Project „SOPHIA“ - Final Report

(Study of Propeller Icing Hazard in Mini-UAV Aviation)

Meteomatics GmbH, St. Gallen 2017-05-01

Overview

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Project Partners:

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

BAZL Bundesamt für Zivilluftfahrt

vario

RAIL TEC ARSENAL

University of Reading

Meteomatics Company Profile

meteomatics
Your Experts in Weather Data Processing.

- Weather service provider
- Specialized on industrial weather forecasts, high-resolution local weather models and data distribution
- Located in St. Gallen, Switzerland
- 20 employees with strong backgrounds in physics, mathematics and computer sciences
- Strategic partnerships with e.g. MeteoSchweiz, RUAG, ECMWF
- Over 10 years of experience, customers in various sectors

VATTENFALL

SRF METEO

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
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DAIMLER

FUJITSU

References

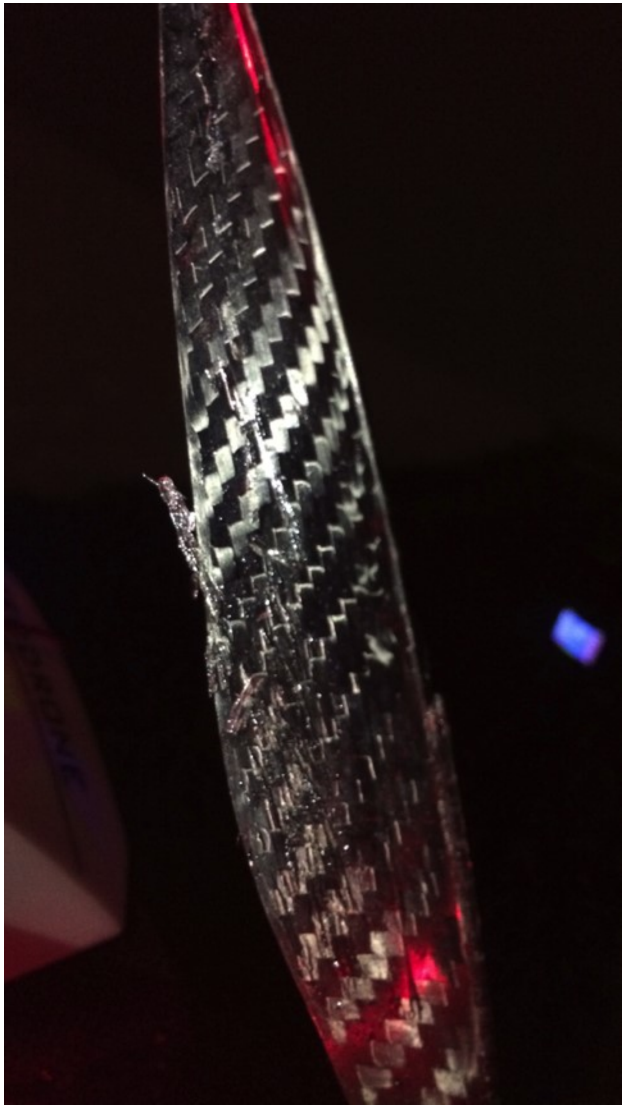
gas union
MeteoGroup
BKW
endios
ALPIQ
Kanton Uri
soptim Zukunft gestalten
SRF METEO
ENNI Energie & Umwelt Niederrhein
TenneT
Kanton Graubünden
ONZO®
DAIMLER
FUJITSU
RUAG
ESO
Kanton St.Gallen
yuso.be energy marketing
WINGAS
e2m
HYDRO
Q met
swarco
Leipziger Stadtwerke
VENIOS® Uniting IT and Energy
CKW
Energy Weather
uniper
ELE Emscher Lippe Energie GmbH
swissgrid
ECMWF European Centre for Medium Range Weather Forecasts
WATTELSE Optimised Building Automation
SBB CFF FFS
VATTENFALL
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Bundesamt für Zivilluftfahrt BAZL
Eidgenössisches Departement des Innern EDI
Bundesamt für Meteorologie und Klimatologie MeteoSchweiz
Hochschule Bochum Bochum University of Applied Sciences BO
SolarCar Team
LAMBRECHT meteo
innogy
RWE
montel

Meteodrones

- Currently the forecasts for fog and thunderstorms are quite insufficient
- Caused by a lack of adequate weather information in the lower atmosphere
- Meteomatics develops a new kind of weather observation instrument: **Meteodrones**
- Vision
  - Fully-automated network of Meteodrones
  - Running in 24 / 7 mode
  - Providing continuously information of the lower atmosphere
- The precision of fog and thunderstorm forecasts would be improved significantly!

SOPHIA Project Motivation

- During test flights with our Meteodrone we experienced ice accumulations that had a negative impact on the controllability
- Ice accumulations cause also problems for e.g. passenger aviation and helicopters
- Increasing risks for the public since more and more unmanned aerial vehicles (UAVs) are used; also commercially
- No study exists which analyzes Icing on UAVs



1mm thin clear ice during test flights in Icing conditions

SOPHIA Project Overview / Goals

Phase 1

- Define test setup
- Examine ice accumulations on propellers and the body of the UAV during different Icing conditions
- Test the effectivity of different Anti-Icing agents

Phase 2

- Analysis of the tests
- Build a model that represents Icing for different conditions
- Sketching further Anti-Icing strategies

Phase 3

- Implement Anti-Icing strategies in prototype
- Validate the findings in field tests

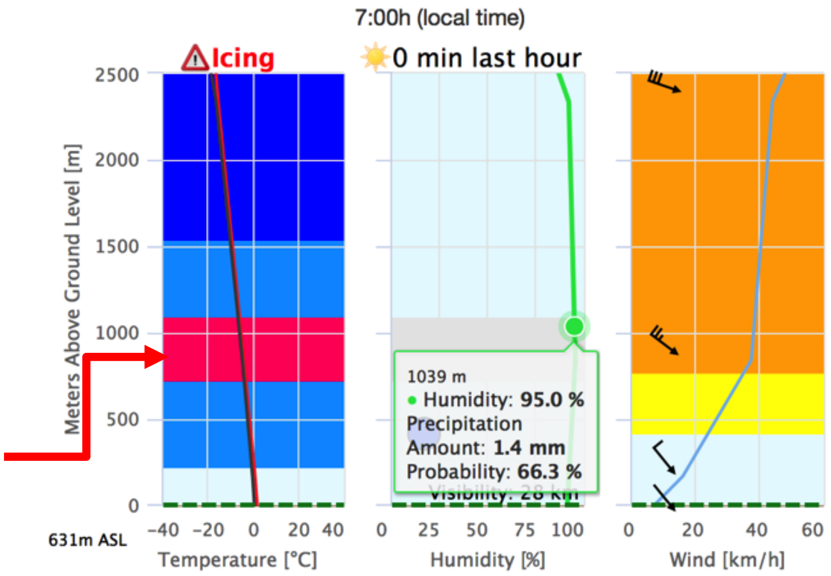
Current Project Status

- Achievements
  - ✓ Test-flights in real Icing-conditions
  - ✓ We designed and built a test setup that withstands harsh Icing conditions
  - ✓ We tested the Icing in different environments: outdoors during winter, in an indoor ski slope and in the **Vienna Climatic Wind Tunnel (VCWT)**
  - ✓ Six different weather conditions were tested and documented in the VCWT (considering EASA CS25/CS29 Appendix C guidelines)
  - ✓ The effect of the Icing on the current model of the Meteodrone was observed and documented
  - ✓ The taken measurements and photographs were analyzed thoroughly
  - ✓ Various learnings about Icing and the test setup have been made
  - ✓ Tested different Anti-Icing methods
  - ✓ A reliable heating method for the propellers was found.

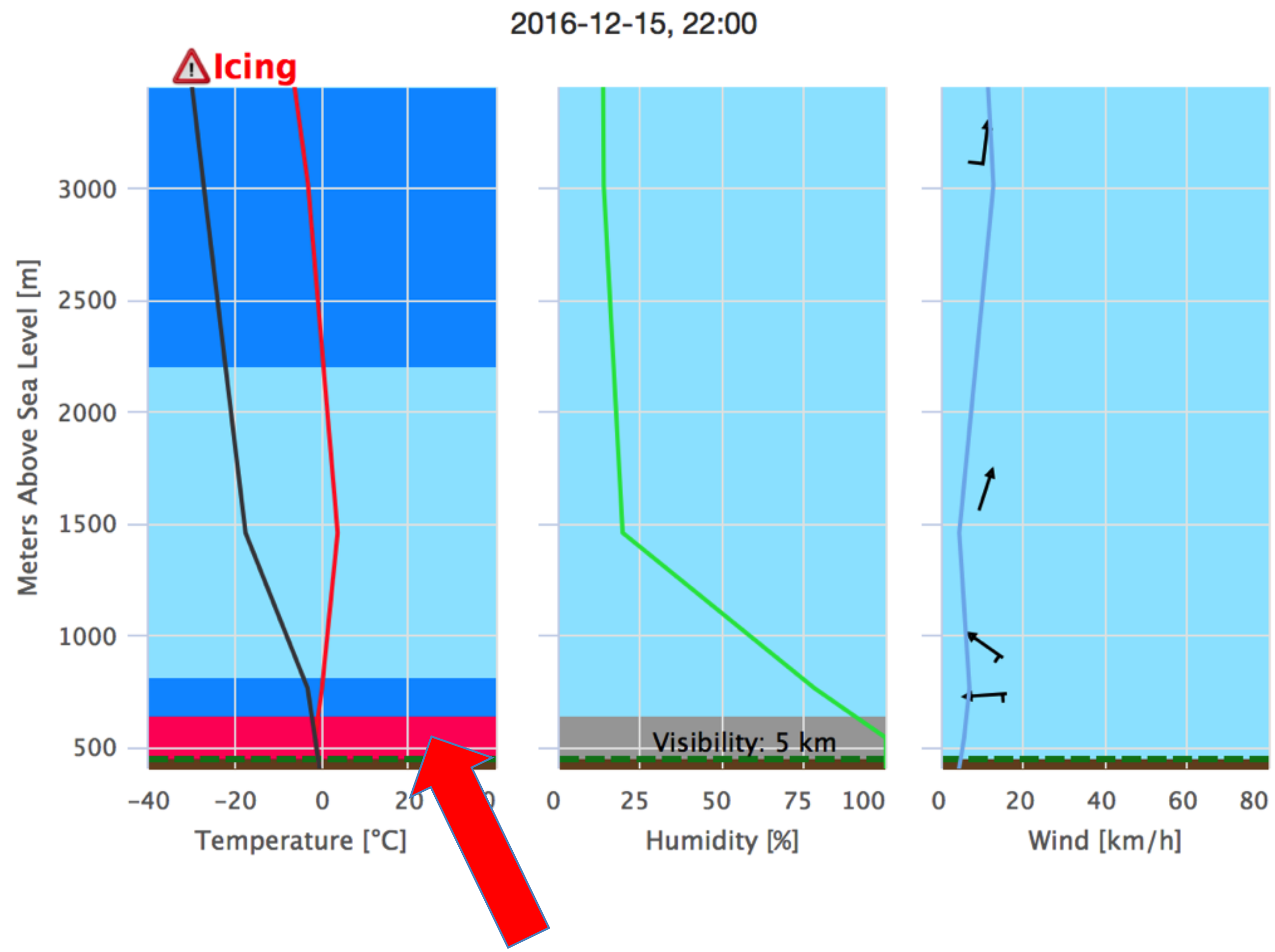
Icing Conditions

- Two key-conditions:
  1. **Air temperature < 0°C**
  2. Visible humidity:
     → **Relative humidity > 95%**

- Drone-weather by Meteomatics:
  - Forecast of the meteorological parameters **temperature**, **relative humidity** and **wind** for every hour and different altitudes.
  - Icing conditions are highlighted in pink.
  - Is used for Meteo-briefings of drone pilots



Test flights under real Icing Conditions 1/6



Forecasted Icing Conditions in the lowest 300m above ground level (AGL) for the night of 15.12. – 16.12.2016.

Test flights under real Icing Conditions 2/6

- Two test flights im Amlikon under forecasted Icing Condtions during the night of 15.12. to 16.12.2016.

- **Flight 1: Meteomatics Meteodrone SUI-9993**
  - Weather:
    - Ground: Air temperature 1°C and relative humidity 95%
    - At a height of 565m AGL: Air temperature -2°C and relative humidity 100%
  - **Due to the weather conditions, ice was formed on the propellers.**
    - The autopilot system wasn‘t able to control the system anymore.
    - The emergency rescue system was manually initiated by the pilot at an altitude of 399m AGL during the descent at 15.12.2016 21:59 UTC.
    - The rescue system was successfully initiated and the parachute opened at a height of 100m AGL.

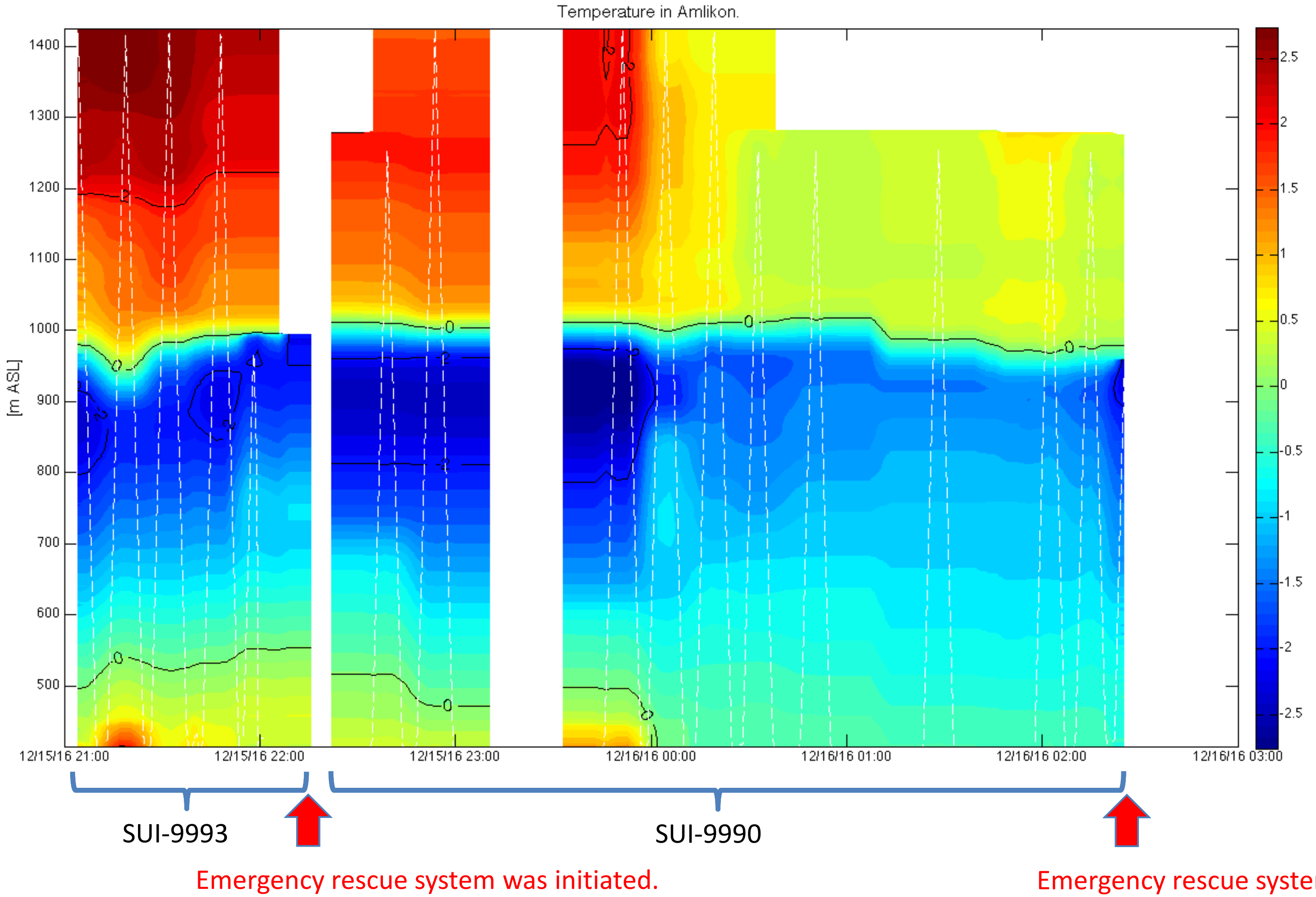
Test flights under real Icing Conditions 3/6

- **Flight 2: Meteomatics Meteodrone SUI-9990**
  - Weather:
    - Ground: Air temperature -0.3°C and relative humidity 89%
    - At a height of 534m AGL: Air temperature -2.5°C and relative humidity 95%

  - **Due to the weather conditions, ice was formed on the propellers.**
    - The autopilot system wasn‘t able to control the system anymore.
    - The emergency rescue system was manually initiated by the pilot at an altitude of 239m AGL during the descent at 16.12.2016 02:26 UTC.
    - The rescue system was successfully initiated and the parachute opened at a height of 100m AGL.

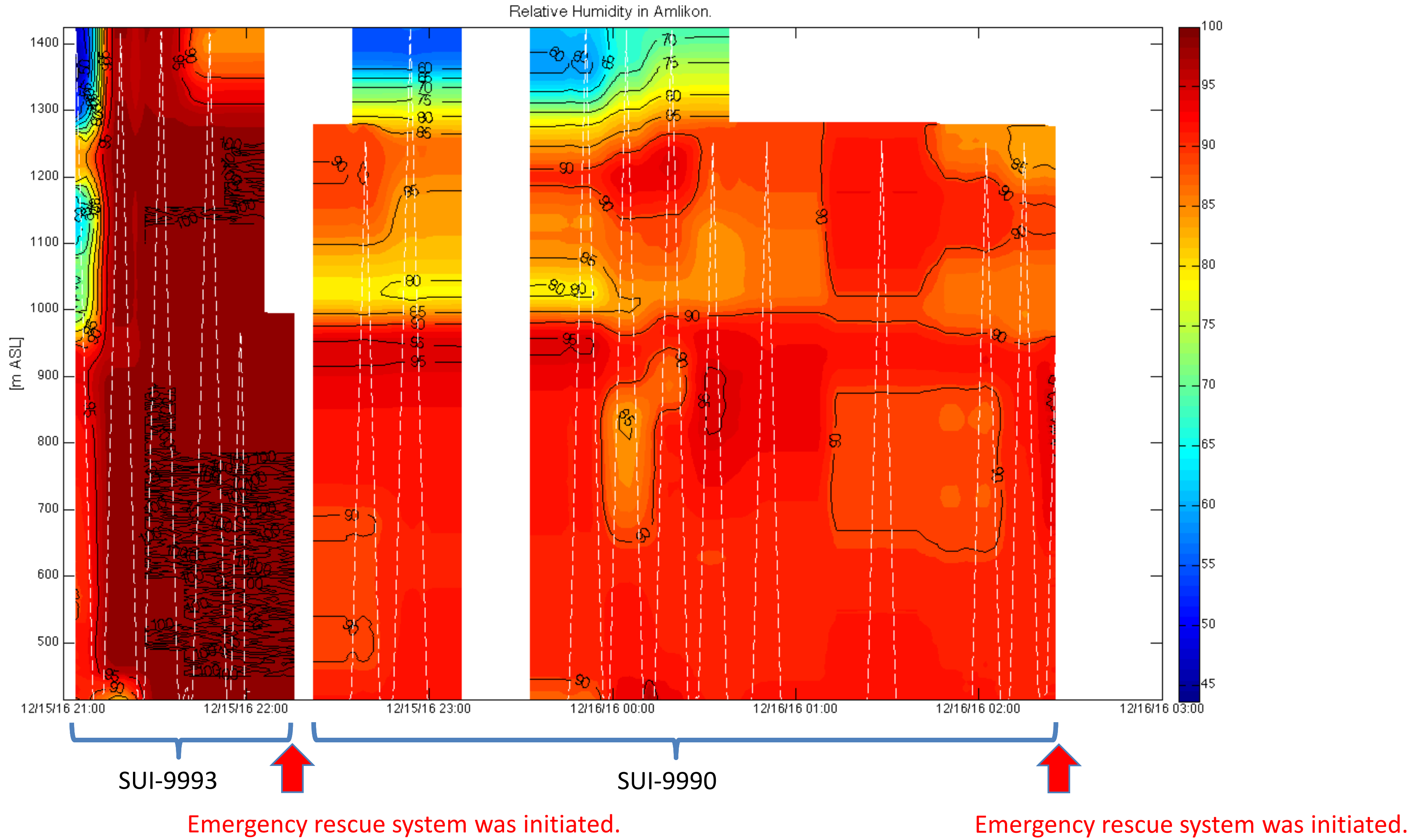
Test flights under real Icing Conditions 4/6

- Icing conditions during the test flights were approved by the Meteodrone measurements: **Air temperature [°C] < 0°C**



Test flights under real Icing Conditions 5/6

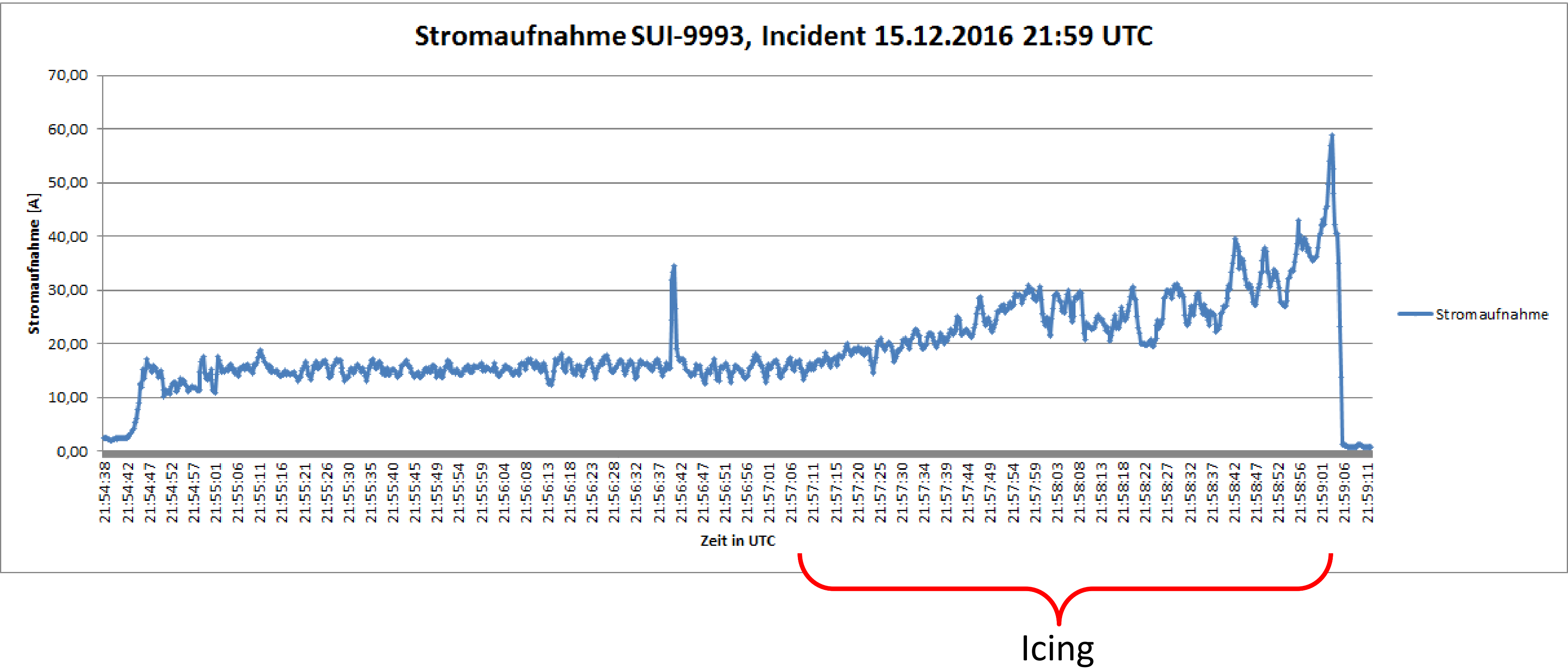
- Icing conditions during the test flights were approved by the Meteodrone measurements: **Relative humidity [%] > 95%**



Test flights under real Icing Conditions 6/6

- Influence of Icing on power input

  → Power input increases during Icing.



Test Designs for detailed tests

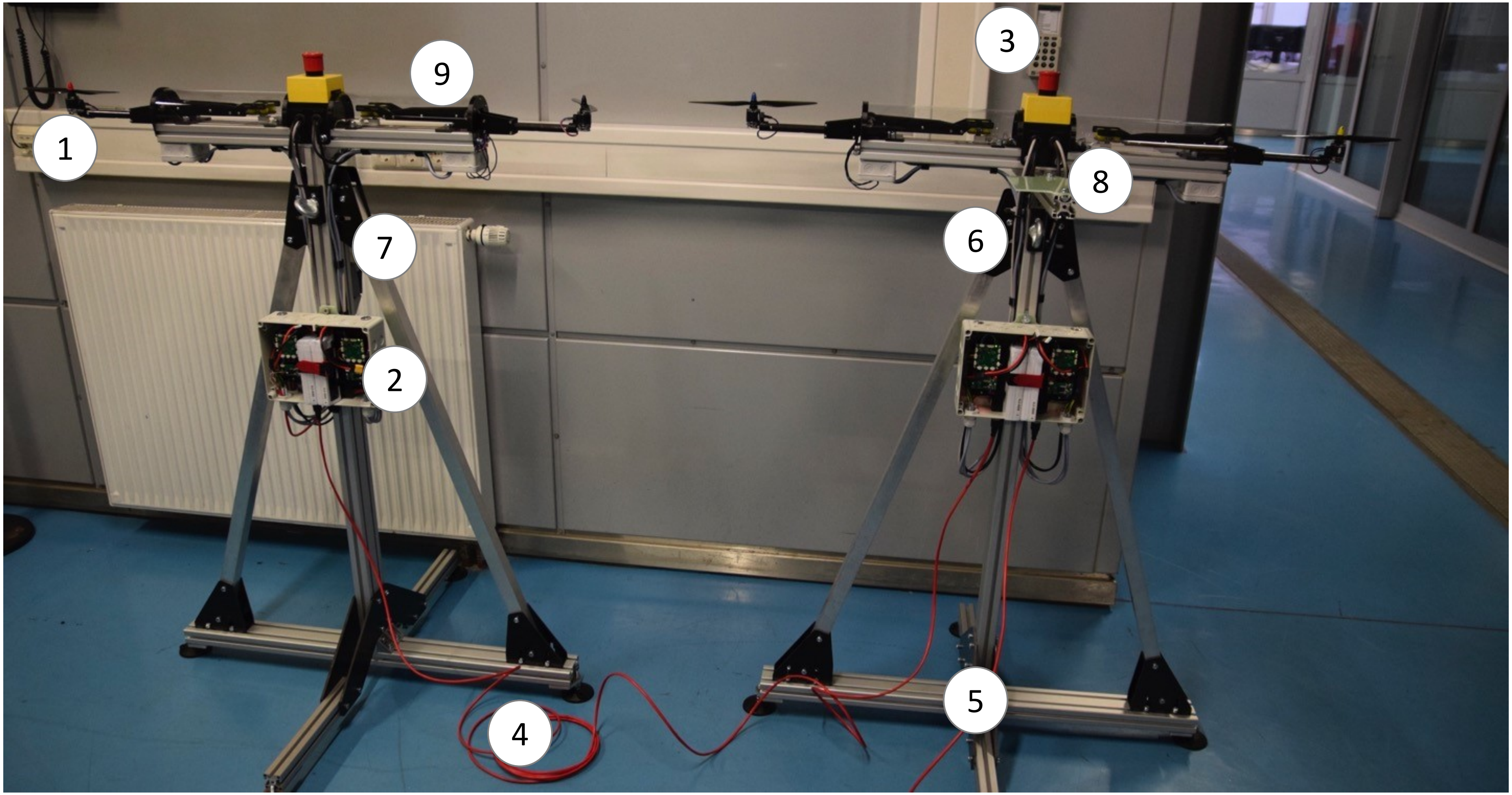
Outdoor / Indoor ski slope

- During development
- 1 test stand, 1 propeller
- 2-4 hours

VCWT (as planned)

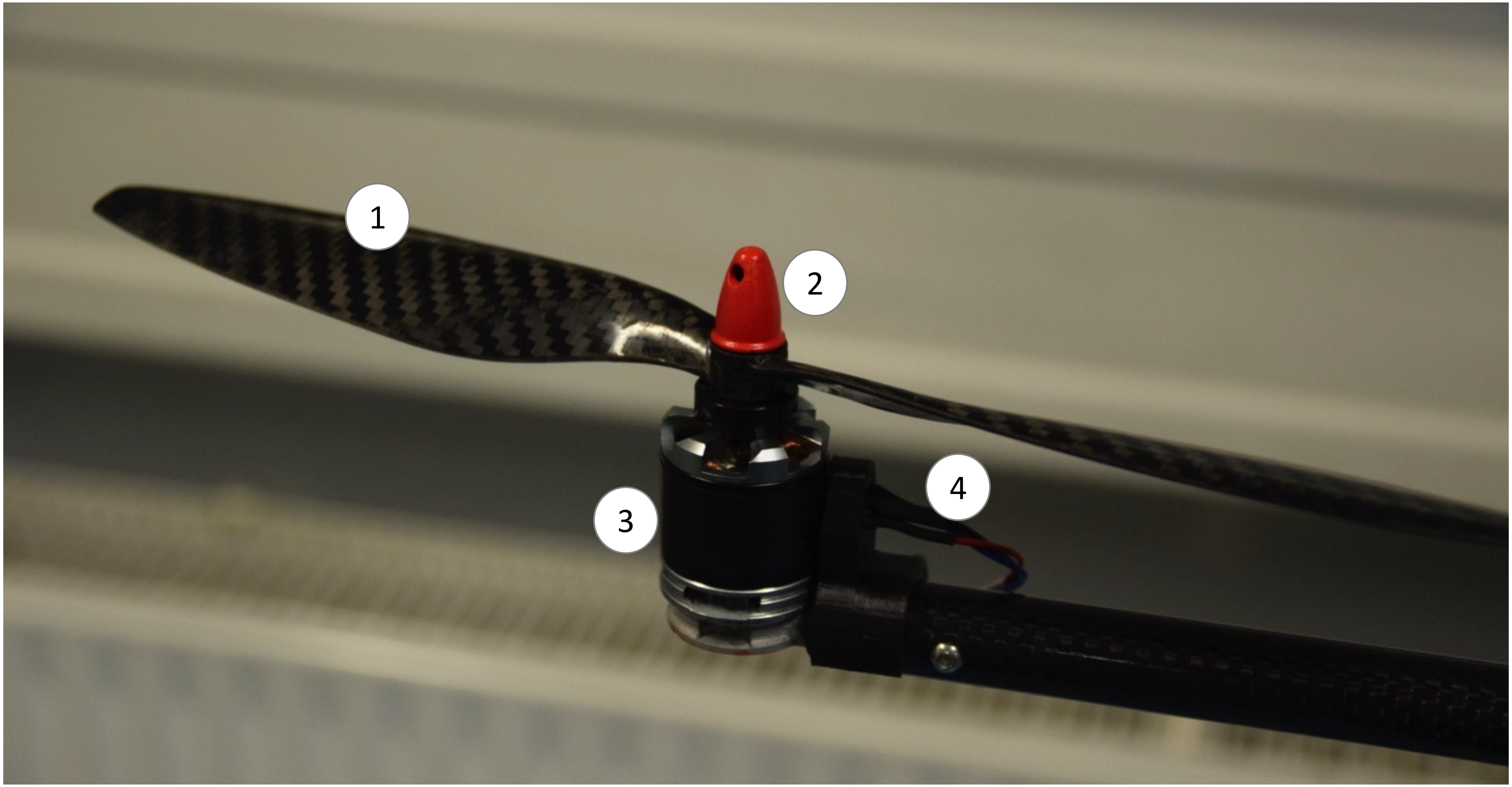
- 2 stands with together 4 parallel propellers
- 10 different weather conditions (2 stratiform clouds, 6 cumuliform clouds, wet snow, dry snow)
- 2 different test scenarios: interval test and continuous test
- 3 different flight states (up, hover, down)
- 2 different Anti-Icing agents
- 10 hours of testing

Test Setup – Overview



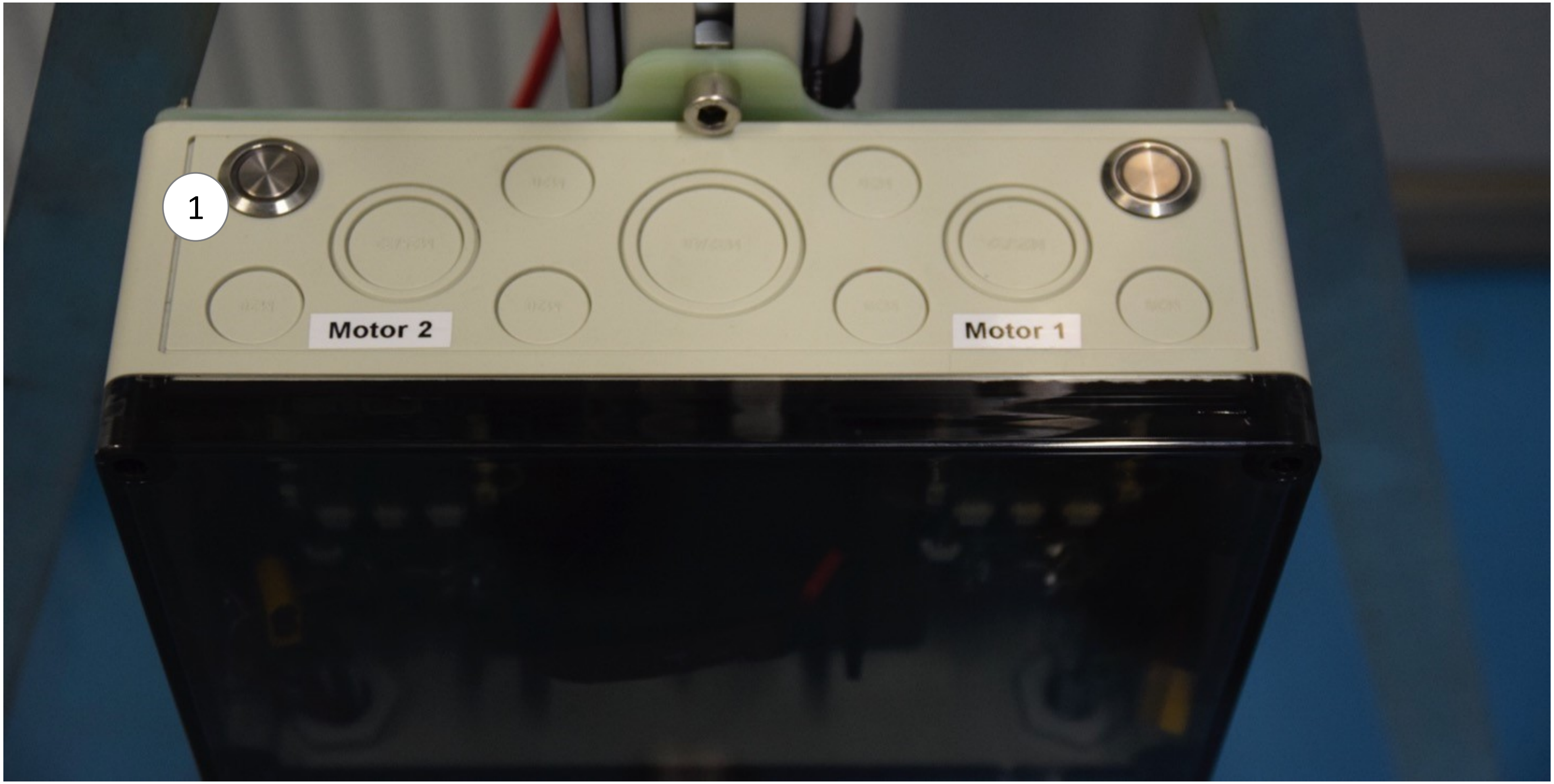
1: rocker with motor and propeller, 2: control unit, 3: emergency switch, 4: connection cable (30m to control room), 5: stable stand that can be fixated, 6: additional fixation points, 7: temperature/humidity sensor, 8: mount for LWC sensor, 9: waterproof cover of the rocker

Test Setup – Motor and Propeller



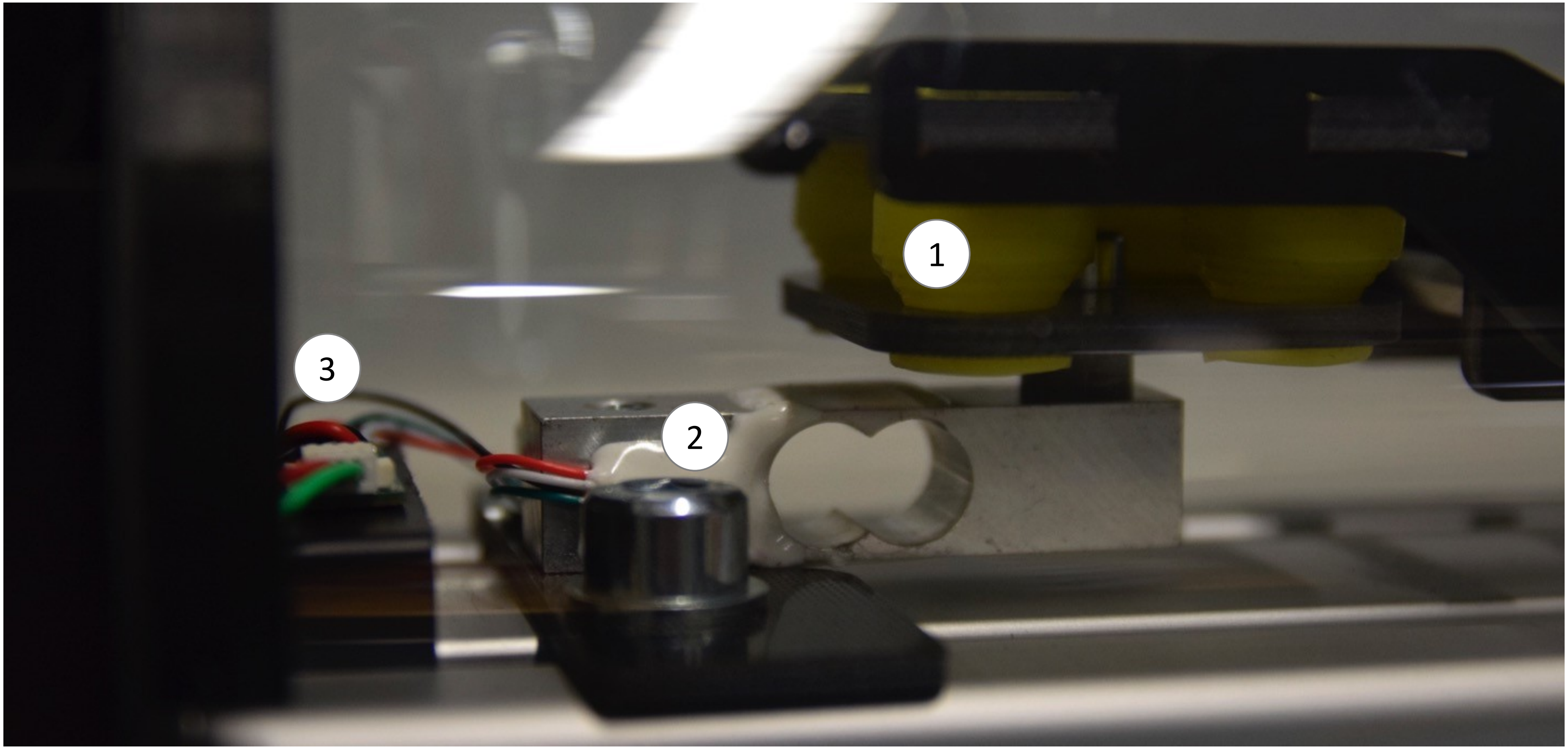
1: propeller blade, 2: uniquely colored cap for each propeller, 3: motor, 4: RPM measurement

Test Setup – Control Unit



1: control button to pause/restart motor

Test Setup – Rocker Detail



1: vibrations absorber, 2: force measurement cell, 3: control board

Test Setup – Outdoor

Outdoor tests conducted on February 27th, 2016 on top of the Kahler Asten mountain in Germany

Test Setup – At an indoor ski slope

Tests conducted on March 11th, 2016 at an indoor ski slope near Cologne/Germany

Test Setup – In the VCWT‘s larger wind tunnel

Tests conducted in the Vienna Climatic Wind Tunnel on March 18th, 2016

Actual Test Design / VCWT adjustments

- Occurred Problems:
  - De-Icing of propellers with warm air between tests took quite long
  - Massive accumulation of ice during propeller stops for ice observation
  - Snow generator of VCWT was defect
  - Problems with the stability of the power supply during initial setup
  - Most Anti-Icing agents did not show any effect

- Adjusted test setup:
  - 6 different weather conditions (2 stratiform clouds, 4 cumuliform clouds)
  - 1 test scenario: interval test with longer intervals
  - 1 flight state (hover)
  - 4 different Anti-Icing agents
  - 6 hours of testing

Test Scenarios VCWT

No.	Start	End	Temperature	LWC	MVD	Condition
1	11:58	12:19	-2 °C	0.6 g/m^3	20 µm	Stratiform Cloud
2	13:12	13:31	-5 °C	0.5 g/m^3	20 µm	Stratiform Cloud
3	13:45	14:19	-5 °C	1.25 g/m^3	30 µm	Cumuliform Cloud
4	15:57	16:08	-10 °C	1.4 g/m^3	25 µm	Cumuliform Cloud
5	17:10	17:26	-20 °C	0.7 g/m^3	30 µm	Cumuliform Cloud
6	18:18	18:29	-10 °C	0.8 g/m^3	32.5 µm	Cumuliform Cloud

- The technical abilities of the VCWT limited the testable conditions
- Large diameters would have required a stronger wind in the tunnel but nobody could have been inside during tests (no ice observation/photos)
- Focus on smaller LWCs since they are more relevant for real clouds

Test Scenarios VCWT

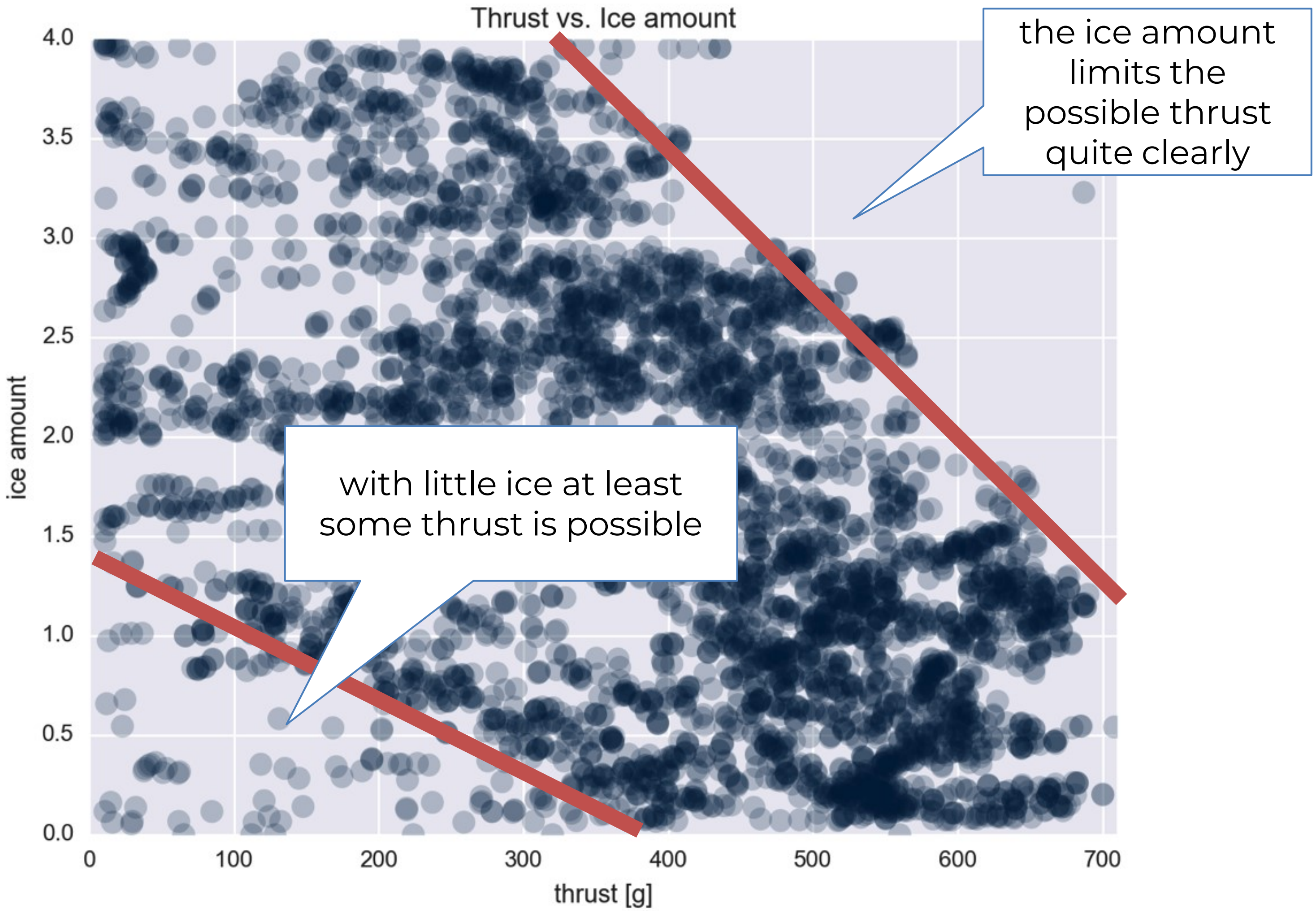
Glossary

VCWT	Vienna Climatic Wind Tunnel
RTA	RailTech Arsenal (operator of the VCWT)
LWC	Liquid Water Content
MVD	Median Volume Diameter
LDWC	Liquid Droplet Water Content
RPM	Revolutions per Minute

Results – Impact on the propellers

- Ice amount was taken from the photographs (see example photographs in the appendix)
  - 0: no ice
  - 1: merely visible ice
  - 2: few ice (less than 2mm)
  - 3: much ice (less than 4mm)
  - 4: extreme ice
- Photographs only available when motor was stopped
  - Quite inaccurate values between the photographs (interpolation)
- **Weak negative correlation found between ice amount and thrust**
  - more ice means less thrust
  - **a certain ice amount limits the possible thrust very clearly**
  - **with little ice at least medium thrust is still possible**
  - maybe clearer evidence if more, and more accurate ice amount data

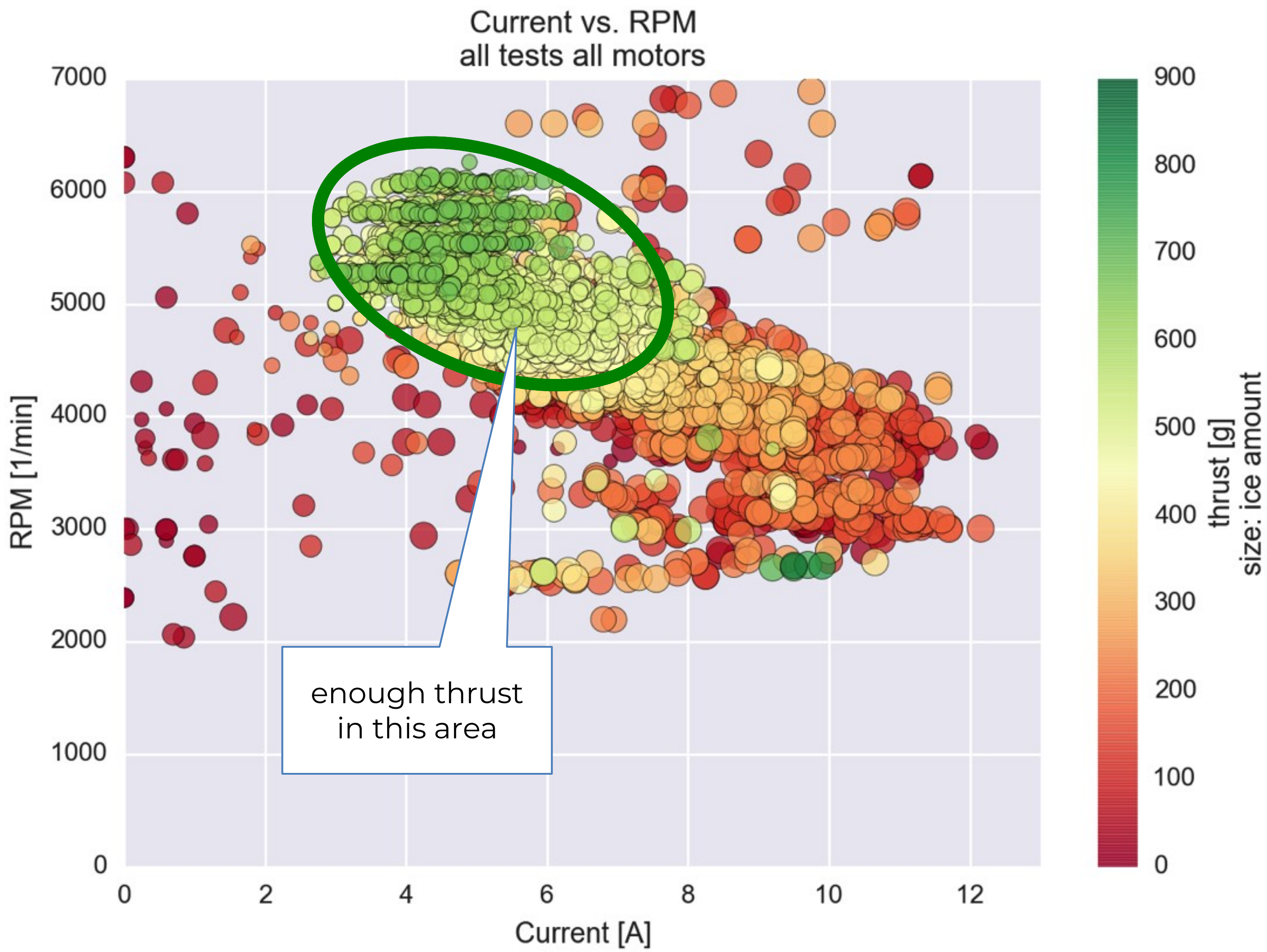
Negative correlation between ice amount and thrust



Results – Impact on the propellers

- Icing is visible in RPM/Current relationship
  - In our specific example: thrust is OK:
    - when RPM between 5000 and 6000 and
    - when current is between 3 and 6 ampere
- Many measurements recorded
- **Quite precise detection of ice possible**
  - depending on desired thrust (up, hover, down)
  - with previous calibration

Icing is visible in RPM/Current relationship



Results – Impact of LWC, MVD and Temperature

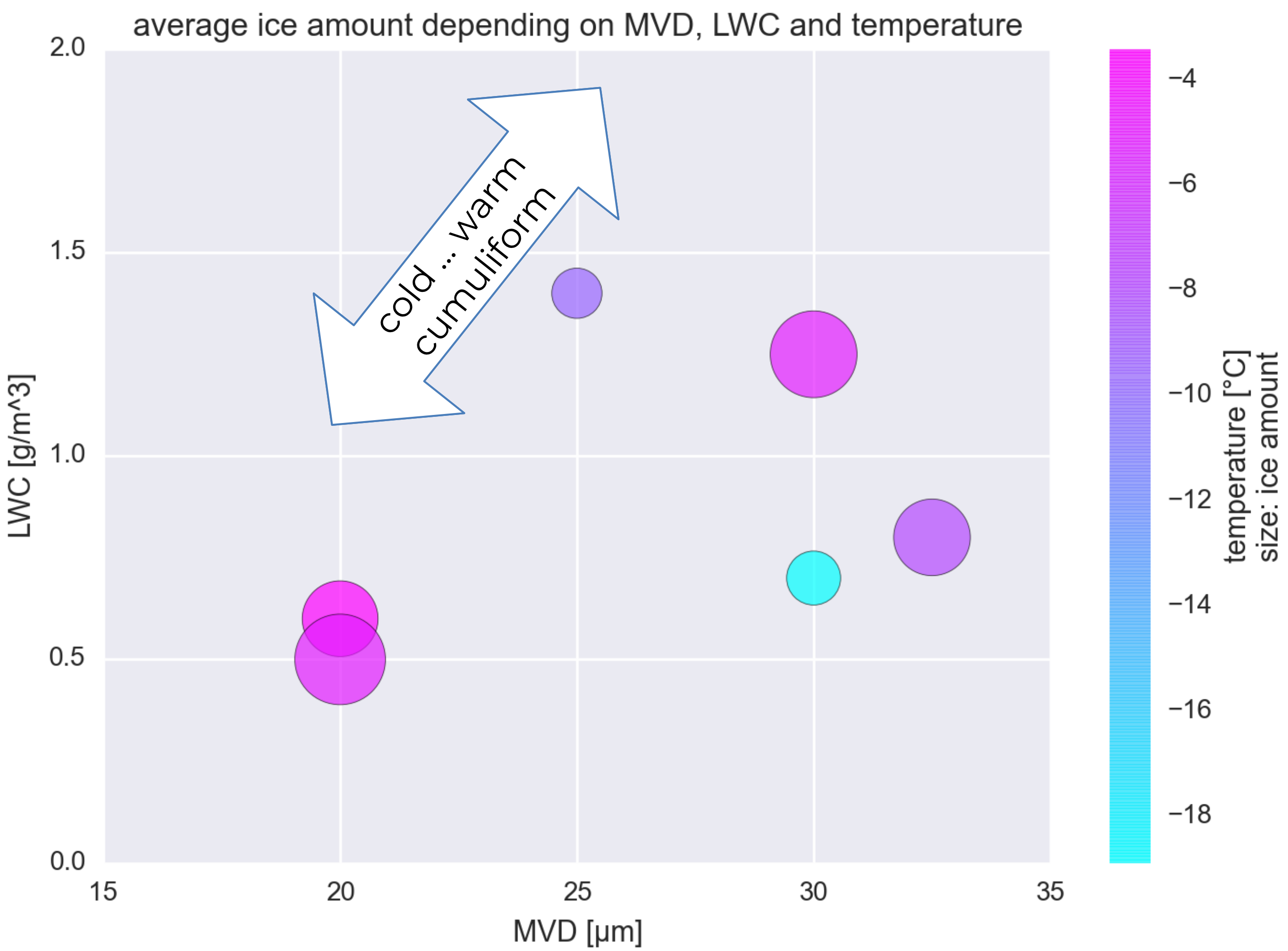
- The amount and speed of Icing depends on LWC, MVD and temperature
  - In general more ice at warmer temperatures
  - Faster Icing at high LDWC and warmer temperatures

- Combination of LWC and MVD: LDWC (Liquid Droplet Water Content)

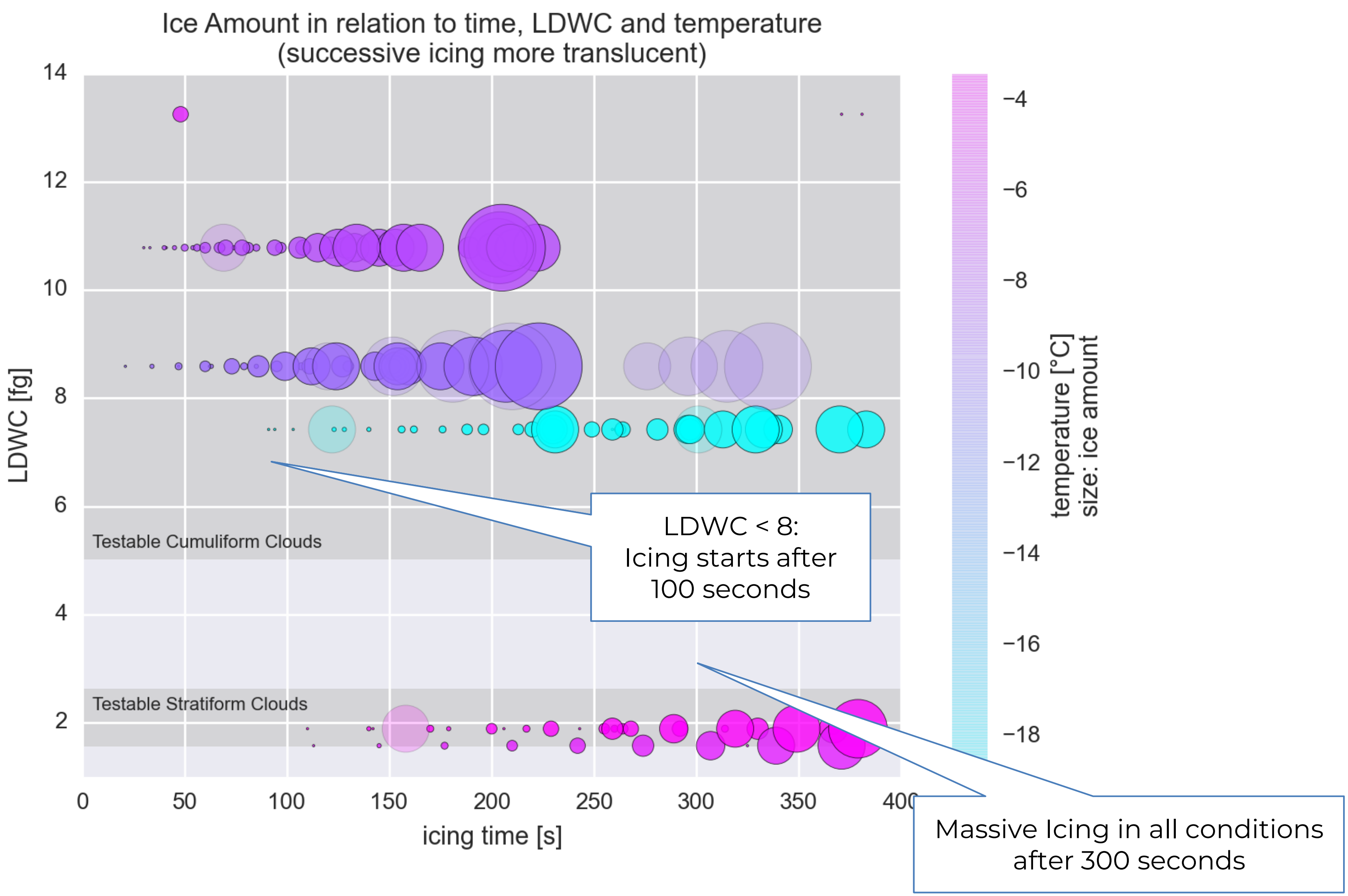
$$LDWC = LWC \cdot \frac{4}{3}\pi \left(\frac{MVD}{2}\right)^3$$

- **LDWC < 8 fg (mostly stratiform cloud conditions):**
  - **About 100 seconds until Icing starts (1:40 minutes)**
- **All conditions:**
  - **massive Icing not later than 300 seconds (5 minutes)**

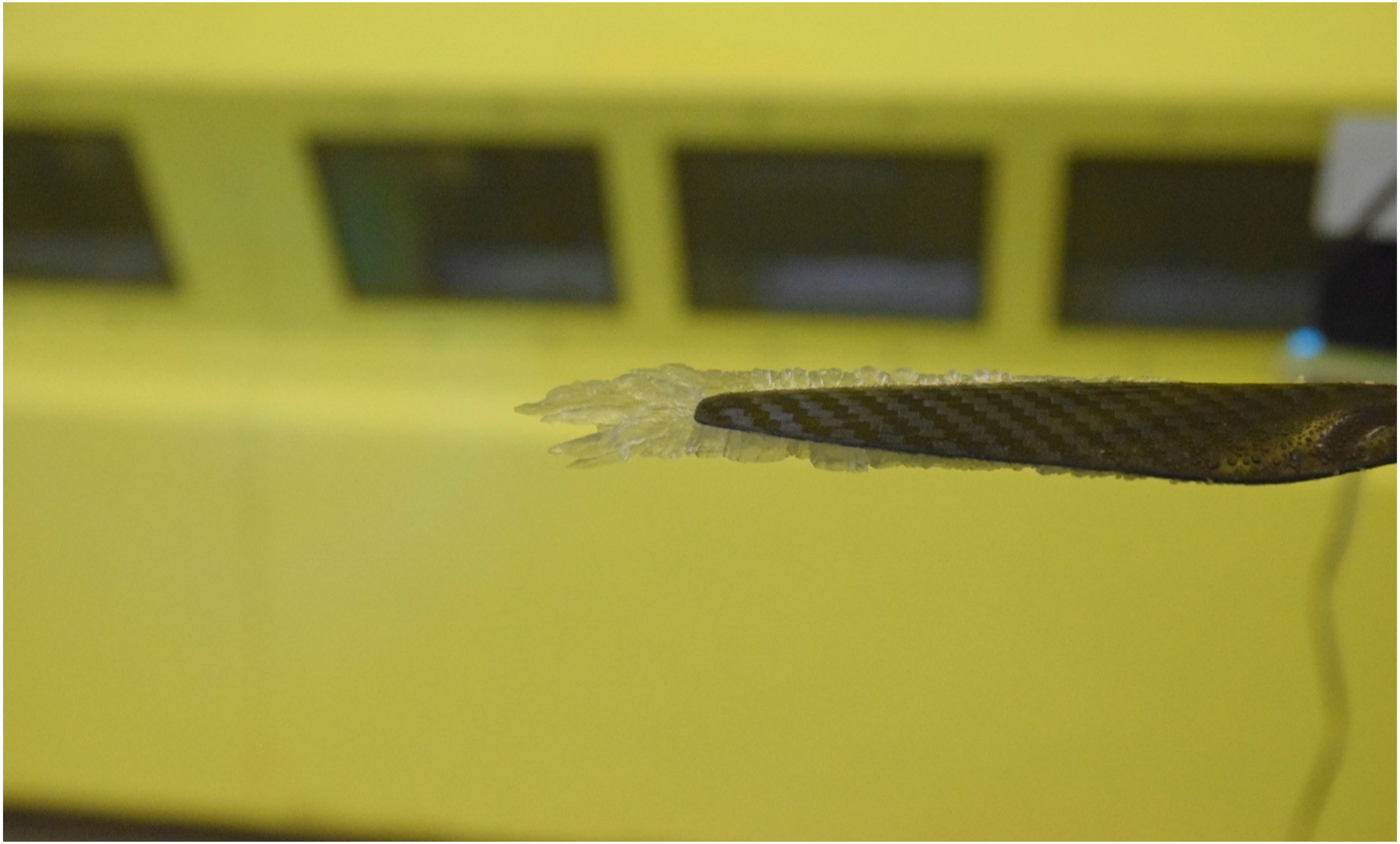
In general more ice at higher temperatures



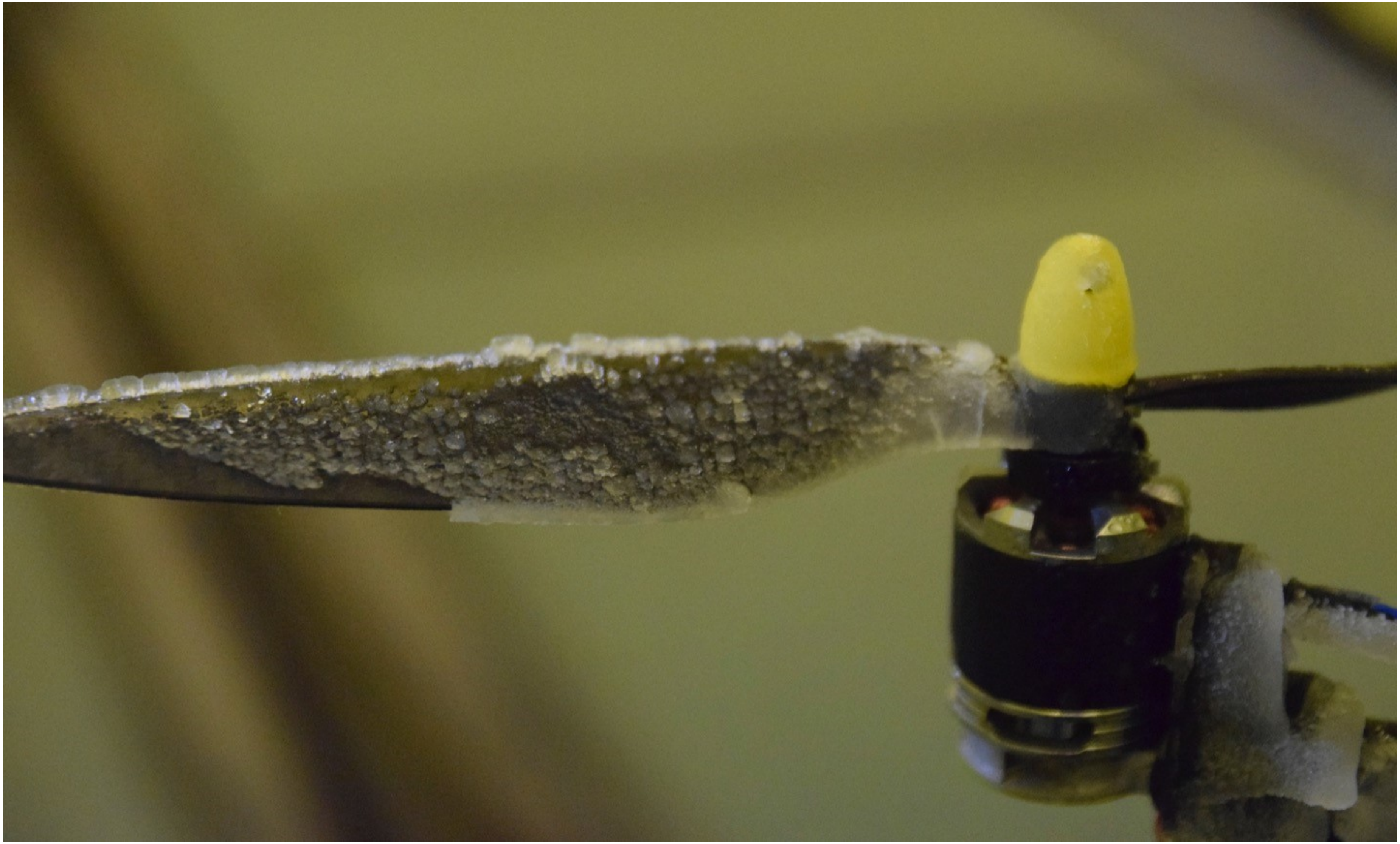
Faster Icing at high LDWCs and warmer temperatures



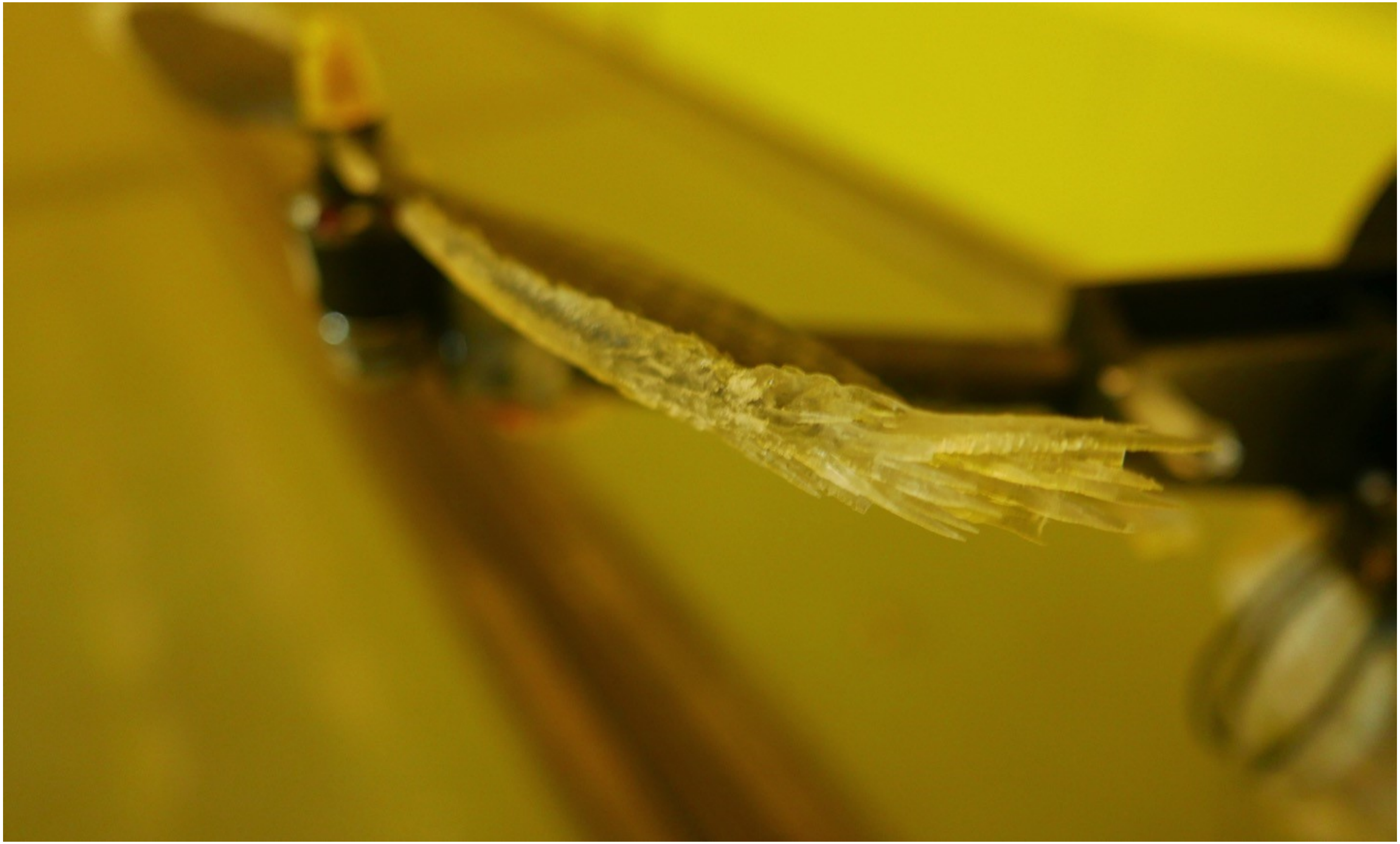
Clear ice (-2°C, MVD=20μm, LWC=0.6g/m^3)



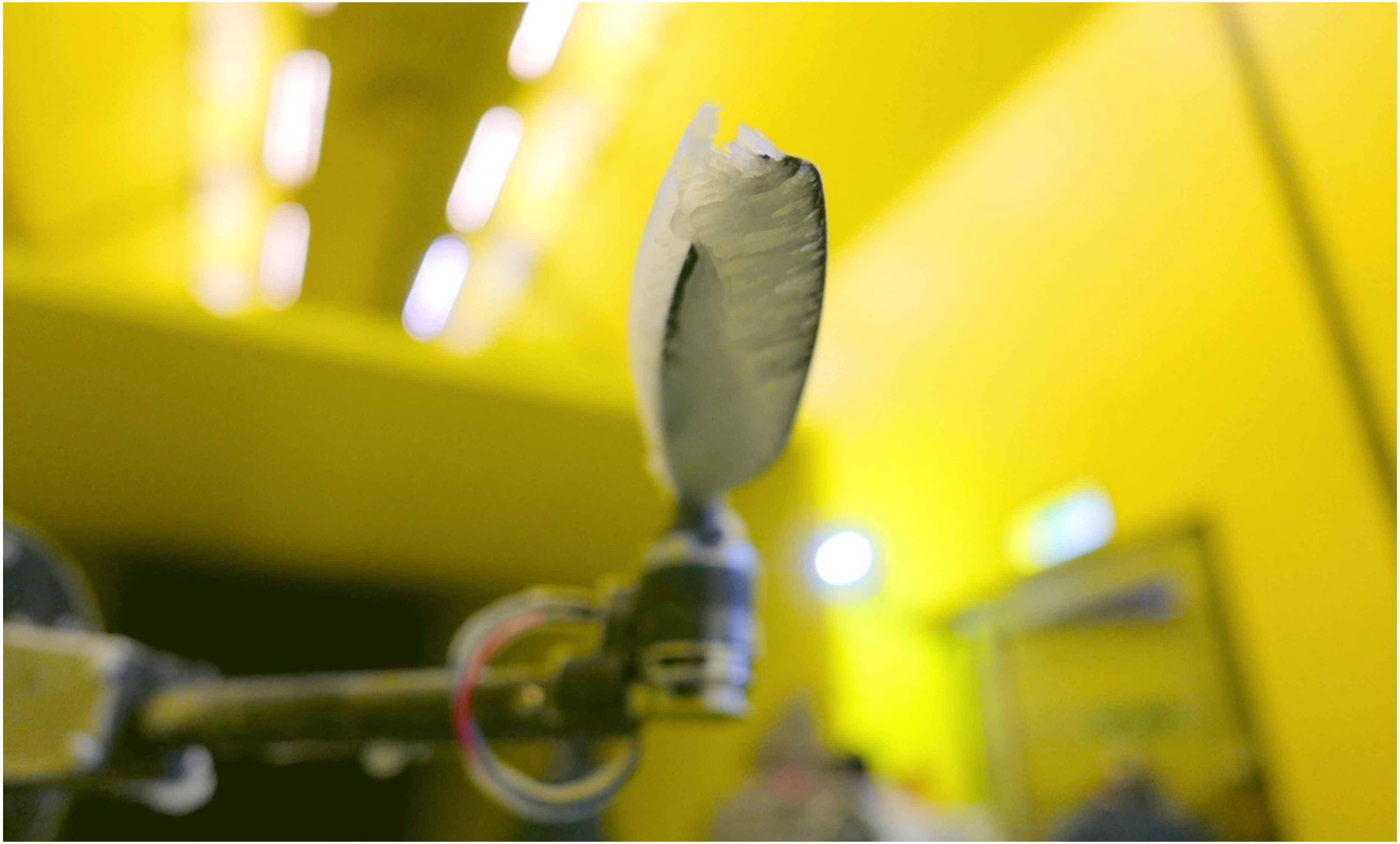
Ice cover (-5°C, MVD=20μm, LWC=0.5g/m^3)



Extreme clear ice amount (-5°C, MVD=30μm, LWC=1.25g/m^3)



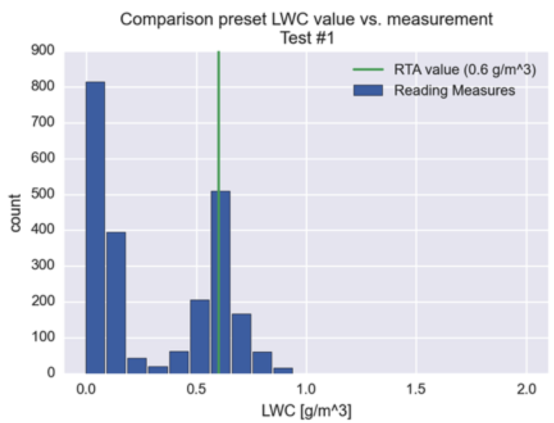
Icing under the propeller (-10°C, MVD=25μm, LWC=1.4g/m^3)

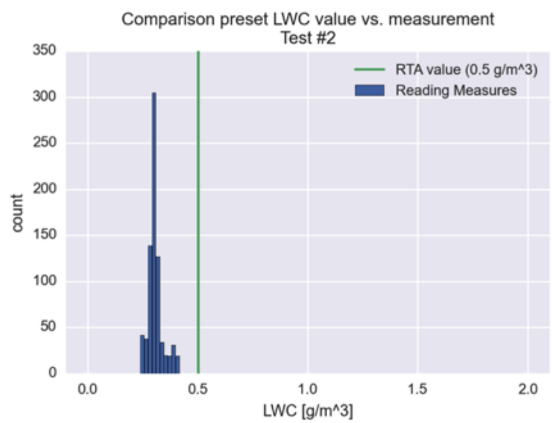


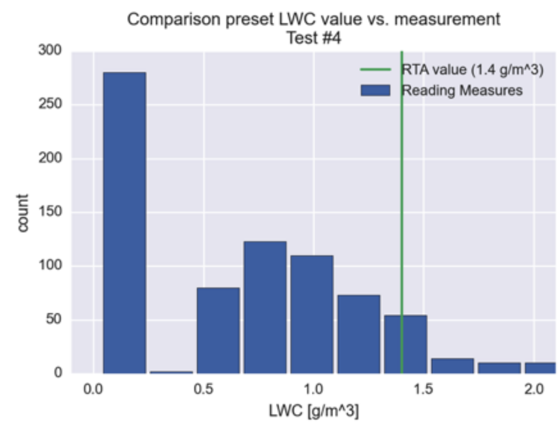
Hard rime (-20°C, MVD=30µm, LWC=0.7g/m^3)

LWC measurements

- Dr. Keri Nicoll from the University Reading is developing lightweight cloud sensors to measure the LWC
- During the tests in the VCWT, Dr. Nicoll conducted tests of these sensors in parallel to the Icing tests in the same weather conditions
- The measured LWC spectrum values showed some difference to the values preset in the VCWT
- **Application onboard the Meteodrone maybe in future version**





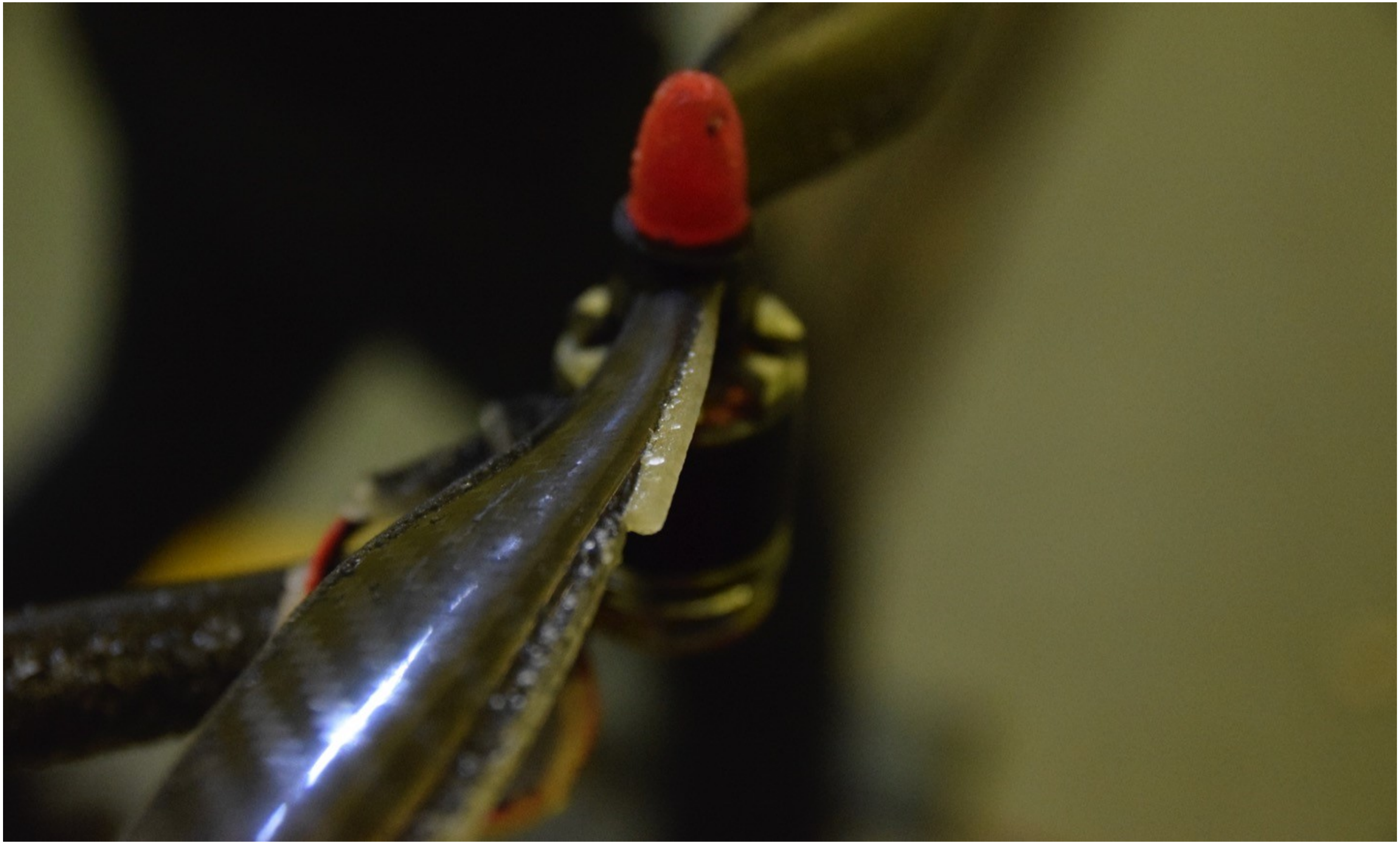


Results – Effectivity of different Anti-Icing Agents

- Different de-Icing and Anti-Icing agents were tested
- None of these showed full protective effect
- **Effect depends on viscosity**
  - low viscosity: agents 1,3 slipped from the props very fast, no effect
  - higher viscosity: agents 2,4 had a delaying effect on the ice (maybe 1 or 2 minutes)
- **Not enough data to get clear evidence**

1: wind shield defroster (de-Icing)
2: door rubber gasket protection (Anti-Icing)
3: wind shield defroster (de-Acing)
4: cooler protection concentrate (Anti-Icing)

Test 1, Motor 2 (much ice that already broke, no agent)

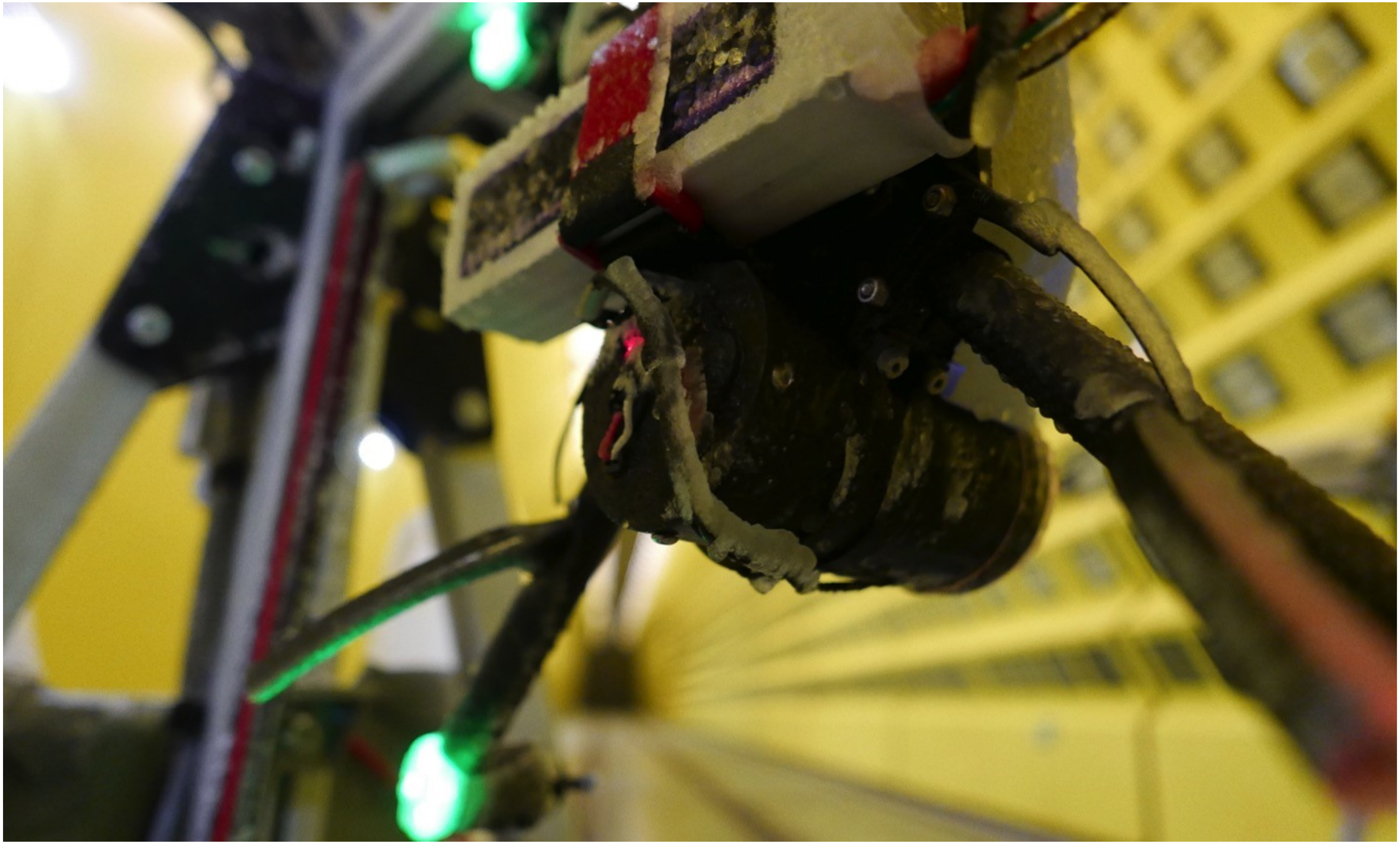


Test 1, Motor 4 (little ice due to Anti-Icing agent #2)

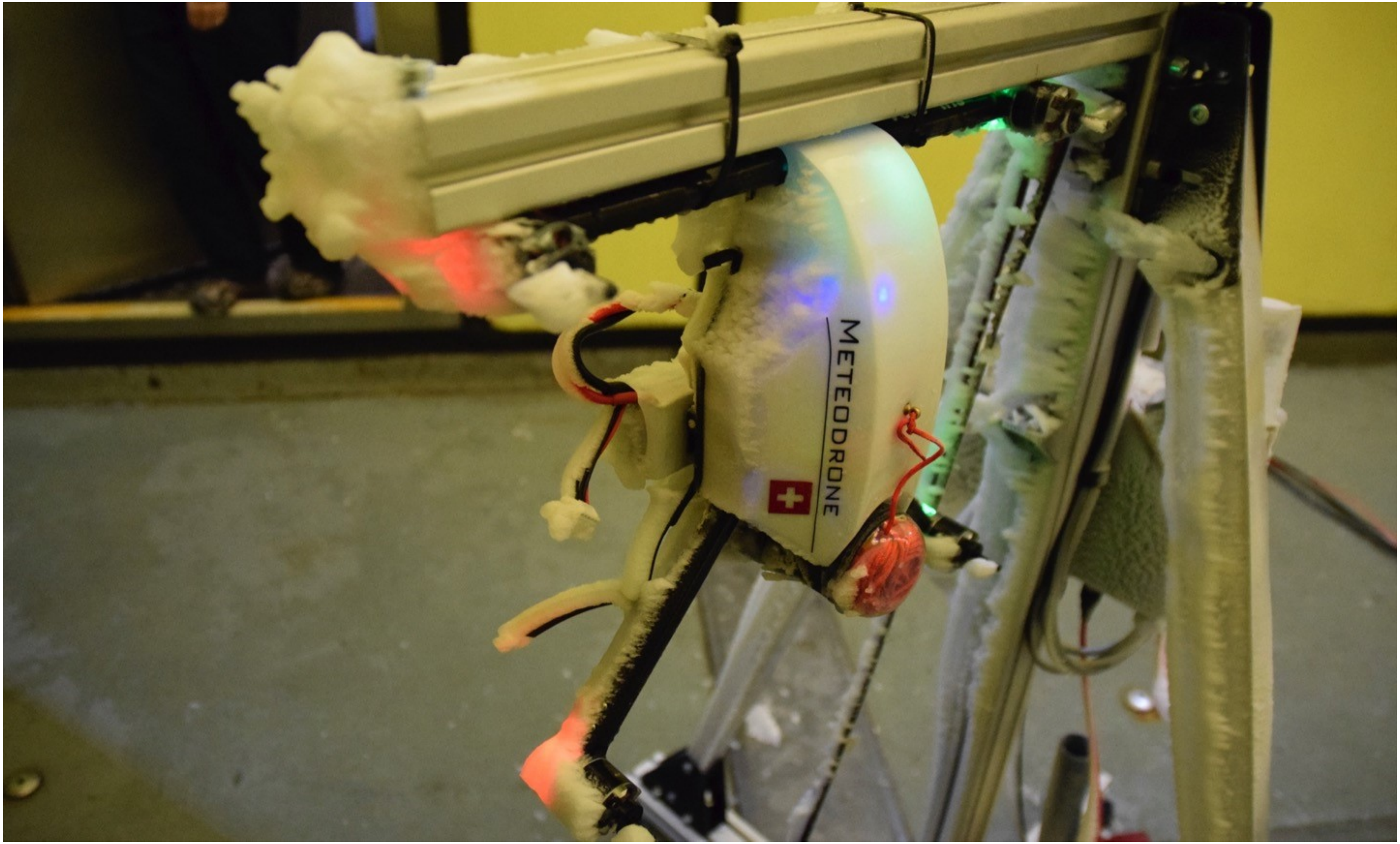
Results – Impact on the Meteodrone‘s body

- During all tests one Meteodrone was placed in the test chamber
  - Energy supply connected, activated (position lights and heating on)
  - No propellers mounted
- The Icing on the body, the sensors and the parachute cap was documented
- Results
  - The electronics worked all the time (6 hours at up to -20°C)
  - The sensors stayed ice-free at all times
  - The parachute cap iced at -20°C
    - possible voltage drop in the battery after over 6 hours

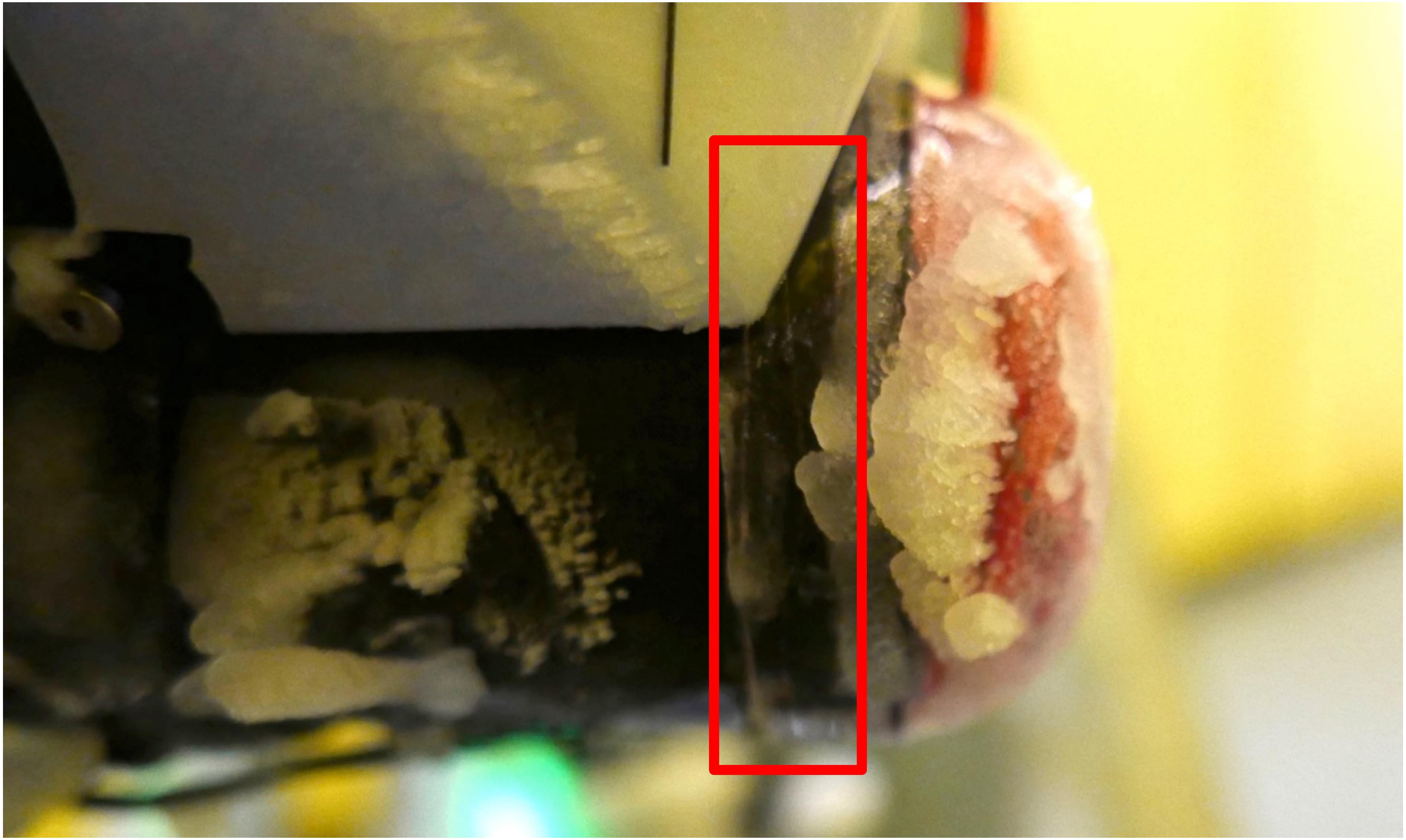
Meteodrone body ice after 20 minutes



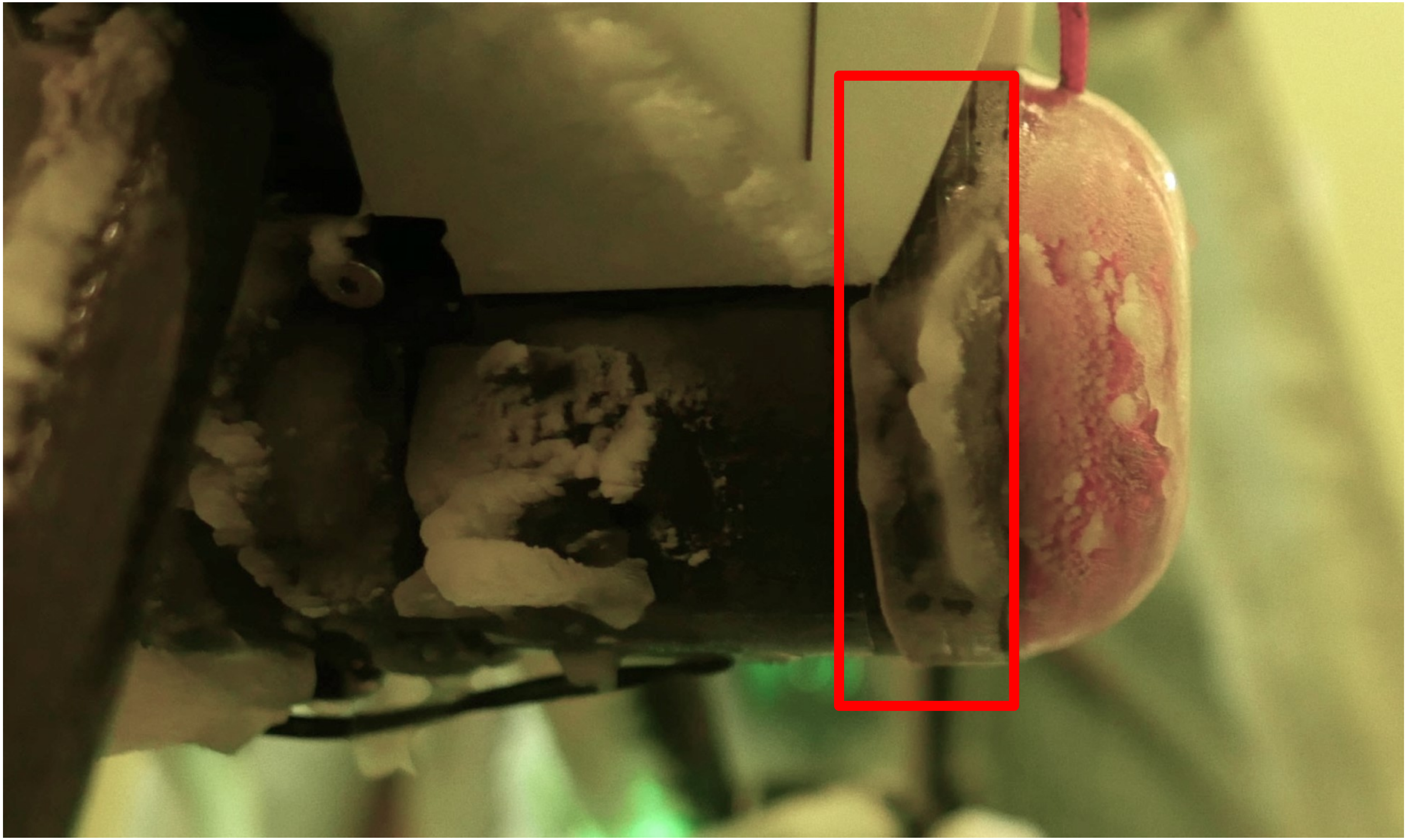
Meteodrone body ice after 4 hours



Ice-free parachute cap at -10°C (Heating works)



Iced parachute cap at -20°C



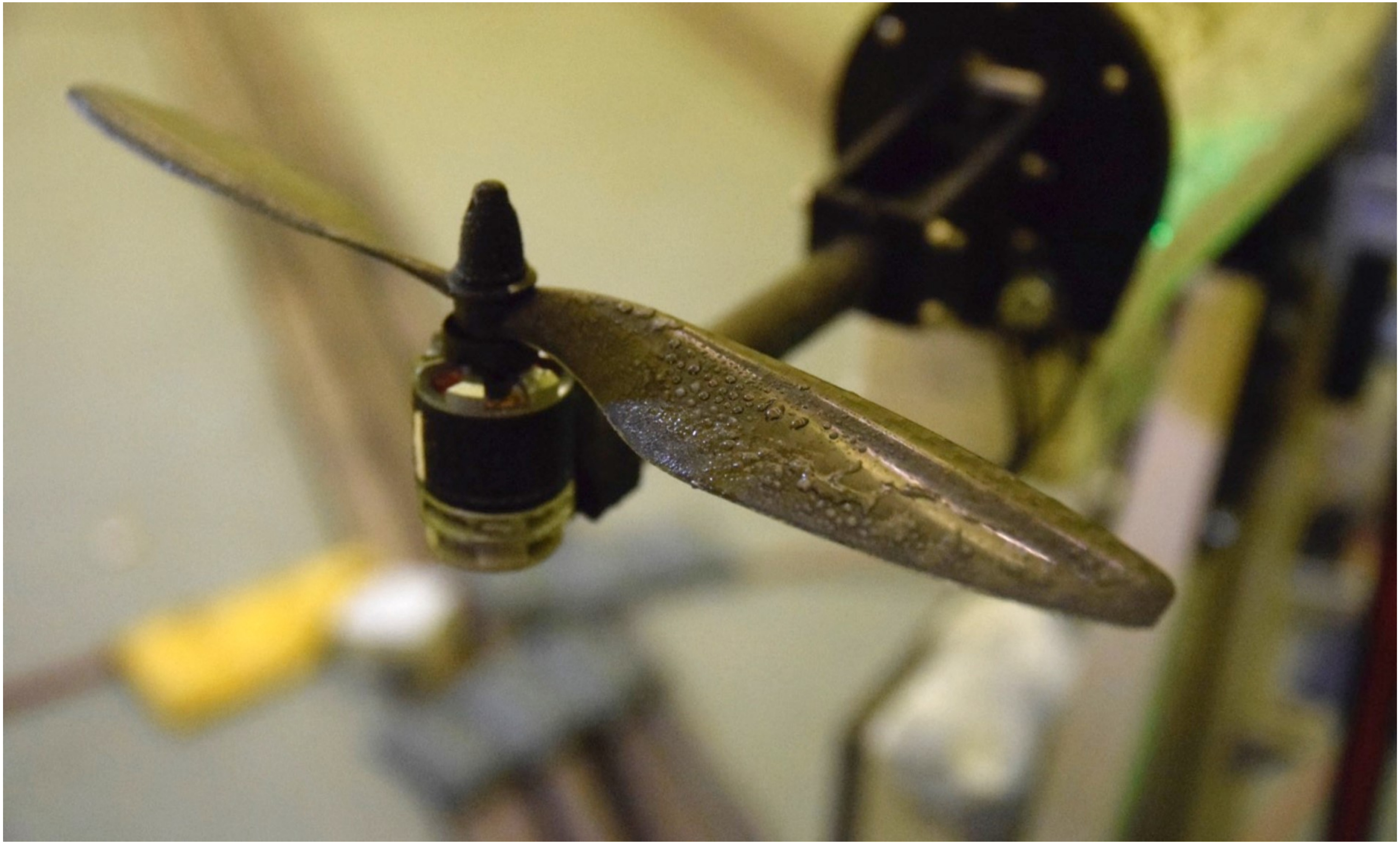
Anti-Icing Strategy Overview

- The experiences from the VCWT showed that Icing occurs fast and strong
- It is mandatory to implement some of the following strategies:

Avoid Icing conditions (do not start or emergency descent)	Avoid or delay ice accumulations	Remove ice accumulations in-flight
• Recognize Icing conditions from meteorological forecasts and measurements • Detection of beginning ice from RPM and Current	• Coating of the UAV‘s body and the propellers • Heating • Atomizing Anti-Icing-agents during flight	• Heating • Atomizing de-Icing-agents during flight • Vibrations to shake off ice • Dilatation to break away ice

Example Ice Amount 0 – No ice

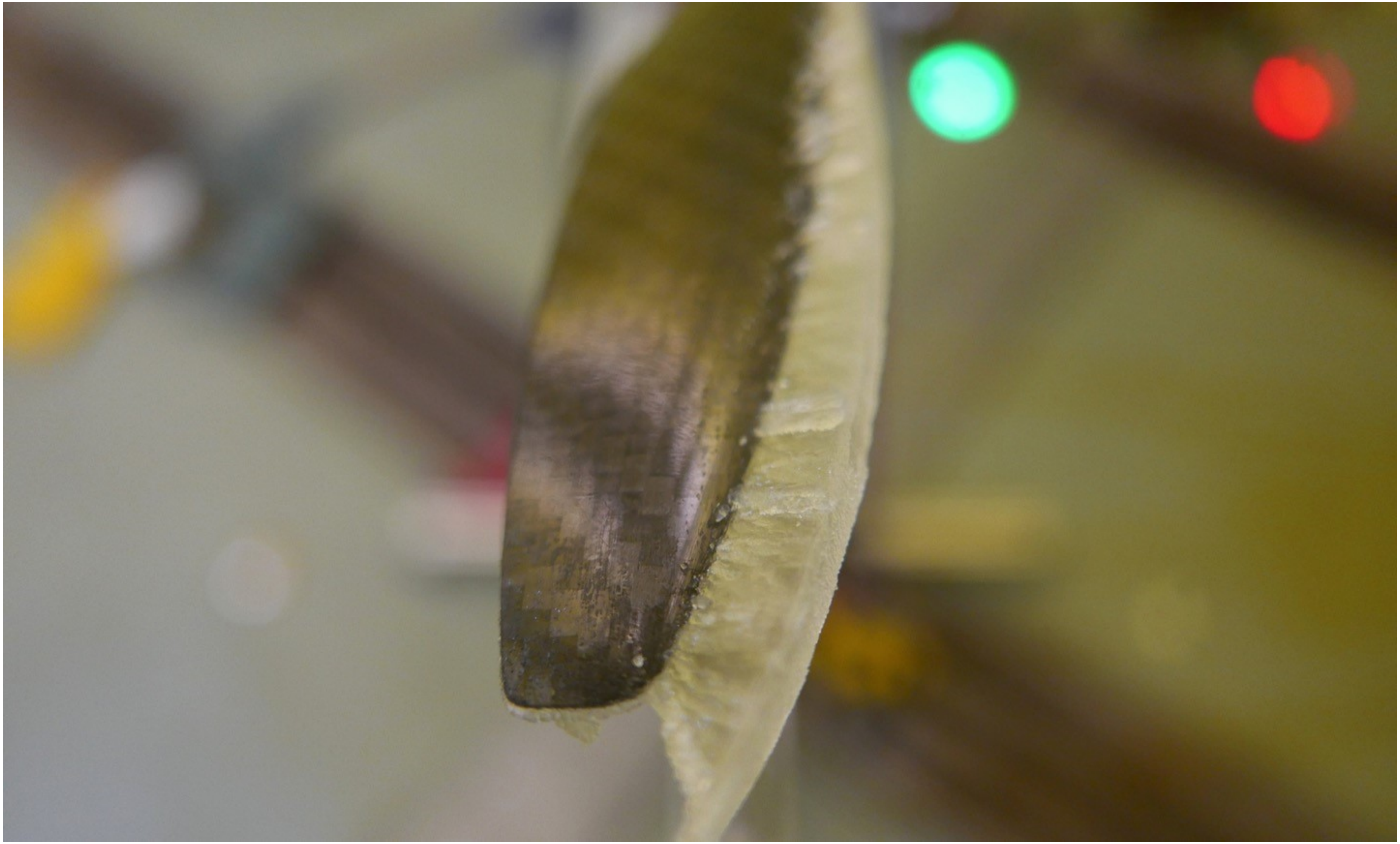
Example Ice Amount 1 – Merely Visible ice



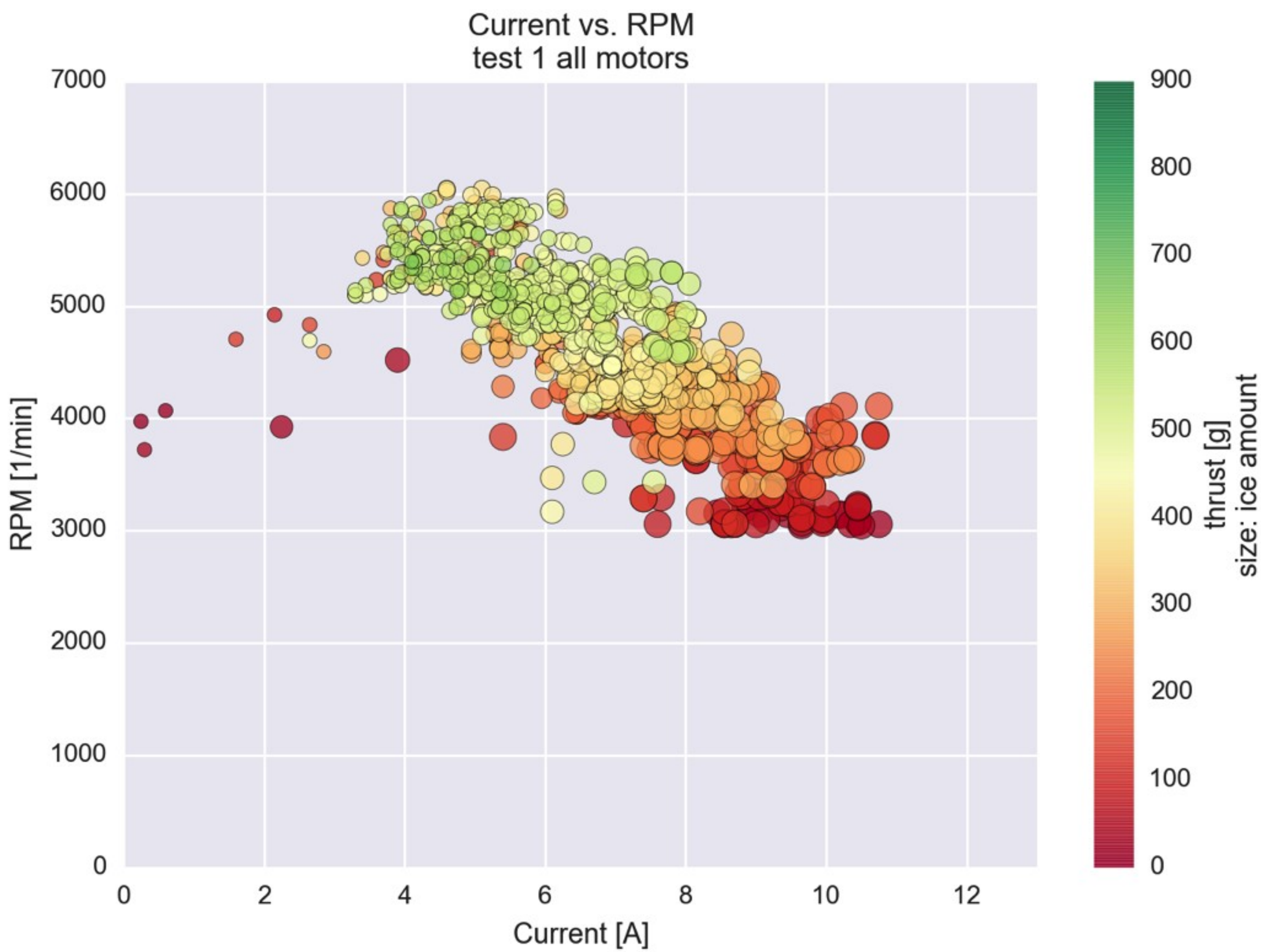
Example Ice Amount 2 – Little ice (max. 2mm)

Example Ice Amount 3 – Much ice (max. 4mm)

Example Ice Amount 4 – Extreme ice (> 4mm)

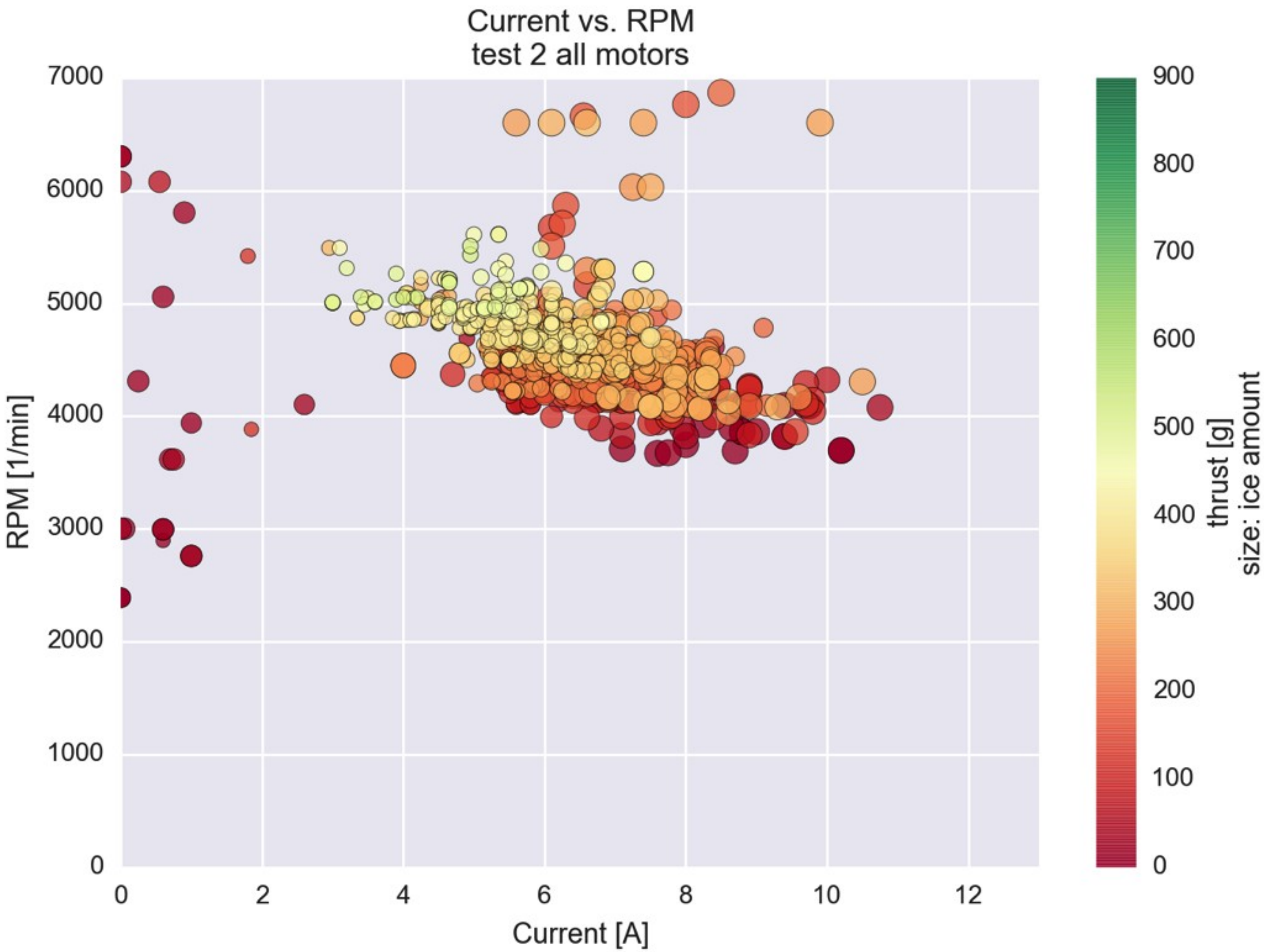


Detailed Result Charts



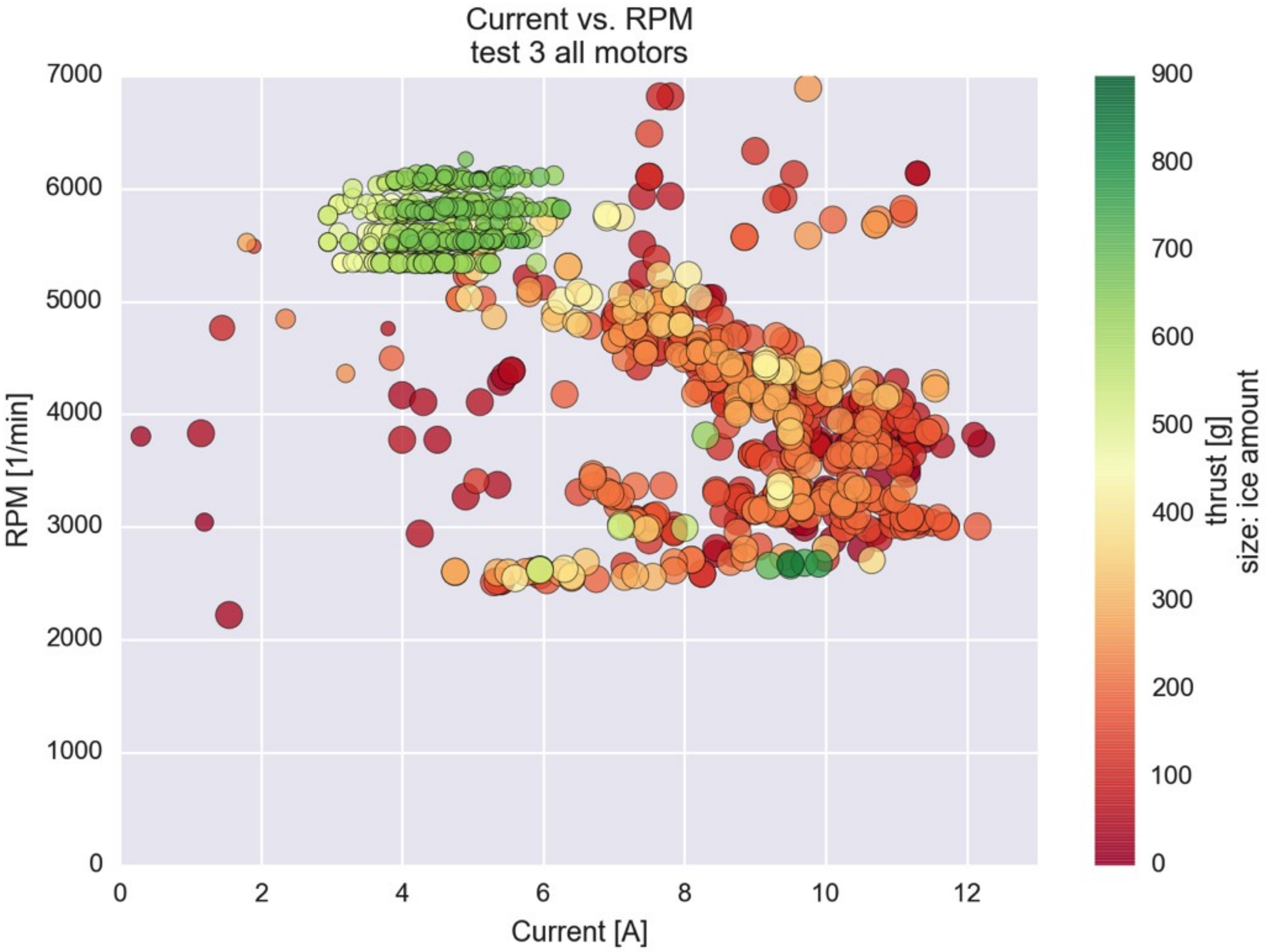
No.	Start	End	Temperature	LWC	MVD	Condition
1	11:58	12:19	-2 °C	0.6 g/m^3	20 µm	Stratiform Cloud

Detailed Result Charts



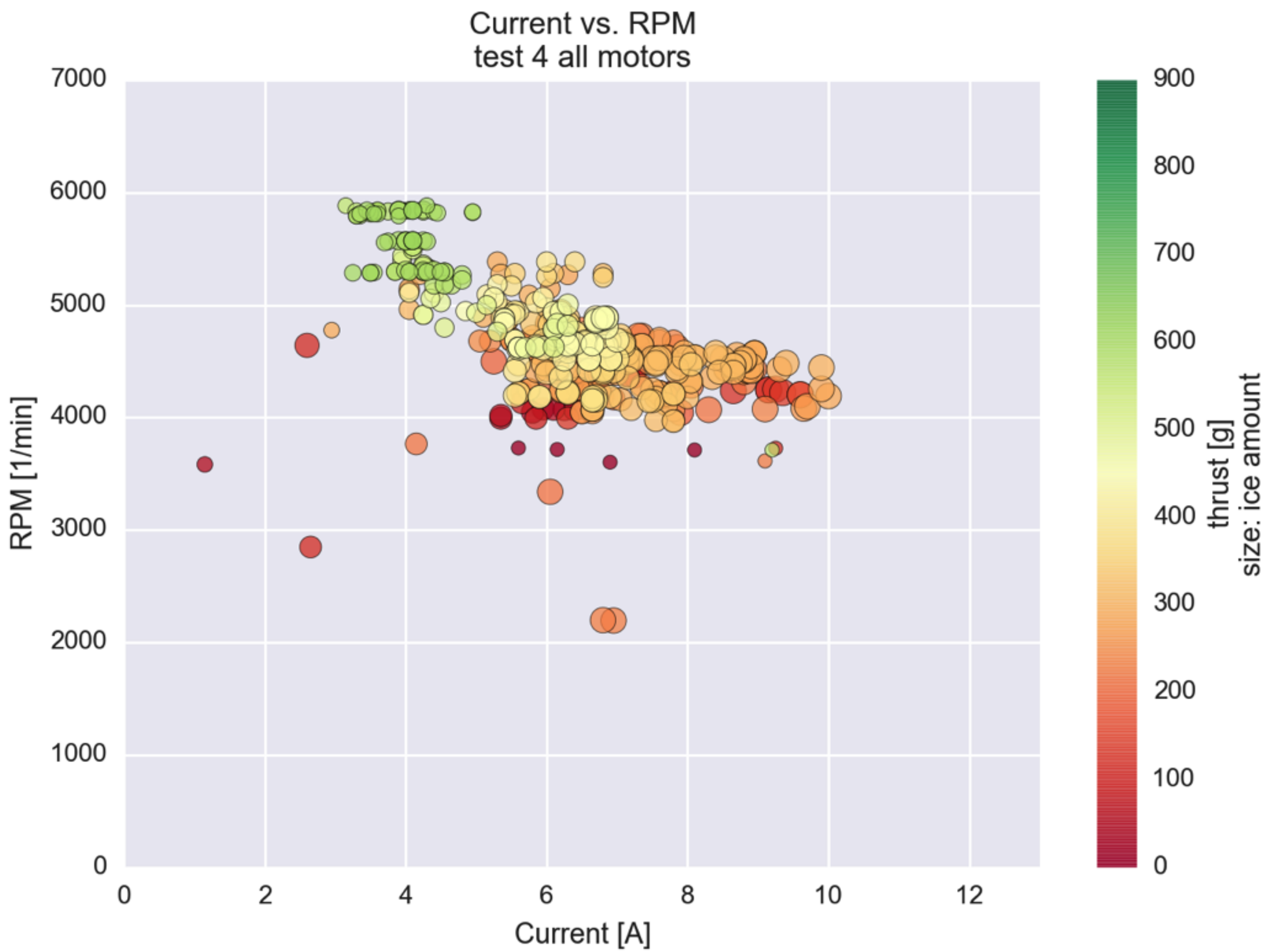
No.	Start	End	Temperature	LWC	MVD	Condition
2	13:12	13:31	-5 °C	0.5 g/m³	20 µm	Stratiform Cloud

Detailed Result Charts



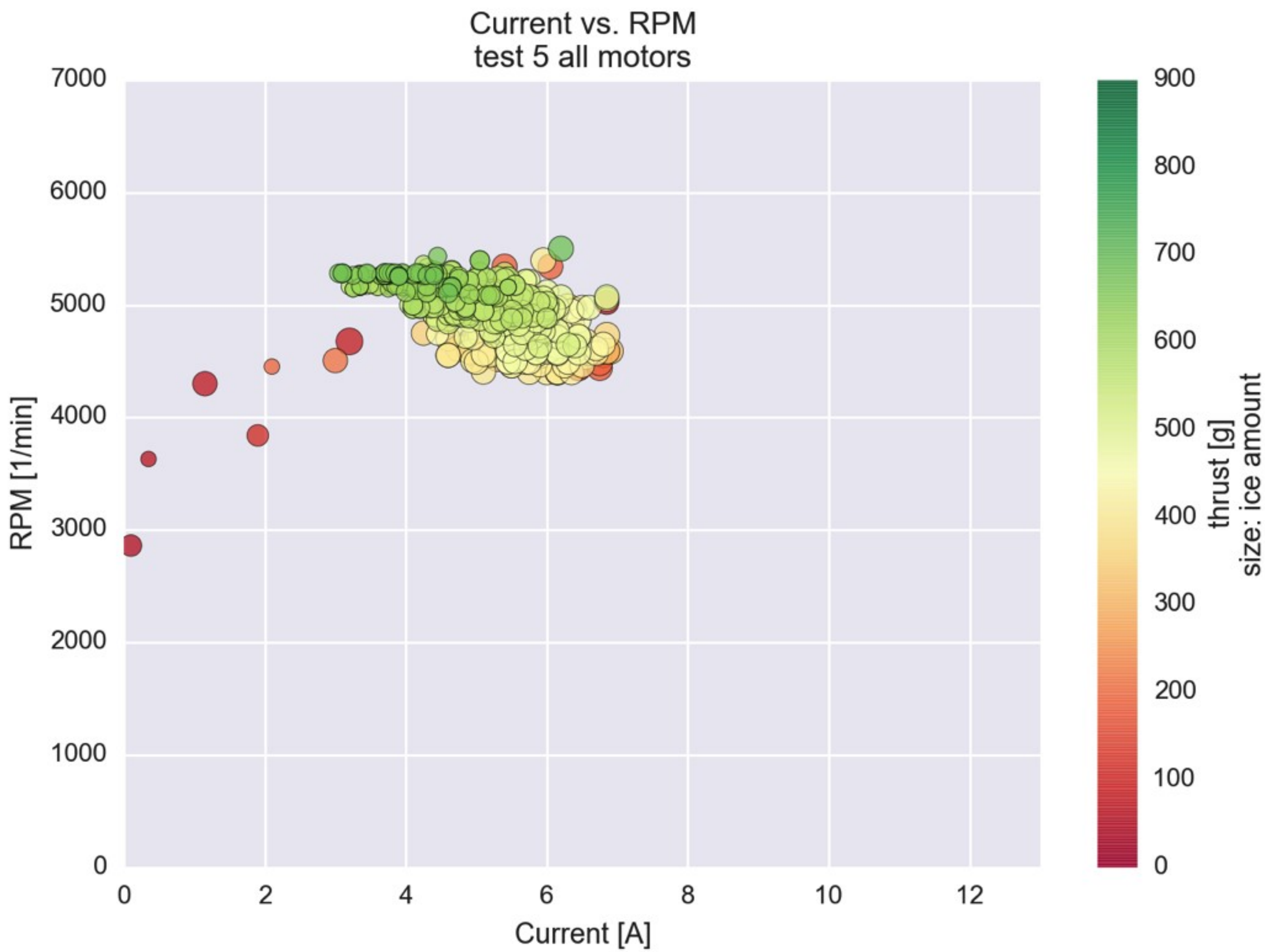
No.	Start	End	Temperature	LWC	MVD	Condition
3	13:45	14:19	-5 °C	1.25 g/m^3	30 µm	Cumuliform Cloud

Detailed Result Charts



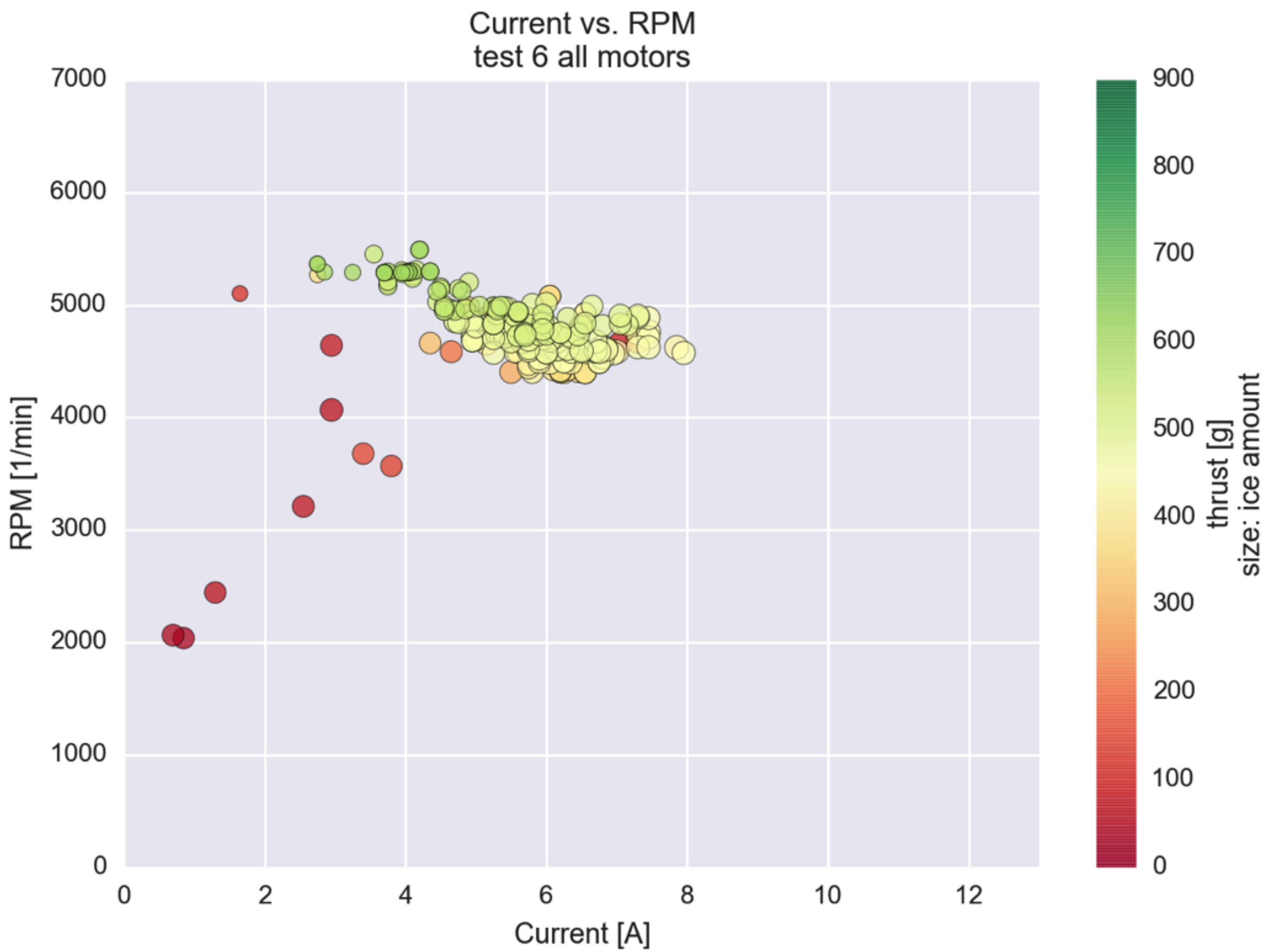
No.	Start	End	Temperature	LWC	MVD	Condition
4	15:57	16:08	-10 °C	1.4 g/m^3	25 µm	Cumuliform Cloud

Detailed Result Charts



No.	Start	End	Temperature	LWC	MVD	Condition
5	17:10	17:26	-20 °C	0.7 g/m^3	30 µm	Cumuliform Cloud

Detailed Result Charts



No.	Start	End	Temperature	LWC	MVD	Condition
6	18:18	18:29	-10 °C	0.8 g/m^3	32.5 µm	Cumuliform Cloud

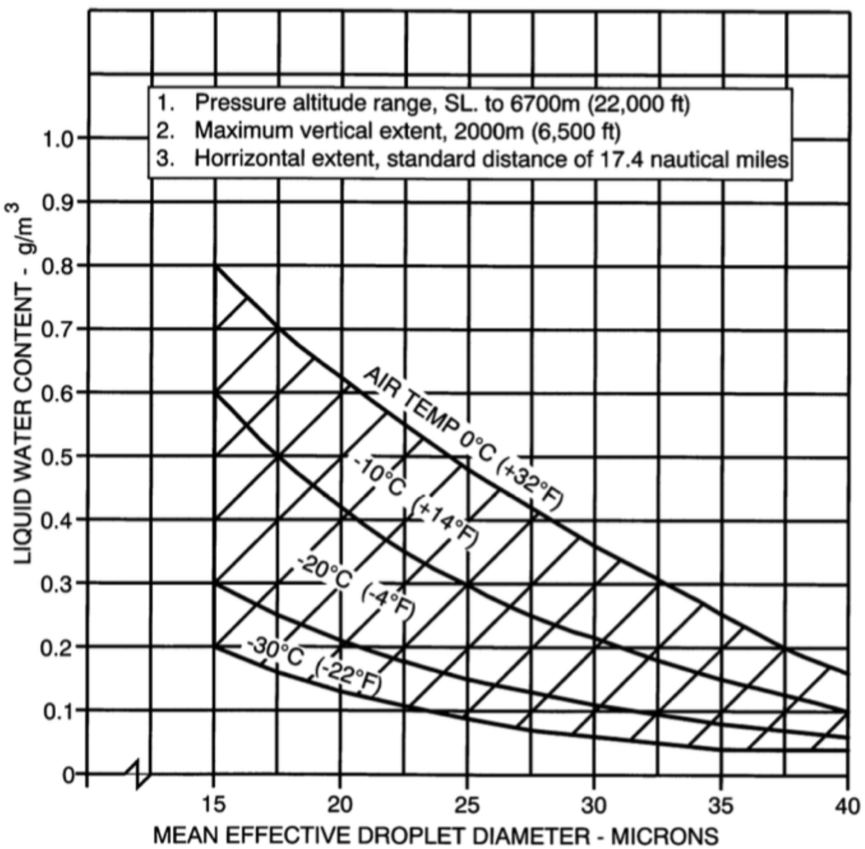


FIGURE 1

CONTINUOUS MAXIMUM (STRATIFORM CLOUDS)
ATMOSPHERIC ICING CONDITIONS
LIQUID WATER CONTENT VS MEAN EFFECTIVE DROP DIAMETER

Source of data – NACA TN No. 1855, Class III –M, Continuous Maximum.

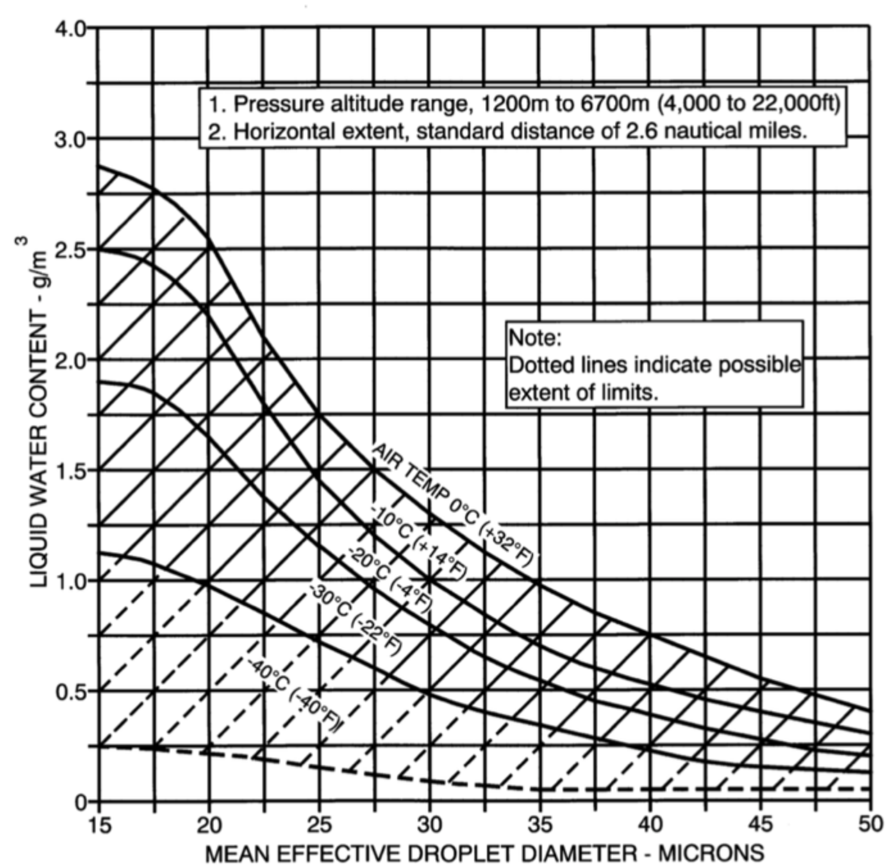
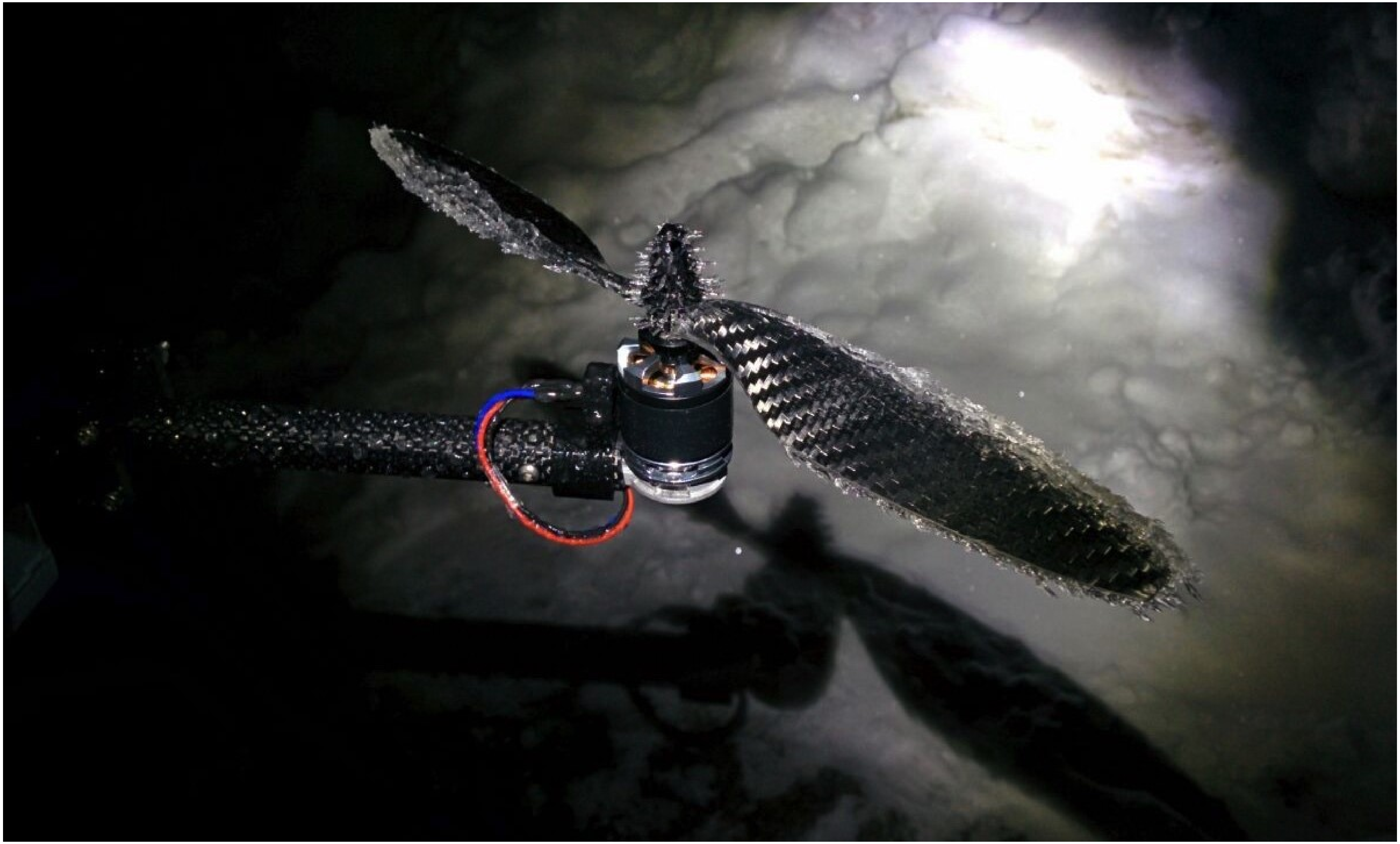


FIGURE 4

INTERMITTENT MAXIMUM (CUMULIFORM CLOUDS)
ATMOSPHERIC ICING CONDITIONS
LIQUID WATER CONTENT VS MEAN EFFECTIVE DROP DIAMETER

Source of data – NACA TN No. 1855, Class II – M, Intermittent Maximum

More Impressions



More Impressions

More Impressions

More Impressions

More Impressions

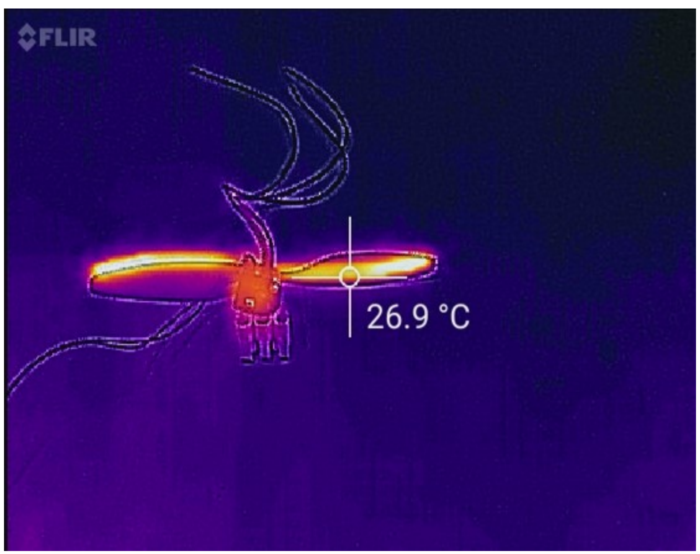
Heating of the propeller

- How to get electrical power into the propeller?
  - Conduction on rotating axis with a hollow shaft and brushes.
  - Development of an appropriate slip ring.
    - Problem: Normal slip rings cannot manage the high drive of the Meteodrone. → strong erosion
- How to heat the propeller in a uniformly distributed way?
  - Pullheim experiment
    - Two single-wire circles
  - More robust system is needed.
    - Solution: flexible foil

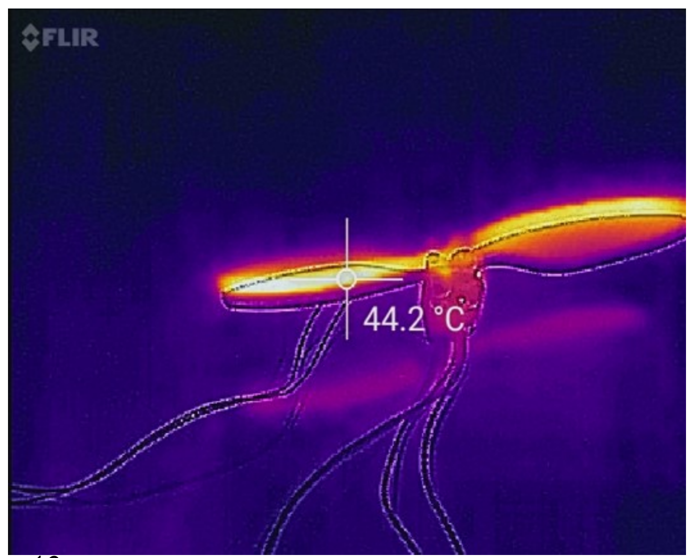
IR Images from propeller heating*

2 sec.

6 sec.



4 sec.



10 sec.

Experiment with single wire:

Distinct heating of the propeller was already achieved after a few seconds

*) *Not rotating in these images.*

Conclusions 1/2

- **Icing poses a serious threat for UAVs**
  - Reduced thrust of the propellers
  - Increasing weight of the UAV‘s body
- **Icing occurs fast and strong after entering Icing conditions**
  - Icing starts not later than 100 seconds (in VCWT)
  - Flying is not possible anymore in the conditions after 300 seconds (the propellers cannot produce enough thrust anymore) (in VCWT)
- **Only small differences between varying weather conditions**
  - Faster Icing at higher (“warmer“) but still negative temperatures
  - Faster Icing in cumuliform clouds than in stratiform clouds
- **Icing can be detected observing RPM and current**
  - Start of Icing can be recognized by an increasing power input during the flight
- **The Meteodrone‘s electronic does withstand the harsh Icing conditions**

Conclusions 2/2

- **It‘s necessary to prevent the Icing before it starts**
- **Different Anti-Icing methods were tested**
  - Liquid Anti-Icing agents are not reliable
  - Vibration did not work sufficiently as an Anti-Icing method
- **Heating of the propellers is the solution**
  - Conduction on rotating axis with a hollow shaft and brushes.
  - Flexible foil: Uniformly distributed heating of the propeller during different experiments

Outlook

- **Use this propeller heating method for the operational flights during the winter season 2017/2018**
- **Continue the development and improvement of this system and work also on new Anti-Icing methods**
  - E.g. work with different material (nanotechnology)