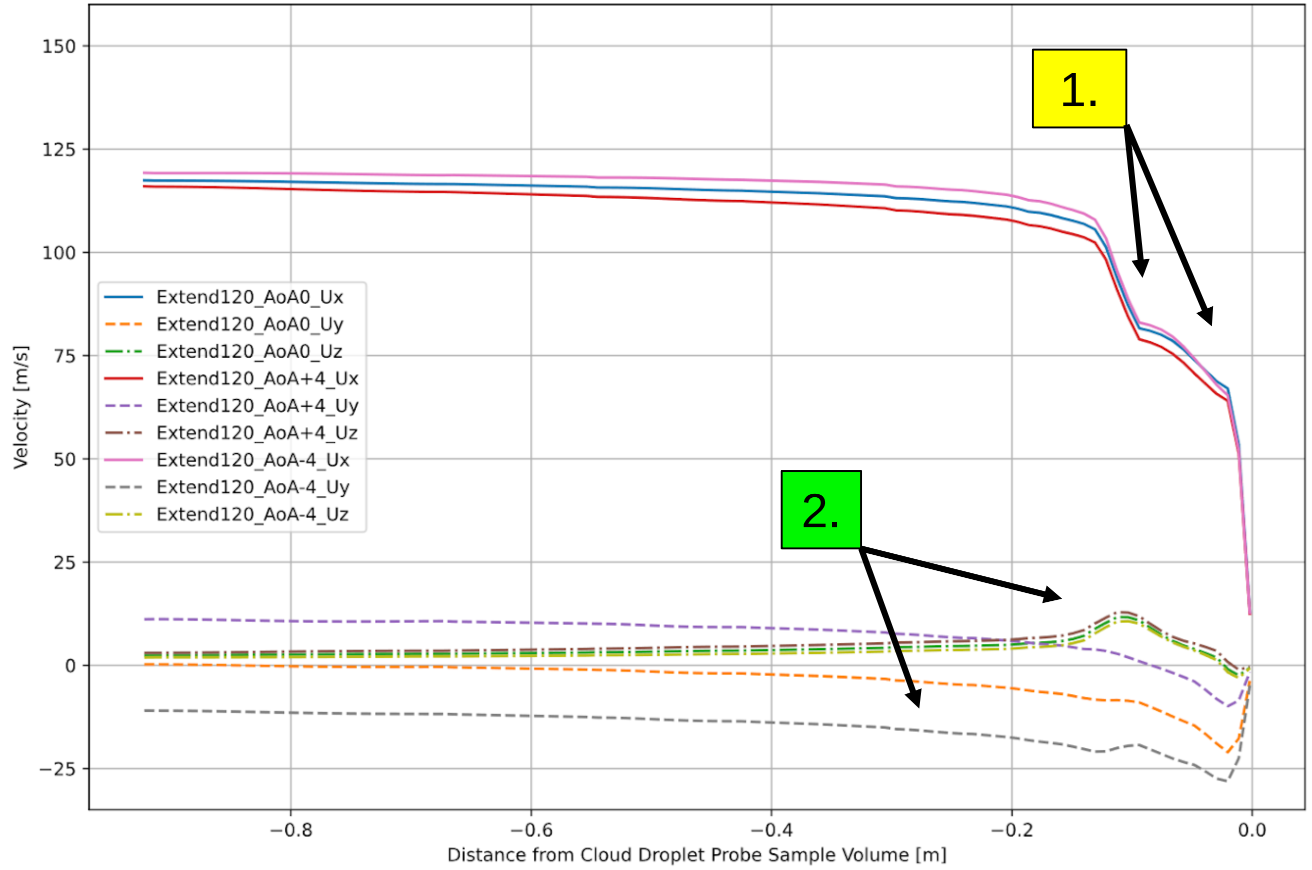
Extended Pylon – Velocity Ahead of CDP

- Flow deceleration contained to within a meter ahead of the instrument.
- ‘Two moment’ deceleration within velocity component along flight direction
- 1. Increased departure from freestream compared to Navy Pylon. Little variation due to sawtooth profiles.
- 2. Similar downward and outboard velocities between pylons.



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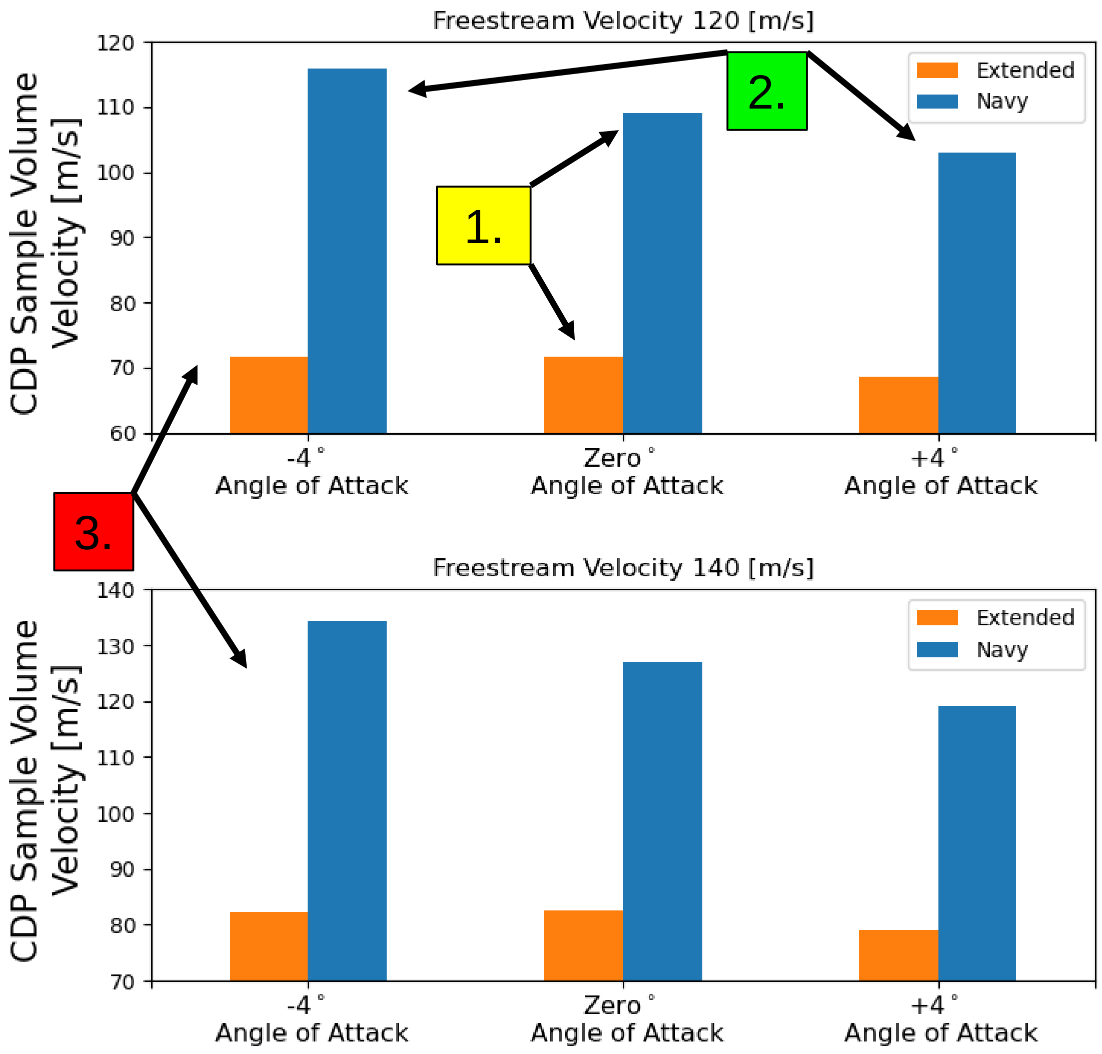
Velocity within CDP Sample Volume

- All twelve simulations shown.
- 1. Across all angle of attacks, Navy pylon is much closer to freestream conditions than Extended Pylon.
- 2. Navy pylon is dependent on angle of attack.
- 3. Departure from freestream conditions is independent of initial configuration.



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Summary

- As expected for subsonic aerodynamic flow, both NASA P-3 Orion pylon configurations result in deceleration of airflow in front of and behind the pylon locations.
- Successfully simulated NASA P-3 vertical cloud profiling maneuvers
  - Known as Sawtooths
- The Navy Pylon configuration results in closer to freestream conditions within the CDP sample volume.
  - However, dependent on the angle of airflow at the instrument location.
- The Extended Pylon configuration resulted in larger departure from freestream conditions.
  - However, independent on the angle of the airflow at the instrument location.

Conclusions

- Computational Fluid Dynamics software and tools have progressed to the point researchers are capable of conducting this analysis for their own observing platforms.
  - Need three-dimensional computer aided design (CAD) models
  - Open source software (access to Docker; OpenFOAM, FreeCAD, PyVista)
  - Server/Cluster with sufficient memory
- Analysis of the airflow around aircraft in-situ microphysical instrumentation should be performed before manufacturing of mounts.
- Recommended that in-situ atmospheric instrumentation be placed ahead of the leading edge of the aircraft wing with acknowledgement that significant departure from freestream conditions are to be expected and corrected for within the dataset.

Recommendations

- As indicated within this study, wing-mounted instrumentation will affect the relative airflow at the sampling location, regardless of the placement ahead or behind the leading edge of the aircraft.
- Recommended that in-situ atmospheric instrumentation be **placed ahead of the leading edge of the aircraft wing** with acknowledgement that significant departure from freestream conditions are to be expected and corrected for within the dataset.
- It is also critical to model standard sampling profiles, as the results of this analysis show the placement of instruments can be influenced by these profiles.
- It is recommended that every moving observational platform undergo computational fluid dynamic analysis to understand the airflow around any potential mounting position before pylon is manufactured.
- It is recommended that the placement of total temperature probes and pitot static probes accompany in-situ instrumentation on the pylon assembly, as these observations will give support to any computational fluid dynamics analysis.

Acknowledgments

- Thank you to family and friends for support these many years.
- Thank you to the dissertation committee for support and resources to explore this topic.
- Thank you to Mike and Dave for the opportunity to conduct airborne research onboard the UND Citation II and NASA P-3 Orion.
- Thank you to everyone who showed attended a dissertation defense on a late summer Friday afternoon!

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Extra Slides

CDP Sample Volume

SOLUTIONS	FREESTREAM [m/s]	Ux [m/s]	Uy [m/s]	Uz. [m/s]	Umag % of Freestream
NASA_extendedPylon_v2_tas120 aoa0_900T33	120	71.64	-16.37	3.07	61%
NASA_extendedPylon_v3_tas120 aoaPos4_900T33	120	68.46	-5.67	4.525	57%
NASA_extendedPylon_v3_tas120 aoaNeg4_900T33	120	71.5	-25.49	2.67	63%
NASA_extendedPylon_v3_tas140 aoa0_800T20	140	82.543	-19.15	3.68	61%
NASA_extendedPylon_v3_tas140 aoaPos4_800T20	140	78.87	-6.67	5.28	57%
NASA_extendedPylon_v3_tas140 aoaNeg4_800T20	140	82.25	-29.88	3.12	63%

SOLUTIONS	FREESTREAM [m/s]	Ux [m/s]	Uy [m/s]	Uz. [m/s]	Umag % of Freestream
NASA_navyPylon_v2_tas120 aoa0_900T33	120	109.07	-10.58	6.99	92%
NASA_navyPylon_v3_tas120 aoaPos4_900T33	120	102.98	-1.48	10.82	86%
NASA_navyPylon_v3_tas120 aoaNeg4_900T33	120	115.89	-19.95	4.49	98%
NASA_navyPylon_v3_tas140 aoa0_800T20	140	126.96	-12.55	8.40	91%
NASA_navyPylon_v3_tas140 aoaPos4_800T20	140	119.18	-1.95	11.98	86%
NASA_navyPylon_v3_tas140 aoaNeg4_800T20	140	134.44	-23.40	5.41	98%
NASA_noPylons_v2_tas120 aoa0_900T33. Navy CDP Location	120	121.41	-3.58	3.88	101%
NASA_noPylons_v2_tas120 aoa0_900T33. Extended CDP Location	120	118.49	-1.55	3.00	99%

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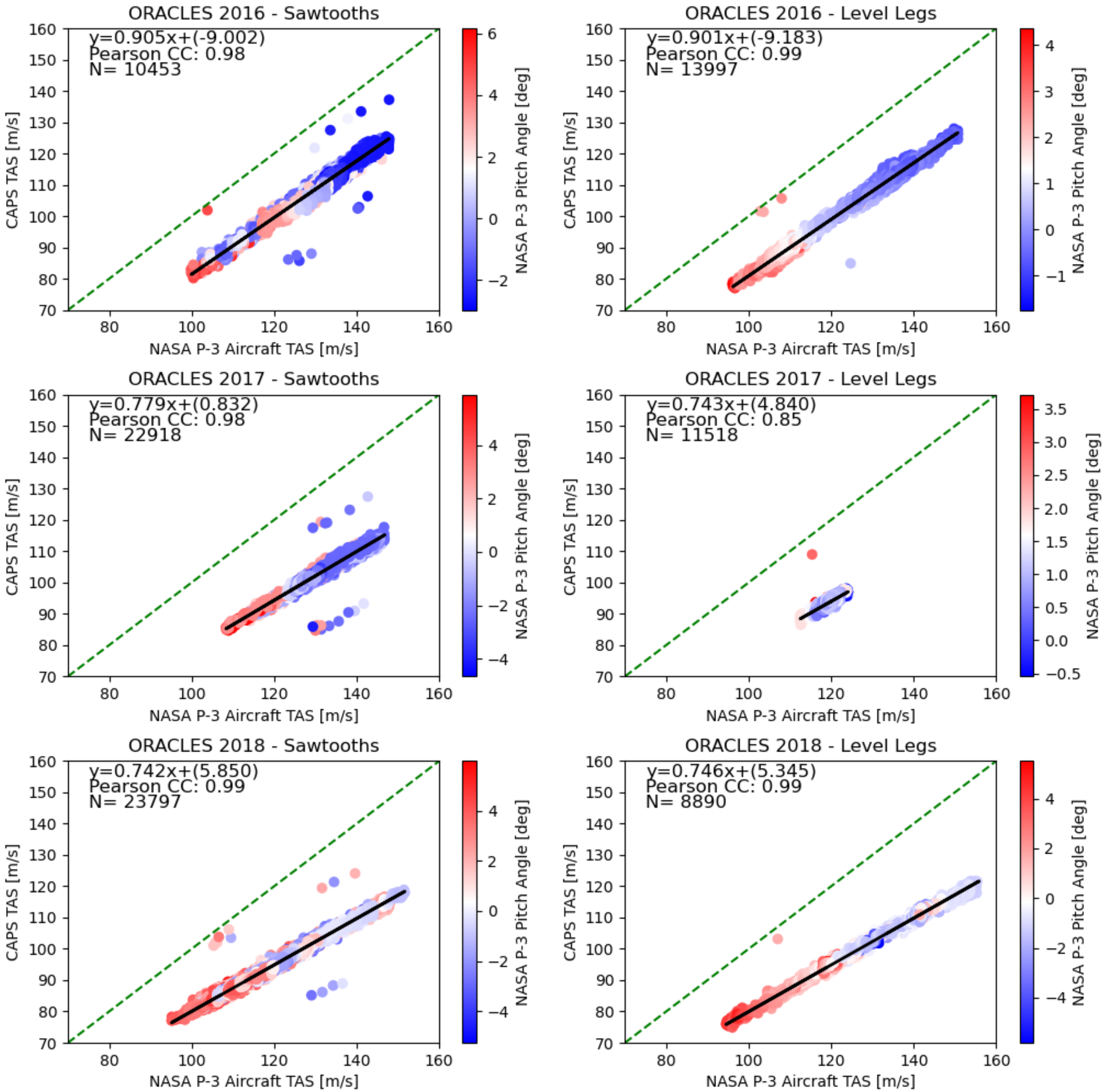
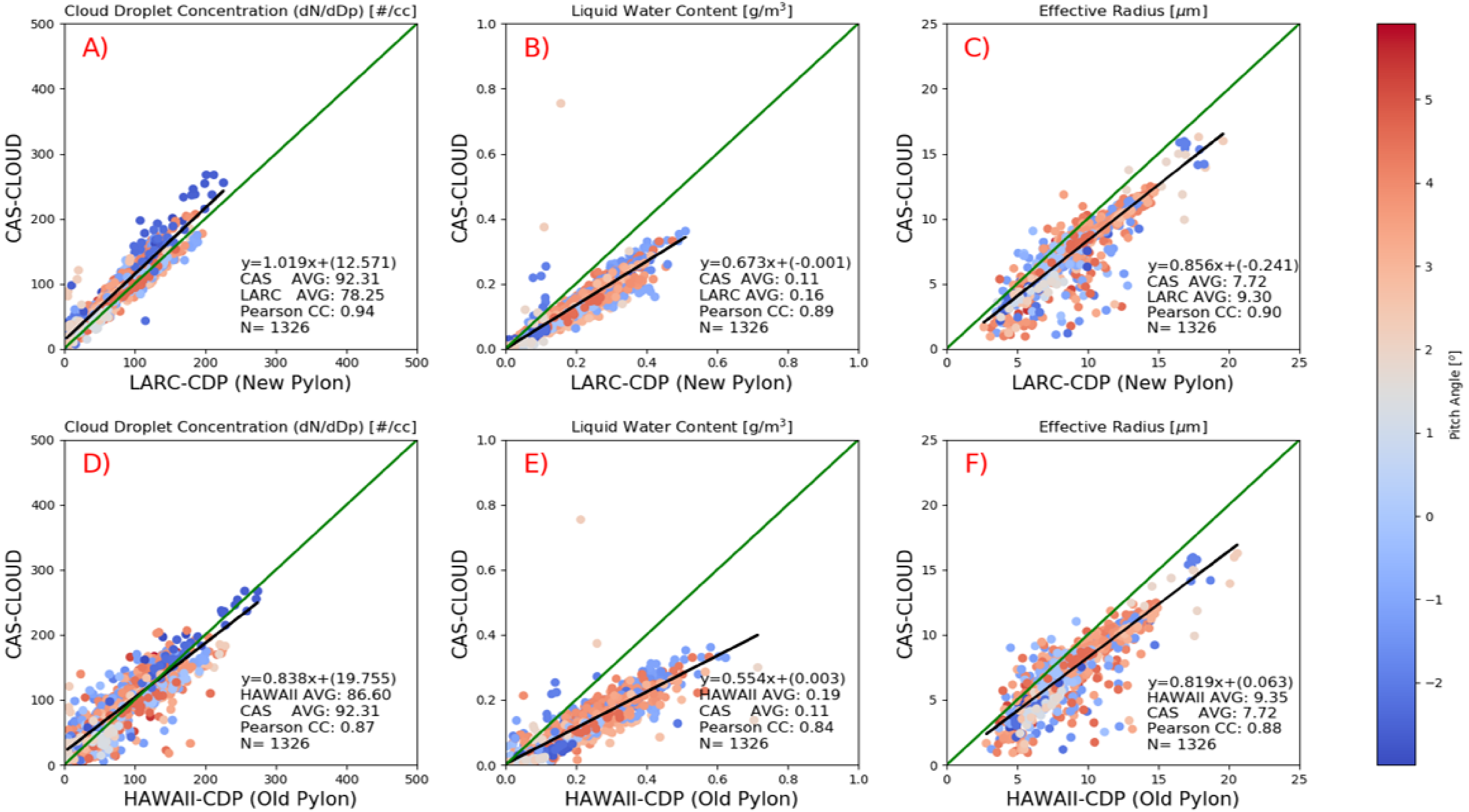
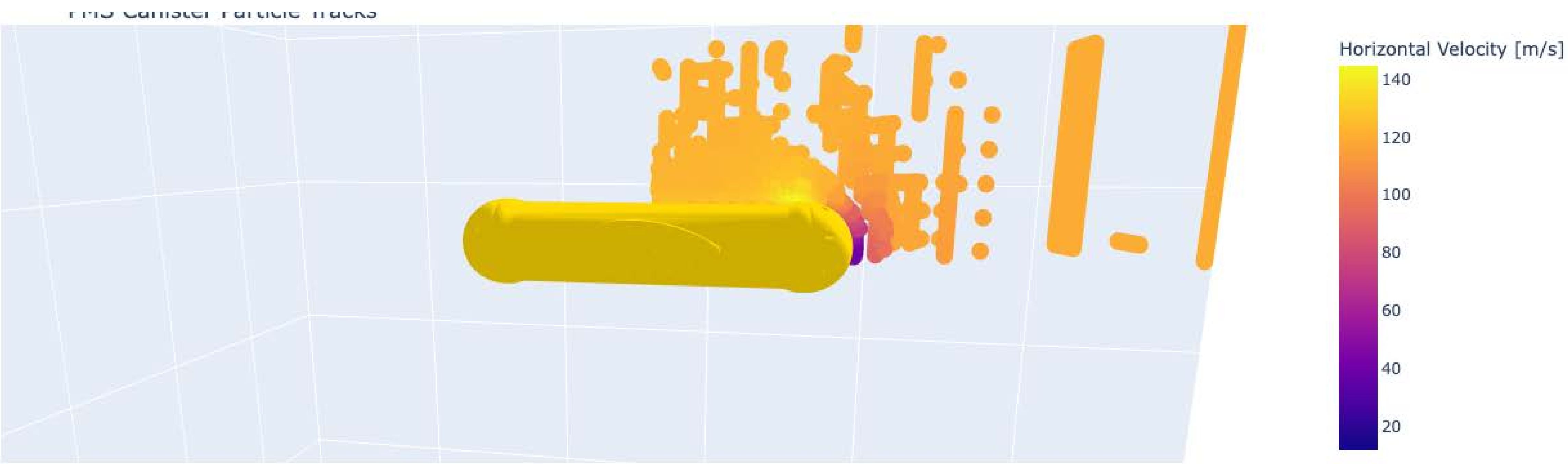


ORACLES 2016 - Sawtooths
y=0.905x+(-9.002)
Pearson CC: 0.98
N= 10453
ORACLES 2016 - Level Legs
y=0.901x+(-9.183)
Pearson CC: 0.99
N= 13997
ORACLES 2017 - Sawtooths
y=0.779x+(0.832)
Pearson CC: 0.98
N= 22918
ORACLES 2017 - Level Legs
y=0.743x+(4.840)
Pearson CC: 0.85
N= 11518
ORACLES 2018 - Sawtooths
y=0.742x+(5.850)
Pearson CC: 0.99
N= 23797
ORACLES 2018 - Level Legs
y=0.746x+(5.345)
Pearson CC: 0.99
N= 8890
CAPS TAS [m/s]
NASA P-3 Aircraft TAS [m/s]
NASA P-3 Pitch Angle [deg]

ORACLES 2018 - SAWTOOTHS - [5 #/cc cloud threshold]

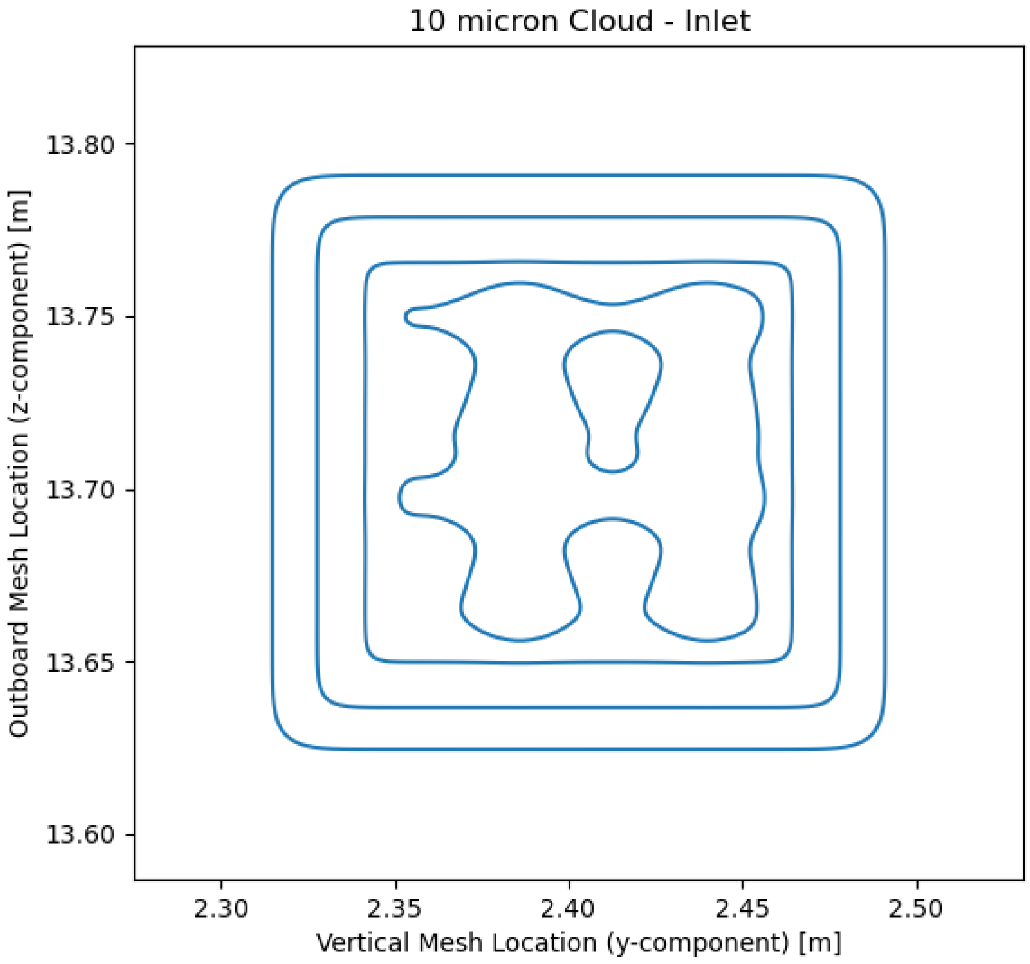


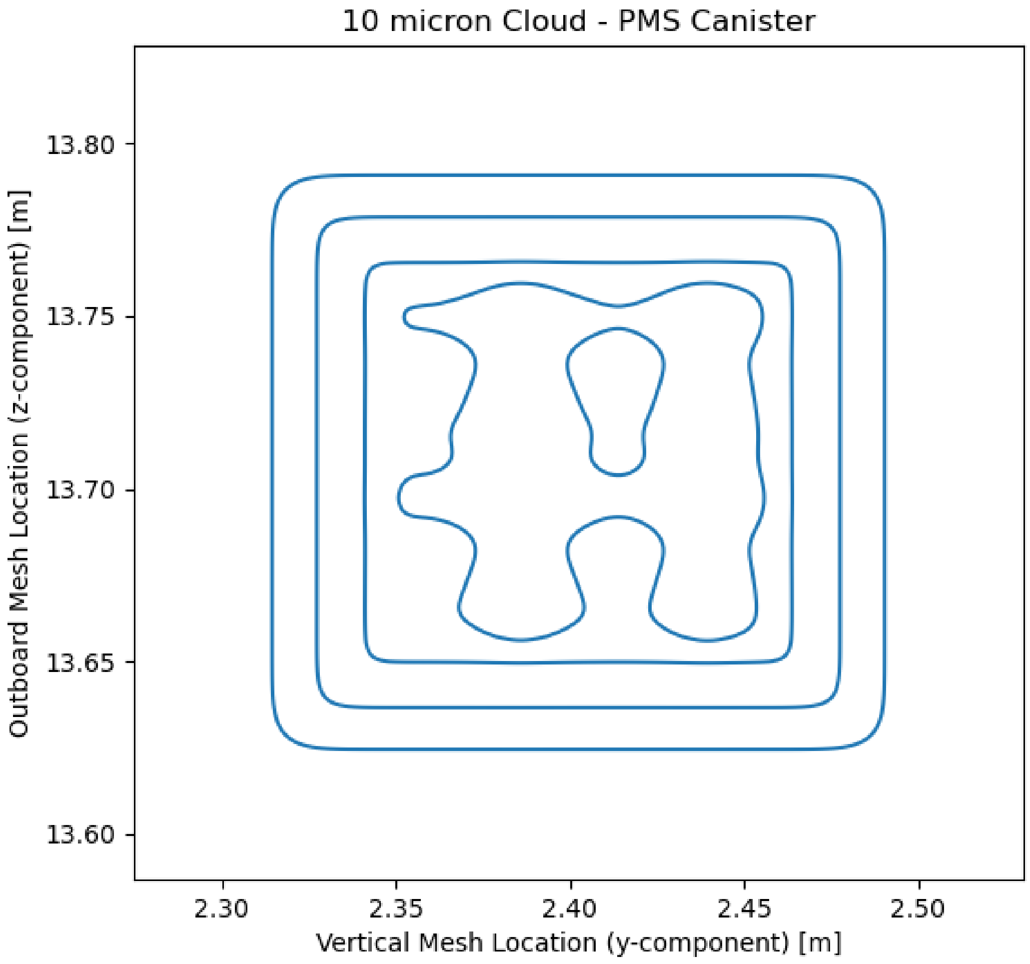

Horizontal Velocity [m/s]
140
120
100
80
60
40
20

Navy Pylon – Zero Angle of Attack; 120 m/s initialization

50K simulated particles, 100#/cc, 10 microns

90% Sampling Efficiency





Extended Pylon – Zero Angle of Attack; 120 m/s initialization
50K simulated particles, 100#/cc, 10 microns
~70% Sampling Efficiency