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EUFAR 2020: The measurement of air temperature in atmospheric research:

Air temperature characterization in Wake Turbulence & Contrail flow: NRC flight research 2019/2020

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12th Nov 2020. virtual presentation to the EUFAR Workshop

ACKNOWLEDGEMENTS:

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National Research Council Canada Conseil national de recherches Canada

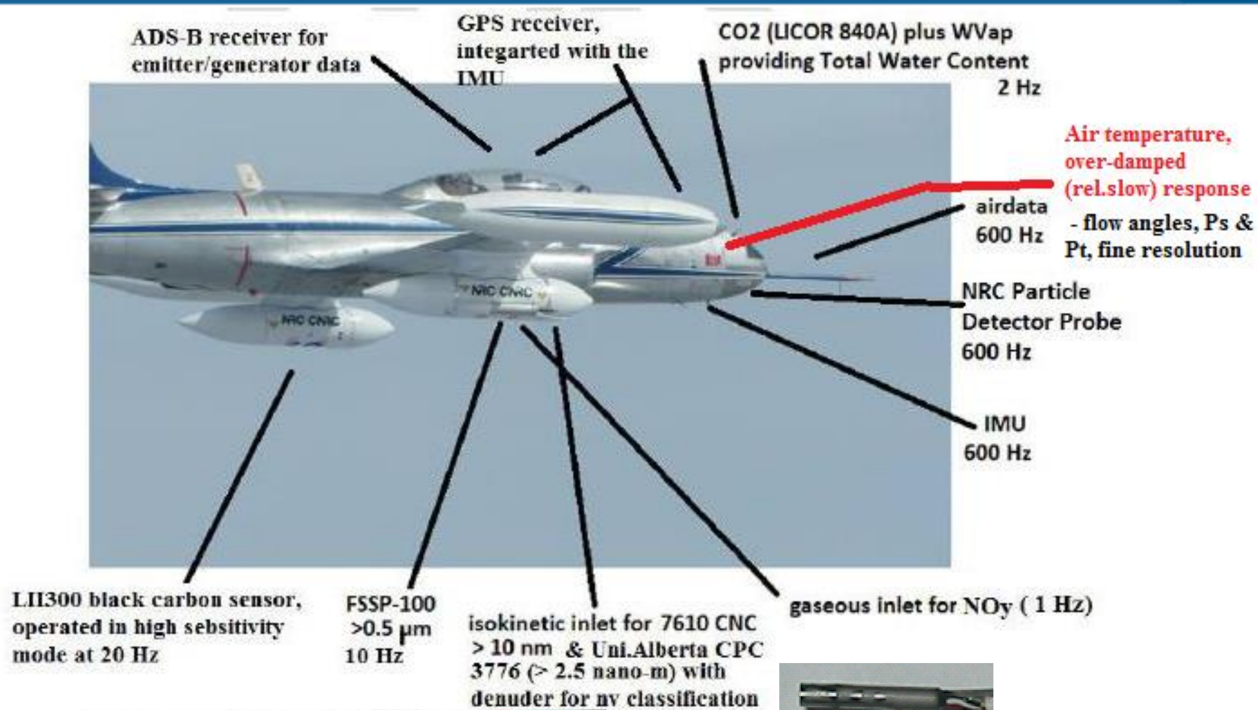
Canada

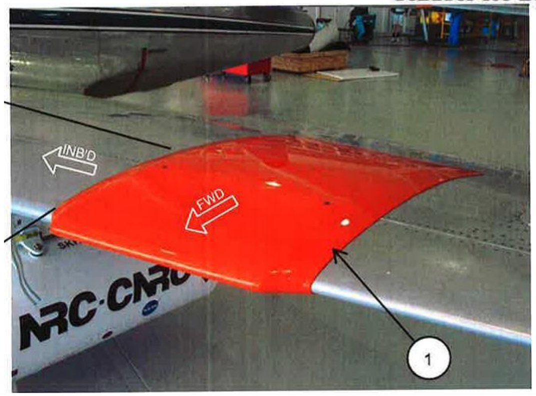
Air temperature in Jet transport wake & contrail flows

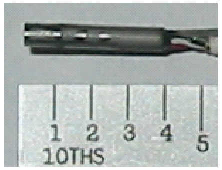
Outline:

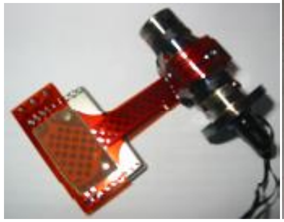
- **Statement of the *need* for advanced air temperature sensing, by examples of flight research data of wake turbulence & contrail flows**
- **NRC flight research in the UTLS:**
- ***Experimental details, results, discussion for:***
  - **Wake turbulence**
    - Heavy & Super Jet Transport wake generators
    - NRC T33 measurement research jet
    - Case studies:
      - A388 wake-flows, 5-30 Nm
      - NRC Falcon 20 wake flow, ¼-5 Nm
  - **Contrails**
    - Biofuel (43-100%) generator/emitters, NASA DC-8, Air Canada A320's, NRC Falcon 20 [100% CH, ACCESS II, CAAFER, CAAFCEB 92% SPK], Mach Number 0.72-0.82
    - measurement NRC CT-133 (sensor data: FSSP-100, CN7610, LiCor840, Picarro), Mach Number 0.56-0.62

Air temperature in Jet transport wake & contrail flows









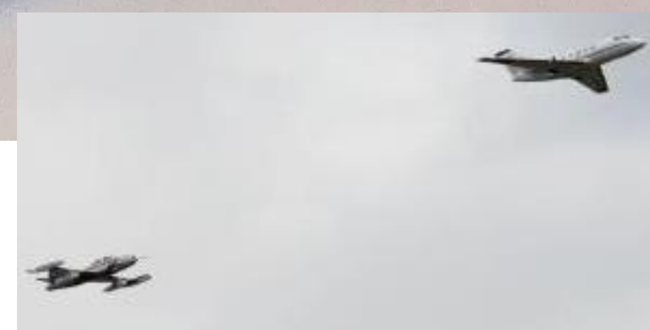
Experimental details:

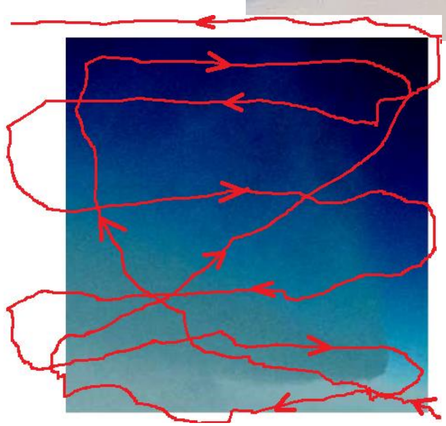
- **Measurement aircraft, NRC T33:**
  - Wing-glove, chordal surface pressures (600/1200 Hz)
  - Highly responsive inertial @ 600 Hz – fine spatial resolution;
  - Likewise, Ps, Pt, flow cosine sensing designed for accurate 600 Hz, enabling fine resolution of intricate vortex flowfields (***WV*** = ***V****A* - ***V****G*), *but*
    - Air temperature sensing is an axially displaced Rosemount TAT (over-damped, comparatively slow response, but A-D sampled at 600 Hz)

Air temperature in Jet transport wake & contrail flows

Experimental details:

- **Flight methodology – wake turbulence**
    - ATC-intercept of Heavy & Super size jets
    - In-trail against NRC Falcon 20
    - *Manoeuvres*
        - *Lateral traverses through port & stbd vortex cores*
        - *Vertical traverses through a single vortex core*
- **Flight methodology - contrails**
    - NRC Falcon – climb in-trail (many wake vortex core crossings) & cruise (contrails), undertake lateral & vertical traverses, concatenate to form holistic cross-sectional contours of contrail parameters

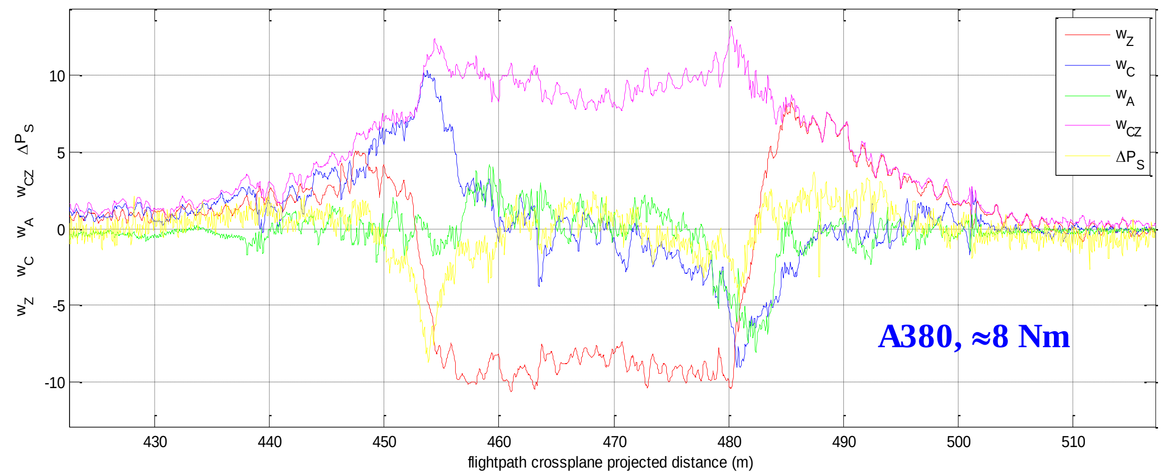


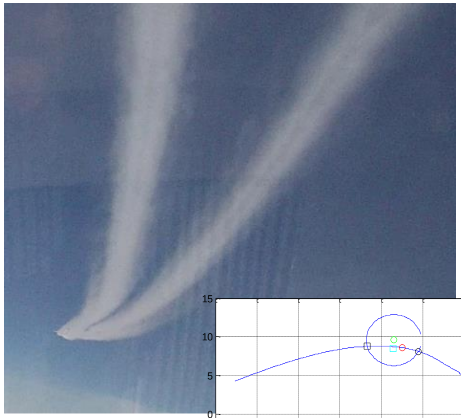


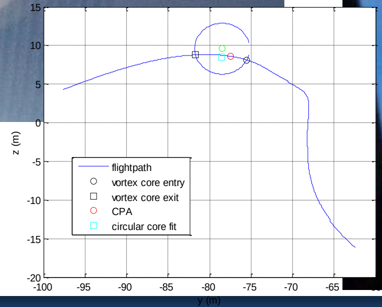
Air temperature in Jet transport wake & contrail flows

Experimental details:

- **Analysis methodology – wake turbulence**
  - Lateral traverses => vortex spacing & comparable port & stbd states (rarely symmetric)
  - any vortex core penetration
    - From core entry & exit (defined as maximum tangential velocity) estimate vortex core centre, radius, vorticity distribution & relate velocities, Ts, Ps, axial & radial flows to the derived centre.
    - Although wake vortices might look homogenous, depending, they are generally discontinuous (thin condensate delineates a structure, not fully understood nor modelled)



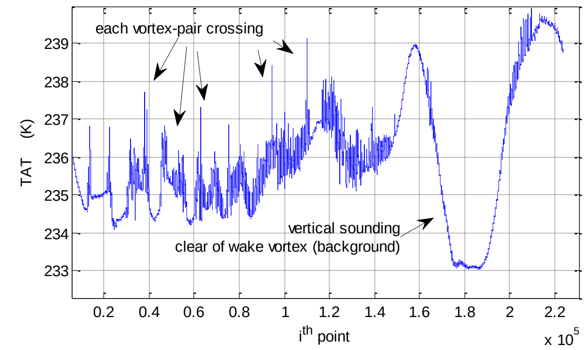


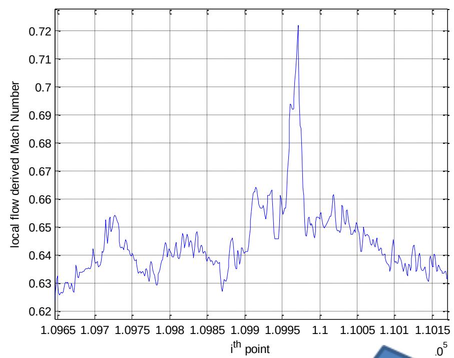


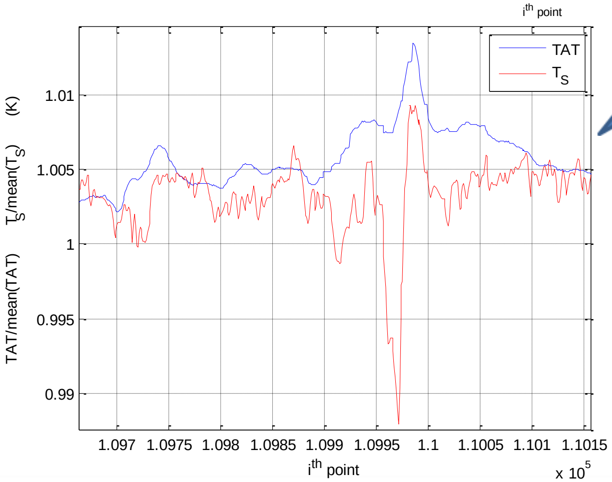
Air temperature in Jet transport wake & contrail flows

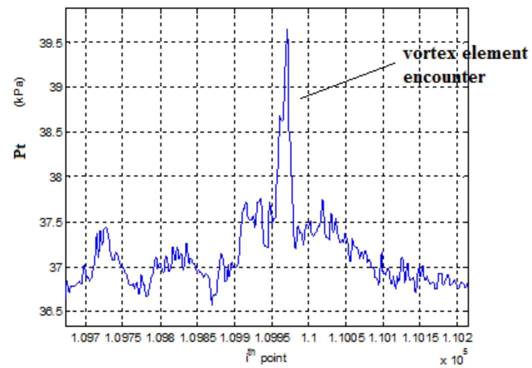
Experimental details:

- **Air temperature sensing – from TAT to Ts in WV**
- TAT (note the generally warm WV flowfield)
- Ps, Pt identify vortex encounter, confirmed by α,β probes
- Local derived M => Ts, with augmented frequency content

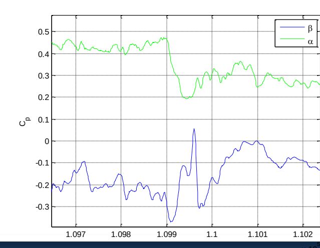


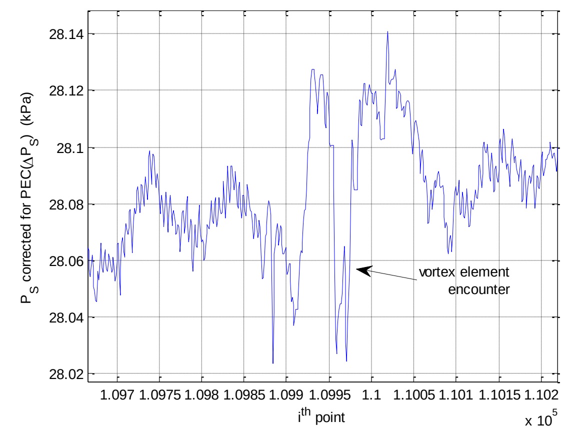






Flow angle probes (vortex confirmation)





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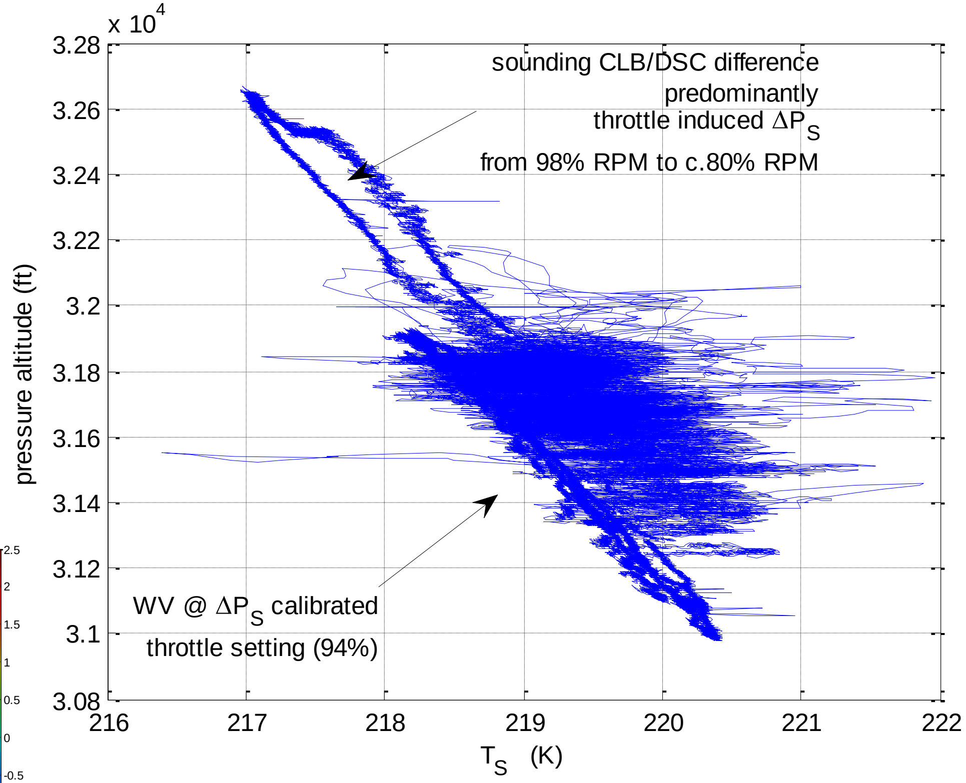
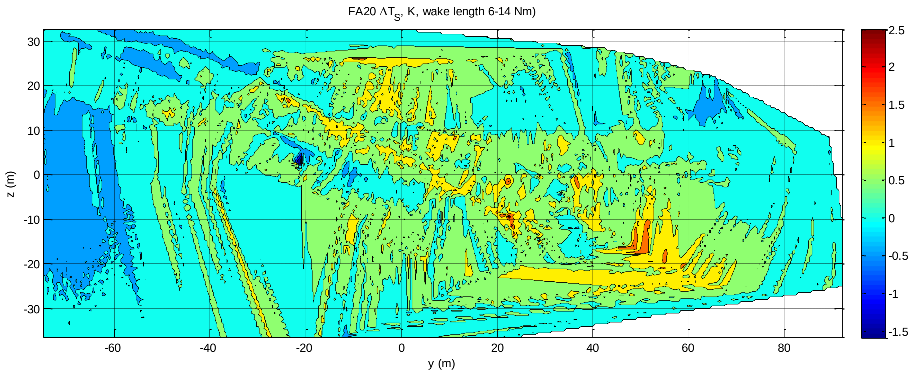
Experimental details:

- **Air temperature sensing –Ts profile**
- T_S highlights 'warm' nature of the A388 WV flowfield (on this occasion, not always)
- Superimposed with warm & cool vortex induced T_S perturbations





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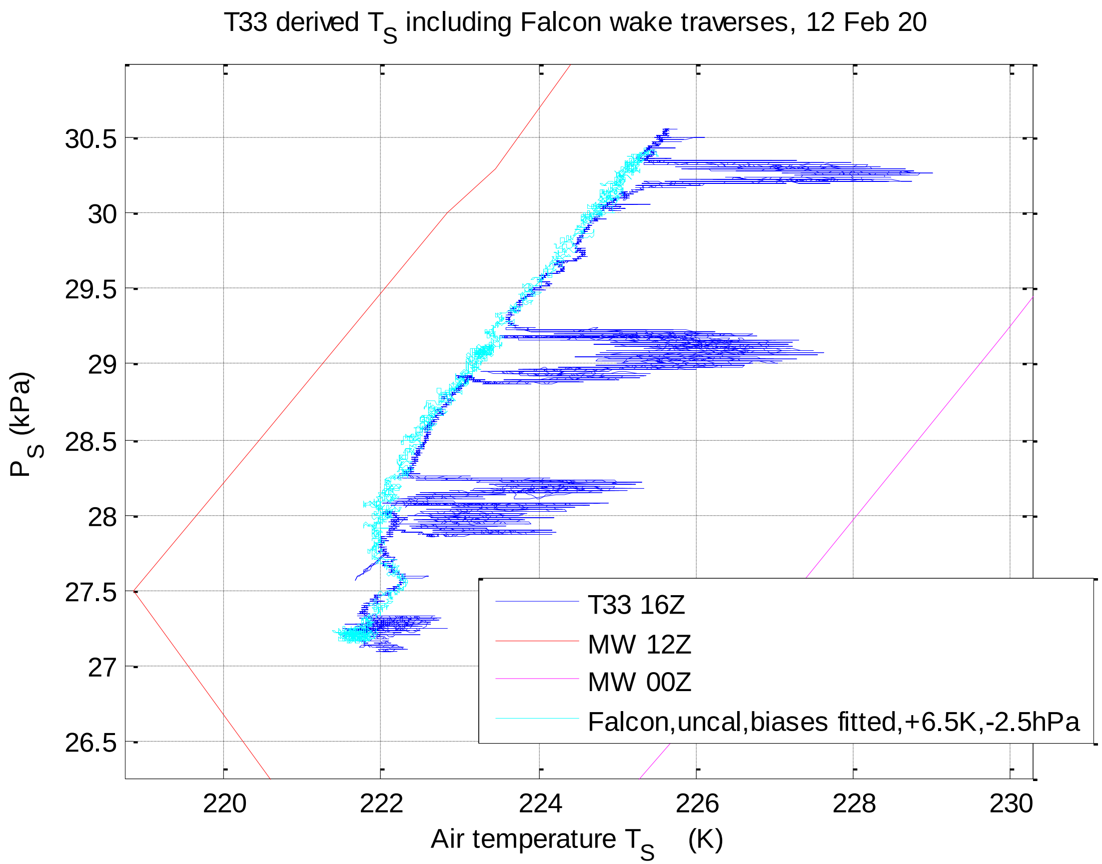
Experimental details:

- **A further derived Ts profile example**
- T33 behind the NRC Falcon (uncal.airdata)
    - Falcon corrected by fitted biases, trends thereafter match
- Again T_S highlights 'warm' nature of the Falcon wake (close-in, ¼-2 Nm)
- Comparison with ECCC met balloon data (12 hourly), diurnal effect evident



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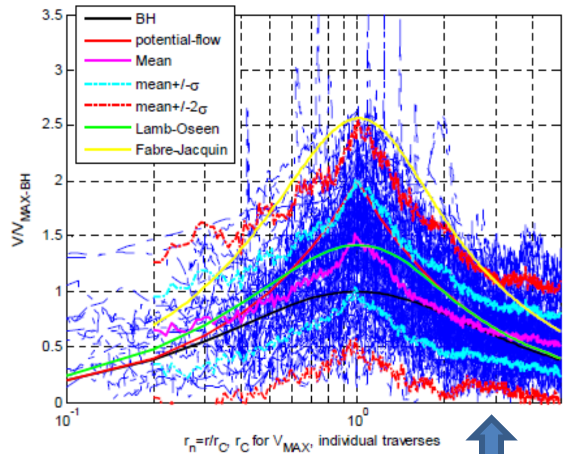
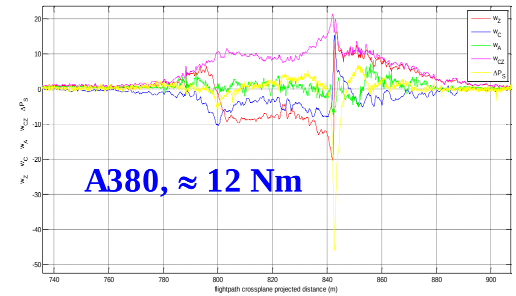
WV analysis & discussion:

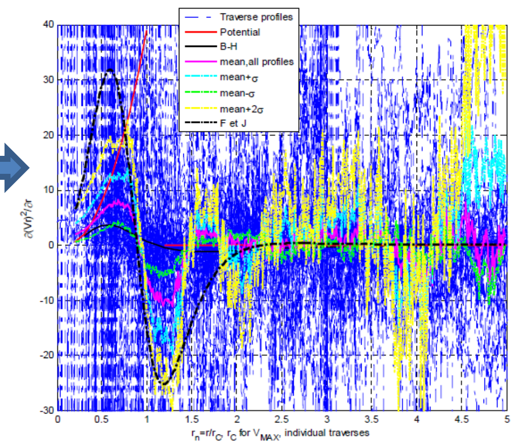
- Vortex profiles, normalized:-
  - Variety of rounded (B-H) to highly peaked vortex profiles, with the latter of greatly reduced spatial scale, spatiotemporally varying in the axial direction, with core radii also varying
  - Highly peaked were vented vortices, with Ps relaxed to ambient on the core C.L., i.e. annular vorticity, discretized circumferentially
  - With radial flow instability ($d^2(r^2\Omega)^2/dr^2 < 0$ where $\Omega(r)=V(r)/r$.)



B747,767,777,A330,340,380

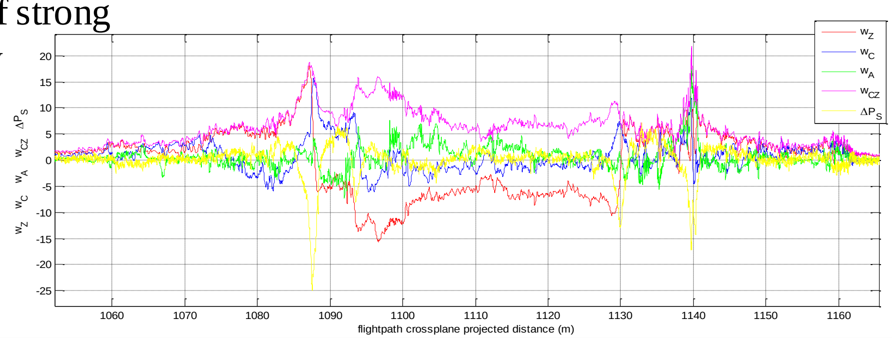


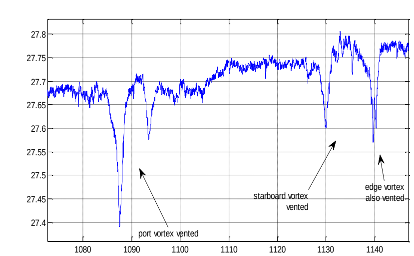
A380, ≈ 12 Nm



- Suggests the existence of strong axial flows for continuity

A380, ≈16 Nm





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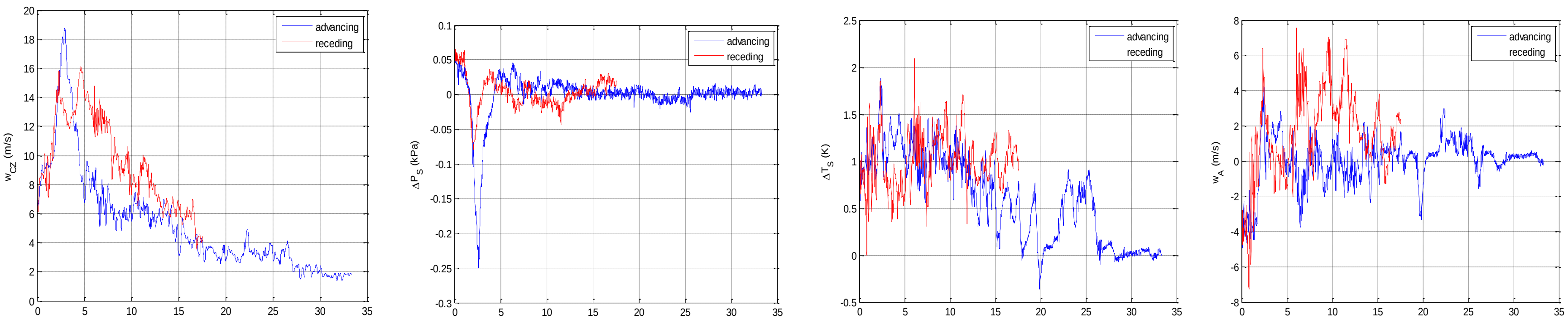
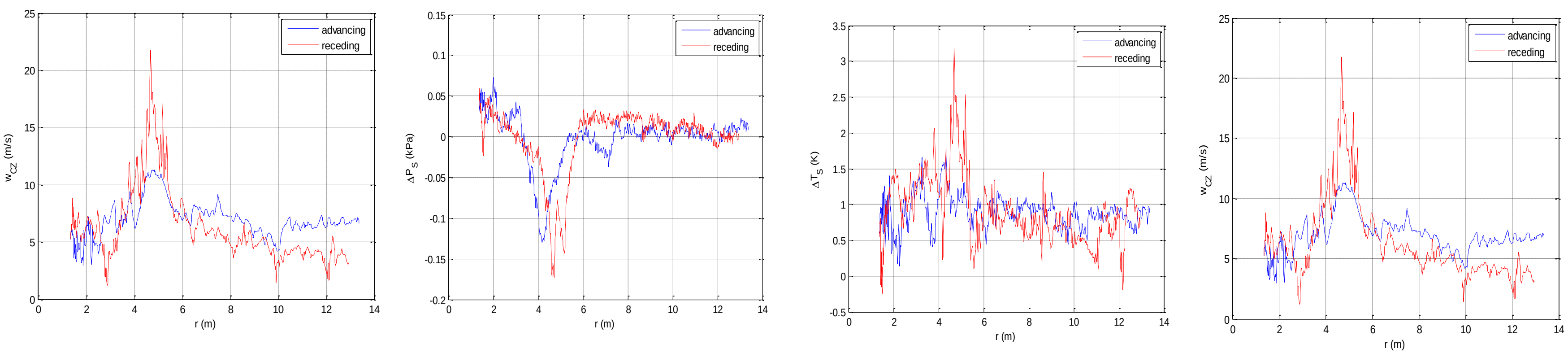
WV analysis (cont.):

- Vortices, A388, 16 Nm (prev.page, asymmetry & annularity evident):-
  - *Port vortex*



  - *Starboard vortex*



- Ps expansion with velocity (ω association), both vented
- Strong Ts correlation with axial flow is suggested (over-page)

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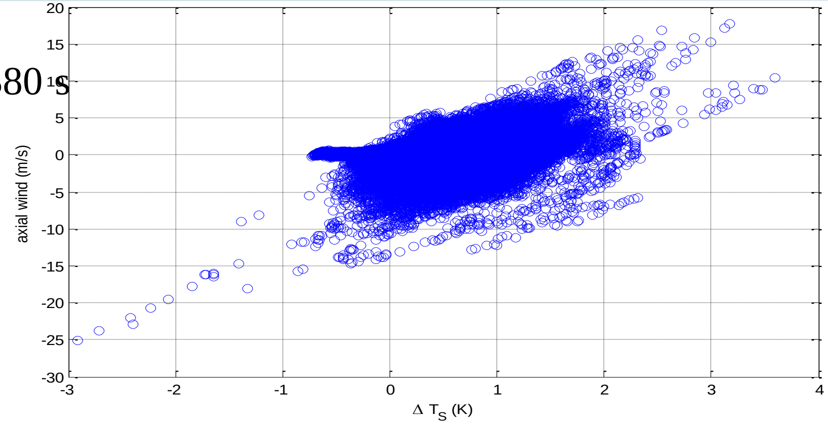
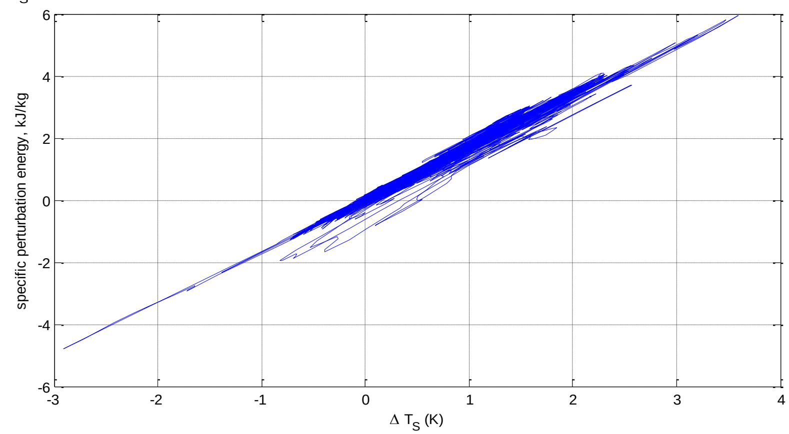
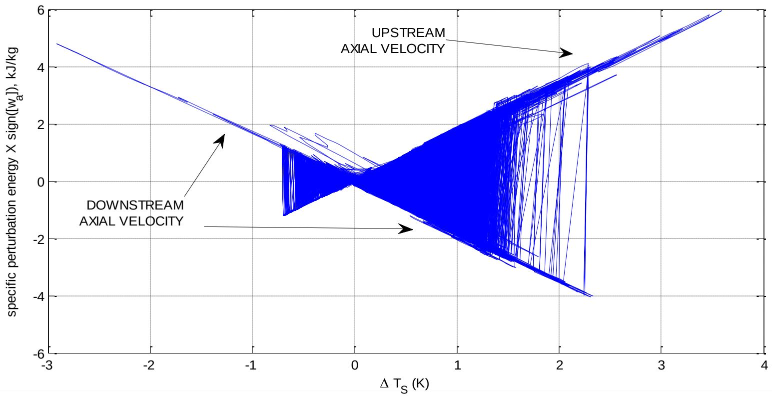
WV Ts analysis:

- For all vortex profiles of this A380 s from 5-20 Nm:
  - Axial flow ~ Ts





  - If specific perturbation energy is considered, $(Cp+Cv)\Delta T+\Delta Ps/\rho+ ½ V_v^2/1000$ kJ/kg
  - & if x sign(axial-flow), then downstream & upstream flow division is evident



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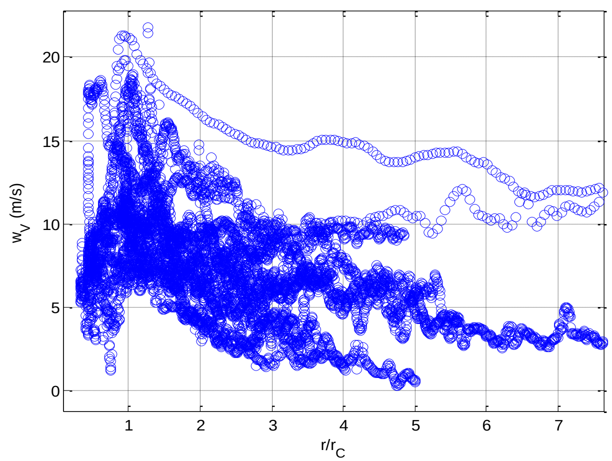
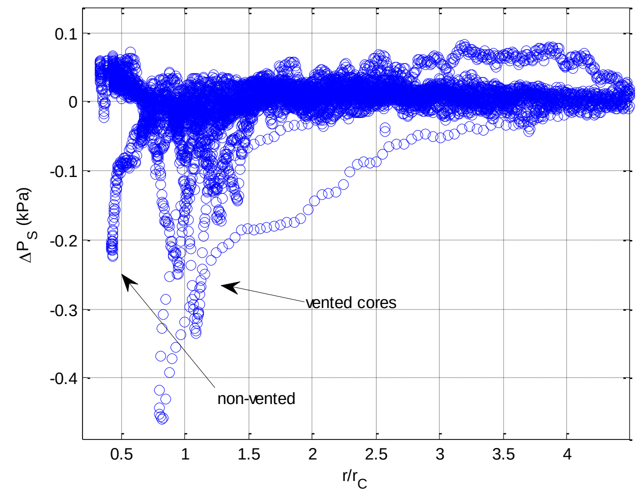
WV Ts analysis:

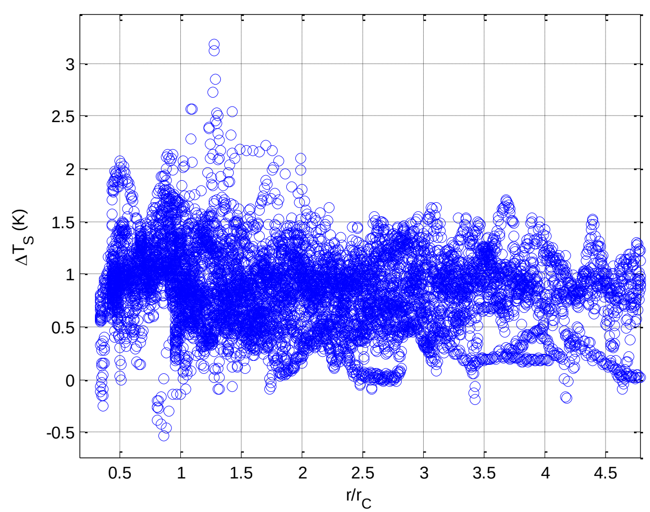
- Radial structure of thermal & axial perturbations (normalized r/r_c):

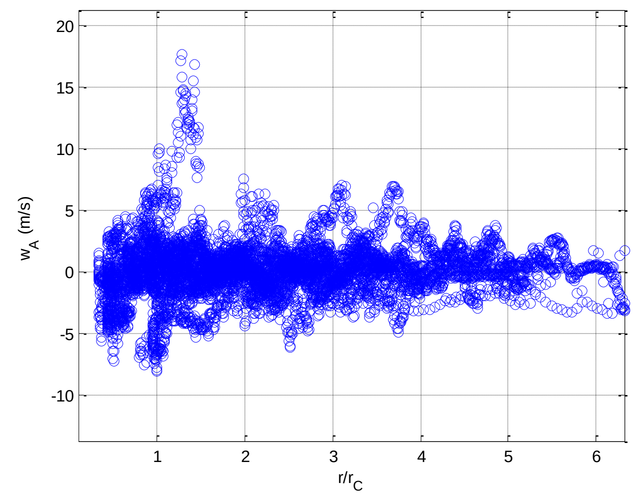
- - suggests cooling is within vortex cores, as is downstream axial flow
- Whilst heating is outside adjacent to core edges

    - Similar non-vented & vented cores, but more intensive w_A for vented cores, except downstream flow was radially displaced towards the core edge for the latter









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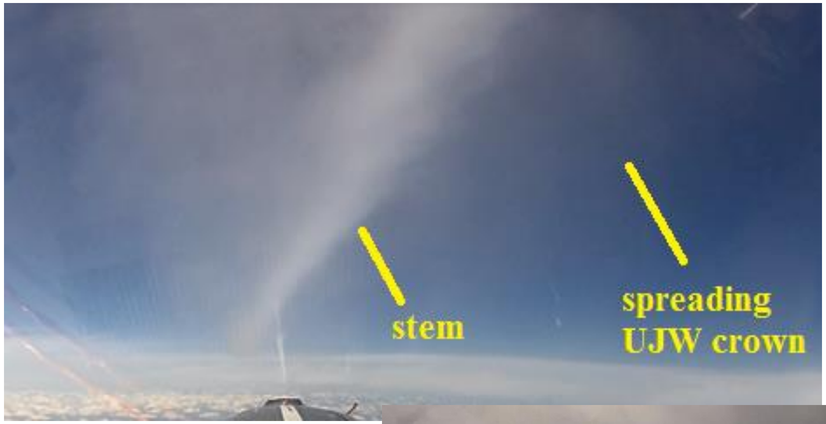
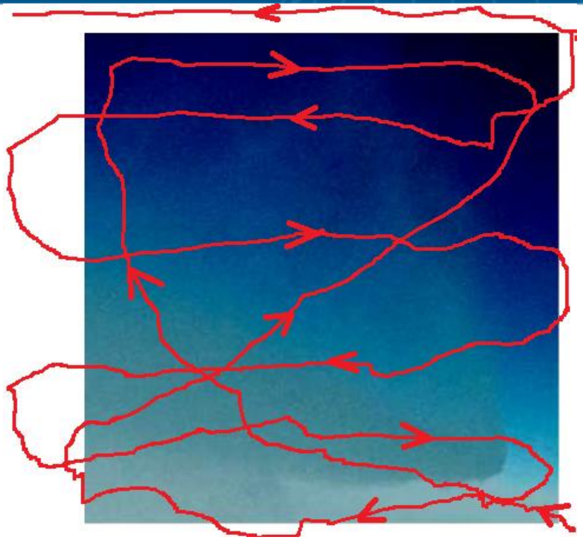
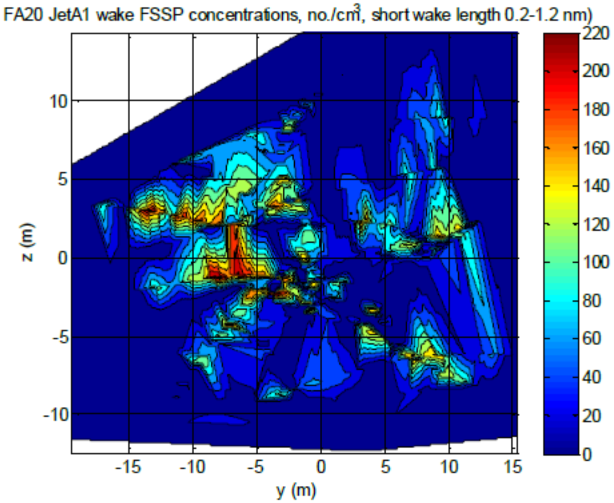






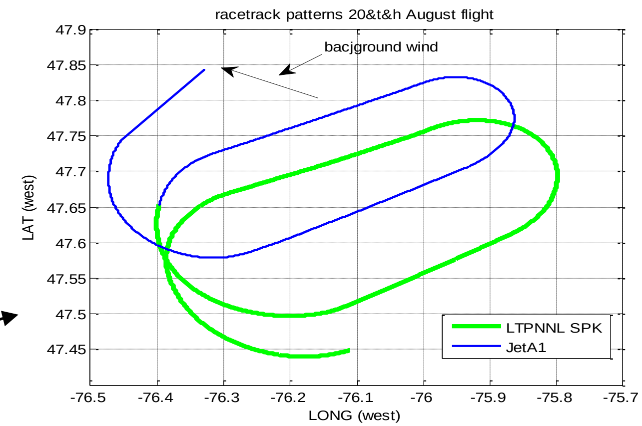
Experimental details:

- **Analysis methodology - contrails**
  - Generally eight lateral & vertical traverses, are concatenated to form holistic cross-sectional contours of contrail parameters
    - Ice particle #/cc, RHice, Ts

Air temperature in Jet transport wake & contrail flows

Civil Aviation Alternate Fuel Contrail Optical Measurements Research (CAAFCOMR)

- **Aircraft**
- Generator/emitter, NRC Falcon 20 [100% CH, ACCESS II, CAAFER, CAAFCEB 92% SPK], Mach Number 0.72-0.82
- measurement NRC CT-133 (sensor data: FSSP-100, CN7610, LiCor840, Picarro), Mach Number 0.56-0.62
- **Racetrack flight patterns – trail, 0.5-25 km**
- Short, 20th Aug 19 (sublimating), M0.72
- Long, 28th Aug 19 (M0.72), 12th Feb 20 (M0.82) (persistent)



- **Fuels**
- 100% ATJ SPK & Jet A1

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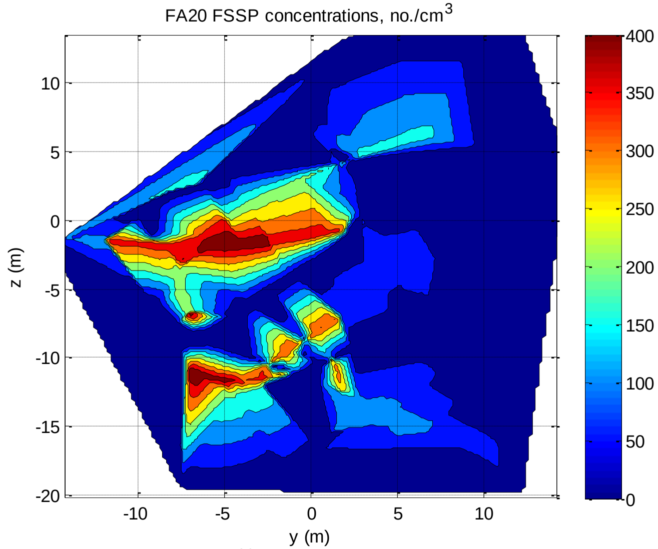
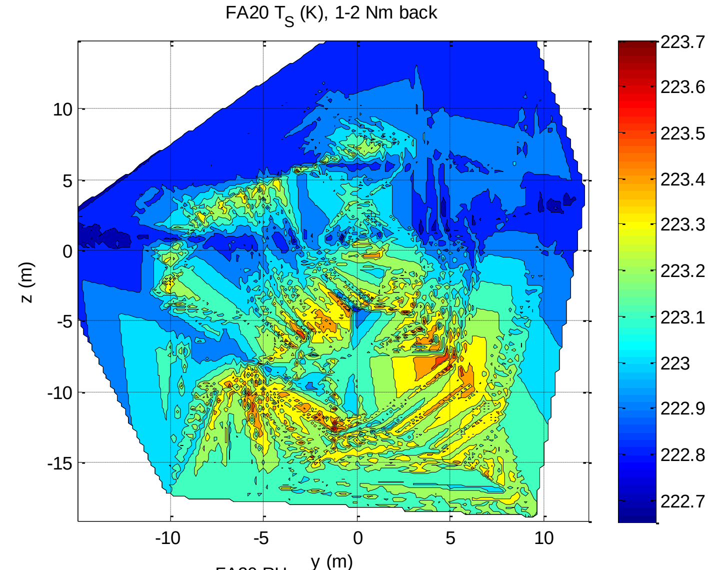
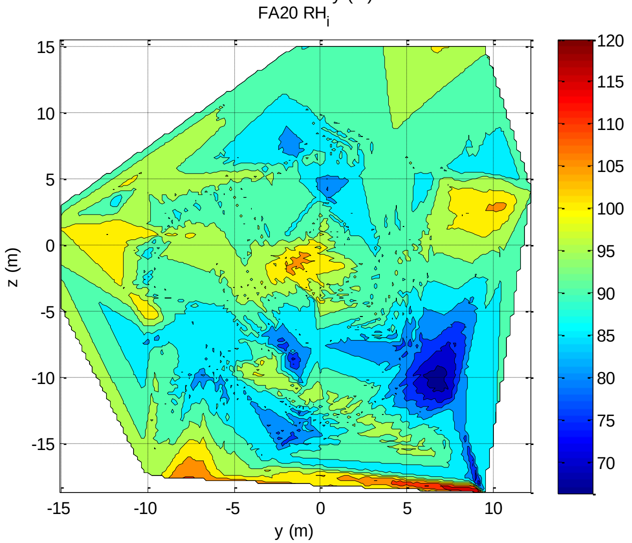
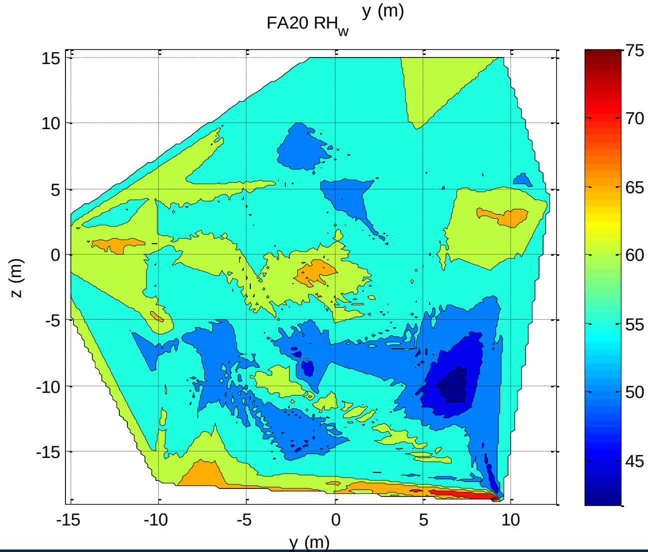
FA20 Contrail analyses:

- ***X-sections:***
- **Ice #/cc, T_S, RH_{ICE}, RH_W,**
- RH_{ICE} & ice #/cc have an interplay (contrail is a continuous formation/growth/ sublimation process across the X-section)
- *however*, the depleting correlation with warm T_S is evident, even though max ΔT_S was just 1 K in this instance









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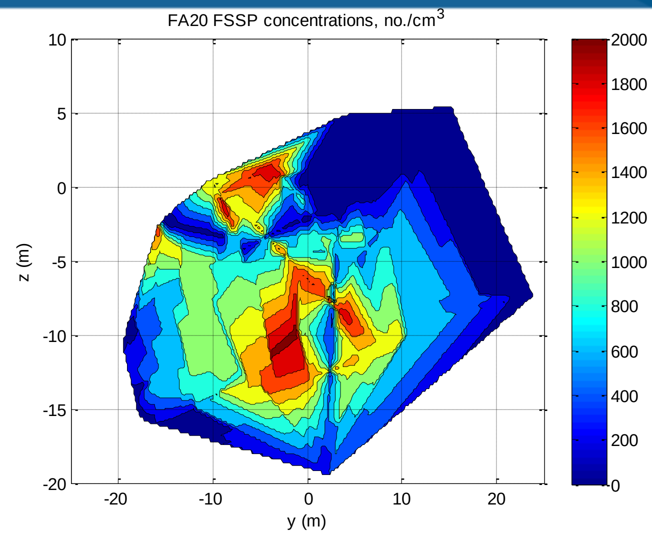
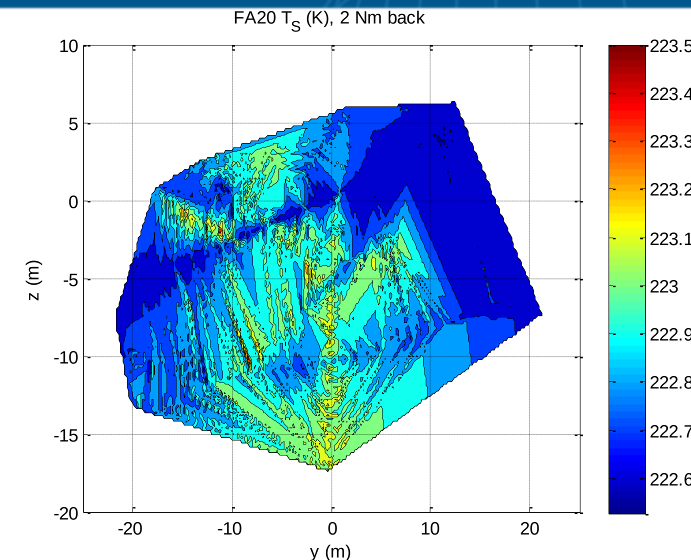
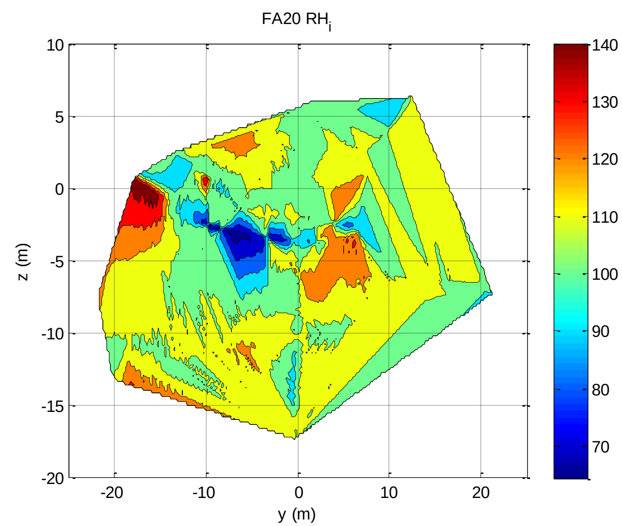
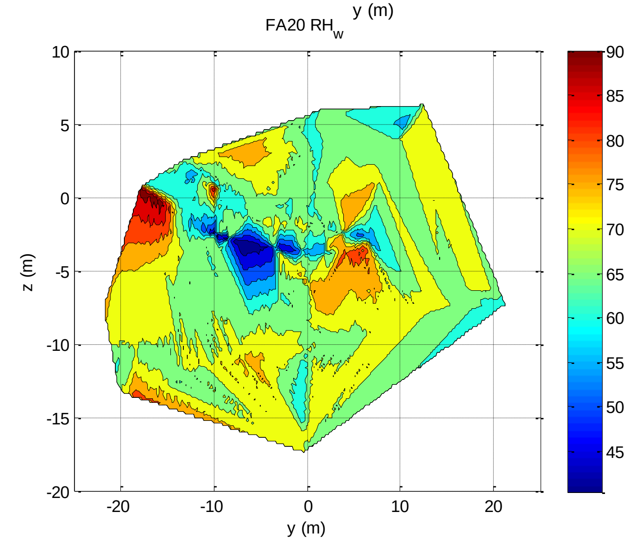
FA20 Contrail analyses:

- ***X-sections:***
- **Ice #/cc, T_S, RH_{ICE}, RH_W, further downstream**
- Thicker contrail (higher background RH)









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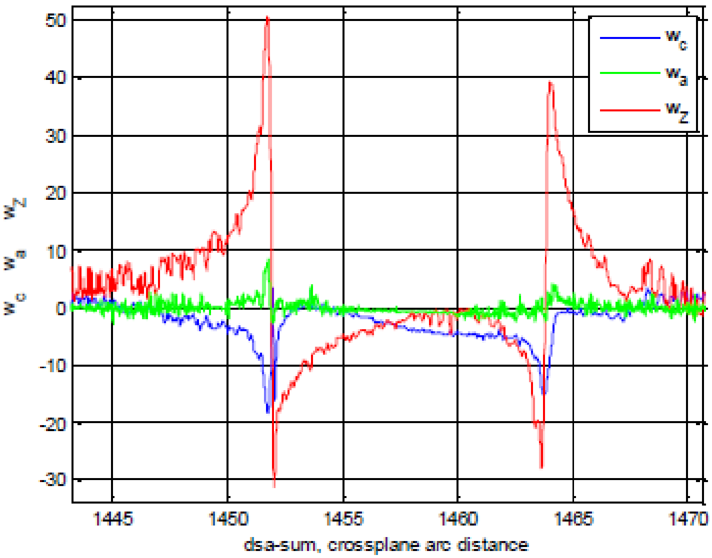
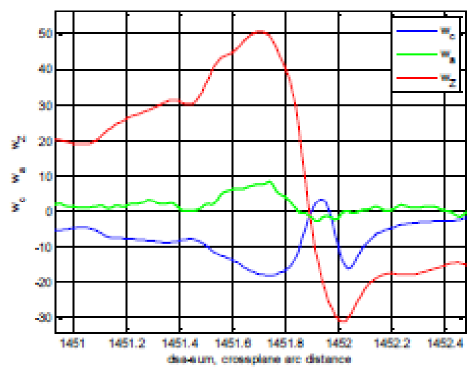
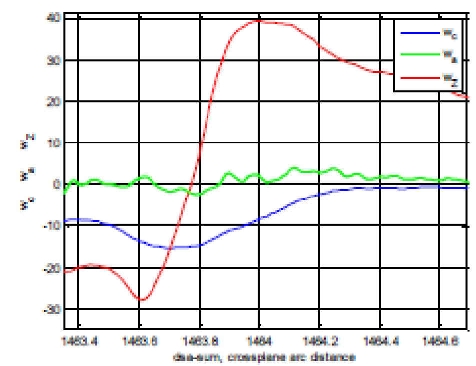
FA20 wake vortex filaments (≈25b back):



Vortex pair (velocity components)



port vortex



starboard vortex

Figure 6: NRC Falcon 20 trailing vortex flowfields, at $\approx 25b_{FA}$ wake length:- vortex pair lateral traverse, giving estimated core radii 0.25 to 0.3 m, and less intense axial flow – nevertheless, upstream and centred upon core edges..

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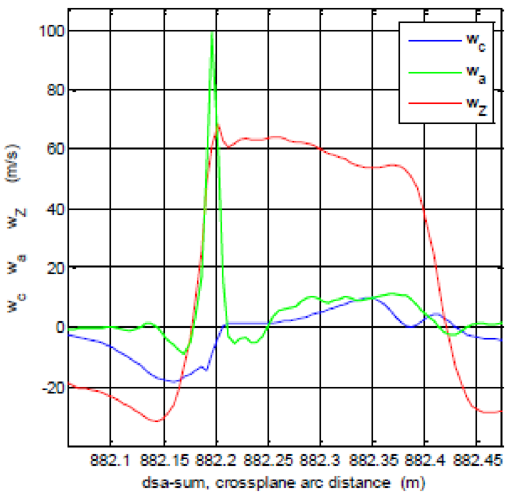
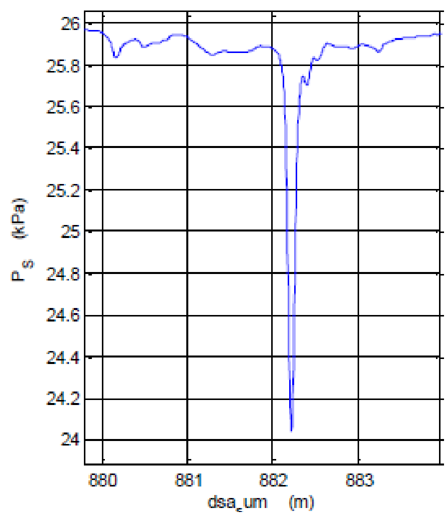
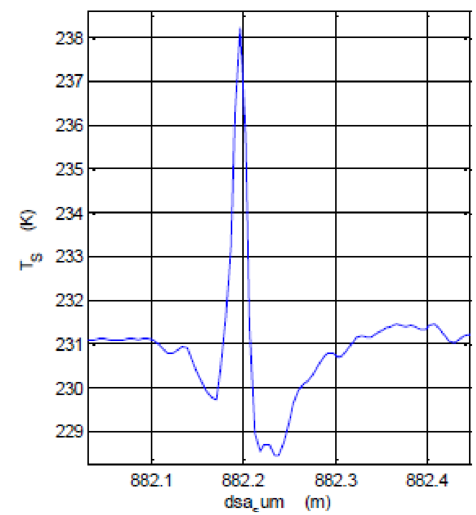
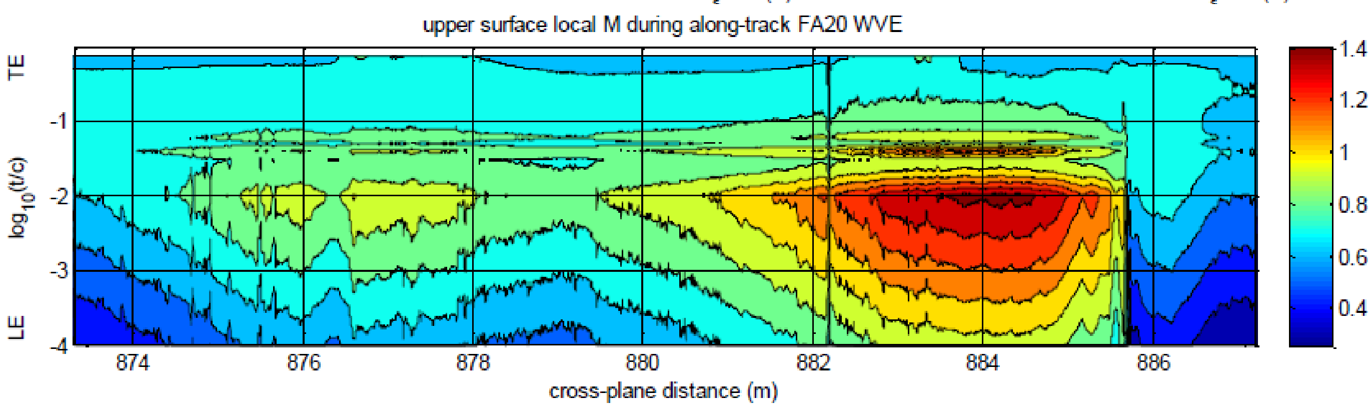
FA20 wake vortex filaments (≈25b back) cont.:

- *Using multiple sensors for confirmation*









upper surface local M during along-track FA20 WVE

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CONCLUSIONS:

Air temperature effects in wake vortex & contrail behaviour:

- Is complex, subtle, important;
- WV modal capture by modelling & full contrail characteristics unlikely to be captured without fine definition of air temperature perturbation distributions & spatiotemporal trajectories:
    - But T_S is derived from TAT with strong P_S, P_T dependency, need directs measurement (*at* a very high rate, at least 600 Hz) for quasi-independent assessment ('quasi' relating to the residual magnitude of convective heat transfer).

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