SENS4ICE

SENSORS AND CERTIFIABLE HYBRID ARCHITECTURES FOR SAFER AVIATION IN ICING ENVIRONMENT

Fiber Bragg Grating Sensors ice detection

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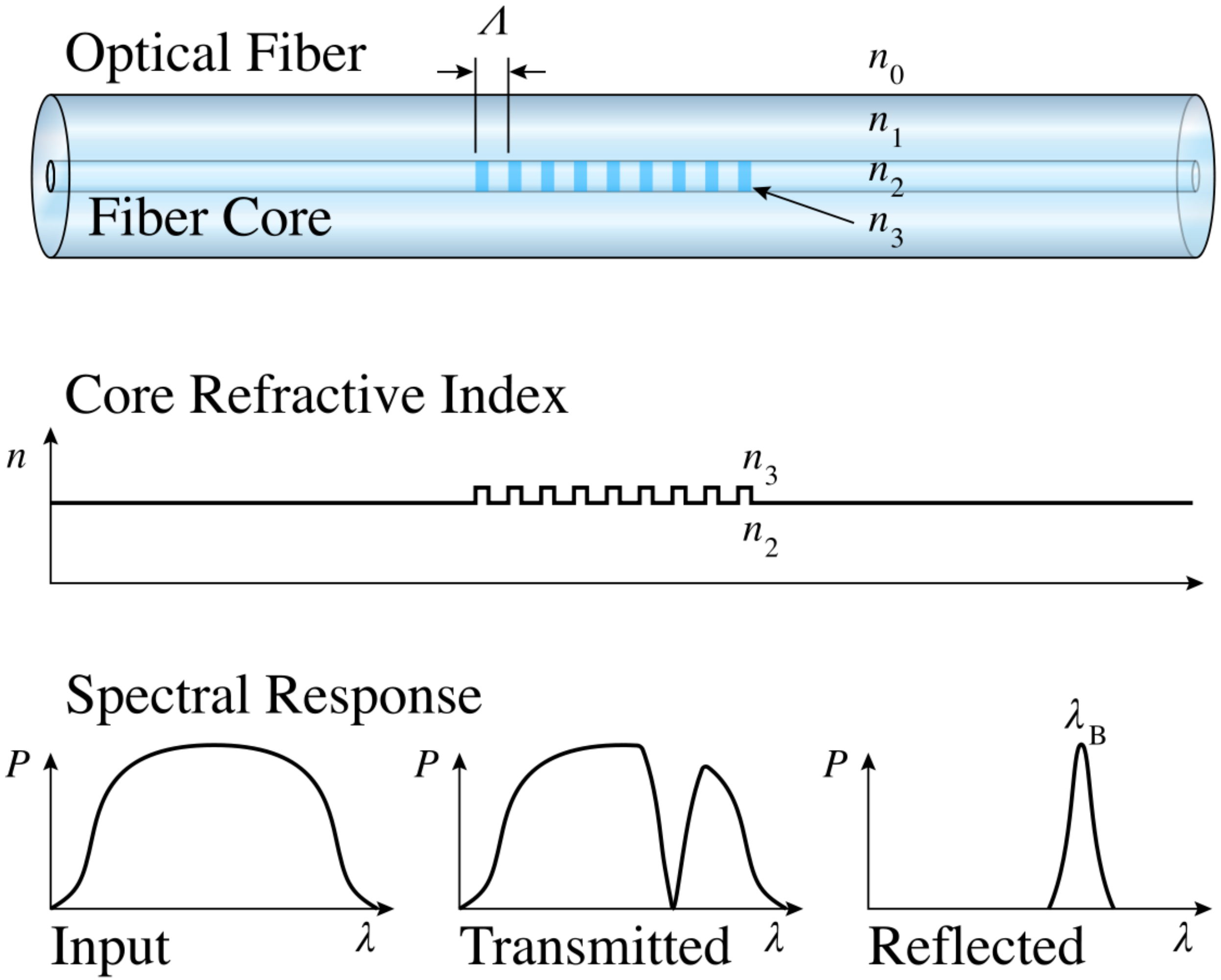
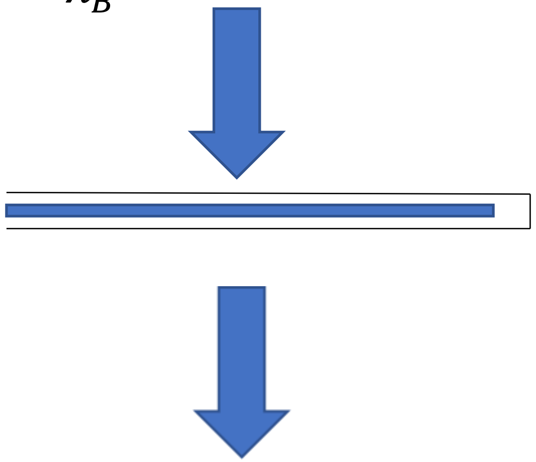
How do Fiber Bragg Gratings work?

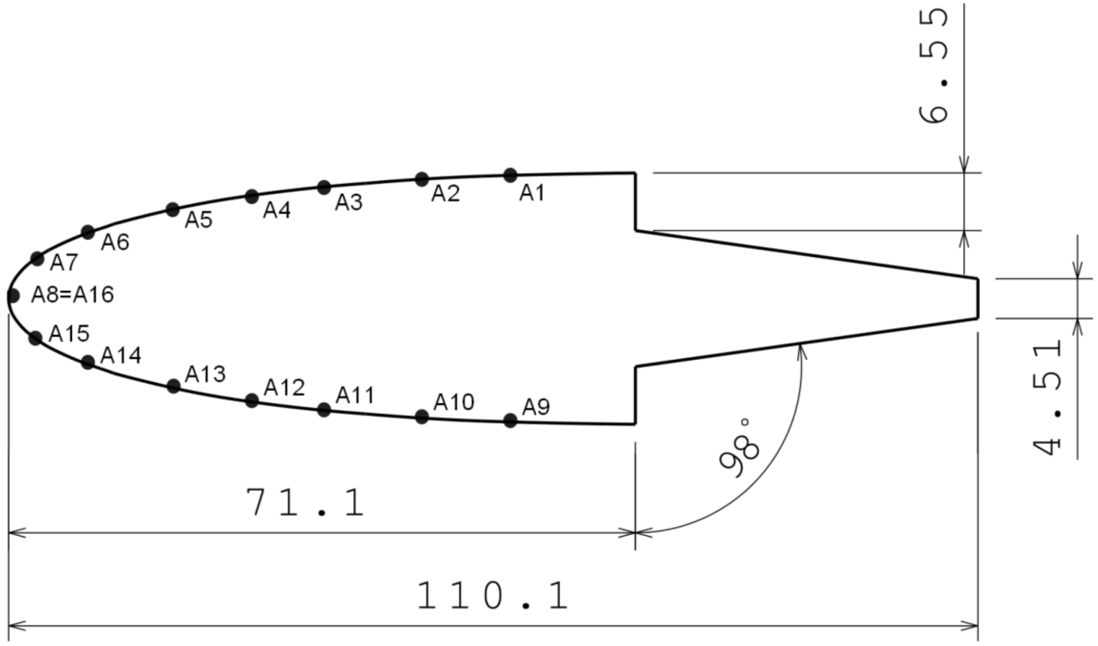


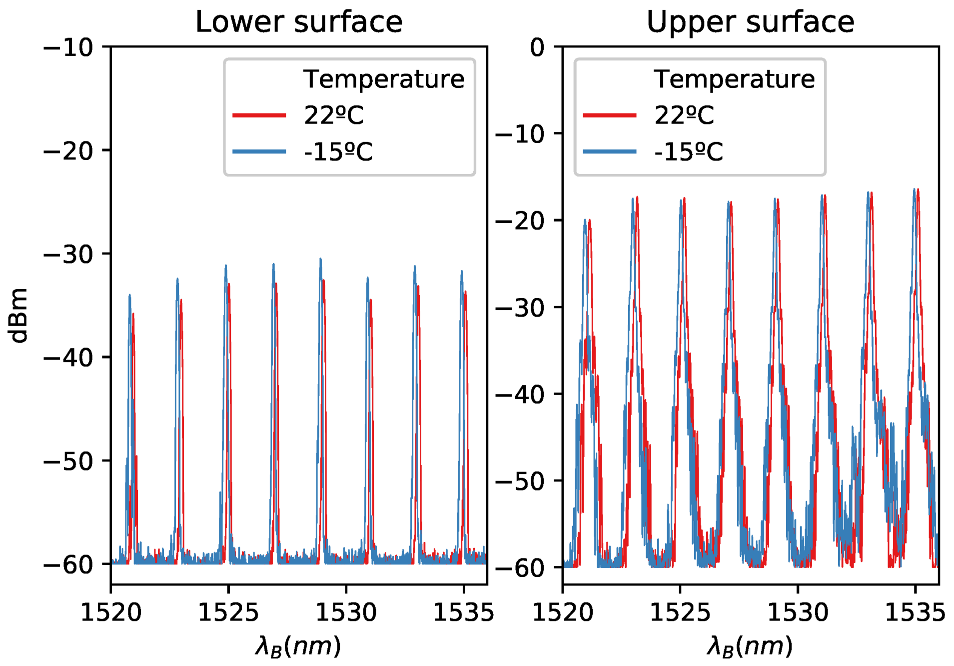
$$\frac{\Delta\lambda_B}{\lambda_B} = k_\varepsilon \varepsilon + F(T)$$



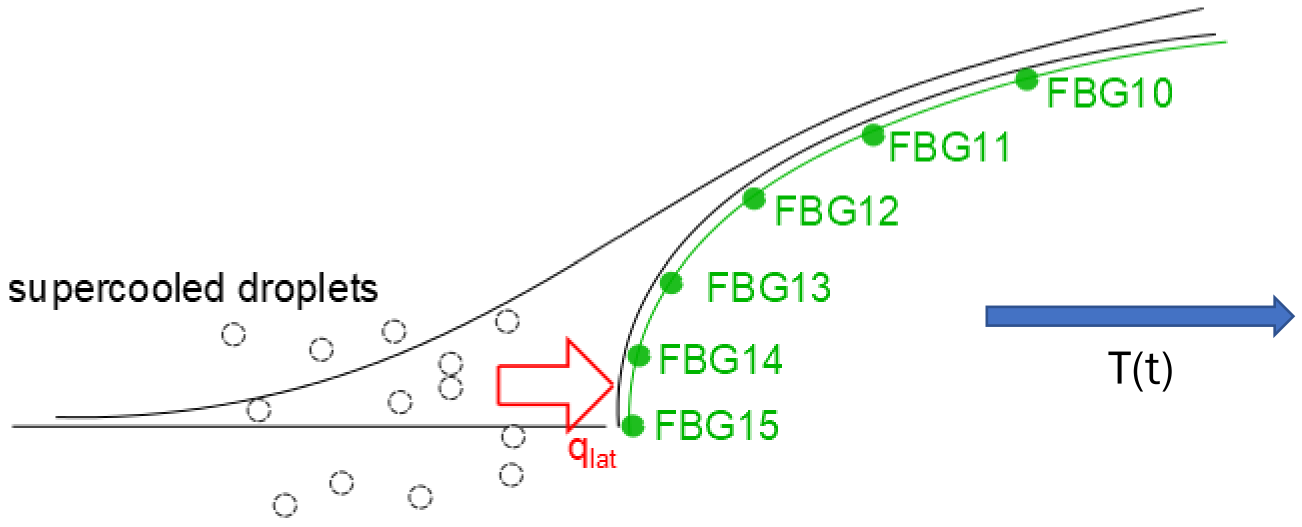
$$\frac{\Delta\lambda_B}{\lambda_B} = F(T)$$

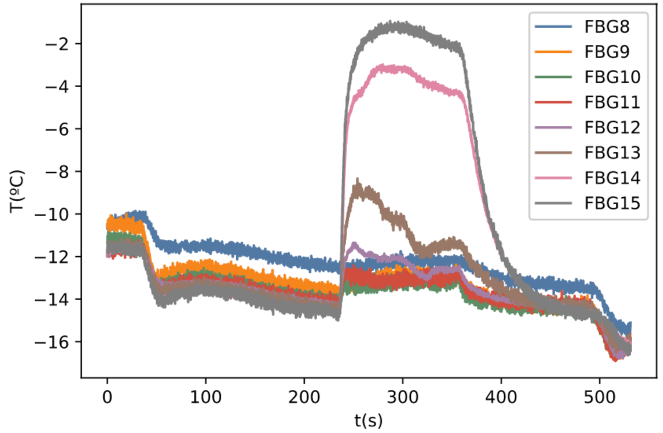
Temperature distribution in an airfoil





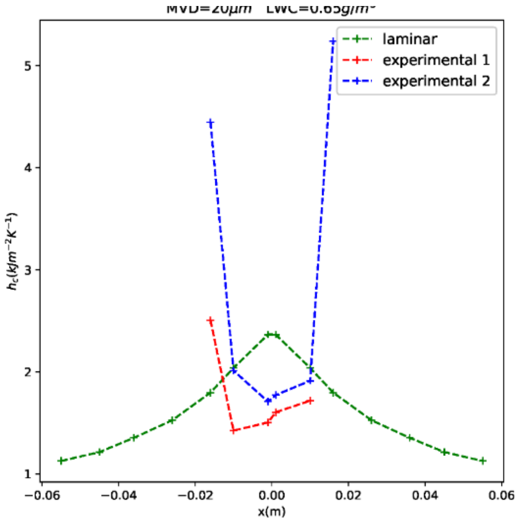
Heat Flux Distribution

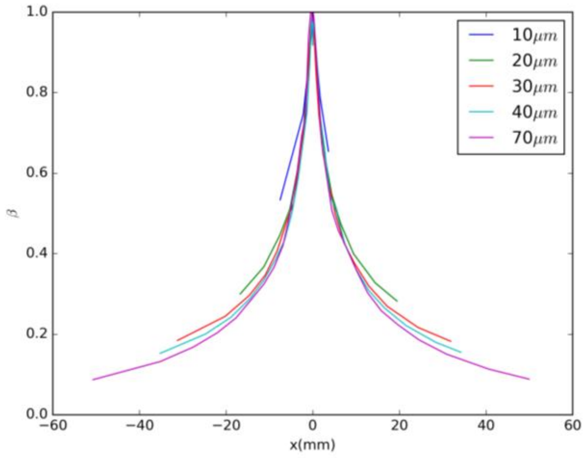




$$F(f, T_{sur}, \dot{m}_{imp}) = q_{lat} + q_{evap} + q_{sens} + q_{kinetic} + q_{con} = 0$$

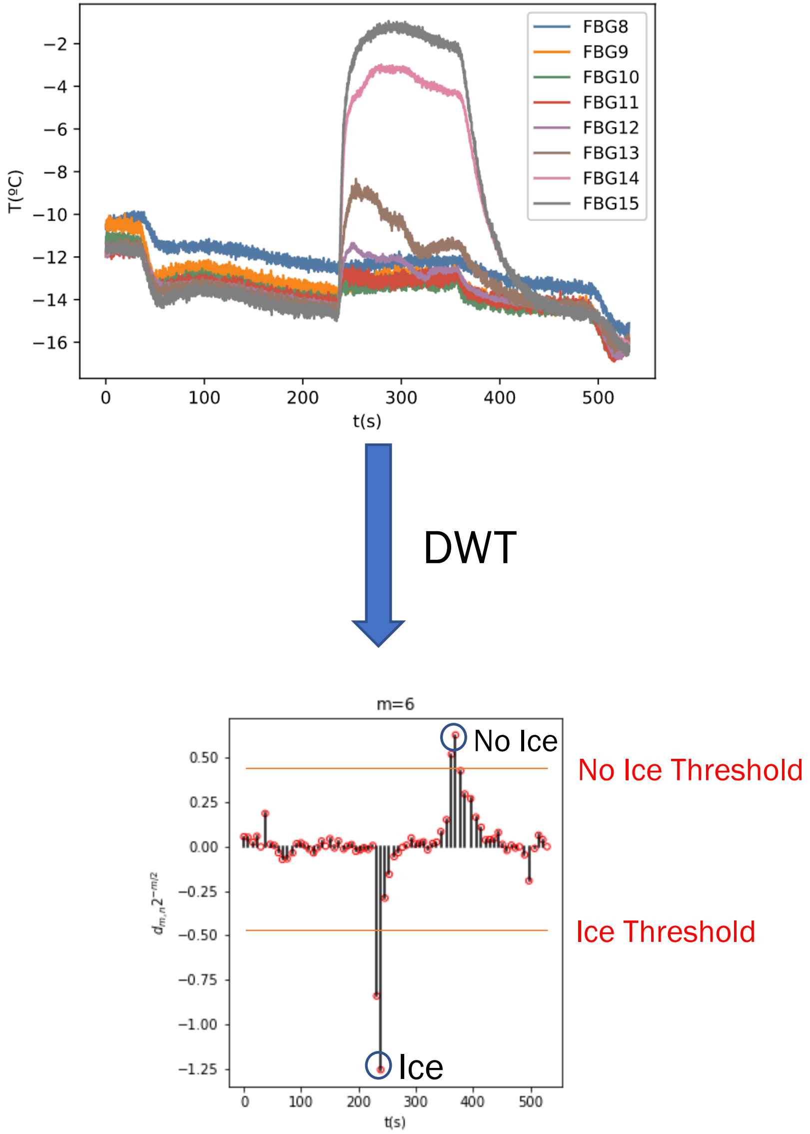
$$\dot{m}_{imp} = \beta \, V \, LWC$$

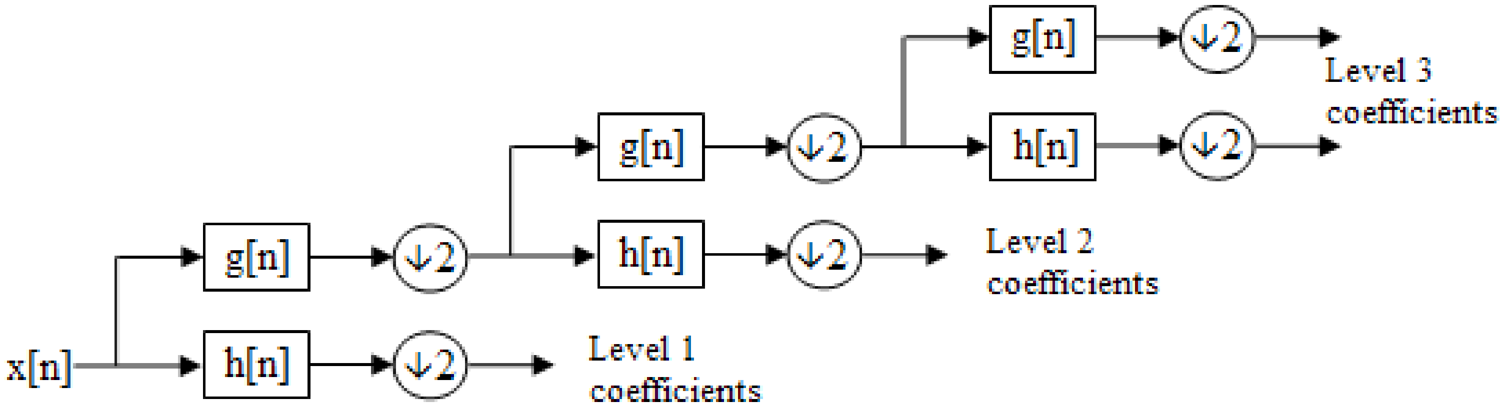




Detection Principles

- Detection is based on abrupt temperature changes
- In order to define what is abrupt Discrete Wavelet Analysis (DWT) is used
  - DWT can classify the signal in function of its abruptness
  - Thresholds were optimized for maximize detection and minimize false positives



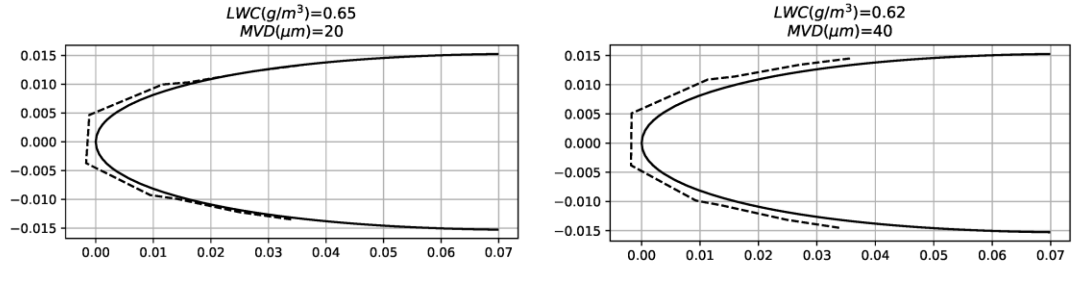


Ice Accretion Rate indirect Calculation

- Ice accretion rate could be calculated from the heat flux equation
- Uncertainty in:
  - Ice density (changes depending on the conditions)
  - Convective heat transfer coefficient
  - Ice thickness already accreted (energy lost in conduction

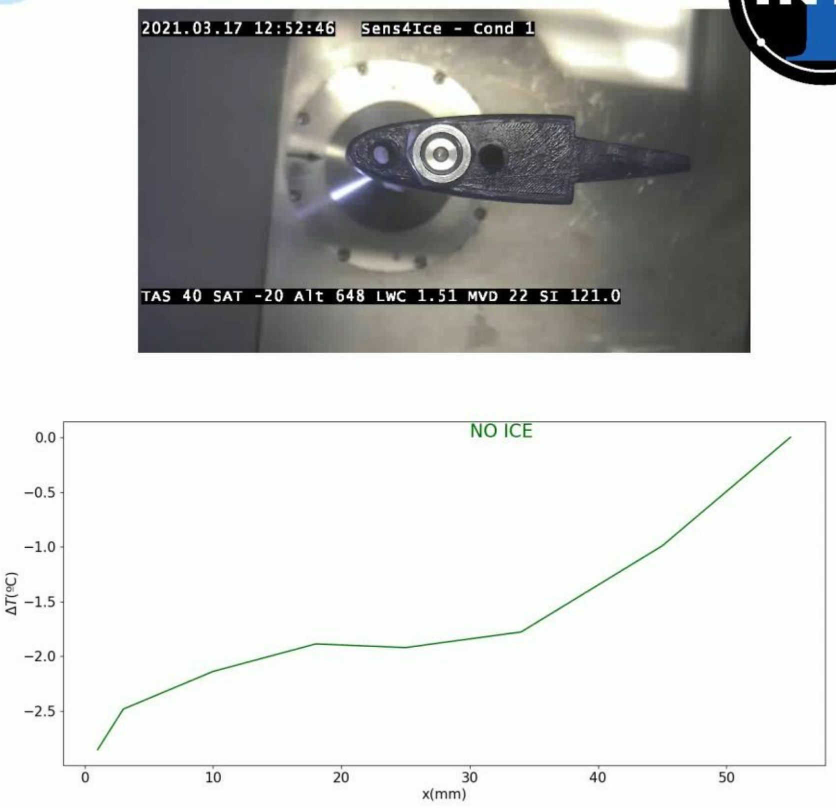
$$\frac{d\Delta}{dt} = \frac{h_0(T_{sur} - T_{rec})}{\rho_{ice}\left(c_{p,is}(T_{sur} - T_{mp}) + \frac{V_\infty^2}{2} + L_f - c_{p,w}(T_{mp} - T_\infty)\right)}$$

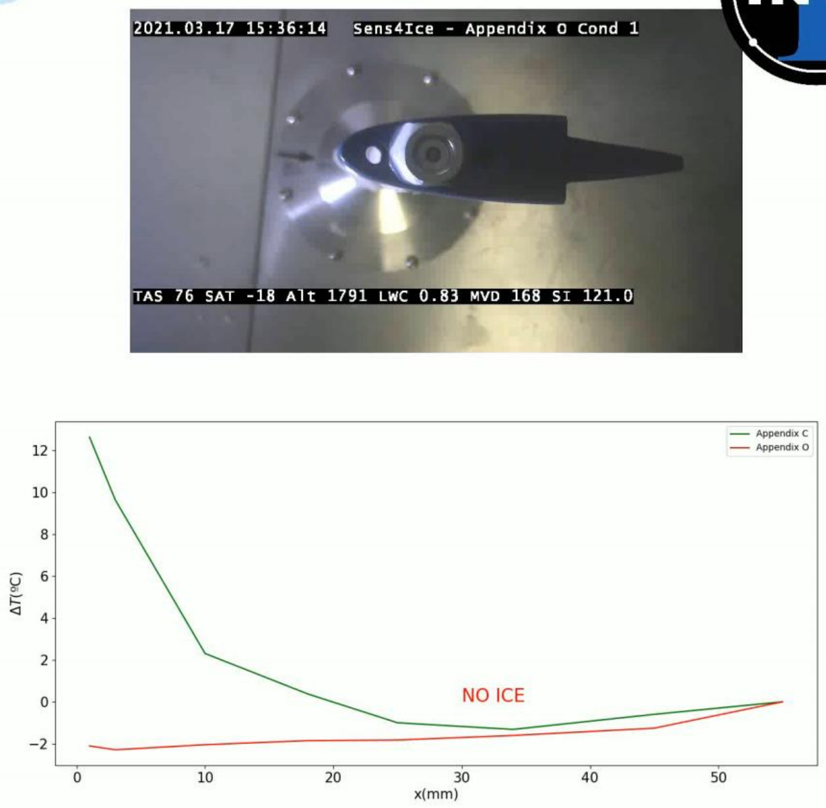
- The ice accretion rate can be calculated all over the chord



(a) (b)

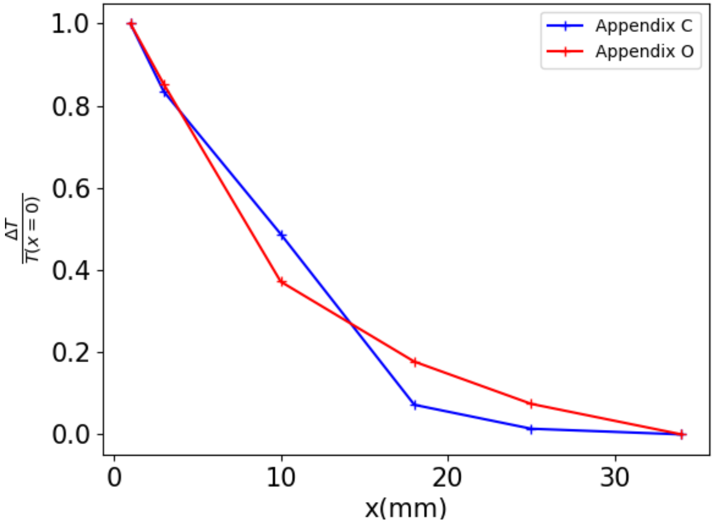
Appendix C/O Discrimination

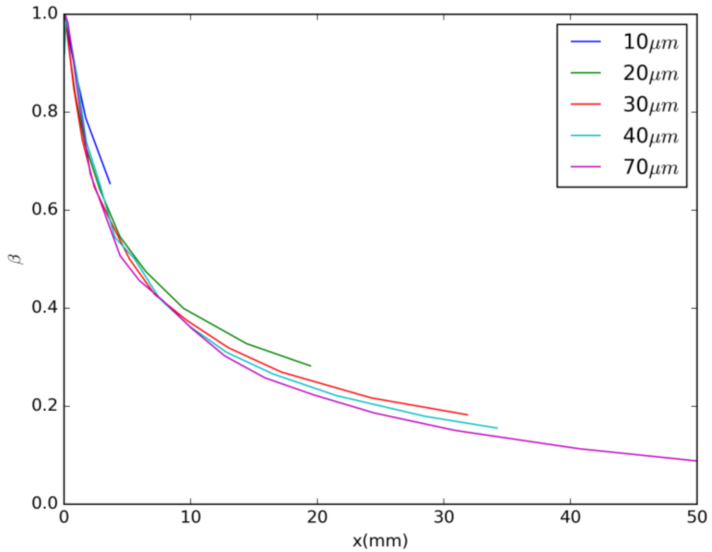


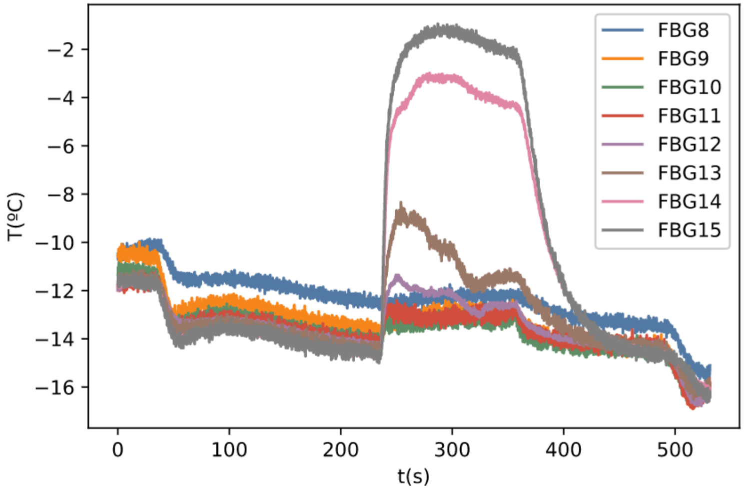


EXAMPLE

- **Appendix C: MVD = 22 µm**
- **Appendix O: MVD = 167 µm**

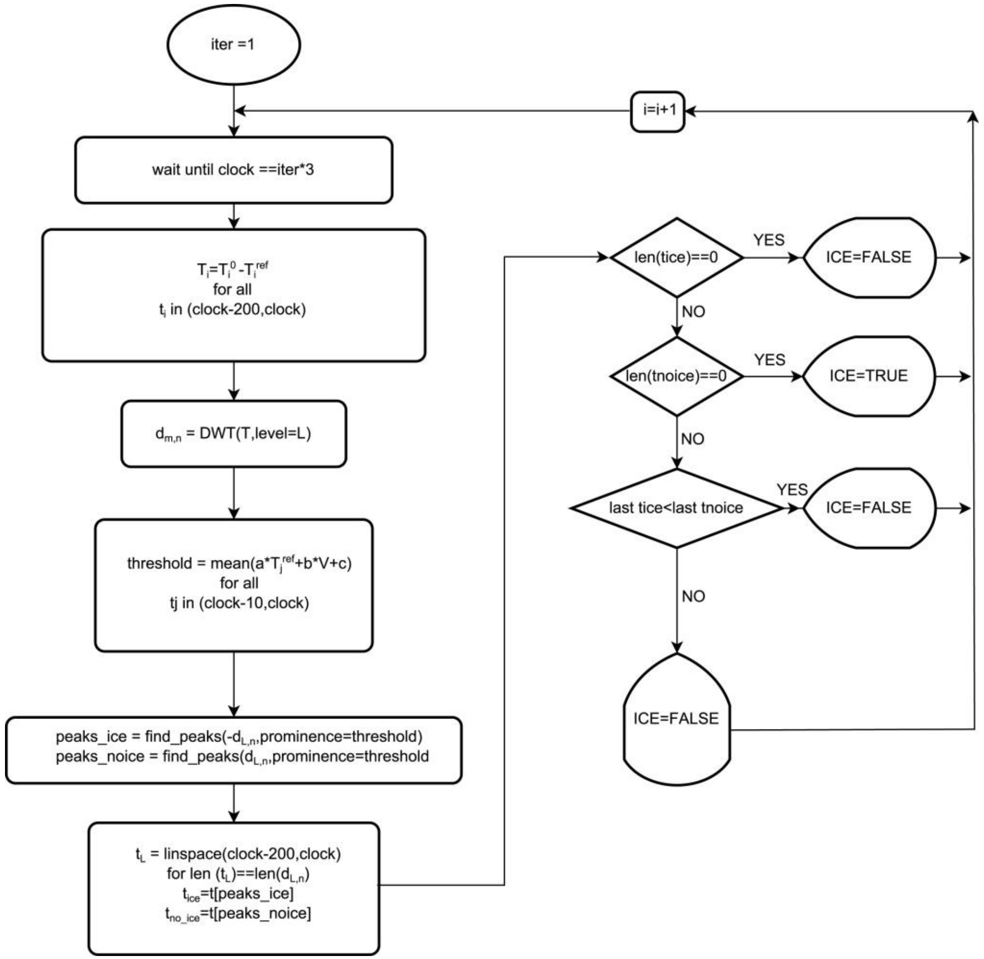






Icing Wind Tunnel Results

- According to ED-103 standards
- The tests were carried out in NRC
- The data was post processed and a LWC and IAR assessment was done
- An Appendix C/O discrimination was done
- Detection time was measured and compared with ED-103 standard
- The sensor detected when the fogging started and ended



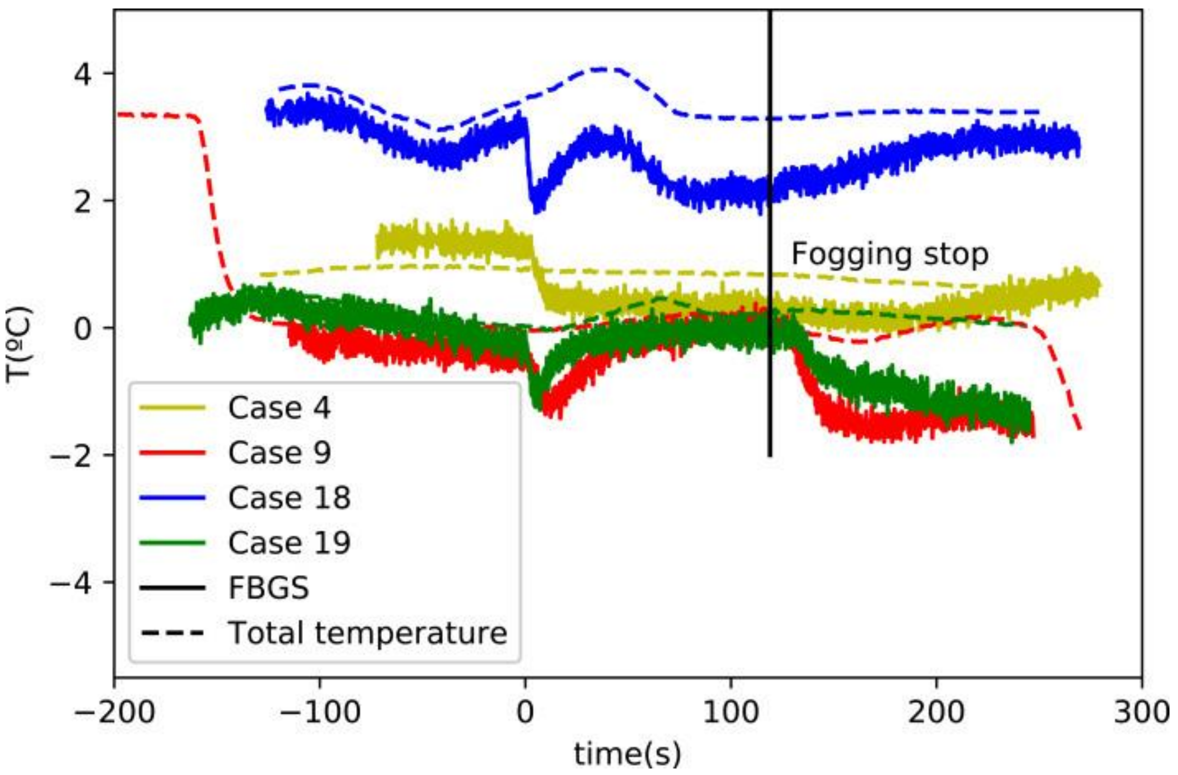
TEST MATRIX

Case	Condition	Airspeed [m/s]	Static Temperature [°C]	MVD [µm]	LWC [g/m³]	Case	Condition	Airspeed [m/s]	Static Temperature [°C]	MVD [µm]	LWC [g/m³]
1	LW-C CM	40,1	−20	15	0,3	19	LW-C IM	84,9	−3,5	35	1
2	LW-C CM	40,1	−10	20	0,42	20	unimodal	76,1	−17,7	163,5	0,82
3	LW-C CM	84,9	−10	23	0,34	21	unimodal	40,1	−17,7	122	0,46
4	LW-C CM	40,1	0	23	0,54	22	LW-FZDZ	79,7	−20	106	0,4
5	LW-C CM	84,9	−20	30	0,11	23	LW-FZDZ	79,7	−25	20	0,29
6	LW-C CM	84,9	−10	40	0,1	24	LW-FZDZ	84,9	−15	20	0,35
7	LW-C CM	84,9	−10	35	0,15	25	LW-FZDZ	84,9	−10	20	0,38
8	LW-C CM	84,9	−30	35	0,05	26	LW-FZDZ	84,9	−3,5	20	0,42
9	LW-C CM	84,9	−3,5	30	0,35	27	LW-FZDZ	84,9	−25	20	0,15
10	LW-C IM	40,1	−20	22	1,5	28	LW-FZDZ	84,9	−15	20	0,18
11	LW-C IM	40,1	−10	28	1,2	29	LW-FZDZ	84,9	−10	20	0,2
12	LW-C IM	84,9	−20	23	1,3	30	LW-FZDZ	84,9	−3,5	20	0,21
13	LW-C IM	40,1	−20	42	0,3	31	LW-FZDZ	84,9	−25	110	0,18
14	LW-C IM	84,9	−20	20	1,75	32	LW-FZDZ	84,9	−15	110	0,22
15	LW-C IM	84,9	−10	20	2,25	33	LW-FZDZ	84,9	−10	110	0,23
16	LW-C IM	84,9	−10	20	0,5	34	LW-FZDZ	84,9	−3,5	110	0,26
17	LW-C IM	84,9	−20	31	0,75	35	unimodal	84,9	−10	180	0,25
18	LW-C IM	84,9	0	20	2,5	36	unimodal	84,9	−10	220	0,25

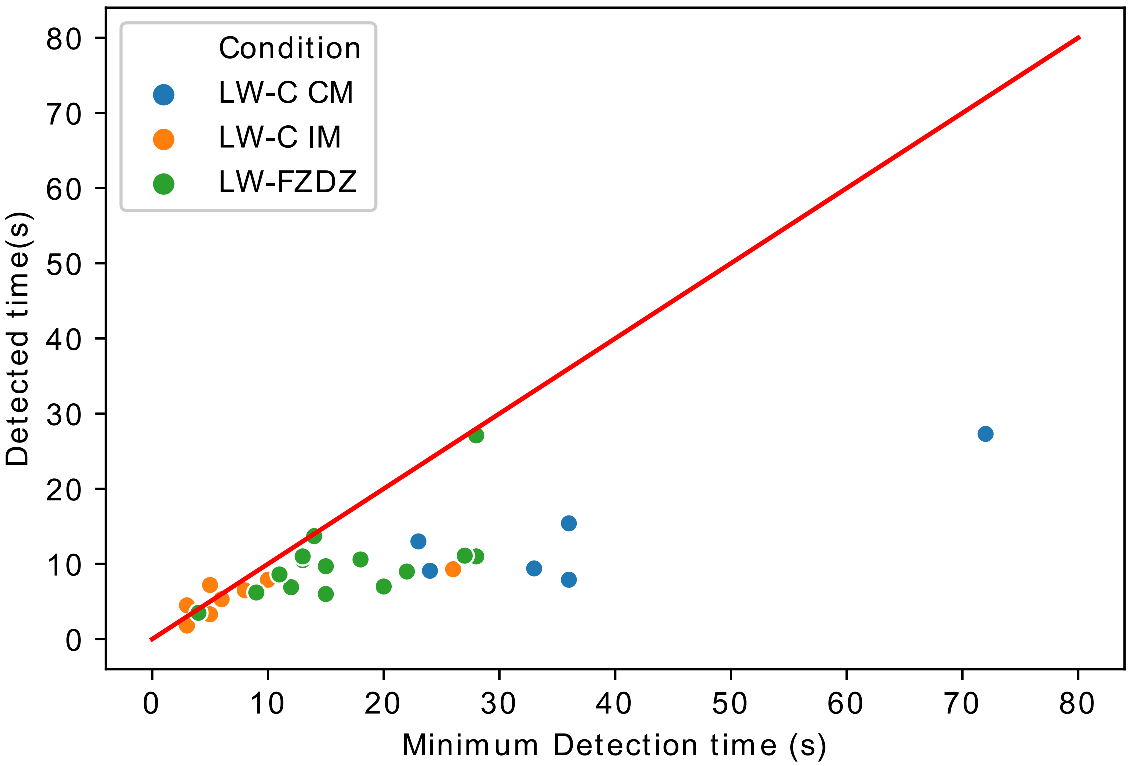
DETECTION

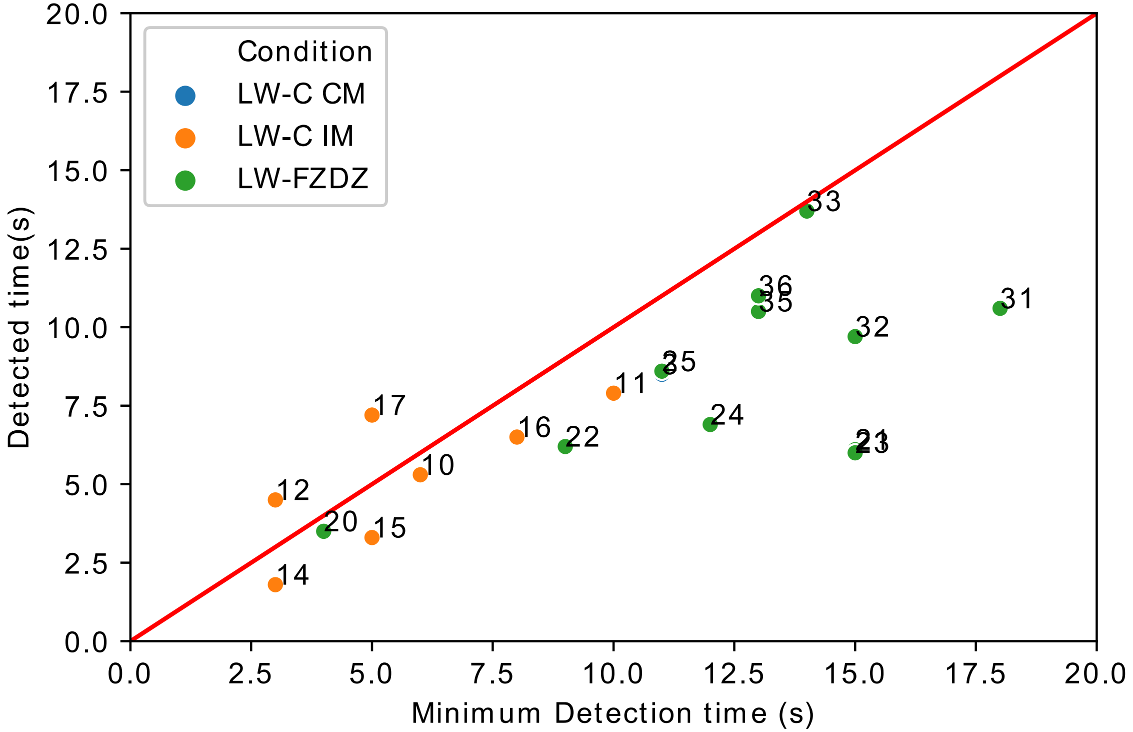
Case	Detection	Case	Detection	Case	Detection	Case	Detection
1	Y	10	Y	19	N	28	Y
2	Y	11	Y	20	Y	29	Y
3	Y	12	Y	21	Y	30	Y
4	N	13	Y	22	Y	31	Y
5	Y	14	Y	23	Y	32	Y
6	Y	15	Y	24	Y	33	Y
7	Y	16	Y	25	Y	34	Y
8	Y	17	Y	26	Y	35	Y
9	N	18	N	27	Y	36	Y

False Negatives Analysis



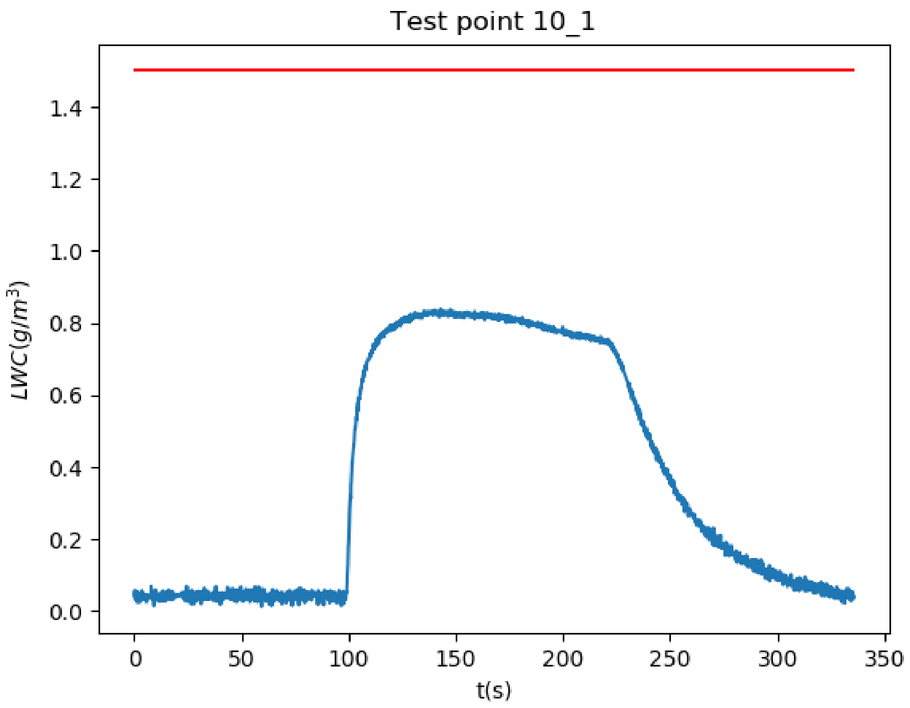
Detection Time





LWC Prediction

Case	LWC	LWC pred	Case	LWC	LWC pred	Case	LWC	LWC pred
[-]	[g/m³]	[g/m³]	[-]	[g/m³]	[g/m³]	[-]	[g/m³]	[g/m³]
1	0,3	0,35	13	0,3	0,46	25	0,38	0,2
2	0,42	0,3	14	1,75	0,5	26	0,42	0,3
3	0,34	0,2	15	2,25	0,5	27	0,15	0,2
4	0,54	-	16	0,5	0,4	28	0,18	0,2
5	0,11	0,2	17	0,75	0,5	29	0,2	0,1
6	0,1	0,1	18	2,5	-	30	0,21	ND
7	0,15	0,1	19	1	-	31	0,18	0,3
8	0,05	ND	20	0,82	0,5	32	0,22	0,2
9	0,35	-	21	0,46	0,4	33	0,23	0,2
10	1,5	0,9	22	0,4	0,3	34	0,26	0,2
11	1,2	0,7	23	0,29	0,4	35	0,25	0,2
12	1,3	0,6	24	0,35	0,2	36	0,25	0,2



Flight Tests Results