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SENSORS AND CERTIFIABLE HYBRID ARCHITECTURES
FOR SAFER AVIATION IN ICING ENVIRONMENT

Fiber Bragg Grating Sensors ice detection

FINAL DISSEMINATION EVENT OF SENS4ICE PROJECT

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Directorate General for Research and Innovation, Brussels, Belgium – 29 November 2023

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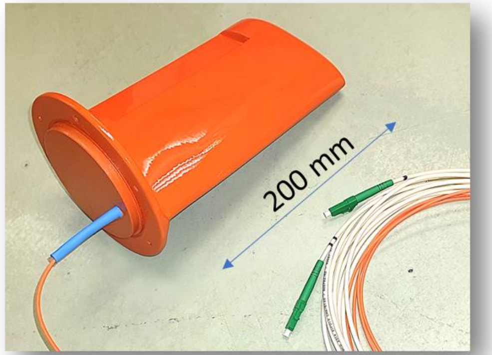
Introduction and Physical Principles

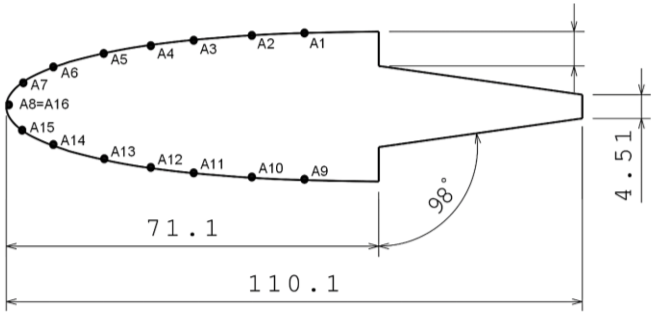
Fiber Optic Detector, FOD, different packaging



FOD FT

FOD IWT

ICE/no ICE, LWC, ACC-rate, App C/O



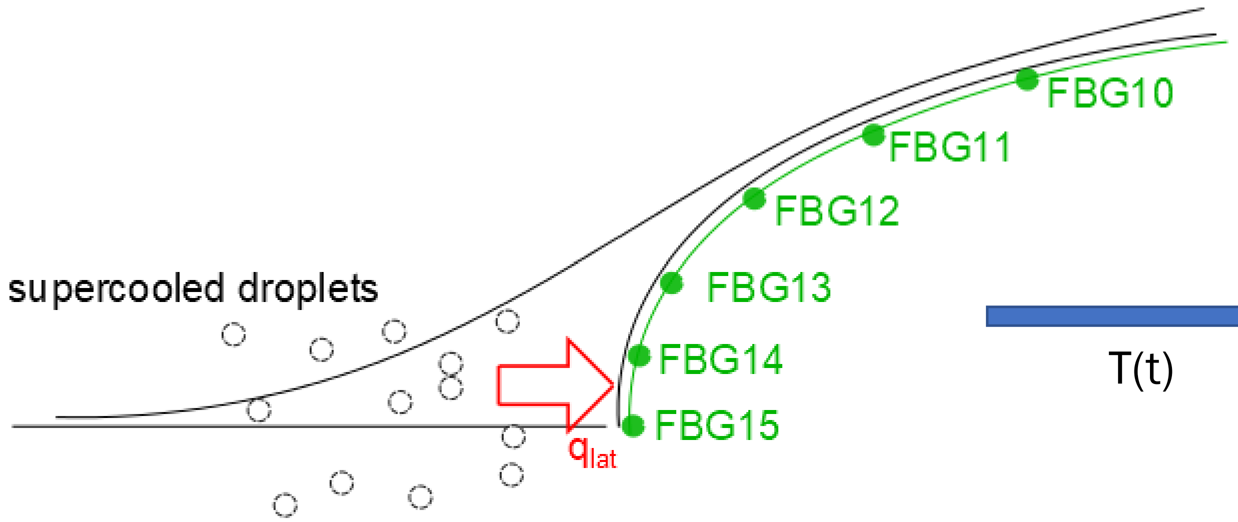
Point sensors

ICE/no ICE, LWC, ACC- rate

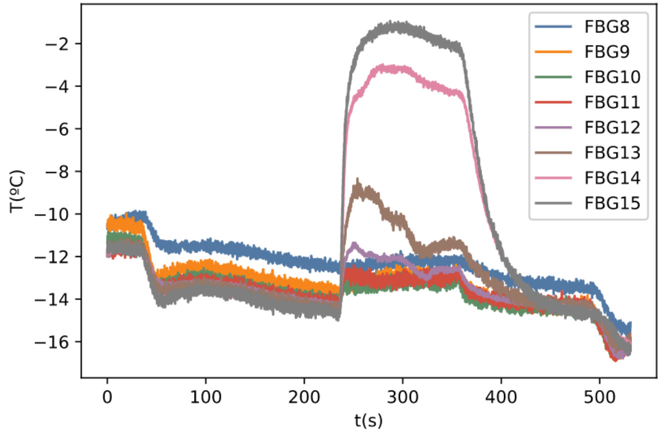
- FOD is a latent heat transfer sensor
- Latent energy causes an abrupt temperature rise

- An optic fiber placed in the probe measures the temperature distribution along the chord
- The temperature measurement is made by **Fiber Bragg Gratings**
- Depending on the icing cloud conditions, the abruptness of the signal and the number of gratings that detect ice would change

Heat Flux Distribution

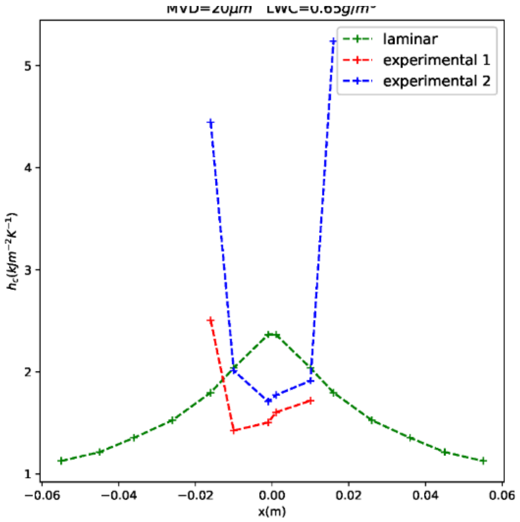


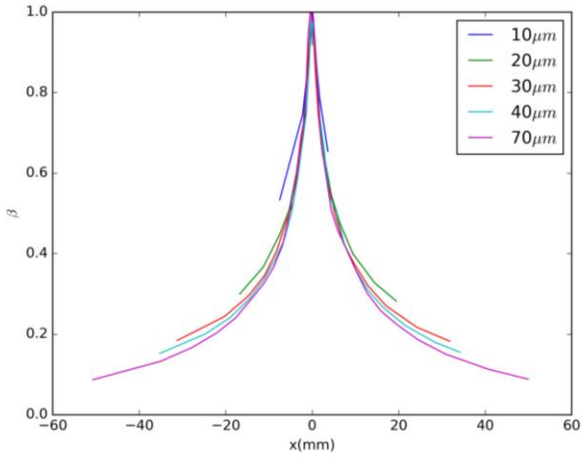
T(t)



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

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





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Detection Principles

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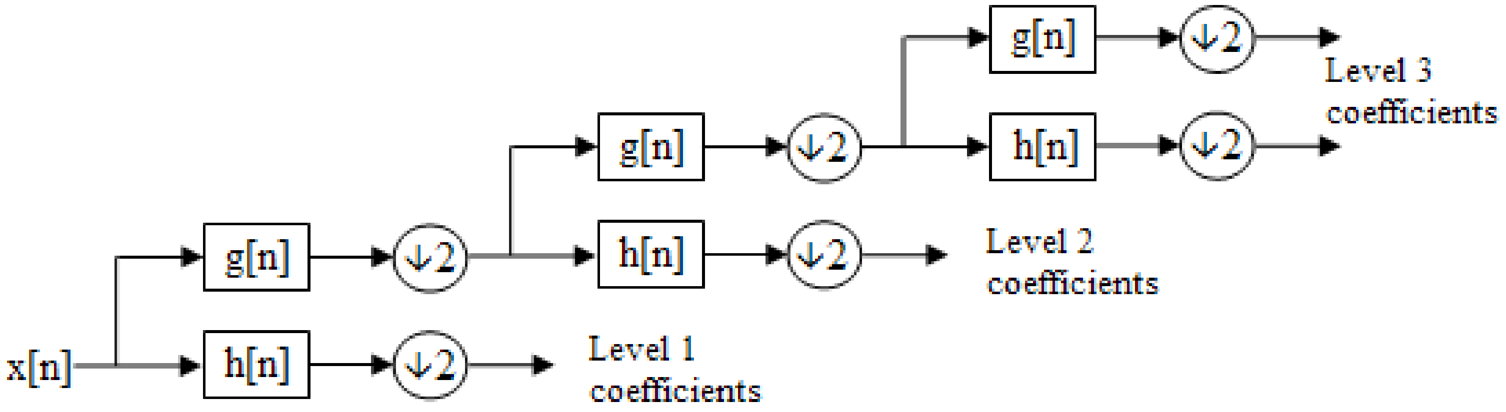
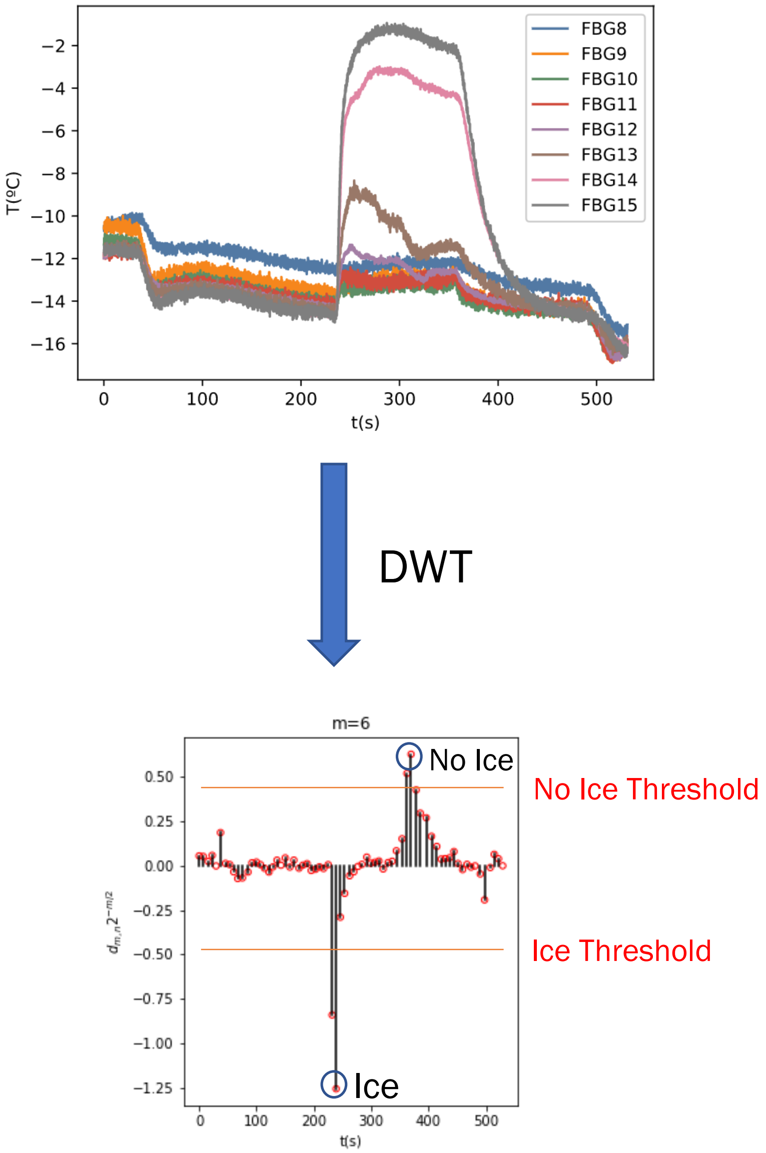
Detection Principles

Detection is based on abrupt temperature changes

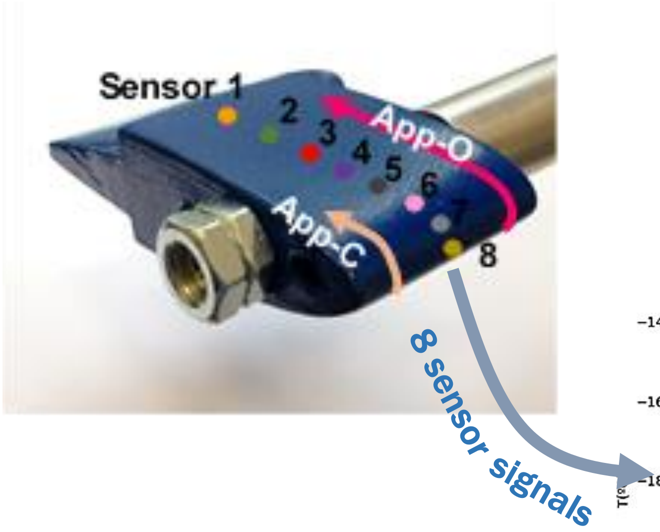
In order to define what is abrupt Discrete Wavelet Analysis (DWT) is used

- DWT can classify the signal in function of its abruptness
- Thresholds were optimized for maximize detection and minimize false positives



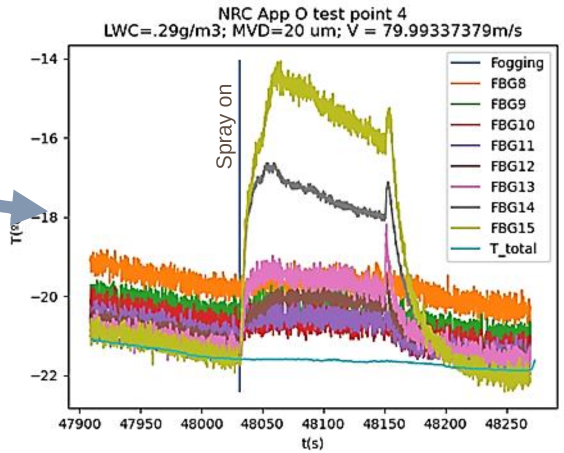


INTA: Fiber Optic Detector (FOD) - Accretion



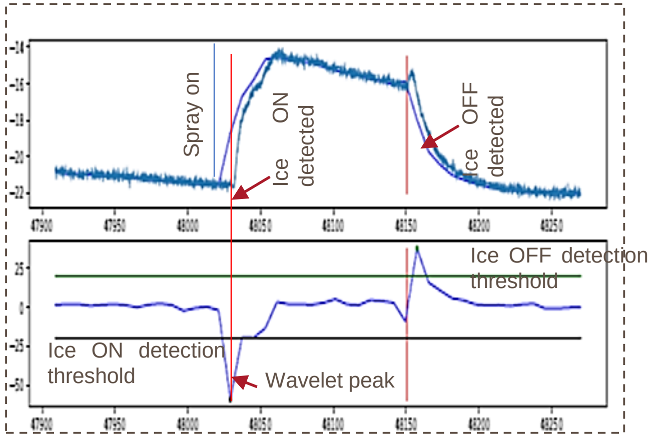
Analysis principle:
Wavelet analysis (WA) of the sensor responses

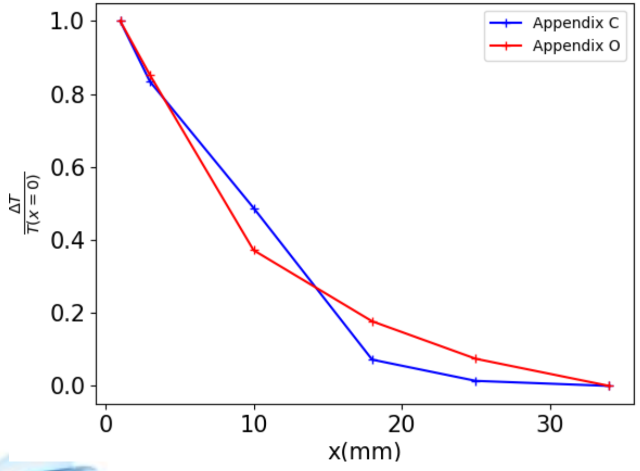
A wavelet is a mathematical function used to divide a given function or continuous-time signal into different scale components.



Filtering

Wavelet analysis





Analysis of the Output Data Parameters:

- ACC/O-: Enter/Exit: WA
- ACC_RATE: Heat balance in the stagnation point
- LWC: impinging mass flow in the stagnation point
- App-C/ App-O discrimination:

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ICE ACCRETION RATE

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Ice Accretion Rate indirect Calculation

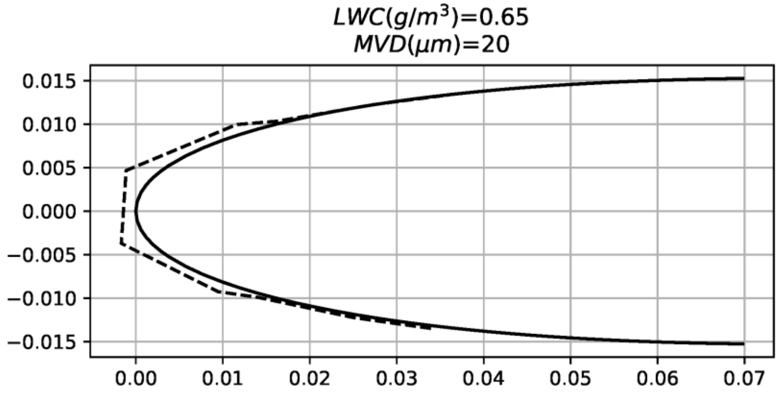
Ice accretion rate could be calculated from the heat flux equation

Uncertainty in:

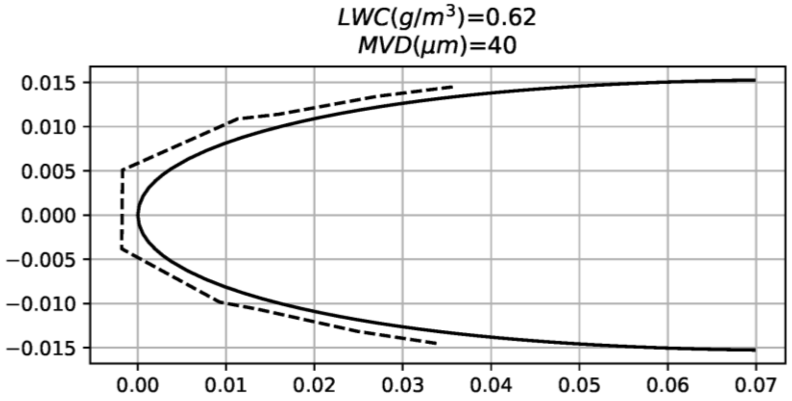
- Ice density (changes depending on the conditions)
- Convective heat transfer coefficient
- Ice thickness already accreted (energy lost in conduction)

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

The ice accretion rate can be calculated all over the chord



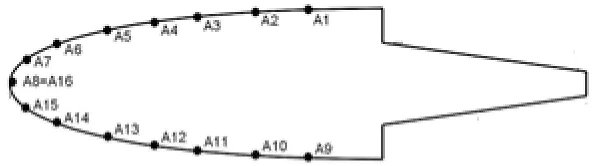
(a)

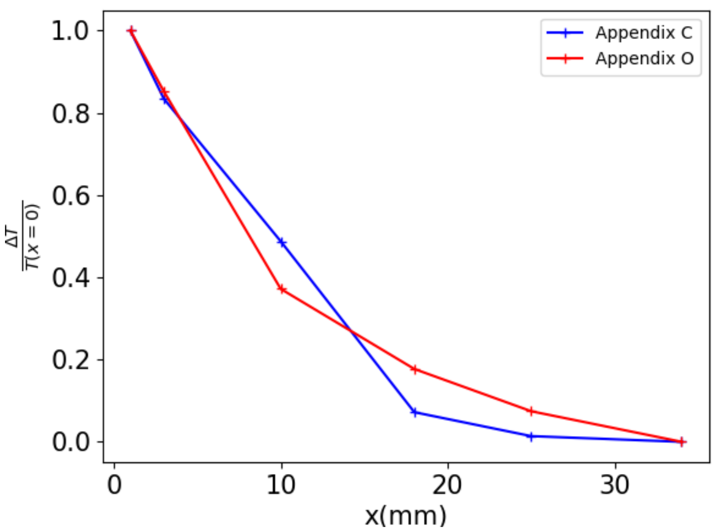


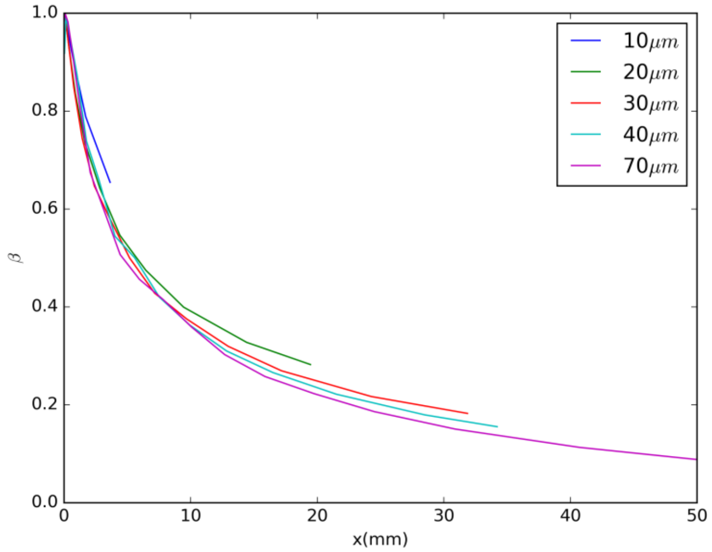
(b)

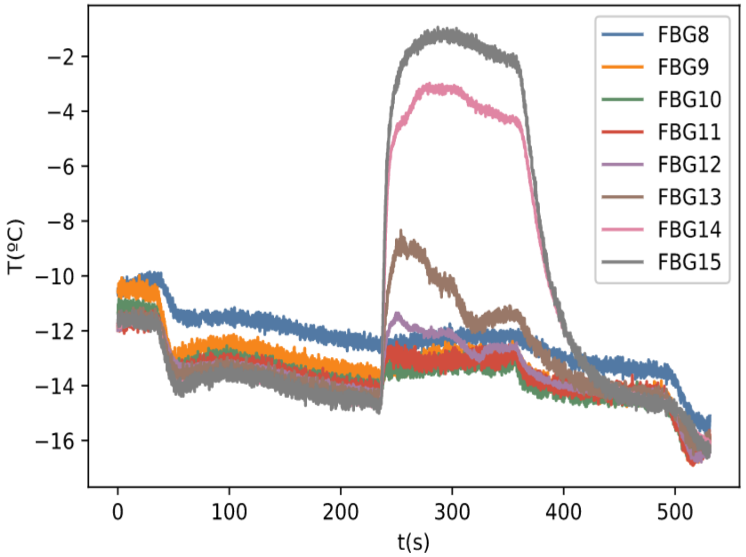
EXAMPLE App C/O discrimination

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









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ICING WIND TUNNEL RESULTS

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Icing Wind Tunnel Results

According to ED-103 standards

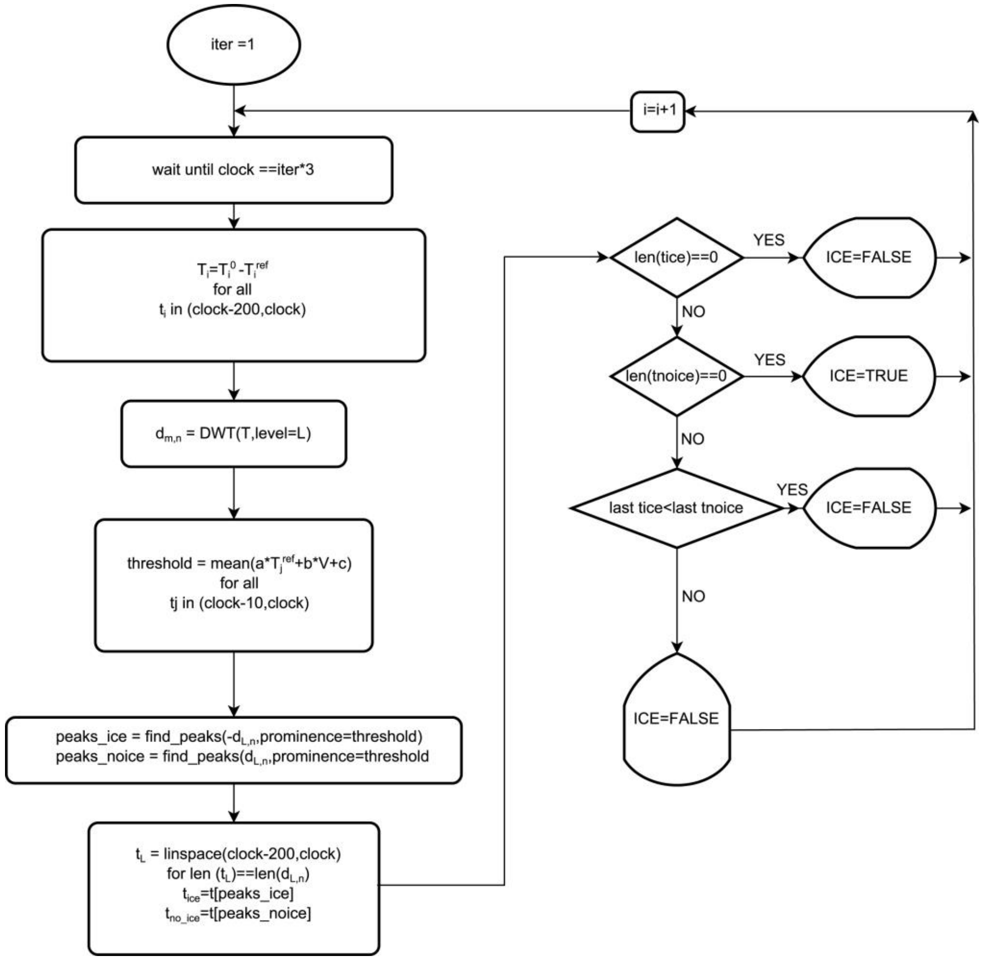
The tests were carried out in NRC

The data was post processed and a LWC and IAR assessment was done

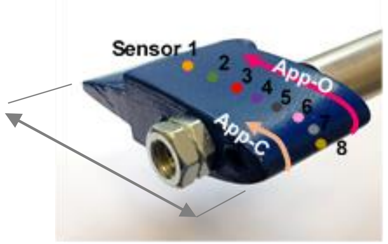
An Appendix C/O discrimination was done

Detection time was measured and compared with ED-103 standard

The sensor detected when the fogging started and ended



TEST MATRIX and RESULTS IWT



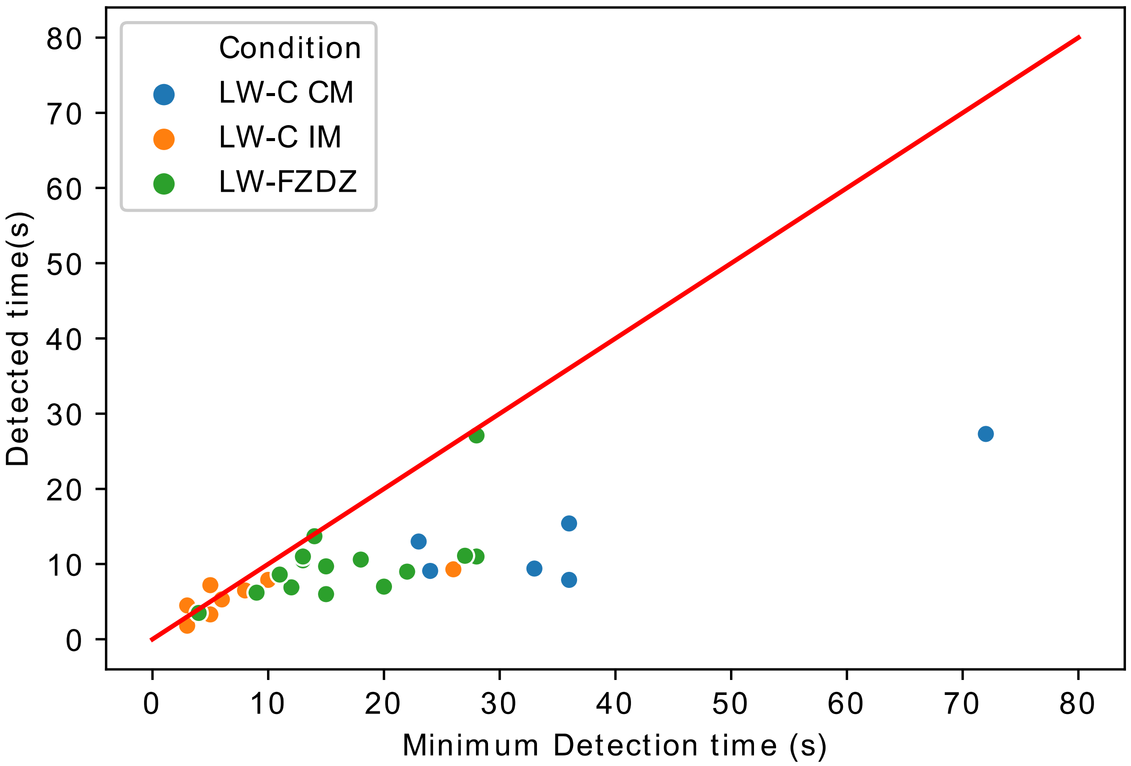
Case	Condition	Airspeed [m/s]	Static Temperature [°C]	MVD [µm]	LWC [g/m³]	Case	Condition	Airspeed [m/s]	Static Temperature [°C]	MVD [µm]	LWC [g/m³]
1	LW-C CM	40,1	−20	15	0,3	19	LW-C IM	84,9	−3,5	35	1
2	LW-C CM	40,1	−10	20	0,42	20	unimodal	76,1	−17,7	163,5	0,82
3	LW-C CM	84,9	−10	23	0,34	21	unimodal	40,1	−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

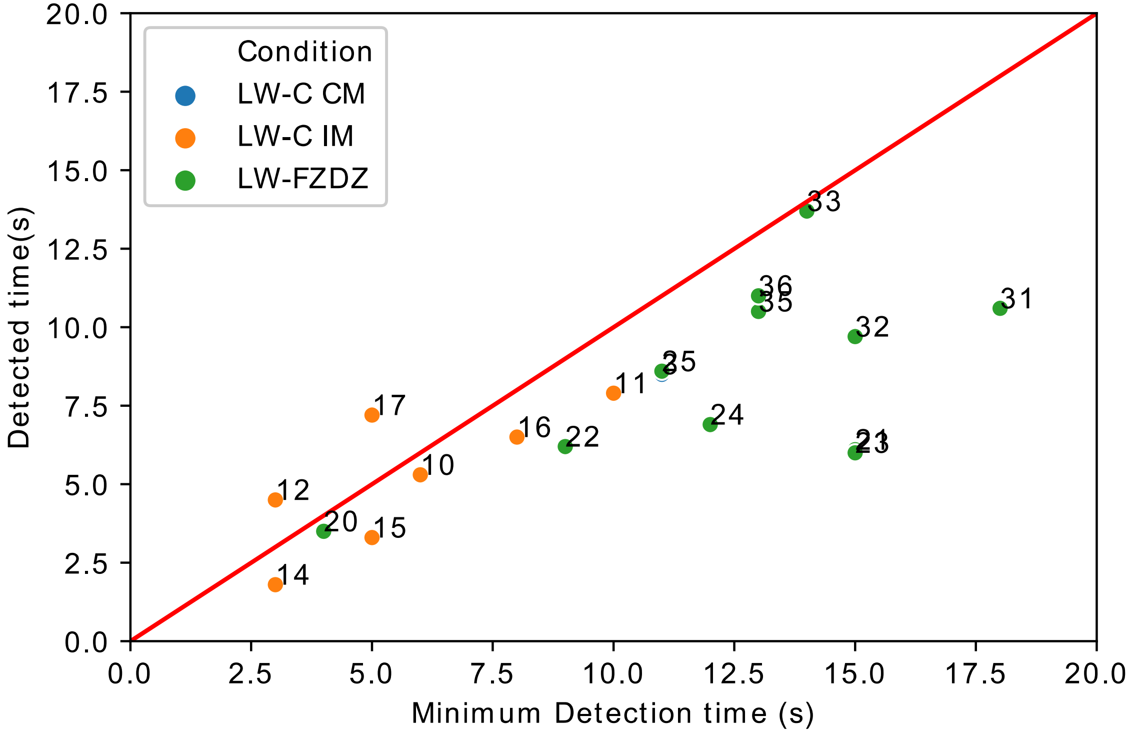
Detected

Not Detected

Test	Test Points Detected [%]	Test Points detected within Response Time [%]	Test Points detected within 1.5X Response Time [%]	LWC Avg Meas Error [%]	ACC_RATE Avg Meas Error [%]
Appendix C Test Points	90	87	90	**75* (41)**	**66**
Appendix C Repeat Points	100	100	100	**20**	**33**
Appendix O Test Points	82	93	93	**36**	**48**
Appendix O Repeat Points	100	100	100	**25**	**33**

Detection Time





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FLIGHT TESTS RESULTS

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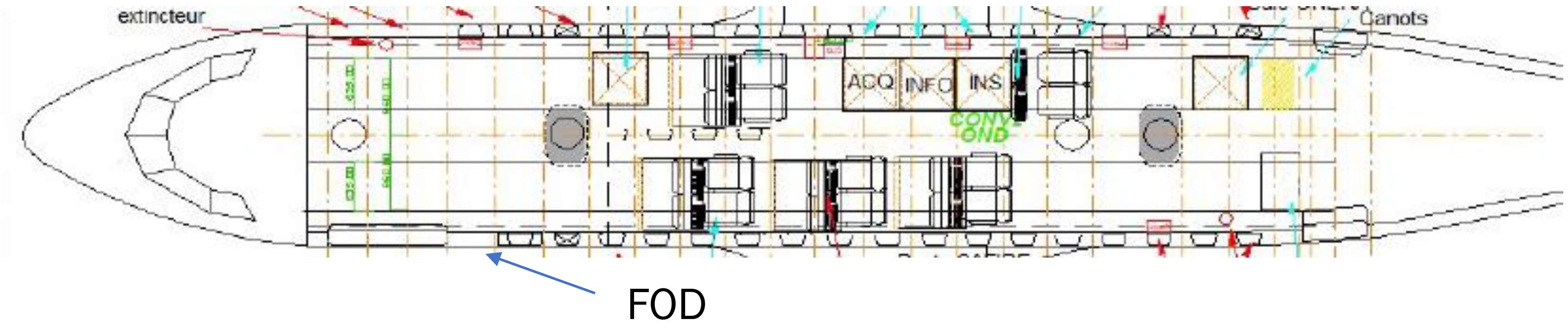
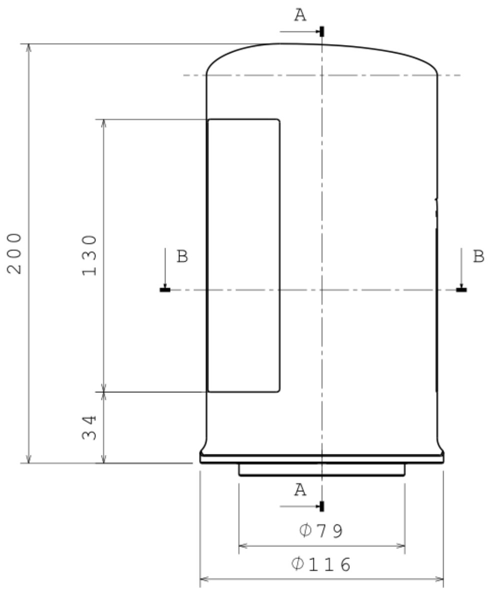
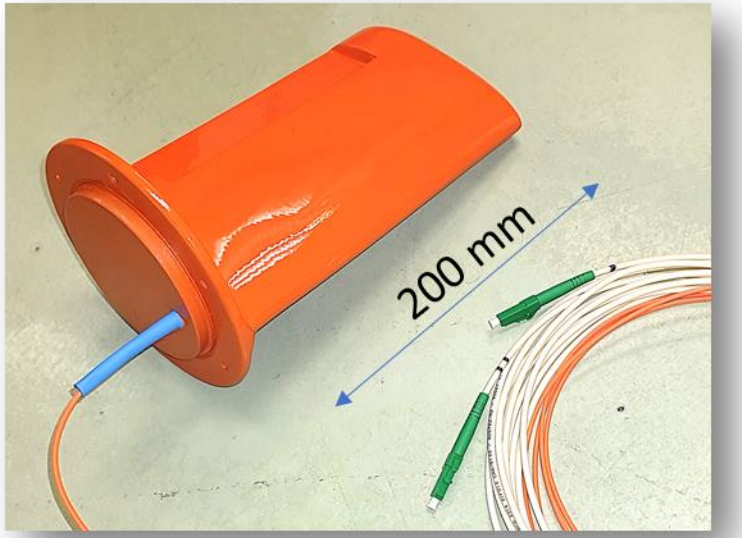
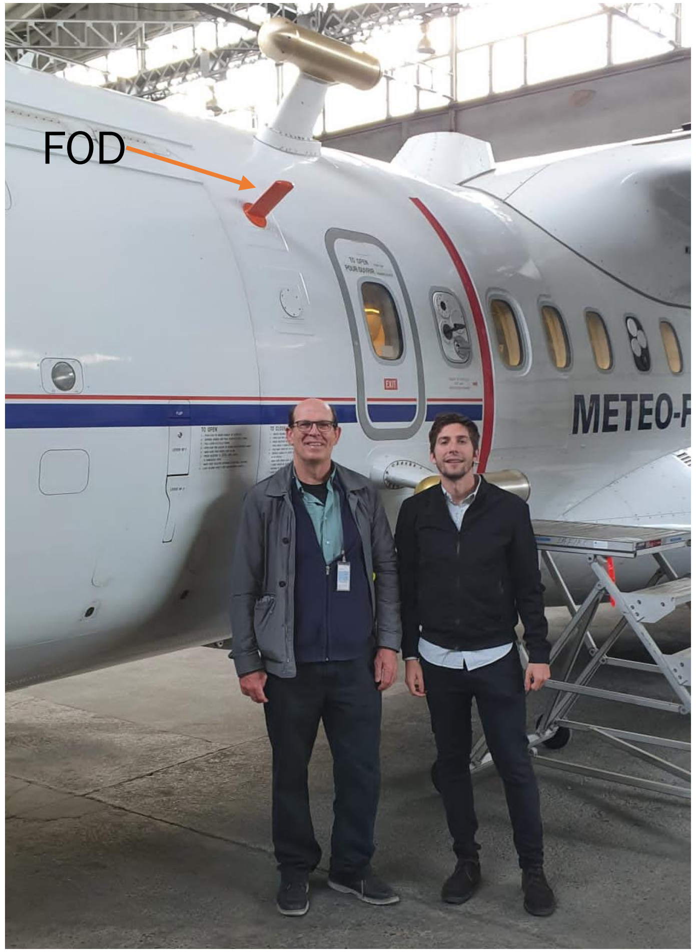
Flight Tests FOD-INTA

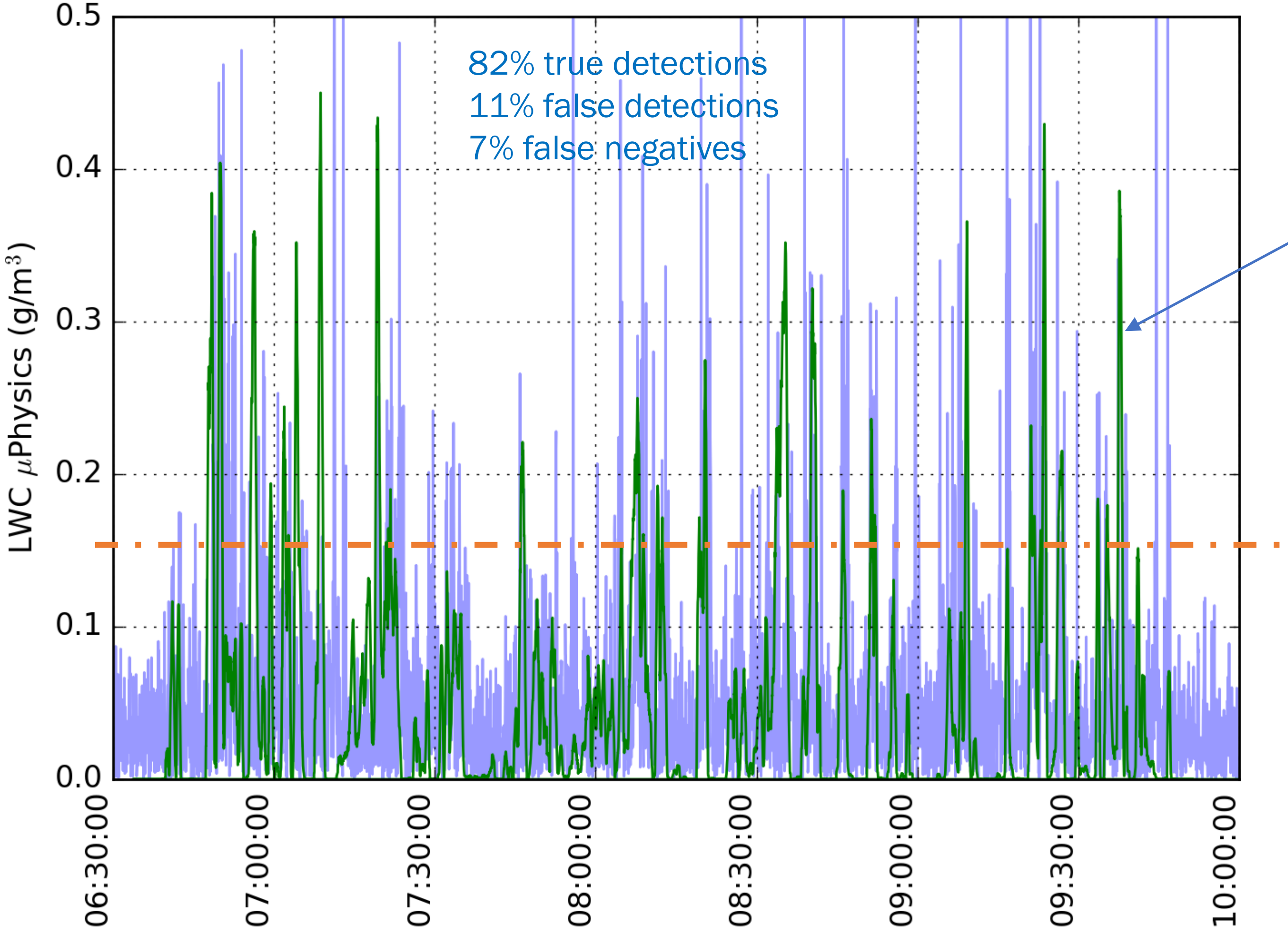






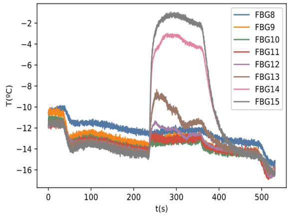


FOD-INTA FT- Results



Very spiky LWC inside clouds. Not easy comparable to IWT

Threshold FOD Wavelet detection



All flights	LWC all	LWC ≥0,1
detected [%]	78	93

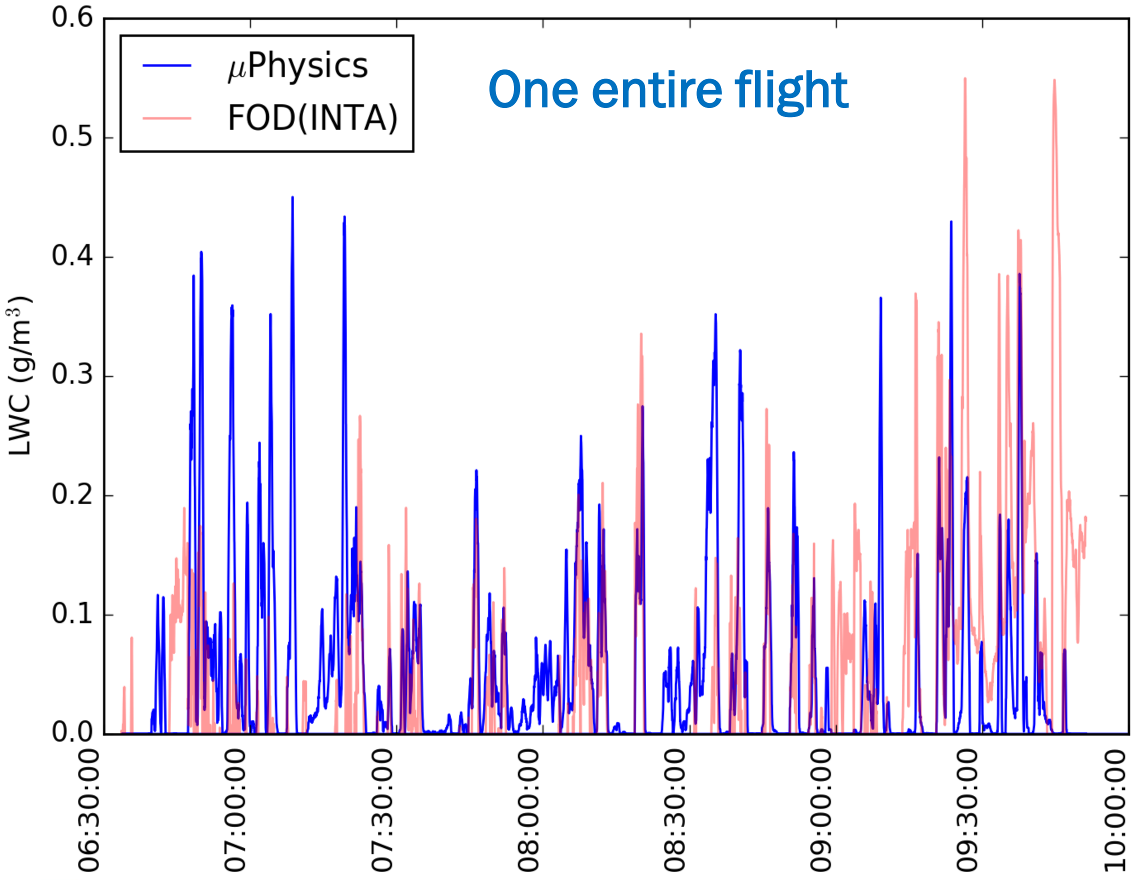
Green: NEVZOROV

Blue: FOD wavelet

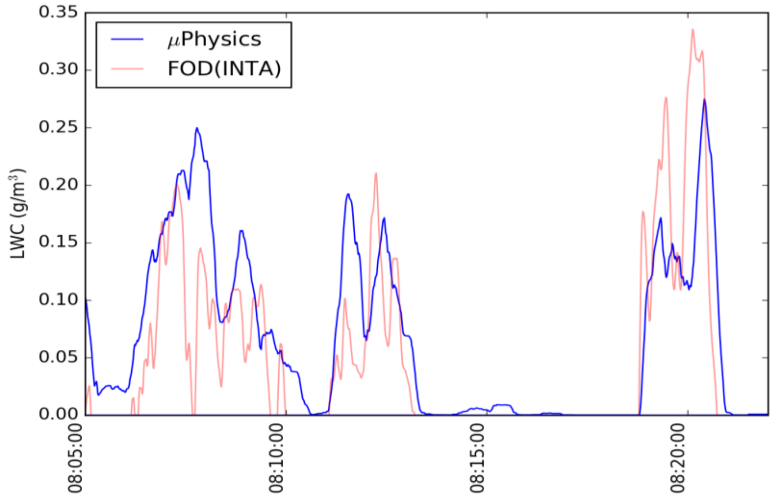
FOD-INTA FT- Results

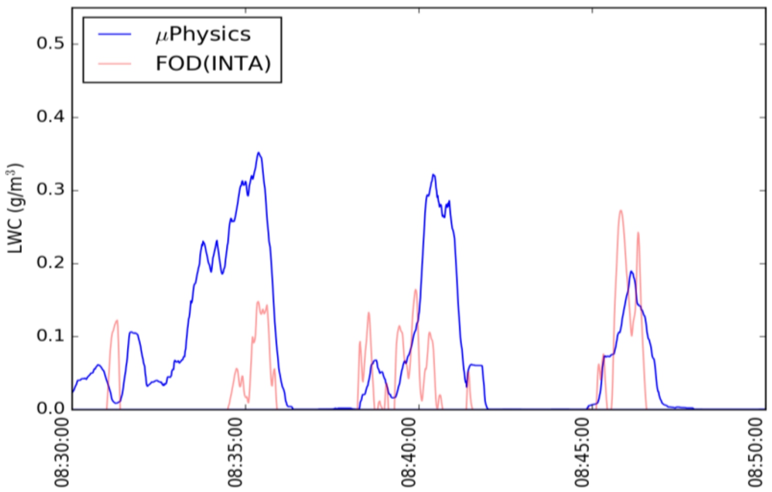
- Comparison from LWC measured by FOD and NEVZOROV

27.04.2023



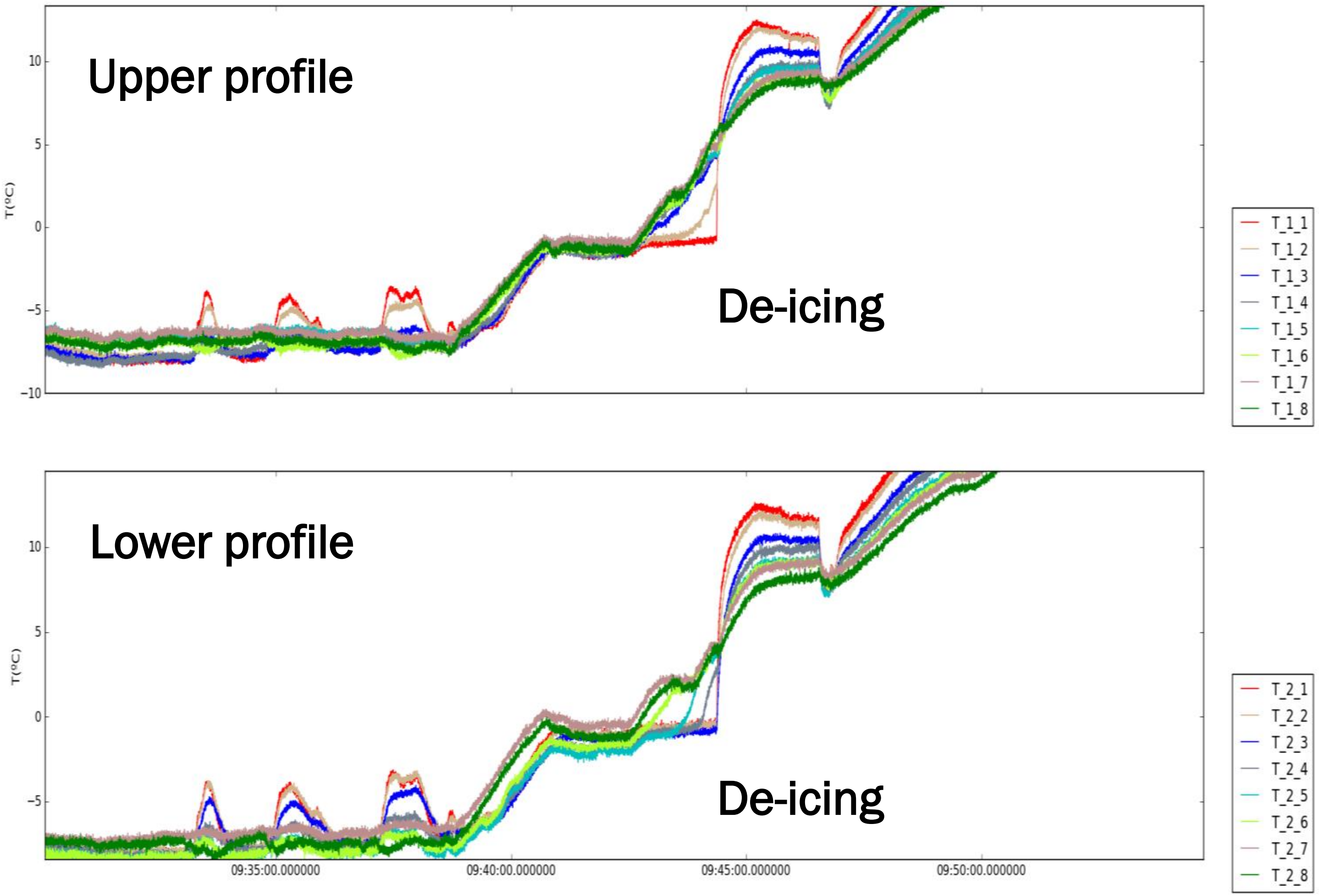
Details





FOD-INTA FT- Results

- Improvement of App O detection capability during de-icing
  - Ice accreted on sensor shows quite clear the ice layer accreted on the profile
  - An automated de-icing needs to be integrated to take advantage of this capability



CONCLUSIONS

Fiber Optic Detector, FOD is a combined atmospheric and accretion sensor

FOD, based on latent heat detection, has demonstrated good performance in IWT and FT

IWT

- LWC error 25 to 75%
- ACC-rate error 33 to 66%
- Test points detected within response time: 87%
- Failed in 2/36 conditions
- App O test points detected: 82%

FT

- Good agreement with NEVZOROV
- Clear LWC value is difficult to give due to the typical spiky cloud LWC

Gaps and future needs

- **FOD will be improved with automatic de-icing**
  - Possibility of increasing the sensibility after ice is formed
  - Improved App O detection with improved probe geometry
- Saving cost with the interrogator
  - Other cheaper interrogators are being tested
  - Two possibilities are being thought:
    - Very small interrogator manufactured by Redondo Optics (for the ice point sensors)
    - Other very small device made by Fisens (FiSpec FBG X100)
- Ice accretion rate estimation
  - The ice accretion is calculated through the equilibrium temperature.
  - Change the configurations so there is not thermal inertia
- Possibility of embedding the optic fiber in a structure without an icing probe

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