

ICE GENESIS

Creating the next generation of 3D simulation means for icing

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Selection of most suitable instrumentation for IWT/T calibration

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DEC	Websites, patents filing, press & media actions, videos, etc.	
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Deliverable Contributors

Authors

Organisation	Authors' name
CNRS	SCHWARZENBOECK Alfons

Contributors

Organisation	Contributors' name
CNRS	FEBVRE Guy, DUPUY Régis, GOURBEYRE Christophe, COUTRIS Pierre
CU	PERVIER Hugo
TSAGI	MILLER Alexey
CAO	PETROW Victor
AIH	DEZITTER Fabien
NRC	FULEKI Dan
EPFL	BERNE Alexis
RTA	FERSCHITZ Hermann, BREITFUSS Wolfgang
DLR	VOIGT Christiane, HELLER Romy

Internal Reviewers

Organisation	Internal Reviewers' name
DLR	Romy HELLER
RAINBOW VISION	Sawitree SAENKAEW, Gérard GREHAN

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1 Glossary

2D-P	2D Precipitation Probe
2D-S	2D Stereo Probe
2DVD	2D Video Disdrometer
A/C	Aircraft
AIH	Airbus Helicopters
BCP	Backscatter Cloud Probe
BWV	Background Water Vapour
CAS-DPOL	Cloud Aerosol Spectrometer with Depolarization
CAPS	Cloud Aerosol Particle Spectrometer
CCD	Charge-Coupled Device
CDP	Cloud Droplet Probe
CIP	Cloud Imaging Probe
CNRS	Centre National de Recherche Scientifique
CPI	Cloud Particle Imager
CSI	Cloud Spectrometer and Impactor
CVI	Counterflow Virtual Impactor
CWC	Cloud Water Content
CWT	Climatic Wind Tunnel
MINDEF/DGA	Direction Générale de l'Armement
DMT	Droplet Measurement Technology
DLR	Deutsches Zentrum für Luft- und Raumfahrt
EPFL	Ecole Polytechnique Fédérale de Lausanne
F/T	Flight Test
FCDP	Fast Cloud Droplet Probe
H160	Airbus Helicopters H160 (formerly X4)
HAIC	High Altitude Ice Crystals
HSI	High Speed Imaging
HVPS	High Volume Probe Spectrometer
IAG	Industrie Automatisierungsgesellschaft mbH

IKP	Isokinetic Evaporator Probe
IWC	Ice Water Content
IWT	Icing Wind Tunnel
LaMP	Laboratoire de Météorologie Physique
LWC	Liquid Water Content
MASC	Multi Angle Snowflake Camera
MMD	Median Mass Diameter
MMDmax	Median Mass Diameter Dmax
MPS	Meteorological Particle Spectrometer
NRC	National Research Council Canada
OAP	Optical Array Probe
PIP	Precipitation Imaging Probe
PSD	Particle Size Distribution
PIV	Particle Imaging Velocimetry
RICE	Rosemount Ice Detector
RTA	Rail Tech Arsenal
SAFIRE	Service des Avions Français Instrumentés pour la Recherche en Environnement
SVI	Snowflake Video Imager
TAS	True Airspeed
TRL	Technology Readiness
TSAGI	Central Aerohydrodynamic Institute named after N.E. Zhukovsky
TDL	Tunable Diode Laser
TWC	Total Water Content
W/T	Wind tunnel

2 Executive Summary

Within the European ICE-GENESIS project, the deliverable D5.3 is closely related to Task 5.2 of work package WP5. This task is dedicated to instrumentation assessment and selection for IWT calibration, in particular:

- a) State of the art and discussion of the specification of the needs for IWT snow measurements
- b) Review of the available instrumentation for artificial snow particle properties and bulk snow water content measurements (ground-based instrumentation, particularly adapted for use in wind tunnels), and also snow cloud homogeneity (e.g. laser sheet).
- c) Selection of most suitable calibrated instrumentation for IWT calibration.

In a first step WP5 supports developing snow test capabilities and/or upscaling of IAG snow fall technology by assessing snow representativeness of artificially produced innovative natural like snow in IAG Climatic Chamber. This first step will not yet take into account potential fragmentation effects of ice particles once injected in high speed wind tunnels. For assessing the representativeness of artificially produced ice particles, the deployment of a multi-angle snowflake camera (MASC) has been suggested in the ICE GENESIS proposal. The MASC instrument is a recently developed sophisticated multi angle imaging instrument with in total 3 greyscale camera systems. In past few years first datasets of natural ice particles were gathered with the MASC instrument in the scientific community (also EPFL partner of the ICE GENESIS project). Additional MASC data (natural and artificial ice particles: by EPFL and CNRS partners) will be gathered during ICE-GENESIS in order to compare natural ice with artificially generated ice particles. Unfortunately, the MASC has been designed for vertically falling snow, but is not adapted (and therefore cannot be used) for use in wind tunnels with ice particle velocities far beyond fall velocities. Also we will not discuss in detail the selection of the MASC instrument for this preliminary study of falling snow (see Task 5.3 of DoW).

In a second step, RTA will upscale/integrate the IAG snow generation system in their Climatic Wind Tunnel and WP5 will provide support to assess number PSD and TWC with adequate instrumentation. Mainly in this context the Task 5.2 with D5.3 is dedicated assessing and selecting IWT snow instrumentation for final IWT calibration.

Since also TsAGI and NRC work on snow test capability developments within WP7, the snow instrumentation assessment and selection for PSD, IWC, and artificial snow cloud homogeneity, concurrently benefits to those two international partners.

The work performed in order to produce the deliverable D5.3 is entirely related to the choice of most suitable instrumentation for snow microphysics research on IWT research facilities, which means different IWT facilities (of RTA, TsAGI, and NRC) have to take into account installation possibilities and constraints of homogeneous sampling area (has to be known).

The main measurement objectives that we have to meet with the selected instrumental payload for IWT are listed below. These objectives are also taking into account ongoing discussions within the Technostream Snow work-packages (WP5, WP7, WP10):

1. Guarantee measurement reliability of large ice particle properties (size dependent crystal number and mass) up to 10 mm (and beyond if possible): Use of imaging instruments like PIP, HVPS
2. Ensure the snow IWC measurement capabilities of bulk snow water content containing large snow crystals: Use of bulk CWC instruments like IKP, NEVZOROV and/or ROBUST probes (to be characterized), CVI evaporator probe
3. Allow a reasonably good morphological analysis and in best case retrieve an indicator for dry and wet snow of the snow particles (snow crystals, snowflakes): Use of high resolution grey scale imager as CPI or HSI, others...
4. Ensure cloud homogeneity in IWT measurement section (e.g. with laser sheet technology, grid mesh, etc...)

3 Specification of W/T measurement needs for snow & review of available instrumentation for artificial snow measurements (PSD, bulk, snow cloud homogeneity in W/T), and final selection

3.1 Introduction: setting new standards for snow certification

The deliverable D5.3 is inserted in close relation to the artificial snow generation in IWT facilities in order to calibrate IWT for artificial snow properties. After developing snow test capabilities (work within WP7) by RTA, TSAGI, and NRC, with acceptable snow quality / capacity (storing and transport issues), WP7 will fine-tune the distribution/setting of the parameters to influence the size of the snowflakes, the quality and the quantity in a reproducible way as well as bringing it into the air stream of the IWT.

An important means of verification of the **artificial snow properties** present in operating IWC facilities will be added by WP5 with the primary role to demonstrate with adequate snow instrumentation that **IWT artificial snow properties are fulfilling snow microphysical specifications similar as those for natural snow** (snow particles sizes, snow WC, dry/wet snow aspect/properties, etc...).

Therefore, it is evident that deliverables D5.1 (... assessment and selection of most suitable snow instrumentation for F/T in natural snow conditions...) and D5.3 (... assessment and selection of most suitable snow instrumentation for IWT/T in artificial snow conditions) are closely related. This is why the introduction of setting new standards for snow certification already presented in deliverable D5.1 is partly repeated here, in order to make the D5.3 a somewhat independent document.

Snow crystals (water vapour and riming growth regimes) and snowflakes (aggregates of many single ice crystals) together are denoted snow particles.

Natural ice crystals can form in mixed-phase clouds, where nucleated ice crystals grow via water vapour deposition at the expense of evaporating supercooled liquid water droplets once the environment becomes sub-saturated with respect to water. This so called Bergeron-Findeisen effect corresponds to a net transport of water vapour from the liquid to the ice phase; in this phase transition, water vapour transforms directly into solid (Libbrecht & Kenneth, 2007). Also collision processes between liquid droplets and solid ice particles lead to growth of snow particles via riming. Finally, aggregation which is crystal to crystal collision may be the major growth mode leading to formation of snowflakes (Gultepe 2017). Efficient aggregation mostly appears at air temperatures near 0°C and is predominantly affected by the air temperature and the shape of the aggregating ice crystals. Columns and needles aggregate into rather small flakes, while aggregates of dendritic crystals tend to become large. Snowflake diameters (Pruppacher & Klett, 2010) are mainly between 1 and 5 mm, ranging up to 15 mm. Snowflake density (Rasmussen et al., 1999) varies as a function of snow particle diameter, ranging from 0.005 to 0.2 g cm⁻³, and is as a first approximation inversely proportional to snowflake diameter, i.e. the larger the flakes, the lower the density. This constant of proportionality between snowflake diameter and the density of the snowflake is almost four times larger for wet than for dry snowflakes.

The shape of the ice crystals depends on the temperature and humidity of the clouds, with a large variety of resulting crystal shapes. The “Snow Crystal Morphology Diagram” from Furukawa and Wettäuffer (2007) classifies the shapes into (1) plates and dendrites (from 0 to -3 °C), (2) needles, columns and prisms (from -3 to -10 °C), (3) solid, thin, and sectorial plates and dendrites (from -10 to -22 °C), and finally (4) solid plates and columns (below -22 °C), according to cloud temperature and water vapour content. The diagram solely takes into account the growth of ice particles by water vapour diffusion. The two other modes (riming, aggregation) related to particle collision (crystal-droplet, crystal-crystal) are not considered in that diagram, which therefore is of reduced value, when discussing the variety of natural ice and snow particles.

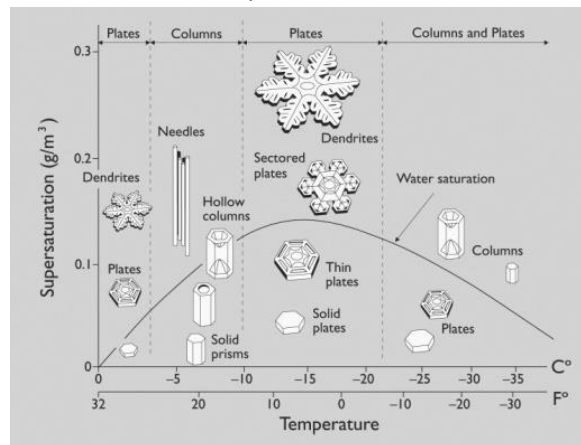


Figure 1 - Snow Crystal Morphology Diagram

The interaction of existing three modes of crystal growth, which are pure water vapour deposition and in addition aggregation and riming growth modes usually generates highly irregular shaped larger ice crystals. A selection of typical snow crystal shapes is presented in Figure 2 from Praz et al (2017). Their study of snow particle properties from ground based MASC (Garrett et al 2012) data, resulted in 6 different snow particle classes, as there are small particles, columnar particles, planar crystals (plates, dendrites), combination of columns and plates, aggregates, and graupel.

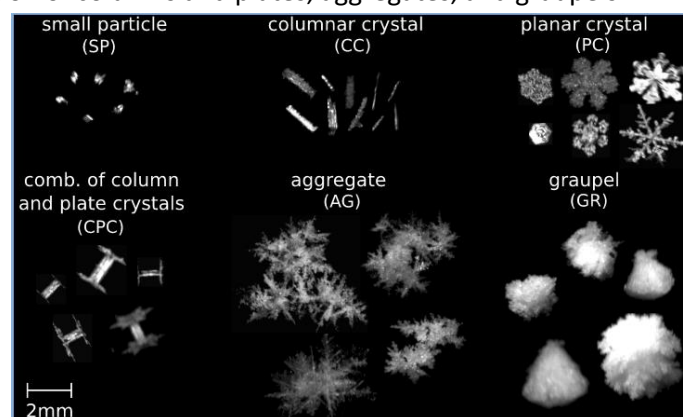


Figure 2 – Snow particle shapes from MASC data according to Praz et al (2017)

The production mechanisms of artificial ice are little comparable to above growth processes in natural snow particle formation, except some approaches to produce crystals from pure vapour

diffusional growth and the fact that mixing of ice crystals with supercooled water drops during artificial ice generation should lead, to some extent, to artificial riming.

Main types of the artificial snow production mechanisms are:

- Grinding technique: Mechanical shaving of ice blocks / using a grinding mill: The grinding mechanical process produces randomly shaped ice particles by typically feeding frozen ice blocks into rotating circular saw blades. Ice blocks feed rate and speed of rotating cutters allow varying the size of the crystals
- Freeze out technique: To initialize freezing of droplets, those are cooled down below freezing temperature for pure water, the minimum super-cooling limit temperature is around -40°C , depending on drop size and water purity the freezing temperature can be between -40°C and almost 0°C . The ice crystals are close to spherical and of rather high density, therefore don't compare well with natural ice crystals.
- Diffusional growth in cloud chamber: Once ice crystals nucleated in this chamber, cloud chambers allow to simulate the growth by diffusion and aggregation by setting up an environment close to atmospheric conditions. Unfortunately, cloud chambers do not allow to produce artificial ice crystals at a rate required for icing wind tunnel investigations. Therefore wind tunnel facilities have to set up means of ice storage, subsequently feeding the IWT during test runs of limited time periods. According to the temperature dependence (Figure 1), column type artificial crystals are observed at -5°C , while plate type crystals are created at -15°C .
- A newer concept of ice particle production is currently set up at IAG. Thereby, a very cold, slowly rotating cylinder experiences riming features from impacting smaller cloud droplets. The continuously riming surface is shaved from the cylinder with a cutting device and also additional cloud water is locally sprayed into the cooling chamber with falling ice before sampling at the ground. An additional fan serves to direct and/or disperse the produced ice cloud before sampling at the ground. This generation technique still needs to be implemented in a W/T.

Aggregation growth of artificial ice in wind tunnel facilities can hardly be achieved/implemented (due to sedimentation and lack of vertical motion possibilities in IWT), whereas aggregation plays the major role in growth of natural snow particles.

These important obvious discrepancies in ice formation processes between natural snow formation and artificial snow production is limiting the comparison of artificial with natural snow to the exclusive comparison of respective particle properties, where artificial snow particle properties (used for studying accretion phenomenon in IWT facilities) have to be evaluated with respect to what is observed for natural snow (leading to accretion during flights in snow conditions). The work performed in IWT facility calibration, primarily has to quantify the microphysical properties (3D size, crystal mass, mass-size relation, fractal dimension, differentiation dry and wet snow, number and mass size distributions) of individual artificial snow crystals as well as of entire artificial snow crystal populations (per volume of air) in order to validate the artificial snow for the calibration of the IWT capabilities.

3.2 Specification (snow microphysics) of snow measurements for wind tunnel calibration

Due to the large range of snow crystal sizes, often several measurement instruments have to be combined to cover the complete size range of snow particles (instruments with overlapping size ranges). No single instrument is available covering the wide range snow crystal and snow-flake sizes, in order to retrieve entire PSD, MMD, and IWC.

In-situ measurements of snow cloud microphysical parameters in the crucial temperature range between -10°C and +2°C should retrieve subsequent artificial snow cloud information in close relation to expected natural snow properties:

- Number concentration of snow cloud particles (snow crystals/flakes), whereby the maximum value will not exceed 1 crystal per liter.
- Size of the snow particles in the range from several tens/hundreds of μm to 4-5 cm (e.g. Lawson et al 1993; Lawson et al 1998.)
- The resulting snow mass concentration or total water content (TWC) that may reach up to 1 g/m³ (a maximum value of for snow water content is therefore fixed at twice this value: 2 g/m³)
- Discrimination of liquid cloud particles 'in case of complementary injection of supercooled water droplets,...') from ice phase, i.e. the capability to distinguish LWC and IWC (TWC=LWC+IWC)
- Snow crystal/flake habit information (geometrical aspect, growth mode, ...) impacting the hydrometeor density and fall speed
- Retrieval of the ice density information of individual snow particles and/or within specific size classes
- If possible, melting ratio of snow particles or at least separation between dry and (partially) wet snow.

Also the overall thermodynamic and dynamic context has to be monitored:

- temperature,
- relative humidity,
- static pressure,
- IWT wind speed

Another separate constraint in W/T studies and request within ICE GENESIS is snow cloud homogeneity. Thereby, the W/T operator has to ensure homogeneity of artificial snow properties throughout a defined sampling section of the tunnel.

The relative uncertainty in the quantification of defined parameters for cloud microphysical properties shall be targeted to not exceed 20%. Data (microphysical properties, meteorological parameters, IWT parameters) shall be time stamped with synchronized time base. The instrument location for snow crystals/flakes shall be outside the boundary layer of the wind tunnel and within the defined homogeneous sampling section to be used for W/T studies. The design of the probes shall minimize the effects of the instrumentation on the measured values; e.g. avoid shattering of crystals on probe tips. Probes have to ensure de-icing to be protected against ice accretion. The instrumentation shall communicate data in quasi real time and status to operators in order to determine if the instrumentation is properly working for the objectives of the W/T test.

3.3 State of the art airborne microphysical instruments particularly suited for snow particle measurements (PSD, bulk, W/T homogeneity)

Microphysical data of snow crystal properties rely primarily on instrumental means used for studying these properties, e.g. data from measurements performed within the frame of the European HAIC project (Dezitter 2013, Leroy et al., 2016 & 2017). Particularly, precipitation-sized particles can be measured with binary OAP probes as there are the cloud imaging probe CIP, the stereoscopic 2D-S, the precipitation imaging probe PIP, and the high volume particle sampler HVPS. Note that few greyscale OAP probes exist, however limited to 3 greyscale levels. Further CCD camera based imaging probes exist, as there are the high resolution cloud particle imager CPI or the high speed imager HSI, both being 256 greyscale imagers, which should allow to access to morphological and particularly surface properties (as for instance qualitative separation into dry and wet snow). All those imaging probes have their specific image resolution (e.g. pixel dimension from 2.3 μm for the high resolution imager CPI to 200 μm for the elder state of the art 2D-P imaging probe) and a maximum measurable particle size, without particle truncation, proper to each instrument (e.g. from 0.96 mm (64 photodiodes of CIP_15 μm imager) to 19.2 mm (128 photodiodes with 150 μm pixel size of the HVPS)). We have to keep in mind that those state of the art imaging probes allow retrieving geometric information of the 2D image (diameter, 2D surface/area, 2D perimeter, 2D fractal dimension, 2D area ratio, 2D aspect ratio, 2D roundness,...), which represents one single projection of the oriented 3D crystal as it passes through the imaging laser beam. This means that we further have to work on retrieving 3D information or parametrizing 2D-3D analogies (as for example mass, volume, 3D surface) in order to better communicate with the modelling community (WP10), if needed.

Bulk IWC measurements in snow conditions are challenging and rather often of somewhat limited reliability. This is particularly true for hot wire type TWC devices lacking a well-defined collection efficiency, which is difficult to parametrize as a function of particle size, air density, aircraft or wind tunnel TAS, etc.... A promising technology has been designed for the HAIC project and consists of the Isokinetic Evaporator Probe IKP (Strapp, 2016), which can be operated in wind tunnels but also on research aircraft. At Cranfield University a ground based IKP has been designed for use in wind tunnels (see HAIC project). Both IKP versions require the precise knowledge of the vapour mixing ratio (background water vapour BWV) and respective uncertainty. Aircraft use of the IKP technology is of course more difficult due to spatiotemporal variations in BWV as compared to rather constant BWV in W/T test runs. An alternative solution that could be useful in ICE GENESIS is the CVI/CSI technology (at least for ATR-42 flight tests) and related hygrometric measurement of melted / evaporated snow ice water content with TDL and other techniques (dew-point, Lyman absorption). However, the CVI technology may have difficulties to process snow water contents beyond 1 g/m³.

Another significant challenge within ICE GENESIS will be to reconcile both ground based and airborne instrumentation whenever the two instrumental setups may differ, such that datasets from A/C and IWT studies are comparable.

Finally, snow cloud homogeneity measurements in W/T have to ensure cloud uniformity. Cloud uniformity tests may be conducted by installing a mesh inside the cross-section that would accrete ice

and thickness has to be measured. A uniform cloud should be defined when during ice accretion experiments, the variation in thickness of ice accreted ice spatially remains within ± 20 percent of the tunnel centerline ice accretion thickness [SAE ARP 5905]. Since the snow water content should be in a first order proportional to the accreted ice thickness, an ice thickness measurement within ± 20 percent of the thickness at the centerline of the tunnel should define what we may denote then a uniform cloud.

3.4 Recommendations for IWT snow microphysics instrumentation (available in the scientific community) thereby meeting above specifications

This paragraph provides recommendations in order to define the most adequate instrumental payload for IWT snow research in order to meet the objectives of the ICE GENESIS project.

1. Need of precipitation particle imaging probes for largest crystal sizes beyond 1-2 mm up to even several tens of mm. This request is motivated by the fact that 80-90% of ice crystal mass (average value) can be found beyond 1 mm, which was the case for recently gathered snow data on an H160 helicopter from Airbus Helicopters (AIH). Three flights had been performed in 2017 where MMD_{max} of about 2000-3000 μm were calculated from cumulative mass distributions. In order to fulfil this size specification, the two precipitation imaging probes PIP and HVPS, available in the ICE GENESIS community, are capable of sizing crystals up to 6.4 mm (PIP 64 photodiodes at 100 μm pixel resolution, twice the resolution of the legacy 2D-P probe) and 19.2 (HVPS 128 photodiodes at 150 μm pixel resolution), respectively. The more the ice particle is at the upper size limit of a corresponding probe, the higher is the probability of truncated images, that need to be reconstructed, however with some uncertainties (in general the retrieved reconstructed image underestimates real size and mass, when image truncation occurs). This is why the availability of the new HVPS and of state of the art PIP probes at LaMP-CNRS and DLR institutes are of major importance.
2. Need of cloud particle imaging probes for intermediate crystal sizes between 50 μm and 1-2 mm, in order not to miss information in that size range, even though not much mass contribution to snow water content is expected in the range below 1 mm. This is why the use of best quantitative array probes such as the 2D-Stereo probe (DLR, CNRS-LaMP) is recommended in order to complement PIP or HVPS OAP probes. Also, there may a potential that snow crystal fragmentation in a wind tunnel may produce non-negligible submillimetric crystal mass that needs to be documented. The 2D-S has a pixel resolution of 10 μm (and 128 photodiodes) as compared to a standard cloud imaging probe CIP (64 photodiodes) of a pixel resolution of 25 μm (CNRS; DGA CAPS containing a greyscale CIP of 25 μm resolution). Another instrument candidate in that field should be the 15 μm resolution greyscale CIP (also 64 photodiodes), the probe is part of another DGA CAPS combination probe). All those probes are considered to be quantitative probes with a large sampling volume (thousands and ten thousands of particle images measured per second), allowing good PSD statistics within short time intervals (1s, 5s).
3. Need of high resolution imaging probes. Recall that combinations of OAP imaging probes are spanning the entire snow particle measurement size range with extremely large sampling volumes for good statistics of snow particle PSD. In contrast, high resolution imaging probes that are based on CCD cameras, have extremely limited sample volumes that do not allow reasonably good particle statistics with high frequency. However, the latter high resolution imaging probes considerably improve the knowledge of cloud particle morphological information (with potential to create a proxy or an indicator of the presence of liquid water in the snow particle, thus distinguishing at least dry and wet snow), as has been presented in Praz et al., (2017) for the MASC multiple camera system. Amongst the high resolution probes two very sophisticated imagers are available within ICE GENESIS as there are the Cloud Particle Imager (CPI) and the High Speed Imager (HSI). Both probes are excellent instruments for morphological analysis of

individual snow particles, but should be considered semi quantitative or even qualitative in terms of cloud particle statistics (PSD, IWC,..., etc)! Whereas the CPI is an available well-established state of the art high resolution imager, the alternative probe is the high speed imaging probe HSI measuring up to 2.5 mm, which will be available soon at CNRS-LaMP. First HSI tests with the new probe are planned for end of 2019 at CNRS-LaMP. Whereas common OAP greyscale probes have maximum 3 greyscale levels, the CPI and HSI have 256 greyscales, which then give much more morphological insights. The most important feature of the 256 levels of greyscale, however, should be the idea of possibly distinguishing dry and wet snow, as has been presented by Praz et al (2017) for the MASC ground-based instrument composed of three separate camera systems. Comparing both high resolution imagers CPI and HSI, an advantage of the HSI over the CPI constitutes the fact that the HSI is an open path probe, whereas the CPI represents a closed path instrument, subject to considerable shattering artefacts as large (snow) particles impinge on the circular inlet of the CPI.

4. Need of bulk IWC measurement devices. The need for implementation of reliable snow water content measurements in W/T applications is extremely challenging. During HAIC project the two probes ROBUST and NEVZOROV (Korolev 1998) have been compared/evaluated with respect to the IKP-2 reference measurement of IWC. Results from these comparisons could be used for snow water content retrievals in W/T applications. The Cranfield University IKP seems to be the first choice for snow measurements in W/T. Whereas background water vapour BWV measurement on A/C is difficult due to unknown spatiotemporal variabilities of the BWV, and thus uncertain, this measurement can be performed with more confidence in W/T applications due to rather constant BWV in time. The Snow CVI could be a backup probe. This instrument has not been foreseen for W/T tests yet. Despite the fact that the CVI technology can be considered a reference instrument for snow WC without even the BWV uncertainty, the instrument is limited to an upper value of 1 g/m³ of WC, which may not be sufficient for various wind tunnel settings. Major drawbacks of the NEVZOROV and ROBUST hot wire technology probes are sampling efficiencies, which have been estimated for smaller ice particles from the HAIC dataset, and are less well known for larger snow particles to be studied and quantified in terms of snow WC in the frame of ICE GENESIS.
5. In case that liquid cloud droplet are injected into the IWT in addition to the snow type particles there is a clear need for phase discrimination of particles (solid/liquid). We suggest to use data from high resolution imaging probes (HSI or CPI), NEVZOROV probe, Rosemount Ice Detector, and/or cloud droplet spectrometer. Retrieval of supercooled LWC and some probe efficiencies (response functions), at least with respect to smaller ice, partly have been evaluated within the HAIC project.
6. Need for artefact minimization during snow particle sampling. Avoidance of possible small ice crystals contamination (and loss of large snow particles) due to ice particle shattering. Reduction of the possible artefacts created by particle breakups (Korolev 1998, 2005) and bouncing off surfaces ahead of the instrumentation sample volume: new 2D-S probe tips, HVPS and PIP open path instruments won't sample smallest debris, HSI also is an open path instrument with anti-shatter tips, CDP anti-shattering tips. A higher risk for snow particle fragmentation exists for the closed path high resolution imager CPI. This would mean that shape recognition and morphological surface analysis is only possible in a qualitative sense. Still there is a potential to classify ice particles / fragments according to the presence of wet or dry snow. In contrast, the bulk snow water content instruments IKP and also the CVI inlet just serve as snow water content devices and break ups are not of a problem, since only the integral mass concentration of

condensed water should be retrieved. In addition, CNRS implemented inter-arrival time analysis for spectrometer and imaging instruments which is the precise arrival time measurements of individual particles performed by data acquisition systems of the majority of probes CDP, 2D-S, CIP, PIP, and HVPS.

7. Unfortunately, no single instrument covers the range from $1\mu\text{m}$ to several tens of mm. A selection of adequate instrumentation will be deployed to cover the range for ice crystal populations.

3.5 Falling snow measurement instruments for preliminary artificial snow analysis (not useable for W/T applications)

Ground based in-situ precipitation measurements focus on hydrometeor characteristics such as fall speed, size, shape, and density. State of the art optical imaging disdrometers can measure fall speed along with projected particle views (for size and shape analysis). Current instruments are the multi-angle snowflake camera (MASC) with tentative reconstruction of 3D hydrometeor shapes and several purely 2D two-dimensional video disdrometer (2DVD; Thurai 2005)), Snowflake Video Imager (SVI; Newman 2009), or the Meteorological Particle Spectrometer (MPS). Unfortunately, those disdrometers were not designed for W/T applications, with respective horizontal wind speeds in research W/T that are a factor of 10-100 higher compared to vertical fall speeds of natural snow particles. This is why optical imaging disdrometers are considered suitable and even excellent instrumental means for characterizing falling snow. However, these disdrometers are of limited (and even of no) use for W/T applications.

We are discussing here solely the usefulness of disdrometer instruments in order to compare natural falling snow with artificially generated snow before feeding the artificial snow into the W/T. Particularly, greyscale imaging probes (CCD cameras) illustrate the usefulness for the request to distinguish wet from dry snow.

More in detail, the multi-angle snowflake camera (MASC) is a new instrument for capturing high-resolution photographs of snow and ice particles in freefall from three views, while simultaneously measuring their fall speed. In the MASC system, the horizontal resolution is between 10 μm and 37 μm for different cameras and the vertical resolution at 1m/s fall speed is 40 μm (Notaros et al.). Praz et al (2017) developed a high level algorithm for particle type recognition (already presented in Fig 2 of section 3.1), quantification of the particle riming degree and differentiation of dry from wet snow for each individual snow particle (see Fig below).

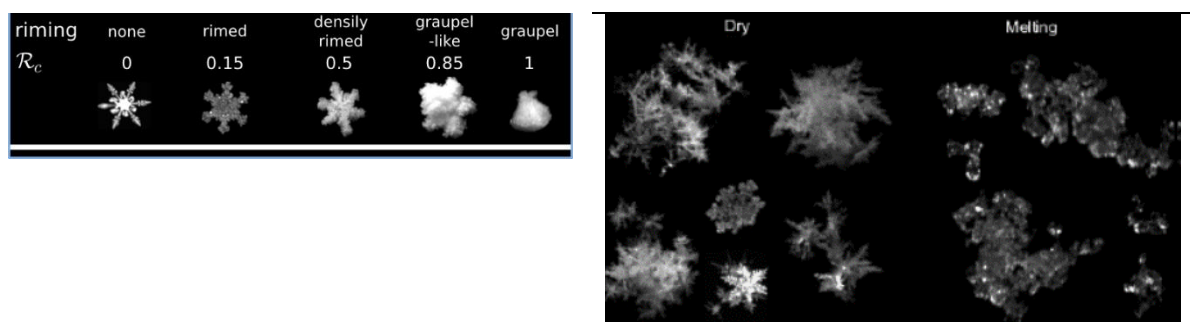


Figure 3 – Snow particle normalized riming degree (left) and wet – dry snow qualification (right) for MASC data according to Praz et al (2017) from MASC grey scale image analysis

A homemade extended version of the MASC has been designed at Colorado State University. The CSU customized system has been complemented with 2 externally added cameras. Note that the horizontal resolution of the 2DVD is approximately 160–170 μm (compared to 35 μm for the MASC), which is not sufficient to resolve details of the complexity of ice particles in winter precipitation. The MPS is also a quite new device for 2D imaging and fall speed of precipitating ice, but resembles more an OAP array probe than the 2DVD disdrometer, or the triple camera MASC instrument.

In contrast to ground-based disdrometers that are not suitable for W/T use, above mentioned OAP probes (sections 3.3 & 3.4) are mainly probes designed for use on A/C and thus can be easily implemented in W/T applications due to the necessary cloud particle velocity relative to the probe (true air speed; TAS). Typically, cloud particles move axially across the OAP laser beam and the velocity for OAP is generally beyond 10-20 m/s, which clearly exceeds snow crystal fall speeds. Below this velocity, deviations from axial movement and TAS become significant, consequently increasing respective uncertainties in microphysical properties retrieved from OAP probes.

Therefore, within the ICE GENESIS project, the preliminary analysis of artificial ice and subsequent comparison with natural ice will be performed with data from the MASC instrument gathered on the one hand in the IAG climatic chamber for the artificial ice and on the other hand during ground-based snow measurement campaigns in the Alps and also in Korea. In addition, ICE GENESIS will gather its proper natural snow data (puy de Dôme, Alpine site) for further analysis and comparison with artificial ice, thereby adding a new means of the simultaneous measurement of the mass of individual snow particles.

3.6 Detailed overview of state of the art instrumentation for W/T applications in snow conditions

In this section, detailed information for instrumentation (particle spectrometers & imagers, bulk measurement devices, snow cloud homogeneity devices,...) for wind tunnel applications in snow conditions is provided. The tables are partly identical with those in deliverable D5.1 for A/C applications and were partly adapted/extended with specific information for W/T applications.

3.6.1 Particle imaging probes OAP

Table 1: OAP – Part 1

Instrument (Manufacturer)	Name	Nominal size range	Size resolution	Sampling frequency	Parameters provided
2D Imaging Probes OAP for quantitative snow crystal number PSD					
HVPS version 3 (SPEC)	High Volume Particle Spectrometer	150 µm - 19.2 mm	150 µm	Asynchronous, 0.1 - 10 Hz. 1-5 sec sampling is typical	number PSD, morphology, calculation / estimation of mass PSD, MMD, IWC
PIP (DMT)	Precipitation Imaging Probe	100 µm - 6.4 mm	100 µm (64 photodiodes)	Asynchronous, 0.1 - 10 Hz. 1-5 sec sampling is typical	number PSD, morphology, calculation / estimation of mass PSD, MMD, IWC
CIP (DMT)	Cloud Imaging Probe	25 µm - 1.6 mm	25 µm (64 photodiodes)	Asynchronous, 0.1 - 10 Hz. 1-5 sec sampling is typical	number PSD, morphology, calculation / estimation of mass PSD, MMD, IWC
2D-S (SPEC)	2D Stereo Probe	10 µm - 1.28 mm	10 µm (128 photodiodes)	Asynchronous, 0.1 - 10 Hz. 1-5 sec sampling is typical	number PSD, morphology, calculation / estimation of mass PSD, MMD, IWC

Table 2: OAP – Part 2

Instrument / Manufacturer	Performance / complementary information	Dimensions (weight; length x width x height)	Power Requirements	W/T	Instrument can be provided by
HVPS version 3 (SPEC)	Data interfacing via Ethernet Cat 5 !!	13 kg; SPEC canister	< 600 watts of 115VAC, 400 or 60 Hz, and <200 watts of 28 VDC	x	CNRS-LAMP / DLR
PIP (DMT)	10 – 200 m/sec	9.5 kg in DMT canister 4.8 kg probe alone	110V AC (50Hz): 0.7A De-icing: 28V CC: 9A	x	CNRS-LAMP / DLR
CIP (DMT)	10 – 300 m/sec (for 25-µm CIP) 10 - 180 m/sec (for 15-µm CIP) -40 °C to +40°C Altitude: 0 - 50,000 ft	9.5 kg in DMT canister	28VDC: 11A for probe system, anti-ice heaters either 13A (standard tips) or 17A (Korolev tips)	x	CNRS-SAFIRE

2D-S (SPEC)	2 independent imaging systems, data interfacing via Ethernet Cat 5 !!	8.6 kg; 89 cm x 18 cm x 18 cm; SPEC canister	28V CC: 10A 220V AC (50Hz): 1.8A (PC) 110V AC (50Hz): 3.4A (PC) De-icing/lasers: 110V AC (50Hz): 3.9A	x	CNRS-LAMP / DLR
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3.6.2 Particle Imaging probes CCD

Table 3: CCD – Part 1

Instrument (Manufacturer)	Name	Nominal size range	Size resolution	Sampling frequency	Parameters provided
2D Imaging Probes CCD (256 grey scales) for more detailed crystal morphology					
HSI (ARTIUM)	High Speed Imager	3 µm - 4 mm	3 µm (2000*900)	single particle mode; max 400 frames/s	size, detailed morphology
CPI version 1 (SPEC)	Cloud Particle Imager	2.3 µm - 2.3 mm	2.3 µm (1000*1000)	single particle mode; max 40 frames/s	size, detailed morphology
PIV (NRC)	Particle Imaging Velocimetry, shadowgraphy	10 - 1500 µm	1.3 µm per pixel	2.2-5 frames per second	size, detailed morphology

Table 4: CCD – Part 2

Instrument / Manufacturer	Performance / complementary information	Dimensions (weight; length x width x height)	Power Requirements	W/T	Instrument can be provided by
HSI (ARTIUM)	Small sampling volume!	canister probe 10 kg standalone	28VDC (300 W) electronics / pc 110 VAC de-ice (1,4 kW)	x	CNRS-LAMP
CPI version 1 (SPEC)	Max 40 frames per sec or trigger mode (in focus particle) small sample volume!	Probe/ CPI housing 19kg Probe: 690x360x160mm	De-icing: 115V AC (50/400Hz): 4.6A 110V AC (50hz): 9.3A PC: 220V AC (50Hz): 0.7A 110V AC (50hz): 1.4A Electronics: 110V AC (50hz): 0.7A	x	CNRS-LAMP
PIV (NRC)	Particle Imaging Velocimetry using backlit shadowgraphy setup. Resolution can be decreased to proportionally increase the maximum particle size. This backlit technique will be applied to alternate lighting and imaging system for ease of use.	Non-intrusive instrument outside W/T		x	Installation NRC icing research wind tunnel

3.6.3 Particle scattering spectrometers

Table 5: Scattering probes – Part 1

Instrument (Manufacturer)	Name	Nominal size range	Size resolution	Sampling frequency	Parameters provided
Scattering Probes for droplet number PSD & liquid detection					
CAS-DPOL (DMT)	Cloud and Aerosol Spectrometer with Depolarization	0.5 - 50 μm	2 μm	0.05 - 40 Hz	droplet / small ice crystal number PSD, estimation LWC
CDP-2 (DMT)	Cloud Droplet Probe	2 - 50 μm	2 μm	Selectable, 0.04 to 20 seconds	droplet number PSD, estimation LWC
FCDP (SPEC) ¹⁾	Fast Cloud Droplet Probe	2 - 50 μm	2 μm	single particle	droplet number PSD, estimation LWC
BCPD (DMT)	Backscatter Cloud Probe with Polarization Detection	2 - 50 μm	2 μm	0.05 - 25 Hz	droplet number PSD, estimation LWC

Table 6: Scattering probes – Part 2

Instrument (Manufacturer)	Performance / complementary information	Dimensions (weight; length x width x height)	Power Requirements	W/T	Instrument can be provided by
CAS-DPOL (DMT)	>1000 particles/second --> coincidence	11.5 kg; 100 cm x 32 cm x 28 cm	28 VDC	x	DLR
CDP-2 (DMT)	Altitude: 0 - 50,000 feet -40 to 40 °C 10 - 250 m/sec 0 - 2,000 particles/cm ³	Probe: 1.37 kg Electronics in canister : 0.82 kg 26.7 cm x 17.5 cm x 21.6 cm	System 28 VDC at 2A De-ice 28 VDC at 12A	x	CNRS-LAMP
FCDP (SPEC) ¹⁾	stand alone or combination with other probes	2.5 kg; 28 cm x 15 cm x 23 cm	28 VDC, 115 VAC	x	CNRS-LAMP / DLR
BCPD (DMT)	a modification for larger particles might be possible within SENS4ICE project	1.5 kg; 15 cm x 13 cm x 5 cm	28 VDC, 5 A	x	DLR

3.6.4 Combination probes

Table 7: Combination probes – Part 1

Instrument (Manufacturer)	Name	Nominal size range	Size resolution	Sampling frequency	Parameters provided
Use of Combination Probes					
CAPS (DMT) = CAS-DPOL + CIP	Cloud and Aerosol and Precipitation Spectrometer (CAS-DPOL + CIP-15 or CIP-25)	0.5 - 50 μm (particle); 15 μm - 0.96 mm / 25 μm - 1.6 mm (precipitation)	see CAS-DPOL above	see individual probes above	see individual probes above
	CIP-15: Cloud Imaging Probe	15 μm - 0.96 mm	15 μm	0.05 - 25 Hz	
	CIP-25: Cloud Imaging Probe	25 μm - 1.6 mm	25 μm	0.05 - 25 Hz	
2D-S/FCDP (SPEC)	(2D-S + FCDP)	2 - 50 μm ; 10 μm - 1.28 mm	see individual probes above	see individual probes above	see individual probes above

Table 8: Combination probes – Part 2

Instrument (Manufacturer)	Performance / complementary information	Dimensions (weight; length x width x height)	Power Requirements	W/T	Instrument can be provided by
CAPS (DMT) = CAS-DPOL + CIP	see individual probes above	20.4 kg	see individual probes above	x	DLR, DGA
		11.5 kg; 98 cm x 18 cm x 18 cm	28 VDC, 11A probe system, 13A anti-ice heaters		
2D-S/FCDP (SPEC)	see individual probes above	11.1 kg	see individual probes above	x	LaMP, DLR

3.6.5 Bulk snow water content devices

Table 9: Bulk WC probes – Part 1

Instrument (Manufacturer)	Name	Nominal size range	Sampling frequency	Parameters provided
Bulk WC				
IKP Cranfield University (Only for IWT)	Isokinetic Probe	0-20 g/m ³	1Hz	TWC
IKP-2 (NASA, SEA, ECCO) (Not available within ICE GENESIS)	Isokinetic Evaporator Probe	0-10 g/m ³	1Hz	TWC
Snow CVI	Counterflow Virtual Impactor	max 1 or 2 g/m ³	1 sec	TWC or snow WC

ROBUST Probe	WCM-3000 ROBUST Water Content System	0 - 10 g/m ³	1-20 Hz	TWC (calculation for assumed phase: liquid or ice); TAS < 150 m/s SL – 45,000 ft
NEVZOROV Probe Sky Tech Research	idem	0.003-3 g/m ³	1 Hz	LWC, TWC, IWC
RICE Probe	Rosemount Ice Detector	qualitative supercooled LWC detector	1-NN Hz	supercooled water detector

Table 10: Bulk WC probes – Part 2

Instrument / Manufacturer	Performance / complementary information	Dimensions (weight; length x width x height)	Power Requirements	W/T	Instrument can be provided by
IKP Cranfield University (Only for IWT)	TWC ground measurement	Probe: 0.7m Length, 1 kg (X2)	230 Vac (3 kW) for pumps 230 Vac (2 kW) for main heater 230 Vac (500 W) for pipe heater 230 Vac (200 W) for IKP control system	x	Cranfield University
IKP-2 (NASA, SEA, ECCC) (Not available within ICE GENESIS)	10-200 m/s Background water vapour needed	Dimensions: 157 x 18 x 36 cm 29 kg with gondola;	≤ 2000 W	x	NASA, SEA, ECCC
Snow CVI	40 – 200 m/sec; Max. 1-2 g/m ³ ; does not distinguish LWC from IWC	Probe inlet outside ATR fuselage: 770*400*134mm 6.5 kg; Synthetic supply air in ATR cabin.	To be determined after power supply modifications of standard CVI to Snow CVI.	x	CNRS-LAMP
ROBUST Probe	WCM-3000 Robust Water Content System; Element heated to 140°C; TWC probe 0 - 10 g/m ³ ; does not distinguish LWC from IWC	Sensor: 0.5 kg; Power supply in canister: 5kg Data acquisition: 15kg 3.05 “ x .46 “ x .95” sensor external 5.45 “ x 3.25 “ x 3.25” sensor overall ;	28V DC : 41A (6-7g/m ³ at 200m/s ~20A for probe system, anti-ice heaters and sensor element in expected snow conditions (T, WC, ATR and YAK-42 TAS)	x	CNRS-SAFIRE / AIRBUS
NEVZOROV Probe Sky Tech Research	deep cone version; 10-180 m/s ; 0.003-3 g/m ³ ; Distinguish LWC from IWC!	Pillar 10*9*5 cm, control box 2HU	Sensor deice 28VDC (28W), Pillar deice 110 VAC (300W), Probe power 28 VDC 12 A	x	CNRS-SAFIRE / DLR
RICE Probe	Rosemount Ice Detector ; A/C	385.6 grams;	28 VDC, 330W	x	CNRS-SAFIRE

	probe for supercooled water detection – qualitative; operates properly at T < -8°C	Probe max. diameter / dimension : 82.55 mm			
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3.6.6 Sensors for meteorological parameters in icing W/T

Table 11: Meteorological sensors

Meteorological sensors	Parameter provided	Sensor limitation	Sampling frequency	Instrument provided by
Temperature	Dry temperature	< 1°C	>1 Hz	RTA, NRC, TSAGI
Relative Humidity	RH and water-vapour concentration	< 3% (IKP equipped with proper BWV measurement)	> 1Hz	RTA, NRC, TSAGI
Horizontal wind speed in sample section	Horizontal speed and direction, vertical wind w	< 5% (< 10% near sampling volume of calibration probe)	> 10 Hz	RTA, NRC, TSAGI
Static Pressure	p	< 10 hPa	1 Hz	RTA, NRC, TSAGI

3.6.7 Cloud homogeneity in sampling sections of icing W/T

Table 12: Cloud homogeneity devices

Cloud homogeneity	Parameter provided	Sensor limitation	Sampling frequency	Instrument provided by
Laser sheet	Physical homogeneity in sample section	To be investigated. Pb of cloud penetration (thick cloud, large sampling section)..	1 Hz	To be rented RTA, TSAGI
Icing mesh (Perhaps of limited applicability for dry/wet snow that may not stick or may not result in sufficient accretion thickness....?)	Icing homogeneity in sample section.	± 20 in accretion thickness of the tunnel centerline (SAE ARP 5905)	10 min	RTA, TSAGI
Horizontal / vertical icing bar (see comment about icing mesh)	Icing homogeneity in sample section	± 20 in accretion thickness of the tunnel centerline (SAE ARP 5905)	10 min	RTA, TSAGI
Variable spatial (roboter) positioning system of snow probe support. For measurement use IKP TWC device and traverse the tunnel.	Icing homogeneity in sample section.	± 20 in TWC of the tunnel centerline (analogy to SAE ARP 5905)	~ order of min	RTA, NRC, TSAGI

Snow test facilities / brief description

Test facilities, such as RTA, TSAGI, and NRC started working on concepts of generating artificial ice particles, using grinding techniques, thereby mechanically shaving ice blocs, or freeze out techniques / atomising nozzles (snow guns) with a control system of the IWT ambient temperature, wind speed, water and air supply as well as water temperature. However, the generated artificial ice particles of those two techniques do not necessarily meet the microphysical properties of the variety of natural snow properties (e.g. size, shape and density). This is why investigating new technologies of snow particle production (ice crystals / snowflakes) for the generation of naturally equivalent snow is one of the main objectives within the Snow stream (mainly WP5 & WP7 & WP10) of the ICE GENESIS project.

In the frame of HAIC a promising technique of diffusional crystal growth with further aggregation has been implemented in the Braunschweig cloud chamber (including storage devices). Subsequently, the artificial ice particles (produced by implementing two of the three natural growth regimes: water vapour diffusion, aggregation) were fed into the wind tunnel during investigations in the wind tunnel. Today, this technique produces rather small ice particles, but has not been optimized for producing very large ice crystals or snowflakes and also does not produce artificial ice crystals at a rate required for icing wind tunnel investigations.

Another promising snow production technique has been set up at IAG. In principal, this technique uses a very cold, slowly rotating cylinder that experiences riming features from impacting smaller cloud droplets. The continuously riming surface is shaved from the cylinder with a cutting device and also additional cloud water is locally sprayed into the cooling chamber, interacting with produced falling ice before being sampled at the ground (and future injection into the RTA icing wind tunnel).

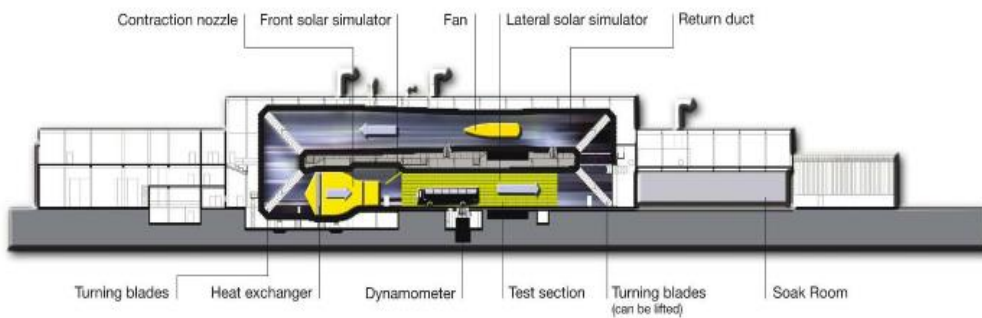
Within Task 5.2 and dedicated deliverable D5.3, the overall objective is thus to define instrumental means for artificial snow particle quantification in terms of microphysical properties (Number PSD, snow density as a function of size (and thus mass PSD), particle shape/morphology, and if possible information on the dry/wet state of the snow particles in the snow).

In other words, D5.3 will not discuss growth processes and obvious differences of those, when comparing natural and artificial snow. D5.3 is solely dedicated to best quantify snow particle properties in close collaboration with WP10 and of course WP7.

3.6.8 RTA

RTA offers using a smaller Climatic Wind Tunnel (small CWT) and/or the larger Climatic Wind Tunnel (large CWT). Initially, the Vienna Climatic Wind Tunnels operated by Rail Tec Arsenal have been designed to offer the opportunity to analyse the effects of a variety of weather conditions on vehicles and components under realistic operating conditions. Even though the facility has been designed for climatic tests on rail vehicles, the facility is increasingly used for the aviation industry, thereby offering optimal testing conditions. RTA's CWT can simulate different forms of precipitation such as rain and freezing rain and also wet and dry snow, for IWT within ICE GENESIS. Thus, the wind tunnel allows simulating flights through different cloud types in a temperature range of -2°C to -30°C with engines running.

Small Climatic Wind Tunnel (small CWT)



Large Climatic Wind Tunnel (large CWT)

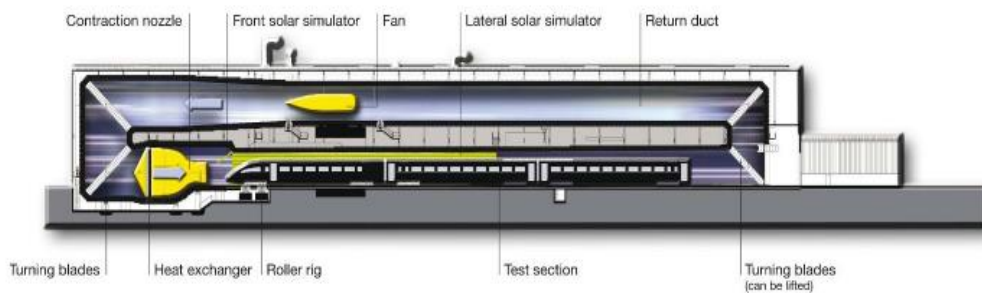


Figure 4 – Available small and large CWT from RTA

In a collaborative effort RTA is working with IAG, in order to implement the IAG snow production technology of the slowly rotating cylinder briefly mentioned in section 3.1. The cylinder experiences ice accretion from impacting smaller cloud droplets. The continuously riming surface is shaved from the cylinder with a cutting device and also additional cloud water is locally sprayed into the cooling chamber with falling ice before sampling at the ground. An additional fan serves to direct and/or disperse the produced ice cloud before sampling at the ground.



Figure 5 – IAG rotating cylinder for snow production (left) and climatic chamber test setup with MASC instrument for characterization of the artificial snow particles

RTA is currently developing the concept for integration of at least three of these rotating cylinder snow generators (periodically moving over the injection cross section) into the Climatic Wind Tunnel. The RTA CWT characteristics are presented in below table.

RTA	Snow capability	
	Small CWT	Large CWT
Altitude	SEA LEVEL	SEA LEVEL
Static Temperature range	-45°C to +60°C	--45°C to +60°C
Air speed	50 m/s	80 m/s
Snow technique	IAG technique – rotating cylinder	IAG technique – rotating cylinder
Snow representativity (dry/wet snow)	Dry and wet	Dry and wet
MMD (dry/wet snow), μm	TBD	TBD
Snow density range (dry/wet snow) (kg/m3)	TBD	TBD
TWC range (g/m3) (dry/wet snow)	TBD	TBD
Test section	8,75 m2	8,75 m2
Operating cost (L/M/H)	medium	medium

Table 13: RTA IWT snow capabilities

3.6.9 TSAGI

TSAGI will carry out comparative tests of grinded ice block and snow gun generation systems with the recently fallen snow injection system in the small scale facility EU-1. In a subsequent step, TSAGI will integrate the selected snow generation system in the AHT SD facility, including the analysis of producible snow capacity, functionality, and snow quality versus requirements. The scheme of the ice crystals generation and transportation to the icing wind tunnel is shown below. An ejector system for crystals injection into the flow has been created and tested. Schematic and photos are presented below.

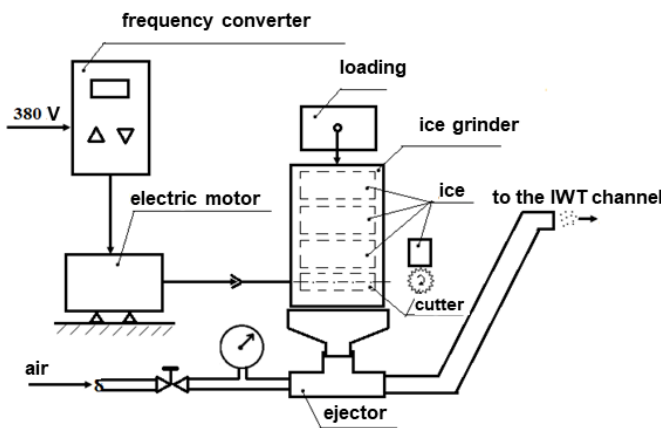


Figure 6 – Schematic of TSAGI ice generation, ejector, and transportation system to the IWT channel.

In addition, a conveyor system for crystals injection into the flow has also been created and tested.

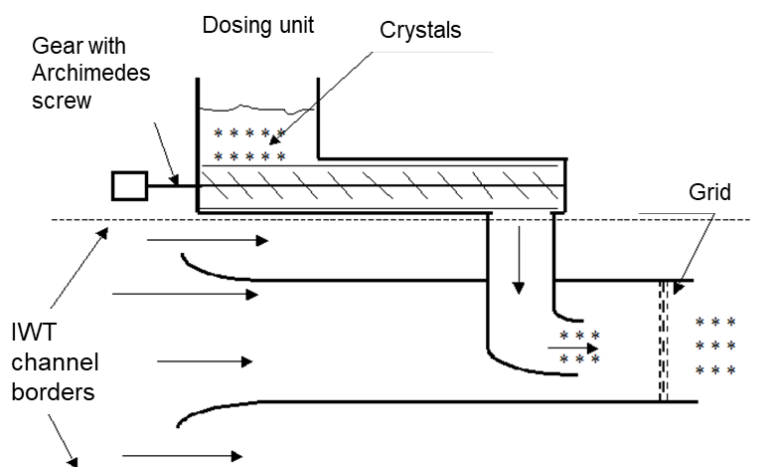


Figure 7 - TSAGI IWT conveyor system for crystals injection into the flow

The TSAGI IWT characteristics are presented in below table.

TsAGI	Snow capability	
	EU-1	AHT SD
Altitude	SEA LEVEL	SEA LEVEL
Static Temperature range	-30...0 °C	-20...0 °C
Air speed	10...120 m/s	10...150 m/s
Snow technique	Natural, grinder, snow gun	Grinder, snow gun
Snow representativity (dry/wet snow)	Dry and wet	Dry and wet
MMD (dry/wet snow), μm	100...2000	100...2000
Snow density range (dry/wet snow) (kg/m ³)	150...350	150...350
TWC range (g/m ³) (dry/wet snow)	0.5...20	0.5...20
Test section (size in mm)	250×250	1000×1000
Operating cost (L/M/H)	low	medium

Table 14: TSAGI IWT snow capabilities

A non-negligible unknown in the ice crystal properties of artificial ice injected in specific IWT will be potential mechanical transformation processes that are difficult to quantify and that we cannot anticipate, before measuring the microphysical properties in those IWT, when the entire system is set up. This statement is true for RTA, TSAGI, and NRC wind tunnels. For example, in June 2019 with the MASC instrument preliminary measurements were performed in the IAG climatic chamber with subsequent analysis of the generated snow particles. A preliminary analysis documents reasonable similarities of natural and artificial snow (overall particle sizes, type/category of particles, riming aspect), however we don't know what may happen once the rotating cylinder snow generator will be

installed and operational in the RTA CWT. Mechanical fragmentation occurring inside the wind tunnel, particularly at the walls, will mainly modify microphysical properties of largest and also most fragile aggregate type snow particles before impacting on test specimen. The question then is how much microphysical snow properties of snow produced in IAG climatic chamber will be altered after injection in RTA CWT. Likewise, the possible mechanical transformation applies for all kinds of icing wind tunnels (thus also TSAGI, NRC icing wind tunnels). A striking example of the possible effect is presented below, illustrating the wind tunnel potential to fragment injected snow particles.

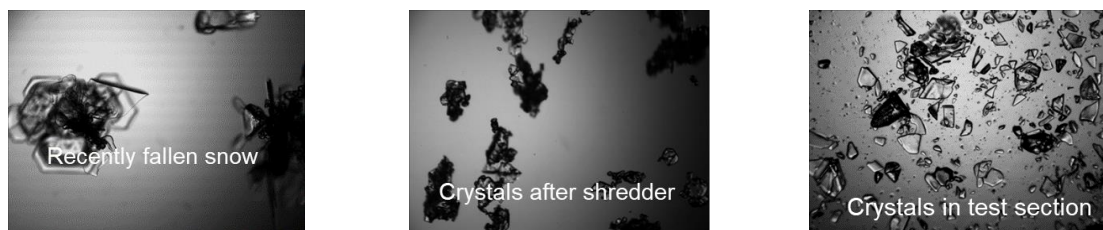


Figure 8 – Potential effect of mechanical transformation processes on the microphysical properties of injected ice particles in the IWT (data from TSAGI partner).

3.6.10NRC

Finally, NRC major experience in icing research wind tunnel will support task 5.2 of selection of most suitable calibrated instrumentation for IWT calibration. NRC will also perform specific icing wind tunnel test in TC5 or RATFac facilities with their validated subset of instrumentation (non-commercial) for calibration purposes (PIV shadowgraphy, NRC version of IKP evaporator probe).

Within ICE GENESIS, NRC will investigate grinding technique and natural fallen snow in TC5 or RATFac test facility, will analyse the producible snow capacity and quality according to the requirements, and will select the most appropriate snow generation system for TRL3 maturity demonstration.

Galeote et al (2010) and Fuleki et al (2015) describe the instrumentation for particle size measurements in the RATFac facility based on a particle imaging velocimetry (PIV) system in which a short duration laser pulse is used to backlight airborne particles. PIV technology produces high resolution images of fast moving airborne particles in a non-intrusive manner. The system is a homemade, non-commercial system. The imaging technique is also used to examine particle morphology and 2D particle trajectory and velocity. Implementing this non-intrusive shadowgraphy technique at the NRC ice crystal test system installed at its research altitude test facility (RATFac) showed that ice particle size distributions could be generated from approximately 60 to 700 micron median mass diameters (MMD's) with the ability to create larger particles well above 1 mm in diameter.

The bulk concentration of ice is measured using the compact isokinetic probe CIKP developed by NRC. The CIKP principle of operation is to ingest and subsequently melt/evaporate cloudy air (hence, hydrometeors and background water vapour). From the resulting total humidity is subtracted an independent measurement of background humidity using RH & TAT probes. The CIKP is fully

comparable to other IKPs having been presented in this document, as there are the NASA IKP-2 and the Cranfield University CU-IKP.

NRC	Snow capability
	RATFac
Altitude	SEA LEVEL to 50 kft (12 km)
Static Temperature range	-45°C to +60°C
Air speed	5 - 100 m/s
Snow technique	Grinding technique, but investigating alternate methods
Snow representativity (dry/wet snow)	TBD- the tunnel can control temperature and humidity independently to precisely control melt.
MMD (dry/wet snow), μm	TBD, goal as per project is 250 to 5000
Snow density range (dry/wet snow) (kg/m ³)	TBD
TWC range (g/m ³) (dry/wet snow)	TBD, goal as per project is 0.5 to 3
Test section	13 cm x 26 cm standard cascade rig Larger test rigs can be installed downstream of icing/snow making system
Operating cost (L/M/H)	medium

Table 15: NRC IWT snow capabilities

3.7 Instrument selection for snow microphysics: generalities

The current state of the art instruments for snow crystal and snowflake particle size and shape determination (and distinction of possible liquid water droplet presence) as well as bulk snow WC measurements that can be used in W/T applications are very close to the possible instruments described in D5.1 of instruments to be used an A/C and are based on the following three principles:

1. Imaging of cloud particles based on CCD camera (snow particle morphology, distinction wet – dry snow) and OAP linear optical array shadowgraphy, which is considered a non-intrusive imaging process (2D image representing one single cross section of a 3D particle passing through the imaging laser beam) to derive concentrations in number and in addition 1D and 2D geometric properties such as diameter, perimeter of 2D image, 2D projected area, 2D image area ratio, image aspect ratio, 2D fractal dimension, 2D image sphericity, with respective distributions of those parameters as a function of particle size/diameter (Leroy et al 2016). Those 2D retrievals of course can be used to guess 3D properties as best as we can from closure studies (Leroy et al 2017, Coutris et al 2018, Fontaine et al 2015), literature parametrizations (Heymsfield et al 2010, Baker and Lawson 2006, Brown and Francis 1990, Fontaine et al 2014) simulations of the arbitrary projection of 3D objects onto a 2D plane (Fontaine et al. 2014). 3D properties include 3D crystal surface, volume, and mass of individual crystals and respective surface, volume, and mass size distributions.
2. Bulk TWC & IWC hot wire devices and evaporators: Basically the techniques are based on the phase change of particles (in order to measure the bulk mass of condensed water).
3. Diffusion of light of single particles (in principal to determine the size of assumed spherical particles of known refractive index) or particle populations. This principle is used by optical scattering spectrometers and helps identifying small spherical remaining liquid droplets (e.g. from additional spray bars to simulate riming).

Numerous instruments are available within research laboratories (particularly CNRS-LaMP and other European partners within ICE GENESIS, as there are DLR, DGA, etc...). Nevertheless, serious gaps associated with instrumental measurement uncertainties and limitations remain and need to be overcome. The measurement of the size distribution of ice crystals is complicated by a number of factors, not the least of which is the lack of a universally accepted definition of size when referring to non-spherical particles (Korolev et al., 2005). Number concentrations of particles smaller than at least 50 μm , derived from classical optical array probes OAPs (of often 25 μm of pixel size) are uncertain by factors of two or three, due to the operating principles, which limits the determination of sample volume using this imaging technique. However, this is of minor importance with respect to mainly large super-millimetric snow particles. Although, advances in high speed electronics have led to the development of higher resolved (10 μm pixel for 2D-S) OAPs like the 2D-S (Lawson et al., 2006) that can measure a more representative particle sample at high airspeeds, OAPs still suffer from contamination by fragments of ice crystals that shatter on the extended arms, or even on aircraft surfaces ahead of the probes depending on measurement location. Newest probe designs greatly reduce the influence of ice shattering (Lance et al., 2010) and new tips have been designed for particle probes that also have been shown clearly to greatly reduce the production of ice fragments from

shattering (Korolev et al., 2011). Software techniques related to elimination of closely spaced particles, assumed to result from shattering, have also been proposed, although not yet rigorously evaluated. In addition to particle imagery for quantitative retrieval of snow microphysical properties from 2D images and qualitative estimations of morphological and phase (dry and wet snow) type parameters, the measurement of the total snow water content is essential for closure studies with image retrievals and also remote sensing radar retrievals of microphysical properties below and beyond the flight altitude.

Distinction and comprehension of different types of snow crystals into more or less rimed aggregates, graupels, pristine columns or plates may benefit from concurrent measurements of liquid and ice phase in snow clouds. This can be accomplished using optical array probes when enough pixels are shadowed to determine the particle shape. Determining the phase of cloud particles smaller than about 100 μm, however, is more challenging. Within HAIC solely a non-depolarizing CDP probe has been used which was a good compromise between robustness of the probe performance and clear supercooled water detection with subsequent estimation of LWC. We consider that as well in artificial as in natural snow conditions the presence of liquid droplets might be of no importance, although it's always better to prove that this is the case, thereby deploying for example a CDP type optical spectrometer.

The dimensional coverage of possible snow crystal and snowflake sizes by various state of the art instruments is schematically illustrated in subsequent figure.

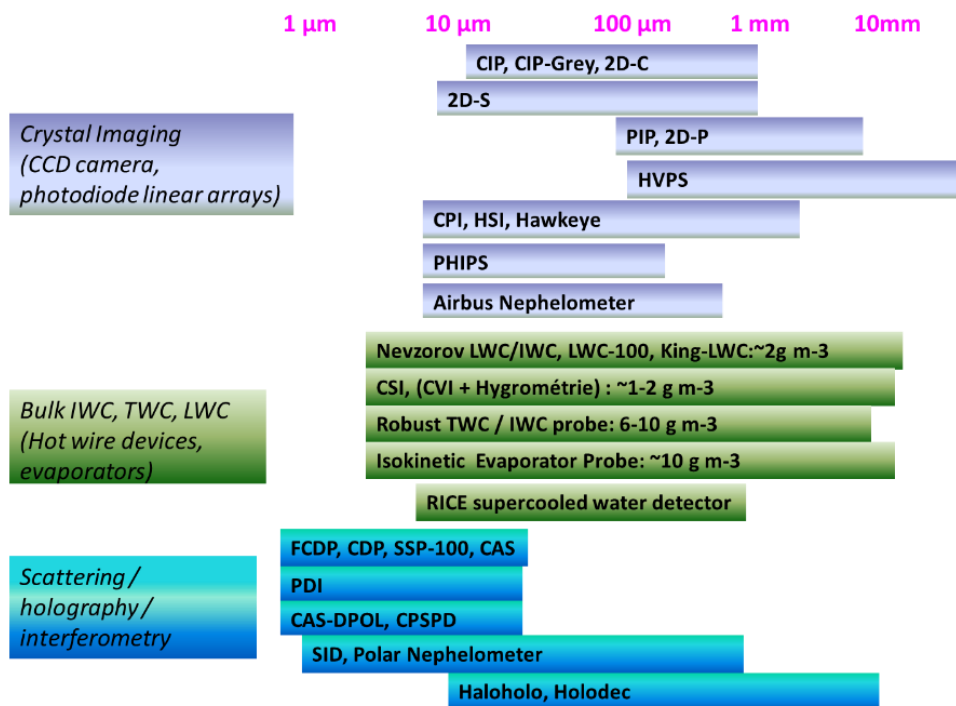


Figure 9 - Multiple instruments to cover complete range from 1 μm to 10 mm and beyond. Task: Choose most reliable set of actual/future instruments combining “Optical spectrometers + 2D crystal imagers + bulk TWC/IWC devices” for multiple IWC retrievals using various methods!

3.8 Instrument selection: Proposition for RTA CWT and TSAGI AHT SD of instruments to be used for W/T calibration studies in snow conditions

The IWT instrumental configuration (all chosen probes for W/T calibration to be installed in parallel if possible) has to be a most sophisticated in-situ microphysical package allowing for state-of-the-art measurements of the snow particle (snow crystals / snowflakes) quantitative and qualitative microphysical properties (spectrometry and imagery of hydrometeors in order to deduce crystal size distributions, habits and indicator of wet or dry snow) from smallest hydrometeors up to snow particles of several tens of millimetres. The work has been performed within task 5.2 in close collaboration with WP10 scientists and respective needs for 3D parametrizations of snow properties to initialize trajectory and accretion models. 3D properties as there are 3D surface, volume, and mass then may be derived/estimated from parametrizations to be established from most appropriate datasets (also MASC data after qualitative reconstruction of the 3D snow particle) and from direct measurement of the snow water content (TWC) for closure studies of ice crystal density for example (Leroy et al, 2016; Coutris et al 2018).

The recommended instrumentation package is a reduced version of what will be installed on the YAK-42 and ATR-42 research aircraft for their respective measurement campaigns (2019/20 and 2020/21) in snow conditions. For W/T applications we don't need probe redundancy (which is always a good idea for A/C instrumentation (see D5.1)). Thus, D5.3 suggests CU IKP for TWC measurement, HVPS (diameter range: 150-19200 μm) and alternatively the PIP (diameter range: 100-6400 μm) for largest precipitation crystals, 2D-Stereo cloud imaging probe (diameter range: 10-1280 μm) or similar (CIP-15 or CIP-25) for sub-millimetric ice crystals, and possibly the FCDP or a CDP-2 (droplet diameter range: 2-50 μm). The precipitation particle imager (preferentially HVPS) is a must. The 2D-S should also give a reasonably good description of submillimetric ice particles (small generated ice, fragments). The TWC reference probe will be the CU IKP, with an alternative TWC instrument which could be the Snow CVI currently designed for the ATR-42 campaign. However, the CVI technology may have difficulties in rough W/T conditions to process snow water contents beyond 1 g/m³. The FCDP/CDP-2 type droplet spectrometer, if needed, should reveal possible presence of droplets coexisting with snow particles, which cannot be measured reliably with high resolution imagers. This package has to be complemented by measurements with a 256 greyscale high resolution imaging device. The best candidate is the HSI imager (alternatively CPI in case that the HSI is not operational) allowing for particle habit classification and morphological analysis via high resolution grey scale information. The CPI is operational, whereas the new open path high resolution imager HSI (high speed imaging probe) is currently designed/produced for CNRS-LaMP at ARTIUM.

As a major conclusion, the instrumental setup suggested for IWT calibration studies is comprised of state of the art instruments covering the recommended size range of "optical spectrometers + 2D imagers" and also considers morphology / wet dry state of the snow particles + reference bulk TWC with measurement redundancy.

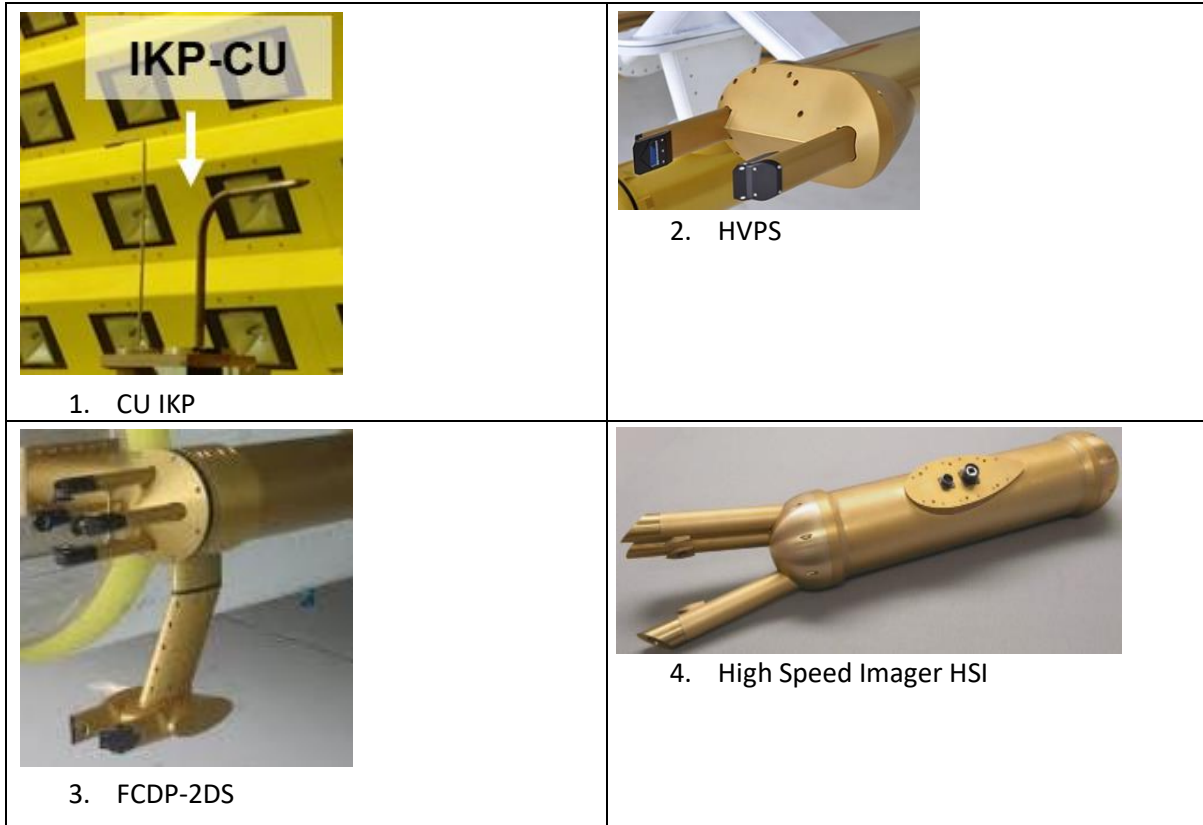


Figure 10 – IWT suggestion of snow instruments to cover recommendations and also requests that emerged from discussions between ICE GENESIS Snow-stream work-packages WP5, WP7, and WP10.

A schematic of the size range coverage of recommended instrumentation is given in figure below.

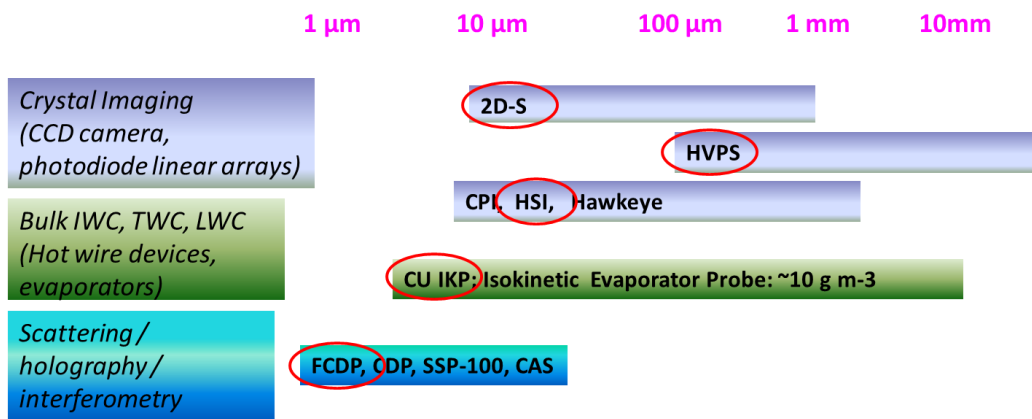


Figure 11 – Size range coverage of IWT recommended instrumentation.

Subsequently the potential alternative cloud microphysics instrumentation for the IWT calibration is presented.






IWT alternative instrumentation		
Equipment		Illustration
Bulk cloud μ-phys Alternative for CU IKP	Counterflow Virtual Impactor (CVI) including High tech humidity sensors (TDL, Licor 580A, Buck dew point sensor, Vaisala sensor) Concept/design: LaMP Production: Enviscope GmbH	
2D-array probes: (10-19200 μm) Alternatives for HVPS and 2DS	Precipitation Imaging Probe (PIP) DMT	
	Cloud Imaging Probe (CIP) DMT	
CCD camera: (10-1000 μm) Alternative for HSI:	CPI Imager (2.3 μm pixel, 1000*1000 pixel) SPEC Inc.	
Opt. spectrometry: (1-50 μm) Alternative for FCDP	Cloud droplet Probe (CDP; together with ROBUST) DMT	

Figure 12 – Snow cloud microphysical instrumentation: alternatives

4 Conclusions

The work performed in order to produce the ICE GENESIS deliverable D5.3 is related to the work performed within task 5.2. This task has been synthesizing the state of the art and specifications of the W/T measurement needs of snow. A review of the relevant and available instrumentation in the scientific community (in particular the ICE GENESIS consortium) has been conducted. A major outcome is that state of the art in situ measurements are particularly adapted for number PSD retrievals from particle images of falling snow and also bulk condensed snow water content measurements. Within limitations of the possible instrumental configuration of RTA CWT and TSAGI AHT SD (wind tunnel cross section, and in particular a possibly reduced homogeneous snow cloud cross section) used in the frame of ICE GENESIS, the most suitable instrumental payloads have been chosen. Parallel use of those chosen instruments during calibration runs is desirable, mitigation would be sequential use for identical W/T system configurations of recommended cloud calibration instruments. The latter concept of course is more time consuming.

The requirements for the selection of the most adequate microphysical payload have been to perform quantitative measurements of rather weak number concentrations of snow particles (below 1 crystal per liter) and of a broad ice particle size range (few tens of micrometres up to 4 cm) and to quantify bulk snow water contents up to maximum 2 g/m³. Other valuable and necessary information should be gathered in W/T measurements with respect to most detailed morphological description of individual snowflakes and if possible qualitative indications with respect to dry/wet nature of snow particles, which is extremely valuable for the ice accretion modelling community within ICE GENESIS. Also indication of possibly coexisting droplets (in case those can be injected in addition to generated snow) would be valuable.

The suggested IWT instrumental configuration for snow calibration is adapted to cover the entire size range of snow particles in IWT and includes 2D imagers for size and morphology, a bulk TWC measurement device, and possibly a complementary optical spectrometer for smallest particles (crystal fragments, droplets). On the large crystal size end, the HVPS is substantially increasing the maximum measurable size range, complemented by the 2DS for sub-millimetric snow particles. HSI high resolution greyscale (256 levels) imager produces images for a more detailed morphological description of the crystal surface which should yield shape recognition, riming degree retrieval, and possibly wet / dry snow distinction, as is performed for the MASC instrument composed of 3 greyscale cameras. 2D-S should also give a relatively good description of the shape of the crystals. The reference TWC device has been chosen with the CU IKP instrument. The FCDP may be of minor use and should be considered an instrumental means to proof (if needed) absence of small droplets or roundish ice particle fragments mechanically produced in a W/T.

Alternative state of the art ice cloud and precipitation probes PIP, CIP, CPI, CVI, are reasonably good alternatives for the recommended instruments which are HVPS, 2DS, HSI, IKP, and FCDP, respectively, and are considered a rather good mitigation plan.

Finally, snow cloud homogeneity measurements in W/T need to be conducted by a laser sheet technology, or by installing an icing mesh or a spatial (roboter) positioning system of snow probe support inside the cross-section. A uniform cloud then is defined when during ice accretion

experiments, the variation in thickness of ice accreted ice spatially remains within ± 20 percent of the tunnel centerline ice accretion thickness [SAE ARP 5905].

NRC will perform specific supplementary icing wind tunnel test in TC5 or RATFac facilities with their validated subset of instrumentation (non-commercial) for calibration purposes (PIV shadowgraphy, IKP evaporator probe).

An intercomparison of artificial snow properties observed in wind tunnels with natural snow is not part of this deliverable and will be discussed within Task 5.5 of WP5.

Also this deliverable and corresponding recommendations try to take into account measurement needs and snow particle parameter definitions (2D and 3D microphysical descriptors) for the modelling community (WP10) that have been more and more clarified in the series of technostream snow meetings and discussions (collaborative effort WP5 & 7 & 10).

5 Bibliography

- Dezitter F., A. Grandin, J.-L. Brenguier, F. Hervy, H. Schlager, P. Villedieu, and G. Zalamansky, 2013: HAIC - High Altitude Ice Crystals. 5th AIAA Atmospheric and Space Environments Conference, American Institute of Aeronautics and Astronautics <http://arc.aiaa.org/doi/abs/10.2514/6.2013-2674>
- Fuleki, D. M., Chalmers, J. Y., and Galeote, B. "Technique for Ice Crystal Particle Size Measurements and Results for the National Research Council of Canada Altitude Ice Crystal Test System," SAE 2015 International Conference on Icing of Aircraft, Engines, and Structures, SAE Technical Paper 2015-01-2125, 2015.
- Furukawa Y. and J. Wettäuffer, Snow and ice crystal, *Physics Today*, pp. 70-71, December 2007.
- Garrett T. J., C. Fallgatter, K. Shkurko, and D. Howlett, Fall speed measurement and high-resolution multi-angle photography of hydrometeors in free fall, *Atmos. Meas. Tech.*, 5, 2625–2633, 2012
- Galeote, B. "Ice Crystal Particle Measurement Using Shadowgraph Imaging Techniques," AIAA Atmospheric and Space Environments Conference, AIAA 2010-7531, 2010.
- Gultepe, I., Heymsfield, A. J., Field, P. R., & Axisa, D. (2017). Icephase precipitation. *Meteorological Monographs*, 58, 6.1–6.36
- Korolev, A. V., Strapp, J. W., Isaac, G. A. and NEVZOROV, A. N. 1998. The NEVZOROV Airborne Hot-Wire LWC–TWC Probe: Principle of Operation and Performance Characteristics. *Journal of Atmospheric and Oceanic Technology* **15**, 1495-1510.
- Korolev AV, Strapp JW, Isaac GA. Evaluation of accuracy of PMS Optical Array Probes. *J. Atmos. Oceanic Tech.* 1998; 15:708–720. doi:<http://dx.doi.org/>
- Korolev A, Isaac G A. 2005. Shattering during sampling by OAPs and HVPS. Part I: Snow particles[J]. *J. Atmos. Oceanic Technol.* ,22: 528-542, doi: 10.1175/JTECH1720. 1.
- Korolev AV, et al. Small ice particles in tropospheric clouds: Fact or artifact? Airborne icing instrumentation evaluation experiment. *Bull. Amer. Meteor. Soc.* 2011; 92(8):967–973. DOI: 10.1175/2010BAMS3141.1
- Lance, S., C. A. Brock, D. Rogers, and J. A. Gordon, 2010: Water droplet calibration of the Cloud Droplet Probe (CDP) and in-flight performance in liquid, ice and mixed-phase clouds during ARCPAC. *Atmos Meas Tech*, **3**, 1683–1706, doi:10.5194/amt-3-1683-2010.
- Lawson, R. P., O'connor D., Zmarzly P., Weaver K., et al., "The 2D-S (Stereo) Probe : Design and Preliminary Tests of a New Airborne, High-Speed, High-Resolution Particle Imaging Probe", *J. Atmos. Oceanic Technol.* 23(11), p. 1462-1477, doi: 10.1175/JTECH1927.1., 2006.
- Lawson, R. Paul, R. E. Stewart, J. W. Strapp, G. A. Isaac, Aircraft observations of the origin and growth of very large snowflakes, *Geophysical Research Letters*, 20, 1, 53-56, 1993.
- Lawson, R.P., R.E. Stewart, and L.J. Angus, *Observations and Numerical Simulations of the Origin and Development of Very Large Snowflakes*, *J. Atmos. Sci.*, 55, 3209–3229, 1998.
- Leroy, D., Fontaine E., Schwarzenboeck A. and Strapp J. W., "Ice Crystal Sizes in High Ice Water Content Clouds. Part I: On the Computation of Median Mass Diameter from In Situ Measurements", *J. Atmos. Oceanic Technol.*, 33(11), p. 2461-2476, 2016.
- Leroy, D., E. Fontaine, A. Schwarzenboeck, J. Strapp, A. Korolev, G. McFarquhar, R. Dupuy, C. Gourbeyre, L. Lilie, A. Protat, J. Delanoe, F. Dezitter, and A. Grandin. 2017. Ice crystal sizes in high ice water content clouds. Part 2: Statistics of Mass Diameter Percentiles in Tropical Convection observed during the HAIC/HIWC project. *J. Atmos. Oceanic Technol.*, doi: 10.1175/JTECH-D-15-0246
- Libbrecht, Kenneth. "The Formation of Snow Crystals Subtle molecular processes govern the growth of a remarkable variety of elaborate ice structures." *Am. Sci* 95.1 (2007): 52-59.

- Newman, A. J., Kucera, P. A., and Bliven, L. F.: Presenting the snowflake video imager (SVI), *J. Atmos. Ocean. Tech.*, 26, 167– 179, 2009.
- Praz C., Y-A Roulet , and A. Berne. Solid hydrometeor classification and riming degree estimation from pictures collected with a Multi-Angle Snowflake Camera. *Atmos. Meas. Tech.*, 10, 1335–1357, 2017. doi:10.5194/amt-10-1335-2017.
- Pruppacher H.R., J.D. Klett, *Microphysics of Clouds and Precipitation* (2. ed.), Springer, 2010
- Rasmussen et al. The Estimation of Snowfall Rate Using Visibility. *J. of Applied Meteorology*, Vol. 38, 10, pp. 1542-1563, 1999.
- Strapp, J. W., Lilie L. E., Ratvasky T. P., Davison C. R. and Dumont C., "Isokinetic TWC Evaporator Probe : Development of the IKP2 and Performance Testing for the HAIC-HIWC Darwin 2014 and Cayenne Field Campaigns", 8th AIAA Atmospheric and Space Environments Conference, American Institute of Aeronautics and Astronautics, doi: 10.2514/6.2016-4059, 2016.
- Thurai, M., and V. N. Bringi, 2005: Drop axis ratios from a 2D video disdrometer. *J. Atmos. Oceanic Technol.*, 22, 966–978, doi:10.1175/JTECH1767.1.