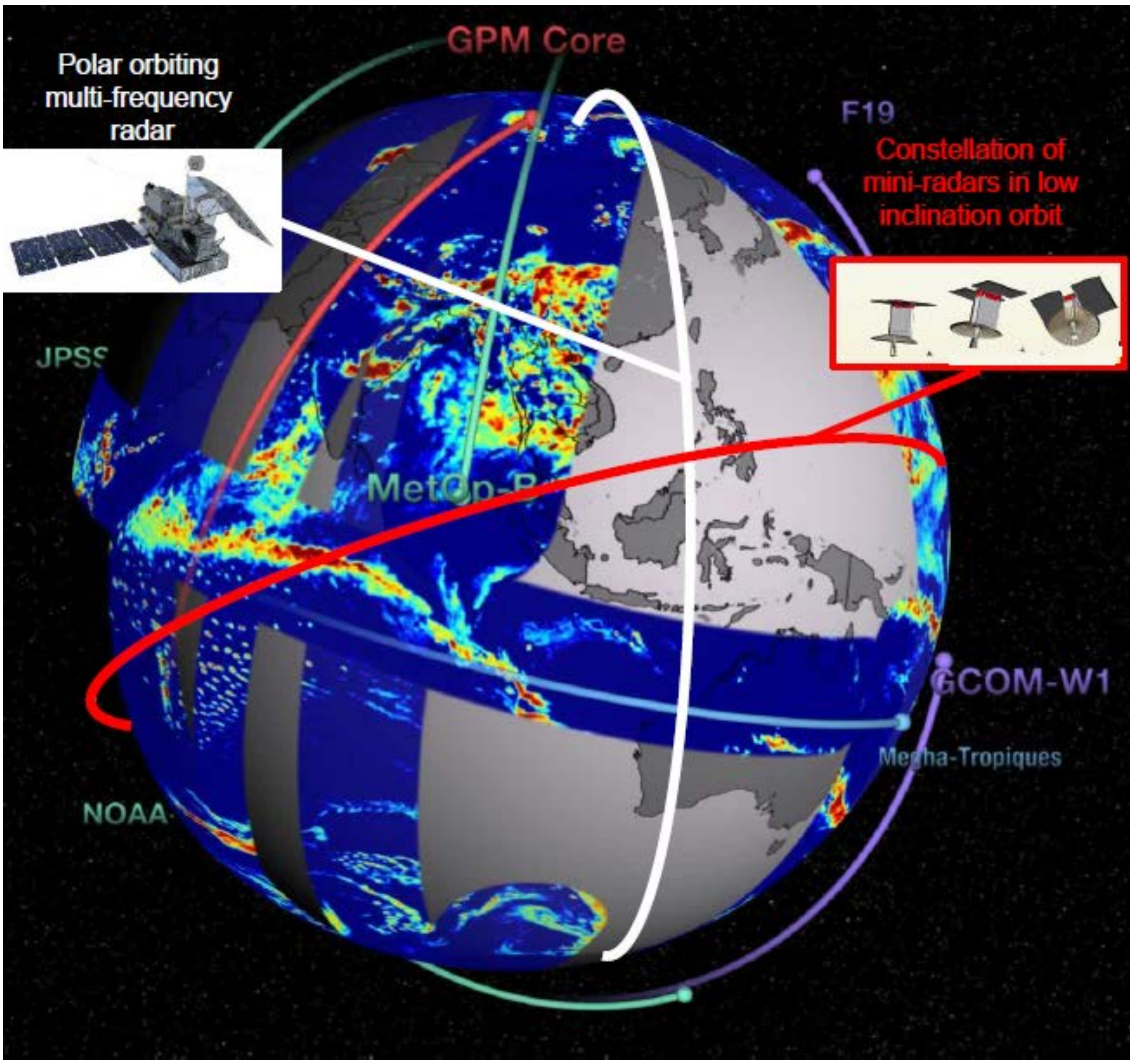
Proposal to ESA
for the
Raincast study

In response to ITT AO/1-9324/18/NL/NA



UNIVERSITY OF LEICESTER

McGill

Consiglio Nazionale delle Ricerche

NRC·CNRC

1) TECHNICAL PART

1.1 TECHNICAL REQUIREMENTS AND OBJECTIVES

This technical proposal has been prepared by Dr. A. Battaglia (University of Leicester, UK), Prof. Dr. P. Kollias (McGill University), Dr G. Panegrossi, Dr .E. Cattani and Dr. M. Montopoli (CNR-ISAC) and Dr. Mengistu Wolde (CNR-Canada) in response to the ESA Invitation to Tender Raincast (ITT AO/1-9324/18/NL/IA) and to the technical requirements of the ITT.

1.1.1 Concise functional analysis of the technical requirements

The *Raincast* is a multi-platform and multi-sensor study to address the requirement from the research and operational communities for global precipitation measurements. *Raincast* aims at identifying and consolidating the science requirements for a satellite mission that could complement the existing space-based precipitation observing system and that could optimally liaise with concurrent efforts currently made by other agencies in this area (especially by NASA and JAXA). Because of the complexity of the cloud and precipitation processes the study must capitalize on the most recent advancement and mission concepts for precipitation observations with state-of-the-art instrumentation and should make full use of the most recent advancements in inversion methods for the estimation of precipitation variables from primary measurements (e.g. latest ice scattering libraries, physical relationships derived by in-situ measurements).

1.1.2 Understanding of the main technical objectives of the ITT

The holistic understanding of the Earth's water and energy cycle remains one of the grand challenges that the international scientific community needs to address in the next decade. Three (out of seven) of the grand challenges posed by the World Climate Research Programme (http://wcrp-climate.org/grandchallenges) are in fact centered around this theme: 1) Clouds, Circulation and Climate Sensitivity; 2) Understanding and Predicting Weather and Climate Extremes, 3)Water for the Food Baskets of the World. These challenges require to predict precipitation (and its evolution in a warmer climate) and to understand how the water cycle will change, how these changes will affect the space-time distribution of rainfall/ snowfall, and how they will impact upon the frequency and magnitude of extremes such as droughts and floods. At a more fundamental level this requires in first place to understand ``Why do convective storms, heavy precipitation, and clouds occur exactly when and where they do?" [RD7].

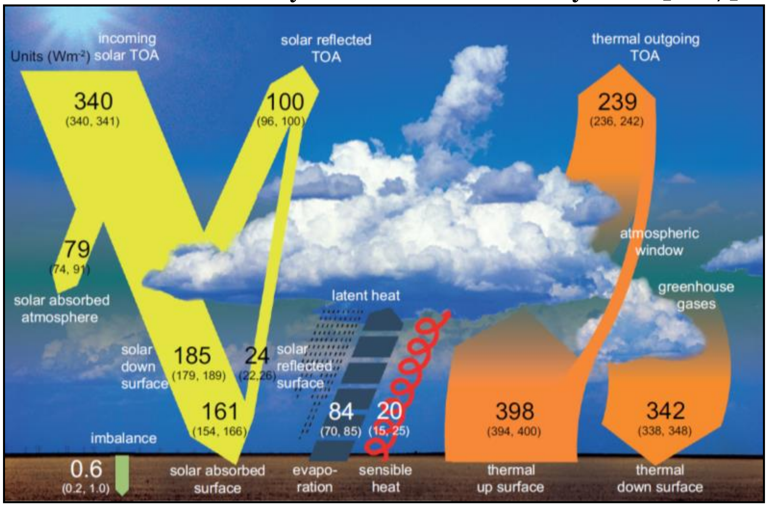


Figure 1.1: global mean energy budget under present climate conditions. Numbers state magnitudes of the individual energy fluxes in W/m², adjusted within their uncertainty ranges to close the energy budgets. Extracted from [IPCC 2013].

As highlighted in [RD1, RD7] in order to properly predict how the water cycle will change in a changing climate it is paramount to obtain accurate and continuous observations of the key variables involved in the energy and water cycles, and precipitation is of course at the heart of both via constituting the main mechanism for transferring water from the atmosphere to the surface and for bringing energy from the surface to the atmosphere via latent heat release (Fig.1.1). Note that the energy budget illustrated in the figure is for *yearly global* variables: ideally observations should aim at providing dataset at regional and local scale and for daily/seasonal temporal scales (e.g. the goal set in the NASA Decadal Survey is to observe ***total precipitation to an average accuracy of 15% over oceans and/or 25% over land and ice surfaces averaged over a 100x100 km region and two to three days***, this should be sufficient to close the budgets at river basin scales).
Because of the spatial and temporal variability of precipitation it is unanimously recognized that precipitation and continuous observations can deliver high profile science and applications only through an integrated approach where Earth Observation satellite and ground-based observations complement a model-based integrated Earth system analysis. In the next decade analyses of precipitation at 1 km and 15 min time steps should become a reality. The scope of the precipitation observing system must therefore be twofold: 1) it needs to continue and improve upon the monitoring of the timing, amount, phase of precipitation, including the vertical structure of hydrometeors of precipitating systems with a better characterization of uncertainties in the observations needed both for scientific inquiry and data assimilation purposes; 2) it should significantly contribute to the precipitation process understanding and therefore improve advanced high-resolution models used to forecast precipitation.

It is therefore an essential prerequisite for shaping a new precipitation mission to outline: 1) the **status of the precipitation observing systems**; 2) the **deficiencies in the current observation systems**; 3) the limitations and weaknesses in models and **lack of understanding on key processes**. Here we will limit our analysis to some of the aspects that we deem can be tackled by future space-borne precipitation observing systems within this ITT study.

Status of the precipitation observing systems and precipitation products

Satellite observations are fundamental to estimate precipitation on a global basis at scales commensurate with the user needs. A wide range of sensors are available for precipitation remote sensing covering visible (VIS), infrared (IR), active and passive microwaves (PMW) from geostationary (GEO) and Low Earth Orbiting (LEO) platforms, as summarized in Tab.1.1 (Michaelides et al., 2009; Kidd and Huffman, 2011).

VIS-IR observations (mainly from GEO) are exploited because of their high time frequency (from 15 to 5 min for the default acquisition modes) and spatial resolution, better than those of the LEO MW sensors. They provide information on cloud top characteristics (top temperature, optical thickness, thermodynamic phase, and effective radius), which can be used to identify precipitating clouds. Nevertheless, precipitation estimate is indirect based on cloud top properties only.

Current status of atmospheric passive microwave (PMW) radiometers
PMW frequencies from LEO sensors are more directly responsive to cloud internal processes and thus to precipitation formation mechanisms because in this portion of the electromagnetic spectrum the passive signal weighting functions receive contributions from the full atmospheric column. Over the ocean the signal comes essentially from the increased amount of emitted radiation from raindrops that makes rain areas somewhat "warmer" that the surrounding "colder" ocean background. Over land, rainfall is detected using the reduction of the upwelling radiation

due to scattering mainly related to ice particles. The relatively low and more or less constant water surface emissivity makes the PMW retrieval methods work more effectively over the ocean. The same is not true over land areas, where the emissivities of soils and vegetation are much higher than those of water and very variable from place to place. This makes the retrieval much more problematic over land where most methods show evident problems. In this respect, higher frequency channels (> 89 GHz) present in some of the conically scanning radiometers [e.g. the Special Sensor Microwave Imager/Sounder, SSMIS, and the Global Precipitation Measurement (GPM) Microwave Imager (GMI)] and cross-track scanners (e.g., Microwave Humidity Sounder, MHS, and Advanced Technology Microwave Sounder, ATMS) may provide essential information.

Instrument	Satellite	Channels	Bands	Resolution (km)	Sampling
AVHRR	NOAA/MetOp	6	VIS-IR	1	Twice daily
MODIS	Aqua/Terra	36	VIS-IR	0.25-1	Twice daily
VIIRS	Suomi NPP/JPSS-1	22	VIS-IR	0.75	Twice daily
SEVIRI	MSG	11	VIS-IR	1-3	15 min
AHI	HIMAWARI	13	VIR-IR	0.5-2	10 min
ABI	GOES-R	16	VIS-IR	0.5-2	15 min Full Disk 5 min CONUS
SSMIS	DMSP	24	19-183 GHz	12.5-75	Twice daily
MHS	NOAA/MetOp	5	89-190 GHz	17-50	Twice daily
ATMS	Suomi NPP/JPSS-1	22	23-183 GHz	16-75	Twice daily
AMSR-2	GCOM-W	6	7-89 GHz	5-10	Twice daily
GMI	GPM *CO*	13	10-183 GHz	5-25	Twice daily
DPR	GPM *CO*	2	13.6 & 35.5 GHz	5	Twice daily
CPR	CloudSat	1	94 GHz	1.4	Once 16-days

Table 1.1. Summary of the main currently in-orbit satellite sensors for precipitation estimation.

Such frequencies are effective in mitigating the effects of the poor knowledge of emissivity and scattering properties of land surfaces that cause misclassifications when retrieving precipitation over land, due to the fact that precipitation estimates at these frequencies rely on the scattering from ice hydrometeors. Such channels are also instrumental in solid precipitation retrieval, with the 150 GHz channel exhibiting the strongest scattering signature associated to precipitation-sized ice particles and only moderately affected by variations in surface emissivity (Levizzani et al., 2011; Laviola et al., 2015). The GMI, currently offers the most appropriate set of microwave frequencies for precipitation retrieval, with 10 dual-polarization window channels from 10 GHz to 166 GHz, and three single-polarization channels, one at 23.8 GHz and two in the water vapor absorption band at 183.31 GHz. GMI provides PMW measurements on a 904 km wide swath at the highest available spatial resolution, ranging from 4.4 km x 7.2 km at the high-frequency channels (> 89 GHz), to 19 km x 32 km at 10 GHz. ATMS is the most advanced among cross-track scanning radiometers, with a swath of 2600 km, angular span up to 52.77° relative to nadir. ATMS has 22 channels, ranging from 23 to 183 GHz. Compared with its predecessors (AMSU and MHS), ATMS has improved resolution and angular sampling, and has the great advantages of a wider swath that practically eliminates the orbital gaps.

Current status of atmospheric space-borne radars

There are currently two atmospheric radars in operation: the GPM-DPR and the CloudSat CPR. Together, these missions have been foundational for characterizing the evolving nature of clouds and precipitation on Earth over the last decade [Skofronick-Jackson et al., 2016].

The Cloud Profiling Radar (CPR) on board CloudSat is a 94 GHz nadir-looking radar [Stephens et al., 2008], unique in its ability to sense condensed cloud particles whilst coincidentally detecting precipitation. It measures backscattered microwave radiation at 485 m vertical resolution with a 1.4×1.8 km effective field of view, from an altitude of 705-730 km. Standard data products include cloud geometric profile, cloud/precipitation classification, optical depth, cloud water content (both ice and liquid) and atmospheric radiative flux/heating rates. CloudSat has been an essential component of the A-Train constellation; examples of products derived from synergistic retrievals with the CALIOP cloud lidar on board CALIPSO -which flies in formation with CloudSat as part of the A-Train constellation- are the ice crystal number concentration, particle size and ice water content in the DARDAR dataset (Delanoe and Hogan, 2010). While the CPR was not specifically designed for rain retrieval, data analysed shown a great potential also for rain estimation and snowfall in particular, providing vertical profiles of snowfall rate along with snow size distribution parameters and snow water content. The estimated minimum sensitivity to rainfall rate is approximately 0.02 – 0.05 mmh−1, whilst the minimum detectable optical depth (using the radar only) is between 0.1 and 0.4 for ice clouds, and between 1 and 5 for low level water clouds [Stephens et al., 2002]. The heritage of CloudSat will be collect by the next European Space Agency (ESA) mission EarthCare, expected for launch in 2021 (Illingworth et al, 2016).

The joint NASA/JAXA **GPM mission** [Hou et al., 2014], launched at the end of February 2014, aims at providing global measurements of precipitation with a higher accuracy and a wider coverage in latitudinal span than those obtained by the TRMM mission [Iguchi et al., 2000; Nesbitt and Anders, 2009]. The GPM core satellite is in a higher inclination orbit than TRMM and thus greater latitudinal extent (60°) and carries a Dual-Frequency Precipitation Radar (DPR), which includes a Ka-band (35.5 GHz) radar and a Ku-band (13.6 GHz) radar -very similar to the TRMM precipitation radar (PR). The 125-km-wide Ka band swath is centered in the 245-km-wide Ku-band swath. The DPR detection performance are slightly improved compared to the TRMM PR (with Minimum Detectable Signal (MDS) of 18 dBZ corresponding to rainfall rates as low as 0.5 mmh^{-1}) with MDS of 14.5 dBZ at Ku (corresponding to rainfall rates as low as 0.3 mmh^{-1}) and 16.3 dBZ at Ka in the matched scan mode [Hamada and Takayabu, 2016]. Lin and Hou [2012] demonstrated that, for Continental US, rain rates lower the 0.5 (0.2) mm/h threshold contribute to 43.1% (11.3%) and 7.0% (0.8%) to the total precipitation frequency and amount, respectively. In the Mid Latitudes these percentages significantly increase. The additional sensitivity of the GPM-DPR is particularly beneficial for shallow convective precipitation over the oceans and for light precipitation in the lower levels of anvil clouds [Hamada and Takayabu, 2016]. The inclusion of a second frequency has already demonstrated:

- the ability to retrieve parameters characterizing the DSD, from which most rainfall and radar parameters can be inferred [Gorgucci and Baldini, 2016];
- value in improving the rain classification [Le et al., 2016, Fig. 1.7];
- the benefit of improving the accuracy of dual-frequency SRTs over the single-frequency counterpart, particularly in the estimation of the Ku-band path attenuation [Meneghini et al., 2015].

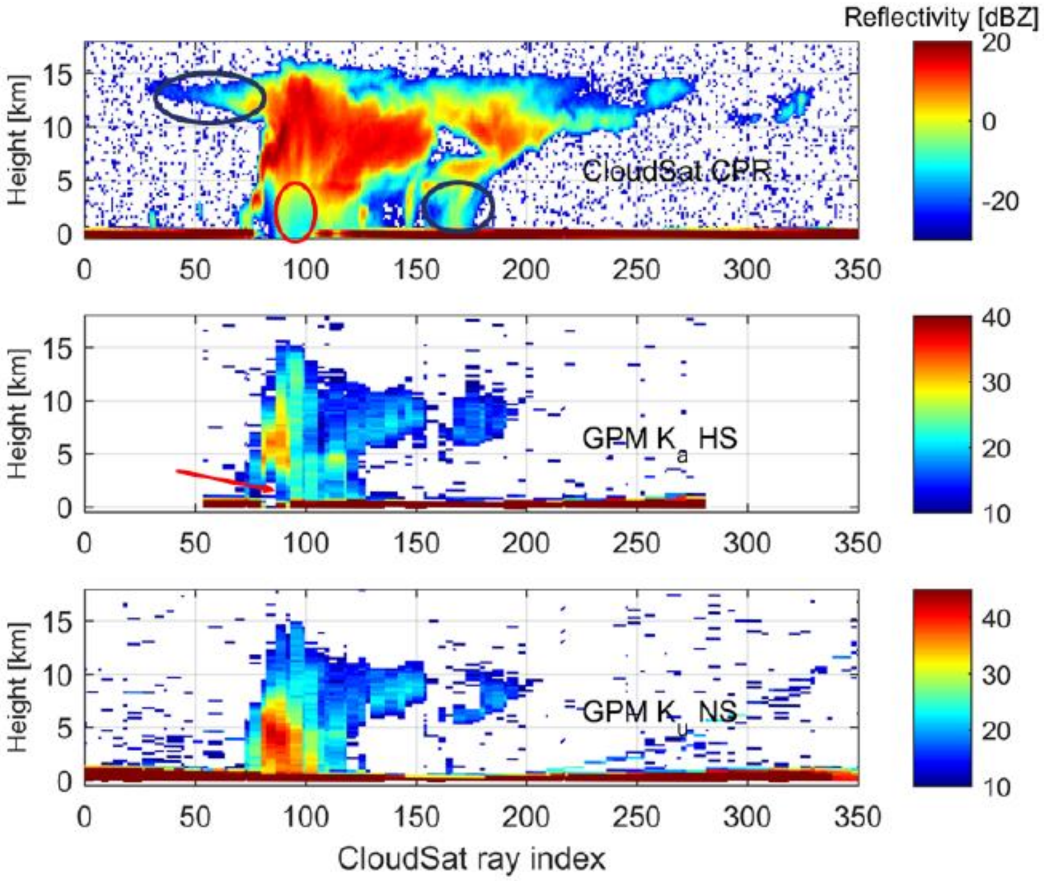


Figure 1.2: CloudSat and GPM coincident overpass observations of a convective precipitation system developed over the Banda Sea in the Maluku Islands of Indonesia. Top row: CloudSat W-band reflectivity; second row: GPM Ka-band reflectivities for the high sensitivity (HS) scan; third row: GPM Ku-band reflectivity for the normal scan (NS). The dataset of coincident overpasses is from the GPM product 2B-CSATGPM from the NASA Precipitation Processing System developed by J. Turk, JPL.

Fig.1.2, which depicts almost coincident observations from the CloudSat CPR and the GPM DPR, epitomizes the potential of spaceborne multi-frequency radar observations of the same precipitating system. Two aspects of the multi-frequency approach are paramount.

Complementarity: cm and mm-radars are effective in mapping different parts of the precipitating system. Thanks to its better sensitivity compared to the GPM DPR, the CloudSat CPR is capable of detecting the high cloud structure, the anvil outflow and the region of light precipitation in front of the heavy precipitating core (black circles). On the other hand, because of its much larger attenuation, the CPR signal is strongly affected by attenuation and multiple scattering in the most intense part of the precipitation (i.e. where even the Ka-GPM observations are fully attenuated, red circle).

Synergy: in the regions where they all produce detectable signals cm and mm-radars can be used synergistically in order to better retrieve cloud microphysical properties. For instance in Fig. 1.2 the large-ice and low-precipitation regions are detected both by the DPR and by the CPR. The signal detected by these radars is the result of the complex interplay between non-Rayleigh and attenuation effects. If the attenuation of the signal from one of the radars becomes too strong then the signal vanishes below the minimum detection threshold.

Combining radars and radiometers

The combined use of passive and active microwave instruments represents a key step forward in the precipitation retrieval from space because it allows to substantially extend the coverage and decrease the revisiting time of active radars. Since 1997 the Tropical Rainfall Measuring Mission (TRMM) hosted the first Precipitation Radar (PR) at 13.8 GHz together with a PMW multi-frequency imager (TMI) and the Lightning Imaging Sensor (LIS) (Kummerow et al., 1998). The synergistic use of active and passive sensors allowed for sensing the precipitation column, providing new insights into tropical storm structure. The GPM Core Observatory (GPM CO) spacecraft with additional channels on the GMI and one the dual-frequency precipitation radar (DPR) with capabilities to sense light rain and falling snow. The non-sun-synchronous 65° inclination orbit allows the GPM CO to sample precipitation across all hours of the day from the tropics to the Arctic and Antarctic circles. An important concept developed within the GPM mission is the realization of a constellation of precipitation observations provided by national and international satellite partners of opportunity, including SSMIS, Advanced Microwave Scanning Radiometer-2 (AMSR-2), the Megha-Tropiques sensors, MHS, and ATMS for a total of 10 satellites (see Fig.1.3). GPM CO has the role of calibrator to ensure unified precipitation estimates from all satellite partners at high temporal (0.5-3.0h) and spatial (5-15 km) scales, aiming at detailed investigations of the precipitation distribution and variability. This concept will be mirrored in this proposal for specifically targeting polar precipitation.

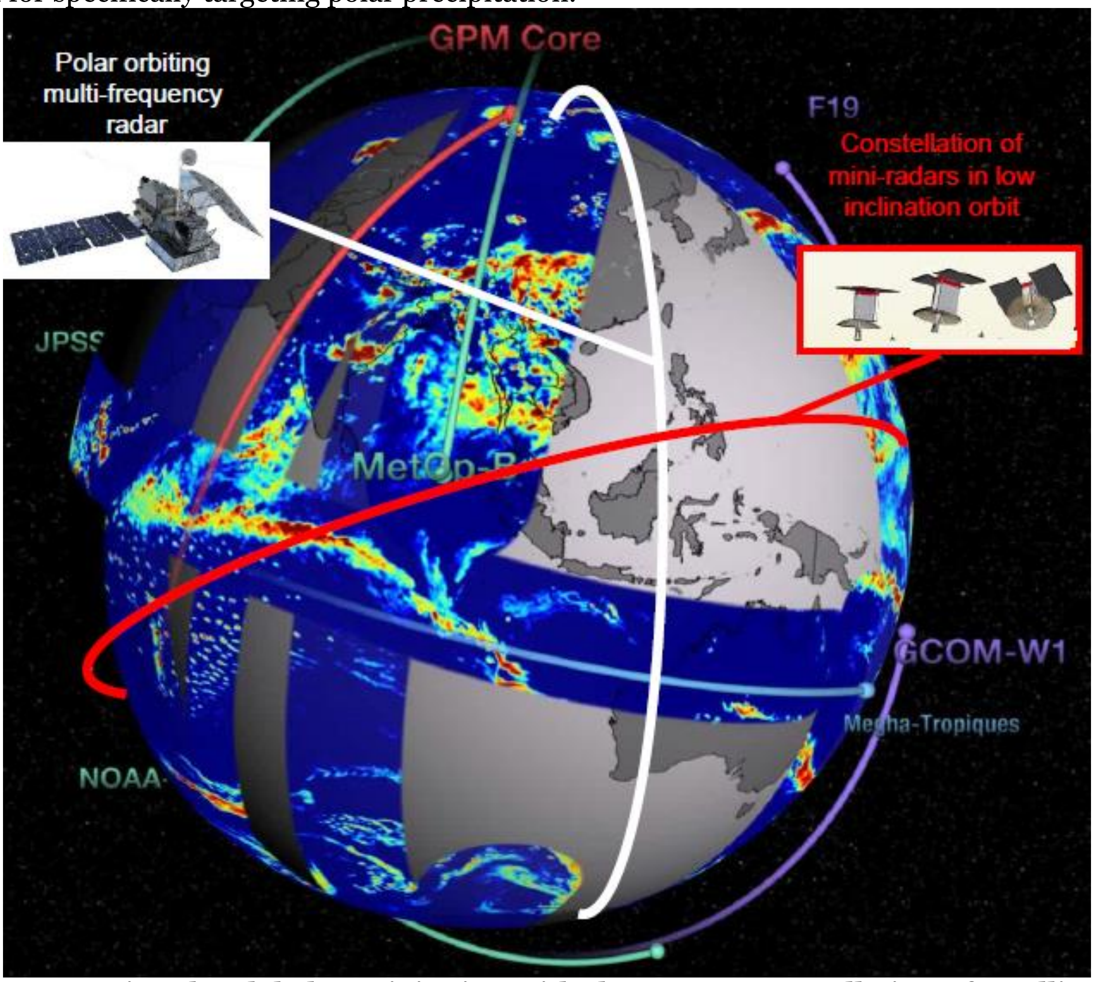


Figure 1.3: mapping the global precipitation with the current constellation of satellite and including two additional observing systems to the current constellation (as starting point for this ITT activity): a polar orbiting platform with a multi-frequency radar payload and a constellation of mini-radars flying in a low-inclination orbit.

New mission concepts in the pipeline or currently under study

Decadal survey radar concepts

The recent decadal survey [RD7] has identified Clouds, Convection, and Precipitation as observing system priorities and a mission with Radar(s) and multi-frequency passive microwave and sub-mm Radiometers as one of the 5 designated mission to be funded in the next decade. The idea therefore follow the GPM concept with the core radar instrument likely to be an evolution of the concepts developed in the previous decade as part of the previous Decadal Survey [The National Academies Press, 2007]. In particular a dual frequency Ka-W (35/94 GHz) band Doppler radar was proposed as part of the *Aerosol Cloud Ecosystems (ACE)* mission, which was recommended by the "Decadal Survey" in 2007. Cross-track scanning, was considered by the ACE Science Working Group as a requirement; while it was initially dropped at W-band on the grounds of technological readiness in 2009 (Tanelli et al. [2009]) it has been more recently reconsidered thanks to new technology advancements in W-band phase array antennas. The need to perform cross-track scanning derives primarily from the need to characterize the 3-D morphology of cloud systems at the meso-β scale, where, in fact, lie the effects of horizontal advection, entrainment and detrainment and the interface region between aerosol and cloud. A second need addressed by such "narrow swath" (of the order of 25 km) is that of improved combined radar-radiometer retrievals of cloud properties. In order to achieve them, the higher resolution instrument (the radar) needs to cover the whole footprint (one at least) of the lower resolution one (the radiometer). Since the radar footprint is of the order of 1 km and all radiometer footprints are at least 5 times larger, a non-scanning radar cannot fill not even one radiometer footprint. In fact, the lack of this capability is one of the major limitations of the CloudSat/CALIPSO synergy with AQUA and TERRA, and will also affect EarthCARE. Furthermore, wider scanning capability (meso–β) improves global coverage and the resulting statistics. It therefore strengthens the reliability of climatological conclusions, it increases the occurrence of observations viable for weather forecasting data assimilation, and it improves the feasibility of cal/val activities. A summary of the fundamental trade-off parameters for ACE is provided in Tanelli et al. [2009] and references cited therein. In general, the challenge can be summarized as follows: the combination of platform velocity, required horizontal and vertical resolution, Minimum Detectable Reflectivity and Doppler accuracy, and the need to cover a swath, limits the amount of resources (i.e., total energy and number of pulses) that can be radiated on each volume of resolution.

More recently the ACE concept has evolved into the Cloud and Precipitation Process Mission (CaPPM) concept, focused at the observation of cloud and precipitation processes. The mission aims at measuring how efficient storms are in generating precipitation and in moistening the upper troposphere, i.e. identifying what is the relationship between low-level convergence, precipitation and upper level detrainment and relating such mechanisms to environmental properties like sea surface temperature, tropospheric humidity, CAPE and the diurnal cycle. This ambitious goal requires to simultaneously measure quantities like the mass flux of condensed water, the flux of dry air, the precipitation and the mass of ice detrained at the top of the storm. The CAPPM team envisions to derive these quantities by deploying a triple-frequency (Ku/Ka/W-band) Doppler radar with spatial resolution sufficient to resolve convective scales at 1-5 km, together with precipitation imaging microwave radiometer capabilities. The combination of three radar frequencies on a single platform allows complete observation of all modes of precipitation from drizzle to deep convection and liquid to ice phase processes. Furthermore, the Doppler capabilities provide a direct link between the storm dynamics and cloud microphysics.

Passive microwave radiometers

Starting from 2021 the EUMETSAT Polar System – Second Generation (EPS-SG) will host two MetOp-SG platforms (Accadia et al., 2016). A new support to precipitation estimate will come from the Microwave Imager (MWI), Microwave Sounder (MWS), and Ice Cloud Imager (ICI). An innovative set of channels in the oxygen absorption band near 50-60 GHz and 118 GHz will enable the retrieval of low precipitation and snowfall by MWI, whereas MWS will host channels from 23.8

to 229 GHz and contribute to the monitoring of the evolution of precipitating systems, being on the same EPS-SG orbit as MWI and ICI, but on a different platform. The ICI, a millimeter and sub-millimeter wave conically scanning radiometer with 11 channels from 183 GHz to 664 GHz, is designed to monitor high altitude ice clouds and for snowfall detection.

Convoys of cube- and small satellites.

Recent scientific and operational applications in different fields, such as climate, meteorology, hydrology, agriculture, have introduced the need for higher space-time monitoring of the Earth's atmosphere and surface. Increased space-time resolution also characterizes clouds and precipitation observations for meteorology and climate, due to their very rapidly evolving structure. Such need cannot be anymore met by the current constellation of environmental and meteorological satellites due to the low revisit time and the high cost of large platforms. New strategies thus become necessary to ensure cost effective and higher space-time resolution earth-observation (EO) initiatives trying to break the traditional trade-off in EO mission design between GEO and LEO missions. Small satellites set the scene both in terms of new observation technologies and replicability of the single sensor translated into constellations that are relatively easy to launch and maintain. Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Small sats (TROPICS), Temporal Experiment for Storms and Tropical Systems – Demonstrator (TEMPEST-D), Radar in a CubeSat (RainCube), Tropospheric Water and cloud ICE (TWICE), and IceCube are small satellite missions focused on cloud and precipitation observations. In this activity particular focus will be dedicated to the RainCube concept. The radar has been designed at the JPL group led by Dr. Tanelli (International Collaborator). Its small size (10 cm×20 cm×20 cm), moderate mass (21 kg) and low power (10 W peak power) requirement enable constellation missions, which can augment our ability to observe weather systems and their dynamics and thermodynamics at sub-diurnal temporal resolutions down to few minutes required to observe developing convection (see example of a measurement of a miniKa Atmospheric Radar in Fig. 1.4). This offers a cheaper solution (e.g. compared to the Doppler capabilities proposed in CAPPM) for capturing the storm dynamics. While the D-Train[1] (Dynamical-Train Mission, PI: Prof. G. Stephens) was not funded as an Earth Venture Mission in the NASA program a RainCube demonstrator mission is currently under way. Dr S. Tanelli is the PI of the radar instrument and is International Collaborator in this proposal. The radar is expected to be released from the ISS on July 13, 2018. First data from the radar will be made available to the consortium.

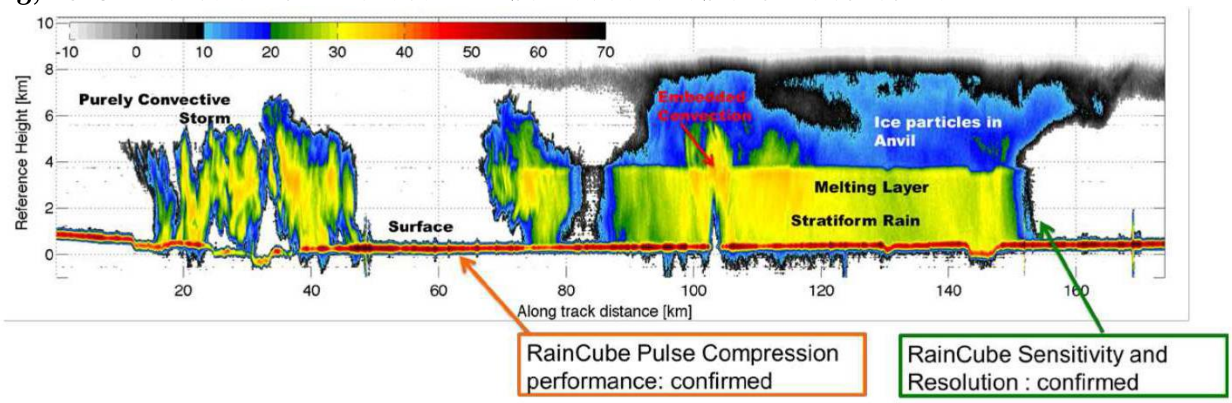


Figure 1.4: Data measured by RainCube as part of an airborne campaign demonstrating miniK$_a$AR performance, both sensitivity and clutter rejection (courtesy of D-Train team).

[1] The mission proposes a constellation of two satellites, separated by 80-90 seconds, orbiting at an altitude of 500 km in a low inclination orbit (28.5°) both quipped with a nadir pointing MiniKaAR. By measuring time-differenced profiles of radar reflectivity (Z) the vertical transports of air, heat and water in tropical deep convection can be investigated.

Deficiencies in the current microwave observing systems

The existing and planned space-borne systems (i.e., TRMM, GPM, CloudSat, EarthCARE and RainCube) offer a holistic view of the hydrological cycle in action. Although not on the same satellite, existing and planned space-borne radars cover the detection of all radiatively and hydrologically important clouds (along with complimentary information from spaceborne lidar systems). However, several gaps in the detection and characterization of precipitation remain, especially when our capabilities in multi-frequency and Doppler measurements are considered. Here is an analysis of some the major remaining gaps.

Shallow precipitation

Due to their low radar reflectivity (typically less than +15 dBZ), the detection of shallow clouds and precipitation is only possible with the 94-GHz space-borne radars. However, when the clouds and precipitation are within the lowest 1-2 km of the atmosphere, their detection is challenged by the strong surface echo. The CloudSat CPR uses a pulse length of 500 m, thus loses information below 1 km and cannot retrieve any information within 750 m of the surface. The EarthCARE is expected to have similar performance, although the higher sensitivity and the oversampling in range (100 m for a 500-m pulse) is expected to provide some improvement. Thus, currently, shallow precipitating systems such as Arctic, lake effect systems and marine boundary layer clouds that are usually confined to the lowest kilometre of the atmosphere pose a detection challenge for existing and planned space-borne radar systems (Kollias et al., 2007; Lamer et al., 2018).

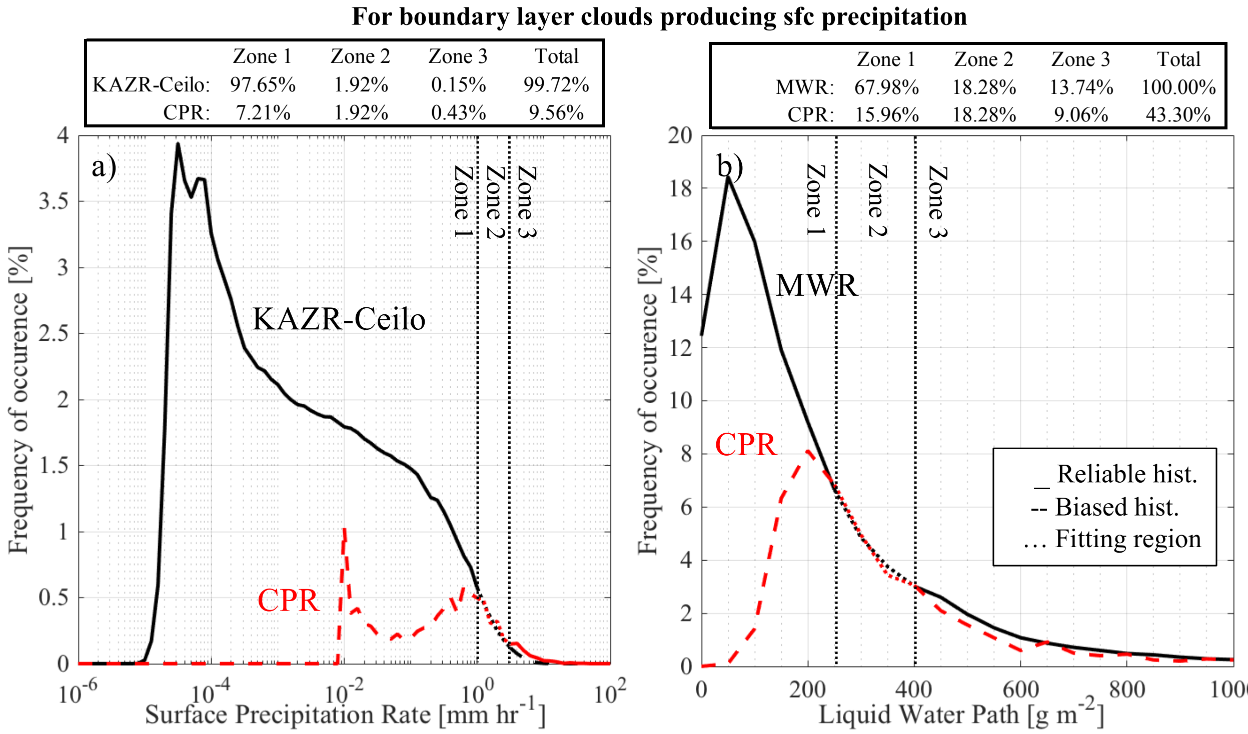


Figure 1.5: During warm low-level precipitation events a) distribution of mean rain rate in the atmospheric column retrieved using ground-based radar/lidar ARM data (black), retrieved using space-borne cloud precipitation radar data (CPR; red). b) Distribution of total liquid water path in the atmospheric column retrieved using ground-based microwave radiometer (black) and space-borne radiometer (red). For comparison, the CPR distributions are scaled to have the same total frequency of occurrence as the ARM distribution in zone 2. In zones 1 and 3 the distribution considered reliable is indicated by a solid line while the distribution believed to be biased is indicated by a dashed line (Lamer et al., 2018).

Snow and High latitude precipitation

The high latitudes regions have experienced, and are experiencing, significant changes brought about by climate change. While the effect on temperatures is relatively well known, the impact on precipitation is less well documented and understood. Recent research provides some initial indications that precipitation has been increasing but verifying or accurately quantifying the magnitudes of these changes is difficult due to little in situ data (Surussavadee and Staelin, 2009). This is especially true in the high-latitude regions where observations and measurements are sparse and the processes poorly known. In polar regions, precipitation is dominated by shallow, low intensity, mixed-phased precipitation, but inter-dispersed with intense weather systems such as Polar Lows (Rasmussen and Turner, 2003) and other high-impact systems (Hanesiak et al. 2009). Very little is known of either extreme due to the paucity of existing measurements and the dissimilarity with precipitation observed elsewhere over the globe: this has the potential to impact forecasts of rapidly developing intense snowfalls in polar mesocyclones over maritime and coastal environments.

Spaceborne microwave (MW) sensors are particularly suitable to detect and quantify snowfall and light precipitation thanks to their unique ability to probe within clouds (e.g., Skofronick-Jacskon et al., 2004, 2013). Spaceborne radars *alone* are not well designed to comprehensively characterize global snowfall. On one hand, cloud-oriented missions (CloudSat and EarthCARE) offer greater sensitivity and latitudinal coverage up to 82°N-S, but their vertical profiles of snow (Kulie and Bennartz, 2009, Hiley et al., 2011, Kulie et al., 2016, Chen et al., 2016, Milani et al., 2018) are contaminated by ground clutter in the lowest 1000 m, and their reduced swath (with a revisiting time of 16 days for a square of 100 x 100 km^2) does not provide the needed coverage for snowfall global monitoring. On the other hand, dual-frequency radar observations are especially valuable in ice/snow cloud conditions since the scatterers are complex with large variability in microphysical properties (e.g., density, size, shape) and the interpretation of single frequency radar observations is challenging (Szyrmer et al., 2012). However, the currently available GPM-CO DPR (Ku- and Ka-band) is insensitive to the light and/or shallow precipitation that dominates the middle and higher latitudes. Casella et al. (2017) have shown that DPR detects only 5-7 % of the global snowfall events with respect to CloudSat, while 29-34 % of the CPR global snowfall mass is detected by DPR (version 4 products). They also showed that by optimally combining the dual-frequency signal (Ku and Ka band), DPR snowfall detection efficacy can increase significantly (up to 54-59% of the CPR snowfall mass). Moreover, the GPM DPR provides dual-frequency radar observations only between 65°N-S. Thus, there is no dual wavelength, precipitation-oriented mission over the high-latitude regions where solid precipitation dominates. This proposal aims at filling this gap.

Passive microwave sensors appear promising for snowfall characterisation. Most of these sensors have high frequency channels (90-190 GHz) that are highly sensitive to snowfall due to the scattering by snowflakes of upwelling radiation (Bennartz and Bauer, 2003, Liu et al., 2013, Skofronick-Jackson and Johnson, 2011, Gong and Wu, 2017). In addition, passive microwave radiometers have a large swath and have been installed on many platforms over the last decades which ensures a good global coverage and lengthy data records. Several approaches have been proposed over the past years to detect and retrieve snowfall using passive microwave radiometers, both conically scanning, such as SSM/T2 (Liu and Curry 1997), SSMIS (You et al. 2015) and GMI (You et al. 2017, Rysman et al., 2018), and cross-track scanning, such as AMSU-B/MHS (Kongoli et al. 2003, Skofronick-Jackson et al. 2004, Ferrato et al., 2005, Surussavadee and Staelin 2009, Noh et al. 2009, Liu and Seo 2013, Kongoli et al., 2003, Laviola and Levizzani, 2011; Laviola et al., 2013) and ATMS (Kongoli et al. 2015, 2018).

Despite these attempts, detecting and quantifying surface snowfall rates using spaceborne microwave radiometers remains a challenging task (Levizzani et al. 2011, You et al. 2017, Skofronick-Jackson et al. 2017). Laviola et al. (2015) analyzed the capabilities of high frequency channels and discussed the limitations of snowfall detection particularly over land due to the contamination on the scattering signal of the cloud by the frozen soil. The high-frequency radiometer channel observations are very sensitive to environmental conditions (e.g., humidity, temperature, frozen or snow covered soils) which affect the measured signal. This problem is particularly acute at high latitudes where the low and variable emissivity of snow or ice-covered surfaces (Prigent et al., 2006, Noh et al. 2009, Foster et al. 2012, Turk et al. 2017) can mask snowflakes scattering signature (Ebtehaj and Kummerow 2017). Finally, low humidity in high latitude regions makes the atmosphere more transparent for channels that probe around the water vapour absorption line and thus increases the surface contamination. In addition, the snow microphysics are very complex and a snow precipitating systems are often composed of a wealth of snow particles with a variety of densities, shapes, particle size distributions and radiative properties (Petty, 1994, Bennartz and Petty, 2001, Kulie et al., 2010, Petty and Huang 2010, Kuo et al., 2016, Olson et al., 2016). Supercooled droplets and melting snow also frequently occur and can strongly affect the observed signal (Kneifel et al. 2010, Liu and Seo 2013, Wang et al., 2013, Johnson et al., 2016).

Recently, studies have been undertaken to assess the information contained in various PMW channel combinations for snowfall detection using spaceborne radar observations of snowfall events globally. These studies have shown that observational datasets built from currently available coincident spaceborne active and passive microwave observations can be exploited not only to refine and develop precipitation retrieval techniques (Kummerow et al., 2015, Casella et al., 2017, Sanò et al., 2016), but also to explore and verify potentials and limitations of current and future satellite missions. In contrast to model-driven approaches (e.g., Eriksson et al., 2015) affected by some limitations in the description of the particle's optical and bulk microphysical properties, these studies have shown that the multi-year, quasi-global, and complementary DPR and CPR measurements offer, in spite of their limitations, a unique and extensive resource to analyse spaceborne microwave radiometer precipitation observational capabilities. For instance, in the work by You et al. (2017) a coincident GPM GMI and DPR database is analyzed to determine optimal channel combinations for snowfall detection over land. In a recent study Panegrossi et al. (2017) analysed an observational datasets built from matched GMI and CloudSat-CPR snowfall observations (mainly occurring at latitudes between 55° and 65°N). The authors provided instructive insights on microwave multi-frequency signals associated with snowfall in cold regions. Panegrossi et al. (2017), as well as You et al., (2017) and Ebtehaj and Kummerow, (2017), have evidenced the need to characterise the extremely variable background surface for each GMI pixel at the time of the overpass, especially at high latitudes (in cold and dry conditions), where high-frequency channels may be affected by the emission and polarisation signal from the surface. While Panegrossi et al. (2018) have analysed the potential of GMI low frequency channels to provide information about the frozen background surface, Rysman et al. (2018) have shown how such information, combined with auxiliary variables of the atmospheric conditions, can be successfully exploited towards snowfall detection and snow water path (SWP) retrieval from GMI observations at higher latitudes.

Lack of understanding on key processes in models

In order to predict future climate and precipitation patterns, what is needed is not only the characterization of cloud and precipitation properties in the current climate, but elucidating the processes operating within the atmosphere to create these clouds and precipitation. By processes, we mean the fundamental mechanisms governing the evolution of embryonic cloud droplets and ice crystals to precipitation sized particles, mechanisms that should be valid no matter what changes in the Earth's circulation are predicted. These nucleation and growth processes from cloud droplets and ice crystals to raindrops, snowflakes, graupel and hail, ultimately determine the distribution of precipitation at the surface. Latent heating, and the vertical velocities associated with it are critical to enhancing our understanding of these microphysical processes, and hence our understanding of hydrometeor nucleation and growth processes, the vertical transport and distribution of hydrometeors, and the dynamical-microphysical feedbacks that occur through phase changes. Such understanding is critical if we are to advance cloud/precipitation processes in Cloud Resolving Models (CRMs) as well as parameterizations in weather and climate models as these numerical models approach cloud-permitting scales. In the tropics and the mid-latitudes, some of the most important challenges include:

- *An inability to represent important modes of variability and convective organization (such as the MJO; Zhang et al, 2013)*. Correctly parameterizing the interactions between shallow and deep convection has been found to be important to the development of the MJO, a problem made difficult by the grid structure of GCMs. The grid structure of GCMs also makes the upscale development and organization of MCSs difficult to represent, thus requiring a better understanding of how to parameterize these processes.
- *Errors in the mean locations of convective precipitation and the double ITCZ (Bellucci et al., 2010) persists in almost all GCM models.* This bias produces unrealistic climates both locally and more far afield.
- *Poor representation or quite often the complete absence of major convective storm phenomena such as MCSs (Cotton, Bryan and van den Heever, 2010 https://www.elsevier.com/books/storm-and-cloud-dynamics/cotton/978-0-12-088542-8)*. MCSs are responsible for a significant amount of the summer and winter rainfall in both the Tropics and the mid-latitudes. They are also important in cloud venting and have unique heating profiles. Incorrectly representing MCSs therefore has significant implications for precipitation, vertical redistribution, and heating.
- *Incorrect diurnal timing of the development, propagation and precipitation of severe convective storms*. Incorrect representation of the diurnal cycle leads to major forecasting errors over the CONUS and other regions (Chakraborty, 2010; Mapes and Neale, 2011*)*.
- *Inaccuracies in the links between storm dynamics and microphysics*. The inability to directly link storm dynamical and microphysical processes in models influences the representation of microphysical processes such as activation (Saleeby and Cotton, 2004), droplet number concentrations, size distributions and autoconversion rates (Morales and Nenes, 2010), and convective invigoration (Storer et al., 2014) all of which have implications for cloud radiative forcing, surface precipitation and vertical heating.

1.1.3 Proposed approach to reach the main technical objectives of the ITT

After a thorough review of the state of the art of the current precipitation observing system and of its gaps the proposing team will identify a few concepts with potential in addressing some of the key scientific questions paramount to progress in precipitation monitoring and in precipitation processes. This selection will be driven by the long-term experience of the proposing team in the field. The PI Battaglia and co-I Kollias are involved in the algorithm development for GPM and EarthCARE and have been involved together with Wolde in several mission proposals to ESA (PPM, CLOUDY, WIVERN), the Canadian Space Agency (Snowsat) and NASA (D-Train, StormSat) while the International Collaborators have had a prominent role in all mission proposals involving multi-frequency radars (Tanelli) and radiometers (Kidd) submitted to NASA in the past decade. The other co-I Panegrossi is part of the GPM Science Team and she is leading the Eumetsat H-SAF. This background knowledge guarantees that the selected concepts for this ITT will align this activity with the needs of the precipitation community.

As a ***first iteration*** the consortium has already established some core ideas that will be expanded during the activity. In order to tackle the complexity of observing precipitation from space it is obvious that a constellation approach must be adopted. Our intention is to develop a couple of concepts that will able to contribute to the overall constellation as illustrated in Fig.1.3.

The **first concept** is essentially focussed at **enhancing the current capability in snow and high latitude precipitation**. This will be done by proposing a constellation similar to the GPM concept but with a core satellite in a polar orbit and equipped with a radar similar to the one proposed for the Polar precipitation Mission at its heart. Since feasibility studies are part of a concurrent ESA activity [AD1] led by the same PI (Battaglia), in this ITT we will focus mainly at the **performance assessment of radar-only snow retrieval capabilities and at the performances of the products of the radiometer constellation**. This research avenue will leverage on the extensive expertise of the proposed team in retrieval algorithm development, field campaign data analysis and cloud modelling. Our work in this area will try to address scientific questions like: what is the advantage of using multi-frequency radar observations compare to single frequency radar observations when comes to retrieving snow microphysics (e.g., water content, characteristic size) and light precipitation? What is the benefit of adding a radiometric mode to a K_a or W or band radar? What is the minimum footprint required for properly exploiting differential reflectivity signal (that can be severely degraded due to non-uniform beam filling)? What are the best radiometric channels for retrieving snow and for which specific and atmospheric/surface scenarios? How are the footprints and the scanning modes (conically vs cross-track) affecting the snow retrieval performances?

Understanding multi-frequency radar capabilities in polar precipitation

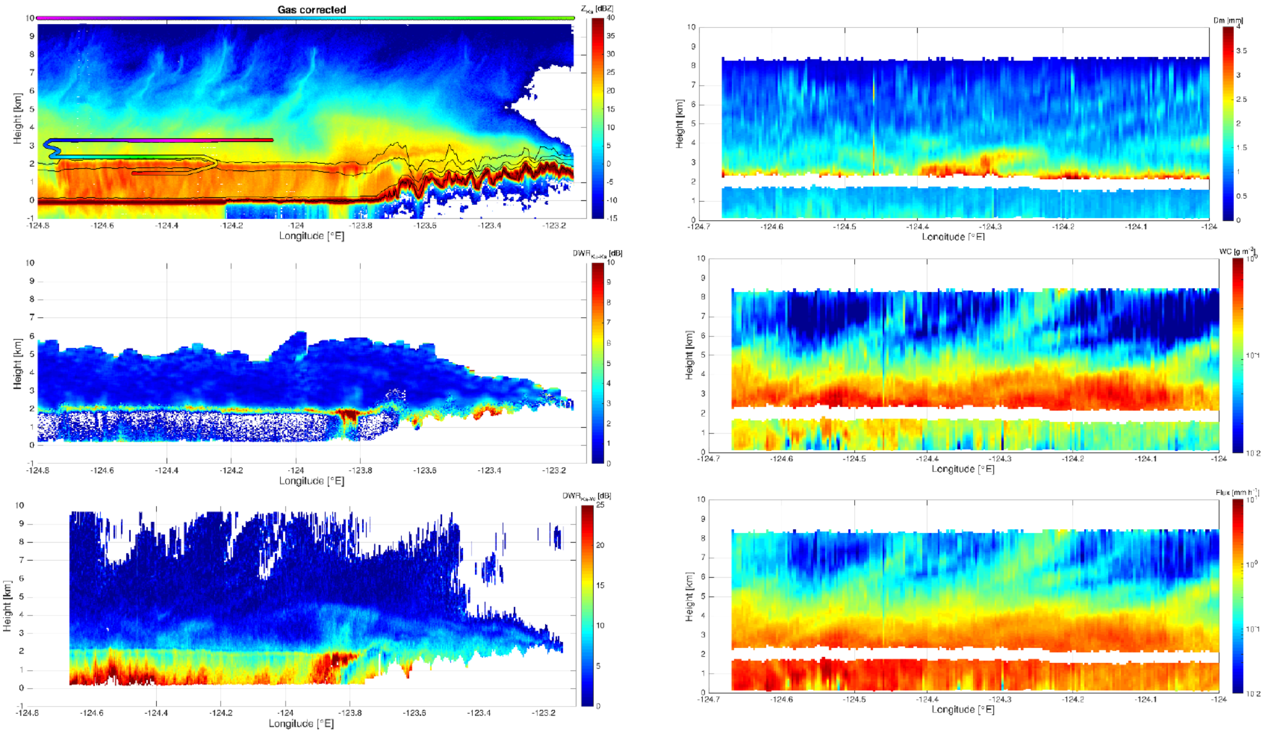


Figure 1.6: Left: gas-corrected K_a-band reflectivity (top), DFR_{Ku-Ka} (centre) and DFR_{Ka-W} (bottom) for a flight on the 1st December 2016 over the OLYMPEX peninsula. Right: retrieved parameters [mean mass-weighted maximum size (top), IWC (centre) and flux (bottom)] for the leg shown in the left panels (extracted from Battaglia et al., 2018)

The performances of the radar instruments can be established by exploiting new multi-frequency datasets and retrieval techniques. In general, because of the difficulty of accounting for attenuation in the higher frequency channels multi-frequency retrievals are based on optimal estimation approaches (L'Ecuyer and Stephens (2002), Grecu et al.(2011), Battaglia et al.(2016), Mason et al.(2017)]) which disentangle non-Rayleigh and attenuation effects by optimizing a cost function via an iterative process based on a forward model radar operator. Bayesian approaches have also been recently developed for retrieving ice only microphysics under the assumption that effective reflectivities can be recovered (Leinonen et al.(2018)). An example of an optimal estimation

retrieval applied to the data collected by the Airborne Third Generation Precipitation Radar (APR-3) flown on board the NASA DC-8 aircraft during the OLYMPEX field campaign (details in Houze et al.(2017)) is shown in Fig.1.6. The retrieved values are comparable with the in situ measurements (Tridon et al., 2018) though it remains challenging, given the uncertainties in the in-situ measurements and the co-location/sampling issues, to draw definitive conclusions about the quality of the retrieval. The Canadian field campaign (see Sect.1.4) will produce a unique dataset in this respect and will allow to test the performance of the triple frequency retrievals and therefore provide a rigorous assessment of the snow retrieval capabilities for a system like the multi-frequency radar envisaged for the core satellite of the precipitation constellation.
In addition, the Canadian dataset will include polarimetric radar data which would be used to enhance the performance of the retrieval techniques. In dual-polarization radar systems, measurements are made at more than one polarization state. The intrinsic backscattering properties of the hydrometeors to the two polarization states enable the characterization of microphysical properties such as size, shape and spatial orientation of the cloud/precipitation particles in the radar resolution volume [Matrosov et al. 1996, Wolde and Vali, 2001]. Hence, it is generally possible to achieve more accurate classification of hydrometeor types using polarization.

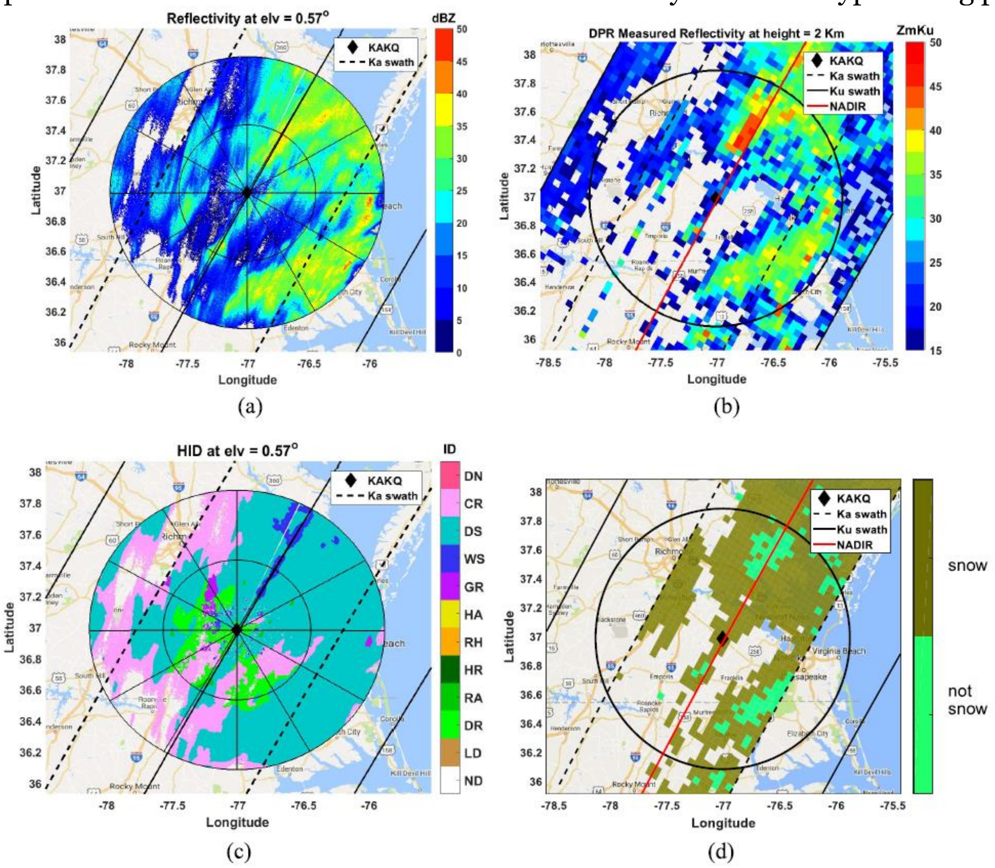


Fig. 1.7: Example of validation of snow products based on S-band operational radar (February 5, 2016). (a) S-band reflectivity of KAKQ radar (VA) (radar elevation angle of 0.57°). (b) DPR Ku reflectivity factor for DPR corresponding overpass. (c) Hydrometeor classification based on S-band dual-polarization measurement. (d) Snow/no snow discrimination DPR inner swath (from Le and Chandrasekar, 2017).

Satellite rain products have been extensively validated by operational ground-based radar networks (e.g. Kirstetter et al., 2013; Kidd et al, 2018, Watters et al., 2018). Less efforts have been done in terms of snow products. Validation of snow products have been carried out mainly within experimental campaigns (e.g. Houze et al. 2017) where specific instrumentation are purposely

deployed. In this respect, it is a custom practice to use ground radar based *S(Z)* power law estimators to convert the radar equivalent reflectivity factor (*Z*) into a liquid equivalent snowfall rate (*S*). However, the large variability of snow growth habits as well as of its particle size distributions (PSDs), snow particle density, water content and orientation makes the radar backscattering power signal extremely variable for the same snowfall rate. Consequently, *S* roughly shows an order of magnitude difference for the same value of *Z* as testified by the plethora of *S(Z)* relations that have been proposed in literature so far (e.g. Gunn and Marshall, 1958; Sekhon and Srivastava, 1970; Puhakka, 1975; Koistinen et al. 2003; Szyrmer and Zawadzki, 2010; Wolfe and Snider 2012; Heymsfield et al. 2016). A similar approach is usually followed for the ground radar-based ice water content (*IWC*) estimates leading to plenty of *IWC(Z)* power law estimators.
Dual polarization radar systems have recently shown some promising potentials to better constrain the *S(Z)* and *IWC(Z)* retrievals. In particular, the method recently proposed by Bukovčić et al. (2017) is suggesting to use a direct combination of *Z* and the specific differential phase shift (*Kdp*) to estimate *S* and *IWC*. The rationale of using a combined *S*(*Z, Kdp*) or *IWC*(*Z*, *Kdp*) estimator is that, under the assumption of an inverse relationship between the ice density and the ice equivalent diameter (actually usually valid for dry snow only), *S* and *IWC* are proportional to the second moment of the PSD, whereas *Z* and *Kdp* are close to the fourth moment and the first moment of the PSD, respectively. Therefore, the product of *Kdp* and *Z* with some optimized exponents might be more directly related to the second moment of PSD, which is closely related to *S* and *IWC*.

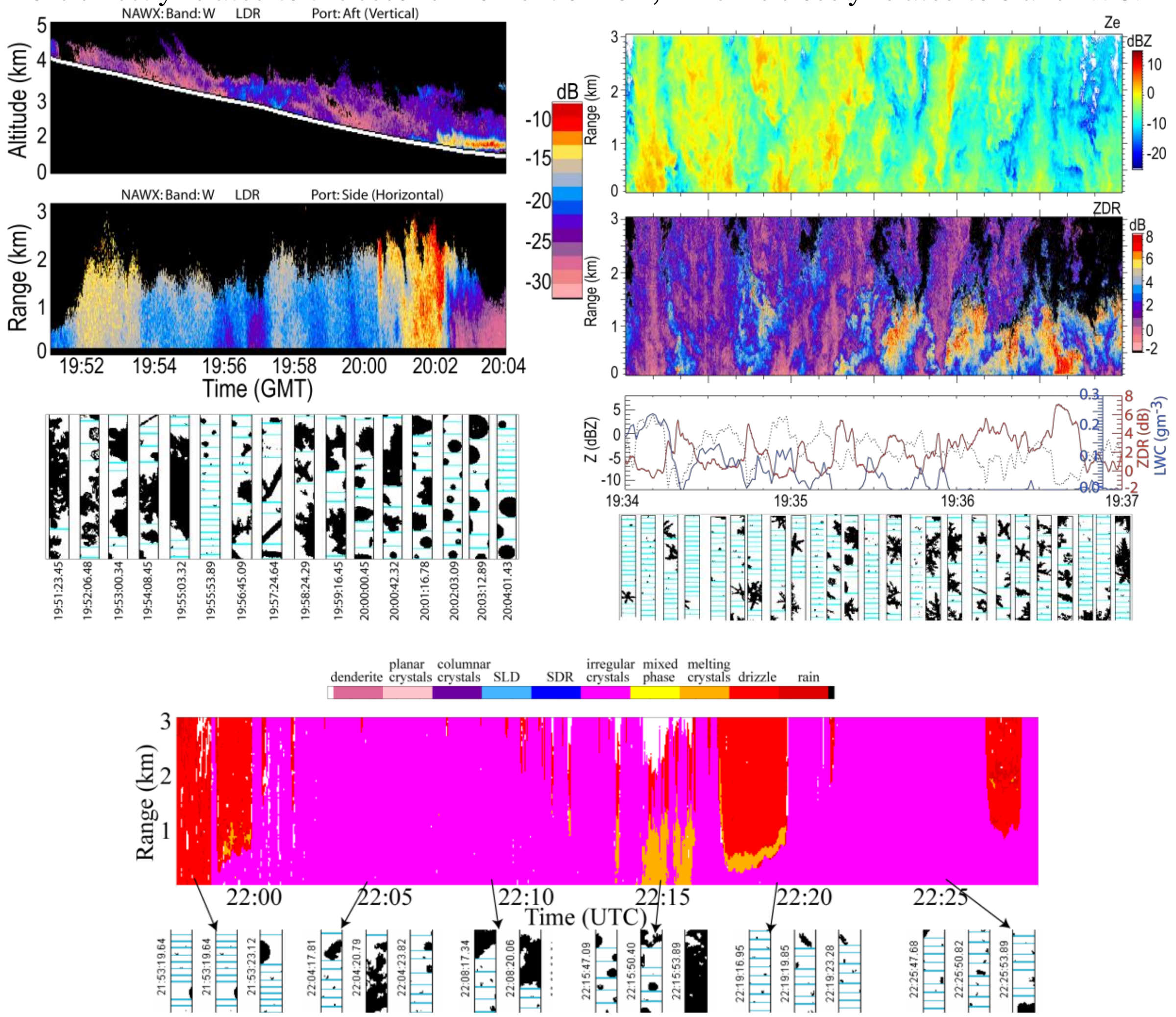


Figure 1.8: ***NRC W-band measurement during the C3VP flight on 01-Mar-07.***

Contrarily, for pristine crystals with high density, which do not exhibit strong size dependence, *Z* and *Kdp* are still close to the sixth moment and the third moment of the PSD (i.e. *Kdp* it is directly proportional to the ice water content for pristine and lightly aggregated crystals).
Obviously, in this retrieval scheme may become important to identify the areas of the precipitation cloud where the assumptions made to derive *S*(*Z*, *Kdp*) and *IWC*(*Z*, *Kdp*) are more likely met. In this respect, a pre-classification step of snow types using polarimetric variables could be applied and then use *S*(*Z*), *IWC*(*Z*) or *S*(*Z*, *Kdp*) and *IWC*(*Z*, *Kdp*) relations. Differential reflectivity (*Zdr*) could drive the snow classification scheme being it insensitive to snow concentration.
One concern when dealing with *Kdp* is on its reliability due to the noise contamination especially in aggregated snow when the signal to noise likely become low. Spatial averages can be applied to mitigate this issue thus reducing the noise level on *Kdp*. Although spatial averages have the unwanted effect of reducing the spatial resolution of the final ground based snow estimation product, this have not be necessarily seen as a drawback if the final goal, as in our case, is to produce quantitative comparison with satellite sensor retrievals with associated footprints of several km^2.
A further advantage of dual-polarization radar is the possibility of achieve classification of the prevailing particle in a radar resolution volume. Fig 1.7 from Le and Chandrasekar (2017) reports an example of the comparisons performed for validating a GPM satellite snow/no snow partitioning algorithm that take advantage from a dual-polarization particle classification algorithm.
The near-coincident airborne dual-polarization radar measurements and in-situ microphysics observations available during RadSnowExp [RD-4] will enable development of effective hydrometeor classification algorithms [Pelon et. al., 2013]. The in-situ data is used as the ground truth to design a fuzzy logic algorithm based on radar polarimetric measurements. Figure 1.8 shows an example of identifying hydrometeor types and phase from dual-polarization measurements using the NAWX radar.

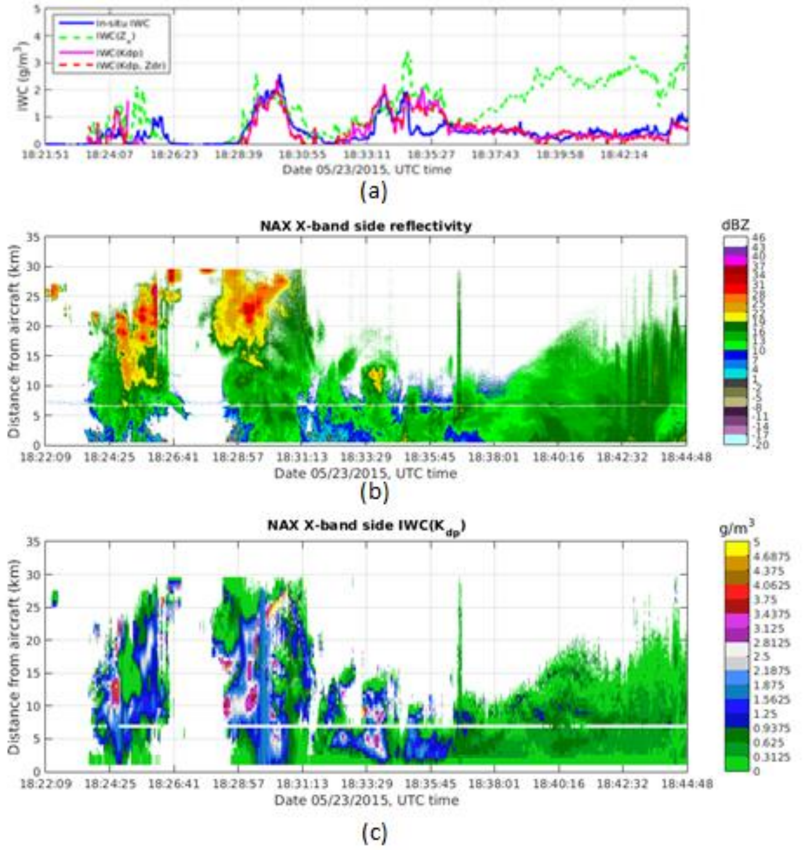


Figure 1.9: Examples of IWC estimates using polarimetric method. Data from the 2015 HAIC-HIWC campaign.

The additional information from hydrometeor classification can be used to adjust the scattering model used in the retrieval algorithms (see Sect. 1.4) and hence, improves their performance. Moreover, knowledge of hydrometeor types has been proven to improve the estimation of hydrometeor amounts (Cifelli et al., 2011). Asides from this, correlations between qualitative measurements and some polarimetric parameters are less dependent on the particle' microphysics properties (such as PSD, orientation). For example, the radar specific differential phase (K_{dp}) is potentially useful for IWC retrieval (Vivekanandan et al. (1994) and Lu et al. (2015)).
Polarimetric approach for IWC retrievals significantly reduces errors compared to the conventional method using radar reflectivity only. Figure 1.9 shows an example of detection and estimation of IWC in the tropical convective cloud from the NRC Convair dual-polarization X-band radar. Although the implementing dual-polarization radar in space is not ready and severely limited by the scanning geometry, the Canadian dataset provide a unique opportunity to explore the benefit of polarization in characterization of arctic cloud and precipitation systems.

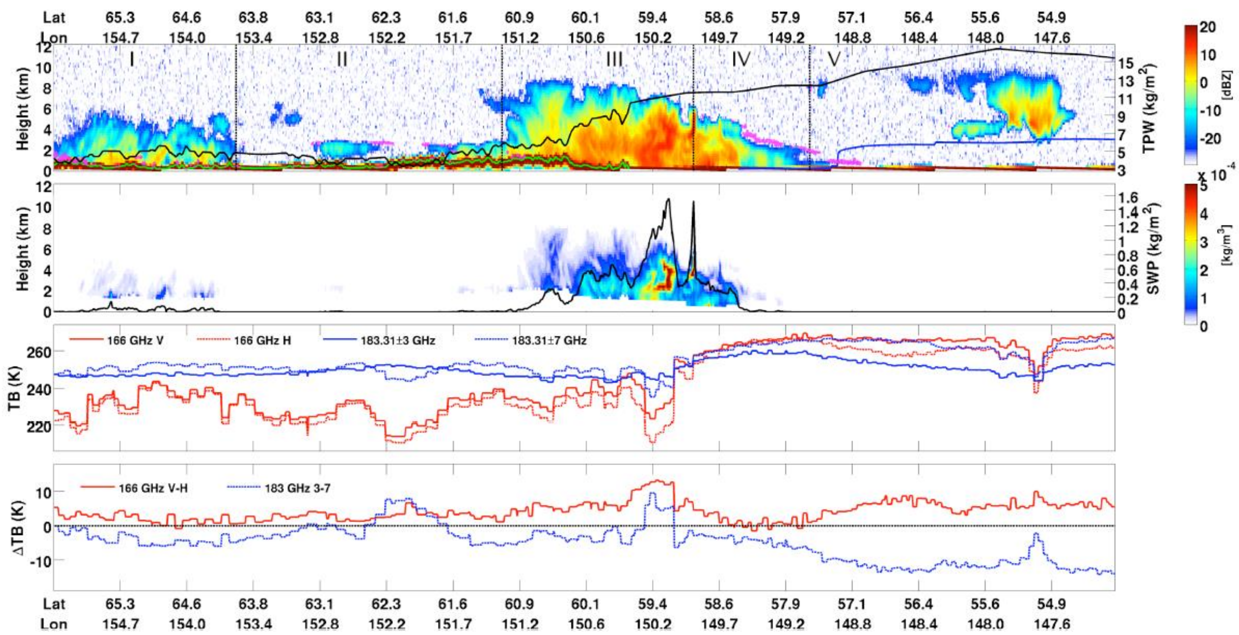


Figure 1.10: Snowfall event on 30 April 2014. From top to bottom, the first panel shows height-lat/lon imagery of CPR reflectivity (colorbar, in dBZ), the freezing level height (blue curve), and TPW (black curve, with values provided on the right-hand side y-axis), along the CloudSat track. In this panel, cloud layers where the DARDAR product identifies supercooled droplets are superimposed and shown in magenta. Second panel shows height-lat/lon imagery of 2C-SNOW snow water content (SWC) (colorbar, in kg m-3) and the snow water path (SWP) (black curve, with values provided on right-hand side y-axis). Third panel: GMI TBs closest to each CPR pixel along the CloudSat track at 166 GHz (V and H polarization, in red), 183.3±3 GHz and 183.3±7 GHz (in blue). Bottom panel shows GMI TB difference (ΔTB) at 166 GHz (V-H, in red), and for the two 183.3 GHz channels (in blue). In the top panel, vertical lines delineate different Sectors (I to V) identified in the discussion. (Figure adapted from Panegrossi et al., 2017).

Understanding multi-frequency radiometer capabilities in polar precipitation

Panegrossi et al. (2017) have illustrated how beneficial the use of observational CloudSat-GPM coincidence datasets is in addressing sensitivity assessment, as well as footprint size, and presence of supercooled liquid water effects, on passive microwave measurements of snowfall. In their study the global NASA GPM-CloudSat coincidence dataset (2B-CSATGPM, Turk, 2018, see Fig.1.2) was combined with DARDAR (liDAR+raDAR) product derived from CPR and CALIPSO lidar measurements (Delanoë and Hogan 2010,http://www.icare.univ-lille1.fr/projects/dardar), supplying predominant particle phase/microphysics composition or constituent classification (e.g., presence of supercooled water).

The analysis quantitatively showed how the high-frequency channel response to snowfall at the surface (in particular the GMI 166 GHz channels, V and H polarization) is critically affected by environmental conditions (e.g., background surface snow cover conditions over land, sea ice concentration over ocean, water vapor content) and by the presence of supercooled droplets, and how such response depends on cloud vertical structure and snowfall intensity.

Figure 1.10 shows a widespread frontal snowfall event in Eastern Russia on 30 April 2014 The highest radar reflectivities are ~15 dBZ in the most intense central snowfall regions (Sector III), while reflectivites are much lower in both the shallow fringe central snowfall zones (Sector II) and the snowfall event located to the north and east (Sector I). It is worth noting that CPR may miss the snowfall in the first 1000-1500 m above the surface because of ground clutter, with possible underestimations in the SWP and surface snowfall rate estimates. In the deeper snowfall segments (Sector III), 166 GHz and 183±7 GHz TBs show some sensitivity to columnar ice content scattering effects that produce decreasing TBs (i.e., ~15-20 K decrease in 166 GHz TBs compared to surrounding regions). In this segment, the 166 ΔTB also show a polarization increase corresponding to the deeper and most intense clouds.

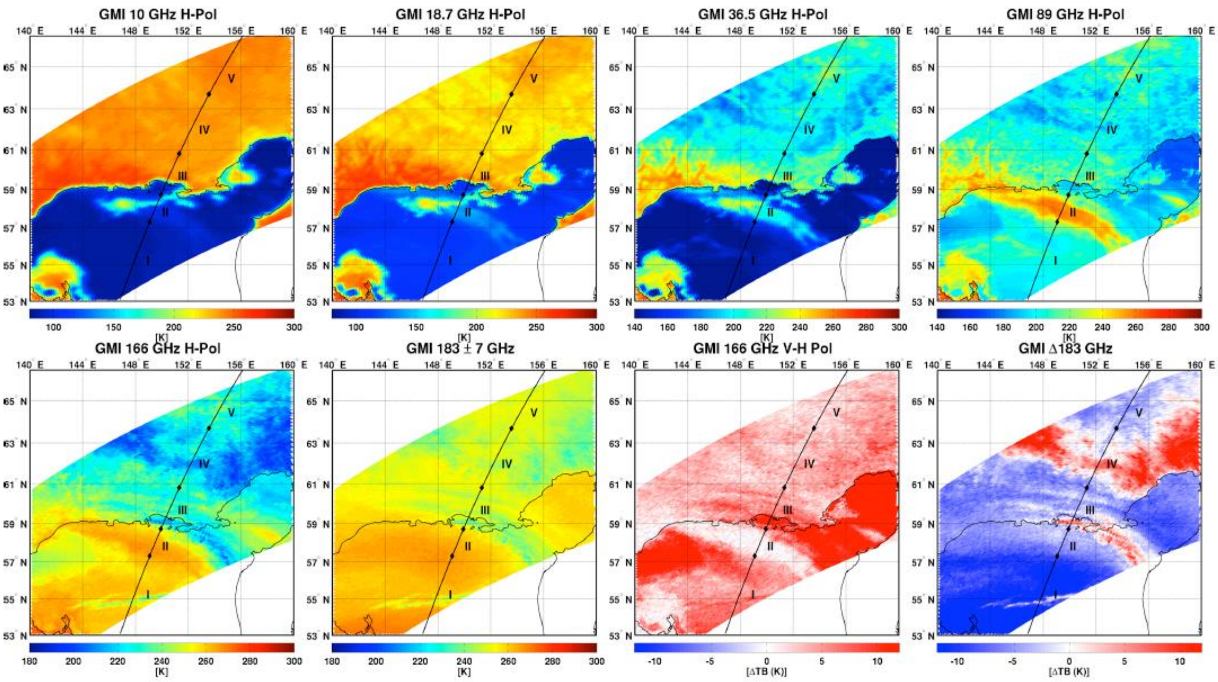


Figure 1.11: GMI TB imagery corresponding to the snowfall event on 30 April 2014 shown in Figure 1.10. Top row from left, 10, 18.7, 36.5, and 89 (H-pol) channels; bottom row from left: 166 (H-pol) and 183±8 channels, ΔTB at 166 GHz (V-H) and at 183.3 GHz (183.3±3 GHz – 183.3±7 GHz). The black line segment in each panel shows the CloudSat track. The sectors (I to V) identified in the discussion are also indicated.

In correspondence of the weaker or shallower snow clouds (Sector I and II, north of 60°N), 166 GHz TBs are higher than in the cloud-free regions because of the effect of supercooled cloud liquid water, as verified by CloudSat DARDAR product (magenta colour layers in the top panel). Cloud liquid water masks frozen hydrometeor scattering effects and further complicate high microwave frequency TB signatures associated with snowfall events. Moving south from 59°N (Sector IV and V), the 166 GHz and 183 GHz TBs progressively increase due to the atmospheric water vapor gradient. This water vapor effect dampens the ice scattering effects due to the shallower and weaker portion of the clouds south of 58.6°N (Sector IV). The effect of the emission by supercooled droplets is evident at 89 GHz (Figure 1.11, top-right panel), while it is not visible at 166 GHz likely because of the stronger emission signal by the water vapor at this frequency. In this region Figure 1.11 shows faint warming signatures also at low frequencies (< 37 GHz) with respect to the radiatively cold oceanic surface background, thus indicating the presence of melting snow or drizzle at very low levels. At 10 GHz and 18.7 GHz frequencies, the emission signal is more evident west of 148°E, where it is very likely associated with predominantly liquid precipitation. Figure 1.12 shows the results from Rysman et al. (2018) for the same frontal snowfall case illustrated in Figures 1.10 and 1.11. Their Snowfall retrievaL ALgorithm fOr gMi (SLALOM), trained using coincident snowfall observations of the CPR on-board CloudSat, retrieves snow water path (SWP) over any surface type fully exploiting the GMI multichannel measurements, without relying on any auxiliary information on the background surface. SLALOM is able to predict snowfall, supercooled water occurrence, and SWP in very good agreement with the Cloudsat products, ensuring at the same time a much larger spatial coverage corresponding to the GMI swath.
In the present study (WP3200), the new generation multichannel MW radiometers such as the GMI (conically scanning, on-board the GPM-CO) or the ATMS (cross-track scanning, on board Suomi-NPP and NOAA-20 satellites) will be used to further analyse the high-frequency microwave channel responses to different snowfall and light precipitation scenarios, in conjunction with their low-frequency channel response to the background surface conditions. The study will be based on the global multi-satellite coincidence datasets including space-borne radar measurements, which have demonstrated to have great potentials for successfully investigating new strategies in the design of future global precipitation missions.

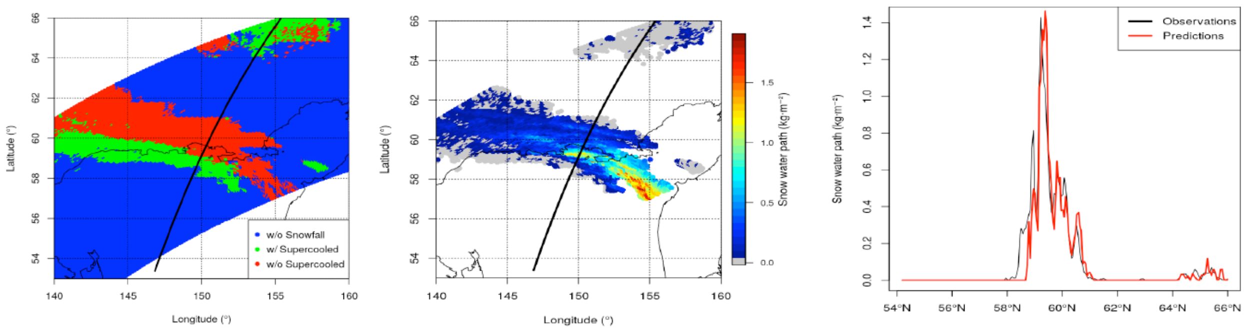


Figure 1.12: Case study of 30 April 2014. Left panel: supercooled droplets classification predicted by the Snowfall retrievaL ALgorithm fOr gMi (SLALOM) (blue: without snow, green: with snowfall and supercooled droplets and red with snowfall and without supercooled droplets) and CloudSat track in black. Middle panel: retrieved SWP by SLALOM on the GMI swath, and CloudSat track in black. Right panel: SWP cross section along CloudSat track according to CloudSat 2C-SNOW-PROFILE (V05) product (black) and SLALOM (red) (Figure adapted from Rysman et al., 2018).

In addition PMW products will be assessed by exploiting the snow retrieval capabilities of the ground based radars of the US NEXRAD; we will focus on the North part of the country where snowfall storms are more likely to occur and dual-polarization radar are easily available. In particular, we plan to apply the method proposed by Bukovčić et al. (2017) for the ground truth snow and ice water content retrievals trying to evaluate the impact of the radiometer spatial resolutions and scanning modes.

The second concept that we would like to explore focuses on advancing our **understanding of vertical transports of water vapor and condensate by atmospheric moist convection**. This will be done by proposing a mission similar to the D-Train mission that utilizes a constellation (a pair) of micro-satellites that fly in formation 60-90 seconds apart, each flying a miniature, nadir-pointing Ka-band atmospheric radar (miniKaAR). Each miniKaAR provides the conventional range-resolved power backscattered from hydrometeors expressed by the equivalent radar that carry Ka-band radars. By making time-sequenced profiles (Fig. 1.13) of radar reflectivity (Z) separated seconds apart (ΔZ), D-Train provides a measure of the movement of water upward, which traces the movement of air upward in strong convection.

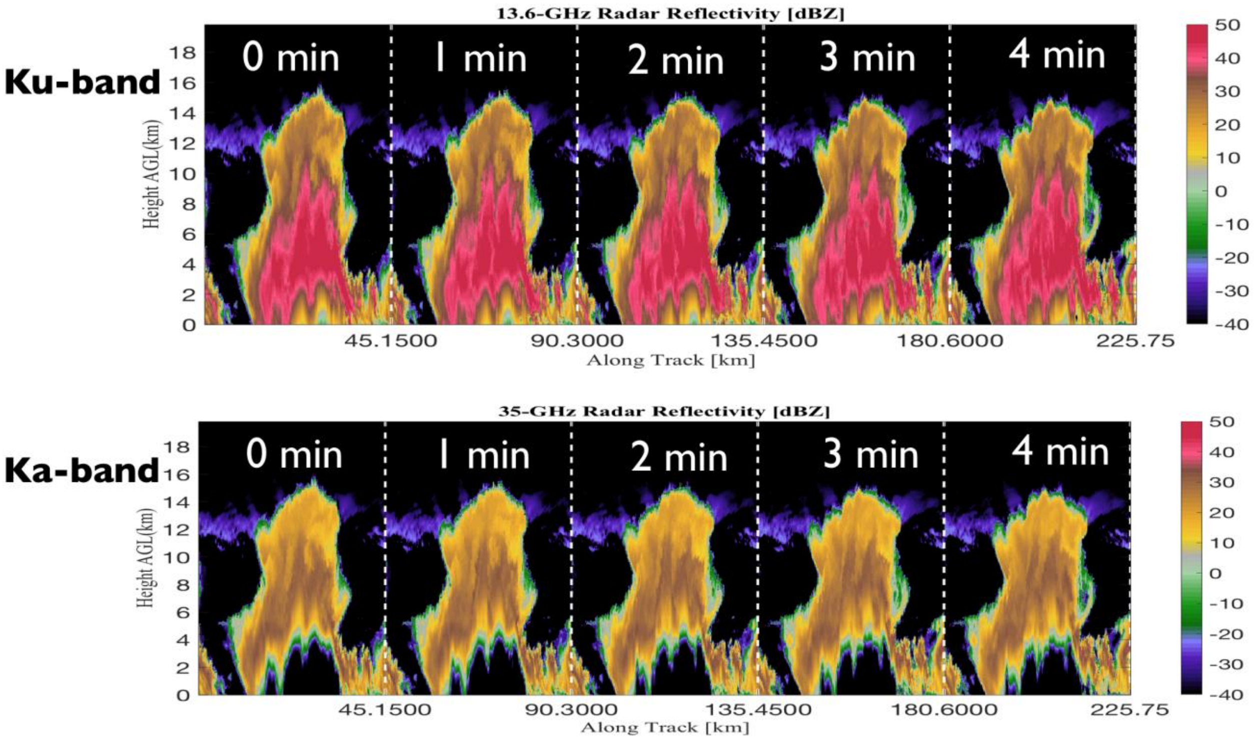


Fig. 1.13: Forward simulated time sequence of radar reflectivity (dBZ) spaced by 60 sec apart from an ultra-high model resolution (50-m) simulation of a tropical convective cloud at Ku- (top) and Ka-band (bottom).

Together Z and **Δ**Z/ **Δ**t (Fig. 1.14) can be used to provide: (i) the mass fluxes of condensed water mass and dry air and (ii) the rates at which the upper regions of convective storms are moistened. The profiles of Z additionally provide profiles of condensed water M in the column and the precipitation falling from convective storms.

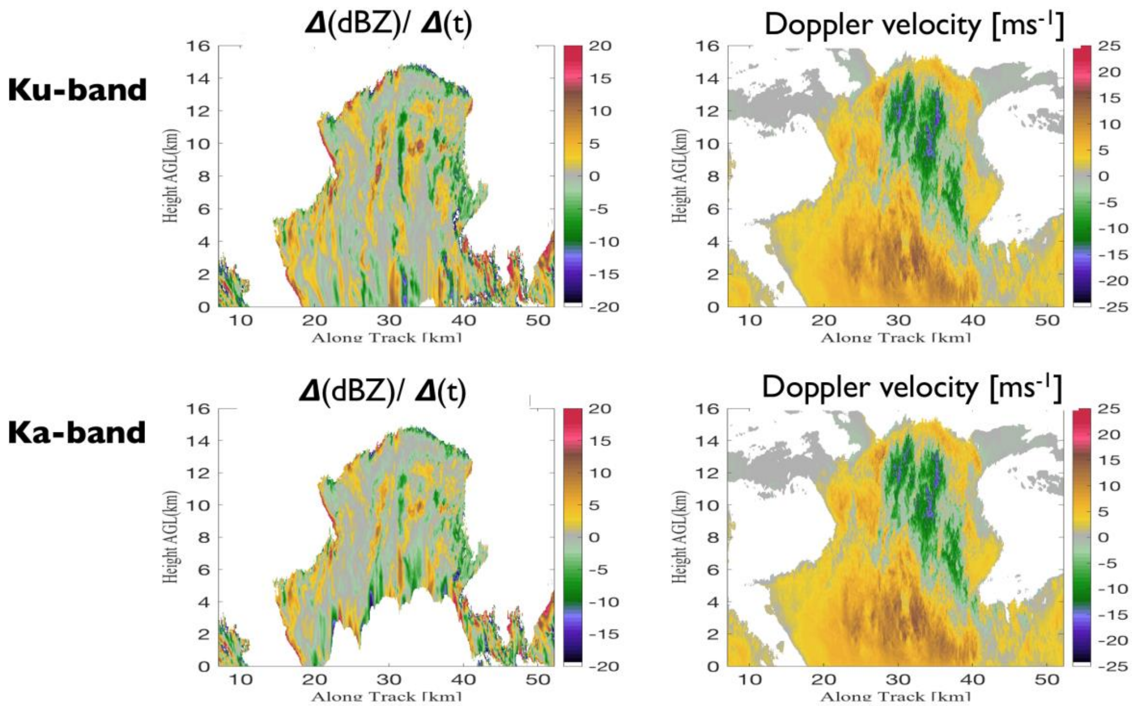


Fig 1.14: Estimated ΔZ/ Δt (using two consecutive Z-field observations from a pair of satellites space by 60 sec) and the corresponding mean Doppler velocity (as estimated directly by the numerical model).

On July 13, 2018 the RainCube satellite was released from the International Space Station (ISS) into orbit. RainCube (Radar in a CubeSat, Peral et al., 2015) is a technology demonstration mission to enable Ka-band precipitation radar technologies on a low-cost, quick-turnaround platform. A 6U cubesat includes the radar electronics, the compact lightweight deployable 0.5 m antenna and the bus systems. We are in communication with the RainCube team and we will get access to observations from RainCube, the first incarnation of the type of microsatellites that can be used in the proposed constellation. The analysis of the RainCube observations will allow us to exam the performance of the pulse compression scheme used for achieving the detection capabilities of RainCube using very little power and a very small antenna. In addition to the analysis of the RainCube observations, we have access to ultra-high-resolution model simulation of tropical ocean convection using the System for Atmospheric Modeling (SAM, Khairtoudinov and Randall 2003). We plan to use the SAM simulations and our forward, space-borne Doppler simulator to investigate the ability of a constellation of micro-satellites to study the vertical transport of air and condensate in deep convective clouds.

1.2 POTENTIAL PROBLEM AREAS:

1.2.1 Identification of the main problem(s) or problem area(s) likely to be encountered in performing the activity

The WP 3100 assumes the airborne data will be collected during the 2018 fall and early winter season. NRC has committed the resources and we do not anticipate any issues. Like any other airborne campaigns technical issues on the aircraft and key instrument might arise or the weather conditions during the Intensive operation period might not provide diverse cloud and precipitation conditions. If this happens we will use other available data (like those from NASA field campaign as done in the parallel activity, [AD-3]) and/or extend the flight data collection period if endorsed by NRC and ESA.

1.3 TECHNICAL IMPLEMENTATION / PROGRAMME OF WORK

1.3.1 Proposed Work Logic

The logic of the proposed work with the link to the work-packages is illustrated in Fig.1.15 and already discussed in Sect. 1.1.3. As a preliminary assessment we have identified three overarching themes that will originate from the first survey phase (WP1000 and WP2000) and will be further refined at the first progress meeting. These themes will be aligned to the ESA strategy but they will also tend to find a common ground with the International Community and specifically, via our International Collaborators with current efforts at NASA in order not to duplicate efforts but instead of strengthening the case for a constellation of satellites that can target the different gaps of the current observing system. The WP 3000 will be devoted to exploiting different datasets in order to consolidate the scientific requirements for (first iteration):

1. multi-wavelength radars on a polar orbits to better quantify high-latitude precipitation and be used as calibrator for the constellation of PWM radiometers;
2. the constellation of PWM radiometers for detecting and quantifying snow-rates;
3. a constellation of small satellites for the characterization of convective motions.

This analysis will allow to define and assess the readiness of different mission concepts with payload technology selection and trade-off (antenna, feed, backend). All these elements will contribute to draw a roadmap towards the development of a precipitation-oriented mission (WP 5000).

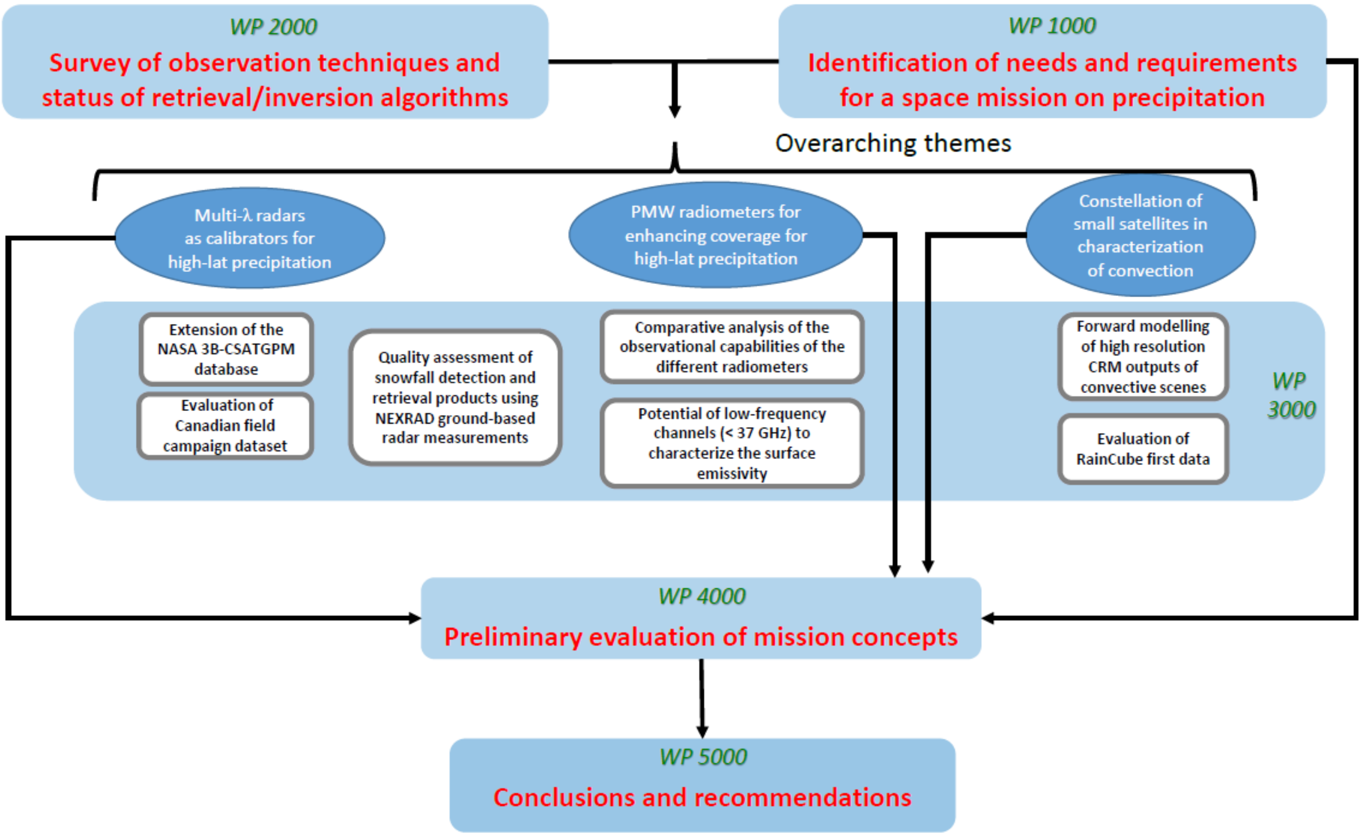


Figure 1.15: Pathway toward a precipitation mission concept definition.

1.3.2 Contents of the proposed work

1.3.2.1 Work Breakdown Structure (WBS)

A breakdown of the working hours within each WP is shown in Table 2.1 whereas the schedule for the proposed activities, covering from the start of the activity until the end of the Contract is shown in Fig. 2.2.

Work Package Description (WPD)

WP 1000 (Task 1): identification of needs and requirements for precipitation space missions (UoL)

The objective of the task is a review of the relevant scientific and technical literature describing the science and user needs for space missions on precipitation. We will also explore the limitations and weaknesses in models and lack of understanding on key precipitation processes, which could represent major scientific questions for the next generation of precipitation space missions.
Task 1 will be led by UoL the support of McGill and CNR-ISAC and inputs from the international partners (in-kind contributions) trying to align this activity to current developments at NASA.

WP 2000 (Task 2): survey of observation techniques and status of retrieval and inversion algorithms (CNR-ISAC and UoL)

The objective of this task is a collection and review of the most innovative precipitation observation techniques and retrieval algorithms. In particular we will cover the status and the deficiencies of the precipitation observing systems; a first iteration of such a review is already presented in this proposal (Sect.1.1.2).
The task is split into two different subtasks:

- WP 2100: review of the observation techniques. This task will review the state-of-the-art observation techniques for the satellite remote sensing of precipitation with a focus on the recent advances in solid and light precipitation retrieval. This will include geostationary and polar satellite missions and sensors ranging from IR to MW currently operational and planned for the near future. A survey of the new small satellite mission concepts will also be carried out. Critical gaps in the observational techniques will be identified with reference to the still open issues in the precipitation remote sensing, e.g. precipitation at high latitudes.
- WP 2200: review of the status of retrieval/inversion techniques. We will review the state of the art inversion techniques with focus at passive microwave methods (including Bayesian, neural network, etc), radar-only methods (including dual and triple frequency methods) and combined radar-radiometer algorithms as adopted in current GPM core satellite. Synergies between active and passive instrument in the MW spectral range and the blending of IR and PMW observations will be discussed as a tool to enhance the precipitation remote sensing capability.

WP 2100 andWP2200 are led by the CNR-ISAC and UoL, respectively. McGill and the International Collaborators will provide support.

WP 3000 (Task 3): Evaluation of experimental datasets

The goal of WP3000 is to provide quantitative criteria and guidelines for the design of the future mission dedicated to global precipitation monitoring. The three overarching themes illustrated in Fig. 1.6 will be explored by making use of novel experimental datasets.

WP 3100: evaluation of Canadian field campaign dataset (NRC)

In WP3100, detailed evaluation of the extensive airborne and ground based datasets from the RadSnowExp will be presented. For the RadSnowExp project, the NRC Convair will be equipped with state-of-the-art in-situ sensors, triple frequency (Ka, X, and W-band) polarimetric Doppler radars, two lidars (zenith and nadir pointing) and a G-band radiometer. The project will be carried

out at Iqaluit, NU, Canada for about 10 days and conduct 6-8 flights (total of 30 hours) Intensive Operation Period (IOP). The ECCC Iqaluit ground-site is equipped with many in-situ and remote sensing systems including a scanning Ka-band polarimetric radar, multiple lidars and radiometers. The ground site also has frequent satellite overpasses.
The tasks of WP 3200 are described below:

- Evaluates, update the fuzzy logic based hydrometeor classification algorithm: the classification algorithm developed at NRC will be fined tune to best performance with artic data collected in the Canadian field campaign. Advanced microphysics probes will provide extended range of particles size and types. The method performance will be validated with various types of clouds/precipitation in different weather conditions (NRC+Korolev).
- Evaluate, update and refine multi-frequency radar algorithms for snow retrieval and test scattering models: the near-coincident radar data and in-situ measurements offer means for testing existing snow retrieval algorithms and scattering models (UoL+NRC)
- Evaluate, update and refine multi-frequency, polarimetric radar algorithms for ice water content (IWC) retrieval: Observed IWC from in-situ probes will be correlated to radar equivalent reflectivity factors Z_e measured at X, Ka and W-band frequencies. From the joint distribution, power-law $IWC - Z_e$ relationships are derived considering the temperature variability. This approach uses bulk measurements of IWC and nearly coincident radar data and does not use assumptions on cloud microphysics or backscattering calculation. Alternatively, an approach using polarimetric radar observations will be studied. Kdp and Zdr measurements from a W-band down looking antenna and X-band side looking antenna will be used in this task. Spatial distribution of IWC in artic clouds will also be analysed (NRC+McGill).

WP 3200: evaluation of CloudSat/GPM co-located dataset (CNR-ISAC)
WP3200 will focus at PMW capability to detect and quantify snowfall and light precipitation at higher latitudes. To pursue this goal, complex relations between PMW observations and space-time co-located GPM as well as Cloudsat spaceborne radar observations of snowfall and light precipitation events, will be analysed. In particular, in this study, a similar approach to You et al. (2017) and Panegrossi et al. (2017) will be used to analyse snowfall and light precipitation observational capabilities of PMW sensors currently available, with particular focus on higher latitudes and cold regions. Observational datasets built from co-located measurements by the most advanced currently available MW radiometers (cross-track scanning ATMS and MHS, and conically scanning GMI) and by spaceborne radar observations (both GPM DPR and CloudSat CPR), will be exploited to fulfil the following three goals: 1) analyze multi-channel response of the different radiometers (in particular high-frequency channels > 90 GHz, V and H polarizations when available) to cloud and precipitation structure, with focus on conditions and precipitation regimes where precipitation detection and retrieval is more challenging (e.g., light precipitation and snowfall in cold/dry regions); 2) explore the potential of low-frequency channels to characterize the background surface (presence of sea ice, different types of snow cover), at the time of the observation; 3) compare and analyse the observational capabilities of the different radiometers (accounting for their channel assortment, spatial resolution, and viewing geometry), in relation to the same observed scene as depicted by the space-borne radars and ancillary environmental variables.

The most updated version of the global NASA GPM-Cloudsat coincidence dataset (3B-CSATGPM, Turk, 2018) covering over 3.5 y time period (March 2014-November 2017) will be used in the study (see also Fig.1.2). It includes:

- Various GPM precipitation products from DPR, DPR+GMI, and GMI (liquid and frozen) (V05)
- Various CloudSat products providing CPR reflectivity profiles, precipitation profiles (liquid

and solid), surface precipitation rate, cloud type (e.g., 2C-SNOW-PROFILE, 2C-PRECIP-COLUMN, 2B-CLOUD-CLASS);

- ECMWF Auxiliary meteorological variables from ECMWF analysis (ECMWF-AUX CloudSat product) [i.e., 2-m temperature (T2m), specific humidity, surface pressure, total precipitable water (TPW)];
- The associated MODIS thermal channels (11 channels), and the 3x5 MODIS cloud mask.
- Triple coincidences with MHS or ATMS, when either NOAA-19 (MHS) or NPP (ATMS) was available within the +/-15-min window.
- TELSEM surface index and snow/Ice Cover flag.

The 3B-CSATGPM dataset includes 1154 cases where there are triple coincidences (GPM+CloudSat+ATMS), 826 cases where there are triple coincidences (GPM+CloudSat+MHS), and 233 cases with four coincidences (GPM+CloudSat+ATMS+MHS).

The tasks of WP 3200 can be structured as follows:

3.2.1 extension of the NASA PPS 3B-CSATGPM database to include ancillary variables needed to characterize the atmospheric and environmental conditions associated to each observed scene. The CloudSat DARDAR (liDAR+raDAR) product (http://www.icare.univ-lille1.fr/projects/dardar) derived from combined CPR and CALIPSO lidar measurements and the simulated CloudSat 94 GHz brightness temperature (product provided by S. Tanelli, NASA JPL) will be also added in the dataset (G.Panegrossi, with support from P. Sanò and S. Tanelli);

3.2.2 analysis (case studies and aggregated TB analysis) of GMI, ATMS, and MHS multi-channel response to the cloud and precipitation structure available from coincident spaceborne radar measurements in the 3B-CSATGPM dataset, in relation to the environmental conditions. The focus will be on high-frequency window channels [i.e., 89, 150-166 GHz (V and H polarization for GMI)] and the water vapor absorption band channels around 183.31 GHz. A comparative analysis of the observational capabilities of the different radiometers (accounting for their channel assortment, spatial resolution, and viewing geometry), in relation to the same observed scene as depicted by the spaceborne radars and by ancillary environmental variables, will be also carried out (S. Laviola (cross-track), G. Panegrossi (conical), with support from M. Kulie, P. Sanò);

3.2.3 quality assessment of currently available snowfall detection and retrieval products for active (Cloudsat CPR and GPM DPR) and passive (GMI and ATMS) MW sensors, using ground-based radar measurements for selected case studies occurring at higher latitudes (e.g., operational NEXRAD and Canadian network, and/or field campaign data) (M. Montopoli, K. Mroz, A. Battaglia, B. Puigdomènech with support from L. Baldini, M. Kulie);

3.2.4 investigation of the potential of low-frequency channels (< 37 GHz) to characterize the background surface (presence of sea ice, different types of snow cover) at the time of the observation (G. Panegrossi, with support from L. Brocca).

WP 3300 (Task 3): evaluation of RainCube first data and forward modelling of high resolution CRM outputs of convective scenes (McGill)

In this WP, we plan to analyse the RainCube observations. We will evaluate the performance of RainCube radar to detect precipitation, its sensitivity and the impact of the surface echo. In addition, in this WP, we plan to use ultra-high-resolution model simulation of tropical ocean convection using the System for Atmospheric Modeling (SAM, Khairtoudinov and Randall 2003) and a forward radar operator to investigate the potential of using the $\Delta Z/\Delta t$ to estimate the vertical transport of air and condensate in deep convective clouds (see Fig.1.14) (B. Puigdomènech with support from K. Mroz, A. Battaglia and P. Kollias).

WP 4000: Preliminary evaluation of mission concepts (McGill)
In this WP, we will refine the concept for a multi-frequency radar targeting high latitude precipitation. This will require the identification of radar characteristics and radar performance with a limited trade-off space. We will also discuss the requirements needed for the radar to act as a calibrator for the radiometers (e.g. scanning swath, sensitivity) and the potential benefit of a radiometric mode (McGill, UoL). We will also investigate which radiometers (conically vs scanning) and which suite of frequencies are most effective in detecting and retrieving solid precipitation and in which weather conditions (presence of supercooled water, small/large SWP) (CNR-ISAC).
We will also draw some initial conclusions on the potential of RainCube; in particular we will discuss the resolution requirements and the model/observations consistency. In addition, we will provide a general assessment of the scientific readiness level of the mission concept and identify secondary mission applications and potential products (McGill, UoL).

WP 5000: Conclusions and recommendations (UoL)
The recommendations for future precipitation missions will be summarized in a final report which will include a roadmap pinpointing at remaining issues/risks related to science and technology challenges with respect to SRL and TRL, respectively. Potential platform options will also be identified. The report will be based on at least two peer-reviewed publications that are envisaged as an important contribution and outcome of this activity. UoL will lead this activity but all partners will contribute.

WP 6000: Management and reporting (UoL)
This WP has no specific task in SoW since it encloses the overall management of the activity (preparation of meetings, minutes, progress reports, etc.). It encompasses:
1. Generation of templates and proofreading for all Task Reports and Recommendation Document;
2. Control version of the documents;
3. Actions and risks that will happen during the whole project;
4. Preparation of data packages for deliveries to ESA, including final documentation and presentations.
The WP responsibilities are summarized in each WPD while the consortium work share is detailed in Table 2.1.

Work Package Description (WPD)
All the PSS-A20 form are attached hereafter.

WORK PACKAGE DESCRIPTION PSS-A20

<table>
<tr><td>PROJECT: Raincast PHASE: 1</td><td>WP: 1000</td></tr>
<tr><td>WP Title: Identification of needs and requirements for space mission on precipitation

Company: University of Leicester
WP Manager: Alessandro Battaglia
WP Support: Giulia Panegrossi (CNR) Pavlos Kollias (McGill)
Start Event: T0 Planned Date: 1/10/2018
End Event: T0+2.0 months Planned Date: 30/11/2018</td><td>Sheet 1 of 1

Issue Ref
ITT ESA-EOPSM-FUTM-SOW-3302
Issue Date
16/04/2018</td></tr>
<tr><td>Inputs:
The SOW and all applicable and reference documents
This proposal
Authorization to proceed from ESA
Requirements as specified by WMO, National Weather Services, cloud modellers
Literature papers
International Collaborators’ inputs
Tasks:
Review of the relevant scientific and technical literature describing science and user needs for space missions on precipitation

Outputs:
WP1000 Technical Report</td><td></td></tr>
</table>

<table>
<tr><td>PROJECT: Raincast PHASE: 1</td><td>WP: 2100</td></tr>
<tr><td>WP Title: review of the observation techniques
Company: CNR
WP Manager: Elsa Cattani (CNR-ISAC)
WP Support: Alessandro Battaglia (UoL)
Start Event: T0+1 Planned Date: 1/11/2018
End Event: T0+5.0 months Planned Date: 31/1/2019</td><td>Sheet 1 of 1

Issue Ref
ITT ESA-EOPSM-FUTM-SOW-3302
Issue Date
16/04/2018</td></tr>
<tr><td>Inputs:
The SOW and all applicable and reference documents
This proposal
Literature
International Collaborators’ inputs
WP1000 TR
Tasks:
1. A review of the state-of-the-art observation techniques for the satellite remote sensing of precipitation will be performed with a focus on the recent advances in solid and light precipitation retrieval. Geostationary and polar satellite missions currently operational and planned for the near future (e.g., MSG, MTG, GPM, NOAA, MetOp, Suomi NPP, JPSS, DMSP, CloudSat, EPS-SG, EarthCare, etc.) will be analysed with considerations on the applicability and limitations of IR, active and passive microwave (MW) spectral channels.
2. A survey of the new small satellite mission concepts (e.g. TROPICS, TEMPEST-D, RainCube, TWICE, IceCube) will be carried out. Small satellites appear to be the clear development avenue both in terms of new observation technologies and replicability of the single sensor translated into constellations that are relatively easy to launch and maintain. The review will explore the constraints and possibilities of such platforms in terms of payload capabilities and what instrument technology can be accommodated within these constraints, and establish a roadmap in the area of small microwave and (sub)millimetre wave instruments.
3. Critical gaps in the observational techniques will be identified with reference to the still open issues in the precipitation remote sensing, e.g. precipitation at high latitudes.

Outputs:
Reviewed material to be included in the WP2000 TR</td><td></td></tr>
</table>

<table>
<tr><td>PROJECT: Raincast PHASE: 1</td><td>WP: 2200</td></tr>
<tr><td>WP Title: review of the status of retrieval/inversion techniques
Company: UoL
WP Manager: Alessandro Battaglia (UoL)
WP Support: Giulia Panegrossi (CNR-Italy)
Start Event: T0+1 Planned Date: 1/11/2018
End Event: T0+5.0 months Planned Date: 31/1/2019</td><td>Sheet 1 of 1

Issue Ref
ITT ESA-EOPSM-FUTM-SOW-3302
Issue Date
16/04/2018</td></tr>
<tr><td>Inputs:
The SOW and all applicable and reference documents
This proposal
Literature
International Collaborators' inputs
WP1000 TR

Tasks:
review of the state of the art inversion techniques with focus at
1. Passive microwave methods (including Bayesian, neural network, etc) as adopted in current operational algorithms for spaceborne conically and cross-track scanning radiometers;
2. radar-only methods (including dual and triple frequency methods) as adopted in current operational space-borne radars (CloudSat CPR and GPM DPR) and for airborne radars;
3. combined radar-radiometer algorithms as adopted in current GPM core satellite;
4. synergies between active and passive instrument in the MW spectral range and the blending of IR and PMW observations.

Outputs:
Reviewed material to be included in the WP2000 TR</td><td></td></tr>
</table>

<table>
<tr><td>PROJECT: Raincast   PHASE: 1</td><td>WP: 3100</td></tr>
<tr><td>WP Title: evaluation of Canadian field campaign dataset
Company: CNRC
WP Manager: M. Wolde
WP Support: Battaglia (UoL) & Kollias (McGill)
Start Event: T0+3.0 months   Planned Date: 1/1/2019
End Event: T0+14.0 months   Planned Date: 30/11/2019</td><td>Sheet 1 of 1

Issue Ref
ITT ESA-EOPSM-FUTM-SOW-3302
Issue Date
16/04/2018</td></tr>
<tr><td>Inputs:
The SOW and all applicable and reference documents
This proposal
Data from parallel activity

Tasks:
1. Perform detailed analysis of the airborne in-situ and near-coincident triple frequency radar data and evaluates, update hydrometeor classification algorithms.
2. Evaluate, update and refine multi-frequency radar algorithms for snow retrieval.
3. Analysis of polarimetric responses to different cloud and precipitation conditions.
Outputs:

Reviewed report</td><td></td></tr>
</table>

<table>
<tr><td>PROJECT: Raincast PHASE: 1</td><td>WP: 3200</td></tr>
<tr><td>WP Title: evaluation of CloudSat/GPM co-located dataset
Company: CNR
WP Manager: Giulia Panegrossi (CNR-ISAC)
WP Support: Battaglia (UoL), Kulie (MTU), Brocca (CNR-IRPI), Tanelli (NASA JPL)
Start Event: T0+4.0 months Planned Date: 1/2/2019
End Event: T0+14.0 months Planned Date: 30/11/2019</td><td>Sheet 1 of 1

Issue Ref
ITT ESA-EOPSM-FUTM-SOW-3302
Issue Date
16/04/2018</td></tr>
<tr><td>Inputs:
• The SOW and all applicable and reference documents
• This proposal
• Data from parallel activity
• NASA PPS GPM-Cloudsat coincidence dataset 3B-CSATGPM (Turk, 2018)
• Operational NEXRAD and Canadian network (and/or field campaign data)
• Literature (see bibliography)
Objectives:
1) Assessment of snowfall and light precipitation observational capabilities of the most advanced currently available space-borne passive MW sensors through the exploitation of satellite-based and ground-based observational datasets (gap analysis);
2) To provide quantitative criteria and guidelines for the design of the future mission dedicated to global precipitation monitoring in terms of PMW capability to detect and quantify snowfall and light precipitation at higher latitudes (gap filling).
WP description:

Snowfall and light precipitation observational capabilities of PMW sensors currently available, with particular focus on higher latitudes and cold regions, will be analysed following a similar approach to You et al. (2017), and Panegrossi et al. (2017). Complex relations between PMW observations and space-time co-located GPM as well as Cloudsat radar observations of snowfall and light precipitation events will be analysed. Observational datasets built from co-located measurements by the most advanced currently available MW radiometers (cross-track scanning ATMS and MHS, and conically scanning GMI) and by spaceborne radar observations (both GPM DPR and CloudSat CPR), will be exploited to fulfil the following three goals: 1) analyse multi-channel response of the different radiometers (in particular high-frequency channels > 90 GHz, V and H polarizations when available) to cloud and precipitation structure, with focus on conditions and precipitation regimes where precipitation detection and retrieval is more challenging (e.g., light precipitation and snowfall in cold/dry regions); 2) explore the potential of low-frequency channels to characterize the background surface (presence of sea ice, different types of snow cover), at the time of the observation; 3) compare and</td><td></td></tr>
</table>

analyse the observational capabilities of the different radiometers (accounting for their channel assortment, spatial resolution, and viewing geometry), in relation to the same observed scene as depicted by the spaceborne radars and ancillary environmental variables. The most updated version of the global NASA PPS GPM-Cloudsat coincidence dataset (3B-CSATGPM, Turk, 2018) will be used, with current temporal coverage March 2014-November 2017. ***Tasks:*** 1) extension of the NASA 3B-CSATGPM database; (G.Panegrossi, with support from P. Sanò and S. Tanelli); 2) analysis of GMI, ATMS, and MHS multi-channel response to the cloud and precipitation structure available from coincident spaceborne radar measurements in the 3B-CSATGPM dataset (S. Laviola (cross-track), G. Panegrossi (conical), support from M. Kulie, P. Sanò); 3) quality assessment of currently available snowfall detection and retrieval products for active and passive MW sensors, using ground-based radar measurements for selected case studies occurring at higher latitudes (e.g., operational NEXRAD) (M. Montopoli, with support from L. Baldini, M. Kulie, K. Mroz,); 4) assessment of the potential of low-frequency channels (< 37 GHz) to characterize the background surface (presence of sea ice, different types of snow cover) at the time of the observation (G. Panegrossi, with support from L. Brocca). ***Outputs:*** D4: Report Gap analysis of the currently available spaceborne passive MW observations exploiting advanced experimental spaceborne and ground-based radar datasets. The output from WP3200 will be used in WP4000 and WP5000 towards the proposal for gap filling requirements of future PMW precipitation monitoring missions.	

PROJECT: *Raincast* PHASE: 1	WP: 3300
WP Title: evaluation of RainCube first data and forward modelling of high resolution CRM outputs of convective scenes Company: McGill University WP Manager: Pavlos Kollias WP Support: Battaglia (UoL) Start Event: T0+4.0 months Planned Date: 1/2/2019 End Event: T0+14.0 months Planned Date: 30/11/2019	Sheet 1 of 1 Issue Ref ITT ESA-EOPSM-FUTM-SOW-3302 Issue Date 16/04/2018
Inputs: The SOW and all applicable and reference documents This proposal WP1000 TR WP2000 TR ***Tasks:*** Evaluate first light observations from the RainCube satellite (miniature Ka-band radar) that was recently launched by JPL https://www.jpl.nasa.gov/cubesat/missions/raincube.php and assess its ability to detect deep precipitation Perform forward simulations of RaInCube-like systems using ultra-high-resolution model output (50 m) and assess the trade-off related to antenna size and sensitivity for monitoring precipitation processes ***Outputs:*** D4 contribution to the report regarding the ability of the RainCube satellites to study precipitation process (mass transport) and its diurnal cycle.	

<table>
<tr><td>PROJECT: Raincast   PHASE: 1</td><td>WP: 4000</td></tr>
<tr><td>WP Title: Preliminary evaluation of mission concepts

Company: McGill University
WP Manager: Pavlos Kollias
WP support: A. Battaglia (UoL), G. Panegrossi (CNR-Italy)
Start Event: T0+12.0 months   Planned Date: 1/10/2019
End Event: T0+16.0 months   Planned Date: 31/1/2020</td><td>Sheet 1 of 1

Issue Ref
ITT ESA-EOPSM-FUTM-SOW-3302
Issue Date
16/04/2018</td></tr>
<tr><td>Inputs:
The SOW and all applicable and reference documents
This proposal
WP1000 TR
WP2000 TR
WP3000 TR

Tasks:
Using the datasets agreed with ESA and explored in WP1,2 and 3, we will evaluate the sensitivity, resolution and multi-parametric capabilities we need at Ka-, W- and G-band) frequencies for the detection of all significant precipitation.

In addition to coverage gaps, we will discuss the capabilities needed for detecting precipitation processes and their diurnal cycle.

Furthermore, we will define and assess the readiness of different mission concepts with payload technology selection and trade-off (antenna, feed, backend) (McGill supported by UoL);

Identify the role of secondary mission applications and products.

Outputs:

D5: Description Report (McGill U. supported by UoL)</td><td></td></tr>
</table>

<table>
<tr><td colspan="2">PROJECT: Raincast PHASE: 1</td><td>WP: 5000</td></tr>
<tr><td colspan="2">WP Title: Conclusions and recommendations
Company: University of Leicester
WP Manager: Alessandro Battaglia
WP Support: All (CNR-ISAC, NRC, McGill)
Start Event: T0+16.0 months Planned Date: 1/2/2020
End Event: T0+18.0 months Planned Date: 31/3/2020</td><td>Sheet 1 of 1

Issue Ref
ITT ESA-EOPSM-FUTM-SOW-3302
Issue Date
16/04/2018</td></tr>
<tr><td colspan="2">Inputs:
WP1000 TR
WP2000 TR
WP3000 TR
WP4000 TR
International Collaborators' consultation
Tasks:

Identification of remaining issues/risks related to science and technology challenges with respect to SRL and TRL, respectively.
Definition of a technology and science (UoL and McGill) roadmap
Recommend a model philosophy for future initiatives (All)

Outputs:
D6 Final Report (All)
D7 Manuscript for a journal article
D8 Mission requirement Document
D9 Technical data package</td><td></td></tr>
</table>

<table>
<tr><td colspan="2">PROJECT: Raincast PHASE: 1</td><td>WP: 6000</td></tr>
<tr><td colspan="2">WP Title: Management and reporting
Company: University of Leicester
WP Manager: Alessandro Battaglia

Start Event: T0 Planned Date: 1/10/2018
End Event: T0+18.0 months Planned Date: 31/3/2020</td><td>Sheet 1 of 1

Issue Ref
ITT ESA-EOPSM-FUTM-SOW-3302
Issue Date
16/04/2018</td></tr>
<tr><td colspan="2">Inputs:
WP1000 TR
WP2000 TR
WP3000 TR
WP4000 TR
WP5000 TR

Tasks:
Generation of templates and proofreading for all Task Reports and Recommendation Document (UoL)
Control version of the documents (UoL)
Actions and risks that will happen during the whole project (UoL)
Preparation of data packages for deliveries to ESA, including final documentation and presentations (UoL).

Outputs:
Summary and final Reports (UoL)
Technical Data Package (including all reports and presentations) (UoL)</td><td></td></tr>
</table>

1.4 BACKGROUND

1.4.1 Existing own concepts/products relevant to the activity and/or to be used

RadSnowExp field campaign data

The RadSnowExp field campaign will be conducted out of Iqaluit (~63N), Nunavut, Canada (Fig. 1.16). National Resaerch Council Canada (NRC) and Environment and Climate Change Canada (ECCC) have world-class facilities for providing multi-sensor in-situ and remote sensing measurements of atmospheric conditions in addition to cloud macro and microphysical properties. The NRC Convair-580 is a twin-engine, pressurized aircraft capable of long distance operation (up to 5 hours endurance) while carrying several racks of instrumentation, as well as and up to a dozen research crew members. The extensive instrumentation payload capabilities of the NRC Convair-580 were developed by NRC, ECCC and others through a multiyear collaboration on airborne atmospheric research. The aircraft has multiple underwing and wingtip pylons that can carry a multitude of cloud physics and remote sensing instruments. For the RadSnowExp project, the NRC Convair will be equipped with triple frequency (Ka, X, and W-band) polarimetric Doppler radars (Fig. 1.17, Table 1.2), two lidars (zenith and nadir pointing), a G-band radiometer and an array of state-of-the-art in-situ sensors (Table 1.3).

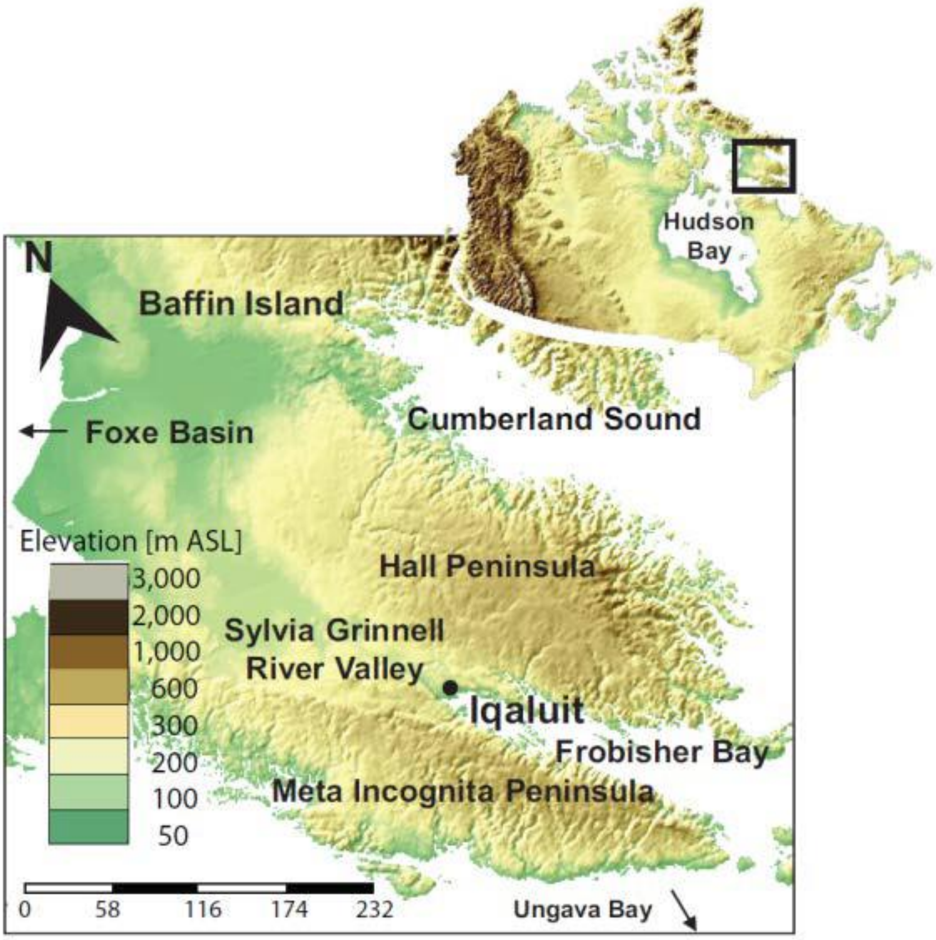


Figure 1.16: Topography of Baffin Island.

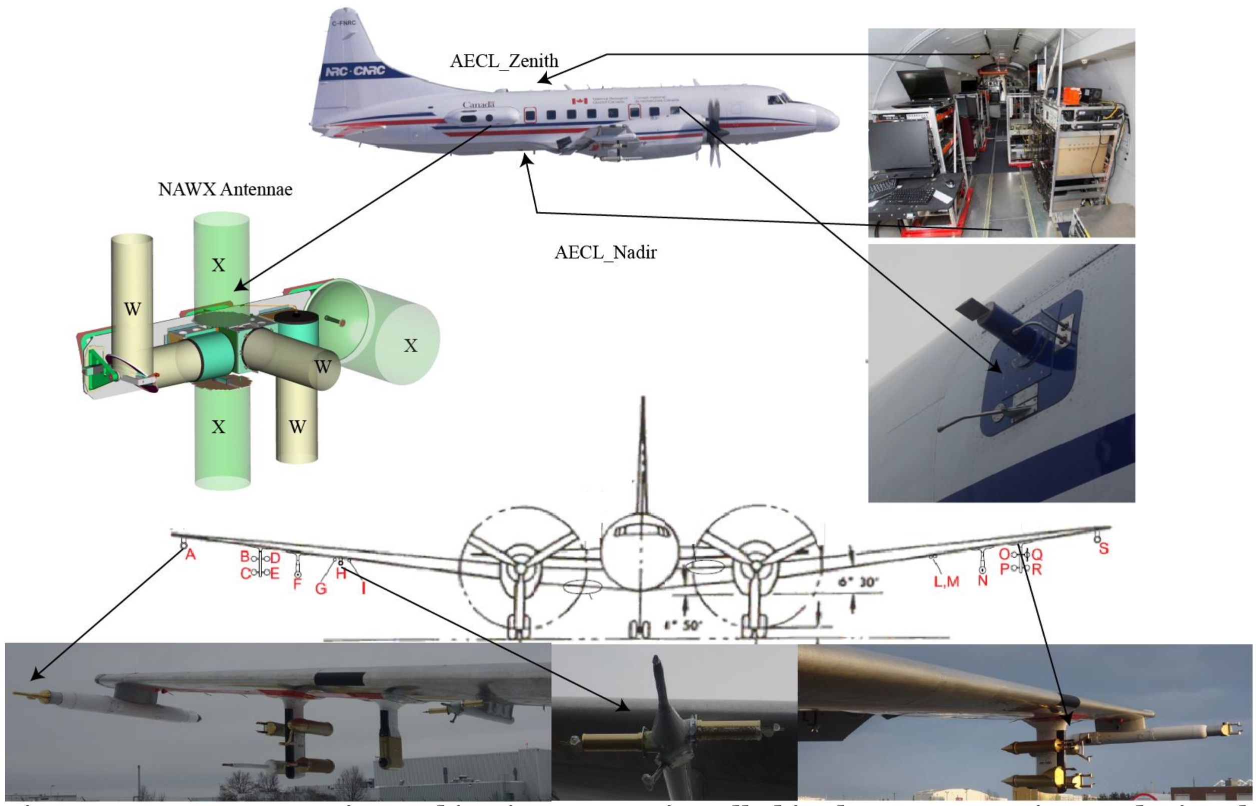


Figure 1.17: Remote sensing and in-situ sensors installed in the NRC Convair-580 during the 2017 BAIRSII-WERVEX Experiment.

Table 1.2: Basic specifications of the NRC Airborne W- and X-band (NAWX) radar

NAWX specifications	X-band	W-band
RF output frequency	9.41 GHz +- 30 MHz	94.05 GHz
Peak transmit power	25 kW magnetron split between two ports	1.7 kW typical
Transmit polarization	H and V	H or V
Maximum Pulse Repetition Rate	5 kHz	15 kHz
Transmitter max. duty cycle	0.1%	3 %
Pulse width	0.11-1 microseconds	0.1-10 microseconds (standard or linear FM chirped)
Antenna ports (electronically selectable)	4 (between two pairs)	5
Receiver cannels	2	2
Receiver polarization	Simultaneous H and V	Co and cross-polarization
Doppler	Pulse pair and FFT	Pulse pair and FFT
Transmitter Front-end Losses	1.5 dB typical	3.5 dB typical
Receiver front-end losses	1.5 dB typical	3.0 dB typical
LNA noise figure	2.8 dB typical	4.8 dB typical
IF output to digital receiver	60 MHz	54 MHz
Antennas	2 x 12" dual-polarization 1 x 12" single-polarization	1 x 24" dual-polarization 2 x 18" single-polarization
Minimum detectable @ 5 km	-30 dBZ (60 m resolution with 10x pulse compression)	-5 dBZ (150 m resolution)

Table 1.3: In-situ sensors available for RadSnowExp. There will be a lot of redundancy in the measurements, and probes can be swapped based on performance and weather conditions.

In-situ	NRC	ECCC
Aircraft state parameters	Multiple GPS & INS systems	
Atmospheric state parameters	Aventech Aircraft Integrated Meteorological Measurement System (AIMMS-20) – Temperature, humidity, pressure and 3D wind Chilled mirror & Licor Dew Point (x2) – Td Rosemount 858 – 3D airflow / 3D wind	Reverse flow T sensor
Liquid and Total Water Content	SkyPhysTech Nevzorov (Analog) Scientific Engineering Associates Icing Detector	ECCC Nevzorov (digital)
Extinction		ECCC Extinction Meter
Icing	Goodrich Icing Detector	
Cloud Particle Spectra (<50 μm)	DMT Cloud Droplet Probe (CDP-2) SEPC Inc. Fast Cloud Droplet Probe (FCDP)	DMT CDP-2; PMS FSSP-100
Cloud Particle size and Image	DMT Cloud Imaging Probe (CIP) SPEC two-dimensional Stereo (2D-S) probe PMS 2D-C	DMT CIP PMS 2D-C SPEC 2D-S probe Artium High Speed Imaging Probe (HSI)
High Resolution Particle Image		SPEC Cloud Particle Imager (CPI)
Large particle size and Image (100 um to 6.2 mm)	DMT Particle Imaging Probe (PIP)	SPEC High Volume Precipitation Spectrometer (HVPS)
Aerosol size distribution	DMT Ultra-High Sensitivity Aerosol Spectrometer (UHSAS)* - Canister option (0.06 – 1 μm)	UHSAS – Cabin Passive Cavity Aerosol Spectrometer Probe (PCASP)
Remote Sensing	NRC	ECCC
Cloud structure and dynamics – Radar	NRC W and X-band Polarimetric Radar System (NAWX)	
	University of Wyoming Ka-band Precipitation Radar (KPR) - Rental	
Cloud structure and icing – Lidar	Alpenglow 355 nm Elastic Cloud Lidar – AECL (Zenith)	AECL (Nadir)
LWP & PWV		ProSensing G-band (183 GHz Radiometer (GVR)
Other	NRC	ECCC
Video and pictures	Nadir video camera and crew camera	
Data and chat (ground-aircraft) communications	PLANET Navigation system	

The ECCC Iqaluit supersite is equipped with new meteorological instruments based on active, remote sensing technologies as part of the Canadian Arctic Weather Science (CAWS) Project. Its purpose is to enhance existing surface meteorological observations. Observations at the Iqaluit supersite (Fig. 1.18) provide near-real time data to the public, scientific researchers, and operational forecasters, via "ecpass.ca", in order to advance the performance of Canada's weather prediction system over the Arctic region. Being at ~63° N latitude, this site experiences frequent overpasses by polar-orbiting satellites, and that enables ground-based V&V studies for research satellites such as A-Train, GPM and EarthCARE (Fig. 1.19). Data collected at the site is used for model verification studies, e.g. during the WMO Year of Polar Prediction Project (2017-2018).

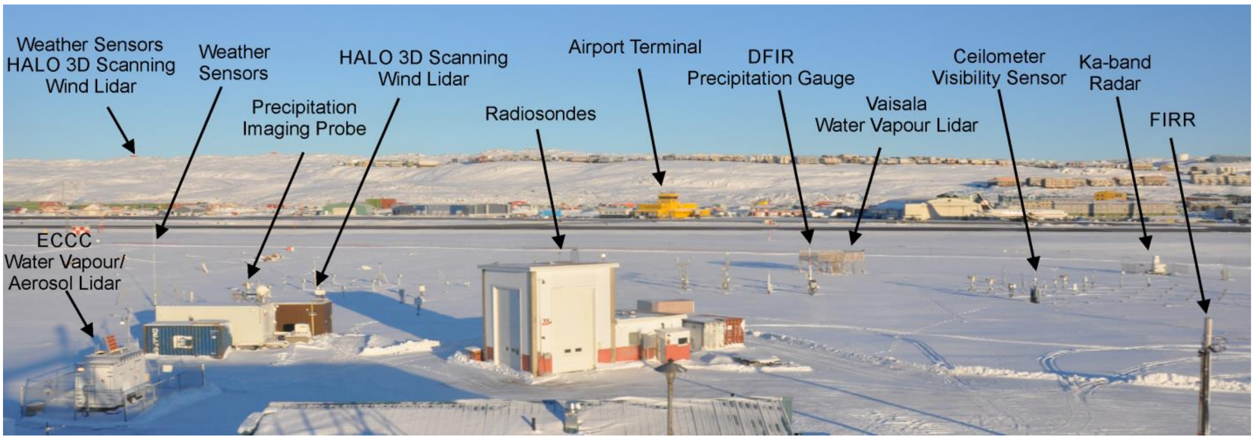


Figure 1.18: The ECCC Iqaluit, NU supersite.

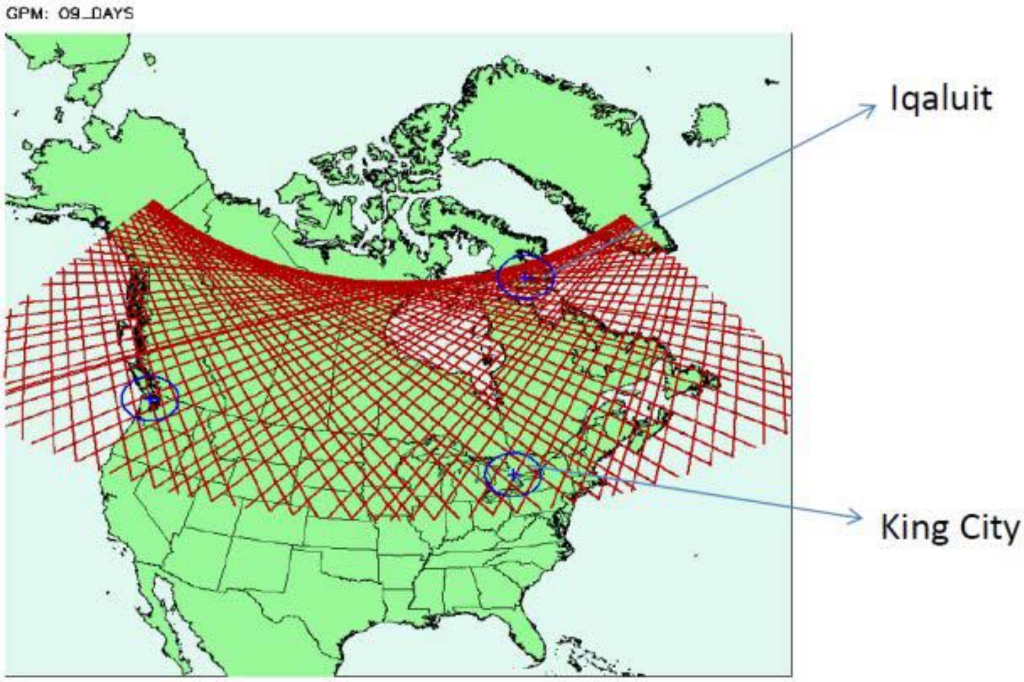


Figure 1.19: GPM orbits over Canada for a 10-day period.

Table 1.4 lists the instruments at the Iqaluit supersite. It includes a Doppler weather radar and lidars, water vapour and aerosol lidars, radiation flux sensors, and different fog and precipitation measurement devices. This is also an ECCC site for the inter-comparison of solid precipitation gauges and has a Double Fence International Reference. The instruments have demonstrated excellent survivability and data quality during extreme Arctic conditions with no operator support required. Observations provide: (1) detailed, high temporal-resolution profiles of wind, water vapour, cloud microphysics, and aerosol measurements; (2) horizontal, and in some cases 3D, mapping of these variables; (3) complementary analysis of ground-return signal over Arctic terrain; (4) coordinated pan-Arctic studies using other Arctic sites; (5) aircraft V&V field campaign studies; (6) long-term satellite measurement cal/val; and (7) classification of hydrometeor phase.

Table 1.4: List of ECCC sensors at the Iqaluit supersite

Instrument	Manufacturer	Install Date	Operation	Measurement(s)	Temporal/spatial resolution
Precipitation Imaging Package (PIP)	NASA/ Wallops	Sept. 2014	380 frame/s grey-scale camera with back-lighting	Particle imagery, DSD, precip. rate and density estimation	1 min / surface obs. only
4 Cameras	Campbell Scientific	Sept. 2015	High-resolution images of the site	Ka-Radar, Lidar, and Sky-view images	5 min / 1080p
Ka-Band Radar	METEK	Sept. 2015	Scanning pulsed dual-polarization Doppler Radar	Line-of-sight wind speed and direction, cloud & fog backscatter, depolarization ratio	10 min / 10 m res. up to ~25 km range
Ceilometer	VAISALA	Sept. 2015	Pulsed (8 kHz) diode laser Lidar	Cloud intensity, cloud octa and height, aerosol profiles, MLH	5 min / 5 m vert res. up to 7.5 km a.g.l.
PWD 52 Visibility Sensor (x2)	VAISALA	Sept. 2015	Forward-scatter measurement	Visibility, precipitation type	1 min / surface obs. only
Doppler Lidar	HALO	Sept. 2015	Pulsed (10 kHz) scanning at 1.5 µm (Mie scattering)	Line-of-sight wind speed and direction, aerosol backscatter, depolarization ratio	5 min / 3 m res. up to ~3 km range
Surface met obs.	Misc.	Ongoing	Misc.	Surface T, RH, pressure, winds, precipitation	1 min / surface obs. only
Radiosondes	VAISALA	Ongoing	Balloon-launched sonde	Profiles of T, RH, pressure, winds	12 hours / ~15 m res. up to ~30 km a.g.l.
4k Pantilt Camera	Axis	Oct. 2016	High-resolution images of the site	Automated pivoting camera for images in all directions	5 min / 4k
Canadian Autonomous Arctic Aerosol Lidar (CAAAL)	ECCC	Oct. 2016	355/532/1064 nm transmitter & 6 ch. receiver	Aerosol and water vapour profiles; particle size and shape information	1 min / 3 m res. up to ~15 km a.g.l.
2nd Doppler Lidar	HALO	Oct. 2017	Pulsed (10 kHz) scanning at 1.5 µm (Mie scattering)	Line-of-sight wind speed and direction, aerosol backscatter, depolarization ratio	5 min / 3 m res. up to ~3 km range
Scintillometer	Scintec	June 2018	Large-aperture optical transmitter/receiver	Turbulence, crosswind, heat flux	5 min / max 6 km path length
Fog Measuring Device (FMD)	TBD	June 2018	Fog sensor	Fog intensity, water vapour at surface	TBD
Far-IR Radiometer (FIRR)	LR Tech.	June 2018	Zenith/Nadir-viewing infrared radiometer	Thin-ice clouds, downwelling IR radiation, cloud microphysics	10 min / NA
Surface radiation fluxes	TBD	June 2018	Surface radiation sensors (diffuse and direct)	Short- and long-wave up- and downwelling radiation	TBD
Water Vapour Lidar	VAISALA	June 2018	Pulsed Lidar system	Profiles of aerosols, 24-hr water vapour profile	~20 minutes / 10 m up to `3 km agl

The RadSnowExp's Intensive Operation Period (IOP) will be conducted in November 2018 as it is the month with the highest occurrence of frozen precipitation over the Baffin Island regions (Fig. 1.20). Precipitation events over the region during autumn season are typically associated with synoptic scale cyclonic systems and last many days. Orography and presence of sea ice also influence precipitation events over the region. As a result, we expect to sample diverse cloud and precipitation types (stratiform, large frontal systems and orographic clouds).

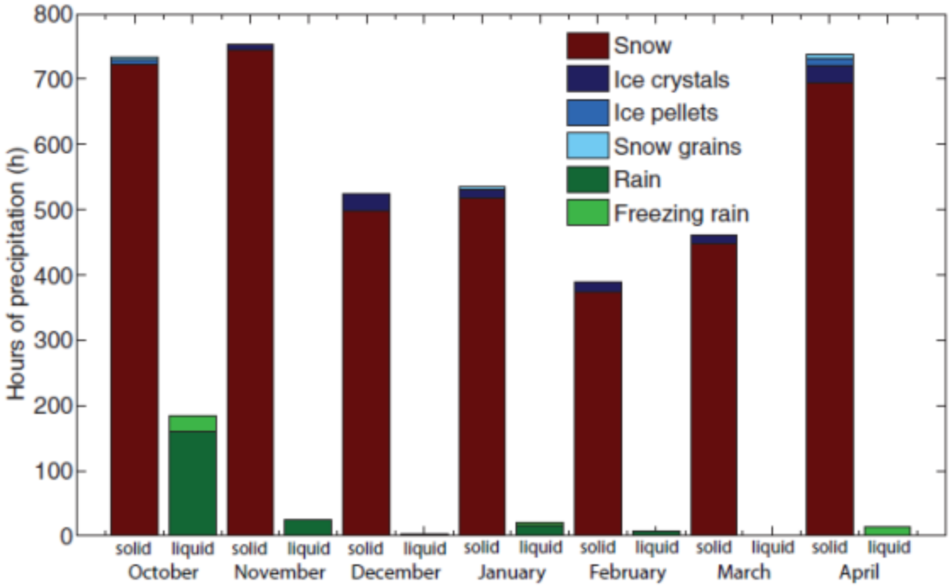


Figure 1.20: Monthly hours of precipitation of different precipitation types from 1955-96 (Gascon et al. (2010))

Precipitation retrieval algorithm developed at CNR-ISAC, and relevant for the proposed study

183-WSL (Laviola et al., 2011, 2013, 2015): 183-WSL a regression-based precipitation rate retrieval algorithm, with cloud classification, and snow detection module, for the cross-track scanning radiometers, originally developed for AMSU/MHS and recently adapted to ATMS.

PNPRv1 and PNPRv2 (Sanò et al., 2015, Sanò et al., 2016): two precipitation retrieval algorithms based on Neural Network approach, for the cross-track scanning radiometers AMSU/MHS (v1) and ATMS (v2), used operationally within EUMETSAT H SAF to provide surface precipitation rate estimates (with indication of phase) over the MSG full disk area.

SLALOM (Rysman et al., 2018): a newly developed algorithm able to detect snowfall and to retrieve the associated snow water path (SWP) over any surface type using the GPM-CO GMI conically scanning radiometer. The algorithm is trained on coincident snowfall observations of the Cloud Profiling Radar (CPR) onboard CloudSat (2C-SNOW-PROFILE product). It is composed of three modules for i) snowfall detection, ii) supercooled droplets detection and iii) SWP retrieval. This algorithm takes into account environmental conditions to retrieve SWP, but does not rely on any background surface auxiliary data. The snowfall detection module is able to detect 83 % of snowfall events compared to CPR, including light SWP (down to $1x10^{-3}$ kg/m^2) with a false alarm rate of 0.12.

PNPR-GMI (Sanò et al., 2018): A newly developed *global* rainfall rate retrieval algorithm for the GPM-CO GMI based on Neural Network approach. A separate module for snowfall rate retrieval based on SLALOM (Rysman et al., 2018) will be implemented.

Scattering Tables

UoL have access to a large amount of scattering tables. This is documented in the parallel ITT activity ``Multi-frequency radar instrument study" and in a recent review paper (Kneifel et al, 2018). These scattering Tables will be used extensively in WP 3100.

Radar simulators
UoL and McGill have long experience in space-borne radar simulators. Battaglia and Kollias have developed several simulators and applied to different cloud scenarios (e.g. Battaglia et al., 2018, Burns et al, 2016, Battaglia and Kollias 2015, Kollias et al, 2014). The McGill group has access to latest version of the EarthCARE Simulation (ECSIM) and state-of-the-art forward modelling capabilities for spaceborne Doppler radar system. These simulators will be applied in WP3300 to the convective scenes in order to assess the RainCube potential.

Microphysics retrieval algorithm
In order to verify the achievement of the scientific objectives thorough retrieval studies will be performed in the framework of this activity. The retrieval technique will be built upon the extensive work already done in OE theory (Rodgers [2000]) and upon techniques developed in preparation of the EarthCARE mission (the PI and co-I Kollias
are part of the EarthCARE Algorithm Development Team) and for the combination of multi-frequency radars for the NASA-JAXA GPM mission [Grecu et al., 2004, 2011; Battaglia et al., 2015a], its related airborne field campaigns [Battaglia et al., 2016a, Tridon et al., 2018].

CRM simulations of convective clouds
The McGill team has also access to the following model outputs: i) high resolution model output from the Environment and Climate Change Canada (ECCC) Global Climate Model. Each scene uses a double-moment microphysics scheme with multiple hydrometeor types, has an along track length of 6200 km, a horizontal resolution of 250 m and a vertical resolution of 100 m and ii) ultra-high resolution (50-m) over a 150x150x20 km domain (Fig. 1.21) of tropical convective clouds using the System for Atmospheric Modeling (SAM) model (SAM, Khairtoudinov and Randall 2003). The SAM model retains the large turbulent eddies and smaller (sub-grid scale) eddies are modelled using Kolmogorov's inertial scaling. SAM includes comprehensive radiative transfer model and cloud/rain microphysics.

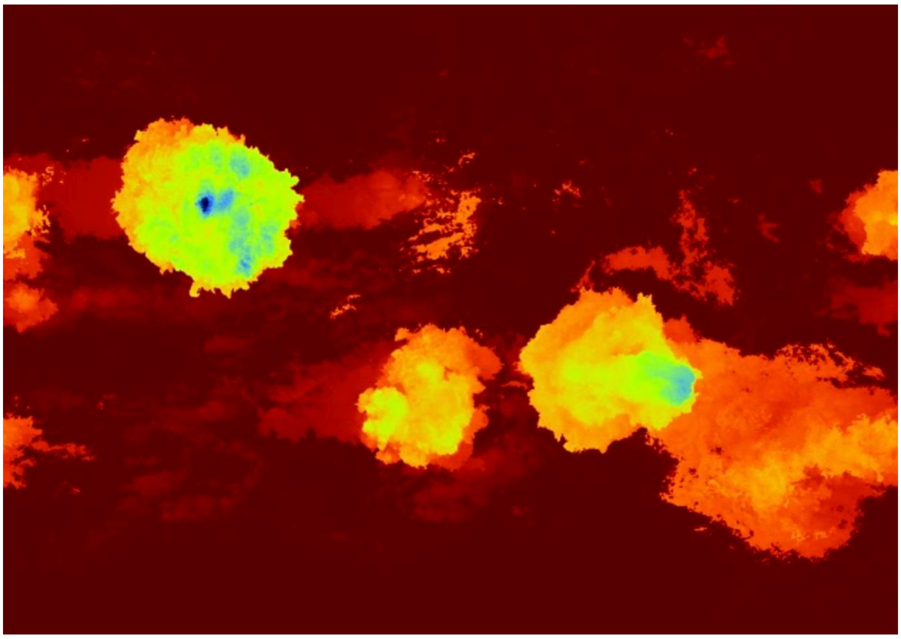


Fig. 1.21: Upwelling longwave radiation from the open ocean tropical convective clouds.

1.4.2 Third Party's concepts/products relevant to the activity and/or to be used

CloudSat Brightness Temperatures
Our International Collaborator S. Tanelli has developed a brightness temperature product from CloudSat by using the noise level estimate and by using AMSR-E as a calibrator. An example of such product is shown in Fig. 1.22. Some studies have used such product in warm clouds (Mace et al., 2016). The value of such TBs for polar precipitation has not been explored yet. This will be part of the activities in WP3200.

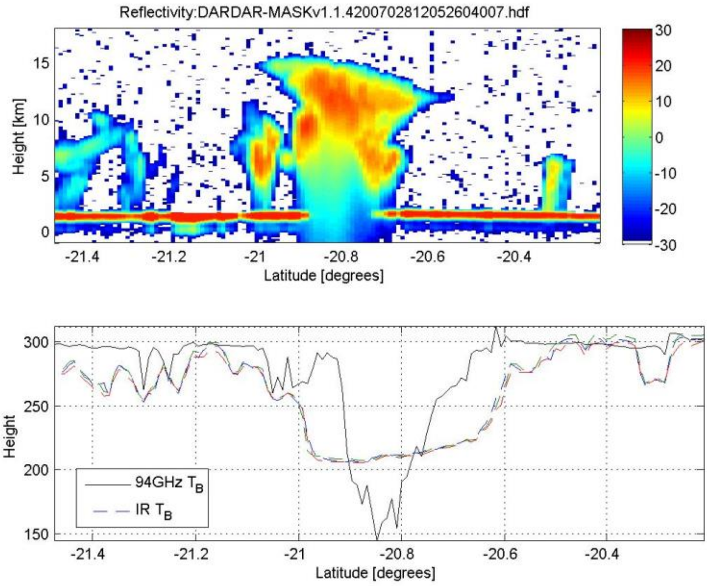


Figure 1.22: CloudSat reflectivity over a convective tower (top panel) with the corresponding brightness temperature (bottom panel) and IR T_B from the CALIPSO Infrared Imager Radiometer.

NASA 3B-CSATGPM product (Turk, 2018), made available at NASA Precipitation Processing System (PPS, https://pps.gsfc.nasa.gov).

Coincident CloudSat/GPM dataset covering over 3.5 y time period (March 2014-November 2017) including: GMI brightness temperatures (L1C V5); GPM V5 products; CloudSat CPR reflectivity profiles, precipitation rate profiles, surface precipitation rate, and environmental variables available from the 2C-SNOW-PROFILE, 2C-PRECIP-COLUMN, 2B-CLOUD-CLASS products; Auxiliary meteorological variables from ECMWF analysis (ECMWF-AUX CloudSat product) [i.e., 2-m temperature (T2m), specific humidity, surface pressure, total precipitable water (TPW)]; associated MODIS thermal channels (11 channels), and the 3x5 MODIS cloud mask; TELSEM surface index and snowIceCover flag. The CloudSat-GPM V3B datasets, also includes 1154 cases where there are triple coincidences GPM+CloudSat+ATMS, 826 cases where there are triple coincidences GPM+CloudSat+MHS, and 233 cases where there are all four coincidences GPM+CloudSat+ATMS+MHS.

1.4.3 Background of the companies

Details are provided in the Implementation proposal.

1.5. TECHNICAL RESERVATIONS – TECHNICAL COMPLIANCE:

1.5.1 Reservations

There are no technical reservations.

BIBIOGRAPHY

[AD-1] Multi-frequency radar instrument study; Statement of Work

[AD-2] Assessment of science requirements and specific observation needs; prepared as part of the "Multi-frequency radar instrument study"

[AD-3] State of the Art and preliminary assessment of innovative radar concepts; prepared as part of the "Multi-frequency radar instrument study"

Accadia, C., S. Di Michele, V. Mattioli, J. Ackermann, S. Thonipparambil, and P. Schlüssel: Next generation of EUMETSAT microwave imagers and sounders: new opportunities for cloud and precipitation retrieval. 8th IPWG and 5th IWSSM Joint Workshop, 3-7 October, 2016, Bologna-Italy.

Battaglia, A., and P Kollias, Error Analysis of a Conceptual Cloud Doppler Stereo-radar with Polarization Diversity for Better Understanding Space Applications, Journal of Atmospheric and Oceanic Technology, 2015, doi: http://dx.doi.org/10.1175/JTECH-D-14-00015.1

Battaglia, A., K. Mroz, T. Lang, F. Tridon, S. Tanelli, G. Heymsfield, and L. Tian, 2016a: Using a multi-wavelength suite of microwave instruments to investigate the microphysical structure of deep convective cores. J. Geophys. Res. Atm., dOI:10.1002/2016JD025269.

Battaglia, A., Dhillon, R and A. Illingworth, 2018: Doppler W-band polarization diversity spaceborne radar simulator for wind studies, Atm. Meas. Tech. Disc..

Battaglia, A., Tanelli, S., Tridon, F, Kneifel, S., Leinonen J, Kollias, P., Triple-frequency radar retrievals, chapter in the book Satellite precipitation measurement, Editor in Chief: Vincenzo Levizzani, Springer

Bellucci, A., S. Gualdi, and A. Navarra, 2010: The double ITCZ syndrome in coupled general circulation models: The role of large-scale vertical circulation regimes. *J. Climate*, **23**, 1127–1145

Bukovčić, Petar & Ryzhkov, Alexander & Zrnić, Dusan & Zhang, Guifu. (2017). Polarimetric Radar Relations for Quantification of Snow Based on Disdrometer Data. Journal of Applied Meteorology and Climatology. 57. 10.1175/JAMC-D-17-0090.1.

Burns, D., P. Kollias, A. Tatarevic, A. Battaglia, S. Tanelli, The Performance of the EarthCARE Cloud Profiling Radar in Marine Stratiform Clouds, 2016, Journal of Geophysical Research: Atmospheres, 10.1002/2016JD025090.

Casella, D.; Panegrossi, G.; Sanò, P.; Marra, A. C.; Dietrich, S.; Johnson, B. T.; Kulie, M. S. Evaluation of the GPM-DPR snowfall detection capability: Comparison with CloudSat-CPR. *Atmospheric Res.* **2017**, *197*, 64–75, doi:10.1016/j.atmosres.2017.06.018.

Casella D., L. M. Amaral, S. Dietrich, A. C. Marra, P. Sanò, and G. Panegrossi, The Cloud Dynamics and Radiation Database algorithm for AMSR2: exploitation of the GPM observational dataset for operational applications, IEEE J. of Sel. Topics in Appl. Earth Obs. and Rem. Sens. (J-STARS), 10(*8), DOI :* 10.1109/JSTARS.2017.2713485*, 2017*

Chakraborty, A., 2010: The skill of ECMWF medium-range forecasts during the Year of Tropical Convection 2008. *Mon. Wea. Rev.*, **138**, 3787–3805.

Cifelli, R., V. Chandrasekar, S. Lim, P. Kennedy, Y. Wang, and S. Rutledge, 2011: A new dual-polarization radar rainfall algorithm: Application in Colorado precipitation events. J. Atmos. Oceanic Technol., 28, 352–364.

Delanoë, J.; Hogan, R. J. Combined CloudSat-CALIPSO-MODIS retrievals of the properties of ice clouds. *J. Geophys. Res.* **2010**, *115*, doi:10.1029/2009JD012346.

Eriksson P., M. Jamali, J. Mendrok and S. A. Buehler: On the microwave optical properties of randomly oriented ice hydrometeors, Atmos. Meas. Tech., 8, 1913–1933, 2015, doi:10.5194/amt-8-1913-2015

Ebtehaj, A. M.; Kummerow, C. D. Microwave retrievals of terrestrial precipitation over snow-covered surfaces: A lesson from the GPM satellite. *Geophys. Res. Lett.* **2017**, *44*, 6154–6162, doi:10.1002/2017GL073451.

Ferraro, R.R., Weng, F., Grody, N.C., Zhao, L., Meng, H., Kongoli, C., Pellegrino, P., Qiu, S., Dean, C.: NOAA operational hydrological products derived from the Advanced Microwave Sounding Unit. IEEE Trans. Geosci. Remote Sens. 2005, 43, 1036-1049.

Gorgucci, E. and L. Baldini, 2016: A self-consistent numerical method for microphysical retrieval in rain using GPM dual-wavelength radar. *Journal of Atmospheric and Oceanic Technology*, **33 (10)**, 2205–2223, doi:10.1175/JTECH-D-16-0020.1, http://dx.doi.org/10.1175/ JTECH-D-16-0020.1.

Grecu, M., L. Tian, W. S. Olson, and S. Tanelli, 2011: A Robust Dual-Frequency Radar Profiling Algorithm. J. Appl. Meteorol. Climatol., 50, 1543–1557.

Grecu, M.,W. S. Olson, and E. N. Anagnostou, 2004: Retrieval of precipitation profiles from multiresolution, multifrequency active and passive microwave observations. J. Appl. Meteorol., 43, 562–575.

Gunn, K. L. S., and J. S. Marshall, 1958: The distribution with size of aggregate snowflakes. J. Meteor., 15, 452–461, doi:10.1175/1520-0469(1958)015,0452:TDWSOA.2.0.CO;2.

Hamada, A. and Y. N. Takayabu, 2016: Improvements in detection of light precipitation with the global precipitation measurement dual-frequency precipitation radar (gpm dpr). *J. Atmos. Ocean Technol.*, **13**,653–667.

Hanesiak, J. and co-authors, 2009: Storm studies in the Arctic (STAR). *B Am Meteorol Soc* doi: 10.1175/2009BAMS2393.1

Heymsfield A., S.Matrosov, and N. Wood, 2016: Toward improving ice water content and snow-rate retrievals from radars. Part I: X and W bands, emphasizing CloudSat. J. Appl. Meteor. Climatol., 55, 2063–2090, doi:10.1175/JAMC-D-15-0290.1

Houze, R., et al., 2017: Olympic Mountains Experiment (OLYMPEX). Bull.Amer. Met. Soc., https://doi.org/10.1175/BAMS-D-16-0182.1.

Illingworth, A. J., et al., 2015: The EarthCARE Satellite: the next step forward in global measurements of clouds, aerosols, precipitation and radiation. Bull. Amer. Met. Soc., doi: http://dx.doi.org/10.1175/BAMS-D-12-00227.1.

International Panel for Climate Change, 2013: Climate Change 2013-The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the IPCC. Tech. rep., IPCC 2013.

Khairoutdinov, M. F., and D.A. Randall, 2003: Cloud-resolving modeling of the ARM summer 1997 IOP: Model formulation, results, uncertainties and sensitivities. *J. Atmos. Sci.*, 60, 607-625

Kidd, C., and G. Huffman, 2011: Review – Global precipitation measurement. Meteorol. Appl., 18, 334-353.

Kidd, C., and V. Levizzani, 2011: Status of satellite precipitation retrievals. Hydrol. Earth Syst. Sci., 15, 1109-1116.

Kidd, C., J. Tan, P.-E. Kirstetter, and W. Petersen, 2018: Validation of the Version 05 Level 2 pre691 cipitation products from the GPM Core Observatory and constellation satellite sensors. Quar692 terly Journal of the Royal Meteorological Society.

Kirstetter, P.-E., Y. Hong, J. Gourley, M. Schwaller, W. Petersen, and J. Zhang, 2013: Compari699 son of TRMM 2a25 products, version 6 and version 7, with NOAA/NSSL ground radar–based 700 national mosaic QPE. Journal of Hydrometeorology, 14 (2), 661–669.

Stefan Kneifel, Jussi Leinonen, Jani Tyynela, Davide Ori, Battaglia, A., Scattering of Hydrometeors, chapter in the book Satellite precipitation measurement, Editor in Chief: Vincenzo Levizzani, Springer

Koistinen, Y., D. Michelson, H. Hohti, and M. Peura, 2003: Operational measurement of precipitation in cold climates.

Kollias, P., W. Szyrmer, I. Zawadzki, and P. Joe, 2007b: Considerations for spaceborne 94 GHz radar observations of precipitation. Geophys. Res. Lett., 34, L21803, doi: 10.1029/2007GL031 536.

Kollias, P., S. Tanelli, A. Battaglia and A. Tatarevic, Evaluation of EarthCARE Cloud Profiling Radar Doppler Velocity Measurements in Particle Sedimentation Regimes, J. Atm. Ocean. Tech., 2014, 31(2), 366-386.

Kongoli, C.; Pellegrino, P.; Ferraro, R.R.; Grody, N.C.; Meng, H.: A new snowfall detection algorithm over land using measurements from the Advanced Microwave Sounding Unit (AMSU). Geophys. Res. Lett. 2003, 30,doi:10.1029/2003GL017177

Kongoli C., H. Meng , J. Dong , and R. Ferraro: A Hybrid Snowfall Detection Method from Satellite Passive Microwave Measurements and Global Forecast Weather Models. Q .J. Roy. Meteor. Soc., 2018, https://doi.org/10.1002/qj.3270

Kucera, P., E. E. Ebert, F. J. Turk, V. Levizzani, D. Kirshbaum, F. J. Tapiador, A. Loew, and M Borsche, 2013: Precipitation from space. Bull. Am. Meteorol. Soc., doi:10.1175/BAMS-D-11-00171.1

Kulie, M. S.; Bennartz, R.; Greenwald, T. J.; Chen, Y.; Weng, F. Uncertainties in Microwave Properties of Frozen Precipitation: Implications for Remote Sensing and Data Assimilation. *J. Atmospheric Sci.* **2010**, *67*, 3471–3487, doi:10.1175/2010JAS3520.1.

Kulie, M. S.; Bennartz, R. Utilizing Spaceborne Radars to Retrieve Dry Snowfall. *J. Appl. Meteorol. Climatol.* **2009**, *48*, 2564–2580, doi:10.1175/2009JAMC2193.1.

Kulie, M. S.; Milani, L.; Wood, N. B.; Tushaus, S. A.; Bennartz, R.; L'Ecuyer, T. S. A Shallow Cumuliform Snowfall Census Using Spaceborne Radar. *J. Hydrometeorol.* **2016**, *17*, 1261–1279, doi:10.1175/JHM-D-15-0123.1.

Kummerow, C., W. Barnes, T. Kozu, J. Shiue, and J. Simpson, 1998: The Tropical Rainfall Measuring Mission (TRMM) sensor package. J. Atmos. Oceanic. Technol., 15, 809-817, https://doi.org/10.1175/1520-0426(1998)015%3C0809:TTRMMT%3E2.0.CO;2

Kummerow, C. D.; Randel, D. L.; Kulie, M.; Wang, N.-Y.; Ferraro, R.; Joseph Munchak, S.; Petkovic, V. The Evolution of the Goddard Profiling Algorithm to a Fully Parametric Scheme. *J. Atmospheric Ocean. Technol.* **2015**, *32*, 2265–2280, doi:10.1175/JTECH-D-15-0039.1.

Lamer, K., E. Luke, P. Kollias, 2018: Long-term Observations of Marine Boundary Layer Clouds Drizzle Intensity: Vertical and Horizontal Structure. Submitted to GRL

Laviola, S., V. Levizzani, E. Cattani, and C. Kidd: First validation of retrieved rain rates and snow cover mask of the 183-WSL retrieval method. 12th Specialist Meeting on Microwave Radiometry and Remote Sensing of the Environment, MicroRad 2012, doi: 10.1109/MicroRad.2012.6185242

Laviola, S., and V. Levizzani: The 183-WSL fast rain rate retrieval algorithm. Part I: Retrieval design. Atmospheric Research, Volume 99, Number 3-4, p.443-461, (2011)

Laviola, S., V. Levizzani, E. Cattani, and C.Kidd: The 183-WSL fast rain rate retrieval algorithm. Part II: Validation using ground radar measurements. Atmospheric Research, Volume 134, p.77-86, (2013)

Laviola, S., J. Dong, C. Kongoli, H. Meng, R. Ferraro, and V. Levizzani: An intercomparison of two passive microwave algorithms for snowfall detection over Europe. Geoscience and Remote Sensing Symposium (IGARSS), 2015 IEEE International, Volume 2015-November, p.886-889, (2015), doi: 10.1109/IGARSS.2015.7325907

Le, M., V. Chandrasekar, and S. Biswas, 2016: Evaluation and Validation of GPM Dual-Frequency Classification Module after Launch. *J. Atmos. Ocean Technol.*, **33 (12)**.

L'Ecuyer, T. S. and G. L. Stephens, 2002: An estimation-based precipitation retrieval algorithm for attenuating radars. J. Appl. Meteorol., 41 (3), 272–285.

Leinonen, J., et al., 2018: Retrieval of snowflake microphysical properties from multi-frequency radar observations. Atm. Meas. Tech. Disc., https://doi.org/10.5194/amt-2018-73.

Levizzani, V., S. Laviola, and E.Cattani, 2011: Detection and measurement of snowfall from space. Remote Sens., 3, 145-166, doi:10.3390/rs3010145.

Levizzani, V., C. Kidd, K. Aonashi, R. Bennartz, R. R. Ferraro, G. J. Huffman, R. Roca, F. J. Turk, and N.-Y. Wang, 2018: The activities of the International Precipitation Working Group. Quart. J. Roy. Meteor. Soc., doi:10.1002/qj.3214.

Lin, X. and A. Y. Hou, 2012: Estimation of rain intensity spectra over the continental United States using ground radargauge measurements. J. Climate, 25, 1901–1915, doi:10.1175/JCLI-D-11-00151.1.

Liu, G.; Seo, E.-K. Detecting snowfall over land by satellite high-frequency microwave observations: The lack of scattering signature and a statistical approach. *J. Geophys. Res. Atmospheres* **2013**, *118*, 1376–1387, doi:10.1002/jgrd.50172.

Lu, Y, K. Aydin, E. E. Clothiaux and J. Verlinde, 2015: Retrieving Cloud Ice Water Content Using Millimeter- and Centimeter-Wavelength Radar Polarimetric Observables. J. Appl. Meteor., 54, 596-604.

Mace,G.G., S.Avey, S.Cooper, M.Lebsock, S. Tanelli, and G. Dobrowalski (201 6),Retrieving co-occurring cloud andprecipitation properties of w arm marineboundary layer clouds with A-Train data,J. Geophys. Res. Atmos., 121,4008–40 33,doi:10.1 002/ 2015JD 0236 81

Mapes, B., and R. Neale (2011), Parameterizing Convective Organization to Escape the Entrainment Dilemma, *J. Adv. Model. Earth Syst.*, 3, M06004, doi: 10.1029/2011MS000042

Mason, S. L., J. C. Chiu, R. J. Hogan, and L. Tian, 2017: Improved rain rate and drop size retrievals from airborne Doppler radar. Atmos. Chem. Phys., 17, 11 567–11 589, doi.org/10.5194/acp-17-11567-2017.

Matrosov, S. Y., R. F. Reinking, R. A. Kropfli, and B. W. Bartram, 1996: Estimation of ice hydrometeor types and shapes from radar polarization measurements. J. Atmos. Oceanic Technol.,13, 85–96.

Meischner P., Ed. Weather Radar, Principles and Advanced Applications, Springer, 78–114.

Meneghini, R., H. Kim, L. Liao, J. A. Jones, and J. M. Kwiatkowski, 2015: An Initial Assessment of the Surface Reference Technique Applied to Data from the Dual-Frequency Precipitation Radar (DPR) on the GPM Satellite. *J. Atmos. Ocean Technol.*, **32 (12)**, 2281–2296, doi:http://dx.doi.org/10.1175/JTECH-D-15-0044.1.

Michaelides, S., V. Levizzani, E. Anagnostou, P. Bauer, T. Kasparis, J.E. Lane, 2009: Precipitation: Measurements, remote sensing, climatology and modeling. Atmos. Res., 94, 512-533.

Milani, L., M. Kulie, D. Casella, S. Dietrich, T. L'Ecuyer, G. Panegrossi, F. Porcu', P. Sano', N. Wood, CloudSat Snowfall Estimates over Antarctica and the Southern Ocean: An Assessment of Independent Retrieval Methodologies and Multi-Year Snowfall Analysis, Atmos. Res., *23, 121-136., DOI*: 10.1016/j.atmosres.2018.05.015, 2018

Morales, R., and A. Nenes, 2010: Characteristic updrafts for computing distribution-averaged cloud droplet number and stratocumulus cloud properties. *J. Geophys. Res.*, **115,** D18220, doi:https://doi.org/10.1029/2009JD013233

Panegrossi G., J-F. Rysman, D. Casella, A. C. Marra, P. Sanò, and M. S. Kulie, CloudSat-based assessment of GPM Microwave Imager snowfall observation capabilities, Rem. Sensing, 9(12), 1263; doi:10.3390/rs9121263, 2017.

Panegrossi G., J.-F. Rysman, D. Casella, P. Sanò, A. C. Marra, S. Dietrich, Mark S. Kulie, Exploitation of GPM/CloudSat coincidence dataset fro global snowfall retrieval, Proceedings IGARSS 2018, 23-27 July, 2018, Valencia, Spain, 2018.

Pelon J., G. Vali, G. Ancellent, G. Ehret, P. H. Flamant, S. Haimov., G. Heysfiel, D. Leon, J. M. Meed, A. Pazmany, A. Protat, Z. Wang and M. Wolde, 2013: Airborne Measurements for Environmental Research: Methods and Instruments – Chapter 9: Lidar and Radar Observations

Peral, E., Travis Imken, Jonathan Sauder, Shannon Statham, Simone Tanelli, Douglas Price, Nacer Chahat, Austin Williams, "RainCube, a Ka-band Precipitation Radar in a 6U CubeSat," Proceedings of the 31st Annual AIAA/USU Conference on Small Satellites, Logan UT, USA, Aug. 5-10, 2017, paper: SSC17-III-03.

Puhakka, T., 1975: On the dependence of the Z–R relation on the temperature in snowfall. Preprints, 16th Conf. on Radar Meteorology,Houston, TX, Amer. Meteor. Soc., 504–507

Rasmussen, E.A. and Turner, J. 2003: Polar Lows: Mesoscale Weather Systems in the Polar Regions. Cambridge University Press: Cambridge. 612pp

[RD-1] ESA-GEWEX EARTH OBSERVATION AND WATER CYCLE SCIENCE PRIORITIES

[RD-4] Technical Assistance for the deployment of airborne and ground-based measurements in support of future precipitation mission; Statement of Work

[RD-5] ESA 2014 Workshop on Novel Mission Concepts for Snow and Cryosphere Research. Summary Report.

[RD-6] Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) mission: https://tropics.ll.mit.edu/CMS/tropics/

[RD-7] Committee on the Decadal Survey for Earth Science and Applications from Space, Space Studies Board and Division on Engineering and Physical Sciences; “Thriving on Our Changing Planet A Decadal Strategy for Earth Observation from Space”, PDF is available at http://nap.edu/24938

Rodgers, C. D., 2000: Inverse methods for atmospheric sounding: theory and practice. World Scientific,River Edge, NJ, 238 pp.

Rysman, J-F., G. Panegrossi G., P. Sanò, A. C. Marra, S. Dietrich, L. Milani, M. S., Kulie, SLALOM: An all-surface snow water path retrieval algorithm for the GPM Microwave Imager, Rem. Sensing, *submitted*

Saleeby, S. M., and W. R. Cotton, 2004: A large-droplet mode and prognostic number concentration of cloud droplets in the Colorado State University Regional Atmospheric Modeling System (RAMS). Part I: Module descriptions and supercell test simulations. *J. Appl. Meteor.*, **43,** 182–195

Sanò, P., Panegrossi, G., Casella, D., Di Paola, F., Milani, L., Mugnai, A., Petracca, M., and Dietrich, S.: The Passive microwave Neural network Precipitation Retrieval (PNPR) algorithm for AMSU/MHS observations: description and application to European case studies, Atmos. Meas. Tech., 8, 837-857, doi:10.5194/amt-8-837-2015, 2015.

Sanò, P., Panegrossi, G., Casella, D., Marra, A. C., Di Paola, F., and Dietrich, S.: The new Passive microwave Neural network Precipitation Retrieval (PNPR) algorithm for the cross-track scanning ATMS radiometer: description and verification study over Europe and Africa using GPM and TRMM spaceborne radars, Atmos. Meas. Tech., 9, 5441-5460, doi:10.5194/amt-9-5441-2016, 2016.

Sanò P., G. Panegrossi, D. Casella, A. C. Marra, L. P. D'Adderio, J.-F. Rysman, S. Dietrich, The Passive Microwave Neural Network Precipitation Retrieval (PNPR) algorithm for the Conical Scanning GMI Radiometer, Rem. Sensing, *submitted*, 2018

Sekhon, R. S., and R. C. Srivastava, 1970: Snow size spectra and radar reflectivity. J. Atmos. Sci., 27, 299–307, doi:10.1175/1520-0469(1970)027,0299:SSSARR.2.0.CO;2.

Skofronick-Jackson, G.; Johnson, B. T. Surface and atmospheric contributions to passive microwave brightness temperatures for falling snow events. *J. Geophys. Res.* **2011**, *116*, doi:10.1029/2010JD01443

Skofronick-Jackson, G., W. A. Petersen, W. Berg, C. Kidd, E. F. Stocker, D. B. Kirschbaum, R. Kakar, S. A. Braun, G. J. Huffman, T. Iguchi, P. E. Kirstetter, C. Kummerow, R. Meneghini, R. Oki, W. S. Olson, Y. N. Takayabu, K. Furukawa, and T. Wilheit, 2017: The Global Precipitation Measurement (GPM) mission for science and society. Bull. Amer. Meteor. Soc., 98, 1679–1695, doi:10.1175/BAMS-D-15-00306.1.

Stephens, G. L., et al., 2008: CloudSat mission: Performance and early science after the first year of operation. J. Geophys. Res., 113, D00A18, doi:10.1029/2008JD009982.

Storer, R. L., S. C. van den Heever, and T. S. L'Ecuyer (2014), Observations of aerosol-induced convective invigoration in the tropical east Atlantic, *J. Geophys. Res. Atmos.*, 119, 3963–3975, doi:10.1002/2013JD020272

Surussavadee, C. and Staelin, D.H. 2009: Satellite Retrievals of Arctic and Equatorial Rain and Snowfall Rates Using Millimeter Wavelengths. IEEE T Geosci. and Remote S. 47, 3697-3707

Szyrmer, W., and I. Zawadzki, 2010: Snow studies. Part II: Average relationship between mass of snowflakes and their terminal fall velocity. J. Atmos. Sci., 67, 3319–3335, doi:10.1175/2010JAS3390.1.

Tanelli, S., S. L. Durden, E. Im, G. Heymsfield, P. Racette, and D. Starr, 2009: Next-generation spaceborne cloud profiling radars. *Radar Conference*, IEEE, Ed., 1–4, 10.1109/RADAR.2009.4977116.

The National Academies Press, (Ed.) , 2007: *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond.*

Tridon, F., et al., 2018: The microphysics of stratiform precipitation during OLYMPEX: compatibility between 3-frequency radar and airborne in situ observations. J. Geophys. Res., under submission

Turk, F. J.; Haddad, Z. S.; You, Y. Principal Components of Multifrequency Microwave Land Surface Emissivities. Part I: Estimation under Clear and Precipitating Conditions. *J. Hydrometeorol.* **2014**, *15*, 3–19, doi:10.1175/JHM-D-13-08.1.

Turk, F. J. CloudSat-GPM Coincidence Dataset 3b_CSATGPM, 2018.

Vivekanandan, J., V. N. Bringi, M. Hagen, and P. Meischner, 1994: Polarimetric radar studies of atmospheric ice particles. IEEE Trans. Geosci. Remote Sens.,32, 1–10.

Watters, D., Battaglia, A., Mroz, K. , Tridon, F., Validation of the Version-5 Surface Rain Rate Products from the Global Precipitation Measurement Mission Core Observatory over Great Britain and Ireland, 2018 conditionally accepted in J. Hydrometeorology

Wen, Y., P. Kirstetter, J.J. Gourley, Y. Hong, A. Behrangi, and Z. Flamig, 2017: Evaluation of MRMS Snowfall Products over the Western United States. J. Hydrometeor., 18, 1707–1713, https://doi.org/10.1175/JHM-D-16-0266.1

Wolde, M., and G. Vali, 2001: Polarimetric signatures from ice crystals observed at 95GHz in winter clouds. Part I: Dependence on crystal form. J. Atmos. Sci., 58, 828–841.

Wolfe, J. P., and J. R. Snider, 2012: A relationship between reflectivity and snow rate for a high-altitude S-band radar. J. Appl. Meteor. Climatol., 51, 1111–1128, doi:10.1175/JAMC-D-11-0112.1.

Wood, N. B.; L'Ecuyer, T. S.; Bliven, F. L.; Stephens, G. L. Characterization of video disdrometer uncertainties and impacts on estimates of snowfall rate and radar reflectivity. *Atmospheric Meas. Tech.* **2013**, *6*, 3635–3648, doi:10.5194/amt-6-3635-2013.

Wood, N. B.; L'Ecuyer, T. S.; Heymsfield, A. J.; Stephens, G. L.; Hudak, D. R.; Rodriguez, P. Estimating snow microphysical properties using collocated multisensor observations. *J. Geophys. Res. Atmospheres* **2014**, *119*, 8941–8961, doi:10.1002/2013JD021303.

You, Y.; Wang, N.-Y.; Ferraro, R.; Rudlosky, S. Quantifying the Snowfall Detection Performance of the GPM Microwave Imager Channels over Land. *J. Hydrometeorol.* **2017**, *18*, 729–751, doi:10.1175/JHM-D-16-0190.1.

Zhang, C., J. Gottschalck, E. D. Maloney, M. W. Moncrieff, F. Vitart, D. E. Waliser, B. Wang, and M. C. Wheeler (2013), Cracking the MJO nut, *Geophys. Res. Lett.*, 40, 1223–1230, doi: 10.1002/grl.50244

2) IMPLEMENTATION PART

2.1 TEAM ORGANISATION AND PERSONNEL

2.1.1 *Proposed team*

The structure of the proposed consortium includes the Department of Physics, University of Leicester (UK) as the Prime Contractor. Dr. A. Battaglia will act as a project manager, Dr. P. Kollias will lead the McGill efforts, Dr. G. Panegrossi will be the PI for the CNR-ISAC while Dr. M. Wolde will be the PI for NRC. Battaglia, Kollias and Wolde have been working together on space-borne radar applications and ground-based mm-wave radar measurements in the last ten years under ESA, NERC and US Department of Energy funding and have participated to several International mission proposals involving cloud and precipitation radars. They have also been involved together in several field campaigns funded by ESA and by NASA.

University of Leicester

The group headed by A. Battaglia part of the Earth Observation Science group at the University of Leicester has a strong vocation to microwave active and passive remote sensing studies of clouds and precipitation, with a particular focus on multi-frequency radars. The group is currently developing multi-frequency inversion techniques both from ground and from air-borne and space-borne platforms. Dr. Battaglia has been involved in previous ESA studies relevant for this activity: he is the PI of the ESA Multi-frequency Instrument study, he was the PI for the University of Bonn in the DAME (Doppler Air Measurement Estimate) activity, he was the PI for the WISDR (Capability of atmospheric parameter retrieval and modeling for WIde-Swath spaceborne Doppler Radars) project (ITT AO/1-6661/11/NL/LvH), he was the co-I in the project WIVERN (WInd VElocity Radar Nephoscope) led by Prof. Illingworth funded by UK Center Earth Observation Instrumentation to support the study of a space-borne conically scanning millimeter radar for wind observations and of the ESA-funded Doppler Wind Radar Demonstrator study (AO/1-8140/14/NL/MP) also led by Prof. Illingworth, and he has been involved in the VARSY activity as a consultant. He is also Member of the EarthCARE Mission Advisory Board.

CNR-ISAC

The CNR-ISAC is a public organization whose duty is to carry out, promote, spread, transfer and improve research activities in the main sectors of knowledge growth and of its applications for the scientific, technological, economic and social development of the Italy. The CNR activity is focused on seven macro-areas of interdisciplinary scientific and technological research, that correspond to seven departments. The Earth Observation activities are carried out by Department of Earth System Science and Environmental Technologies (DTA) with aim to gather knowledge and predict the behaviour of the Earth system and its resources, so as to help a sustainable future for the planet and mankind. DTA has given to its Institute of Atmospheric Sciences and Climate (CNR-ISAC) the mandate to represent CNR and its Institutes in this Project and to coordinate all CNR activities. CNR-ISAC has more than 30-year experience on meteorology and climate sciences including: study of the basic processes of climate dynamics and variability, atmospheric dynamics and composition, earth observations of the atmosphere/ocean and ocean dynamics. The Institute participates with its Clouds and Precipitation Physics

(CAPE) Group whose focus is the study of physical processes of precipitation formation at all scales from cloud microphysics to climate. CNR-ISAC has a substantial success record and experience in operational programs and project coordination and has a recognized expertise in supporting and promoting observational activities for climate, environmental and ocean monitoring, based on the integration of different kinds of observational techniques (in-situ and remote sensing). This results in a portfolio of around 100 active projects each year. CNR-ISAC brings to the project the scientific knowledge and the operational expertise on precipitation that is recognised at international level. It is a leading institution in remote sensing activities for meteorology and climatology funded by ESA, EUMETSAT, ECMWF, and cooperating with NASA, NOAA and other major institutions worldwide for producing satellite-based algorithms and climate analyses of precipitation, and mission concepts.
Rainfall and snowfall are key research topics dwelling on the existing and future constellations of meteorological and environmental satellites in orbit.
Specific expertise concerning the present project is:

- development of algorithms for passive and active remote sensing of precipitation from space and from the ground;
- development of algorithms for cloud structure studies from satellite;
- studies of atmospheric processes at the climatological scale;
- validation studies of satellite precipitation measurements.

Main projects of the CNR-ISAC team relevant to the ITT include:

- EURAINSAT 2001-2005 Project coordinator of the EC FP5 project "European satellite rainfall analysis and monitoring at the geostationary scale" (EURAINSAT);
- GLOWASIS 2011-2012 Partner of the EC FP7 project "A collaborative project aimed at pre-validation of a GMES Global Water Scarcity Information Service (GLOWASIS);
- eartH2Observe 2013-2017 Partner of the EC FP7 project "Global Earth Observation for integrated water resource assessment" (eartH2Observe);
- Scientists of the Institute are Chairperson of the Science Advisory Group (SAG) of the MET sensor of the PostEPS satellite and recently participated to the SAG of the ESA Geosounder concept.
- EUMETSA HSAF The Institute leads the precipitation products activities in EUMETSAT's Satellite Application Facility on Support to Hydrology and Water Management (H SAF).
- Copernicus Climate Change Service (C3S_312b) 2018-2021. ISAC responsible for the Essential Climate Variable Precipitation.

Another CNR-DTA institute that will be partially involved in the project through one of its leading scientist (Dr. Luca Brocca, as expert in-kind) is the Research institute for geo-hydrological protection (IRPI). CNR-IRPI has an internationally recognized excellence on the exploitation of remote sensing and ground observations for improving our understanding of hydrological processes as well as advancing hydrological/hydraulic modelling for the mitigation of natural hazards such as floods, landslides and drought. CNR-IRPI is (has been) involved in several projects and activities involving satellite observations funded by ESA and EUMETSAT.

McGill University
McGill University is Canada's best-known institution of higher learning and one of the world leading research-intensive universities. With students coming to McGill from about 140 countries, our student body is the most internationally diverse of any medical-doctoral university in Canada. Substantial observing atmospheric capabilities are already in place at McGill's Department of Atmospheric and Oceanic Sciences (AOS) (www.mcgill.ca/meteo). AOS is the largest university atmospheric-oceanic sciences group in Canada. It offers academic programs at both the undergraduate and graduate levels, covering a broad range of topics, ranging in scale from the microphysics of raindrops to the global circulation patterns observed in the atmosphere and oceans. It currently has over 40 undergraduate and over 50 graduate students, many of whom come from abroad.

In addition to the radar group, the Department is home to the "clouds" group that is specializing in the use of millimeter wavelength radars in weather and climate research. The McGill's clouds group is headed by Prof. Kollias (Project Manager of the proposed DORSY activity) and focuses on the "*cloud problem*", i.e., the understanding of the microphysical, dynamical and radiative processes that act at the cloud scale and their accurate representation in numerical models is the central theme of my research. The clouds group research focuses on processes such as precipitation initiation in liquid and ice water clouds (e.g., drizzle formation), the role of turbulence and entrainment in cloud evolution, mixed-phase clouds, the cloud-aerosol interaction, and the raindrop size distribution evolution under the action of vertical drafts and evaporation. Synergetic remote sensing observations from both space-based and ground-based sensors and their clever use through the development of new inversion algorithms and adaptive sampling strategies constitute our group approach for probing clouds and precipitation in their natural environment. The group has also pioneered the development of forward models at all radar frequencies and has substantial background in cloud and precipitation measurements using radars from a variety of platforms.
Prof. Kollias has considerable experience as project manager in previous ESA studies related to EarthCARE and more general spaceborne radar activities. Examples are the "Cloud and Aerosol Synergistic Products from EarthCARE Retrievals (CASPER)", the "Doppler Effect Modelling for Air Motion Estimates (DAME, ITT AO/1-5909/08/NL/CT)", the "Dimensional VARiational Retrievals of Synergistic EarthCARE Products (VARSY, ITT AO/1-6823/11/NL/CT) and the "Doppler Radar and Synergy Products for EarthCARE (DORSY, ITT AO/1-7880/14/NL/CT, on going).

Another component that is expected to enhance the output of the proposed study are the international collaborator from NASA GFSC, NASA JPL and that are currently involved in different concepts currently under study in preparation of the implementation of the Decadal Survey 2017. The overall structure (see Fig 2.1) is kept agile and simple to minimize management while the time dedication of key personnel is illustrated in Table 2.1.

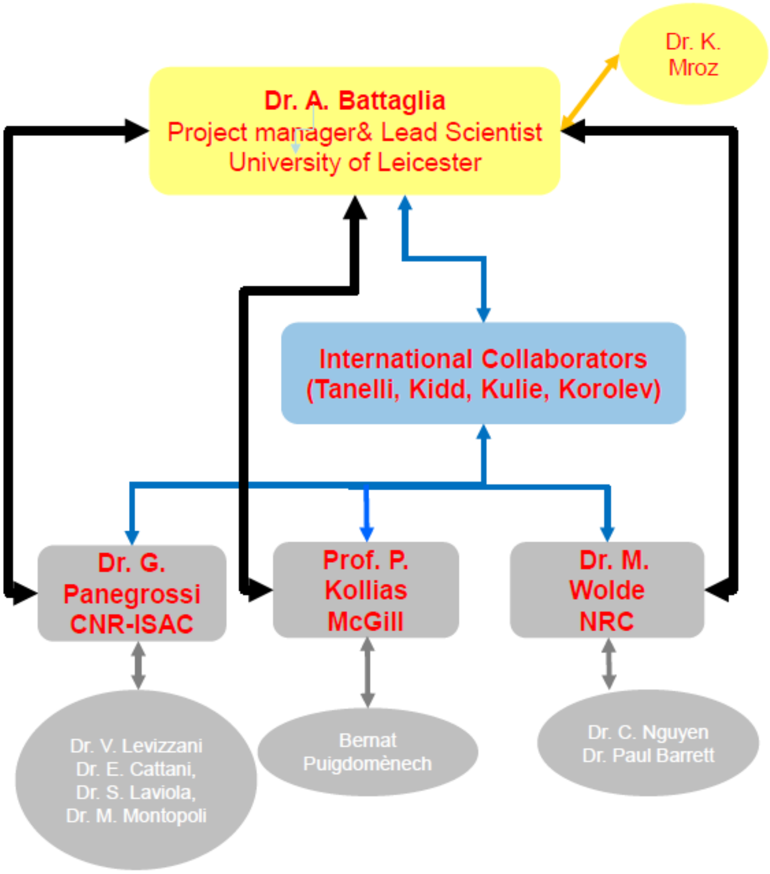


Figure 2.1: Structure of the consortium and relation with the Prime (University of Leicester) of the activity and the other subcontractors.

2.1.1.1 Overall team composition, key personnel

The University of Leicester is proposed as the Prime. The person appointed as a Project Manager is ***Dr. Alessandro Battaglia*** (6.5% of the time). He is currently Associate Professor in the Department of Physics and he is the Leader of the Radar group in the Earth Observation Science group led by Prof. H. Boesch. He has extensive experience in active and passive microwave modelling, he has developed radar forward modelling capable of simulating Doppler space-borne radars, he has worked on polarization diversity and developed retrieval algorithm for multi-frequency observations. He is a member of the NASA Precipitation Measuring Mission Science Team, Member of the ESA MAG of SKIM and EarthCARE, and author or co-author of more than 60 journal peer-reviewed papers.
He will coordinate the activities with the scientists involved in the project with the following responsibilities:

- Focal contact point for all the technical and managerial matters of the project.
- Identification of the project risks, monitoring of them and implementation of the identified mitigation factors.
- Identifications of the deviations with respect to the Management Plan, definition and implementation of the recovery plan.
- Production and distribution of the Minutes of Meetings.

- Monitoring of the resolution and implementation of the action items and recommendations included in the Minutes of Meetings.

The project manager shall be responsible for reporting periodically to the highest level of management of the company the progress of the project. He shall identify and report, the potential problems in the development of the project, in such a way that, in the case of need, the company may react immediately.
Dr Battaglia will be the WP leader for WP1000 (45 mh), WP2200 (45 mh), WP5000 (45 mh) and WP6000 (96 mh) and will provide support in WP2100 (23 mh), WP3100 (23 mh), WP3200 (23 mh), WP3300 (23 mh) and WP4000 (45 mh).
Concerning contractual issues Dr. Brian Berry is the main point of contact.
Dr. Kamil Mroz will be the proposed PDRA working on this project at the University of Leicester. He has been a PDRA in the Radar Group at the University of Leicester for 3 years. He will dedicate 50% of his time in this activity for the entire duration of the project. He is an experienced researcher with strong background in radar meteorology and retrieval analysis. He will be responsible for the forward modelling and the retrieval development, and its testing and application to the airborne datasets and the cloud resolving model scenes. He will be involved in WP1000 (125 mh), WP2100 (50 mh), WP2200 (125 mh), WP3100 (150 mh), WP3200 (100 mh), WP3300 (100 mh), WP 4000 (100 mh) and WP5000 (75 mh).

University of McGill will be Subcontractor.
Prof. Dr. Pavlos Kollias is the lead of the U. of McGill team. Kollias is an International Faculty at the U. of Cologne and Professor at Stony Brook University, NY USA. Kollias supports a broad initiative to develop space-borne and ground-based radar technology and applications expertise at U. of Cologne. Kollias is an international leader in the application of short wavelength radars for cloud and precipitation research from ground-based and space-based platforms. He is the leader of the DOE Atmospheric Systems Research (ASR) radar science group. He is a member of the Mission Advisory Group and algorithm development team of the European Space Agency Earth Clouds Aerosols Radiation Experiment (EARTHCARE) Explorer Mission. He has served as a member at the National Science Foundation Engineering Research Center for the Collaborative Adaptive Sensing of the Atmosphere. Kollias also served for three years (2007-2009) as Associate Chief Scientist for the US DOE Atmospheric Radiation Measurements (ARM) program. His work has been honoured through the Award Canada Research Chair in Radar Application in Weather and Climate Research and in 2013 through the prestigious Humboldt Research Fellowship for experienced researchers. He is author or co-author of 110 journal papers in the areas of millimeter wavelength radar research, cloud and precipitation physics. Dr. Kollias will spend 10 % of his time in this project (in-kind).
Mr. Bernat Puigdomenech Treserras received a BSc in computer engineering with a specialization in software engineering in 2009 from Polytechnic University of Catalonia, Barcelona, Spain. Since then, Mr. Puigdomenech have been working as a research assistant at the Department of Atmospheric and Oceanic Sciences, McGill University. His research interests include: Numerical Weather Prediction, ground-based and space-borne radars, data visualization and development of operational applications and scientific software.

National Research Council Canada (NRC) will be Subcontractor.
Dr. Mengistu Wolde is the overall lead of the NRC team involved in the project. Dr. Wolde is a Senior Research Officer and the leader of the NRC Airborne Environmental Sensing Team. He has over 20 years of experience in participating and/or leading aircraft field campaigns. He gained his PhD in 1999 working on a unique dataset of radar backscatter from ice crystals using the first fast switching 95 GHz polrimeteric airborne radar installed on the University of Wyoming King Air. Since 2005, he has been the NRC Convair-580 facility manager and the lead NRC scientist of the research aircraft. As a lead scientist for the Convair research aircraft, he was the PI for many projects that included the development and integration of the NRC W and X-band Radar (NAWX). For this project, he will be the WP3100 manager and lead the analysis of the in-situ airborne dataset (atmospheric state and cloud microphysics).
Dr. Cuong Nguyen will be responsible for the analysis of the triple-frequency radar in WP3100. He is an Associate Research Officer of the NRC Airborne Environmental Sensing Team. He received a Ph.D in 2013 from the Radar and Communication group at Colorado State University, USA. His research focuses on radar signal processing, radar detection and estimation algorithms, modeling and simulation of radar systems and data quality control. Dr. Nguyen has extensive experience working with both ground based and airborne weather/cloud radar systems. He has participated in many research projects and field campaigns and was granted four US patents in the field of weather radar signal processing.
Dr. Paul Barrett is an experienced airborne research scientist with a Master of Physics degree (MPhys (Hons), 2002) from the University of Sheffield (UK) and Ph.D. (on part time study) from the University of Leeds in 2017. After completing his MPhys., Dr. Barrett worked in the private sector in the UK for four years and then joined the UK Met Office in 2007, where he has been working as a research scientist for the last 11 years. At the UK Met Office, he worked as a mission scientist and instrument specialist for over 100 research flights on the UK Facility for Airborne Atmospheric Measurements (FAAM) BAe 146 and Cessna 421 aircraft. Dr. Barrett is offered a permeant position at NRC and expected to join the NRC Airborne Environmental Sensing Team in November 2018. Paul will be working in the analysis of the aircraft data collected during the RadSnowExp flight campaign focussing on characterization and identification of mixed phase clouds.

CNR-ISAC will be Subcontractor.
Dr. Giulia Panegrossi will lead the CNR unit. She is currently full-time permanent researcher the CNR-ISAC (Cloud and Precipitation Physics Unit) and coordinates and supervises the scientific activity related to development of precipitation retrieval algorithms and operational products based on the exploitation of passive and active microwave (MW) sensors on board LEO operational and research satellites (including MetOP, GPM, JPSS-1, GCOM-W1, CloudSat, EPS-SG). This activity is carried out in the context of national and international projects with focus on global precipitation monitoring and estimation, hydrology, and water cycle assessment (e.g., EUMETSAT H-SAF, FP7 Earth2Observe, Copernicus projects C3S_312b and C3S_511 SQUARE4ECVs, PRIN 20154WX5NA). Other research activities include snowfall, cloud and precipitation microphysics, MW radiative transfer, modelling and observational analysis of heavy precipitation events. As member of the Precipitation Measurement Mission Science

Team, of the EUMETSAT H-SAF Project Team, and of national and international working groups, she promotes and carries out scientific collaborations with different institutions (i.e., NASA, MTU, SSEC-UW-Madison (USA), CTPEC-INPE (Brazil), CNRS (France)).
Other key personnel in the CNR-ISAC team will be ***Dr. Vincenzo Levizzani*** (Director of Research at CNR-ISAC), as well as ***Dr. Elsa Cattani***, ***Dr. Sante Laviola***, and ***Dr. Mario Montopoli*** (full-time Researchers at CNR-ISAC) (see CV section for details).

In addition, the CNR team will contribute to the project with three experts (in-kind): Dr. Paolo Sanò and Dr. Luca Baldini (CNR-ISAC), and Dr. Luca Brocca (CNR-IRPI).
Paolo Sanò (Ph.D.) has been at CNR-ISAC since 2006, first as post-doc, then as term researcher. He is currently responsible for the algorithms development in EUMETSAT H SAF and is the principal developer of the H SAF precipitation retrieval algorithms and operational products for cross-track scanning radiometers (AMSU/MHS and ATMS). He is currently working on surface precipitation estimation from satellite-based passive microwave measurements using neural network approaches. He is also involved in other international collaborations on snowfall monitoring from spaceborne microwave sensors. He is author and co-author of several peer-reviewed publications (see http://www.isac.cnr.it/it/user/1015/biblio for additional information).
Luca Baldini received the Laurea degree in electrical engineering and the Ph.D. degree in Methods and technologies for environmental monitoring from the University of Florence, Florence, Italy, in 1988 and 1994, respectively. In 2001, he joined as Researcher CNR-ISAC, Rome, Italy, where he is in charge of research on radar techniques applied to the characterization of microphysics and quantitative estimation of precipitation, and ground validation of precipitation measurements from satellite-borne sensors. He is member of NASA PMM science team and Mission Advisory Group of EarthCare (http://www.isac.cnr.it/it/users/luca-baldini).
Luca Brocca he is a Researcher at CNR-IRPI of Perugia since 2009. He works on the use of satellite soil moisture and precipitation data for improving hydrological applications related to flood and landslide prediction, water management, rainfall estimation, drought monitoring, erosion modelling, and numerical weather prediction. He recently developed the algorithm, called SM2RAIN, for estimating rainfall from soil moisture data. The SM2RAIN algorithm is (has been) adopted for rainfall retrieval under four ESA projects (SMOS+Rainfall, WACMOS-MED, WACMOS-Irrigation and ESA CCI SM), two EUMETSAT projects (H SAF, Satellite Application Facility on Support to Operational Hydrology and Water Management, and GLOBAL-SM2RAIN) and the NASA's Early Adopter program for SMAP. (http://hydrology.irpi.cnr.it/people/luca-brocca).
In the project Dr. Cattani will lead WP2100, with the contribution by Dr. Levizzani. Dr. Luca Brocca (CNR-IRPI), will also participate to WP2100 as expert (in-kind). They will also contribute to WP2200, and WP4000.
Dr. Panegrossi will contribute to WP1000, WP4000, and WP5000, and will lead WP3200, where the activity will see a strict collaboration and coordination among the CNR scientists and international collaborators involved on the different tasks. In WP3200 Dr. Panegrossi will be responsible for Task 3.2.1, and 3.2.4, and co-responsible for Task 3.2.2 for the work related to conically scanning radiometers. Dr. Sante Laviola will be co-responsible for Task 3.2.2 for the work related to cross-track radiometers (and he will contribute to WP2200 and WP4000). Dr. Mario Montopoli will be responsible for Task 3.2.3 with support from the Univ. of Leicester (Dr. Kamil Mroz) (and will contribute

to WP4000 and WP5000). WP3200 will also benefit from the participation of the three experts (in-kind) in the CNR team, Dr. Paolo Sanò (CNR-ISAC), for Task 3.2.1, and Task 3.2.2, Dr. Luca Baldini, for Task 3.2.3, and Dr. Luca Brocca (CNR-IRPI), for Task 3.2.4.

International Collaborators

International collaborators will also participate to WP3200 (and to other Tasks in the project). Dr. Mark Kulie (MTU, USA, member of the PMM Science Team), already engaged in scientific activities with CNR-ISAC on snowfall observation by active and passive MW sensors since 2015, will be involved in WP3200, as well as WP4000 and WP5000. A Visiting Scientist appointment for Dr. Mark Kulie at CNR-ISAC is planned in the course of 2019. Dr. Simone Tanelli (NASA JPL) will be involved in WP3200 (Task 3.2.1) and in WP 3300. He will provide the first data from the Ka-band Raincube radar. Dr. C. Kidd will be involved in the definition of requirements for precipitation missions (WP1000) and in WP3200.

Dr. Kulie's research interests are primarily associated with snowfall remote sensing using a combination of spaceborne and ground-based sensors. Past research has focused on understanding and properly simulating snowfall scattering signatures observed in combined microwave radiometer (e.g., AMSR-E, MHS, SSM/I, SSMIS) and radar (CloudSat, NEXRAD) observations. His current research focuses on developing global snowfall datasets using spaceborne radar and radiometer products (CloudSat, GPM), creating a global convective snow census (CloudSat), characterizing the seasonal cycle of convective snow (CloudSat), evaluating reanalysis and climate model global snowfall datasets with analogous spaceborne datasets, and GPM radiometer surface snowfall detection using CloudSat and surface radar datasets as ground truth. He also collects ground snow microphysical observations (snow particle type, density, fall speeds, and size distribution) and profiling radar data to characterize microphysical differences associated with different snowfall modes (see also CV section for further details).

Dr. Kidd is currently a Research Scientist within the Earth System Science Interdisciplinary Center at the University of Maryland, located at NASA's Goddard Space Flight Center. His area of expertise focuses upon the retrieval of precipitation from multi-spectral, multi-sensor satellite observations, together with the collection and representation of precipitation from surface observations (both radar and gauges). He has developed a number of retrieval schemes utilizing passive microwave observations and combined passive microwave/infrared observations for global precipitation estimation. His recent work has concentrated upon retrievals from cross-track passive microwave sensors that now make up the bulk of the precipitation capable satellite missions. As a past co-chair of the International Precipitation Working Group he has been heavily involved with the validation of precipitation products, particularly at regional to continental scales using national and international radar and gauge data sets. He has also served on a number of advisory panels and committees for new satellite missions. He has a total of over 65 peer-reviewed journal articles and book chapters, together with over 180 conference presentations.

Dr S. Tanelli has more than 20 years of experience in research and development in information processing for atmospheric remote sensing through active and passive systems and development of new systems and instruments for atmospheric monitoring.

He has been:
PI for APR-2 in SEAC4RS (2013) and CPEX (2017) and for APR-3 in ORACLES (EV-S2, 2015-2019) and CAMP2Ex (2019), responsible for APR-2 suite of processing algorithms since 2003; Project Scientist for RainCube (InVEST, 2015-2018), and Lead Radar Engineer since launch for the Cloud Profiling Radar on CloudSat;
Member of CloudSat and PMM Science Teams and Algorithm Development Working Groups.
Responsible for the development of the experimental module for detection of Multiple Scattering and Non-Uniform Beam Filling conditions in the GPM Dual-Frequency Precipitation Radar Products;
Co-lead of the Radar Studies team within the NASA ACE mission Science Working Group;
PI of the SALMON/USPI DOVE project in support of ESA/JAXA EarthCARE's Doppler radar product development, and member of its JAXA's and ESA's Validation Science Teams;
PI of the NASA Earth Observing System Simulator Suite (NEOS3), an advanced multi-instrument simulator suite targeting mainly ACE, GPM and SMAP missions. Lead Engineer for CloudSat radar operations since launch, responsible for CloudSat's L1B algorithm development, including the surface clutter rejection algorithm, and the Brightness Temperature product.

Dr. Alexei V. Korolev is a Research Scientist in Environment and Climate Change Canada's (ECCC) Meteorological Research Branch. After graduation he started his scientific career at the Research Aircraft Facility of the Central Aerological Observatory in Moscow, where he got his PhD degree in 1989 working on cloud microphysics. In 1994 he joined ECCC and continued working on the fundamental problems of cloud microphysics related to mixed phase systems, entrainment and mixing, liquid and ice clouds. Over the course of his career he participated in 36 field campaigns both as a PI, co-PI or project scientist. He is a renown expert in airborne cloud microphysical insrumentation and data processing. The algorithms, that he develped for 2D image processing have became standards for the cloud physics community. He has also designed several airborne instruments, which are currently used internationally on research aircrafts. He has published over 100 papers in peer reviewed journals and books on cloud microphysics and airborne instrumentation. Dr. Alexei will be contributing to the in-situ micriphysics data analysis that will be used for identification of tripple frequencey radar signatures of the airborne data.

2.1.1.2 Reporting lines within the team

Figure 2.1 illustrates the structure of the consortium and the reporting lines between the team. All team leaders will report directly to Dr Battaglia and will keep him updated about the status of the work and of eventual problems. Dr Battaglia will also receive inputs and feedbacks from the International Collaborators. Apart from normal e-mail exchange project teleconferences will be held on a monthly basis.

2.1.1.3 Time dedication of key personnel

The WP responsibilities and the consortium work share are detailed in Table 2.1.

Table 2.1: Consortium work share. The number of working hours is also indicated. If the number is in square bracket the support does not require funding (in kind). Initials for key personnel: AB=Alessandro Battaglia, BP=Bernat Puigdomènech, CN= Cuong Nguyen, EC=Elsa Cattani, KM=Kamil Mroz, GP=Giulia Panegrossi, LBa=Luca Baldini, LBr=Luca Brocca, MK=Mark Kulie, MM=Mario Montopoli, MW=Mengistu Wolde, PB=Paul Barrett, PK=Pavlos Kollias, PS=Paolo Sano', SL=Sante Laviola, VL=Vincenzo Levizzani.

Uni-Leicester	CNR-ISAC	McGill	NRC
WP 1000: identification of needs/requirements for precipitation space mission (UoL, Battaglia)			
Lead: KM 125; AB 15 [30].	Support: GP 20 [20]; VL 24 [20]; [LBr, MK]	Support: BP 20	
WP 2100: review of the observation techniques (CNR-ISAC, Cattani)			
Support: KM 50; AB 8 [15].	Lead: EC 152; VL 60; [60] [LBr]	Support: BP 56; PK [20]	
WP 2200: review of the status of retrieval/inversion techniques (UoL, Battaglia)			
Lead: KM 125; AB 15 [30].	Support: EC 19; VL 12; SL 22; GP [20] [LBr, PS]		
WP 3100: evaluation of Canadian field campaign dataset (NRC, Wolde)			
Support: KM 150; AB 8 [15].		Support: BP 200; PK [10]	Lead: MW 70; CN 200; PB 131
WP 3200: evaluation of CloudSat/GPM co-located dataset (CNR-ISAC, Panegrossi)			
Support: KM 100; AB 8 [15].	Lead: GP 140 [130]; SL 176 [130]; MM 176 [80]; [MK, LBa, PS, LBr]		
WP 3300: evaluation of RainCube first data and forward modelling of high resolution CRM outputs of convective scenes (McGill, Kollias)			
Support: KM 100; AB 8 [15].		Lead PK [40]; BP: 600	
WP 4000: Preliminary evaluation of mission concepts (McGill, Kollias)			
Support: KM 100; AB 15 [30].	Support: GP 20 [20]; MM 22 [20]; SL 22 [20] ;EC [20] [MK]	Lead: PK [40]; BP: 200	MW 15
WP 5000: Conclusions and recommendations (UoL, Battaglia)			
Lead: KM 75; AB 15 [30].	Support: GP 20 [20]; VL 24 [20]; EC 19 [20]; MM 22 [20]; [PS, MK, LBr LBa]	PK [10]	MW 15
WP 6000: Management and reporting (UoL, Battaglia)			
Lead: AB 32 [64].			
Total working hours			
KM 825; AB 82 [164]	GP 200 [210]; VL 120 [100]; EC 190 [40]; SL 220 [150]; MM 220 [120]	BP 1076; PK [120]	MW 100; CN 200; PB 131

2.1.2 Curricula Vitae

CV: Alessandro Battaglia, PhD

EMPLOYMENT

From April 2013: Associate Professor in Physics, University of Leicester, UK
2009-2013: Lecturer in Physics, University of Leicester, Leicester.
2004-2009: Assistant Professor at the Meteorological Institute, University of Bonn.

TECHNICAL AND CURRENT MANAGERIAL EXPERIENCE

Since 2008: Member of the NASA Precipitation Measuring Missions Science Team
Since 2017: Member of ESA EarthCARE MAG
Since 2017: Member of ESA SKIM MAG
2017-18: Principal Investigator of the ESA project Multi-frequency Radar study.
2014-2019: Principal Investigator of the project NCEO Radiation and Rainfall funded by the UK National Center for Earth Observation.
2018-2020: PI of the project Ice processes in Antarctica: identification via multi-wavelength active and passive measurements and model evaluation funded by US-Department of Energy within the Atmospheric System Research program.
2018:2019: PI of the CEOI grant GRACE (G-band RAdar for Cloud Experiment);
2015-2018: Co-Investigator in the ESA DORSY (Doppler Radar Synergistic Products) focused at preparing the Level2 Doppler Radar products for the EarthCARE mission.

EDUCATION

1998-2000: PhD, Department of Physics, University of Ferrara, Italy
1996: Master Course in Particle Physics, University of Padova, Italy
1992-1996: Laurea in Physics, University of Padova, Italy

PUBLICATIONS (2017 onwards)

1. Battaglia, A., Dhillon, R and A. Illingworth, 2018: Doppler W-band polarization diversity spaceborne radar simulator for wind studies, Atm. Meas. Tech. Disc..
2. D. Watters, Battaglia, A., Mroz, K. , Tridon, F., Validation of the Version-5 Surface Rain Rate Products from the Global Precipitation Measurement Mission Core Observatory over Great Britain and Ireland, accepted in J. Hydrometeorology
3. Wolde, M., Battaglia, A., C. Nguyen, A. L. Pazmany, and A. Illingworth, 2018: Implementation of Polarization Diversity Pulse Pair Technique using airborne W-band radar. Atm. Meas. Tech. Disc., in press.
4. Mroz, K., Battaglia A, Lang, T.J., Tanelli, S., Sacco G., Global Precipitation Measuring Dual-frequency Precipitation Radar observations of hailstorm vertical structure: current capabilities and drawbacks, accepted in J. Appl. Meteor. Climatol.,
5. Illingworth, A. J., Battaglia, A. et al., 2018a: Wivern: A new satellite concept to provide global in-cloud winds, precipitation and cloud properties. Bull.Amer. Met. Soc., doi: 10.1175/BAMS-D-16-0047.1, in press
6. K. Mroz, Battaglia, A., et al., Hail detection algorithm for the GPM core satellite sensors, 2017, J. Appl. Meteor. Climatol., 10.1175/JAMC-D-16-0368.
7. Tridon F., Battaglia, A. and D. Watters, Evaporation in action sensed by multi-wavelength Doppler radars, 2017, JGR: Atmospheres, 10.1002/2016JD025998.
8. Battaglia, A. et al., Characterization of surface radar cross sections at W-band at moderate angles, 2017, DOI: 10.1109/TGRS.2017.2682423 IEEE TGRS.
9. Tridon F. and Battaglia, A., P. Kollias and E. Luke, Rain retrieval from dual-frequency radar Doppler spectra: validation and potential for a midlatitude precipitating case study, 2017, QJRMS, doi:10.1002/qj.3010.

CV: Kamil Mroz, PhD

EDUCATION

Ph. D.	Loughborough University, Department of Mathematical Sciences
2014	Title: Bounds on eigenfunctions and spectral functions on manifolds of negative curvature
M. A.	University of Bialystok
2010	Honours diploma (top 5% of students in university) Subjects: Mathematical Analysis, Statistics, Classical Physics, Mechanics Master's thesis title: Functional Algebras invariant under a fixed map

EMPLOYMENT

July 2015-now	NCEO Radiation and Rainfall Scientist, University of Leicester, Department of Physics and Astronomy
2014-2015	Research Assistant, University of Leicester, Department of Physics & Astronomy, Earth Observation Science,

RESEARCH PUBLICATIONS

2018	Mroz, K., Battaglia A, Lang, T.J., Tanelli, S., Sacco G., Global Precipitation Measuring Dual-frequency Precipitation Radar observations of hailstorm vertical structure: current capabilities and drawbacks, accepted in J. Appl. Meteor. Climatol.,
2018	D. Watters, Battaglia, A., Mroz, K. , Tridon, F., Validation of the Version-5 Surface Rain Rate Products from the Global Precipitation Measurement Mission Core Observatory over Great Britain and Ireland, accepted in J. Hydrometeorology
2017	K. Mroz, A. Battaglia, T. J. Lang, D. J. Cecil, S. Tanelli, F. Tridon: Hail-Detection Algorithm for the GPM Core Observatory Satellite Sensors
2016	A. Battaglia, K. Mroz, T. J. Lang, F. Tridon, S. Tanelli, L. Tian, G. Heymsfield: Using a multi-wavelength suite of microwave instruments to investigate the microphysical structure of deep convective cores: MW observations of convective cores
2015	A. Battaglia, K. Mroz, S. Tanelli, and F. Tridon: Multiple-scattering-induced "ghost echoes" in GPM-DPR observations of a tornadic supercell.
2015	A. Battaglia, S. Tanelli, K. Mroz, and F. Tridon: Multiple scattering in observations of the GPM dual-frequency precipitation radar: evidence and impact on retrievals. J. Geophys. Res., 10.1002/2014JD022866.
2014	K. Mroz and A. Strohmaier, Explicit bounds on eigenfunctions and spectral functions on manifolds hyperbolic near a point, J. London Math. Soc. (2014) 89 (3):917-940. doi: 10.1112/jlms/jdu010

PAVLOS KOLLIAS

Adjunct Professor, Department of Atmospheric and Oceanic Science, McGill University, Montreal Canada
Email: Pavlos.kollias@mcgill.ca
International Faculty, Institute for Geophysics and Meteorology, U. of Cologne, Cologne Germany
Email: pkollias@uni-koeln.de
Professor, Stony Brook University, State University of New York, NY USA
Email: Pavlos.kollias@stonybrook.edu

EDUCATION

1996-2000: Ph.D. in Meteorology, University of Miami.
1994-1996: M.S. in Atmospheric Science, The University of Athens, Greece.
1989-1994: B.S. in Physics, The University of Athens, Greece.

EMPLOYMENT

2016 – present, Adjunct Professor, *McGill University, Montreal Quebec, Canada*
2016 – present Professor, *Stony Brook University, Stony Brook NY*
2016 – present International Faculty, University of Cologne, Cologne Germany
2012 - 2016 Associate Professor and Canada Research Chair, *McGill University, Montreal Canada*
2007 - 2012 Assistant Professor and Canada Research Chair, *McGill University, Montreal Canada*
2005 - 2007 Associate Scientist, *Brookhaven National Laboratory, Upton NY*
2004 - 2005 Assistant Scientist, *University of Miami,*
2003 - 2004 Visiting Fellow Scientist, *University of Colorado*, *Boulder CO*
2002 - 2003 Assistant Scientist, *University of Miami, Miami FL*
2001 - 2002 Postdoctoral Associate, *University of Miami, Miami FL*

ACTIVITIES and ASSOCIATIONS

Observer, Mission Advisory Group, Phase D/E, ESA EarthCARE mission, 2017-present
Director, Center for Multiscale Applied Sensing, Brookhaven National Laboratory 2017-present
Member, User Executive Committee, Atmospheric Radiation Measurements program, 2015-present
Leader, Radar Science Group, DOE Atmospheric Systems Research program 2012-present
Member, Mission Advisory Group, Phase C/D, ESA EarthCARE mission, 2012-2017
Associate Editor, AGU Journal of Geophysical Research – Atmospheres, 2012-present
Adjunct Associate Professor, University of Miami, 2011-present
Associate Partner, Initial Training for atmospheric Remote Sensing (ITaRS), 2014-2016
Chair, AMS Committee on Radar Meteorology, 2010-2012
Leader, Vertical Velocity for Climate Modelers Group, DOE/ARM program, 2008-2012
Associate Chief Scientist, DOE Atmospheric Radiation Measurement program, 2007-2009
Member, Executive Committee, National Science Foundation Engineering Research Center on the Collaborative Adapting Sensing of the Atmosphere (CASA), 2008-2012

AWARDS
2013-2014: Humboldt Research Fellowship for experienced researchers

2012-2017: Canada Research Chair in Radar Applications in Weather and Climate
http://www.chairs-chaires.gc.ca/chairholders-titulaires/profile-eng.aspx?profileID=2210
2007-2012: Canada Research Chair in Radar Applications in Weather and Climate
2003-2004: Visiting Scientist Fellowship, Cooperative Institute for Research in Environmental Sciences, University of Colorado

SELECTED RELEVANT PUBLICATIONS

Burns D, **Kollias P**, Tatarevic A, **Battaglia A**, Tanelli S, The Performance of the EarthCARE Cloud Profiling Radar in Marine Stratiform Clouds, 2016, J. Geoph. Res. Atm., in press.

Illingworth A., et al., 2014: THE EARTHCARE SATELLITE: The next step forward in global measurements of clouds, aerosols, precipitation and radiation. Bull. Amer. Meteor. Soc., 96: 2015. doi: 10.1175/BAMS-D-12-00227.1.

Kollias, Pavlos, Simone Tanelli, Alessandro Battaglia, Aleksandra Tatarevic, 2014: Evaluation of EarthCARE Cloud Profiling Radar Doppler Velocity Measurements in Particle Sedimentation Regimes. *J. Atmos. Oceanic Technol.*, **31**, 366–386. doi: http://dx.doi.org/10.1175/JTECH-D-11-00202.1

Kollias P., N. Bharadwaj, K., Widener, I., Jo and K., Johnson, 2013: Scanning ARM Cloud Radars – Part I: Operational Sampling Strategies. Online release, Journal of Atmospheric and Oceanic Technology 2013; e-View doi: http://dx.doi.org/10.1175/JTECH-D-13-00044.1

Kollias P., I. Jo P. Borque P., A. Tatarevic, K. Lamer, N. Bharadwaj, K., Widener, K., Johnson and E. Clothiaux 2013: Scanning ARM Cloud Radars – Part II: Data Quality Control and Processing. Online release, Journal of Atmospheric and Oceanic Technology 2013; e-View doi: http://dx.doi.org/10.1175/JTECH-D-13-00045.1

Kneifel, S., A.von Lerber, J. Tiira, D. Moisseev, **P. Kollias**, and J. Leinonen (2015), Observed relations between snowfall microphysics and triple-frequency radar measurements. J. Geophys. Res. Atmos., 120, 6034–6055. doi:10.1002/2015JD023156

Sy O. O., S. Tanelli, N. Takahashi, Y. Ohno, H. Horie, and **P. Kollias**, 2013: Simulation of EarthCARE Spaceborne Doppler Radar Products using Ground-based and Airborne Data: Effects of Aliasing and Non-Uniform Beam-filling. IEEE Transactions on Geoscience and Remote Sensing, 99 doi: 10.1109/TGRS.2013.2251639

Battaglia, Alessandro, Simone Tanelli, **Pavlos Kollias**, 2013: Polarization Diversity for Millimeter Spaceborne Doppler Radars: An Answer for Observing Deep Convection?. *J. Atmos. Oceanic Technol.*, **30**, 2768–2787.doi: http://dx.doi.org/10.1175/JTECH-D-13-00085.1

Battaglia, A. and **P. Kollias**, 2014: Impact of Receiver Saturation on Surface Doppler velocity measurements from the EarthCARE Cloud Profiling Radar, IEEE Transactions on Geoscience and Remote Sensing.

Battaglia, A. and **P. Kollias**, 2014: Using ice clouds for mitigating the EarthCARE Doppler radar mispointing, IEEE Transactions on Geoscience and Remote Sensing.

Bernat Puigdomènech Treserras

McGill University / Department of Atmospheric and Oceanic Sciences
805 Sherbrooke Street West
Burnside Hall, room 825
Montreal, Quebec H2J 2R2, CANADA
E-mail: bernat.ptreserras@mcgill.ca

Education

2009: B.S. in Computer Engineering followed by a 2-year Software Engineering specialization
Polytechnic University of Catalonia, Barcelona, Spain

Professional Experience

Mr. Puigdomenech is currently a senior research assistant at the McGill clouds group, McGill University, Montréal, Canada. His research involves the use of radars in atmospheric sciences (Numerical Weather Prediction, ground-based and space-borne radars), data visualization software and development of operational applications. He has been involved in a very diverse set of projects including:

- Development of a satellite simulator suitable for model validation and data assimilation
- Evaluation of the NASA GPM Dual-Frequency Precipitation Radar data for precipitation studies
- Probabilistic nowcasting of precipitation using “Analogues”
- Rainfall attractors and predictability
- Study of the contamination of radar data by windmills and other ground echoes
- Development of a ground-based radar simulator for model validation, data assimilation and radar data quality
- Contributions on the development of the Mesoscale Analysis System (MAS)
- Attenuation correction and calibration of the Parana C-band weather radar (Argentina)
- Evaluation of attenuation correction techniques using C-band simulated reflectivity
- Ensemble retrievals of rain parameters from radar measurements
- Radar reflectivity calibration from differential phase measurements
- Study of the scale-dependent performance of the Velocity Echo Tracking (VET) algorithm
- Improving the performance of VET during snow lake effect events
- Post-processing model-predicted rainfall fields in the spectral domain using phase information from radar observations
- Study of a precipitation nowcasting algorithm based on phase information from radar observations
- Evaluation of the MAPLE and WRF optimum forecast blending technique

- Evaluation of various techniques to produce a better radar Constant Altitude Plan Position Indicator
- Exploration of the time-space 3D autocorrelation function of reflectivity radar data

Mr. Puigdomenech has developed several widely-used software packages:

Profilers: Specialized software to analyze and visualize data from several meteorological instruments and numerical weather prediction models; McGill S, X and W- band radars,POSS, Parsivel and Thies disdrometers, WRF and MAS data, MAPLE nowcasts, etc.
MeteosViss: Portable version of Profilers adapted to visualize data from the C-band weather radar network of MeteoSwiss.
IDLCpuPM: Open Source library for parallel processing under IDL https://github.com/bernatp3rs/idl_cpu_pm/wiki
radar.mcgill.ca: JS Marshall Radar Observatory website

and has software contributions to the following:

SIGMA Specialized Geographic Information System (GIS) customized to analyze and visualize meteorological information (radar, satellite, ground-based sensors and NWP data)
GenRad Generation of processed products from the MeteoSat satellite and the MM5 model
HydroVis Interactive hydrological flood detection system based on weather radar data
MAPLE Code refactoring, operational display and improvement of the operational Mcgill Algorithm for Precipitation nowcasting by Lagrangian Extrapolation

His technical skills include advance programming in IDL, Java, C, C++, Fortran, Python, bash scripting, parallel programming OpenMP and MPI. He is familiar with HTML + Javascript, PHP, CMS (WordPress, Joomla), the Exist and SQL data bases and the following computer applications: Eclipse, Rational Rose, ArcGIS, Illustrator and most common productivity packages and most operating operating systems (Windows, OS X, GNU/Linux).

CV: Mengistu, PhD

Education

1999 Ph.D. Atmospheric Science, University of Wyoming, Laramie, WY, USA
1996 M.Sc. Atmospheric Science, University of Wyoming, Laramie, WY, USA
1992 Co-op post-graduate training in satellite-based rainfall estimation, University of Reading, UK
1987 Post-Graduate Diploma in Meteorology, Indian Meteorological Department, Pune, India

Professional Experience

2014 - Present NRC Flight Research Laboratory, Airborne Environmental Sensing Research Team Leader
2005 - Present NRC Convair-580 Facility Manager, Ottawa, Canada
2000 - Present Research Scientist, Flight Research Laboratory, NRC, Ottawa, Canada
1987 – 1993 Meteorologist, Ethiopian National Meteorological Service Agency, Addis Ababa, Ethiopia

Project Management

2000-Present Principal Investigator, Co-PI and/or NRC Project Leader for over 20 major collaborative airborne atmospheric project flight campaigns using the NRC Convair-580 (> 1000 hours Atmospheric Project Flights) that included:
Buffalo Area Icing Research Study – Weather Radar Verification Project (2017-2018): Project focussed on characterization of radar signatures of supercooled, mixed phase and glaciated cloud (NRC Project Lead). Partnerships with MIT, FAA & ECCC;
ESA Doppler Wind Radar Demonstrator Project (2016-2018), PI airborne campaign (~90h).
High Altitude Ice Crystal – High Ice Water Content Project (2015-2016) - Co-PI – International Project aimed to characterize structure, processes and remote sensing signatures of high concentrations of ice crystals in Tropical Convective Clouds (~90 hours);
Global Precipitation Measurement (GPM) mission Cold Season Precipitation Experiment - GCPEx (2011-2012) - Great Lakes and Ontario (~30 hours) – NRC Convair PI;
Indirect and Semi-Direct Aerosol Campaign – ISDAC (2007-2008) ~ Barrow, Alaska (120 hours) – NRC Project Lead
Storm Study in the Arctic – STAR (2007) – Canadian Arctic – Operation at Iqaluit (~70 h)
Canadian CloudSat and CALIPSO Validation Project – C3VP (2006-2007) (~100 flight hours) – NRC Lead and NAWX radar PI

Publications (2018)

Wolde M., A. Battaglia, C. Nguyen, A. L. Pazmany, and A. Illingworth, 2018: Implementation of Polarization Diversity Pulse Pair Technique using airborne W-band radar, *submitted to AMT.*
Illingworth et. Al., 2018, WIVERN: A new satellite concept to provide global in-cloud winds, precipitation and cloud properties, BAMS
Baray, S., Darlington, A., Gordon, M., Hayden, K. L., Leithead, A., Li, S.-M., Liu, P. S. K., Mittermeier, R. L., Moussa, S. G., O'Brien, J., Staebler, R., Wolde, M., Worthy, D., and McLaren, R.: Quantification of methane sources in the Athabasca Oil Sands Region of Alberta by aircraft mass balance, Atmos. Chem. Phys., 18, 7361-7378, https://doi.org/10.5194/acp-18-7361-2018, 2018.
Baibakov, K., M. Wolde, C. Nguyen, A. Korolev and I. Heckman, 2018: Retrievals of ice-water content from an airborne elastic lidar in tropical convective clouds: EPJ Web Conf., 176 (2018) 05051; DOI: https://doi.org/10.1051/epjconf/201817605051
Qu, Z., H. Barker, A. V. Korolev, J. A. Milibrandt, I. Heckman, S. Belair, S. Leroyer, P. A. Vaillancout, M. Wolde, A. Schwarzenbock, D. Leroy, J. W. Strapp, J. N. S. Cole, L. Nguyen, A. Heidinger, 2018: Evaluation of a high-resolution NWP models.

CV: Cuong Nguyen, PhD

Education
2013 Ph.D. Electrical and Computer Engineering, Colorado State University, CO, USA
2007 M.Sc. Electrical and Computer Engineering, Colorado State University, CO, USA
2001 B.Eng. Electronic and Telecommunication, Hanoi University of Technology, Hanoi, Vietnam

Professional Experience
2015-Present Research Officer, Flight Research Laboratory, NRC, Ottawa, Canada
2013-2015 Research Scientist, Electrical and Computer Engineering, Colorado State University, CO, USA
2001-2004 Department of Telecommunication I, Post and Telecommunications Institution of Technology, Hanoi, Vietnam

Project Management
2017 - present CP140 Airborne Radar Support Environment (CARSE)
2015 - present European Space Agency Doppler Wind Radar Demonstrator
2016 - present FAA/NASA Study of Polarimetric Radar Signature of HIWC
2016 - present NRC Airborne Milimeter Imaging Radar Study

RESEARCH PUBLICATIONS (*2015 onwards*)

2018 Cuong M. Nguyen, Mengitsu Wolde and Alexei Korolev: Determination of Ice Water Content (IWC) in tropical convective clouds from X-band dual-polarization airborne radar, *to be submitted to AMT, 2018*

2018 Wolde M., Alessandro Battaglia, Cuong Nguyen, Andrew L. Pazmany, and Anthony Illingworth: Implementation of Polarization Diversity Pulse Pair Technique using airborne W-band radar, *submitted to AMT, 2018*

2017 Cuong M. Nguyen and V. Chandrasekar: An electronic scanning strategy for phased array weather radar using a space-time characterization model, *J. Atmos. Oceanic Technol.*, Vol. 34, No 4, 921-938, 2017.

2017 Battaglia A., Mengistu Wolde, Leo D'Adderio, Cuong Nguyen, Franco Fois, Anthony Illingworth, Rolv Midthassel: Characterization of surface radar cross sections at W-bad at slant angles, IEEE Transactions on Geoscience and Remote Sensing, *IEEE Transactions on Geoscience and Remote Sensing*, 2017.

2016 Si-Chee Tsay, Hal B. Maring, Neng-Huei Lin, Sumaman Buntoung, Somporn Chantara, Hsiao-Chi Chuang, ..., Cuong Nguyen, ..., Ming-Cheng Yen: Satellite-surface perspectives of air quality and aerosol-cloud effects on the environment: An overview of 7-SEAS/BASELInE, *Aerosol and Air Quality Research*, Vol. 16: 2581–2602, 2016..

2016 Adrian M. Loftus, Si-Chee Tsay, Peter Pantina, Cuong Nguyen, Philip M. Gabriel, Xuan A. Nguyen, Andrew M. Sayer, Wei-Kuo Tao, and Toshi Matsui: Coupled Aerosol-Cloud Systems over Northern Vietnam during 7-1 SEAS/BASELInE: A Radar and Modeling Perspective, *Aerosol and Air Quality Research*, Vol. 16, 2768-2785, 2016.

2015 Cuong M. Nguyen and V. Chandrasekar: Polarimetric variables retrieval with clutter suppression for staggered PRT sequences, *JAOT*, Vol. 32, No 4, 2015.

CV: Dr. Paul Barrett

Cloud Physics Research Scientist

Employment History

2007 – present UK Met Office - Observational Based Research: Cloud Physics Research Scientist,

2003 – 2007 A.H Allen Ltd: Asbestos fibre analysis and monitoring using phase contrast microscopy, QC scheme administration, CCD microscope camera development

2003 Kelan Circuits: Printed Circuit Board Manufacture, design, manufacturing, testing.

Education

2012 – 2017 The University of Leeds, UK (part time study)
Institute for Climate and Atmospheric Science
PhD Turbulence and Ice Nucleation in Mixed Phase Mid-Latitude Altocumulus Clouds

1998 – 2002 The University of Sheffield, UK Department of Physics and Astronomy
Physics MPhys (Hons) 2:1 4 year integrated masters undergraduate degree,
Research Project: "Toxic gas detection using Langmuir-Blodgett Thin Films of Porphyrin-Calixarene."
Manufacturing of test slides in clean-room conditions, and testing their IR absorption properties in
presence of reference gases using spectrophotometer.

SKILLS / EXPERIENCE

- Airborne observations of cloud and aerosol microphysics and bulk properties, and radiative properties.
- Analysis of large observational datasets in order to understand physical processes. Application of
  current techniques and development of new calibration and analysis methods.
- Running of large numerical models and analysis of numerical model output, from global to regional
- Numerical Weather Prediction, and high resolution Large Eddy Simulations model.

Publications

Paul Alan Barrett, *PhD Thesis*: Turbulence and Ice Nucleation in Mixed-Phase Altocumulus Clouds in the Mid-Latitudes, Institute for Climate and Atmospheric Science, University of Leeds, **2017**

Paul Barrett, Paul Field, Piers Buchannan, Claire Bartholomew: The Ability of the Met Office Unified
Model (2.2km) to Represent Regions of High Ice Water Content, Met Office Internal Report, **2017**

Paul Barrett, Local airflow properties particle shadow zones at location of new Counterflow Virtual Impactor inlet location. Met Office Report, **2015**

Abel, S. J., Cotton, R. J., **Barrett, P. A.**, and Vance, A. K.: A comparison of ice water content measurement techniques on the FAAM BAe-146 aircraft, Atmos. Meas. Tech., 7, 3007-3022, https://doi.org/10.5194/amt-7-3007-2014, **2014**.

Allen, G., Coe, H., Clarke, A., Bretherton, C., Wood, R., Abel, S. J., **Barrett, P.**, Brown, et. al., South East Pacific atmospheric composition and variability sampled along 20° S during VOCALS-Rex, Atmos. Chem. Phys., 11, 5237-5262, doi:10.5194/acp-11-5237-2011, **2011**.

Steve Abel, **Paul Barrett,** David Walters, Ian Boutle, Jane Mulcahy:, Impact of High Resolution Models on the Representation of Boundary Layers during VOACLS-Rex in the South Eastern Pacific, Met Office
Internal Report, **2010**

CNR Team

CV: Dr. Giulia Panegrossi (CNR-ISAC)

EMPLOYMENT

December 2011-present: Researcher at ISAC-CNR U.O.S. of Rome Via del Fosso del Cavaliere 100, 00133 Rome Italy: remote sensing of clouds and precipitation, development and validation of passive microwave precipitation retrieval algorithms for global precipitation monitoring, and hydrological applications.

Sept. 2008 - Dec. 2011: Research contractor at HIMET (c/o CETEMPS), Via Vetoio, Coppito, 67100 L'Aquila, Italy

Sept. 2004 - Sept. 2005: Environmental Satellite Data Specialist at the Mediterranean Agency for Remote Sensing and Environmental Control (MARSec), Villa dei Papi, Benevento, Italy

Jan. 2000 – Apr. 2004: Research Assistant at the Department of Atmospheric and Oceanic Sciences, University of Wisconsin-Madison, 1225 W. Dayton St., 53711 Madison, WI, USA.

Jan. 1997-Jan. 2000: Research fellowship from the NASA "Earth System Science Fellowship Program"

Apr. 1994 – Dec. 1996: Research fellowship at the Institute of Atmospheric Physics/CNR in Frascati, Italy (supervisor, Dr. Alberto Mugnai): fellowships from Fondazione per la Meteorologia Applicata, funded by the European Space Agency (ESA) (1994-1996); Earth Physics Committee of CNR (Italy (N. 201.02.49, Code 21.02.04 and N. 201.02.48, Code 21.02.02) (1996-1997)

Mar. 1993 – Apr. 1994: Research contractor at the Department, of Physics Sapienza University of Rome, P.le Aldo Moro 2, 00195 Rome, Italy. Advisor: Prof. G. Fiocco,

EDUCATION

May 2004: Ph.D. at the Department of Atmospheric and Oceanic Sciences, University of Wisconsin-Madison, 1225 W. Dayton St., 53711 Madison, WI, USA. Advisor Prof. G. Tripoli.

Feb. 1993: Degree (Laurea with honor) in Physics, Physics Department, Sapienza University of Rome, P.le Aldo Moro 2, 00195 Rome, Italy. Advisor: Prof. G. Fiocco

MAIN PROJECTS

2018-2021: C3S_312b: "Essential Climate Variable (ECV) products derived from observations Lot 1: precipitation, surface radiation budget, water vapour, cloud properties, and Earth radiation budget" she leads the Precipitation ECV Climate Data Record generation

2017-2022: EUMETSAT Satellite Application Facility on Support to Operational Hydrology and Water Management (HSAF) CDOP-2 (2012-2017) and CDOP-3 (2017-2022): Member of the Project Team and of the Precipitation Product development team.

2017-2021: SQUARE4ECVs Scientific Quality Assessment and Report for Essential Climate Variables (ECVs) - Copernicus Climate Change Service (C3S-511) Quality Assessment of ECV products (2017-2021). Staff

2014-2017: Earth2Observe "Global Earth Observation for Integrated Water Resource Assessment" DG Research FP7 project (2014-2017). Staff.

2017-2020: PRIN 2015 "Reconciling precipitation with runoff: the role of understated measurement biases in the modeling of hydrological processes" (2017-2020): Co-PI. Responsible of CNR-ISAC Research Unit and leader of WP 5.

2015-2017: H-SAF Federated Activity between CNR-ISAC and the PMM science Team "Cooperation on the use of combined spaceborne active and passive MW observations for precipitation retrieval" 2015-present. PI

2017: H-SAF Federated Activity between CNR-ISAC, DPC (Italy), CPTEC/INPE (Brazil), and CNRS-GET (France) "Assessment of ground-reference data in Brazil and validation of the H-SAF precipitation products in the perspective of CDOP-3" (2017). Co-PI

TEACHING EXPERIENCE

March 2017: Invited Lecturer for DIPLOMAZIA 2; Science and Knowledge for Diplomacy, sponsored by CNR, Cooperazione Italiana allo Sviluppo, Agenzia Italiana per la Cooperazione allo Sviluppo. Title: Remote Sensing of Precipitation from Space.

4-8 May 2015: Invited Lecturer at the Satellite Meteorology course sponsored by EUMETSAT at CPTEC/INPE in Cachoeira Paulista, Brazil: "Passive microwave precipitation retrieval within H-SAF: potentials, challenges, applications, and future perspectives" (Ref. Invitation letter from Dr. Daniel Vila, Chief of Satellite and Environmental Systems Division at CPTEC/INPE, Brazil, daniel.vila@cptec.inpe.br)

1-5 December 2014: Lecturer at Eumetrain Event Week: Droughts, Floods and Landslides Session 7: Satellite Precipitation products and Application (Ref. email from Magg. Davide Melfi Science Coordinator of the EUMEUSAT H-SAF, October 17, 2014)

14-18 July 2014: Lecturer at EUMETSAT International remote sensing school for hydrological applications 2014: "H-SAF products application for hydrological risk management" (Ref. email from H-SAF Project Manager announcing the school 4 June 2014 and Agenda of the courses available at http://training.eumetsat.int/course/view.php?id=225

Organisational / managerial skills

Within the EUMETSAT H-SAF she coordinates and supervises the development and delivery of operational precipitation products exploiting all current and future microwave radiometers on board LEO satellites, and of combined GEO IR/LEO MW operational products for hydrological applications and precipitation monitoring. As member of the NASA PMM Science Team and as PI of a Federated Activity project between H-SAF and the PMM science Team members she coordinates scientific activities related to development and refinement of satellite precipitation products with focus on mid-high latitudes. Within the Copernicus Climate Change Servis (C3S) *312b* she leads the Precipitation ECV Climate Data Record generation (global daily and monthly mean precipitation estimate) based on passive microwave long-term Level 1 data record. Within the C3S_511, *SQUARE4ECVs,* she is member of the Planned Thematic Assessments and Quality Briefs working group. As Co-PI of a national PRIN 2015 funded project (2017-2020) she is responsible of CNR-ISAC Research Unit and leader of WP 5 (*Improvement of areal rainfall estimates based on integration of radar, raingauges, and satellite sources*). Within the *Earth2Observe DG Research FP7 project (2014-2017)* she supervised development and delivery of satellite precipitation products from space-borne passive microwave radiometers. Supervisor of the H-SAF Visiting Scientist Activity "*Verification study over West Africa of PMW precipitation products using X-pol radar observations* and rain gauges". Coordinated the activity and interactions between CPTEC/INPE, CNRS/IRD, CNR-ISAC and DPC within the H-SAF Federated Activity "*Assessment of ground-reference data in Brazil and validation of the H-SAF precipitation products in the perspective of CDOP-3*".

Honours, Awards, Memberships

Member of the NASA Precipitation Measurement Mission (PMM) Science Team (2014-present)
Member of the European Geophysical Union (2012-present)
Member of CDOP3-HSAF Project Team (2017-2022)
Schwerdtfeger Award at the Department of Atmospheric and Oceanic Sciences of the University of Wisconsin-Madison (1998)
NASA RHG Exceptional Achievement for Science Team – GPM Ground Validation Team (2015)

BIBLIOMETRIC REFERECNES

Google Scholar: https://scholar.google.it/citations?user=aUf4kpUAAAAJ&hl=it&oi=ao
Orcid: http://orcid.org/0000-0002-5170-7087
https://www.scopus.com/authid/detail.uri?authorId=6602865544
WoS ReasercherId: http://www.researcherid.com/rid/C-5702-2015

SELECTED PUBLICATIONS

1. Milani, L., M. Kulie, D. Casella, S. Dietrich, T. L'Ecuyer, G. Panegrossi, F. Porcu', P. Sano', N. Wood, CloudSat Snowfall Estimates over Antarctica and the Southern Ocean: An Assessment of Independent Retrieval Methodologies and Multi-Year Snowfall Analysis, Atmos. Res., *in press*
2. Panegrossi G., J-F. Rysman, D. Casella, A. C. Marra, P. Sanò, and M. S. Kulie, CloudSat-based assessment of GPM Microwave Imager snowfall observation capabilities, Rem. Sensing, 9(12), 1263; doi:10.3390/rs9121263, 2017.
3. Casella, D., Panegrossi G., Dietrich S., Marra A.C., Sanò P., M. S. Kulie, B. T. Johnson, Evaluation of the GPM-DPR snowfall detection capability: comparison with CloudSat, Atmos. Res., 197, 64-75, doi :10.1016/j.atmosres.2017.06.018, 2017
4. Marra A. C., F. Porcu', L. Baldini, M. Petracca, D. Casella, S. Dietrich, A. Mugnai, P. Sanò, G. Vulpiani, G. Panegrossi, Observational analysis of an exceptionally intense hailstorm over the Mediterranean area: Role of the GPM Core Observatory, Atmos. Res., 182, 72-90, doi: 10.1016/j.atmosres.2017.03.019, 2017
5. Casella D., L. M. Amaral, S. Dietrich, A. C. Marra, P. Sanò, and G. Panegrossi, The Cloud Dynamics and Radiation Database algorithm for AMSR2: exploitation of the GPM observational dataset for operational applications, IEEE J. of Sel. Topics in Appl. Earth Obs. and Rem. Sens. (J-STARS), 10(*8), DOI :* 10.1109/JSTARS.2017.2713485, *2017*
6. Ciabatta L., Marra A. C., Panegrossi G., Casella D., Sanò P., Dietrich S., Massari C., Brocca L., Daily precipitation estimation through different microwave sensors: Verification study over Italy, J. of Hydrology, 545, 436-450, doi: 10.1016/j.jhydrol.2016.12.057, 2017.
7. Sanò, P., Panegrossi, G., Casella, D., Marra, A. C., Di Paola, F., and Dietrich, S.: The new Passive microwave Neural network Precipitation Retrieval (PNPR) algorithm for the cross-track scanning ATMS radiometer: description and verification study over Europe and Africa using GPM and TRMM spaceborne radars, Atmos. Meas. Tech., 9, 5441-5460, doi:10.5194/amt-9-5441-2016, 2016.
8. Panegrossi G., D. Casella, S. Dietrich, A. C. Marra, M. Petracca, P. Sanò, A. Mugnai, L. Baldini, N. Roberto, E. Adirosi, R. Cremonini, R. Bechini, G. Vulpiani, and F. Porcù: Use of the GPM constellation for monitoring heavy precipitation events over the Mediterranean region, IEEE J. of Sel. Topics in Appl. Earth Obs. and Rem. Sens. (J-STARS), Volume 9, Issue 6, Pages: 2733 - 2753, doi: 10.1109/JSTARS.2016.2520660, 2016. IF (2015)
9. Casella, D., Panegrossi, G., Sanò, P., Milani, L., Petracca, M., and Dietrich, S.: A novel algorithm for detection of precipitation in tropical regions using PMW radiometers, Atmos. Meas. Tech., 8, 1217-1232, doi:10.5194/amt-8-1217-2015, 2015.
10. Sanò, P., Panegrossi, G., Casella, D., Di Paola, F., Milani, L., Mugnai, A., Petracca, M., and Dietrich, S.: The Passive microwave Neural network Precipitation Retrieval (PNPR) algorithm for AMSU/MHS observations: description and application to European case studies, Atmos. Meas. Tech., 8, 837-857, doi:10.5194/amt-8-837-2015, 2015.

CV: Dr. Vincenzo Levizzani (CNR-ISAC)

Dr. Vincenzo Levizzani is Director of Research and Head of the CNR-ISAC Clouds and Precipitation Physics Division (CAPE) consisting of 30 personnel units. The research interests of Dr. Levizzani are: structure of precipitating systems; physics of intense storms using radar and satellites; satellite precipitation estimation; severe weather analysis; climatology of precipitation.

Main international activities:

Visiting Scientist at the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) (1998-2001).

Member - Working Group on Data Management and Analysis (WGDMA) of the Global Energy and Water Cycle Experiment (GEWEX) of the World Climate Research Programme (WCRP), a program of the World Meteorological Organization (WMO) (2000-2004).

Chairman - Applications Expert Group on Nowcasting and Very Short Range Forecasting for EUMETSAT's Meteosat Third Generation (2001-2002).

Chairman and founder - International Precipitation Working Group (IPWG) of the Coordination Group for Meteorological Satellites (CGMS), sponsored by WMO (2001-2004).

Member - European Commission-NASA Earth Science Working Group (2001).

Member – Advisory Council, European Severe Storms Laboratory (ESSL) (2002-2016).

Member - International Commission on Clouds and Precipitation (ICCP) of the International Association of Meteorology and Atmospheric Sciences (IAMAS) (2004-2012).

Chairman - WCRP-GEWEX Working Group on Precipitation Radar Networks (WGPRN) (2006-2013).

Chairman - Scientific Application Group, METimage sensor EUMETSAT Post EPS satellite (2009-present).

Member - GEWEX Hydroclimatology Panel (2011-2013).

Member - Mission Advisory Group, Geosounder mission of the European Space Agency (ESA) (2013-present).

Member - WMO's Commission on Atmospheric Sciences (CAS) (2013-2015).

Co-Chairman, GK-2A Satellite Algorithm Review Team, Korean Meteorological Administration (KMA) (2015 -present).

Member of the American Meteorological Society Hydrologic Research Awards Committee (2015-2018)

Italian National Delegate with the WMO Commission on Atmospheric Sciences (CAS) (2017-present).

Memberships of scholarly societies:

American Meteorological Society (AMS), American Geophysical Union (AGU), European Geosciences Union (EGU). Fellow of Royal Meteorological Society (FRMetS).

Reviewing activities:

Adv. Geosci., Adv. Water Resources, Aerobiologia, Annales Geophysicae, Atmos. Environment, Atmos. Res., Geophys. Res. Lett., IEEE Trans. Geosci. Remote Sens., Int. J. Environment and Pollution, J. Atmos. Oceanic Technol., J. Appl. Meteor. Climatol., J. Geophys. Res., J. Hydrology, Meteor. Atmos. Phys., Mon. Wea. Rev., Quart. J. Roy. Meteor. Soc., Remote Sens. Environ., Tellus. Associate Editor of *Atmospheric Research.*

Member of review boards for: CONICET, ESA, EUMETSAT, Italian Space Agency (ASI), NASA, NCAR, NOAA, NRL, South African National Research Foundation, Space Research Organization Netherlands (SRON), UK Natural Environment Research Council (NERC), World Meteorological Organization (WMO), and many Universities worldwide.

National and international projects:

Italian coordinator of the field activities within the Mesoscale Alpine Programme (MAP) and member of the MAP-Coordination and Implementation Group.
Coordinator of CNR bilateral projects with CONICET (Argentina), KOSEF (Korea) and MOS (Israel).
Coordinator of projects: ASI, National Group for the Prevention of Hydrogeological Disasters (GNDCI), ESA, EUMETSAT.
Coordinator of the EURAINSAT project and partner of the MUSIC, CARPE DIEM, RISKAWARE, RISKMED, ANTISTORM, GLOWASIS and eartH2Observe of the 5th, 6th and 7th Framework Programmes of the European Commission.

Teaching:

Visiting Professor at the Universidad Nacional de Cordoba (Argentina), Univ. of Urbino, ARPA Emilia-Romagna, Univ. of Firenze, Univ. of L'Aquila.
Professor of Satellite Meteorology, Master in Applied Meteorology, Univ. of Bologna.
Professor of Cloud Physics, Dept. of Physics, Univ. of Bologna (2004-present).
Tutor of 36 degree theses in Atmospheric Physics and Meteorology (Univ. of Bologna), 4 PhD theses (Univ. of Bologna and Evora).

Publications.

Author of **85** papers on international peer-reviewed journals, **99** papers on international conference proceedings, **7** papers on popular journals, **47** invited presentations at international conferences, **116** presentations at international conferences without published paper, **41** papers on national journals and national conference proceedings, **31** scientific reports, **29** contributions to books, **2** times book editor.

5 representative recent publications (last five years)

Beck, H. E., A. I. J. M. van Dijk, **V. Levizzani**, J. Schellekens, and A. de Roo, 2017: MSWEP: 3-hourly 0.25° global gridded precipitation (1979-2014) by merging gauge, satellite, and reanalysis data. *Hydrol. Earth Syst. Sci.*, **21**, 589-615, doi:10.5194/hess-21-589-2017.

Cattani, E., A. Merino, and **V. Levizzani**, 2016: Evaluation of monthly satellite-derived precipitation products over East Africa. *J. Hydrometeor.*, **17**, 2555-2573, doi:10.1175/JHM-D-0042.1.

Kucera, P. A., E. Ebert, F. J. Turk, **V. Levizzani**, D. Kirschbaum, F. J. Tapiador, P. Xiang, A. Loew, and M. Borsche, 2013: Precipitation from space: Advancing Earth system science. *Bull. Amer. Meteor. Soc.*, **94**, 365-375.

Levizzani, V., C. Kidd, K. Aonashi, R. Bennartz, R. R. Ferraro, G. J. Huffman, R. Roca, F. J. Turk, and N.-Y. Wang, 2018: The activities of the International Precipitation Working Group. *Quart. J. Roy. Meteor. Soc.*, doi:10.1002/qj.3214.

Tapiador, F. J., A. Navarro, **V. Levizzani**, E. García-Ortega, G. J. Huffman, C. Kidd, P. A. Kucera, C. D. Kummerow, H. Masunaga, W. A. Petersen, R. Roca, J.-L. Sánchez, W.-K. Tao, and F. J. Turk, 2017: Global precipitation measurements for validating climate models. *Atmos. Res.*, **197**, 1-20, doi: 10.1016/j.atmosres.2017.06.021.

CV Dr. Elsa Cattani

Full-time Researcher at the CNR-ISAC - Clouds and Precipitation Physics (CAPE) Division.

Research interests

Regional climatology studies focused on East Africa precipitation
Satellite remote sensing of cloud and precipitation
Radiative transfer models in the VIS-NIR-IR for cloudy scenarios

International Projects

2014–2017: Global Earth Observation for integrated water resource assessment (eartH2Observe). EC funded collaborative project, 7th Framework Programme

2007 -2016: Satellite Application Facility on Support to Operational Hydrology and Water Management" (H-SAF) EUMETSAT

2011 – 2012: A collaborative project aimed at pre-validation of a GMES Global Water Scarcity Information Service (GLOWASIS). EC funded project, 7th Framework Programme

2005 – 2007: Anthropogenic Aerosol Trggering and Invigorating Severe Storms – ANTISTORM"
STREP Project EC funded, 6th Framework Programme

2005: A microphysical retrieval package for cloud-aerosol interactions using SEVIRI EUMETSAT ITT 04/658

2002–2004: Critical Assessment of Available Radar Precipitation estimation Techniques and development of innovative approaches for environmental management – CARPEDIEM. Shared-cost project co-funfed by the Research DG of the European Commision, 5th Framework Programme

2001 – 2003: European satellite rainfall analysis and monitoring at the geostationary scale – EURAINSAT. *A shared-cost project (contract EVG1-2000-00030) co-funded by the Research DG of the European Commission within the RTD activities of a generic nature of the Environment and Sustainable Development sub-programme (5th Framework programme).*

1999 – 2006: Use of the MSG SEVIRI channels in a combined SSM/I, TRMM and geostationary IR method for rapid updates of rainfall. METEOSAT Second Generation Research Announcement of Opportunity (MSG-RAO) – ESA and EUMETSAT (Project ID 152).

Memberships of scholarly societies

American Meteorological Society (AMS), European Geosciences Union (EGU)

Selected publications

1. **Cattani, E.**, F. Torricella, S. Laviola, and V. Levizzani, 2009: On the statistical relationship between cloud optical and microphysical characteristics and rainfall intensity for convective storms over the Mediterranean. *Nat. Hazards Earth Syst. Sci.*, **9**, 2135-2142.
2. Merino, A., L. López, J. L. Sánchez, E. García-Ortega, **E. Cattani**, and V. Levizzani, 2014: Daytime identification of summer hailstorm cells from MSG data. *Nat. Hazards Earth Syst. Sci.*, **14**, 1017-1033.
3. **Catttani, E**., A. Merino, and V. Levizzani, 2016: Evaluation of monthly satellite-derived precipitation products over East Africa. *J. Hydrometeorol.*, **17**, 2555-2573.
4. Wenhaji Ndomeni, C., **E. Cattani**, A. Merino, and V. Levizzani, 2018: An observational study of the variability of East African rainfall with respect to sea surface temperature and soil moisture. *Quart. J. Roy. Meteor. Soc.*, doi:10.1002/qj.3255.
5. **Cattani, E.**, A. Merino, J. A. Gujarro, and V. Levizzani, 2018: East Africa rainfall trends and variability 1983-2015 using three long-term satellite products. *Remote Sens.*, **10**, doi:10.3390/rs10060931.

Short CV. of Dr. Mario Montopoli Ph.D.

EMPLOYMENT

- *From Dec. 2016 to today*: permanent researcher at National Research Council of Italy (CNR) Institute of Atmospheric Sciences and Climate (ISAC).
- *From Nov. 2014 to Dec. 2015*: fixed term researcher at Sapienza University of Rome, Dept. of Information Electronic and Telecommunication, Rome, Italy.
- *From Dec. 2013 to May 2014*: EuMetSat Visiting Scientist with the H-SAF facility, Department of civil protection, Rome, Italy.
- *From Oct. 2011 to Sept. 2013*: fixed term researcher at University of Cambridge, Dept. of Geography, Cambridge, UK.
- *From May 2006 to Sept. 2011*: Post PhD. Dept. of Information Electronic and Telecommunication, University of L'Aquila, L'Aquila, Italy.

TECHNICAL AND CURRENT MANAGERIAL EXPERIENCE

- *From Oct. 2011 to Sept 2013*: principal investigator of FP7 project RASHCAST (n 273666) on RADAR-based ASH monitoring and foreCASTing by integrating of remote sensing techniques and volcanic plume models.
- *From Feb. 2017 to today*: principal investigator of cooperation NASA project NASAUnifiedWRF on the use of GSDSU radiative transfer simulator.
- *From Jul. 2015 to Jul. 2016*: work package leader within RadioMetOP2 (RadioMeteorological Operations Planner2) ESA-ESOC Contract n. 4000107890/13/D/EF for the characterization of the radio wave propagation channel at Ka band using unconventional radiometer data.
- *From Jan. 2014 to Jun 2015*: work package leader within FP7 Eu. project eartH2Observe (Grant Agreement No. 603608) for the comparison between retrieval of rain precipitation from synthetic aperture radar and ground based radars.
- *From Nov. 2006 to Apr. 2009*: work package leader for a feasibility study of a microwave radiometer for the observation of the Moon within European Student Moon Orbiter (ESA, contract N. ITT/1-6031/09/NL/NA)

EDUCATION

- *Feb. 2008:* Ph.D. degree in radar meteorology from the University of Basilicata, Potenza, Italy, defending the thesis "Microwave radar remote sensing of atmospheric precipitation: spatial-temporal models and inversion statistical techniques."
- *Oct 2004*: master degree in electronic and telecommunication engineering from University of L'Aquila, L'Aquila, Italy

BIBLIOMETRIC REFERENCES

- ISI researchID URL: http://www.researcherid.com/rid/C-8464-2014
- ORCID ID URL : https://orcid.org/0000-0003-0099-0393
- SCOPUS ID URL: http://www.scopus.com/authid/detail.uri?authorId=13404268000
- Personal web page : http://www.isac.cnr.it/en/users/mario-montopoli

PUBLICATIONS (five selected)

(1) *Montopoli M.*, Di Carlofelice A., Tognolatti P. and Marzano F. S., (2011). "Remote sensing of the Moon's subsurface with multifrequency microwave radiometers: A numerical study". Radio Science, 46(1), doi:10.1029/2009RS004311. eISSN: 1944-799X. IF: 1.075, SRJ=0.528

(2) *Montopoli M.*, Cimini D., Lamantea M., Herzog M., Graf H.F., and Marzano F.S., (2013)."Microwave radiometric remote sensing of volcanic ash clouds from space: model and data analysis", IEEE Transactions on Geoscience and Remote Sensing, vol. 51, (9), pp. 4678 – 4691, doi: 10.1109/TGRS.2013.2260343; ISSN: 0196-2892. IF=2.933, SRJ=2.598

(3) Ori D., Maestri T., Rizzi R., Cimini D., ***Montopoli M.*** and Marzano F. S., (2014). "Scattering properties of modeled complex snowflakes and mixed-phase particles at microwave and millimeter frequencies", Journal of Geophysical Research: Atmospheres, 119, 9931–9947, doi:10.1002/2014JD021616; ISSN:2169-8996. IF=3.426, SRJ=2.374
(4) ***Montopoli M.***, Roberto N., Adirosi E., Gorgucci E. and Baldini L., (2017). "Investigation of Weather Radar Quantitative Precipitation Estimation Methodologies in Complex Orography", Atmosphere, 8(2), 34, doi:10.3390/atmos8020034; ISSN: 2073-4433.
(5) Pierdicca N., Rocca F., Rommen B., Basili P., Bonafoni S., Cimini D., Ciotti P., Consalvi F., Ferretti R., Foster W., Marzano F.S., Mattioli V., Mazzoni A., ***Montopoli M***., et. al., (2009), "Atmospheric water vapor effects on spaceborne interferometric SAR imaging: Comparison with ground-based measurements and meteorological model simulations at different scales", IEEE-IGARSS), vol. 5, p. 320 - 323, doi: 10.1109/IGARSS.2009.5417668;

CV Dr. Sante Laviola, PhD

Full-time Researcher at the CNR-ISAC – Clouds and Precipitation Physics (CAPE) Division. Graduated Environmental Engineering, he obtained the PhD in Physics of the Earth System at the University of Basilicata, Italy. His research is mainly focussed on satellite algorithms development for studying precipitation and cloud structure and satellite remote sensing of severe storms. He was Visiting Scientist at the MetOffice, Satellite Application Division (UK), at the Swedish Meteorological and Hydrological Institute (SMHI), Atmospheric Remote Sensing Research Division (Sweden), and at the National Oceanic and Atmospheric Administration (NOAA), Center for Satellite Applications and Research (STAR) Division (USA).

Research interests

- Satellite remote sensing of severe storms
- Mediterranean extreme precipitation
- Algorithm development for studying precipitation and cloud structure
- Precipitation estimation using passive microwave satellite sensors and combined techniques
- Terrestrial Gamma Ray-flashes and Atmospheric Rivers

International Projects

2007 – 2017:	Satellite Application Facility on Support to Operational Hydrology and Water Management (H-SAF). Funded: EUMETSAT.
2007 – 2011:	PROSA–Prodotti di osservazione satellitare per allerta meteorologica PI: Dr. Franco Prodi. Funded: Agenzia Spaziale Italiana (ASI).
2011 – 2012:	Partner of the European Comm. GMES Project "A collaborative project aimed at pre-validation of a GMES Global Water Scarcity Information Service – GLOWASIS", PI: Dr. Rogier Westerhoff, Deltares.
2013 – 2017:	Partner of WP3 of the European Comm. Collaborative Project "Global Earth Observation for integrated water resource assessment - EartH2Observe", PI: Dr. Jaap Schellekens, Deltares
2013 – 2015:	Research Project "NectSnow", PI: Dr. Vincenzo Levizzani. Funded: Project of Interest "NextData".
2014 – 2016:	"Space Advanced Project Excellence in Research and Enterprise (SAPERE)", PI: Andrea Pietropaolo. Funded: Industrial cluster
2014 – 2016:	PON03_00067_6 "Apulia Space, PI: Distretto Tecnologico Aerospaziale – Aerospazio Puglia. Funded: MIUR
2015 – 2016:	"Telerilevamento da satellite della tipologia di precipitazione sulla regione

Antartica", PI: Dr. Daniele Casella. Funded: Programma Nazionale di Ricerche in Antartide (PNRA).

2015 – 2017: Pilot Project "RAilway Meteorological SEcurity System (RAMSES)" PI: Ing. Salvatore Gabriele, CNR-IRPI. Funded: RFI, Direzione Territoriale Produzione Reggio Calabria.

2016 – 2018: Bilateral project CNR-AORI "Comparison of tornadic supercells and their environmental conditions in Japan and Italy", PI: Dr. Miglietta Mario, CNR-ISAC.

2018 – 2020: European Comm. Collaborative Project H2020 "Sentinel Enhancements and Applications for Marine-Land Environment down to Submeso Scales (SEAMLESS)", PI: Prof. Agustín Sánchez-Arcilla, Technical University of Catalonia BarcelonaTech – UPC

Memberships of scholarly societies

- American Meteorological Society (member).
- European Geosciences Union (member)
- Associazione Italiana Telerilevamento (member).
- Associazione Italiana di Scienze dell'Atmosfera e Meteorologia (AISAM)

Selected publications

1. **Laviola S.,** and V. Levizzani, 2011: "The 183-WSL fast rain rate retrieval algorithm. Part I: Retrieval design". Atmos. Res., 99, 443-461.
2. **Laviola S.**, V. Levizzani, E. Cattani, and C. Kidd, 2013:"The183-WSL fast rainrate retrieval algorithm. Part II: Validation using ground radar measurements". Atmos. Res., 134, 77-86.
3. Gascón, E., **S. Laviola**, A. Merino, and M. M. Miglietta, 2016: Analysis of a localized flash-flood event over the central Mediterranean. Atmos. Res., 182, 256- 268, doi:10.1016/j.atmosres.2016.08.00.
4. Gjesteland, T., N. Østgaard, **S. Laviola**, M.M. Miglietta, E. Arnone, M. Marisaldi, F. Fuschino, A. B. Collier, F. Fabro, and J. Montanya, 2015: Observation of intrinsically bright Terrestrial Gamma ray Flashes from the Mediterranean basin. J. Geophys. Res.,120, 12143-12156, doi:10.1002/2015JD023704.
5. Miglietta, M. M., D. Cerrai, **S. Laviola**, E. Cattani, V. Levizzani, 2017: Potential vorticity patterns in Mediterranean "hurricanes". Geophys. Res. Lett., 44, doi:10.1002/2017GL072670.

Biographical Sketch
Dr. Mark S. Kulie

Dept. of Geological and Mining Engineering and Sciences
Michigan Technological University
Houghton, MI 49931

mkulie@mtu.edu
906.487.2498

A. PROFESSIONAL PREPARATION

Univ. of Michigan, Ann Arbor, MI	Meteorology	B.S.E.	1993
North Carolina State Univ., Raleigh, NC	Atmospheric Sciences	M.S.	1996
Univ. of Wisconsin-Madison, Madison, WI	Atmospheric & Oceanic Sci.	Ph.D.	2010

B. APPOINTMENTS

3/17-present: Assistant Professor, Michigan Technological University
3/17-present: Honorary Fellow, Space Science and Engineering Center, Univ. of Wisconsin-Madison
3/11-3/17: Researcher, Space Science and Engineering Center, Univ. of Wisconsin-Madison
1/14-3/17: Affiliate Faculty Member, Department of Atmospheric and Oceanic Sciences, University of Wisconsin-Madison
9/13-5/15: Assistant Lecturer, Department of Atmospheric and Oceanic Sciences, University of Wisconsin-Madison
4/10-3/11: Research Associate/Postdoctoral Researcher, Space Science and Engineering Center, University of Wisconsin-Madison
9/10-12/11: Adjunct Faculty Member, Madison College
9/04-3/10: Graduate Research/Teaching Assistant, University of Wisconsin-Madison
9/03-8/04: Research Intern, University of Wisconsin-Madison
3/97-6/01: Assistant Research Scientist, University of Maryland, Baltimore County/George Mason University/NASA Goddard Space Flight Center
10/96-3/97: Programmer/Analyst, National Environmental Satellite, Data, and Information Service
9/94-9/96: Graduate Research/Teaching Assistant, North Carolina State University

C. RELEVANT PUBLICATIONS

Milani, L, **M. S. Kulie**, D. Casella, S. Dietrich, T. S. L'Ecuyer, G. Panegrossi, F. Porcu, P. Sano, and N. B. Wood, 2018: CloudSat Snowfall Estimates over Antarctica and the Southern Ocean: An Assessment of Independent Retrieval Methodologies and Multi-Year Snowfall Analysis. *Atmos. Res*. Accepted for publication.

Adhikari, A., C. Liu, and **M. S. Kulie**, 2018: Global distribution of snow precipitation features and their properties from 3 years of GPM observations. *J. Clim.,* **31**, 3731–3754, https://doi.org/10.1175/JCLI-D-17-0012.1

Kulie, M. S., and L. Milani, 2018: Seasonal variability of shallow cumuliform snowfall: A CloudSat perspective. *Quart. J. Roy. Meteor. Soc.* Accepted for publication. doi:10.1002/qj.3222

Panegrossi, G., J.-F. Rysman, D. Casella, A. C. Marra, P. Sano, and **M. S. Kulie**, 2017: CloudSat-Based Assessment of GPM Microwave Imager Snowfall Observation Capabilities. *Remote Sensing*. **9(12)**, 1263; doi:10.3390/rs9121263

Casella, D., G. Panegrossi, P. Sanò, A. C. Marra, S. Dietrich, B. T. Johnson, and **M. S. Kulie**, 2017: Evaluation of the GPM-DPR Snowfall Detection Capability: Comparison with CloudSat-CPR. *Atmos. Res.*, **197**, 64-75.

Chen, S., Y. Hong, **M. Kulie**, A. Behrangi, P.M. Stepanian, Q. Cao, Y. You, J. Zhang, J. Hu, and X. Zhang, 2016: Comparison of snowfall estimates from the NASA CloudSat Cloud Profiling Radar and NOAA NSSL Multi-Radar Multi-Sensor System. *J. Hydrology*, http://dx.doi.org/10.1016/j.jhydrol.2016.07.047

Kulie, M. S., L. Milani, N. Wood, S. Tushaus, R. Bennartz, and T. L'Ecuyer, 2016: A shallow cumuliform snowfall census using spaceborne radar. *J. Hydrometeor*, **17**, 1261-1279.

Pettersen, C., R. Bennartz, **M. S. Kulie,** A. J. Merrelli, M. D. Shupe, and D. D. Turner, 2015: Microwave signatures of ice hydrometeors from ground-based observations above Summit, Greenland, *Atmos. Chem. Phys. Discuss.*, **15**, 34497-34532, doi:10.5194/acpd-15-34497-2015, 2015.

Kummerow, C. D., D. L. Randel, **M. Kulie**, N.-Y. Wang, R. Ferraro, S. J. Munchak, and V. Petkovic, 2015: The evolution of the Goddard Profiling Algorithm to a fully parametric scheme. *J. Atmos. Oceanic Technol.*, **32**, 2265–2280. doi: http://dx.doi.org/10.1175/JTECH-D-15-0039.1

Kulie, M. S., M. J. Hiley, R. Bennartz, S. Kneifel, and S. Tanelli, 2014: Triple frequency radar reflectivity signatures of snow: Observations and comparisons to theoretical ice particle scattering models. *J. Appl. Meteor. Clim.*, **53**, 1080-1098.

Hiley, M. J., **M. S. Kulie**, and R. Bennartz, 2011: Uncertainties in CloudSat snowfall retrievals. *J. Appl. Meteor. Clim.* **50**, 399-418.

Kulie, M. S., R. Bennartz, T. Greenwald, Y. Chen, and F. Weng, 2010**:** Uncertainties in microwave optical properties of frozen precipitation: Implications for remote sensing and data assimilation. *J. Atmos. Sci.,* **67**, 3471-3487.

Kulie, M. S. and R. Bennartz, 2009**:** Utilizing spaceborne radars to retrieve dry snowfall. *J. Appl. Meteor. Clim.,* **48**, 2564-2580.

D. SYNERGISTIC ACTIVITIES

- Member: Global Precipitation Measurement mission Radiometer Algorithm Team, Falling Snowfall Subgroup, and Particle Size Distribution Working Group
- Member: American Meteorological Society and American Geophysical Union
- Member: International Precipitation Working Group
- Associate Editor: *Atmospheric Measurement Techniques*

2.2 PLANNING

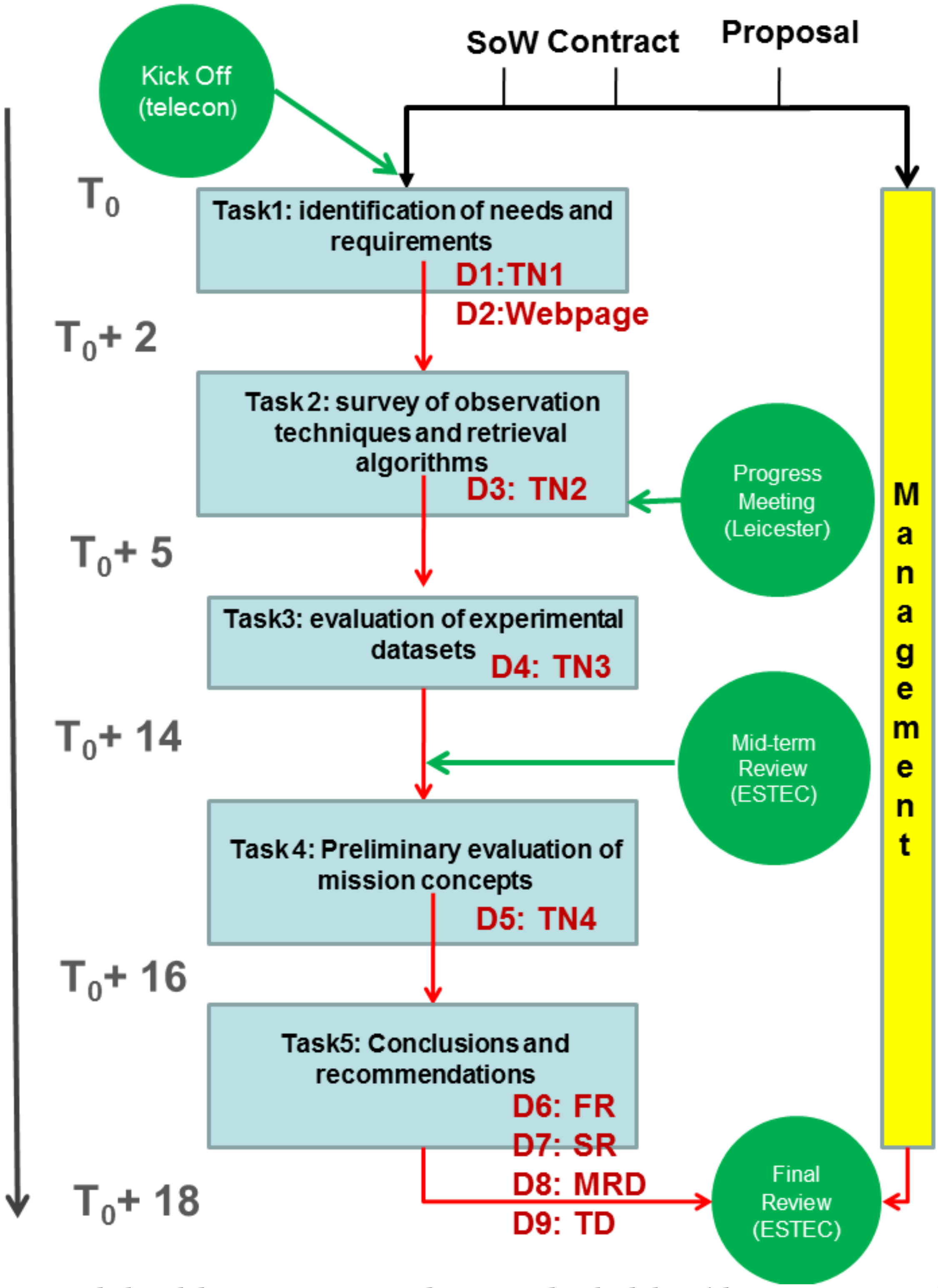


Figure 2.2 Work breakdown structure and proposed schedule with respect to T_0 (in months). Deliverables are indicated in red (TR=technical report, TDP=Technical Data, SR=Summary Report, FR=Final Report).

2.2.1 Proposed schedule and milestones

The project is expected to start in October 2018 and last for 18 months. The proposed schedule with respect to T_0 is illustrated in Figure 2.2. Four meetings (green ovals) are expected during the project: one via telecon, two at ESTEC and one in Leicester. A Gantt chart of the project is also provided in Table 2.2. The schedule of meetings and deliverables has slightly changed with respect to the one proposed in the SoW: the first progress meeting is anticipated to T_0+5 (instead of T_0+6) whereas the MTR is delayed to T_0+14. This is to allow more time to be spent to the activities in Task 3 that are deemed crucial for the outcome of the project.

Table 2.2: Bar chart for the whole project.

<table>
<tr><th>Timeline</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th><th>15</th><th>16</th><th>17</th><th>18</th></tr>
<tr><td>WP 1000: identification of needs and requirements for precipitation space mission</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>WP 2100: review of the observation techniques</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>WP 2200: review of the status of retrieval techniques</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>WP 3100: evaluation of Canadian field campaign dataset</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>WP 3200: evaluation of CloudSat/GPM co-located dataset</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>WP 3300: evaluation of RainCube data and forward modelling of high resolution CRM outputs of convective scenes</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>WP 4000: Preliminary evaluation of mission concepts</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>WP 5000: Conclusions and recommendations</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>WP 6000: Management and reporting</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Milestones</td><td colspan="5">MS1</td><td colspan="9">MS2</td><td colspan="4">MS3</td></tr>
<tr><td>Meetings</td><td colspan="2">KO</td><td colspan="3">PM</td><td colspan="9">MTR</td><td colspan="4">FR</td></tr>
<tr><td rowspan="2">Deliverables</td><td colspan="2" rowspan="2">D1-2</td><td colspan="3" rowspan="2">D3</td><td colspan="9" rowspan="2">D4</td><td colspan="3">D5</td><td></td></tr>
<tr><td colspan="4">D6-7-8-9</td></tr>
</table>

2.3 LIST OF DELIVERABLE ITEMS – SPECIFICATION OF ANY NON-CONFORMANCE

2.3.1 Deliverable Items

Only documentation deliverables are expected from the project as detailed in this list:

1. TN-1 describing the work performed in Task 1
2. Project website
3. TN-2 describing the work performed in Task 2
4. TN-3 describing the work performed in Task 3
5. TN-4 describing the work performed in Task 4
6. Final report
7. Summary report
8. Mission Requirement Document

9. Technical Data Package
10. Contract Closure Summary

They will be distributed in electronic and hard copies according to ESA needs. The deliverables are indicated in red in Figure 2.2. We accept the conditions listed in the Draft Contract (Article 2) included in the RFP/ITT.