Freie Universität Berlin
Department of Geophysics
Institute for Space Science
Anna Katharina Lehmann

Calibrating the static pressure defect

Using an in-flight calibration method

Structure

1. Motivation
2. Measurement System
3. Calibration Methods
4. Model fit Analysis
5. Conclusion
6. Summary

Freie Universität Berlin

1. Motivation

Motivation

Accurate static pressure measurements are needed for:

- Height measurements
- Calculation of dynamic pressure
- Calculation of potential temperature
- Wind vector calculations

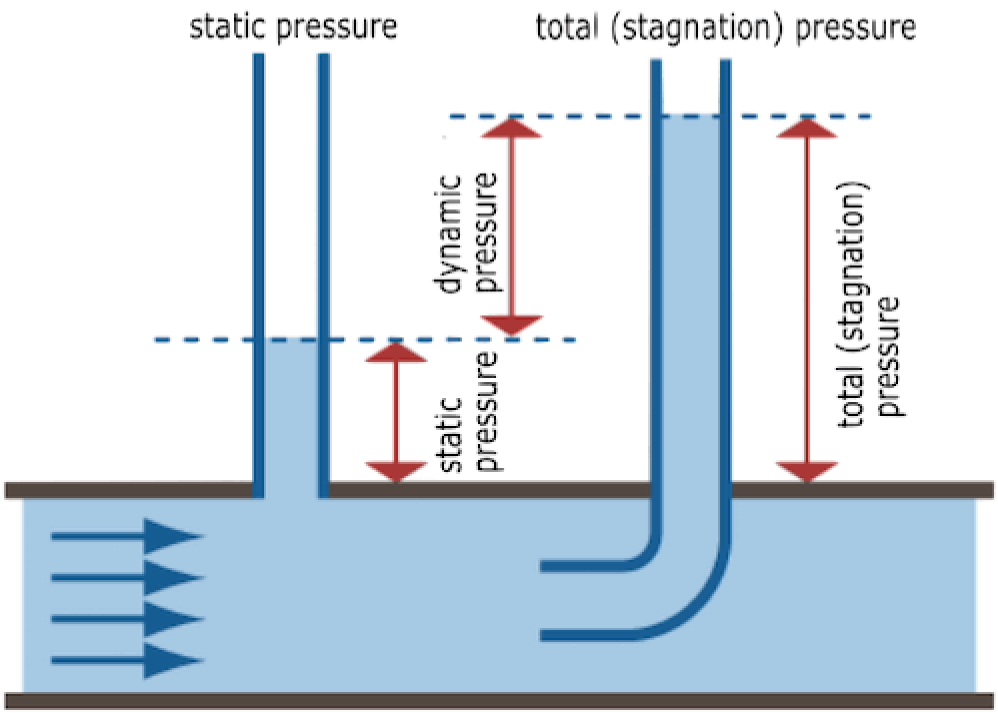
Problem:

Static pressure error depends strongly on location of the pressure probe and aircraft specific factors (like weight or wing shape)

➔ In-flight calibration

2. Measurement System

Static pressure vs Dynamic pressure



(Graphic from: https://tameson.com/pressure-gauges.html)

$$p = \frac{F}{A}$$

$$F = m \cdot \ddot{r}$$

$$q = p_t - p_s$$

A: area

F: force

m: mass

p: pressure

p_s: static pressure

p_t: total pressure

q: dynamic pressure

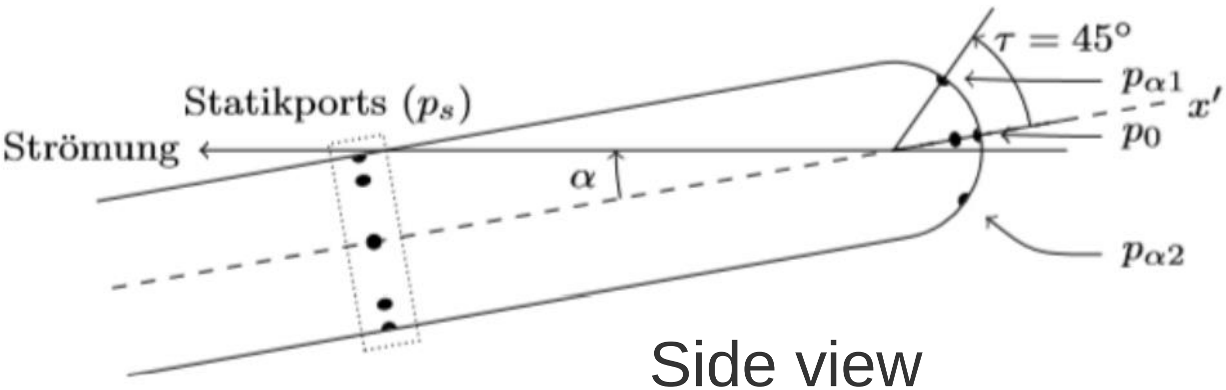
$\ddot{r}$: acceleration

Factors influencing static pressure

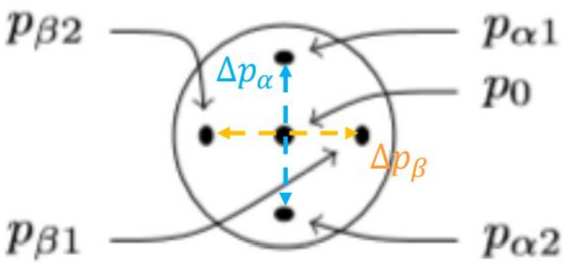
Dependant on	Independent of
Height	Dynamic pressure
Temperature	Angle of attack α
➔ Barometric height	Angle of sideslip β
formular: $p = p_0 \cdot \exp\left[-\frac{gz}{RT_m}\right]$	Acceleration
	Wind direction changes

g: gravitational acceleration
p_0: reference pressure
R: gas constant for dry air
T_m: mean temperature between z and z_0
z: height difference between z and z_0

Static pressure measurement



Side view



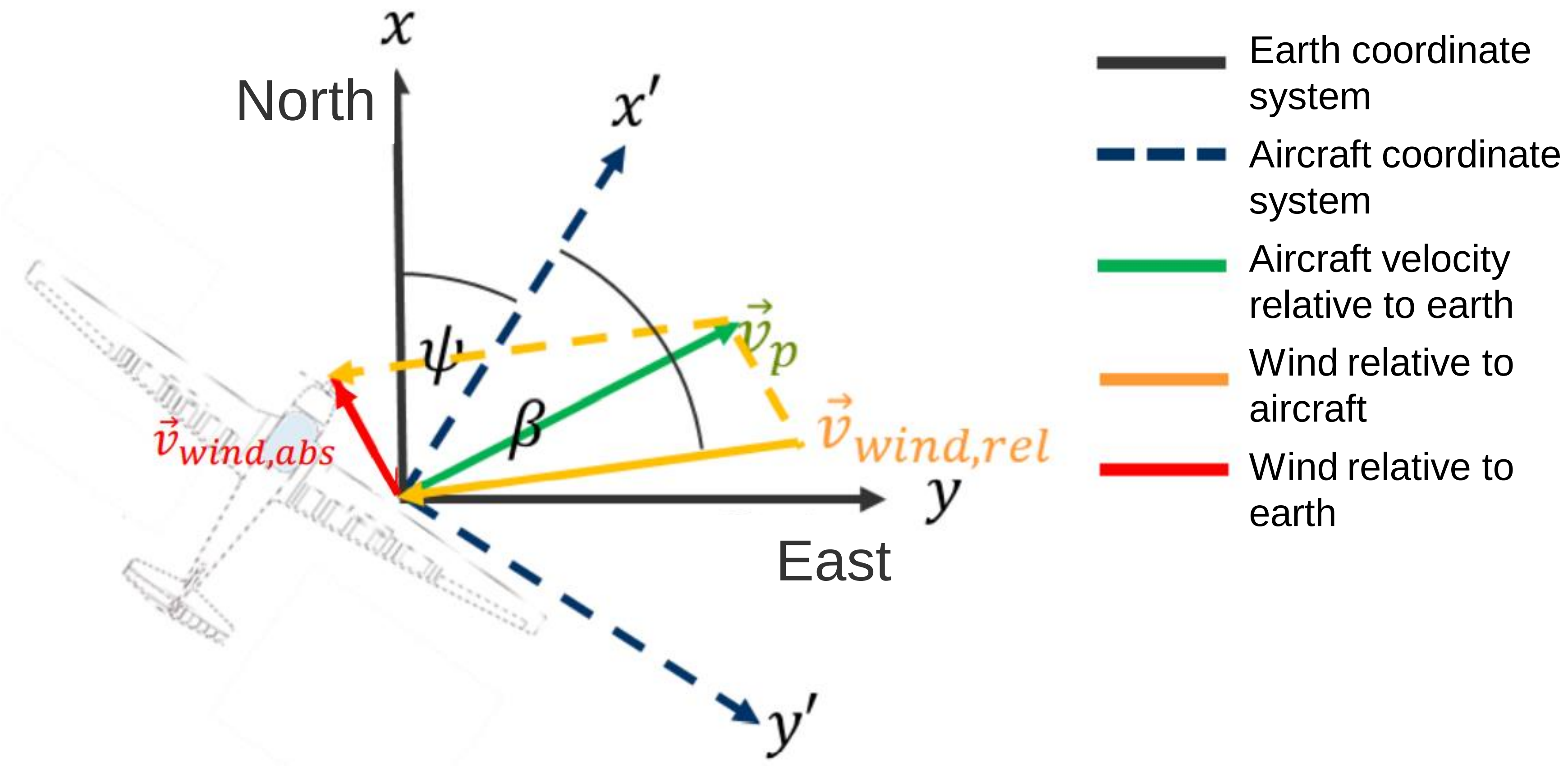
Top view

Rosemount 858AJ for:

- Static pressure measurements
- Dynamic pressure measurements
- Flow angle measurements

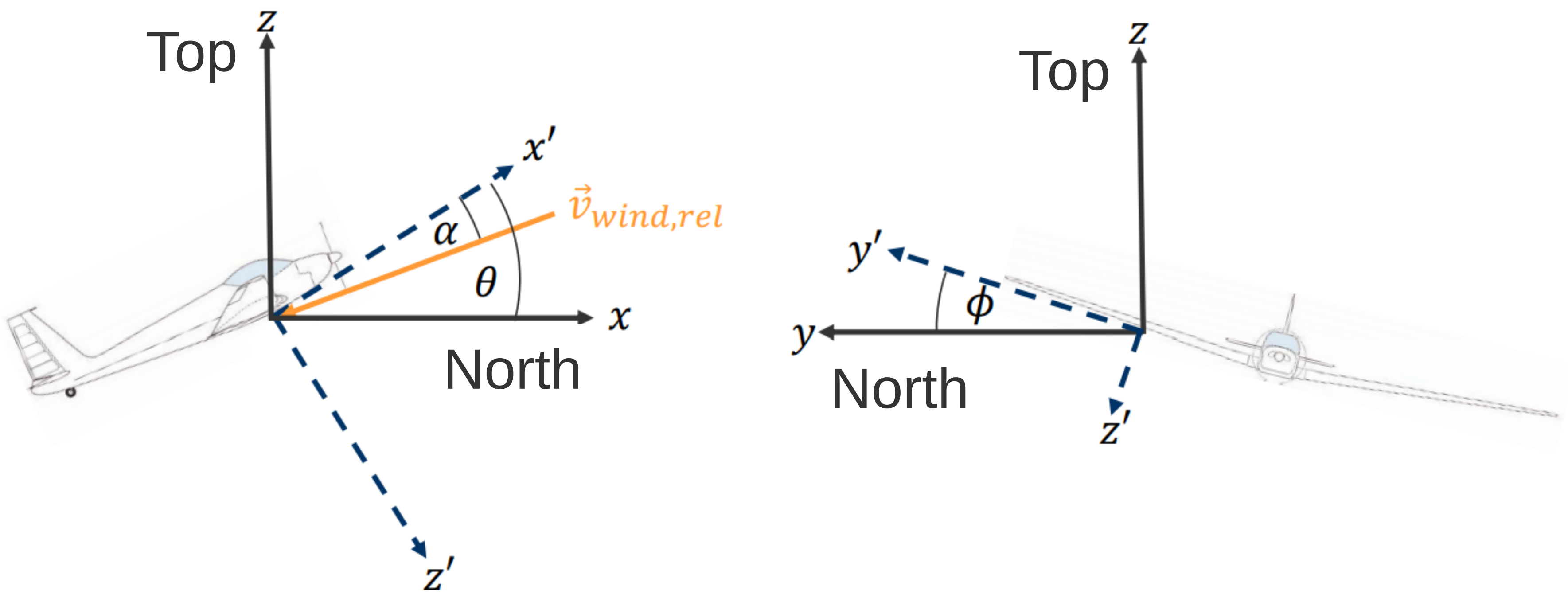
Source: (Bütow, 2018)

Wind vector measurement



Source: (Bütow, 2018)

Wind vector measurement



Source: (Bütow, 2018)

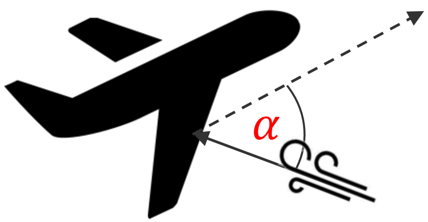
Flow angle computation

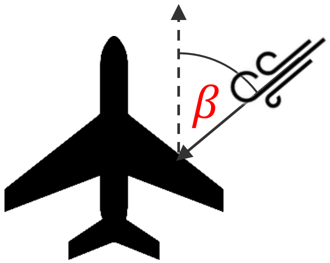
$$\alpha = \frac{1}{C_{k,\alpha}} \Delta\tilde{p}_\alpha - \alpha_0$$

$$\beta = \frac{1}{C_{k,\beta}} \Delta\tilde{p}_\beta - \beta_0$$

$$\Delta\tilde{p}_\alpha = \frac{\alpha_2 - \alpha_1}{q}$$

$$\Delta\tilde{p}_\beta = \frac{\beta_2 - \beta_1}{q}$$





α: angle of attack

α_0: α-angle offset

β: angle of sideslip

β_0: β-angle offset

$C_{k,\alpha}$: Sensitivity coefficient for α

$C_{k,\beta}$: Sensitivity coefficient for β

$\Delta\tilde{p}_\alpha$: α pressure difference divided by q

$\Delta\tilde{p}_\beta$: β pressure difference divided by q

q: dynamic pressure

3. Calibration Methods

List of Methods

Methods using further equipment:

- Reference measurement with trailing cone

If no reference measurement equipment is available:

– **Calibration using calibration flight manoeuvres**

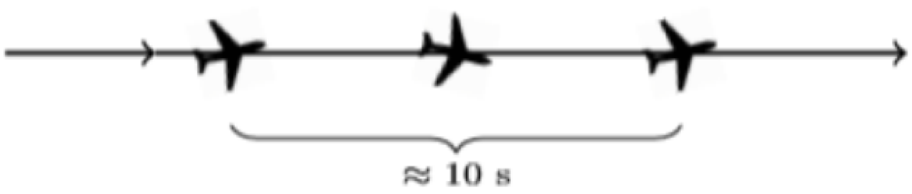
Calibration flight manoeuvres

Assumption: $\frac{dp}{dt} = 0$

Speed runs:

– Gradual variations of aircraft velocity between minimum and maximum

Yawing Oscillations:



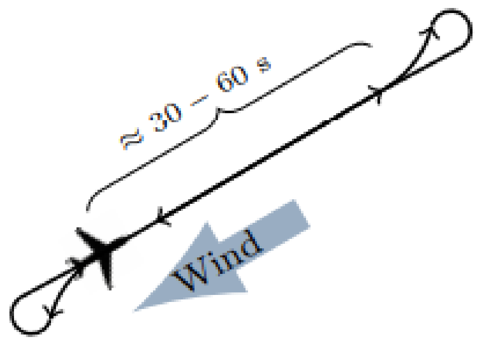
– Oscillations around the yaw angle

Source: (Bütow, 2018)

Calibration flight manoeuvres

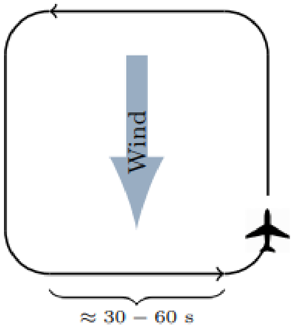
Assumption: $\frac{dp}{dt} = 0$

Reverse heading:



-Fly in one direction
-Turn 180° by first turning 90° in one direction and than 270° in the other

Box:



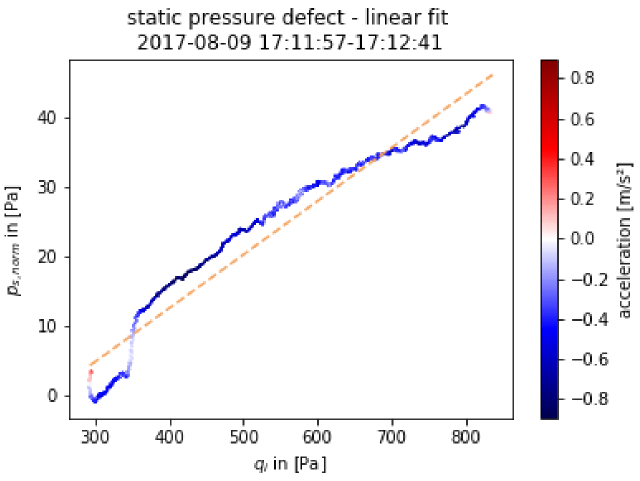
-Fly a wind square pattern

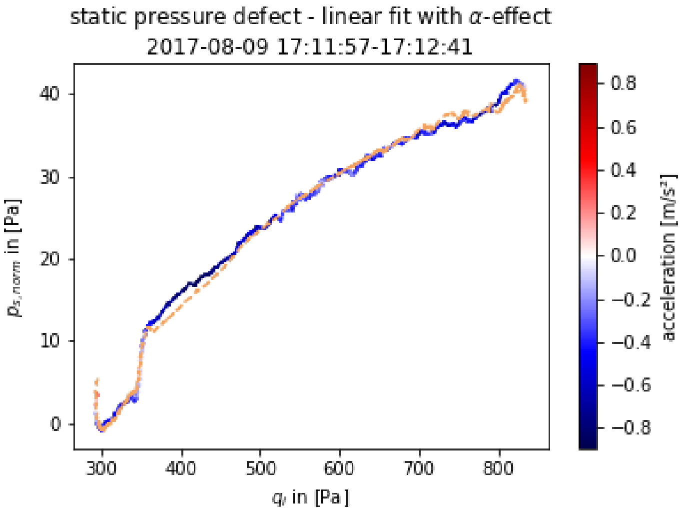
Source: (Bütow, 2018)

Finding the model fit

Theory: The static pressure should not be dependent on the dynamic pressure or the flow angles α and β

Goal: finding a function which describes all systematic dependency of static pressure changes on dynamic pressure and α and β





Finding the curve

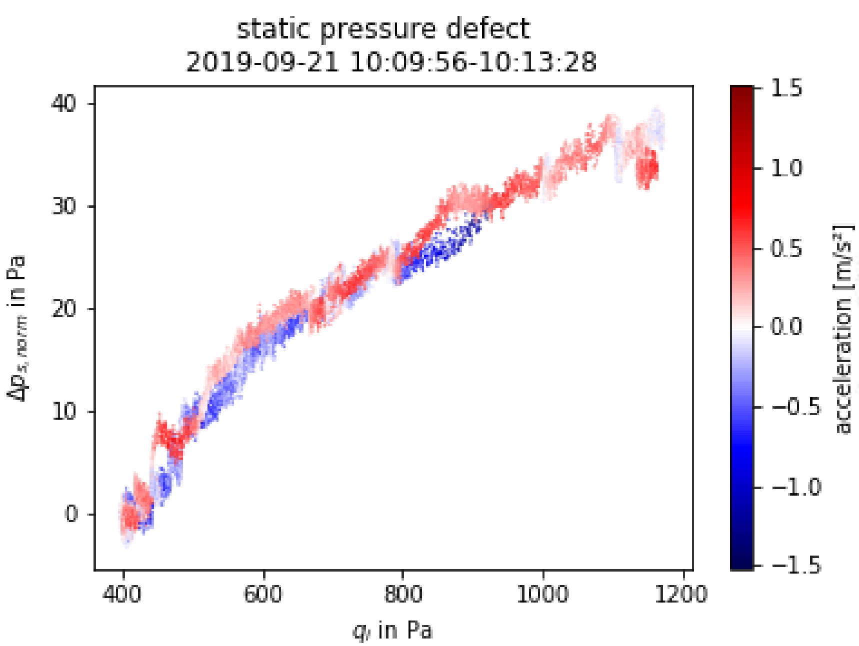
1. Select a reference pressure
2. Normalize the pressure towards the same height using the barometric height function
3. Compute the difference between each static pressure measurement and the reference pressure
4. Plot the Static pressure differences against the dynamic pressure
5. Fit Model against data

Finding the offset

1. Use the straight sections of the reverse heading manoeuvre
2. Compute the Windspeed for each section
3. Build the difference between the mean Windspeed for each section
4. Alternate the Offset value until the difference is minimized

4. Model fit Analysis

Static pressure dependence on Dynamic pressure



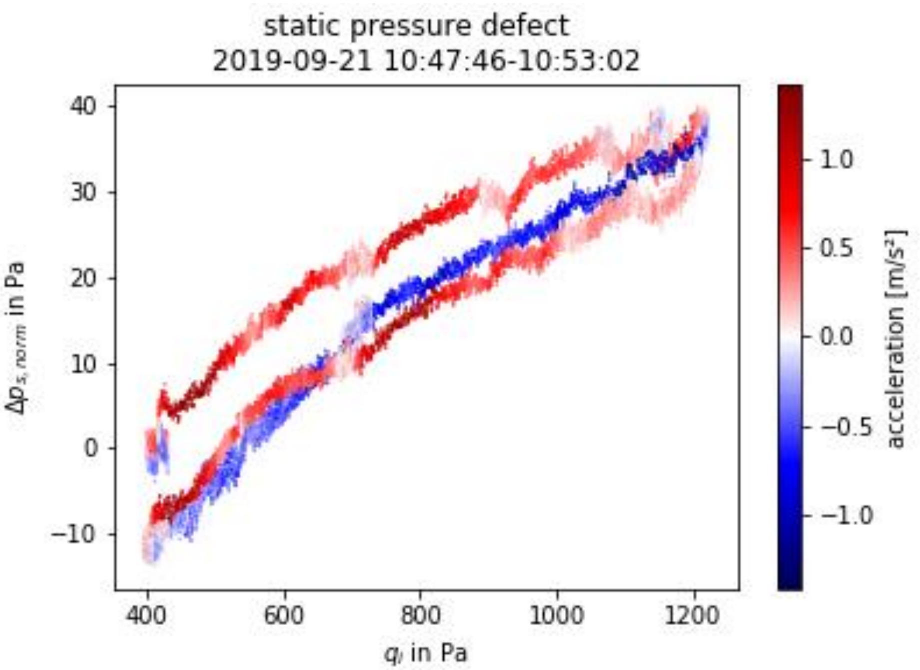


Fig. 1: Static pressure defect dependence on dynamic pressure. The colour bar shows the acceleration.

- Linear relationship
- Effect of α-angle is visible
- Offset between acceleration and deceleration

Static pressure dependence on α

- Quadratic relationship
- To avoid dependence on α calibration use indicated angle of attack

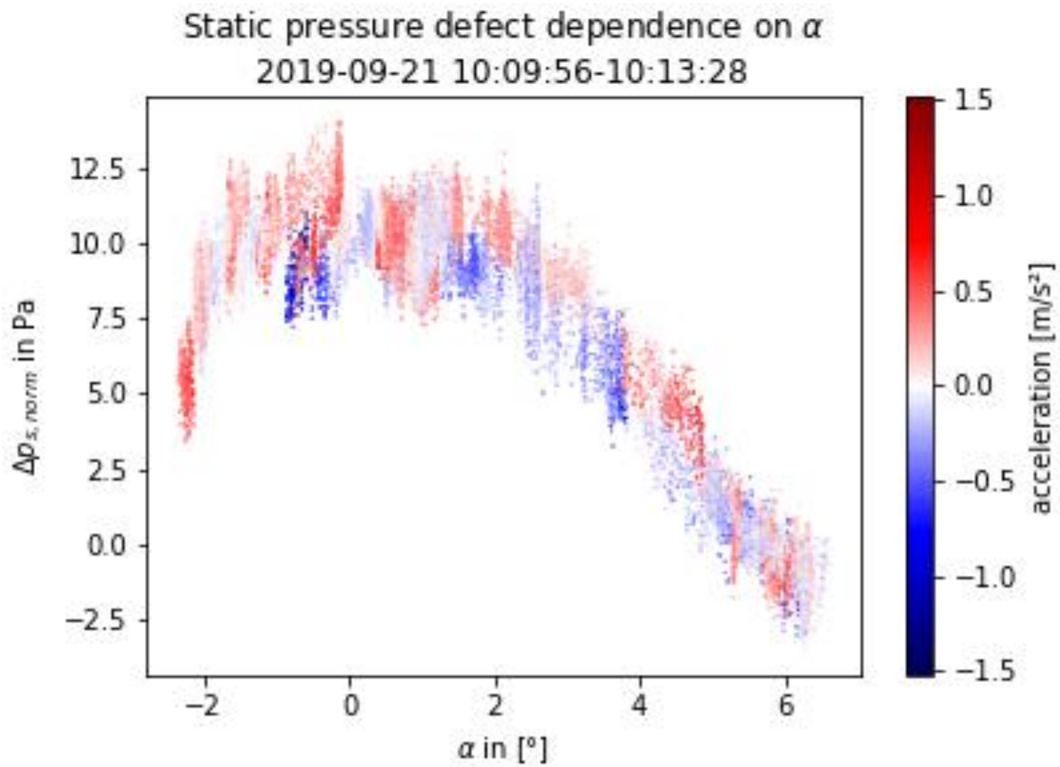


Fig. 2: Static pressure defect dependence on angle of attack. The linear relationship between the dynamic and static pressure was subtracted from the data. The colour bar shows the acceleration.

Static pressure dependence on β

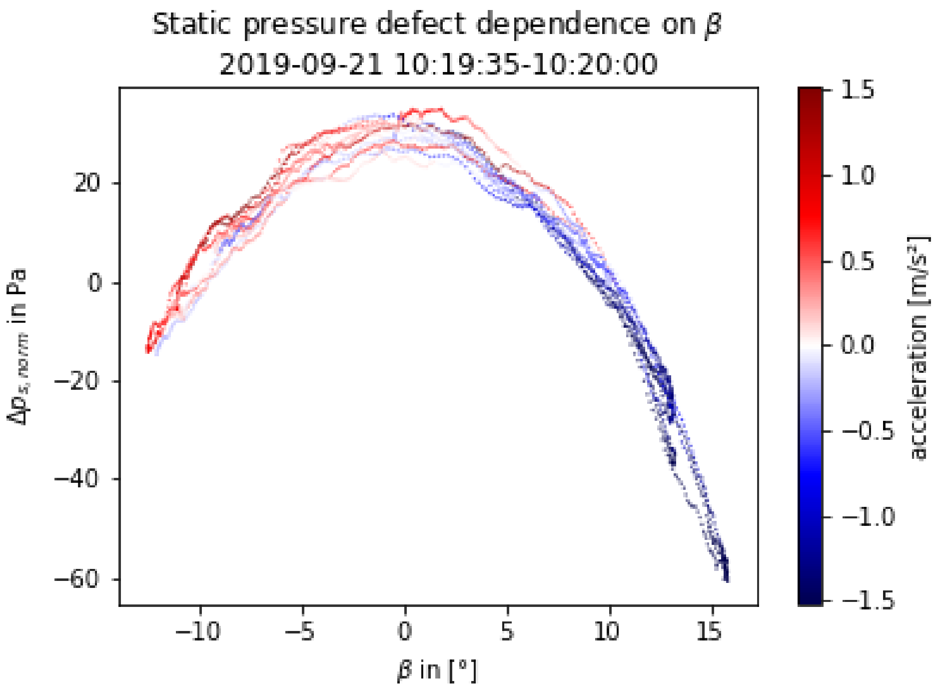


Fig. 3: Static pressure defect dependence on angle of sideslip. The colour bar shows the acceleration.

- Quadratic relationship
- To avoid dependence on β calibration use indicated angle of sideslip

Model fit

Static pressure dependence	**Manoeuvre**
Linear dependence on q	Speed run
Quadratic dependence on α	Speed run
Quadratic dependence on β	Yawing oscillation

Model: $p = q_0 + C_1 \cdot q_i + C_{\alpha,1} \cdot abs(\alpha) \cdot q_i + C_{\alpha,2} \cdot \alpha^2 \cdot q_i + C_{\beta,1} \cdot abs(\beta) \cdot q_i + C_{\beta,2} \cdot \beta^2 \cdot q_i$

q_0: Offset
C_1: linear constant q_i
$C_{\alpha,1}$: linear constant $\alpha \cdot q_i$
$C_{\alpha,2}$: quadratic constant $\alpha \cdot q_i$

$C_{\beta,1}$: linear constant $\beta \cdot q_i$
$C_{\beta,2}$: quadratic constant $\beta \cdot q_i$

Goodness of fit - Speed run Manoeuvre

a) b)

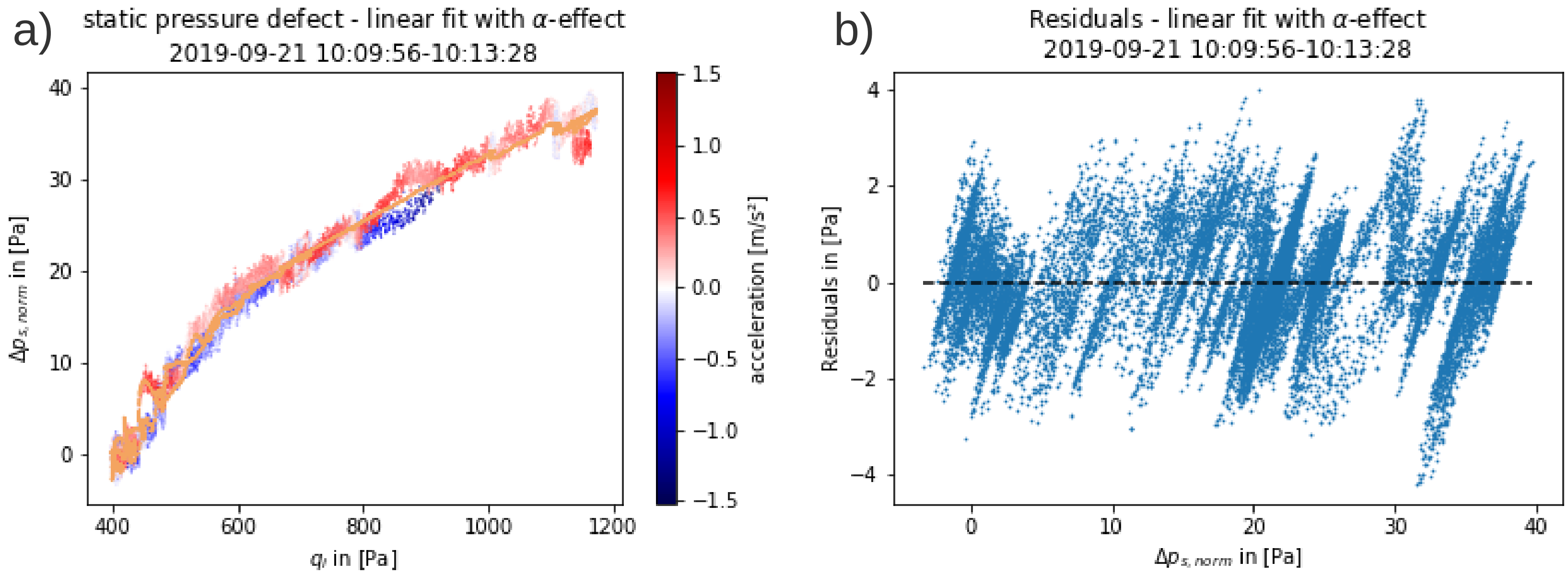


Fig. 4: Model fit with α-effect. a) Comparison between model and data. b) Residuals. Mean $R^2 \approx 0.95$

Goodness of fit - Yawing Manoeuvre

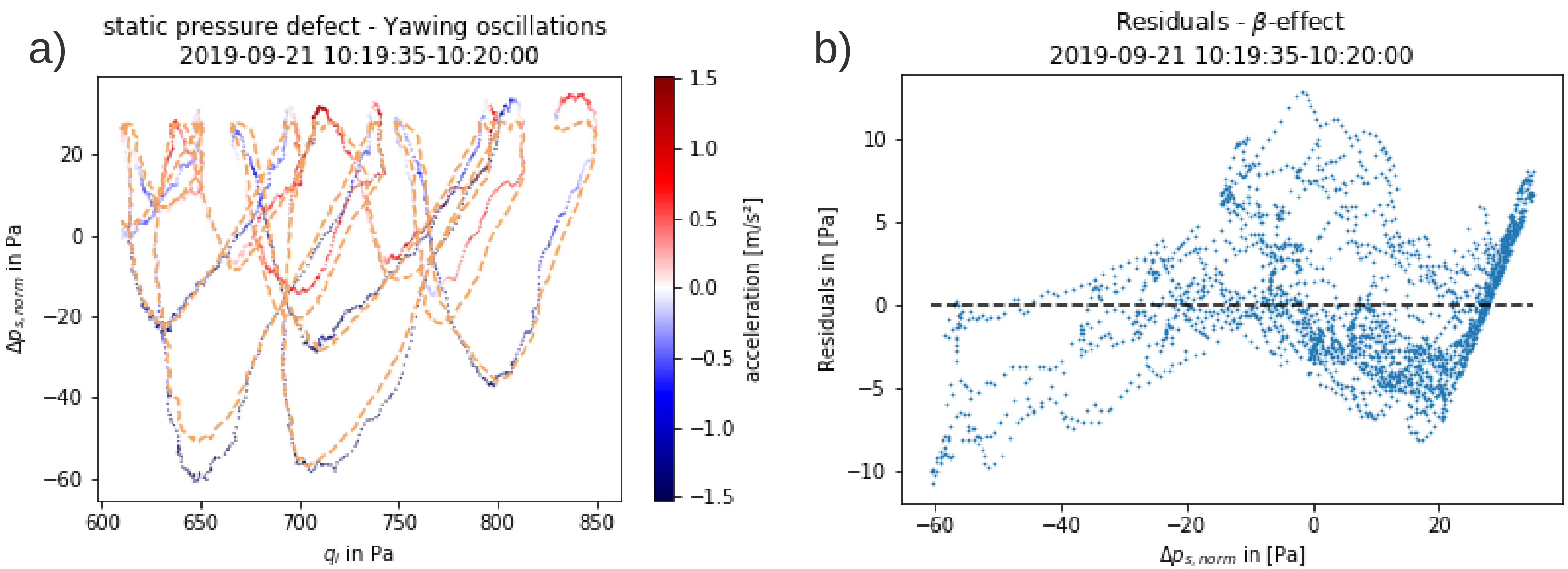


Fig. 5: Model fit with β-effect. a) Comparison between model and data. b) Residuals. Mean $R^2 \approx 0.90$

Wind Vectors – Pitching Oscillations

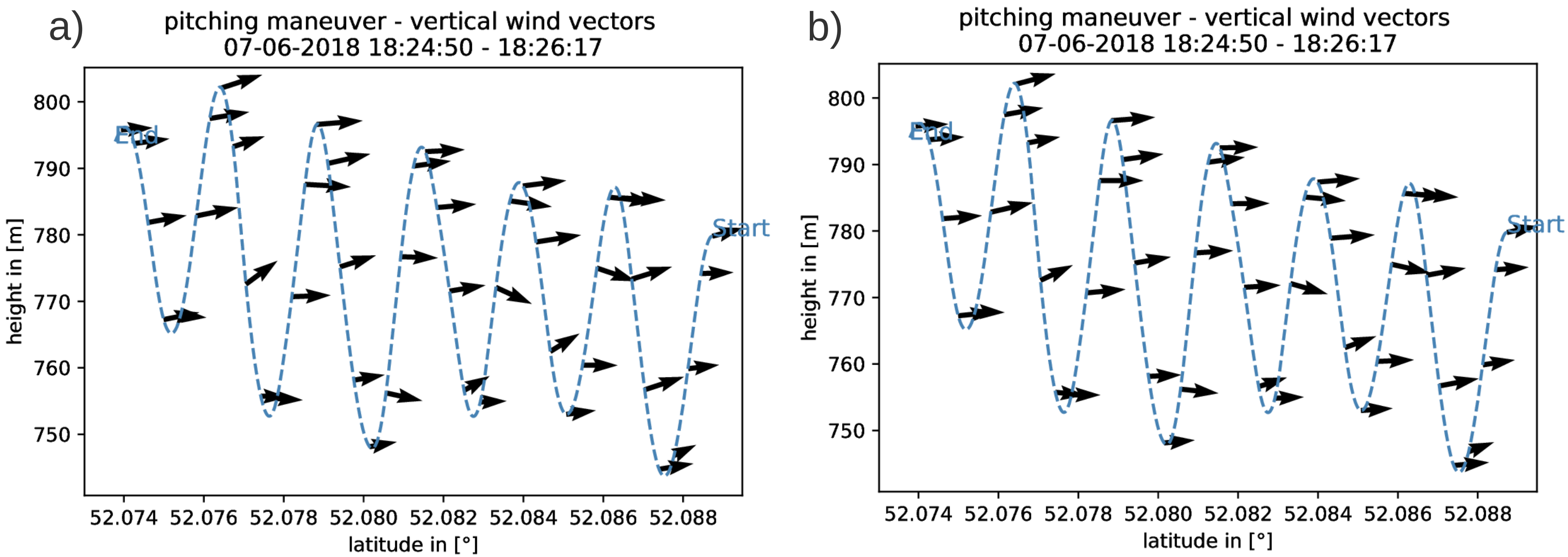


Fig. 6: Uncalibrated vertical wind vectors (a) and calibrated (b) vertical wind vectors calculated for the pitching oscillations performed on the 07.06.2018

5. Conclusion

Conclusion

- There is a linear relationship between $\Delta p_{s,norm}$ and q
- There is a quadratic relationship between $\Delta p_{s,norm}$ and α
- There is a quadratic relationship between $\Delta p_{s,norm}$ and β
- & A small effect caused by windspeed changes and wind direction changes is to be expected
- For the calibration of the β-effect yawing oscillations need to be included into the calibration process

6. Summary

Summary

The static pressure can be used for **calculations of:**

Height, Dynamic pressure,

Potential temperature, Wind vectors

It **changes with**:

Height and temperature

It should **not change with**:

Dynamic pressure, ∠ angle of attack,

∠ angle of sideslip

Therefore it can be calibrated using targeted flight manoeuvres which provoke changes of q, α and β

Appendix

Literature

Bütow, A., 2018. *Kalibrierung eines Turbulenzmesssystems an einem Motorsegler,* Berlin: Freie Universität Berlin - Institut für Weltraumwissenschaften.

Gracey, W., 1980. *Measurement of Aircraft Speed and Altitude.* NASA Reference Publication 1046 ed. Hampton, Virginia: Langley Research Center. https://ntrs.nasa.gov/citations/19800015804

Kalogiros, J. A. & Wang, Q., 2002. Calibration of a Radome-Differential GPS System on a Twin Otter Research Aircraft. *JOURNAL OF ATMOSPHERIC AND OCEANIC TECHNOLOGY,* Volume 19, pp. 159-171. https://doi.org/10.1175/1520-0426(2002)019<0159:COARDG>2.0.CO;2

Mallaun, C., Giez, A. & Baumann, R., 2015. Calibration of 3-D wind measurements on a single-engine research aircraft. *Atmospheric Measurement Techniques*, 15 June, p. 3177–3196. https://amt.copernicus.org/articles/8/3177/2015/amt-8-3177-2015.pdf

Tjernström, M. & Fiehe, C. A., 1991. Analysis of a Radome Air-Motion System on a Twin-Jet Aircraft for Boundary-Layer Research. *American Meteorological Society,* 21 June, Volume 8, pp. 19-40. https://doi.org/10.1175/1520-0426(1991)008<0019:AOARAM>2.0.CO;2

Icon-sources

https://www.flaticon.es/icono-gratis/despegue-del-avion_68380

https://www.flaticon.com/free-icon/wind-weather-lines-group-symbol_55939

https://www.iso.org/obp/graphics/grs/a0b5728d-2d4a-4db6-a8f6-2598b3d8777a_200.png

https://cdn2.iconfinder.com/data/icons/adventure-out-line-2/64/Nature-river-weather-water-three-512.png

http://img.freepik.com/free-icon/dimension-of-line-height_318-32185.jpg?size=338&ext=jpg

https://th.bing.com/th/id/OIP.T_VhP5j8ktHzd__fZcaHbAHaHa?pid=Api&rs=1

https://babele.co/home/wp-content/uploads/2018/06/Accelerators-icon.png

https://cdn1.iconfinder.com/data/icons/weather-and-seasonal-1/64/weathervane-512.png

https://upload.wikimedia.org/wikipedia/commons/thumb/b/bf/Angle_Symbol.svg/1014px-Angle_Symbol.svg.png

https://image.flaticon.com/icons/png/512/2103/2103601.png

https://cdn0.iconfinder.com/data/icons/specs-1/68/parabolic_quadratic_equation_vertex_graph-512.png

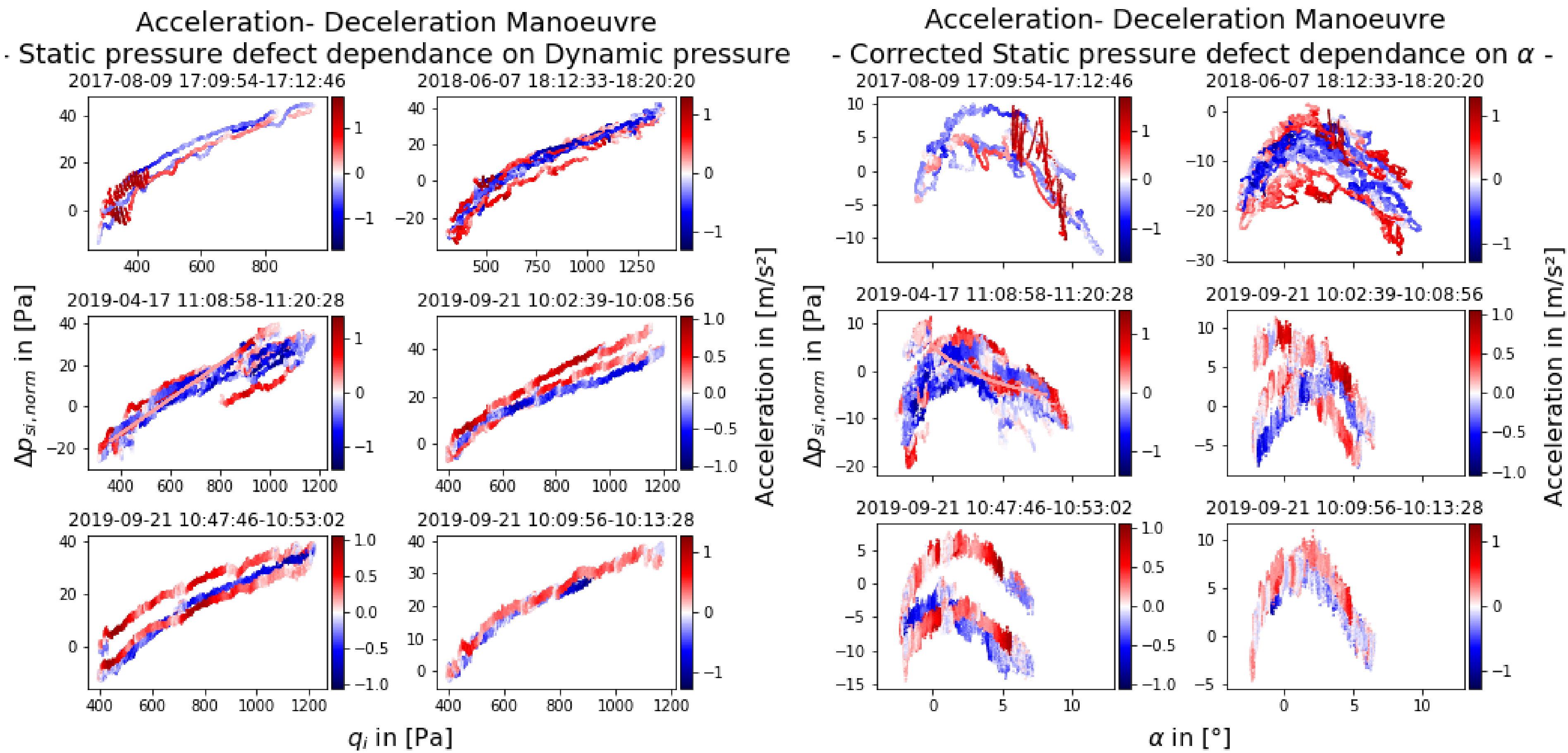
https://maxcdn.icons8.com/Share/icon/Transport/airplane_takeoff1600.png

http://www.clipartbest.com/cliparts/4cb/o7k/4cbo7kkzi.png

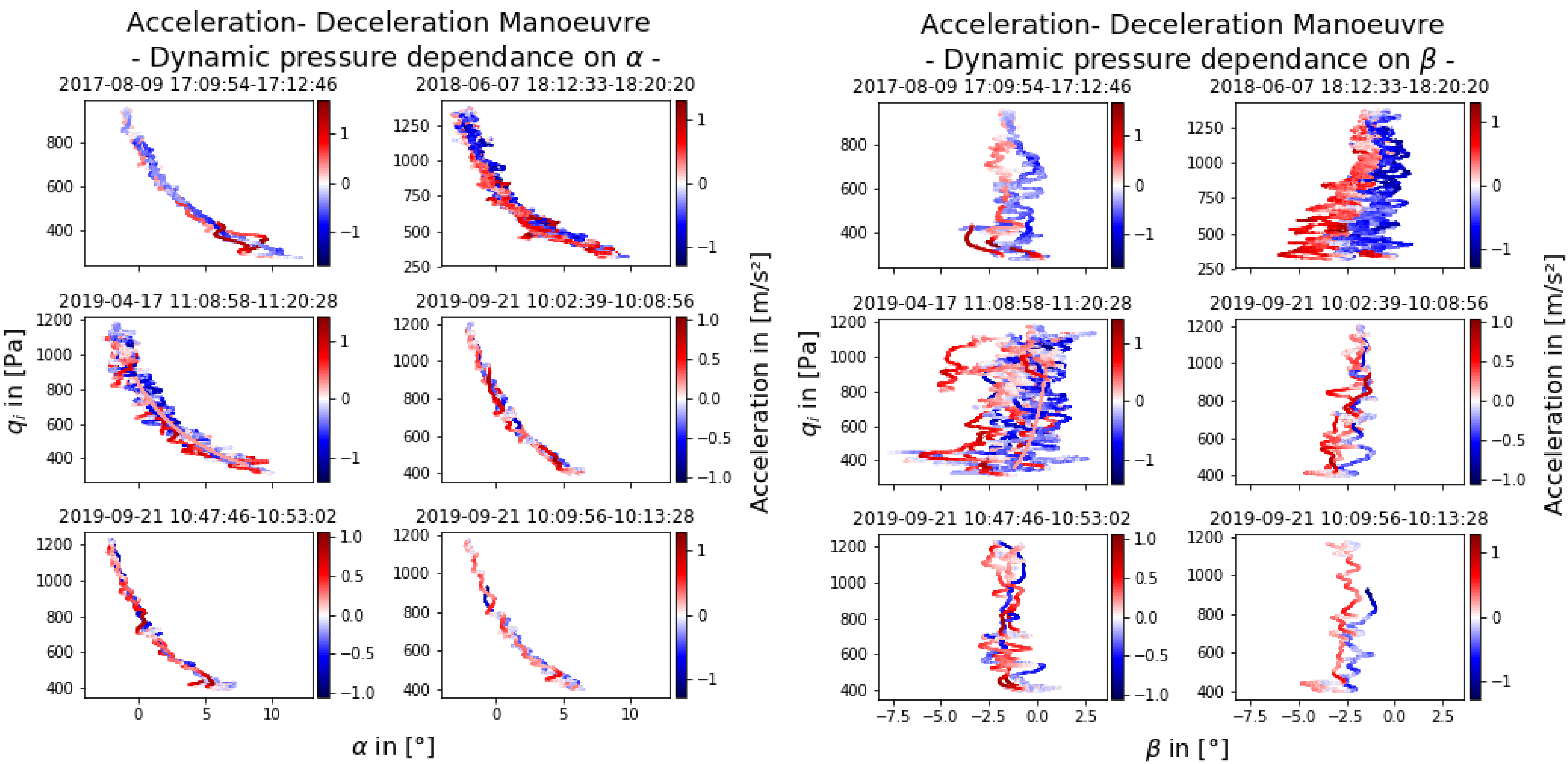
Picture-sources

https://tameson.com/pressure-gauges.html

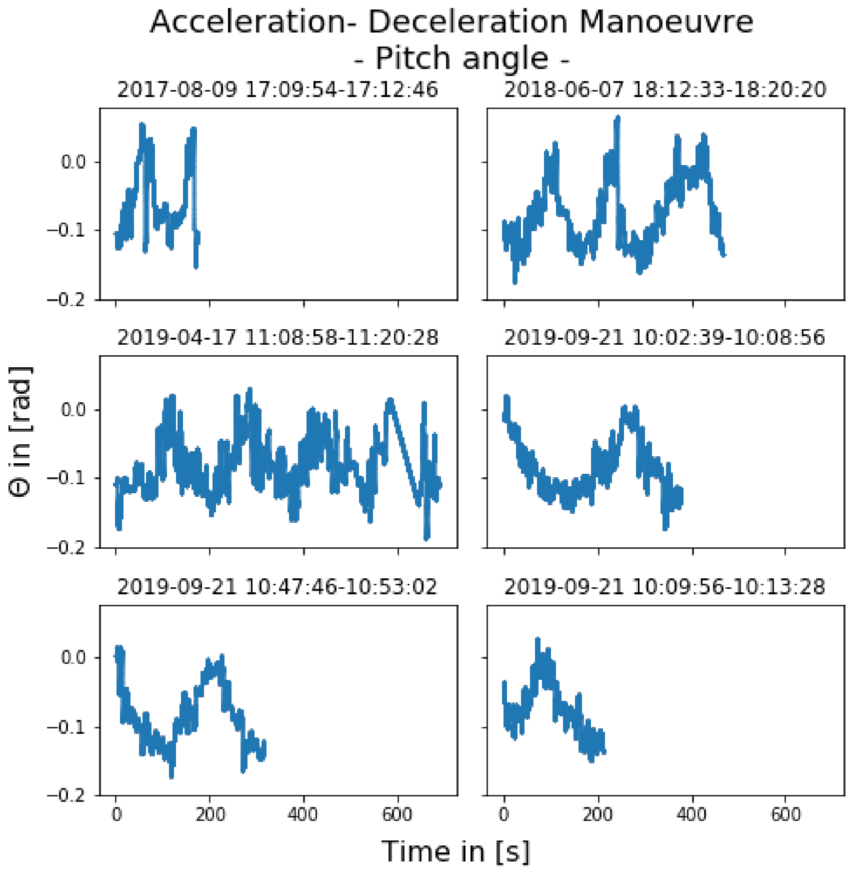
Speed runs - q_i and α vs. $\Delta p_{s,norm}$

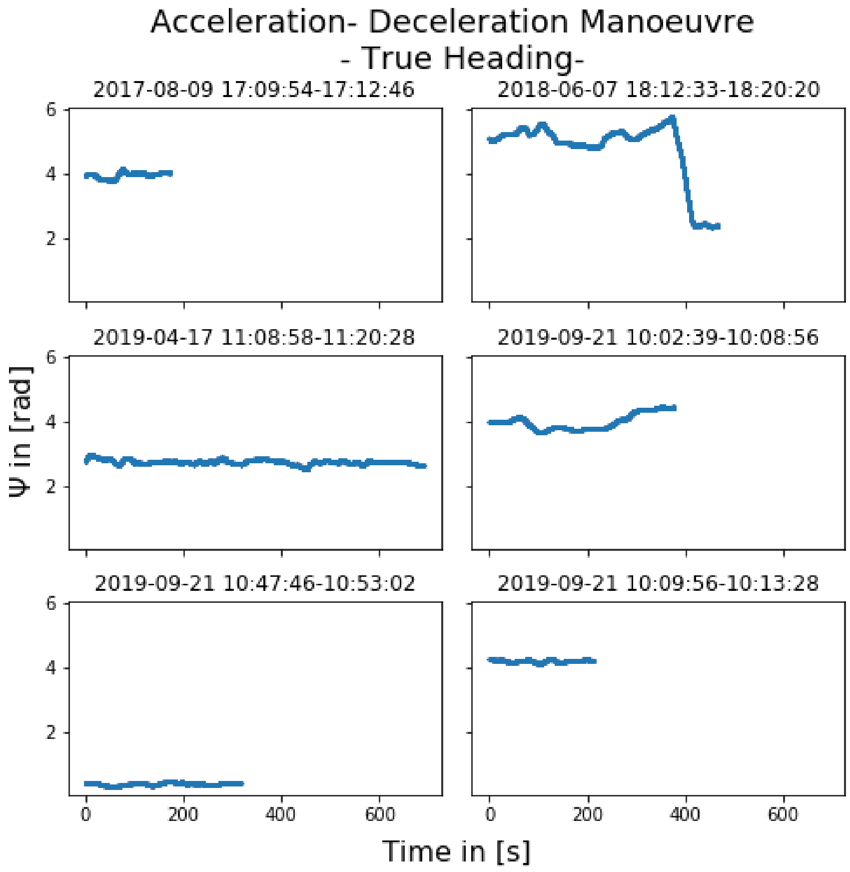


Speed runs - α and β vs. q_i

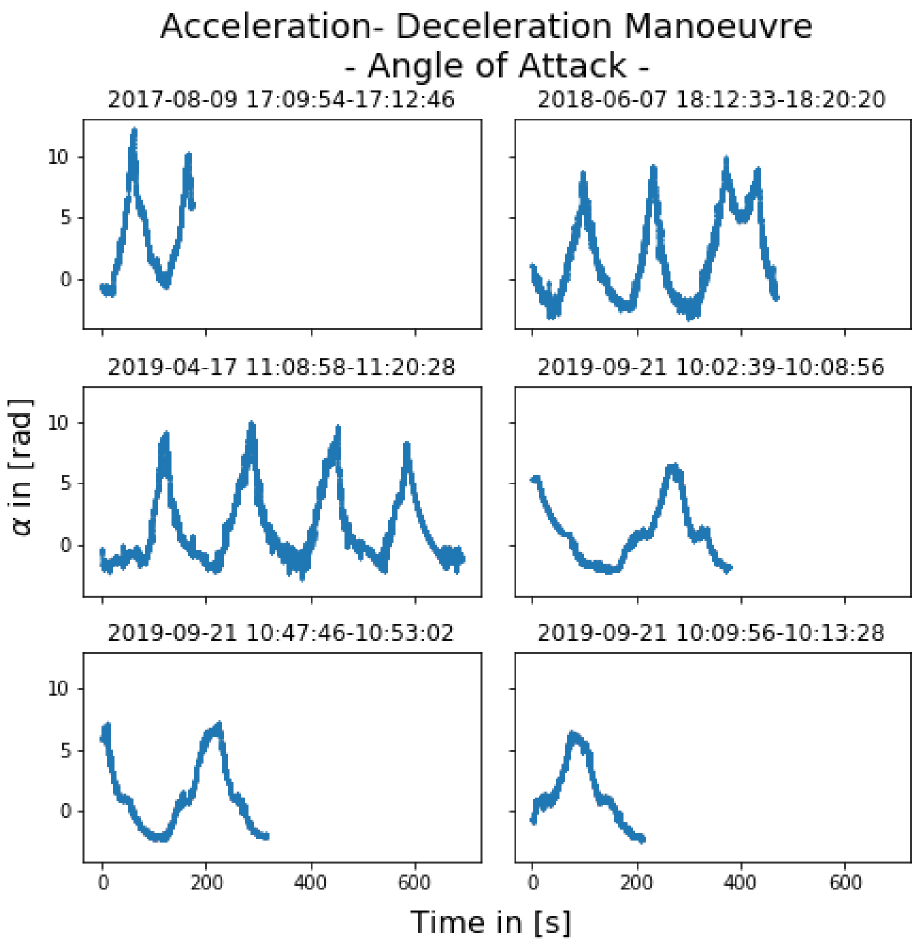


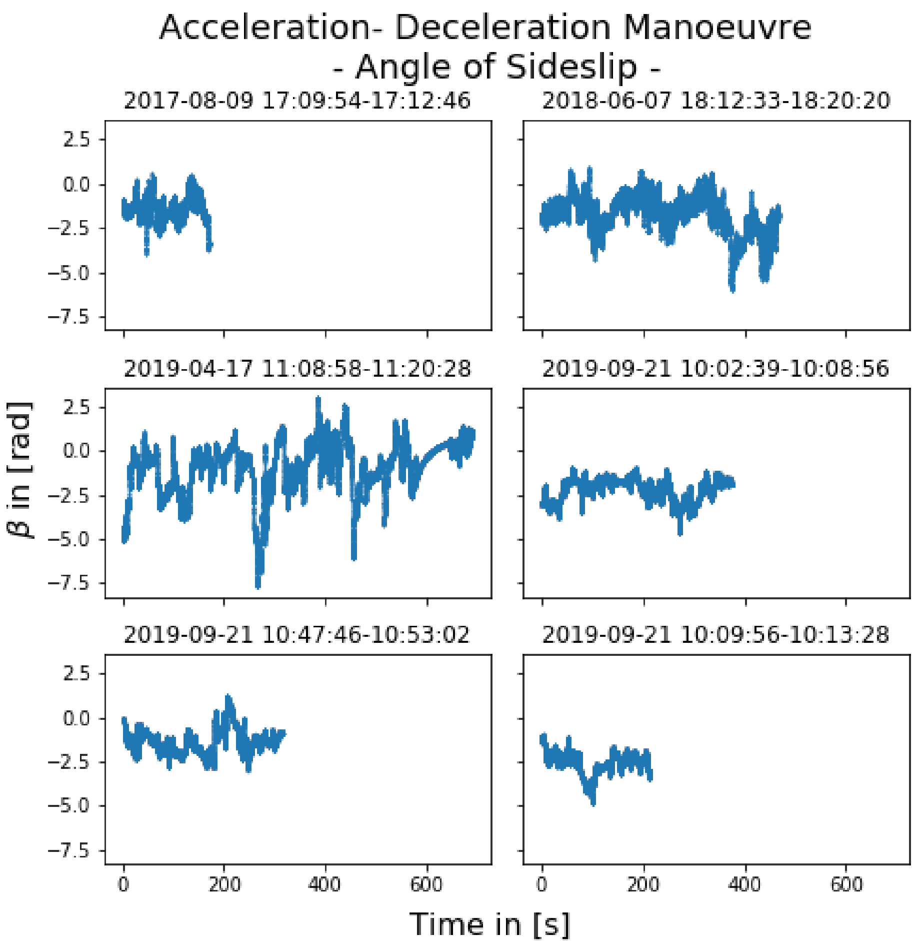
Speed runs - θ and ψ





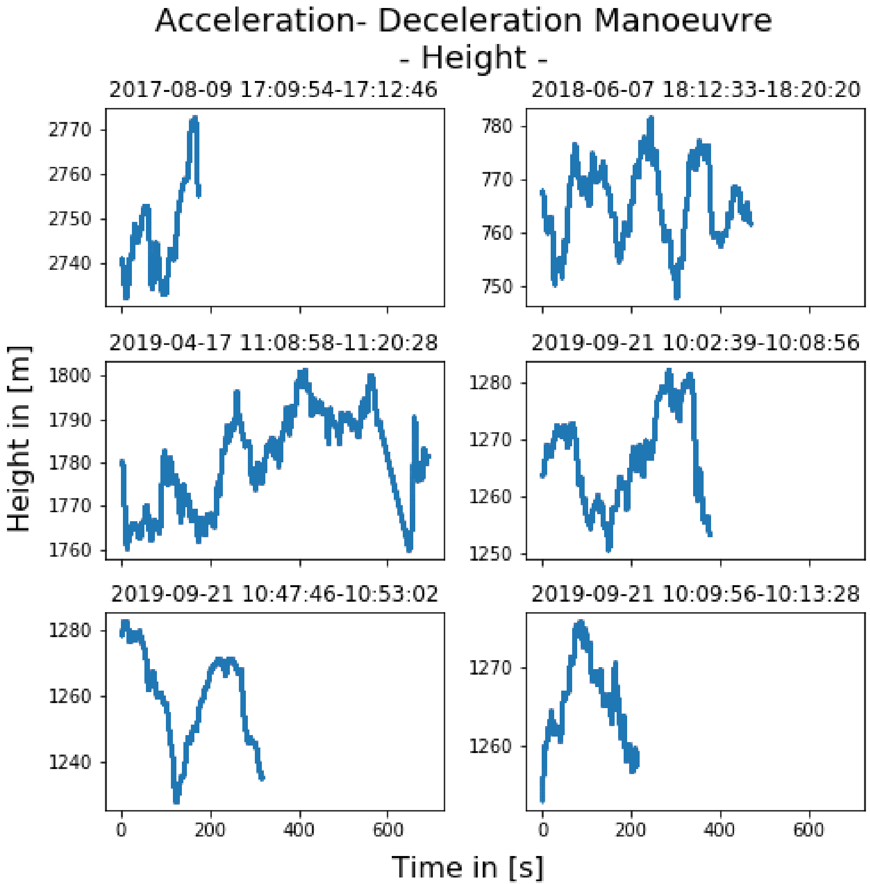
Speed runs - α and β

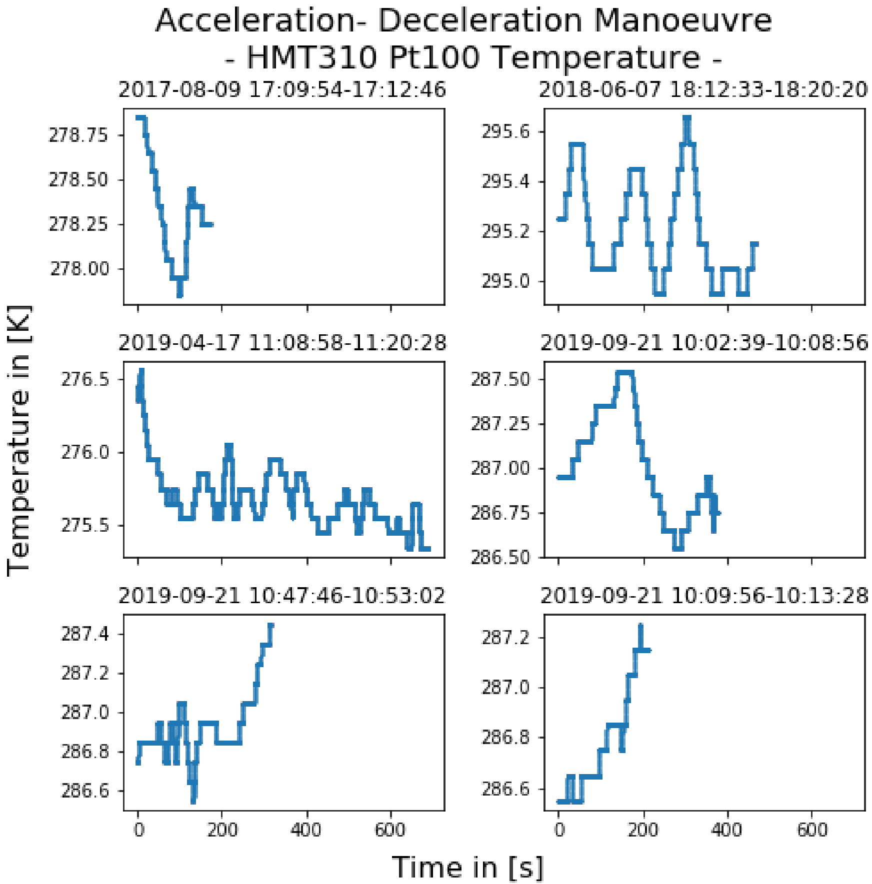




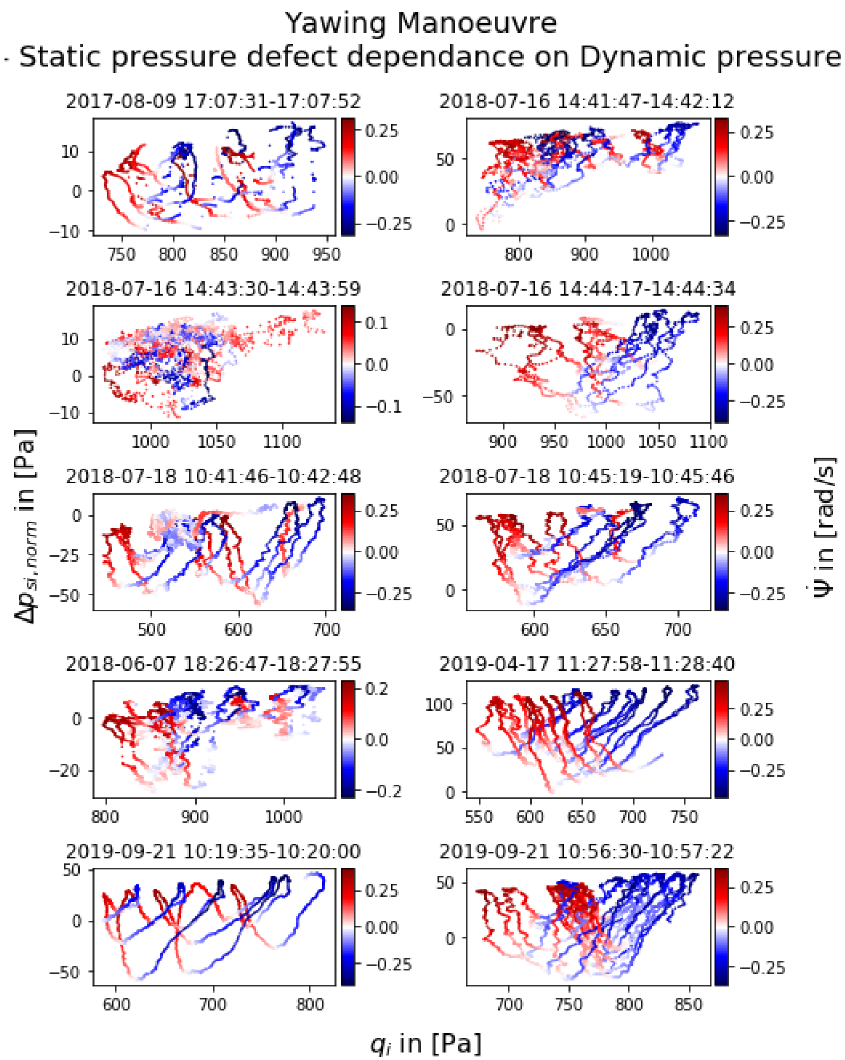
Freie Universität Berlin

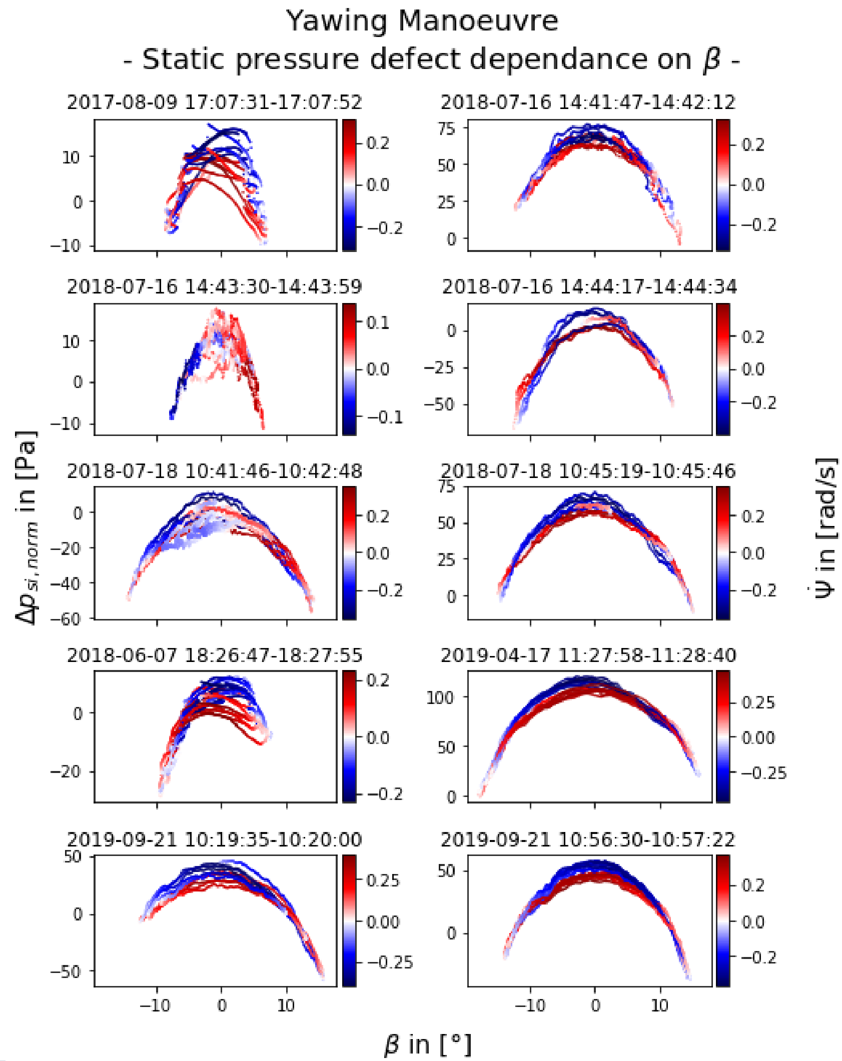
Speed runs – Height and Temperature



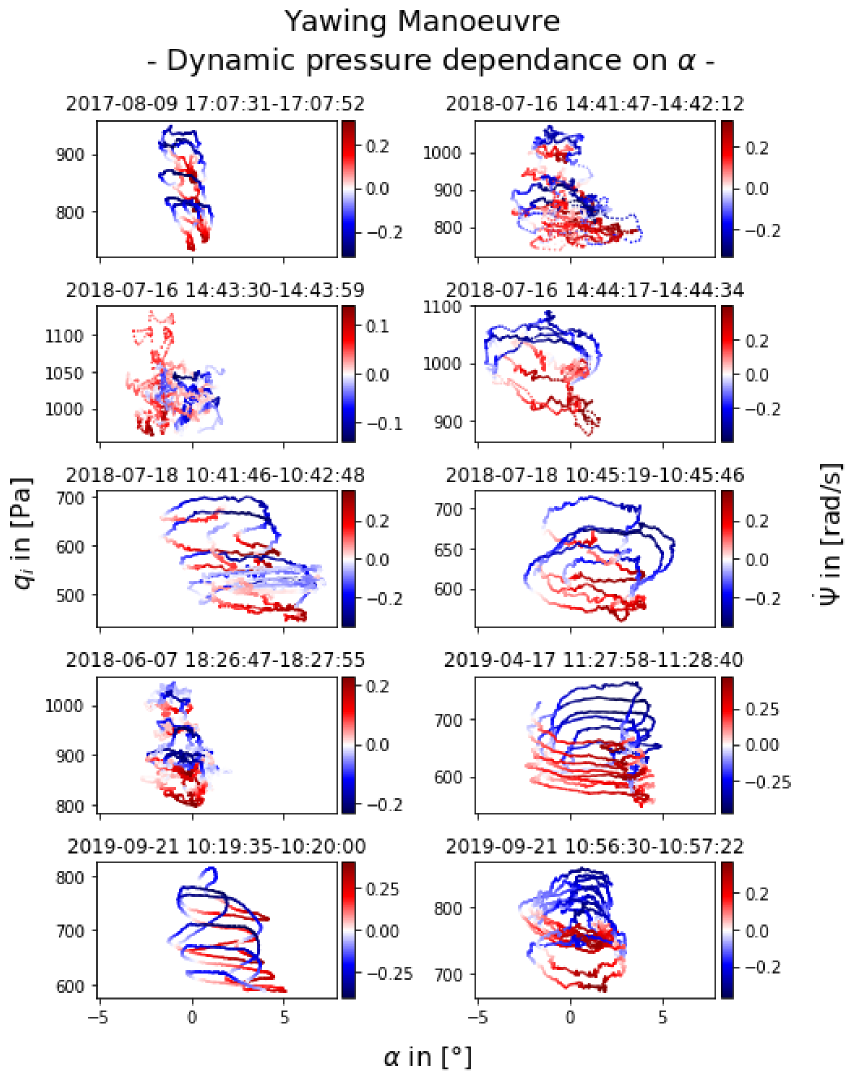


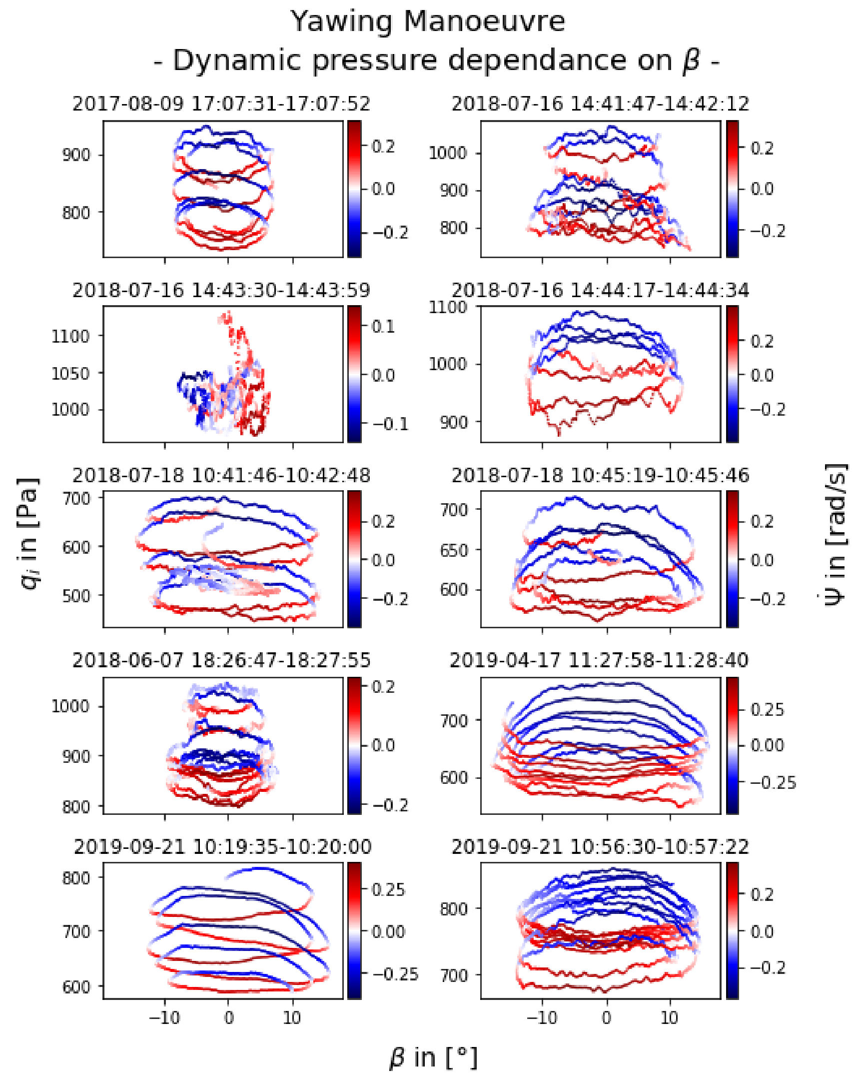
Yawing Manoeuvre – q_i and β vs. $\Delta p_{s,norm}$



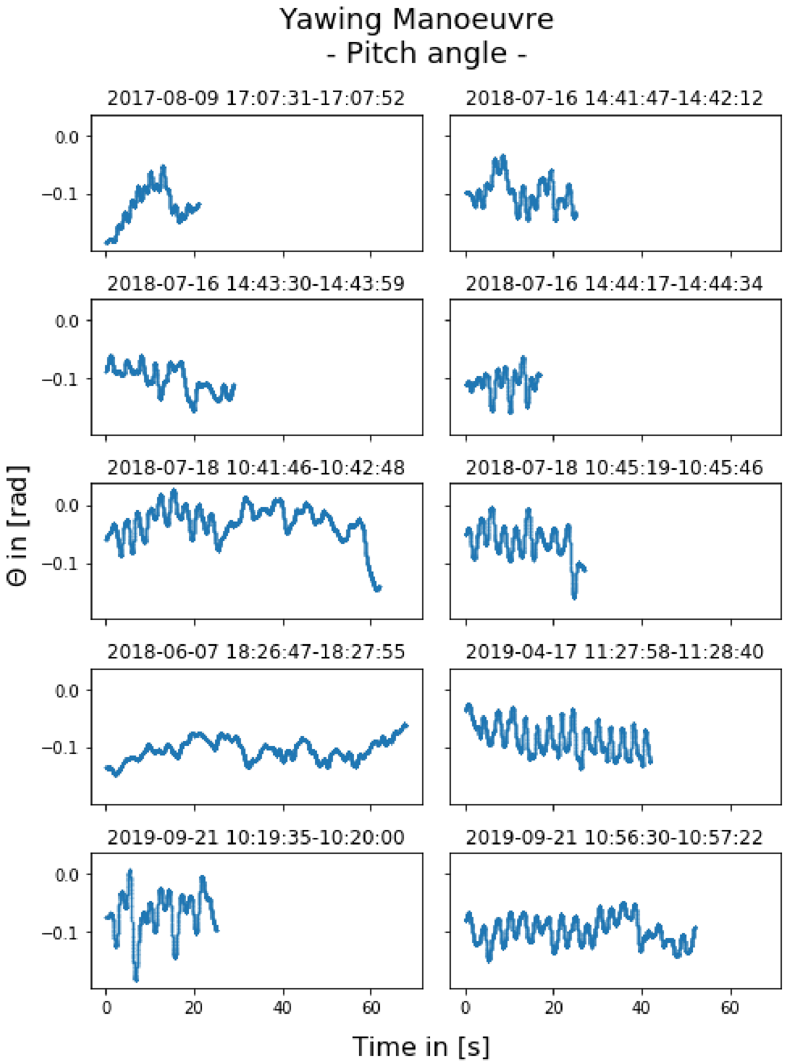


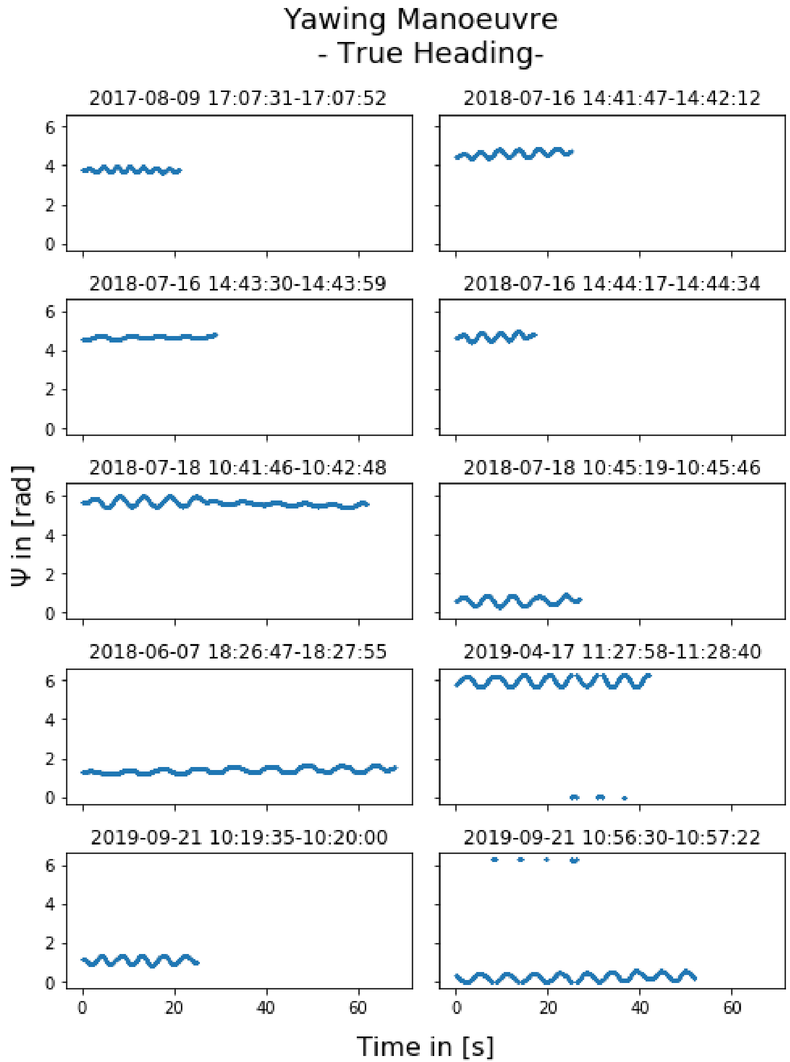
Yawing Manoeuvre – α and β vs. q_i



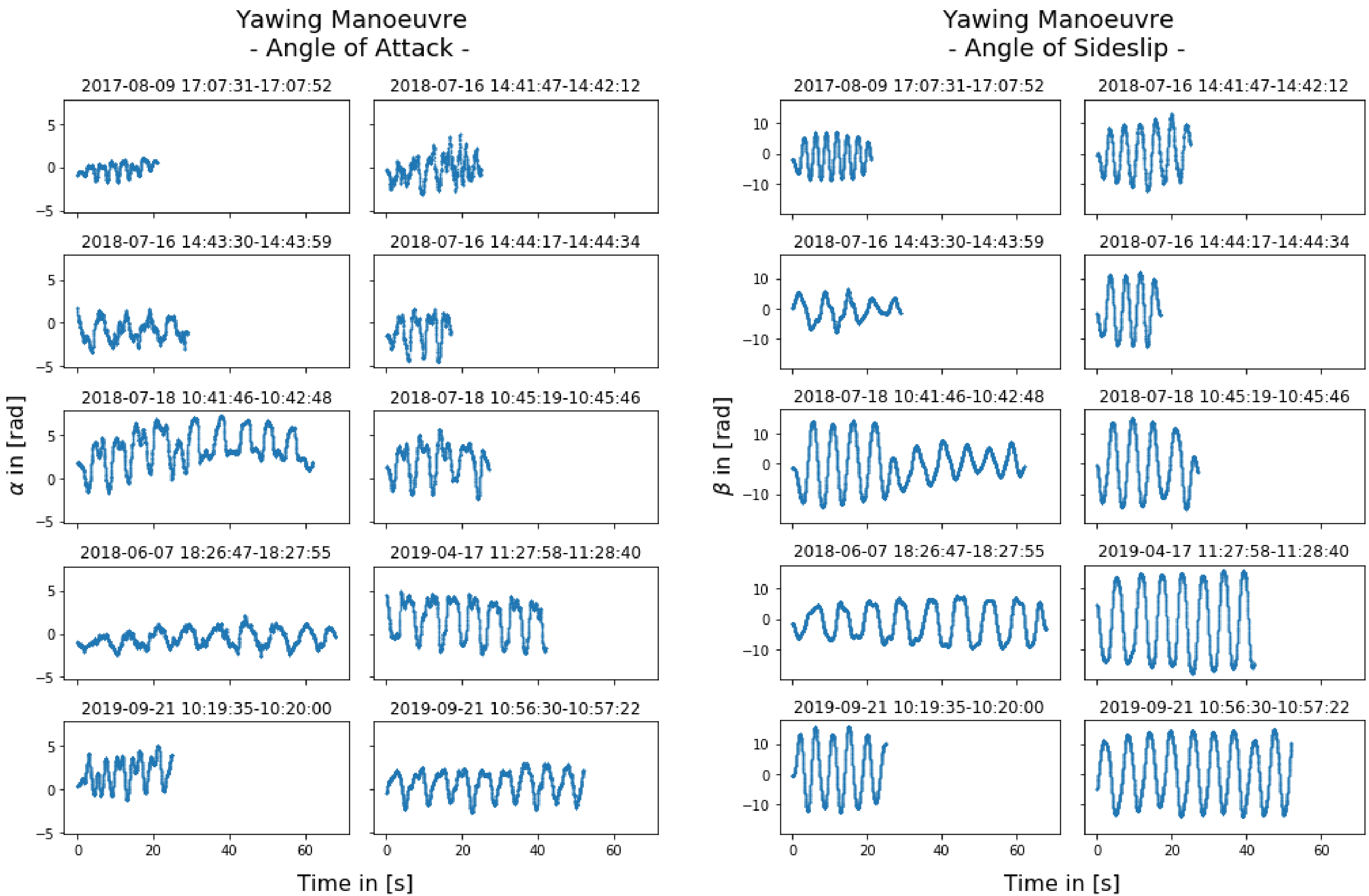


Yawing Manoeuvre – θ and ψ

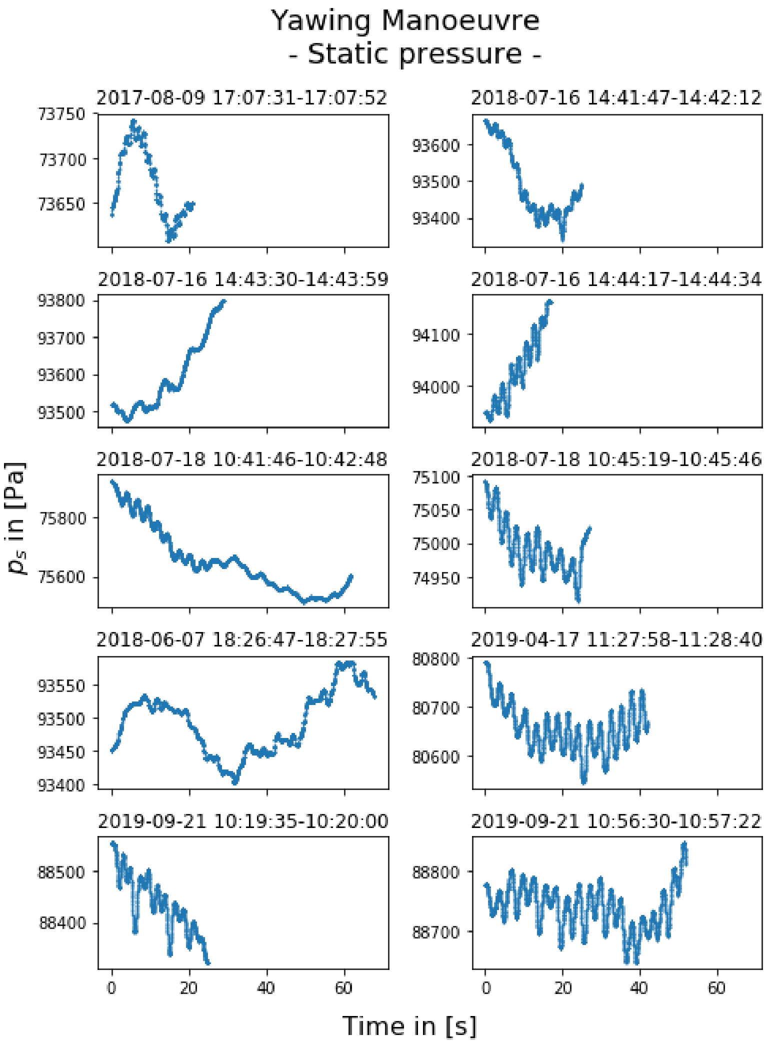


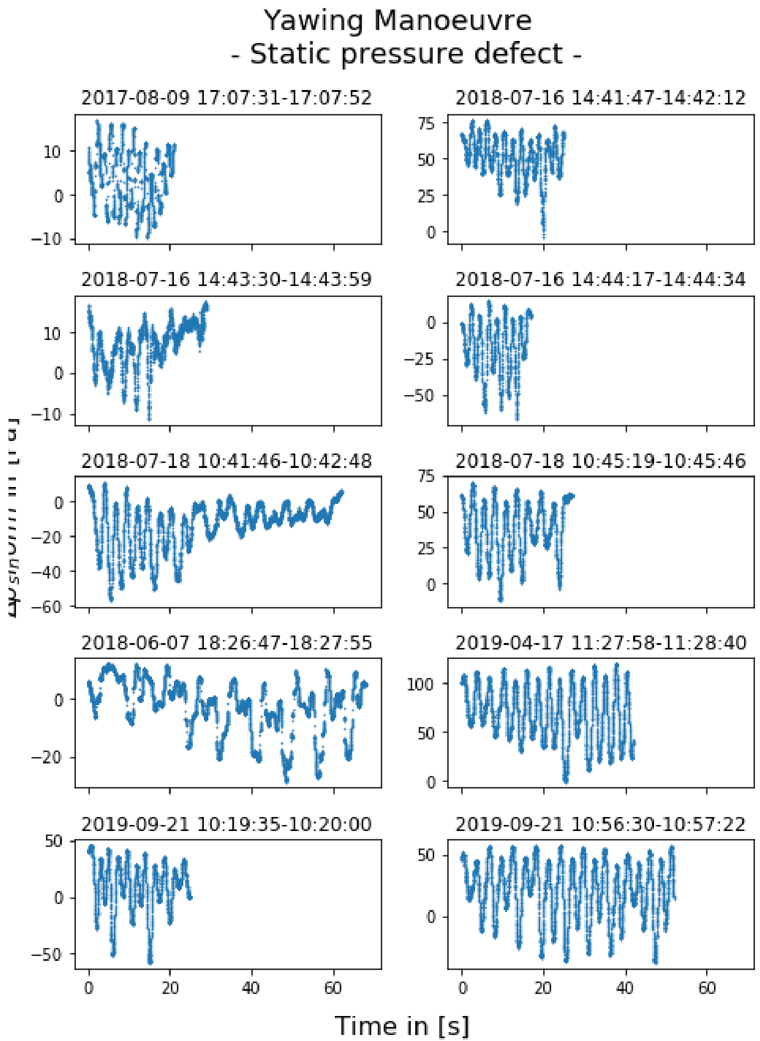


Yawing Manoeuvre – α and β

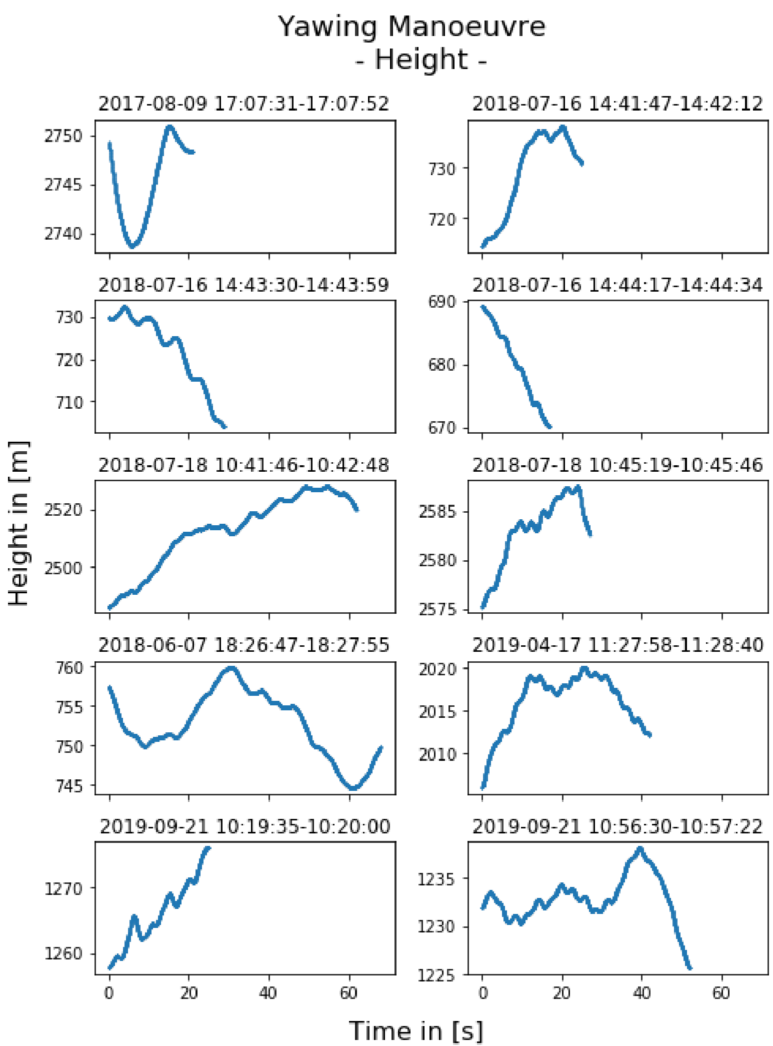


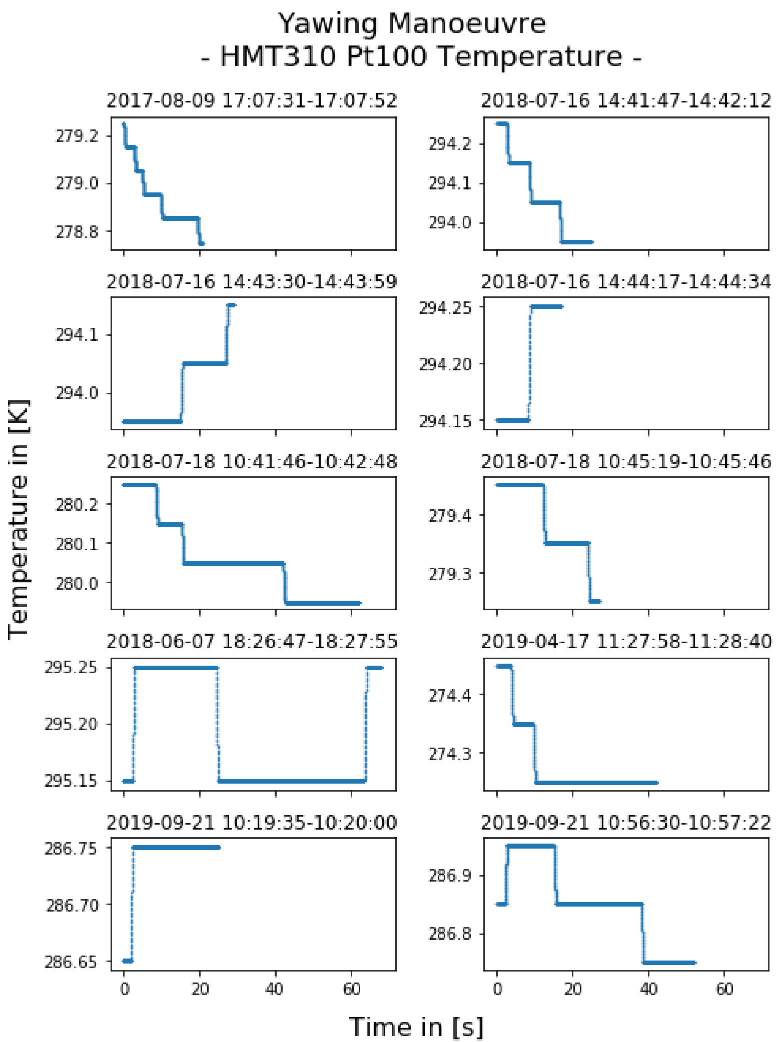
Yawing Manoeuvre – Static pressure





Yawing Manoeuvre – Height and Temperature





Model parameter estimations

configuration file	yawing file	Time interval	C1	C_alp_eff	C_alp_eff2	R2	C_bet_eff	C_bet_eff2	R2
00	00	['2017-08-09 17:07:31', '2017-08-09 17:07:52']	0,047	0,066	-2,251	0,973	-0,082	-0,577	0,737
01	06	['2018-06-07 18:26:47', '2018-06-07 18:27:55']	0,049	0,040	-2,426	0,965	0,097	-1,852	0,841
02	07	['2019-04-17 11:27:58', '2019-04-17 11:28:40']	0,049	-0,134	-1,273	0,930	0,191	-2,149	0,951
03	08	['2019-09-21 10:19:35', '2019-09-21 10:20:00']	0,050	-0,018	-1,875	0,941	0,164	-2,187	0,954
04	09	['2019-09-21 10:56:30', '2019-09-21 10:57:22']	0,046	-0,003	-2,041	0,914	0,161	-2,121	0,973
05	08	['2019-09-21 10:19:35', '2019-09-21 10:20:00']	0,038	0,061	-2,980	0,991	0,158	-2,193	0,967
Mean			0,046	0,002	-2,141	**0,953**	0,115	-1,846	**0,904**