AIRFLOW DISTORTION
(including characterizing inlet performance)

Twohy, Korolev, Nacass, Rogers,
Cziczo, Hermann

OUTLINE

- Intro and Historical Perspective
- Aircraft Influence
  - Boundary layer vs. particle trajectories
  - Shadow zones and concentration regions
- Particle Sampling (ice crystal is one type of particle)
  - Inlet efficiency
  - Inlet types for cloud sampling
  - Inlet housing effects
  - Ice/Inlet Interactions
- Uses of Computational Fluid Dynamics (CFD)
- Recommendations/Take Home Points

WRIGHT FLYER (1903)

Speed: 13 m s^{-1}
Weight: 275 kg
Fuselage: entirely open
Aerodynamic heating: <1K.
Instruments: stopwatch, anemometer, & tachometer.

MODERN JET AIRCRAFT (2010)

Speed: >200 m s^{-1}
Weight: >10,000 kg
Fuselage: solid up to several meters
Aerodynamic heating: up to 20K
Instruments: Tens to 100's of different types

TECHNIQUES FOR DETERMINING FLOW DISTORTION

Early methods

- Wind tunnel tests
- Flight tests - measuring P, tufting & oil streaks
- Potential flow models

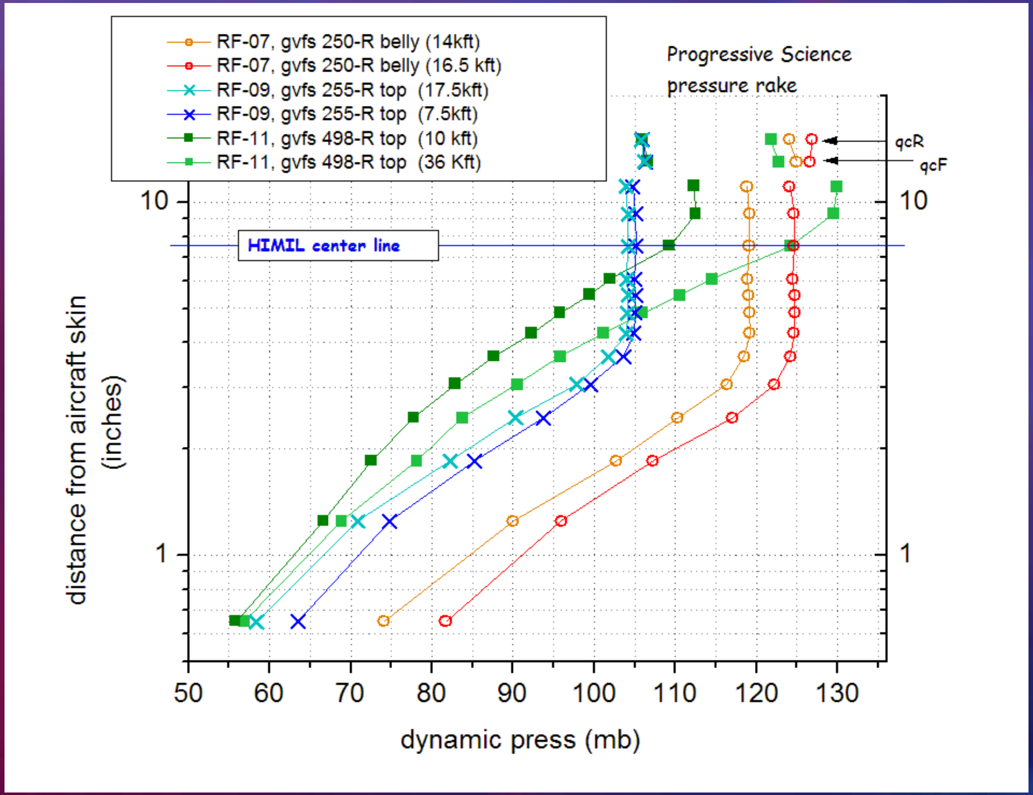
Modern methods (CFD)

- CAD-based modeling, meshing & numerical flow solvers
- Thermodynamics, heat transfer, stress, multi-phase systems
- Turbulence options, steady or non-steady
- Integrated particle trajectory calculations
- Used for instrument design, performance testing, flight certification

AIRCRAFT BOUNDARY LAYER

Dynamic pressure profiles measured at different fuselage locations on NCAR G-V

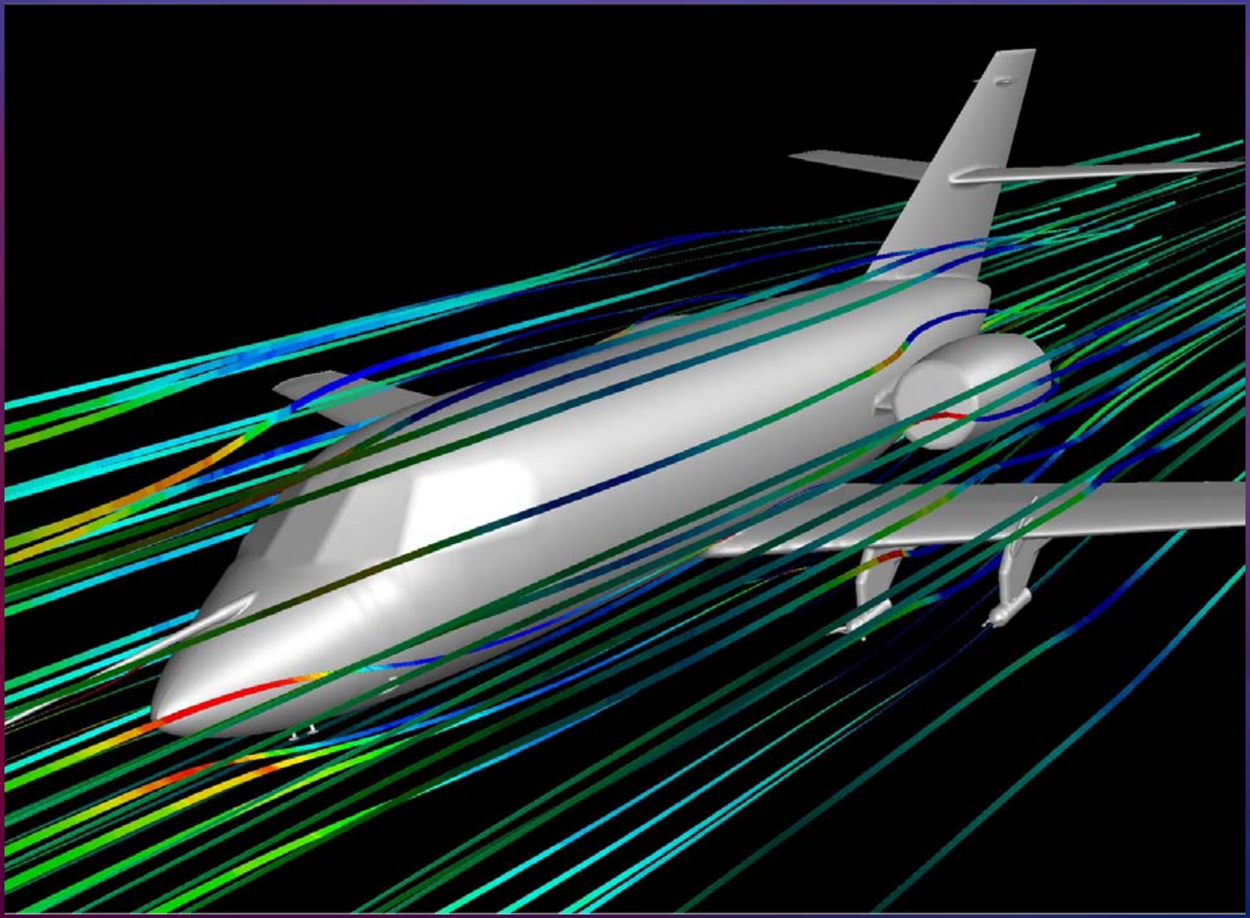
Note boundary layer is thinnest on bottom forward locations and thickest on top rear locations.



Dave Rogers

- Thickness depends not only on distance from nose, but on angle of attack, surface roughness features
- Airspeed and turbulence vary within BL
- Sampling within BL → potential for non-representative sample

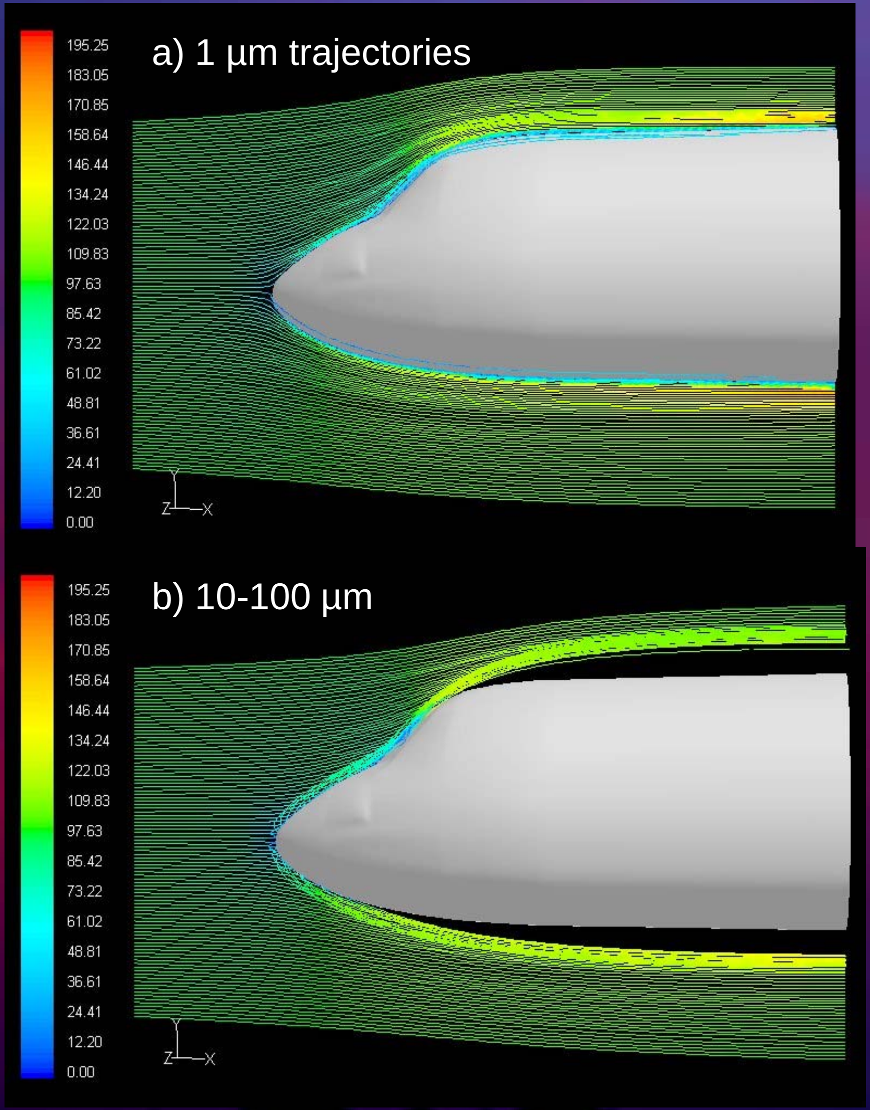
STREAMLINES OF THE FALCON-20



Note streamlines are not always parallel to fuselage and vary with aircraft attitude

Philippe Nacass w/ Gambit-Fluent Software

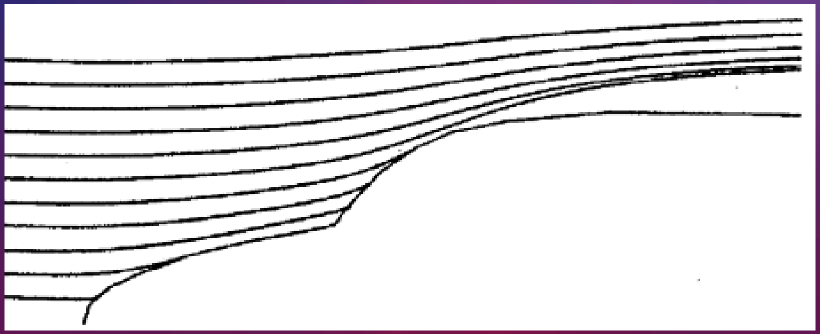
PARTICLE BEHAVIOR AROUND AIRCRAFT FUSELAGE



a) Small particles follow streamlines around fuselage (ATR-42)
b) Intermediate-sized (~100 μm) particles partially deviate from streamlines, creating "shadow zone" aft of high curvature region
c) Large (~1000 μm) particles follow straight trajectories, unaffected by airflow changes (not shown)

Philippe Nacass w/ Gambit-Fluent Software

FUSELAGE SHADOW ZONES



King, 1984: For fuselage locations, the maximum shadow zone depth is 15% to 20% of the fuselage radius

Shadow zone thickness >> boundary layer for cloud particles!

Maximum depth occurs at particle radius with modified Stokes #

$$S_{\text{mod}} = \frac{\left(2a^2 V\rho\right)}{9\eta b} \approx 6$$

$$a \approx \left(\frac{27\eta b}{V\rho}\right)^{0.5}$$

where *a* is the particle radius, *V* is the air velocity, ρ is the particle density, η is the air viscosity, and *b* is the fuselage radius.

This is ~100-150 μm aerodynamic diameter for Electra or P-3 type aircraft

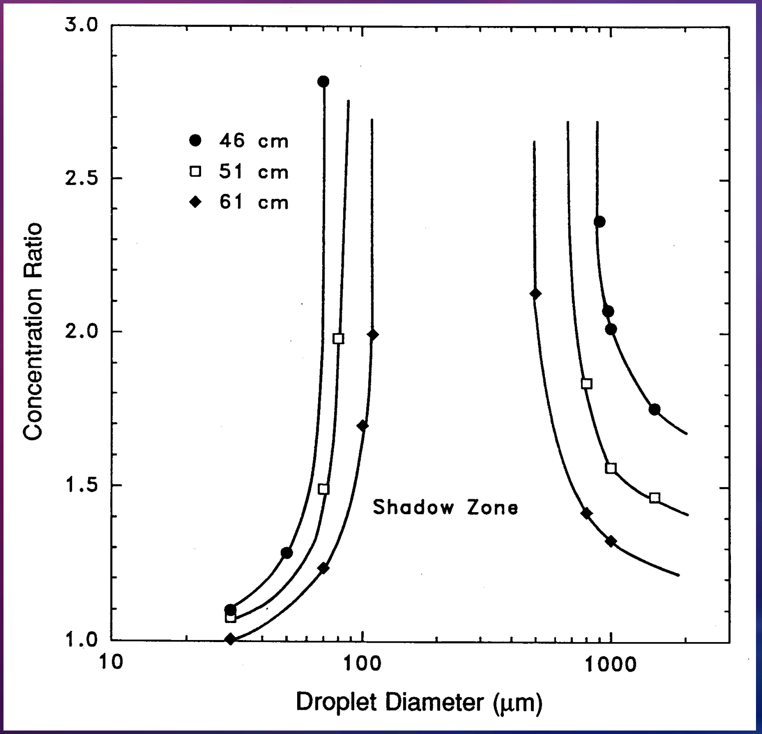
CONCENTRATION REGIONS

Droplets not “shadowed” may have enhanced concentrations relative to freestream

Concentration Ratio

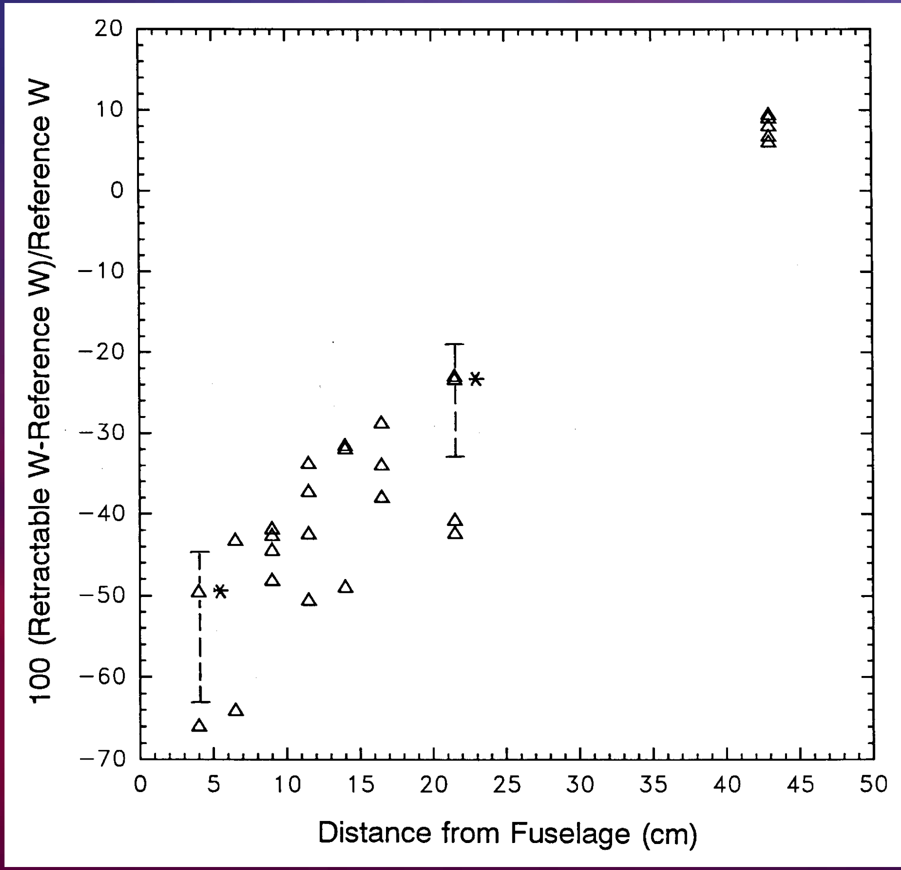
$$CR = \frac{N_{samp}}{N_o}$$

Behind cockpit poor location for microphysics. Sides, bottom, wing better



Electra Overhead Location. Twohy & Rogers, 1993

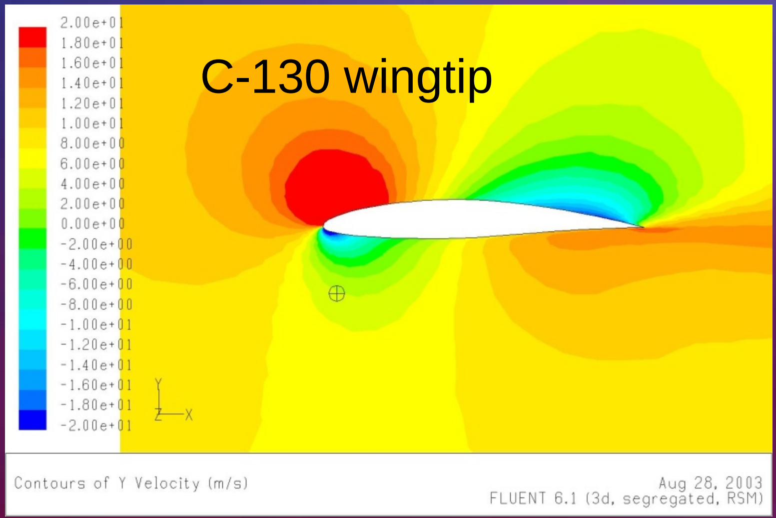
EMPIRICAL MEASUREMENT OF SHADOW ZONE



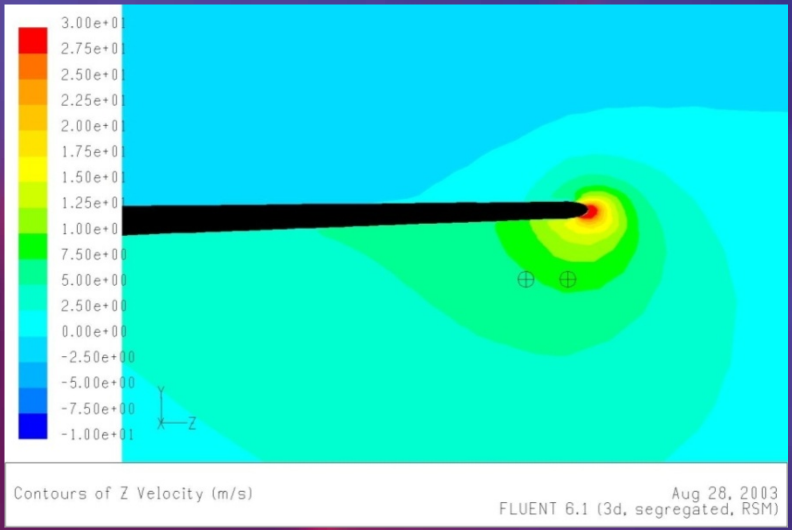
- Measured hot-wire LWC at King Air mounting locations, left & right
- One probe moved different distances from fuselage, other fully extended as reference
- LWC decreased steadily nearer fuselage, indicating shadowing of wider range of drop sizes
- General agreement with models

King Air Overhead Location. Twohy & Rogers, 1993

WING LOCATIONS ALSO HAVE DISTORTION



Velocity in vertical direction

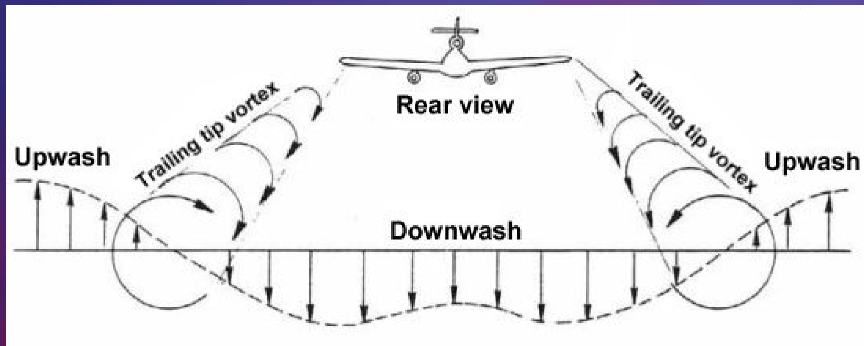


Velocity in horizontal direction

More in Alexei’s Talk on Effects on Measurements

CFD Courtesy Derek Straub

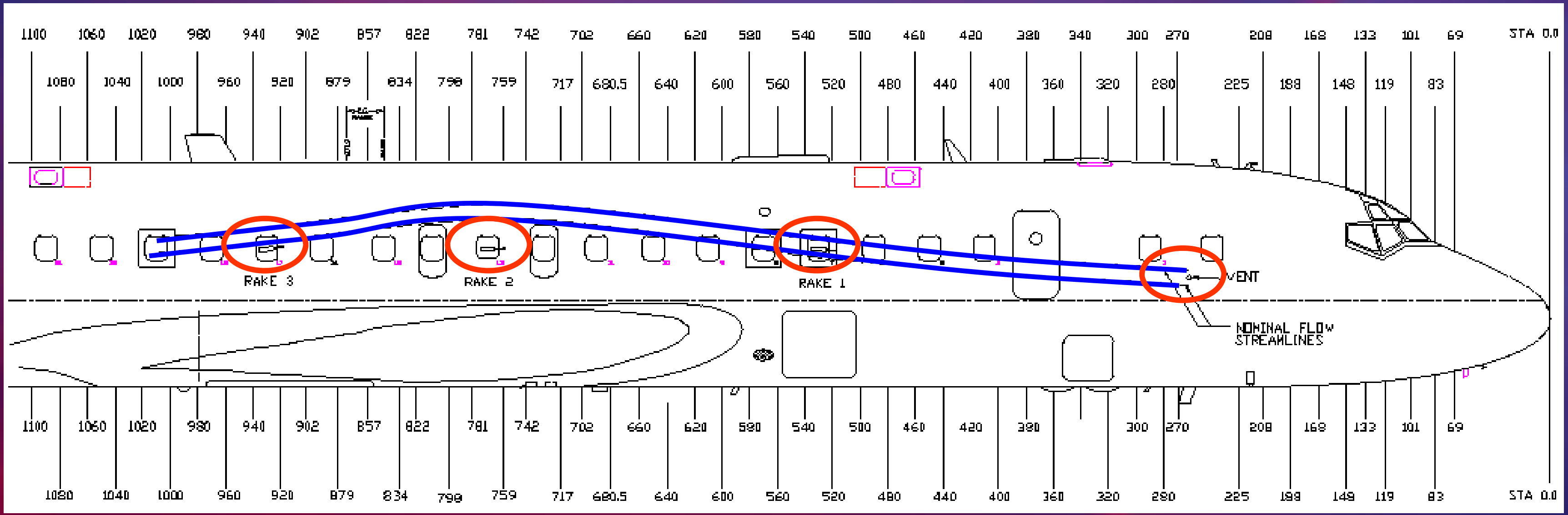
EFFECTS OF WINGTIP VORTICES



Geese fly in the upwash from the wingtip vortices of the bird ahead

Low pressure in wingtip vortices creating visible condensation

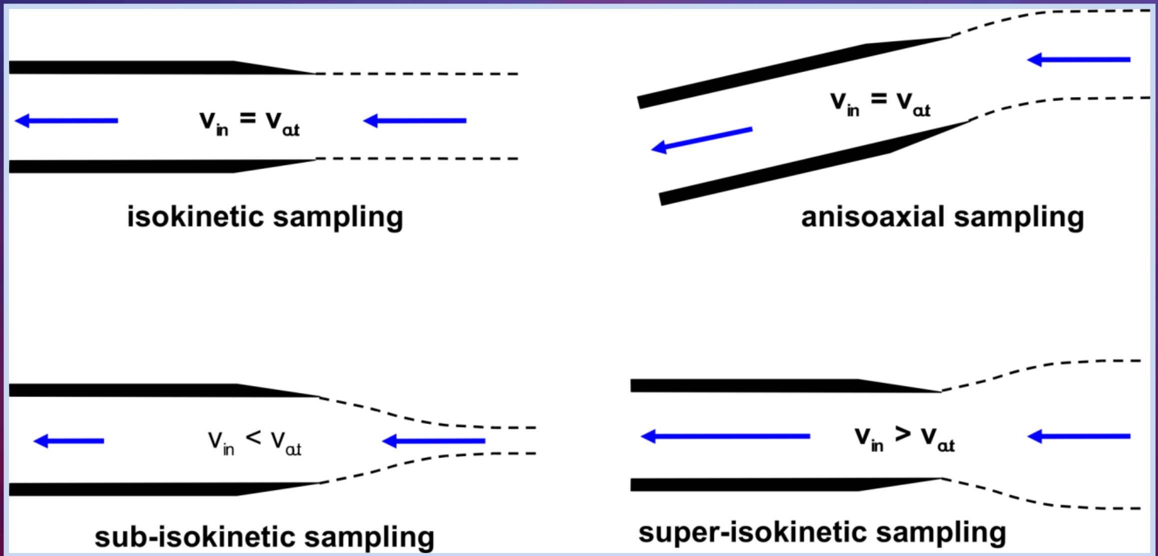
EFFECTS OF UPSTREAM VENTS



Vent and inlet positions on the NASA DC-8 research. Unusual CO_2 and H_2O data. Airflow streamlines are highlighted in blue. Air from a cabin air vent stayed within the aircraft boundary layer for at least ~20 m downstream

Vay et al., 2003

TYPES OF PARTICLE SAMPLING



Sampling regimes for inlets with different velocity ratios and angles

Aspiration efficiency *A* is concentration of particles inside inlet tip to those outside.

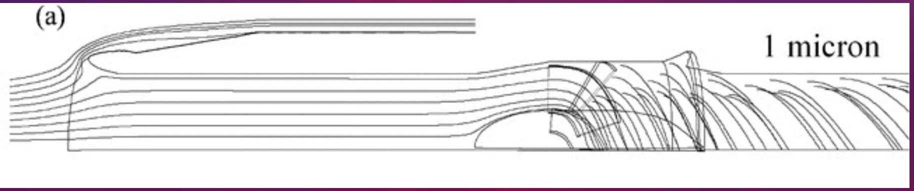
For subisokinetic and superisokinetic sampling in 5 mm inlet,
A will deviate from 1.0 for particles > ~0.6 µm diam.*
All cloud particles do not follow streamlines under these conditions.

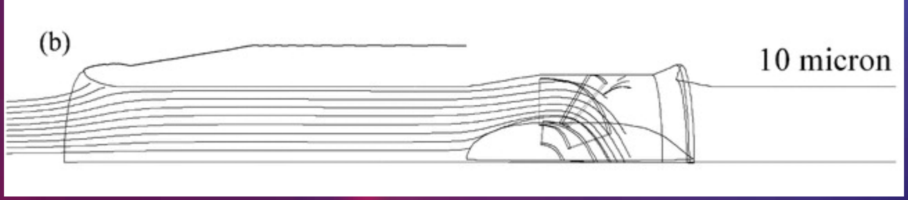
This can actually be a good thing (next slide), or not.

*At 500 hPa, 150 ms^{-1} airspeed, and a particle density of 1.5 g cm^{-3}

CLOUD INLETS USING INERTIAL SEPARATION TO COLLECT DROPLETS

Bulk Water Collectors (slotted rods, axial flow cyclone) collect droplets above a certain size and integrate sample

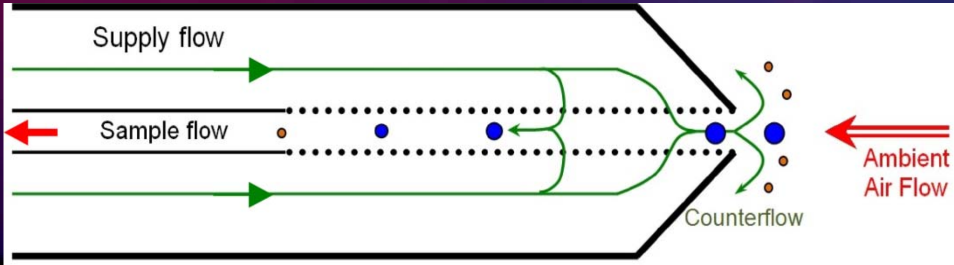




axial flow cyclone collector

Straub and Collett, 2005

Counterflow virtual impactors (CVI) utilize counterflow stream to reject interstitial particles and gases, while droplets or ice crystals are collected and evaporated in sample airstream

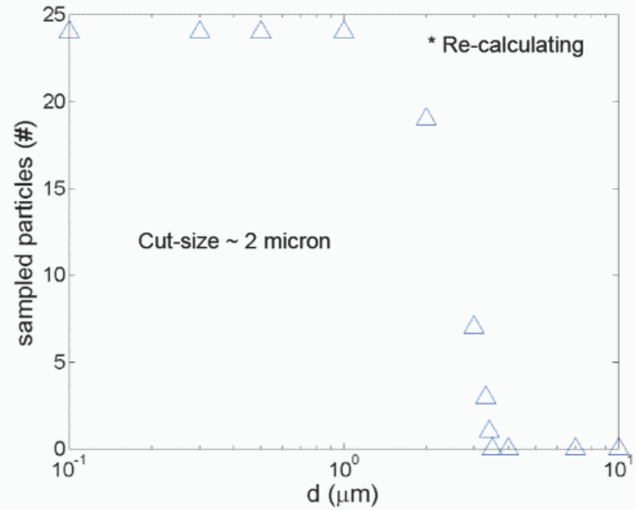


CLOUD INLETS USING INERTIAL SEPARATION TO EXCLUDE DROPLETS

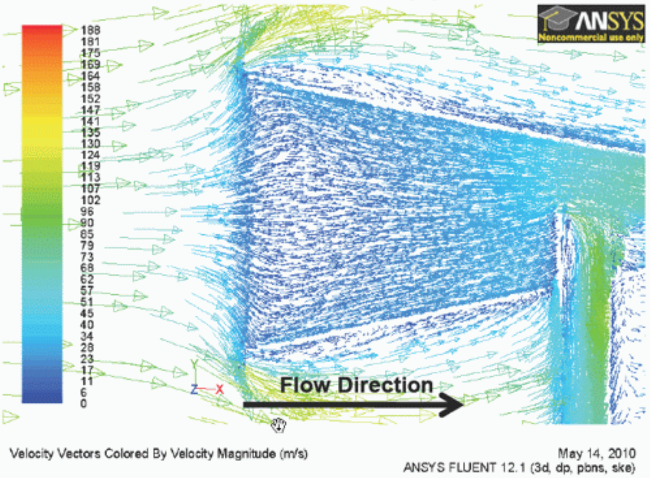
CFD simulations with SMAI

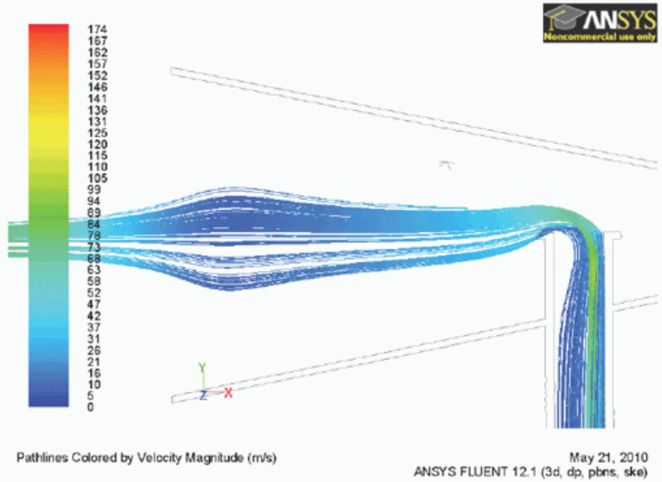
a.k.a Forward Facing Cone

- The fluid dynamics of the SMAI at standard C-130 aircraft conditions will be examined: 875 [mb] at 110 [m/s].
- The domain, set as a hemisphere with the bottom acting as the belly of the plane will have a pressure far-field boundary condition.
- The mesh consisted of approximately 1.1M tetrahedral cells and was solved incompressible, using the standard k-ε turbulence model.



Cross-section velocity vectors in xy plane

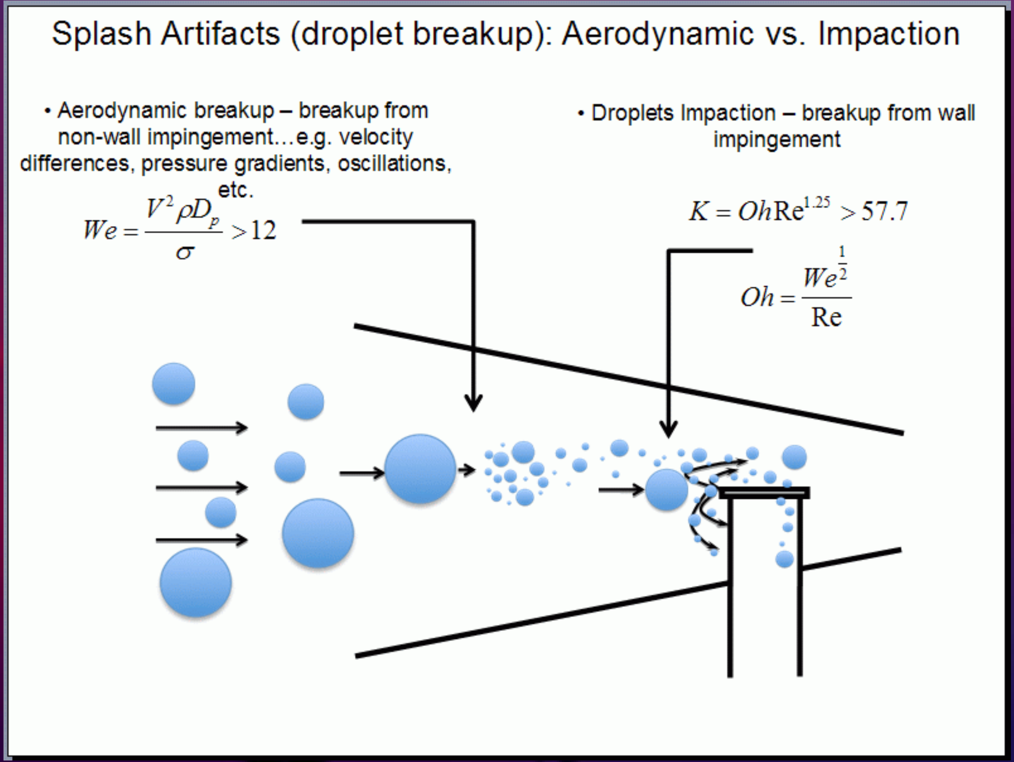




Mohareri, Craig, Dhaniyala, Rogers, 2010

OTHER ARTIFACTS RELATED TO INLETS

- Loss of volatile material due to heating of particles with aerodynamic heating of slowing air
- Large ice and drizzle sized drops are subject to breakup/shatter (discussed in detail in topic 13)

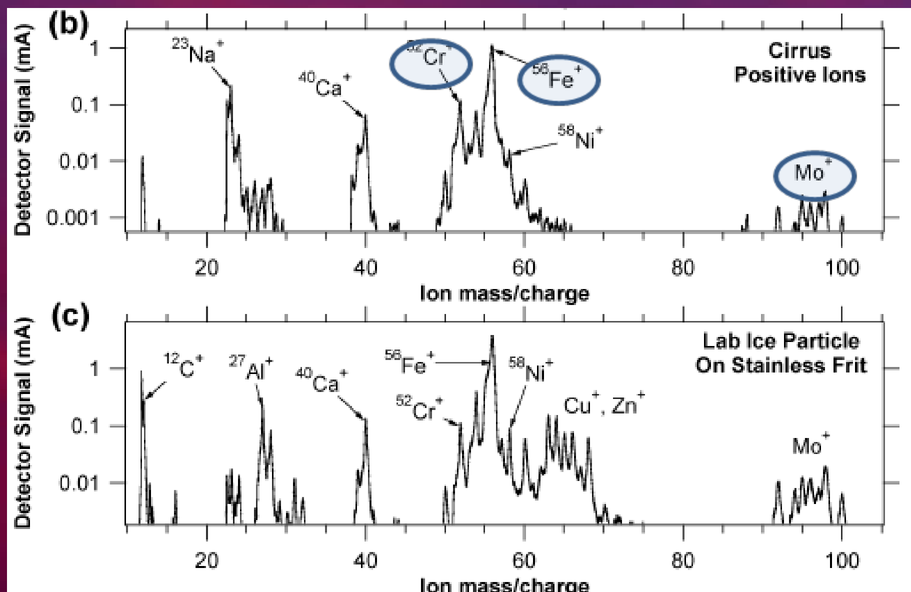


This can occur with or without hitting inlet walls if there is shear to flow

Moharerri, Craig, Dhaniyala, Rogers, 2010

ICE/INLET INTERACTIONS

Ice can abrade inlet material at high speeds: Lab studies showed that CVI frit material produced micrometer-sized stainless steel when impacted by ice crystals. Gold-coated materials much lower frequency, titanium and solid stainless seem better but still some abrasion. Still being researched.



PALMS Mass Spec measured stainless steel in cirrus and lab measurements

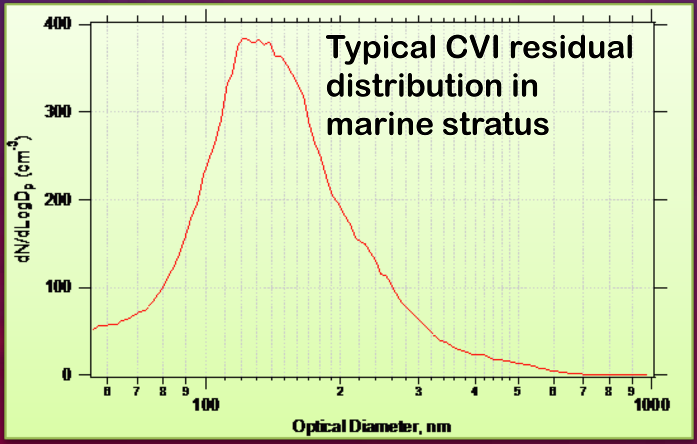
Deposited particles can be resuspended: Space shuttle exhaust particles were later shown to be re-entrained in sample flow by ice clouds.

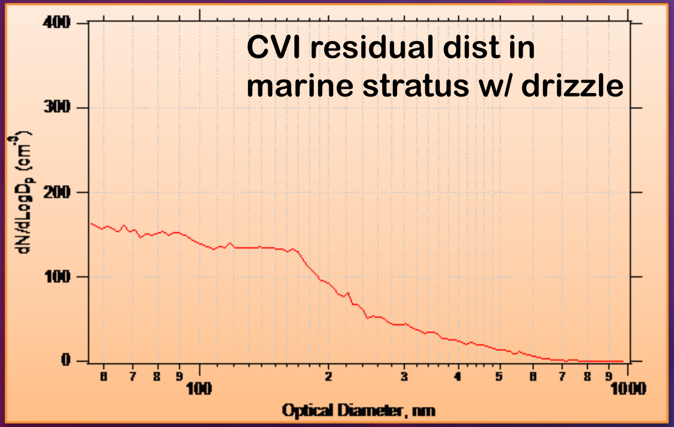
Particle Generation and Resuspension in Aircraft Inlets when Flying in Clouds

D. M. Murphy,[1] D. J. Cziczo,[2] P. K. Hudson,[2] D. S. Thomson,[2] J. C. Wilson,[3] T. Kojima,[4] and P. R. Buseck[4]

BREAKUP OF DRIZZLE DROPS IN CVI

- In marine stratus, clean areas tend to have drizzle patches which break up in CVI
- Results in small droplets, which when evaporated, produce small residual particles





Twohy et al, ms in preparation

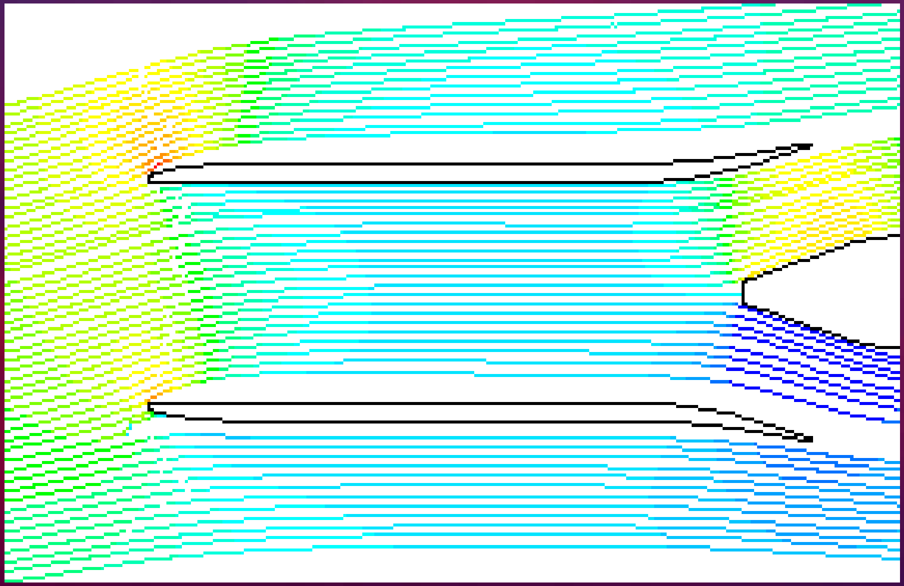
- Doesn't affect chemical mass measurements, but does affect number and size.
- Appears to occur also in large ice, high residual number

(scavenging, droplet solute, wake effects?)--IN from CFDC appears to be reasonable.

Computational Fluid Dynamics

Various Uses

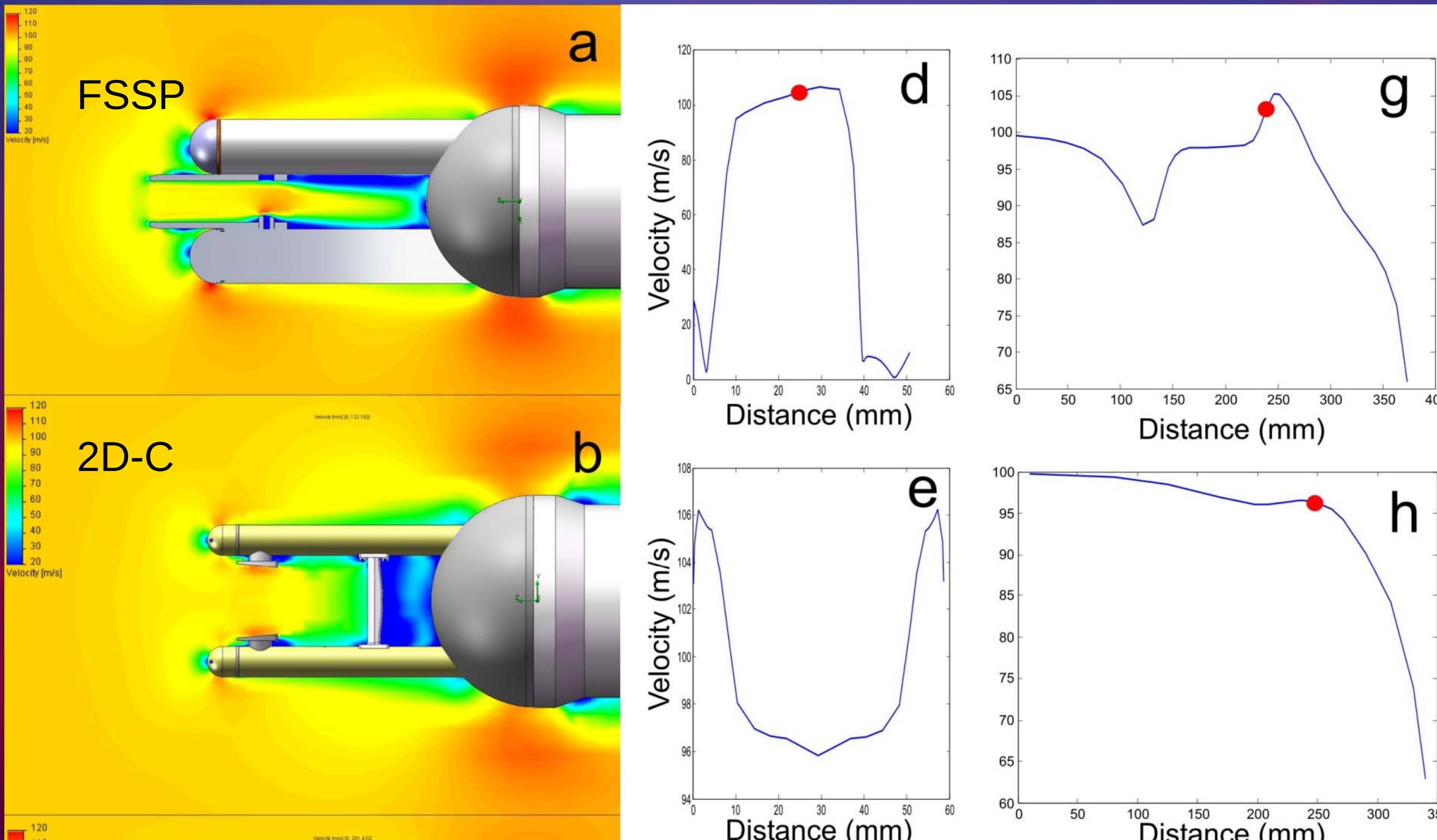
For instrument development: 5 μm particle trajectories with color denoting vertical component of velocity. Shroud straightens smaller droplet sizes



Note: Upstream shrouds have been implicated in breakup of ice crystals

For instrument mounting (see earlier slides)

AIRFLOW DISTORTION BY HOUSINGS

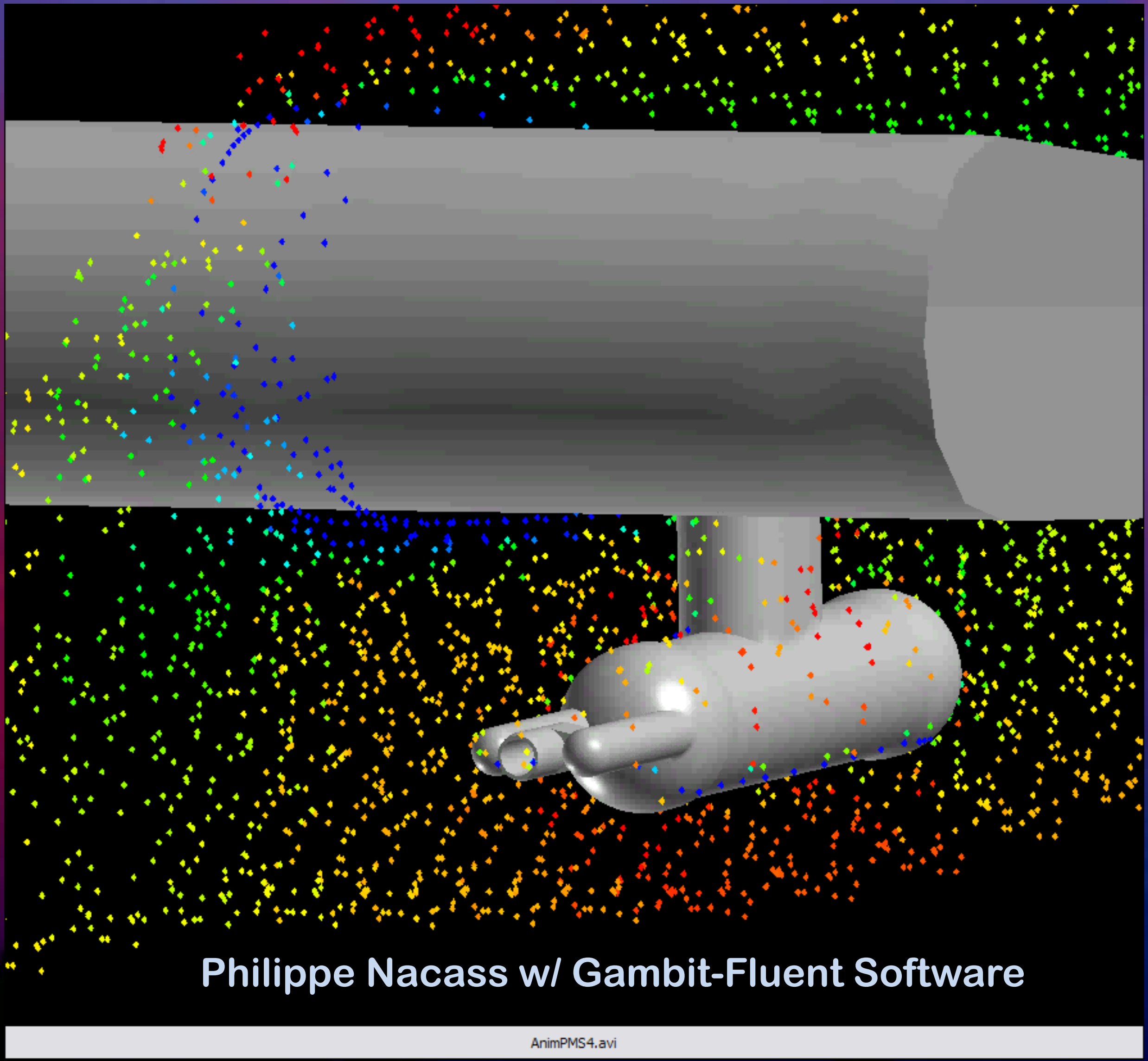


Cross Flow Velocity

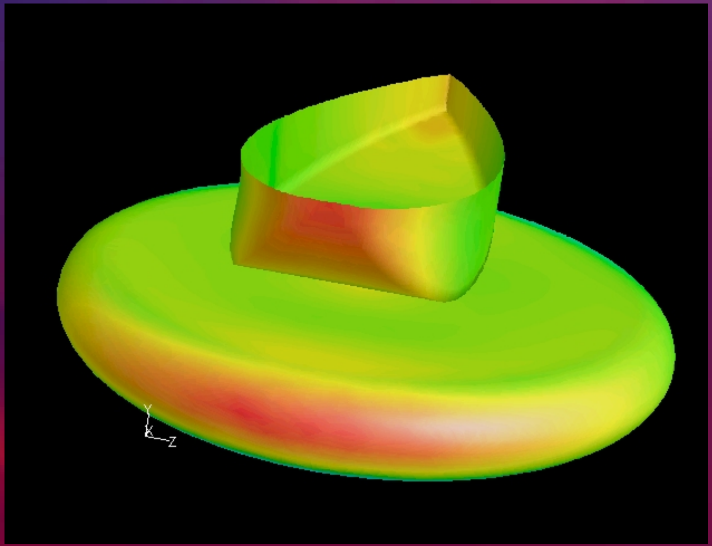
Along Flow Velocity

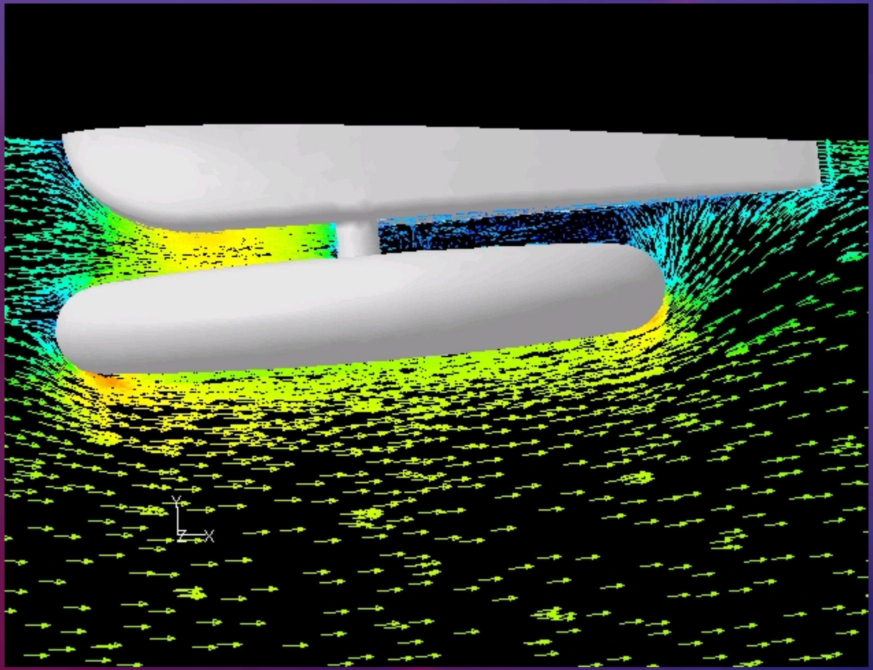
Courtesy Alexei Korolev

INTEGRATED MODEL OF FSSP & WING



USING CFD TO CALCULATE AIR LOADS ON RADAR





Velocity m/s	Lift N	Drag N	Moment N.m
125	*- 1030*	*2680*	*3740*
160	*- 1690*	*4395*	*6130*

Philippe Nacass w/ Gambit-Fluent Software

RECOMMENDATIONS-TAKE HOME POINTS

- Flow field and particle trajectories around the aircraft should be evaluated when choosing a position and orientation for a cloud sampling instrument
- Being outside boundary layer is not sufficient
- CFD modeling of the instrument itself may be used to optimize airflow and particle distribution at sampling point
- Many potential artifacts should be considered including aerodynamic heating, shedding of inlet material and breakup of large cloud drops and ice crystals. Important for aerosol measurements as well as cloud measurements.
- Need a way to separate out and/or collect large droplets/ ice crystals for airborne CVI measurement residual measurements, as well as interstitial aerosol inlet.