

# ICE GENESIS

## Creating the next generation of 3D simulation means for icing

Type of action: Research and Innovation Action

Call identifier: H2020-MG-2018-SingleStage

Topic: MG-2-5-2018 Innovative technologies for improving aviation safety and certification in icing conditions

### Deliverable D5.1

#### Selection of most suitable instrumentation for F/T

EC Grant Agreement number:	824310
Start date of project: 1 January 2019	Duration: 48 months
Lead beneficiary of this deliverable:	CNRS
Due date of deliverable: 30/06/2019	Actual submission date: 02/09/2019
	Version #: R1.1

Project funded by the European Commission within the H2020 Programme (2014-2020)		
Type		
R	Document, report excluding the periodic and final reports	X
DEM	Demonstrator, pilot, prototype	
DEC	Websites, patents filing, press & media actions, videos, etc.	
OTHER	Software, technical diagram, etc.	
ETHICS	Ethics requirement	
ORDP	Open Research Data Pilot	
Dissemination level		
PU	PUBLIC, fully open, no embargo e.g. web	X
PU*	PUBLIC after embargo of 12 months	
RE	RESTRICTED, only for certain members of the consortium (including the Commission Services): specify here which consortium members have access to the document	
CO	CONFIDENTIAL, only for members of the consortium (including the Commission Services)	

CO+IGAB	CONFIDENTIAL, only for members of the consortium (including the Commission Services) and for the ICE GENESIS Advisory Board	
---------	---	--

## Revision History

V #	Date	Description / Reason of change	Author
R0.1	02/07/2019	Draft version	SCHWARZENBOECK Alfons
		Revised version with partners' contributions	SCHWARZENBOECK Alfons DEZITTER Fabien
R1.0	16/07/2019	Version with the reviewers' comments	SCHWARZENBOECK Alfons
R1.1	29/07/2019	Police changed in 'Exec Summary'; Table 10 modified; Another YAK-42 idea added (see few sentences PIP orientation in sect. 3.8)	SCHWARZENBOECK Alfons

## Deliverable Contributors

### Authors

Organisation	Authors' name
CNRS	SCHWARZENBOECK Alfons
AIH	DEZITTER Fabien

### Contributors

Organisation	Contributors' name
CNRS	COUTRIS Pierre, DUPUY Régis, FEBVRE Guy, GOURBEYRE Christophe
AIH	DEZITTER Fabien
CAO	STRUNIN Mikhail, PETROW Victor
TSAGI	MILLER Alexey

### Internal Reviewers

Organisation	Internal Reviewers' name
DLR	HELLER Romy / VOIGT Christiane
DGA	FREUDENREICH Claire

## Table of Contents

---

1	Glossary.....	6
2	Executive Summary .....	8
3	Review of available airborne instrumentation, specification of F/T measurements for snow, and final selection.....	9
3.1	Introduction: setting new standards for snow certification .....	9
3.2	Specification (snow microphysics, installation on aircraft) of snow measurements on aircraft 12	
3.3	State of the art airborne microphysical instruments particularly suited for snow particle measurements .....	13
3.4	Recommendations for ATR-42 and YAK-42D snow microphysics instrumentation (available in the scientific community) thereby meeting above specifications.....	14
3.5	Detailed overview of airborne instrumentation for research aircraft in snow conditions... 16	
3.5.1	Particle imaging probes OAP .....	16
3.5.2	Particle Imaging probes CCD .....	17
3.5.3	Particle scattering spectrometers.....	18
3.5.4	Combination probes.....	19
3.5.5	Bulk snow water content devices .....	19
3.5.6	Other probes.....	21
3.5.7	Sensors for meteorological parameters on ATR-42 & YAK-42 .....	22
3.6	Aircraft specifications .....	22
3.6.1	YAK 42 .....	22
3.6.2	ATR-42 .....	24
3.7	Instrument selection: generalities.....	28
3.8	Instrument selection: YAK-42D cloud instruments to be used for first ICE GENESIS campaign 30	
3.9	Instrument selection: Proposition of ATR-42 instruments to be used for second ICE GENESIS campaign.....	36
4	Conclusions .....	43
5	Bibliography .....	45

## Table of Tables

---

Table 1: OAP – Part 1 .....	16
Table 2: OAP – Part 2 .....	16
Table 3: CCD – Part 1 .....	17
Table 4: CCD – Part 2 .....	17
Table 5: Scattering probes – Part 1 .....	18
Table 6: Scattering probes – Part 2 .....	18
Table 7: Combination probes – Part 1 .....	19
Table 8: Combination probes – Part 2 .....	19
Table 9: Bulk WC probes – Part 1 .....	19
Table 10: Bulk WC probes – Part 2 .....	20
Table 11: Other probes – Part 1 .....	21
Table 12: Other probes – Part 2 .....	21
Table 13: Meteorological sensors .....	22

## Table of Figures

---

Figure 1 - Snow Crystal Morphology Diagram .....	9
Figure 2 - Representative snowflakes with sizes around 2-4 mm, obtained in flight test at -3°C (Source: Airbus) .....	10
Figure 3 - Representative snowflakes with sizes beyond 4 mm, obtained in flight test at -5°C (Source: Airbus) .....	10
Figure 4 – Cumulative mass PSD for Helicopter flights performed in snow conditions during winter 2017/2018.....	14
Figure 5 - Russian aircraft-laboratory Yak-42D “Roshydromet” with basic characteristics.....	23
Figure 6 - Structural diagram of the measuring system of the aircraft-laboratory Yak-42D “Roshydromet” .....	24
Figure 7 - ATR42 – performances and modifications for scientific instrumentation .....	25
Figure 8 - ATR42 during flight mission.....	26
Figure 9 - ATR42 – basic instruments .....	26
Figure 10 - ATR42 – optional instruments .....	27
Figure 11 - Multiple instruments to cover complete range from 1µm 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! .....	29
Figure 12 – Under-wing stations with cloud microphysical sensors .....	30
Figure 13 - Sensor for liquid water content (right). Working places for on-board operators (left) .....	31
Figure 14 - Outside radar antenna of radars and working place of on-board operator.....	32
Figure 15 – Complementary instrumentation from ICE GENESIS consortium for the YAK-42D aircraft .....	34
Figure 16 – YAK-42D instrumental configuration out of multiple instruments to cover complete range from 1µm to 10 mm and beyond. Red circles are for existing YAK-42D cloud instruments. Yellow circles from ICE GENESIS consortium.....	35
Figure 17 – ATR-42 in situ instrumentation: Polar Nephelometer, CPI, PIP dummy (upper left), 2D-S / FCDP (upper right), CVI cloud inlet (lower left) and measurement rack, synthetic dry air for CVI (lower right). .....	37
Figure 18 – ATR-42 configuration out of multiple instruments to cover complete range from 1µm to 10 mm and beyond. Red circles are for chosen ATR-42 cloud instruments.....	39
Figure 19 – Snow cloud microphysical instrumentation .....	42

# 1 Glossary

---

2D-P	2D Precipitation Probe
2D-S	2D Stereo Probe
A/C	Aircraft
AB	Advisory Board
AIH	AIRBUS HELICOPTERS
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
CPSPD	Cloud Particle Spectrometer with Depolarization
CPI	Cloud Particle Imager
CS23	Certification Specification Nr
CSI	Cloud Spectrometer and Impactor
CV-580	Convair-580
CVI	Counterflow Virtual Impactor
DLR	Deutsche Luft und Raumfahrtgesellschaft
F20	Falcon 20
F/T	Flight Test
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
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
IKP-2	Isokinetic Evaporator Probe 2
IWC	Ice Water Content

LaMP	Laboratoire de Météorologie Physique
LATMOS	Laboratoire Atmosphères, Milieux, Observations Spatiales
LWC	Liquid Water Content
MMD	Median Mass Diameter
OAP	Optical Array Probe
PIP	Precipitation Imaging Probe
PSD	Particle Size Distribution
RASTA	RAdar SysTem Airborne
RICE	Rosemount Ice Detector
SP-2	Single Particle Soot Photometer
TAS	True Airspeed
TAT	Total Air Temperature
TDL	Tunable Diode Laser
TWC	Total Water Content
UHSAS	The ultra-high-sensitivity aerosol spectrometer
SAFIRE	Service des Avions Français Instrumentés pour la Recherche en Environnement
W/T	Wind Tunnel

## 2 Executive Summary

---

Within the European ICE-GENESIS project, the Russian aircraft-laboratory Yak-42D “Roshydromet” and the French ATR42 research aircraft from SAFIRE will perform 2 flight test campaigns out of France and Russia representing a total of 75 flight hours. The primary objective is to best characterize snow particle microphysical properties to complement existing partial databases with a set of data for detailed microphysical closure studies of snow crystal populations. These experiments will provide the first modern extensive data set of snow conditions to be taken into account for icing studies and as such will be a unique resource for fundamental research, development of snow capabilities and for airworthiness authorities.

The work performed in order to produce the deliverable D5.1 is entirely related to the choice of most suitable instrumentation for snow microphysics research on above research aircraft, which means we have to take into account payload possibilities, installation constraints, and certification limitations. The work beyond D5.1 to be undertaken subsequently will be to design the flight plans, conduct the two field campaigns and process the observations of basic aircraft, in situ microphysics, and radar observations.

The first measurement campaign with the Russian YAK-42D has been scheduled October 2019 – March 2020, out of Moscow, Russia. Briefly, the Russian aircraft-laboratory Yak-42D “Roshydromet” will be equipped by state of the art instrumentation for in situ microphysical measurements (imaging probes, cloud droplet spectrometer, LWC and TWC sensors) as well as with an on-board Doppler vertical radar (3.2 cm wavelength; upward and downward with active scanning antenna). The second measurement campaign will take place during winter 2020/2021, out of Toulouse, France, thereby operating the French ATR-42. The SAFIRE ATR42 will be equipped with active remote sensing (RASTA airborne cloud radar) and state of the art in situ microphysics measurements (e.g. OAP and high resolution imagers, TWC devices). State of the art best quality measurements of thermodynamic background conditions are essential for both research aircraft. The work to be undertaken subsequently will be to design the flight plan, conduct the field campaign and process the observations of basic aircraft, in situ microphysics and radar instruments. YAK-42D and ATR-42 aircraft are intended flying primarily at flight levels between -10 and 0°C.

**The main objectives that we have to meet with the selected instrumental payload for both research aircraft are to:**

1. Guarantee measurement reliability of large ice particle properties (size dependent crystal number and mass) up to 10 mm (and beyond if possible): PIP, HVPS,...
2. Ensure the snow IWC measurement capabilities of bulk snow water content containing large snow crystals: NEVZOROV and/or ROBUST probes (to be characterized), CVI evaporator probe,...
3. Deploy an instrumental payload allowing the measurement and quantification of supercooled water if any with discrimination of the phase (solid - liquid) of hydrometeors: CDP, CPI/HSI, others...
4. Allow a reasonably good morphological analysis of the snow crystal / snowflakes shape

### 3 Review of available airborne instrumentation, specification of F/T measurements for snow, and final selection

#### 3.1 Introduction: setting new standards for snow certification

Snow crystals (water vapour and riming growth regimes) and snowflakes (aggregates of many single ice crystals) together are denoted snow particles. In nature, ice crystals often 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). 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 sectored plates and dendrites (from -10 to -22 °C), and finally solid plates and columns (below -22 °C), according to cloud temperature and water vapour content. In addition to crystal growth from pure water vapour deposition, aggregation and riming growth modes generate highly irregular shaped larger ice crystals.

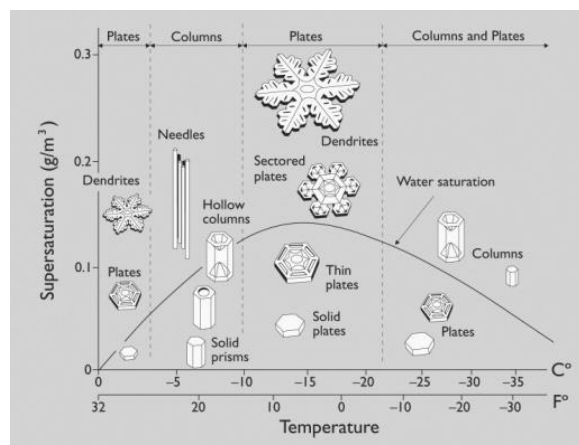


Figure 1 - Snow Crystal Morphology Diagram

Finally, aggregation of crystals thereby forming snowflakes 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 2 and 5 mm, ranging up to 15 mm. Snowflake density (Rasmussen et al., 1999) varies, ranging from 0.005 to 0.2 g cm<sup>-3</sup>, 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.

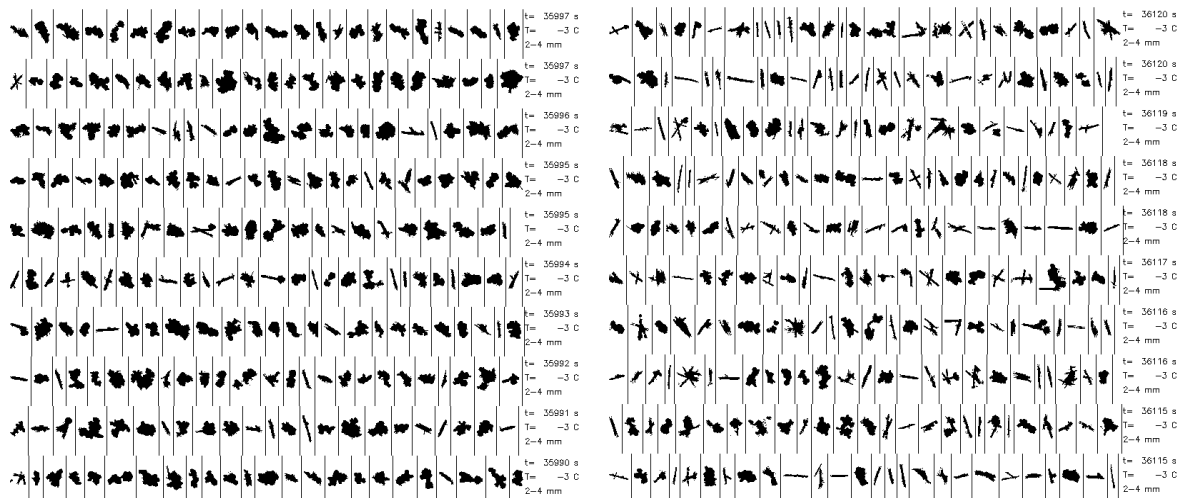


Figure 2 - Representative snowflakes with sizes around 2-4 mm, obtained in flight test at -3°C (Source: Airbus)

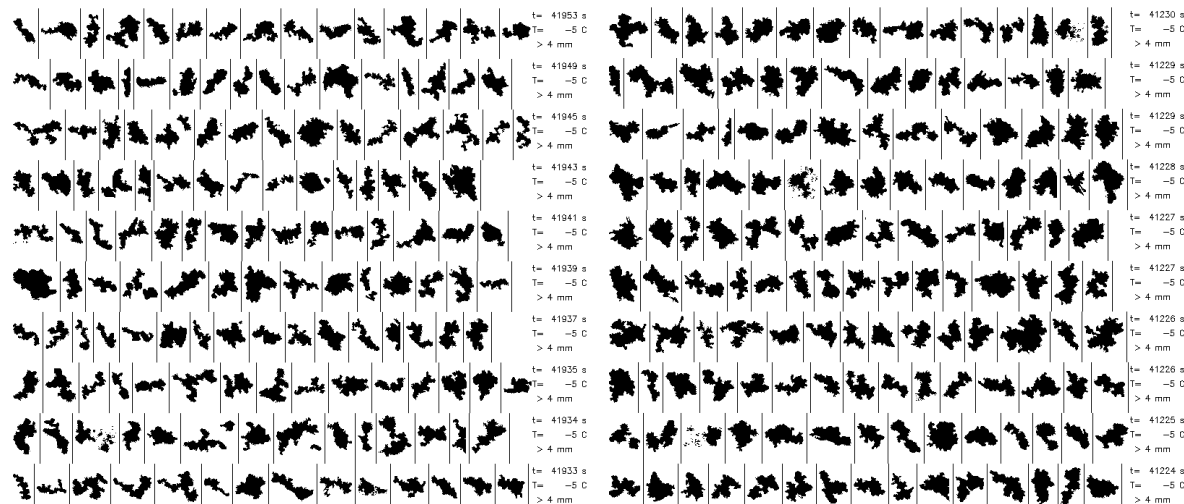


Figure 3 - Representative snowflakes with sizes beyond 4 mm, obtained in flight test at -5°C (Source: Airbus)

For snow certification, aircraft manufacturer must demonstrate that each engine and its air inlet system can operate throughout the flight power range of the engine (including idling) in snow, both falling and blowing, without adverse effect on engine operation (power or thrust loss, surge, stall or flameout), within the limitations established for the aircraft (CS23/25/27/29, §1093(b)). The regulation does not provide the detailed definition of falling and blowing snow conditions and as such no quantified specification of snow has been available for engineering purposes. At most, Advisory Circular (e.g. AC29-2C) provides minimum information on the temperature range to be considered [-4°C - +1°C] and defines a visibility criterion representative of snow water content (1/4-mile or less as limited by snow or about 0,9g/m<sup>3</sup>).

To overcome this deficiency, a first data compilation and analysis effort was undertaken in DOT/FAA/AR-97/66 (Snow and Ice Particle Sizes and Mass Concentrations at Altitudes Up to 9 km (30,000 ft),) to improve the understanding and characterization (engineering specification) of icing

conditions in the atmosphere. The report provided a large database of select in-flight measurements of snow and ice crystal concentrations, sizes, and mass accumulations at flight altitudes. To this end, data from 50 research flights in a variety of wintertime and high-altitude clouds up to 30,000 ft (9 km) and temperatures down to -50°C have been collected from six different research groups. Some 7600 nautical miles of selected quality data have been compiled into a single, computerized database for use in developing the desired information for aircraft engineering purposes. As a result of these analyses, first altitude-graduated table of ice/snow cloud properties was proposed for defining the “falling and blowing snow” requirement but was not introduced in FAR/CS 23.1093, 25.1093, 27.1093, and 29.1093. For falling and blowing snow requirements, gaps remain and additional ground and in-flight measurements are necessary to characterize snow precipitation microphysics.

The ambition of ICE-GENESIS is thus to make decisive progress in the characterization of snow precipitation microphysics through the combined use of ground based measurement, airborne measurement and active remote sensing retrievals of snow properties in the atmospheric column. The work to be undertaken will allow quantifying the microphysical properties (3D size, crystal mass, mass-size relation, fractal dimension, differentiation dry and wet snow, number and mass size distributions) of individual snow crystals as well as entire snow crystal populations (per volume of air) of snow conditions and will provide requirements for the development of test and numerical capabilities.

### 3.2 Specification (snow microphysics, installation on aircraft) of snow measurements on aircraft

The installation requirements and measurement specifications for airborne instrumentation for research aircraft and its application for snow measurements on the YAK-42D and ATR 42 are described. Due to the large range of snow crystal sizes, often several measurement instruments have to be combined to cover the total size range (instruments with overlapping size ranges).

In-situ measurements and remote sensing of snow cloud microphysical parameters in the crucial temperature range between -10°C and +2°C should retrieve subsequent cloud information:

- Number concentration of snow cloud particles (drops if any and snow crystals/flakes), maximum value will not exceed 1 crystal per liter
- Sizes of the snow particles in the range from several tens/hundreds of  $\mu\text{m}$  to 4 cm (even sizes up to 2-6 inches may have been observed in past snowfall events...)
- The resulting total water content (TWC) may reach 1 g / m<sup>3</sup> (maximum 2 g / m<sup>3</sup>)
- Discrimination of liquid cloud particles from ice phase, i.e. distinguish LWC and IWC (TWC=LWC+IWC)
- Snow crystal/flake habit (geometrical aspect, growth mode, ...) impacting the hydrometeor density and fall speed
- Above measurements may be completed with extinction / visibility estimations to characterize the cloud environment from a pilot's point of view
- If possible, melting ratio of snow particles

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

- Temperature, relative humidity, static pressure, horizontal and vertical wind (both local measurements and if possible in the vertical column)
- Cloud vertical extension

The relative uncertainty for cloud microphysical properties shall be targeted to not exceed 20%. Flight data (total pressure (PT), angle of attack ( $\alpha$ ), sideslip ( $\beta$ ), total air temperature (TAT), aircraft roll and pitch, true air speed, position, altitude) are mandatory for the analysis/calculation of microphysical properties and meteorological parameters from research instrumentation. Data (microphysical properties, meteorological parameters, aircraft parameters) shall be time stamped with synchronized time base. The instrument location for snow crystals/flakes shall be outside the boundary layer of the aircraft. The design of the probes shall minimize the effects of the instrumentation on the measured values; e.g. avoid shattering of drops and 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 flight.

### 3.3 State of the art airborne microphysical instruments particularly suited for snow particle measurements

State of the art airborne measurements of snow crystal properties rely primarily on instrumental means used for studies of ice microphysical measurements, e.g. in convective systems as has been performed within the frame of the European HAIC project (Dezitter 2013, Leroy et al., 2016 & 2017). Particularly, precipitation-sized particles can be measured by OAP probes as there are the cloud imaging probe CIP, the stereoscopic 2D-S, the precipitation imaging probe PIP, the high volume particle sampler HVPS, but also by CCD camera type imaging probes as the high resolution cloud particle imager CPI or the high speed imager HSI. All those imaging probes have their specific image resolution (approximately 2-200  $\mu\text{m}$  pixel resolution, e.g. CPI and 2D-P, respectively) and also maximum measurable particle size (approximately 1-20mm in diameter, e.g. CIP\_15 $\mu\text{m}$  and HVPS, respectively). Bulk IWC measurements in snow conditions are of limited reliability. This is true for hot wire type TWC devices lacking a well-defined, since variable collection efficiency, difficult to parametrize as a function of particle size, air density, TAS, etc...

A promising technology has been designed for the HAIC project and consists of the Isokinetic Evaporator Probe IKP-2 (Strapp, 2016), with the drawback of uncertain vapour mixing ratio in continuously changing conditions and respective non negligible uncertainties at temperatures around 0°C. A solution that might be favoured 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). A significant challenge within ICE GENESIS will be to reconcile both ground based and airborne instrumentation whenever the two instrumental setups may differ.

### 3.4 Recommendations for ATR-42 and YAK-42D 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 the ATR-42 and also YAK-42D research aircraft in snow conditions in order to meet the objectives of the ICE GENESIS project with measurement campaigns performed out of Toulouse and Moscow, respectively.

1. Need of imaging probes for large crystal sizes beyond 1 mm up to even several tens of mm. 80-90% of ice crystal mass (average value) was found beyond 1 mm for recently gathered snow data on Airbus Helicopters H160. Three flights had been performed with subsequent cumulative mass distributions.

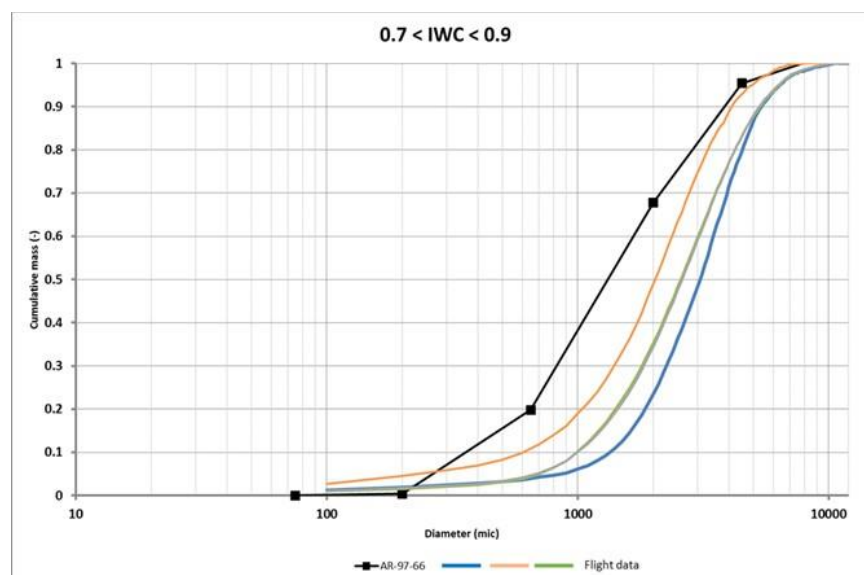


Figure 4 – Cumulative mass PSD for Helicopter flights performed in snow conditions during winter 2017/2018.

MMDmax of about 2000-3000  $\mu\text{m}$  were observed which represents larger values than reported in AR-97/66-Low Alt curve. The precipitation imaging probes PIP and HVPS are capable of sizing crystals up to 6.4 mm (PIP 64 photodiodes at 100  $\mu\text{m}$  pixel resolution, twice the resolution of the legacy 2D-P probe) and 19.2 mm (HVPS 128 photodiodes at 150  $\mu\text{m}$  pixel resolution), respectively, the HSI (high resolution and high speed imaging, under acquisition) is sizing up to 2.5 mm. However, the more the ice particle is at the upper size limit of a corresponding probe the higher the probability of truncated images is. This is why the availability of the new HVPS at CNRS and DLR institutes is of a major advantage.

2. Need of imaging probes for intermediate crystal sizes between 50  $\mu\text{m}$  and 1 mm, in order not to miss information in that size range, even though not much mass contribution to snow water

content is expected in this range. Use of highest resolution array probes such as the 2D-Stereo or 2D-S probe (DLR, CNRS-LaMP) or the high speed imager HSI (CNRS probe acquisition). The 2D-S has a pixel resolution of 10  $\mu\text{m}$  as compared to standard pixel resolution of 25  $\mu\text{m}$  for comparable cloud imaging probe CIP (new probe, SAFIRE). An alternative probe is the high speed imaging probe HSI measuring up to 2,5 mm. First HSI tests with the new probe are planned for autumn 2019 at CNRS-LaMP.

3. Need of bulk IWC measurement devices. The need for implementation of reliable snow water content measurements on research aircraft is extremely challenging. During HAIC project the two probes ROBUST and NEVZOROV have been compared/evaluated (Schwarzenboeck, 2019 & courtesy A. Korolev) with respect to the IKP-2 reference measurement of IWC. Results from these comparisons will be used for snow water content retrievals on both aircraft ATR-42 and YAK-42. The IKP-2 instrument does not seem to be the first choice for snow measurements due to the fact that background water vapour measurement or theoretical assumptions create uncertainties of roughly 200 mg / m<sup>3</sup> compared to snow water content of up to 1 g / m<sup>3</sup> and solely several hundreds of mg / m<sup>3</sup> most of the times. The discussed snow water content measurement problem on aircraft led to the initiative of modifying an existing CVI inlet, certified on the ATR-42, such that the inlet is optimized for use on the ATR-42. For the YAK-42D the CVI is not certified. Certification is beyond the financial means of the ICE-GENESIS project.
4. Need of discrimination of phases of particles (solid/liquid). We suggest to use data from NEVZOROV probe, Rosemount Ice detector, cloud droplet spectrometer and eventually particle spectrometer probe with depolarization CPSPD. Their efficiencies (response functions) with respect to water and ice, respectively, partly have been evaluated within the HAIC project.
5. Avoidance of possible small ice crystals contamination on spectrometer data due to ice particle shattering. Reduction of the possible artefacts created by particle breakups 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. Finally bulk snow water content CVI inlet just serves as snow water content device. 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, CPSPD, 2D-S, CIP, PIP, HSI, etc.
6. 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 crystals measurement: 1-50  $\mu\text{m}$ : CDP or CPSPD; 10-1500  $\mu\text{m}$ : CPI, 2D-S, CIP, HSI; 1-20 mm: PIP and HVPS (precipitation imaging probes).

### 3.5 Detailed overview of airborne instrumentation for research aircraft in snow conditions

In this section, detailed information for instrumentation (particle spectrometers & imagers, bulk measurement devices, radar,...) potentially measuring in snow conditions on research aircraft is provided.

#### 3.5.1 Particle imaging probes OAP

Table 1: OAP – Part 1

Instrument (Manufacturer)	Name	Nominal size range	Size resolution	Sampling frequency	Parameters provided
<b>2D Imaging Probes OAP for quantitative snow crystal number PSD</b>					
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	Use in W/T	Use on A/C (certified)	Instrument can be provided by
<b>2D Imaging Probes OAP for quantitative snow crystal number PSD</b>						
HVPS version 3 (SPEC)	Data interfacing via Ethernet Cat 5	9.5 kg; 90 cm x 28 cm x 18 cm; SPEC canister	< 600 watts of 115VAC, 400 or 60 Hz, and <200 watts of 28 VDC	x	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	x (yes)	CNRS-LAMP / DLR
CIP (DMT)	10 – 300 m/sec (for 25-µm CIP)	9.5 kg in DMT canister	28VDC: 11A for probe system, anti-ice	x	x (yes)	CNRS-SAFIRE

	10 - 180 m/sec (for 15- $\mu$ m CIP) -40 °C to +40°C Altitude: 0 - 50,000 ft		heaters either 13A (standard tips) or 17A (Korolev tips)			
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	x (yes)	CNRS-LAMP / DLR

### 3.5.2 Particle Imaging probes CCD

Table 3: CCD – Part 1

Instrument (Manufacturer)	Name	Nominal size range	Size resolution	Sampling frequency	Parameters provided
<b>2D Imaging Probes CCD (256 grey scales) for more detailed crystal morphology</b>					
HSI (ARTIUM)	High Speed Imager	3 $\mu$ m - 4 mm	3 $\mu$ m (2000*900)	single particle mode; max 400 frames / s	size, detailed morphology
CPI version 1 (SPEC)	Cloud Particle Imager	2.3 $\mu$ m - 2.3 mm	2.3 $\mu$ m (1000*1000)	single particle mode; max 40 frames / s	size, detailed morphology

Table 4: CCD – Part 2

Instrument / Manufacturer	Performance / complementary information	Dimensions (weight; length x width x height)	Power Requirements	W/T	A/C (certified)	Instrument can be provided by
<b>2D Imaging Probes CCD (256 grey scales) for more detailed crystal morphology</b>						
HSI (ARTIUM)	small sampling volume!	canister probe 10 kg standalone	28VDC (300 W) electronics / pc 110 VAC de-ice (1,4 kW)	x	x (TBD)	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: 690x360x160m m	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	x (yes)	CNRS-LAMP

## 3.5.3 Particle scattering spectrometers

Table 5: Scattering probes – Part 1

Instrument (Manufacturer)	Name	Nominal size range	Size resolution	Sampling frequency	Parameters provided
<b>Scattering Probes for droplet number PSD &amp; liquid detection</b>					
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) <sup>1)</sup>	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	A/C (certified)	Instrument can be provided by
<b>Scattering Probes for droplet number PSD &amp; liquid detection</b>						
CAS-DPOL (DMT)	>1000 particles/second - -> coincidence	11.5 kg; 100 cm x 32 cm x 28 cm	28 VDC	x	x (TBDone)	DLR
CDP-2 (DMT)	Altitude: 0 - 50,000 feet -40 to 40 °C 10 - 250 m/sec 0 - 2,000 particles/cm <sup>3</sup>	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	x (yes)	CNRS-LAMP
FCDP (SPEC) <sup>1)</sup>	stand alone or combination with other probes	2.5 kg; 28 cm x 15 cm x 23 cm	28 VDC, 115 VAC	x	x (yes)	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	x (TBDone)	DLR

### 3.5.4 Combination probes

Table 7: Combination probes – Part 1

Instrument (Manufacturer)	Name	Nominal size range	Size resolution	Sampling frequency	Parameters provided
<b>Use of Combination Probes</b>					
CAPS (DMT) = CAS-DPOL + CIP	Cloud and Aerosol and Precipitation Spectrometer (CAS-DPOL + CIP-15)	0.5 - 50 µm (particle); 15 µm - 0.96 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	
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	A/C (certified)	Instrument can be provided by
<b>Use of Combination Probes</b>						
CAPS (DMT) = CAS-DPOL + CIP	see individual probes above	20.4 kg	see individual probes above	x	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	x (yes)	CNRS-LaMP, DLR

### 3.5.5 Bulk snow water content devices

Table 9: Bulk WC probes – Part 1

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

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

Table 10: Bulk WC probes – Part 2

<b>Instrument / Manufacturer</b>	<b>Performance / complementary information</b>	<b>Dimensions (weight; length x width x height)</b>	<b>Power Requirements</b>	<b>W/T</b>	<b>A/C (certified)</b>	<b>Instrument can be provided by</b>
<b>Bulk WC</b>						
<b>IKP Cranfield University</b> (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	Not an A/C version	Cranfield University
<b>IKP-2 (NASA, SEA, ECCC)</b> (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	x	NASA, SEA, ECCC
<b>Snow CVI</b>	40 – 200 m/sec; Max. 1-2 g/m <sup>3</sup> ; 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	x (yes)	CNRS-LAMP
<b>ROBUST Probe</b>	WCM-3000 Robust Water Content System; Element heated to 140°C; TWC probe 0 - 10 g/m <sup>3</sup> ; 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 <sup>3</sup> 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	x (yes)	CNRS-SAFIRE / AIRBUS

NEVZOROV Probe Sky Tech Research	deep cone version; 10-180 m/s ; 0.003-3 g/m <sup>3</sup> ; 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	x (yes)	CNRS-SAFIRE / DLR
RICE Probe	Rosemount Ice Detector ; A/C probe for supercooled water detection – qualitative; operates properly at T < -8°C	385.6 grams Max. diameter : 82.55 mm	28 VDC, 330W	x	x (TBDone)	CNRS-SAFIRE

### 3.5.6 Other probes

Table 11: Other probes – Part 1

Instrument (Manufacturer)	Name	Snow WC / TWC range	Sampling frequency	Parameters provided
<b>Other Probes</b>				
Polar Nephelometer / LAMP	PN	all	1-100 Hz	extinction, scattering phase function
Doppler cloud radar W-band / LATMOS	RASTA; 95GHz cloud radar, 6 antennas	Vert res 60 m; horiz res 225 m	1 Hz	94 GHz reflectivity and Doppler velocity

Table 12: Other probes – Part 2

Instrument / Manufacturer	Performance / complementary information	Dimensions (weight; length x width x height)	Power Requirements	W/T	A/C (certified)	Instrument can be provided by
<b>Other Probes</b>						
Polar Nephelometer / LAMP	measurement independent of TAS	1030*222 mm in PMS canister 15 kg without canister	Deice 115 VAC 450W, Probe 115 VAC 100 W, DAS 100-220 VAC 100 W	x	x (yes)	LAMP
Doppler cloud radar W-band / LATMOS	Attenuation in layers of dense liquid precipitation	installation in ATR cabin: 82x102x150cm; 110 kg	500 W		x (yes)	LATMOS

### 3.5.7 Sensors for meteorological parameters on ATR-42 & YAK-42

Table 13: Meteorological sensors

Meteorological sensors	Parameter provided	Sensor limitation	Sampling frequency	Instrument provided by
Temperature	Dry temperature	Unknown	>1 Hz	Safire TSAGI
Relative Humidity	RH and water-vapour concentration	Uncertainties close to 100%	> 1Hz	Safire TSAGI
u, v, w wind components	Horizontal speed and direction, vertical wind w	Uncertainties for low w	> 10 Hz	Safire TSAGI
Static Pressure	p	Unknown	1 Hz	Safire TSAGI

## 3.6 Aircraft specifications

ICE GENESIS will conduct 2 flight test campaigns, representing a total of 75 flight hours, out of Russia and France with the Russian aircraft-laboratory Yak-42D "Roshydromet" and the French ATR42 research aircraft from SAFIRE to complement existing partial databases with a set of data for detailed microphysical closure studies of snow crystal populations. These experiments will provide a modern extensive data set of snow conditions and as such will be a unique resource for fundamental research, development of snow capabilities, and for airworthiness authorities.

### 3.6.1 YAK 42

The Yak-42D № 42440 aircraft-laboratory "Roshydromet" was built up at the end of 2013 [Borisov et al., 2012] and began to be actively used in atmospheric research and scientific and industrial works on weather modification in 2014. The appearance of the aircraft-laboratory and its basic flight-technical characteristics are documented in Bazanin et al., [2014].

The ICE GENESIS project consortium is aware of the fact that within the very limited time before the beginning of the first flight test campaign in winter 2019/2020 the modification of the payload is not very flexible, with exceptions presented in the payload selection section.

Overall the Yak-42D will perform roughly 50 flight hours for the ICE GENESIS project during upcoming winter 2019/2020 out of Moscow.

- Crew – 3 members;
- Maximum flight level – 10200 m;
- Flight distance – 3500 km;
- Flight speed – from 350 up to 700 km/h;
- Maximum take-off weight – 57 tons;
- Onboard operators – up to 14 members.



Figure 5 - Russian aircraft-laboratory Yak-42D "Roshydromet" with basic characteristics

The measuring system of the Yak-42D "Roshydromet" aircraft-laboratory consists of three structure levels.

- The first level of the Yak-42D "Roshydromet" measuring system are the sensors and measuring systems of individual complexes (temperature and pressure sensors, navigation systems, spectrometers, radar, particle counters, multispectral radiation chambers, etc.).
- The second level is hardware-software complexes into which sensors and measuring systems are combined using special software. These are the complexes responsible for measuring navigation and thermodynamic parameters, atmospheric electricity, solar radiation in the atmosphere, microphysical parameters of clouds, radiolocation of clouds and surfaces, radioactive pollutants, gas and aerosol concentrations in the atmosphere and means for clouds seeding.

- The third level is the on-board local computer net, which integrates the hardware-software complexes into a common on-board measuring system of Yak-42D “Roshydromet” aircraft-laboratory, which includes a data acquisition system, a satellite channel for transmitting operational information and a dispatch system for carrying out a local airplane experiment. At this level all data recording, reserving and exchanging between the complexes are organized, general guidance of the experiment and transfer of operational data to the ground-based data processing and analysis centers are performed.

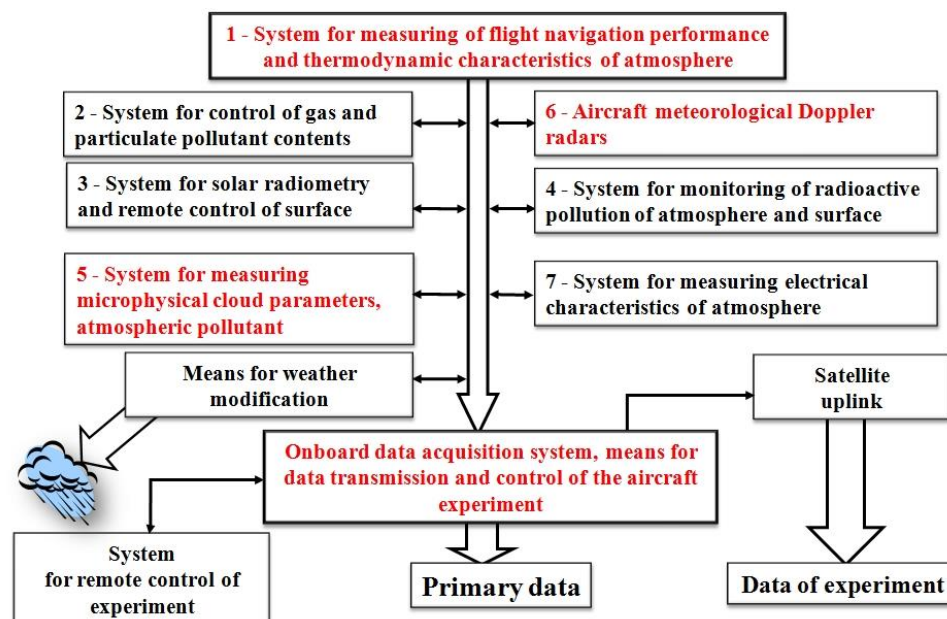


Figure 6 - Structural diagram of the measuring system of the aircraft-laboratory Yak-42D “Roshydromet”


The structural diagram of the measuring system of the aircraft-laboratory Yak-42D “Roshydromet” is presented in the figure above. The red coloured text is highlighting the systems, which are planned to be used for the flight campaign in the frame of ICE GENESIS.

### 3.6.2 ATR-42

The SAFIRE ATR 42 and will be available for 25 research flight hours during the planned field campaign: in winter 2020/21. The ATR 42 is equipped from SAFIRE with basic meteorological measurements, including temperature, pressure, moisture and winds, together with some limited cloud instrumentation from SAFIRE. The main contribution on cloud microphysics instrumentation often stems from CNRS-LaMP, which is the leading French science group in ice cloud in situ characterization, having equipped the ATR-42 and in particular the SAFIRE Falcon 20 in numerous past cloud measurement projects. The fact that CNRS-LaMP is a leading cloud microphysics laboratory in Europe which has flown many ice microphysics campaigns for SAFIRE means that many state of the art instruments are certified and that certification procedures for SAFIRE aircraft are well-known. This makes of course the ATR-42 a more flexible aircraft for dedicated instrumental configurations to be

chosen for the ICE GENESIS flight test campaign. SAFIRE has its own pilots, mechanics, and technical staff for instrument installation and certification services.

Below are presented ATR-42 flight performances, aircraft characteristics for research use, basic instruments and some optional instrumental possibilities that SAFIRE can offer to aircraft users. Beyond these instruments CNRS-LAMP and LATMOS will add most sophisticated cloud instrumentation for snow dedicated research.

Dimensions	
Length: 22.67 m	
Height: 7.75 m	
Wingspan: 24.57 m	
Flying performances	
<b>Speed</b>	
Min speed	70 m/s
Max speed	134 m/s
Usual speed during measurements	100 m/s
Usual speed during transit flights	134 m/s
Ascent rate	6 m/s
<b>Altitude</b>	
Min altitude	Above sea: 200 ft Above ground: 500 ft
Max ceiling	25 000 ft
Usual ceiling during measurements	21 000 ft
Ceiling limitations	n/c
<b>Payload</b>	
Empty weight	11 300 kg
Max take-off weight	16 900 kg
Max payload	4 600 kg
Max scientific payload	3 300 kg (X-coordinate of 2nd point)
Usual scientific payload during measurements	2 000 kg
Scientific payload for max endurance	100 kg (X-coordinate of 1st point)

	Aircraft modifications
Nose boom	a 5 holes probe in the nose for high rate turbulence measurements
Windows	all windows can be equipped with scientific instruments
Openings	top of fuselage: 2 holes D0.150 m, 1 hole D0.20 m, 1 hole D0.40 m ; bottom of fuselage: 1 large front opening W0.40 m x L0.60 m, 1 large back opening W0.40 m x L0.70 m, 2 holes D0.15 m, 1 hole D0.20 m
Hard points	PMS carrying points under the wings (3 per wing max.) Other heavier carrying point around fuselage (4 points)
Inlets	- Isokinetic Aerosol inlet on the front right window - CVI aerosol inlet on the top left of fuselage (on demand) - many chemistry inflow or reverse flow inlets.
Additional systems	see all aircraft modifications in the attached document

Figure 7 - ATR42 – performances and modifications for scientific instrumentation



Figure 8 - ATR42 during flight mission

### Basic instruments

Instrument type	Instrument name Serial type	Operator	Measured parameter	Range	Weight added
Inertial Reference/Navigation System	SAFIRE AIRINS	SAFIRE	Aircraft position, velocity and attitude		3.0 kg
Non dew/frost point hygrometer	SAFIRE relative humidity sensor	SAFIRE	Water Vapour, Relative Humidity		0.0 kg
Incident flow vector probe	SAFIRE Five hole radome	SAFIRE	Airspeed; Incidence angle; Turbulence		0.0 kg
Dew/Frost-point hygrometer	SAFIRE General Eastern 1011B hygrometer	SAFIRE	Dew Point		0.0 kg
Global Positioning System	L1 / L2 GPS-Antennae (5x), NovAtel OEM3	TUBs	Aircraft position, velocity and attitude		0.98 kg
Broad Band Radiometer	SAFIRE Kipp & Zonen CGR4 Pyrgometer	SAFIRE	Hemispheric broadband radiance		0.0 kg
Broad Band Radiometer	SAFIRE Kipp & Zonen CMP22 Pyranometer	SAFIRE	Hemispheric broadband radiance		0.0 kg
Temperature sensor (in situ)	SAFIRE Rosemount PT102E2AL	SAFIRE	Temperature		0.0 kg
Inertial Reference/Navigation System	High Accuracy Inertial Navigation system	NLR	Aircraft position, velocity and attitude		0.0 kg

Figure 9 - ATR42 – basic instruments

## Optional instruments

Instrument type	Instrument name Serial type	Operator	Measured parameter	Range	Weight added
Dew/Frost-point hygrometer	SAFIRE ATR Buck 1011C hygrometer	SAFIRE	Dew Point		0.7 kg
Dew/Frost-point hygrometer	SAFIRE F20 Buck CR-2 Cryogenic Aircraft Hygrometer	SAFIRE	Dew Point		6.0 kg
Cloud Droplet Size Spectrometer	SAFIRE Cloud Droplet Probe	SAFIRE	Cloud droplet size spectra, number concentration and water content,	2-50µm with particule option (30 bins)	1.37 kg
Cloud/Aerosol Microphysics Multi-function Instrument	Cloud Imaging Probe	SAFIRE	Aerosol and cloud droplet properties		11.5 kg
Ozone Analyzer	SAFIRE Environnement 0341M ozone analyzer	SAFIRE	O3 concentration		0.0 kg
Cloud Droplet Size Spectrometer	Meteo-France Fast Forward Scattering Spectrometer	Meteo-France/CNRM	Cloud droplet size spectra, number concentration and water content,		16.5 kg
Cloud Droplet Size Spectrometer	SAFIRE Forward Scattering Spectrometer Probe 300	SAFIRE	Cloud droplet size spectra, number concentration and water content,		15.0 kg
King/CSIRO Liquid Water Content	LWC200	SAFIRE	Liquid water content g/m-3	0 - 3g/m3	0.6 kg
Cloud Liquid and Total Condensate	SAFIRE Nevzorov (unattended version)	SAFIRE	Liquid and Ice water content		5.2 kg
Trace Gas Analyzer	Thermo-Electron 42C NOx sensor	SAFIRE	Trace Gas concentrations		0.0 kg
Ozone Analyzer	SAFIRE THERMO-ELECTRON 49PS	SAFIRE	O3 concentration		0.0 kg
Ozone Analyzer	SAFIRE THERMO-ELECTRON 49S	SAFIRE	O3 concentration		22.0 kg
Trace Gas Analyzer	SAFIRE CO instrument	SAFIRE	Trace Gas concentrations		25.0 kg
Condensation Particle Counter (CPC)	SAFIRE TSI-3022 CPC	SAFIRE	Number concentration of submicrometer aerosol particles		0.0 kg
Aerosol Spectrometer Probe	Ultra High Sensitivity Aerosol Spectrometer	UNIMAN	Aerosol concentration and size distribution spectra		31.0 kg

Figure 10 - ATR42 – optional instruments

### 3.7 Instrument selection: generalities

The current state of the art airborne instruments for snow crystal and snowflake particle size and shape determination as well as bulk snow WC measurements are mainly based on the three principles:

1. Optical scattering spectrometers / holography or interferometry: Diffusion of light of single particles (in principal to determine the size of assumed spherical particles of known refractive index)
2. Crystal imagers based on CCD camera or OAP linear optical array shadowgraphy: Non-intrusive imaging (of a 2D cross section of a 3D particle passing through the imaging laser beam) to derive concentrations in number and surface size distributions and to estimate volume and mass size distributions.
3. Bulk TWC & IWC hot wire devices, and evaporators: Phase change of particles (in order to measure the bulk mass of condensed water).

Numerous instruments are available within research laboratories (particularly CNRS-LaMP and also European partners within ICE GENESIS). Nevertheless, serious gaps associated with instrumental measurement uncertainties and limitations remain and need to be overcome. First, the total number of ice crystals can be overestimated due to ice crystal shattering on the inlets and arms of optical spectrometers (Korolev et al., 2005). Cloud lifetimes are sensitive to the sedimentation velocity of the ice crystals as are the rates of aggregation and riming that depend on the relative fall velocities of ice crystals and supercooled water droplets. 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. Number concentrations of particles smaller than at least 50  $\mu\text{m}$ , derived from classical optical array probes OAPs (of often 25  $\mu\text{m}$  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.

Although advances in high speed electronics have led to the development of higher resolved (10  $\mu\text{m}$  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. The issue of ice shattering as a source of measurement contamination remains a major concern when interpreting measurements from any particle spectrometers mounted on aircraft. A strong general requirement then is to mount cloud probes rather on under wing stations than on the aircraft fuselage. 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.

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  $\mu\text{m}$ , 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. The dimensional coverage of possible snow crystal and snowflake sizes by various state of the art instruments is schematically illustrated in subsequent figure.

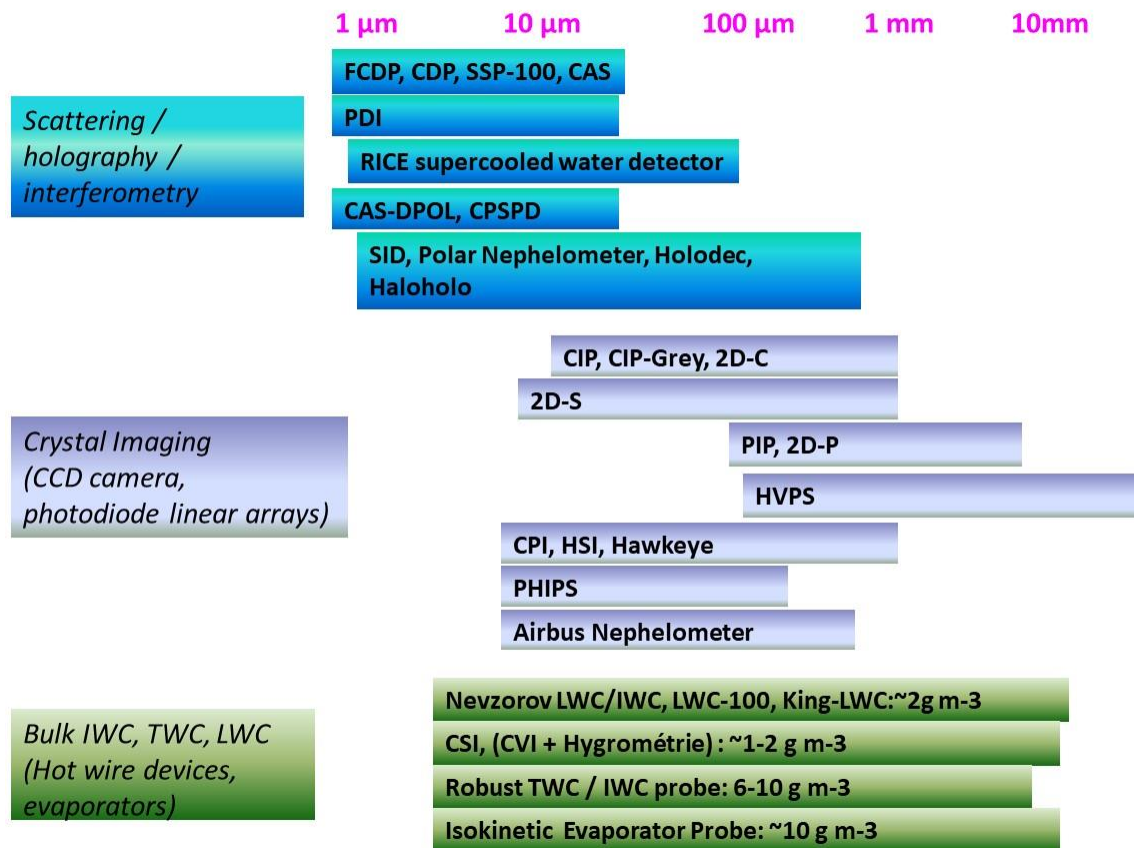


Figure 11 - Multiple instruments to cover complete range from 1 μm to 10 mm and beyond. Task: Choose most reliable set of actual/future instruments combining "Optical spectrometers + 2D crystal imagers + bulk TWC/IWC devices" for multiple IWC retrievals using various methods!

### 3.8 Instrument selection: YAK-42D cloud instruments to be used for first ICE GENESIS campaign

As mentioned earlier, the cloud measuring system of the Yak-42D “Roshydromet” aircraft-laboratory consists of hardware-software packages, whereby sensors and measuring systems are combined using special software. The ICE GENESIS project launched actions to study if several additional sensors that are not part of the YAK-42D state of the art cloud instrumentation package can be added.

YAK-42D provides measurements at the A/C flight level of the concentration and size spectra of cloud particles and atmospheric aerosols of various origins, and also registration of the shape and phase composition of cloud particles [Bazanin et. al., 2015]. For the flight campaign dedicated to snow characterization, the aerosol sensors are kept within the payload, even though the impact of aerosol particles on snow properties is difficult to quantify. Aerosol impact on snow clouds remains an interesting subject, but is not a major objective within ICE GENESIS.

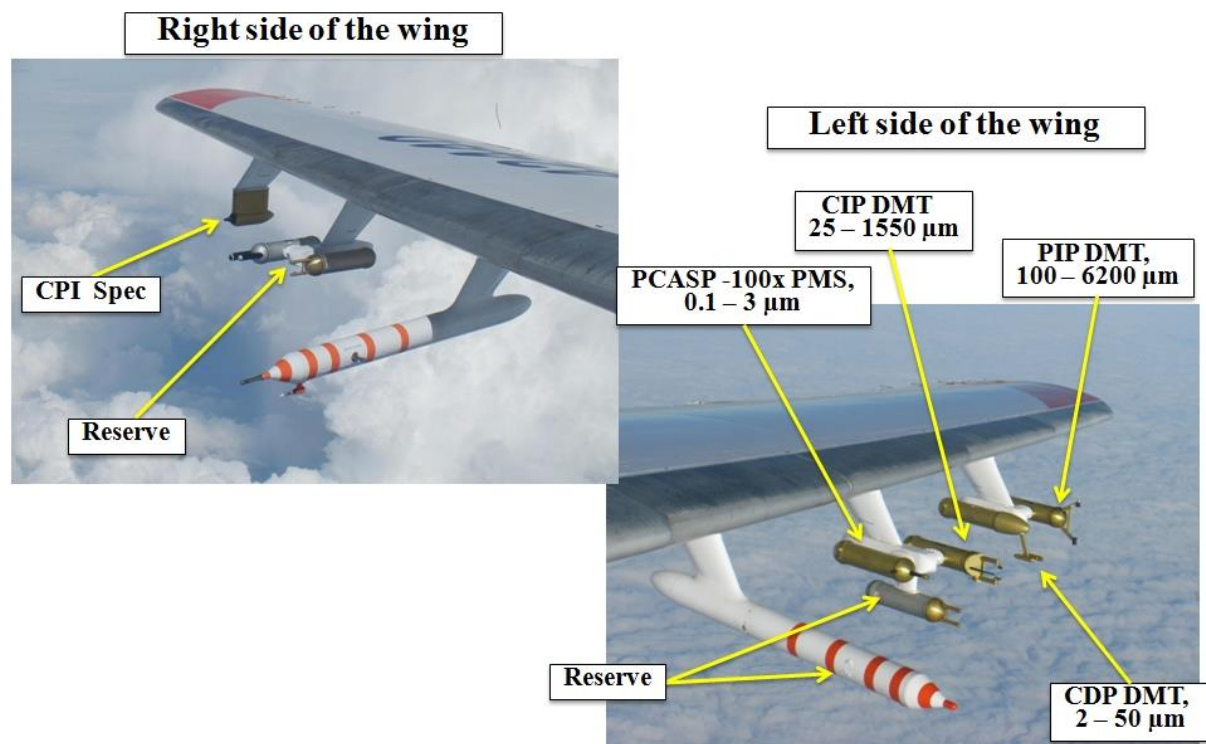


Figure 12 – Under-wing stations with cloud microphysical sensors

**The relevant list of aerosol/cloud in situ sensors and measuring systems is given below:**

- 1) NEVZOROV liquid and total water content sensor, Russia;
- 2) Cloud droplet probe (spectrometer of cloud droplets) CDP, DMT, USA;
- 3) Imager/spectrometer of cloud particles CIP, DMT, USA;
- 4) Imager/spectrometer of precipitation particles PIP, DMT, USA;
- 5) High resolution imager of cloud particles SPEC-CPI, SPEC Inc., USA;
- 6) Ultra-high sensitivity spectrometer for submicron aerosol UHSAS, DMT, USA;
- 7) Data acquisition system M300, DMT, USA.

**The list of measured parameters is as follows:**

- Liquid and total water content in the range from  $0.003 \text{ gm}^{-3}$  up to  $3 \text{ gm}^{-3}$ ;
- Concentration of cloud droplets in the range from 2 to  $50 \mu\text{m}$ ;
- 2D images and concentration of cloud particles in the range from 25 up to  $1550 \mu\text{m}$ ;
- 2D images and concentration of cloud and precipitation particles in the range of 100 up to  $6200 \mu\text{m}$ ;
- 2D images of cloud particles in the range from 2.4 up to  $1000 \mu\text{m}$  with pixel size of  $2.4 \mu\text{m}$ .
- Submicron aerosol size distribution in the range of  $0.055 - 1 \mu\text{m}$ ;



Figure 13 - Sensor for liquid water content (right). Working places for on-board operators (left)

**Aircraft meteorological upward and downward doppler radars (X-band):**

The YAK-42D radar system measures cloud and precipitation (zenith & nadir) of radar reflectivity along the flight path [Azarov *et. al.*, 2014]:

- Coherent Doppler vertical radar with active scanning lattice antenna in the sector of 30° “NADIR”, Russia;
- Coherent Doppler vertical radar with active scanning lattice antenna in the sector of 30° “ZENITH”, Russia.





Figure 14 - Outside radar antenna of radars and working place of on-board operator

### Instrumentation from the ICE GENESIS consortium suggested to be added to the YAK-42D cloud configuration:

In addition to the existing cloud instrumentation on the YAK-42D research aircraft, AIH, CNRS and CAO/TSAGI are working on the possibility to add further probes available within the ICE-GENESIS consortium, as there are particularly the HVPS and 2D-S imagers for large and intermediate size cloud particles, as well as a ROBUST probe which is an additional TWC device.

1. The most interesting instrument to add is the HVPS (High Volume Particle Sizer) from CNRS partner which is capable of measuring largest snowflake sizes which are 3 times larger than PIP probe (YAK-42D instrument) maximum sizes.
2. The 2D-S (2D-Stereo imaging probe) is more a redundant probe to the CIP (Cloud Imaging Probe) on the YAK-42, which are both intermediate size snow particle imaging probes.
3. In order to reconcile A/C OAP with ground based Multi Angle Snowflake Camera (MASC), an idea is to mount a second PIP instrument, one in horizontal laser beam configuration, the other one in a vertical laser beam configuration. In case of oriented snow particles this would give a much better understanding of the oriented 3D shape of falling snow, at least on a statistical basis, and render much more comparable MASC and PIP OAP data. We recall here that the MASC is used for ground studies, whereas OAPs are used on A/C and in W/T during the ICE GENESIS project. Whereas the MASC allows constructing a 3D image, A/C and W/T OAP probes only give one single 2D view of a particle (bias, in case of crystal orientation).
4. Finally, a fourth instrument that could be added, is the ROBUST probe which is a redundant probe to the NEVZOROV probe. The latter is part of the existing cloud instrumentation package on the YAK-42.

2D Imagers			
High Volume Precipitation Spectrometer (HVPS)	SPEC Inc.	OAP probe ; 128 photodiodes ; 150 $\mu$ m resolution ; size range : 150 $\mu$ m – 19,2 mm.	
2D-Stereo (2D-S)	SPEC Inc.	OAP probe; 2 x 128 photodiodes; 10 $\mu$ m resolution; size range: 10 $\mu$ m – 1.28 mm. Stereo probe imaging same particle on two orthogonal planes.	




Precipitation Imaging Probe (PIP)	DMT	OAP probe; 64 photodiodes; 100µm resolution; size range: 100 µm – 6.40 mm.	<p>Two configurations:</p>  <p>Horizontal Laser giving a vertical cross section of passing ice particle</p>  <p>Vertical Laser giving a horizontal cross section of passing ice particle</p>
TWC probe			
WC-3000 ROBUST (ROBUST)	SEA Inc.	ROBUST probe for TWC up to 10 g.m <sup>-3</sup> ; hot wire type device	

Figure 15 – Complementary instrumentation from ICE GENESIS consortium for the YAK-42D aircraft

The YAK-42D payload configuration is adapted to cover the complete size range of optical spectrometers + 2D imagers for size and morphology + bulk TWC. In a first conclusion, the instrumental setup comprised of state of the art instruments covers the recommended size range of snow particles for quantitative PSD measurements, including a certain redundancy.

- The HVPS is increasing the maximum measurable size range.
- The CPI as a high resolution imager with 256 grey scale images for a more detailed description of the crystal surface is of a certain value.
- CIP and 2D-S should also give a reasonably good description of the shape of the crystals.
- The configuration with two PIP probes, one vertical and the other one horizontal should give an important input for A/C and W/T data comparison with 3D image information from ground based MASC measurements.

- The calibration of NEVZOROV and ROBUST probes in snow conditions is unknown, even though the ROBUST probe efficiency has been parametrized with respect to the IKP-2 reference probe and also the NEVZOROV probes has been compared to the IKP-2 in the frame of the HAIC project for temperature ranges around -10°C, which is the temperature range where snow measurements will be performed during ICE GENESIS field studies. The use of the ROBUST probe is also motivated by a potential use of the ROBUST probe aside the reference snow CVI on the ATR-42 snow campaign.

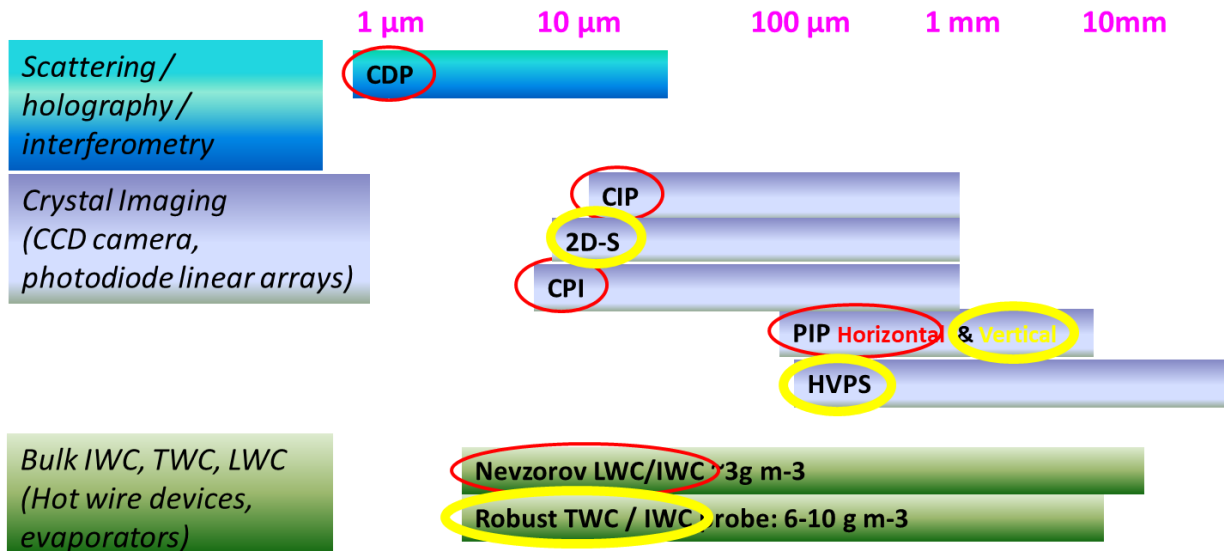


Figure 16 – YAK-42D instrumental configuration out of multiple instruments to cover complete range from 1 μm to 10 mm and beyond. Red circles are for existing YAK-42D cloud instruments. Yellow circles from ICE GENESIS consortium.

### 3.9 Instrument selection: Proposition of ATR-42 instruments to be used for second ICE GENESIS campaign

A first core instrumentation package to be installed primarily under the six wing stations of the ATR-42 has to be a most sophisticated in-situ microphysical package allowing for state-of-the-art measurements of the snow particle (snow crystals / snowflakes) size and mass deduced from direct measurement of the ice mass IWC (TWC respectively) and simultaneous spectrometry and imagery of hydrometeors in order to deduce crystal size distributions from smallest hydrometeors up to snow particles of several tens of millimetres. The in situ microphysical instrumental payload on the ATR-42 then is defined via a combination of adequate probes as there are the Cloud Droplet Probe (CDP, diameter range : 3-50  $\mu\text{m}$ ), the 2D-Stereo cloud imaging probe (2D-S, diameter range : 10-1280  $\mu\text{m}$ ), and the precipitation particle size imaging probes PIP (diameter range: 100-6400  $\mu\text{m}$ ) and HVPS (diameter range: 150-19200  $\mu\text{m}$ ). This package is complemented by measurements of the high resolution cloud particle imager HSI (eventually 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. An interesting feature of this combination is that there are overlapping diameter ranges, allowing for measurement consistency in hydrometeor dimensions (maximum diameter, surface equivalent diameter). The CDP cloud spectrometer should clearly reveal possible presence of droplets coexisting with snow particles, which cannot be measured reliably with high resolution imagers. For the HAIC project, NASA proposed a redesigned IKP-2 probe as the IWC/TWC reference probe having a 100% efficiency. This reference probe served significantly to achieve HAIC regulatory objectives (99<sup>th</sup> percentile of IWC). The major drawback has been the fact that the background water vapour has to be known precisely (recall: the background water vapour value has to be subtracted from the IKP-2 measured value which consists of total condensed water content plus the vapour phase). Whereas at low tropospheric temperatures below  $-40^{\circ}\text{C}$  the background water vapour uncertainty is negligible, this uncertainty becomes considerable at  $-10^{\circ}\text{C}$ . In particular when facing variable sub- or super-saturation with respect to ice and water in time and space (moving aircraft!). This latter uncertainty makes the IKP-2 probe a less promising TWC device in precise quantification of snow TWC on aircraft. The above discussion of IKP-2 use on aircraft at relatively high temperature led to the initiative of modifying an existing CVI inlet, certified on the ATR-42, such that the inlet is optimized for bulk snow water content measurement on the ATR-42. For the YAK-42D the CVI will not be used/certified, since certification is beyond the financial means and limited time delay of the ICE-GENESIS project. Modification of some modules of the existing CVI is necessary, since the actual version has been designed/optimized to sample smallest droplets and crystals of aerodynamic diameters of 4-5  $\mu\text{m}$  for subsequent analysis of the incorporated CCN and IN aerosol particles. The CVI modules/features to be modified are the tip diameter (porous tube where dry air is supplied) to be increased, the adaptation of the diffuser and most significantly the increase of de-icing and evaporation electrical power around the sampling tube. This work is performed in collaboration with Enviscope GmbH, the original company having produced the CVI versions for the ATR-42 and Falcon 20 research aircraft. In addition to the Snow CVI, a simultaneous bulk measurement of condensed total water content TWC (=IWC+LWC) will be performed by using

the Science Engineering Associates (SEA Inc.) ROBUST probe which has been mounted together with the CDP probe in one single PMS canister. For comparison reason with Snow CVI and ROBUST probe, a NEVZOROV probe can be installed on the fuselage of the ATR-42, which is a hotwire bulk TWC/IWC device (Korolev et al. 1998). The NEVZOROV probe has been already used during the 2011 Megha-Tropiques and HYMEX campaigns on the Falcon 20. The NEVZOROV has been modified, lengthening the pylon in order to minimize fuselage effects on the sampling. The NEVZOROV and ROBUST sensors have been mounted on HAIC/HIWC aircraft (CV-580, F20) simultaneously to IKP-2 probes and their collection efficiency could be compared to the reference probe IKP-2. Finally the newest version of the Rosemount Ice Detector, which is in fact a semi-quantitative instrument to detect and measure supercooled cloud water at negative temperatures will be routinely installed. A further device mounted to an ATR-42 under wing station is the Polar Nephelometer, which is unique instrument measuring the scattering phase function. From this can be retrieved the cloud particle phase (liquid, ice, mixed), extinction coefficient, asymmetry parameter, etc...



Figure 17 – ATR-42 in situ instrumentation: Polar Nephelometer, CPI, PIP dummy (upper left), 2D-S / FCDP (upper right), CVI cloud inlet (lower left) and measurement rack, synthetic dry air for CVI (lower right).

The second core instrument on the ATR-42 to be deployed is the multi-beam 95 GHz Doppler cloud radar RASTA (RADar SysTEM Airborne, Protat et al. 2004), which allows retrieving the three-

dimensional (3D) wind and microphysical and radiative properties of clouds (IWC, visible extinction, particle size, terminal fall speed, concentration) to be retrieved in a vertical cross-section along the flight track in thick ice clouds (including precipitating ones). The RASTA radar in its current version includes 3 downward-looking beams (nadir, 28 degrees off-nadir and opposite the aircraft motion, and 20 degrees off-nadir perpendicular to the aircraft motion) and 3 upward-looking beams (zenith, 28 degrees off-nadir perpendicular to the aircraft motion, and 20 degrees off-zenith and opposite the aircraft motion). This unique configuration allows for the retrieval of the three-dimensional wind, a correction for 95 GHz attenuation by cloud particles, and an accurate correction of the navigation angles (using methods such as that proposed by Testud et al. 1995) which is mandatory for accurate 3D wind retrieval. Comparisons with in-situ measurements of the three wind components have also shown that three non-collinear views are mandatory for accurate wind retrievals. Calculations of gains and losses indicate that the downward-looking antennas will be of sensitivity -37 dBZ at 1 km range, while the upward-looking antennas should be at -32 dBZ at 1 km range (because they are smaller, 12 inch instead of 18, because the windows are smaller on the roof of the aircraft than on the belly). Such sensitivity is sufficient to document all stratiform and moderately-convective clouds down to the ground from 12 km height (despite severe attenuation), while allowing for the thin tropical cirrus clouds to be sampled near the aircraft altitude.

As a major conclusion, the instrumental setup for the ATR-42 aircraft is comprised of state of the art instruments covering the recommended size range “optical spectrometers + 2D imagers” and also considers morphology + reference bulk TWC of snow particles, including a certain redundancy. The HSI (a so-called open path instrument to avoid shattering artefacts) if ready by 2020 or the CPI (closed path, thus more prone to crystal shattering) as a backup solution of a high resolution imager with 256 grey scale images for a more detailed description of the crystal surface is a very good qualitative (semi-quantitative) support for morphological analysis. The 2D-S should also give a reasonably good description of the shape of the larger crystals beyond 1 mm. The calibration of NEVZOROV and ROBUST probes in snow conditions is unknown, even though the ROBUST and also the NEVZOROV probes have been compared to the IKP-2 within HAIC for temperature ranges around -10°C resembling snow measurement temperatures. Therefore, the Snow CVI is considered a 100% reference probe, which is due to its measurement principle of isokinetically sampling hydrometeors.

The multi-beam 95 GHz Doppler cloud radar RASTA (RAdar SysTem Airborne, Protat et al. 2004), allows retrieving the three-dimensional (3D) wind and microphysical properties of clouds (IWC, terminal fall speed) in a vertical cross-section along the flight track in thick ice clouds (including precipitating ones). We will therefore get an improved closure of IWC estimates from different measurements and retrieval methods: bulk TWC measurements, TWC from 2D imagery (different approaches: using PSD and crystal geometric parameters, area  $A(D)$ , mass  $m(D)$  relations), combined retrievals (radar reflectivity  $Z$  and terminal fall speed of hydrometeors  $V_{fall}$  + particle size distribution (PSD)).

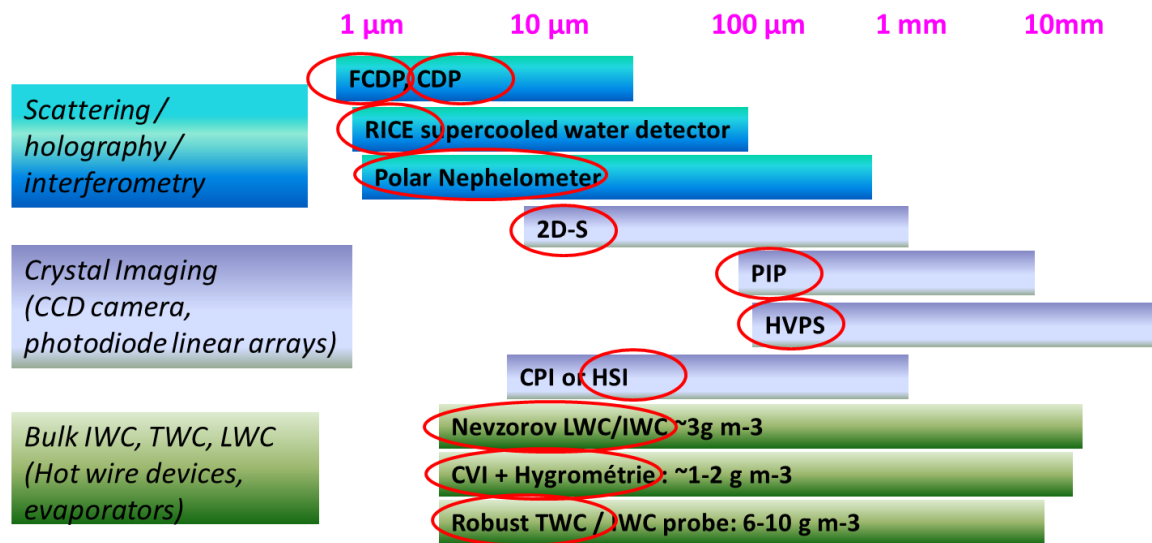



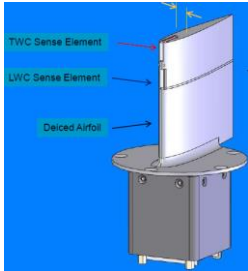







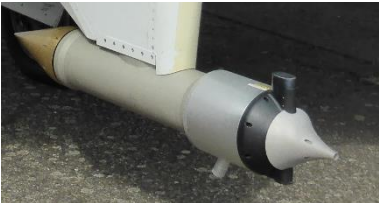


Figure 18 – ATR-42 configuration out of multiple instruments to cover complete range from 1μm to 10 mm and beyond. Red circles are for chosen ATR-42 cloud instruments.

Subsequently the potential cloud microphysics aircraft instrumentation for the ATR-42 campaign is presented.

<b>ATR-42 A/C Payload</b>		
<b>Equipment</b>	<b>Illustration</b>	
<b>Bulk cloud <math>\mu</math>-phys</b>	Counterflow Virtual Impactor (CVI) including High tech humidity sensors (TDL, Licor 580A, Buck dew point sensor, Vaisala sensor) Concept/design: LaMP Production: Enviscope GmbH	
	NEVZOROV probe (Option) SKYTECH company	
	WC-3000 ROBUST (ROBUST) SEA Inc.	
	Rosemount Ice Detector RICE (new model 0871LM5) / Baseline Goodrich	
<b>Opt. spectrometry: (1-50 <math>\mu</math>m)</b>	Cloud droplet Probe (CDP; together with ROBUST) DMT	

	<p>Fast Cloud Droplet Probe (FCDP) SPEC</p>	
<p>CCD camera: (10-1000 μm)</p>	<p>HSI (5μm pixel, 500x500 pixel) ARTIUM</p>	
	<p>Optional to HSI: CPI Imager (2.3μm pixel, 1000*1000 pixel) SPEC Inc.</p>	
<p>2D-array probes: (10-19200 μm)</p>	<p>2D-Stereo Probe (2D-S) SPEC Inc</p>	
	<p>Precipitation Imaging Probe (PIP) DMT</p>	
	<p>High Volume Particle Sampler (HVPS) SPEC Inc.</p>	
<p>Scattering phase function, extinction</p>	<p>Polar Nephelometer (version NP1 or NP2) (Concept/design/production: LaMP)</p>	

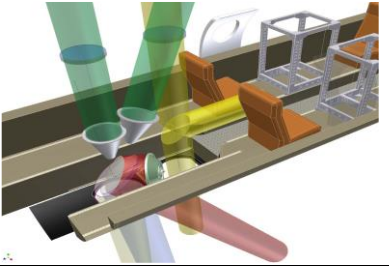
<b>Cloud active remote sensing</b>	RASTA (95 GHz Doppler cloud radar) / Baseline	 A 3D perspective rendering of an aircraft fuselage section. The aircraft is oriented horizontally. Various instruments are mounted on the fuselage. A prominent feature is a large, yellow, cylindrical structure, likely the RASTA radar, mounted on the side. Other instruments include a white cylindrical probe, a red cylindrical probe, and a green cylindrical probe. The aircraft's interior seats and cabin structure are visible through cutaway sections.
------------------------------------	---	---

Figure 19 – Snow cloud microphysical instrumentation

## 4 Conclusions

---

The work performed in order to produce the ICE GENESIS deliverable D5.1 is related to the work performed within task 5.1. This task has been synthesizing the state of the art and specifications of the F/T measurement needs of snow and reviewing the respective available instrumentation in the scientific community (in particular the ICE GENESIS consortium). State of the art in situ measurements are particularly adapted for number PSD measurements (individual snow particle imagery) of falling snow, bulk condensed snow water content measurements, and optical measurements of angular light scattering. In order to extrapolate the knowledge of in situ snow measurements beyond the flight trajectory, limited active remote sensing is used on both aircraft, with in particular cloud radar (Doppler), measuring the reflectivity factor (at least in nadir and zenith directions). Within limitations of the possible instrumental payload of both aircraft used in the frame of ICE GENESIS (number of under wing canisters, certification issues, remaining time before F/T campaign, and pre-configuration of the Russian YAK-42D aircraft, available electrical power and cabin space) the most suitable instrumental payloads have been chosen (for ATR-42) and/or confirmed/extended (for YAK-42 research aircraft).

The requirements for the selection of the most adequate microphysical payload have been to perform quantitative measurements of rather weak number concentrations of snow cloud particles far below 1 crystal per liter and of ice particle sizes from few micrometres (or tens of micrometres) up to 4 cm, the latter are considered as very large snowflakes, and to quantify bulk snow water contents up to maximum 2 g / m<sup>3</sup>. Other valuable and necessary information should be gathered in flight with respect to most detailed crystal morphological description of individual snowflakes and if possible reveal some indications on the dry/wet status of snow particles. These measurements may be completed with extinction or visibility measurements and/or estimations to characterize the cloud environment from a pilot's point of view.

Both, YAK-42D and ATR-42 measurement campaigns focus on the in-situ and active remote sensing characterization of falling snow events. Therefore, one important strategy in the ICE GENESIS project is to evaluate cloud radar observations (reflectivity and Doppler velocity) of snow water content in snow clouds using the state-of-the-art in-situ microphysical measurements from YAK-42D and ATR-42 aircraft. The radar reflectivities will be used to develop/retrieve good estimates of the vertical distribution of IWC.

The suggested YAK-42D and ATR-42 payload configurations are both adapted to cover the complete size range of optical spectrometers + 2D imagers for size and morphology + bulk TWC. Also both A/C are equipped with Doppler radar (W-band for TAR-42 and X-band for YAK-42). As a significant conclusion, the instrumental setup for both A/C is comprised of state of the art instruments covering the recommended size range of snow particles for quantitative PSD measurements, including a certain redundancy. The HVPS is substantially increasing the maximum measurable size range. CPI and/or HSI high resolution imagers producing 256 grey scale images for a more detailed morphological description of the crystal surface is of a good value. CIP and 2D-S should also give a relatively good description of the shape of the crystals.

A considerable effort in bulk TWC measurements consists in the modification of the ATR-42 CVI cloud inlet, thereby adapting the inlet to perform properly in snow conditions. The calibration of NEVZOROV and ROBUST probes in snow conditions is unknown, even though the ROBUST and also the NEVZOROV probes have been compared to the IKP-2 in the frame of the HAIC project for temperature ranges around  $-10^{\circ}\text{C}$  resembling snow measurement temperatures. Therefore, the Snow CVI is considered a 100% reference probe, which is due to its measurement principle of isokinetically sampling of hydrometeors thereby rejecting background water vapour.

The Snow CVI measurements may be used a posteriori for better TWC estimations of ROBUST and NEVZOROV probes on the YAK-42, not having a CVI probe. Snow CVI and ROBUST (and NEVZOROV) should be installed on the ATR-42.

The X-band Doppler radar on the YAK-42D will measure cloud reflectivity factors along the flight track and we'll see within task 5.5, what can be done in terms of extrapolation of microphysical parameters measured along the flight track.

The multi-beam 95 GHz Doppler cloud radar RASTA (RADAR SysTEM Airborne, Protat et al. 2004), allows retrieving the three-dimensional (3D) wind and microphysical properties of clouds (IWC, terminal fall speed) in a vertical cross-section along the flight track in thick ice clouds (including precipitating ones). The dataset will allow an improved closure of IWC estimates from different measurements and retrieval methods: bulk TWC measurements, TWC from 2D imagery (different approaches: using PSD and crystal geometric parameters, area  $A(D)$ , mass  $m(D)$  relations), combined retrievals (radar reflectivity  $Z$  and terminal fall speed of hydrometeors  $V_{\text{fall}}$  + particle size distribution (PSD)).

## 5 Bibliography

---

- Azarov A.S., K.S. Lyalin, E.S. Sukhanov, V.V., Chistyuhin. 2014: “APAA Based X-Band Airborne Weather Radar”, National Research University of Electronic Technology, Moscow, **1**(105), 71 – 77.
- Bazanin N.V., Borisov Y.A., Volkov V.V., Dmitriev V.K., Zhiviglotov D.N., Makosko A.A., Strunin A.M., Strunin M.A., 2014: “Onboard measuring systems of new Russian aircraft-laboratory Yak-42D “Roshydromet” for measuring and recording navigation flight parameters and thermodynamic characteristics of atmosphere”, Russian Meteorology and Hydrology, **11**, 109–121.
- Bazanin, N.V., V.V. Volkov, A.V. Ganshin, B.G. Danelian, D.N. Zhivoglotov, D.V. Kirin, N.O. Krutikov, E.A. Kukanova, A.N. Lukyanov, A.M. Strunin, and M.A. Strunin, 2015: “Aerosol transport characteristics in a megacity area (Moscow) as obtained by aircraft observations”, Problems of cloud physics, Atmospheric aerosols, Weather modification. Collection of papers to the memory of Dr. Nora O. Plaude, Moscow, 89 -117 (in Russian, English resume).
- Besic, N., Figueras i Ventura, J., Grazioli, J., Gabella, M., Germann, U., and Berne, A.: Hydrometeor classification through statistical clustering of polarimetric radar measurements: a semi-supervised approach, *Atmos. Meas. Tech.*, **9**, 4425–4445, doi:10.5194/amt-9-4425-2016, 2016.
- Borisov Y., Petrov V., Strunin M., Khattatov V., Danelyan B., Azarov A., Fomin B., Martanov V., Stasenko V., Vakulovskiy S., Sinkevich A., Sokolenko L., Lepukhov B. 2012: “New Russian aircraft-laboratory YAK-42D «Atmosphere» for environmental research and cloud modification” - Proceedings of the 16<sup>th</sup> International Conference on Clouds and Precipitation, Leipzig, 31 June - 3 August 2012.
- 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>
- 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
- Grazioli, J., Tuia, D., Monhart, S., Schneebeli, M., Raupach, T., and Berne, A.: Hydrometeor classification from two-dimensional video disdrometer data, *Atmos. Meas. Tech.*, **7**, 2869–2882, doi:10.5194/amt-7-2869-2014, 2014. Grazioli, J., Tuia, D., and Berne, A.: Hydrometeor classification from polarimetric radar measurements: a clustering approach, *Atmos. Meas. Tech.*, **8**, 149–170, doi:10.5194/amt-8-149-2015, 2015.
- Gultepe, I., Heymsfield, A. J., Field, P. R., & Axisa, D. (2017). Icephase precipitation. *Meteorological Monographs*, **58**, 6.1–6.36
- Hogan, R. J., D. Bouniol, D. N. Ladd, E. J. O’Connor, and A. J. Illingworth, 2003: Absolute calibration of 94/95-GHz radars using rain. *J. Atmos. Oceanic Technol.*, **20**, 572–580, doi:10.1175/1520-0426(2003)20,572
- 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., Baker, B. A., Schmitt, C. G., and Jensen, T. L.: An overview of microphysical properties of Arctic clouds observed in May and July during FIRE.ACE, *J. Geophys. Res.*, **106**, 14 989–15 014, 2001.
  - 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.
  - 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. Delanoë, 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
  - L. Liao, R. Meneghini, A. Tokay, L.F. Bliven Retrieval of snow properties for Ku- and Ka-band dual-frequency radar. *J. Appl. Meteorol. Climatol.* (2016), 10.1175/JAMC-D-15-0355.1.
  - 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.
  - A Protat, J Pelon, J Testud, N Grand, P Delville, P Laborie, JP Vinson, ... Le projet rali: Etude des nuages faiblement précipitants par télédétection active *La Météorologie* **47**, 23-33
  - 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.
  - Schwarzenboeck, A., A. Calmels, P. Coutris, J Delanoë, F. Dezitter, F. Huet, A. Korolev, D. Leroy, G. McFarquhar, A. Protat, J.W. Strapp (2018). Analysis method used to provide all in situ TWC, IWC, LWC, and corresponding PSD (as a function of maximum and surface equivalent cloud particle diameters) data. *Rapp. tech. EASA HighIWC D3.18 R2.0*. European Aviation Safety Agency.
  - 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.
  - Testud, J., P. H. Hildebrand, W.-C. Lee, 1995: A procedure to correct airborne Doppler radar data for navigation errors using the echo returned from the earth’s surface. *J. Atmos. Oceanic Technol.*, **12**, 800-820.
  - 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.
  - Zhang, G., R. J. Doviak, D. S. Zrnić, R. Palmer, L. Lei, and Y. Al-Rashid, 2011a: Polarimetric phased-array radar for weather measurement: A planar or cylindrical configuration? *J. Atmos. Oceanic Technol.*, **28**, 63–73, doi:10.1175/2010JTECHA1470