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Sub-millimetre wave radiometry for cloud and rain characterization: From simulation to Earth observation mission concept

La radiométrie sub-millimétrique pour la caractérisation des nuages et de la pluie : De la simulation aux concepts de mission d'observation de la Terre

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ABSTRACT

Different studies and instrument/mission proposals have demonstrated the potential of the passive sub-millimetre–millimetre wave (SMMW) radiometry to provide remote measurements for the characterization of clouds and rain. At these wavelengths radiation received by a satellite over ice clouds is dominantly scattered by the ice particles. Vertically integrated ice and water contents, hydrometeor properties and profiles can then be retrieved from the radiometric observations with the use of multi-frequency retrieval schemes based on inversion databases simulating realistic brightness temperatures from in situ or modeled cloud microphysics profiles. Current technological SMMW developments offer new observational perspectives for the characterization of the atmosphere.

RÉSUMÉ

Différentes études et propositions d'instruments ont démontré le potentiel des observations en radiométrie passive aux ondes sub-millimétriques et millimétriques pour caractériser les nuages et la pluie. A ces longueurs d'onde, au-dessus d'un nuage de glace, le rayonnement mesuré depuis l'espace est principalement issu de la diffusion par les cristaux de glace. Les contenus verticaux intégrés en glace et en eau liquide, certaines propriétés des hydrométéores et les profils de microphysique nuageuse peuvent ainsi être restitués grâce à des algorithmes d'inversion basés sur des jeux de températures de brillance réalistes simulées à partir de profils de microphysique nuageuse in situ ou modélisés. Les développements technologiques actuels en détecteurs sub-millimétriques offrent de nouvelles perspectives pour la caractérisation de l'atmosphère.

1. Introduction

Different passive and active remote sensing techniques are currently used to monitor the properties of Earth clouds from space-based scientific and operational spacecrafts on low and geostationary orbits. It includes visible and infrared (IR) imagery (e.g. Meteosat Second Generation (MSG) with 4 visible/Near-IR channels in the 0.4–1.6 µm band and 8 IR

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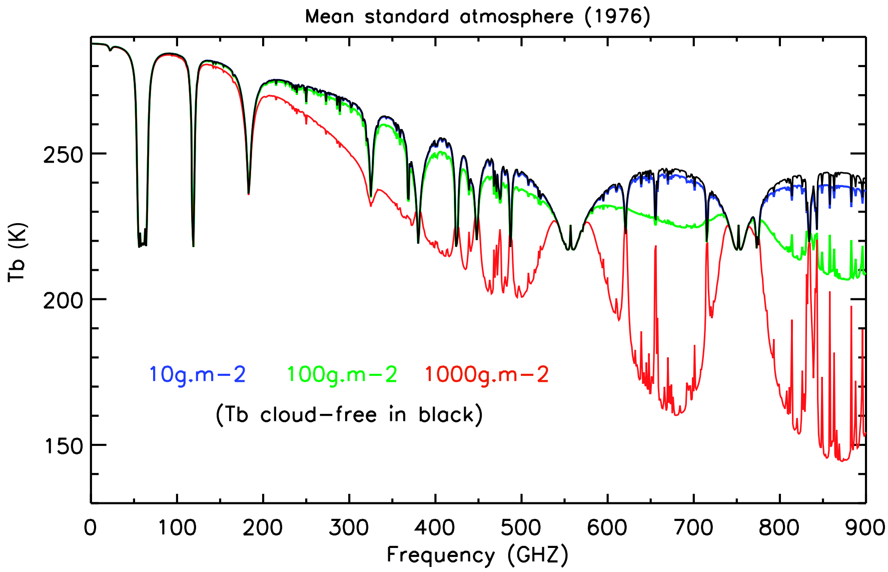

Fig. 1. Simulated brightness temperatures (K) as a function of the frequency for a standard atmosphere with an ice cloud between 7 and 8 km composed of a mono-disperse particle distribution of 100-μm diameter but for three different ice contents [3]. Cloud-free simulation is drawn in black.

channels in the 3.9–13.4 μm band), passive microwave radiometry (e.g. Tropical Rainfall Measuring Mission (TRMM) at 10 to 85 GHz [1]), active microwave radiometry (TRMM Precipitation Radar at 13 GHz [1] or the Cloud Profil Radar of the CloudSat mission at 94 GHz [2]) and Lidar instrumentation (e.g. Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (Calipso) mission operating at 532 and 1064 nm [2]). Such observations are currently available for instance on the A-Train mission [2], which is composed of five satellites forming a train with a large number of sensors sampling almost simultaneously the same part of the atmosphere within few minutes. However one part of the spectrum has not been used yet for the characterization of the clouds from space: sub-millimetre/millimetre wave (SMMW) radiometry measuring the radiation between 200 and 800 GHz. Although already used by limb sounders to characterize atmospheric composition, the maturity of the SMMW technology makes now possible to broaden its application to different observing geometries that can be used to better characterize other properties of the Earth atmosphere from space. Indeed compared to microwave technology, SMMW technology can provide unique measurements for a better inventory of the cloud coverage and for a better characterization of the cloud hydrometeor properties especially for ice clouds. There is an urgent need to validate the present cloud parameterizations in climate models and space SMMW missions can contribute to better represent the ice clouds in the models. Because of their sounding capability – the upper convective cloud layers often block the IR sounding – SMMW radiometers then offer the possibility to track and monitor severe weather events at a spatial sampling resolution at the ground compatible with the typical size of storms (of tens of km). Additionally new compact designs of SMMW receivers offer brand new instrumental concepts like arrays of receivers that open new perspectives in terms of scanning strategy or of accuracy in atmospheric sounding for the observation of the Earth from low and geostationary orbits.

In the following we summarize some European activities that have been performed to promote SMMW radiometry for cloud and rain characterization: we first introduce the SMMW radiometry and the impacts of the atmospheric properties on the SMMW radiances. Second we list the different space-based Earth SMMW observation missions that have been lately proposed in Europe. Third we describe the retrieval algorithms to derive cloud properties from SMMW observations and present the expected retrieval errors derived from radiometric simulations of cloudy scenes. Finally we briefly introduce the International Sub-Millimetre Airborne Radiometer (ISMAR) currently under construction and designed to demonstrate experimentally the relevance of passive SMMW radiometry for cloud and rain characterization.

2. Interaction between clouds and sub-millimetre wave radiation

Fig. 1 from [3] illustrates how the up-welling radiation measured by a spaceborne SMMW sensor would be scattered away by the presence of an ice cloud. Simulated brightness temperatures (by the Atmospheric Transmission at Microwave (ATM) radiative transfer code [4]) for three clouds composed all of one single layer (1-km thick between 7 and 8 km in altitude) with pure ice particles (spheres of 100-μm diameter) but with three different ice concentrations (10, 100, 1000 $\mathrm{g\,m^{-2}}$) are presented. The figure shows how the largest the ice concentration and the highest the frequency, the largest the radiation scattered away, with significant and detectable depression of the brightness temperatures for the higher frequencies (e.g. a depression of 20 K can be expected at 670 GHz between a clear sky and a cloud of 100 $\mathrm{g\,m^{-2}}$ vertically integrated content). Notice that at the low frequencies available from the passive microwave operational radiometers (below 183 GHz; e.g. the Advanced Microwave Sounding Unit-B, AMSU-B) the relatively thin cirrus clouds presented here are

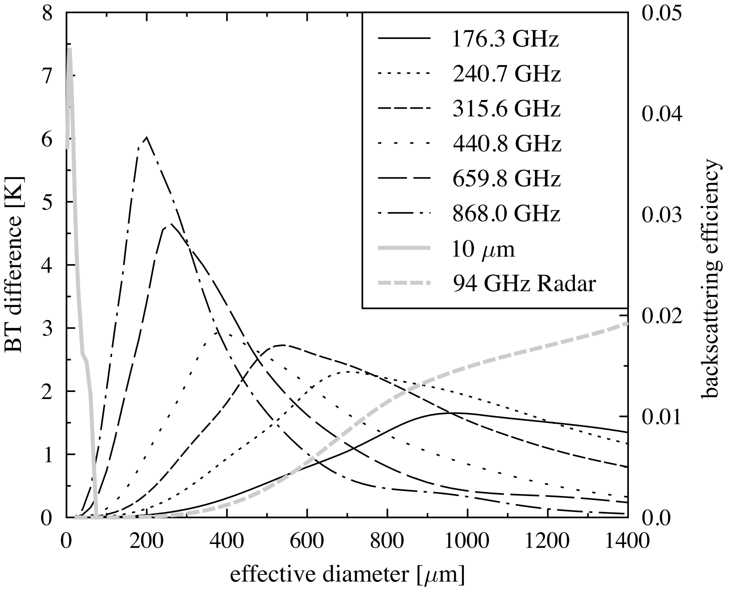

Fig. 2. Difference of brightness temperatures between clear sky and cloudy conditions as a function of the particle diameter at different frequencies and for a given constant cloud content [5].

transparent, i.e., the ice particles scatter away very little of the up-welling radiation, while an SMMW radiometers (at higher frequencies) clearly detect the clouds.

Fig. 2 from [5] presents a sensitivity study of the size of the hydrometeors for constant cloud content as derived from the difference of brightness temperatures in cloud-free sky and in presence of the cloud. The presence of small particles induces large difference of brightness temperatures at high frequency while no impact is observed at low frequency. On the contrary low frequencies are only sensitive to large particles. Consequently measuring simultaneously at different SMMW frequencies can be used to quantify the size distribution of the ice particles and provide accurate measurements of integrated ice content and effective diameter as pointed out in [5,6].

Rain is currently retrieved from space-based detection either from active Low Earth Orbit (LEO) sensor such as TRMM-PR [7] or from passive microwave LEO sensors alone or in conjunction with the IR Geostationary Earth Orbit (GEO) imagery [8]. Because of its sounding capabilities, the passive microwave technique provides a more direct measurement of the cloud column than the IR technique alone, but no microwave sensor is available onboard a geostationary satellite so far. However liquid precipitation can be deduced from SMMW observations through the correlation with ice above the rain as discussed in Section 4.3. Consequently SMMW radiometers could be deployed in geostationary orbit to monitor and track clouds and storms with a spatial resolution close to the size of regular thunderstorms and with a better revisiting time than operational LEO microwave radiometers.

3. European space-based SMMW missions

Several space-based missions have been proposed during the past decade. For instance the CIWSIR (Cloud Ice Water Submillimeter Imaging Radiometer) mission [5] in response to ESA 7th Earth Explorer Core Missions call proposed to deploy on a polar orbit an SMMW radiometer sensing the up-welling radiation at different frequencies ranging from 183 to 664 GHz (see Table 1). The CIWSIR mission aimed at characterizing ice cloud properties such as Ice Water Path (IWP), ice particle size and cloud altitude, based on multi-channel retrieval schemes as explained in Section 4.2.

The GOMAS (Geostationary Observatory for Microwave Atmospheric Sounding) mission [9] was also proposed in response to the same ESA Earth Explorer Core Missions call with the deployment in geostationary orbit of a radiometer operating over a large spectrum (60 to 424 GHz; Table 1). The main objectives of the GOMAS mission were, first, water vapour and temperature profiling and second, tracking and monitoring of severe weather events (i.e. storms).

More recently the CloudIce mission [10] was presented to ESA in response to the 8th ESA Earth Explorer call based on the CIWSIR mission concept to deliver global data on ice clouds, with the secondary objective to demonstrate the benefit of sub-millimetre wave observations for precipitation, an important step towards a possible future deployment of sub-millimetre wave radiometers for a geostationary mission. Although the CloudIce mission was not selected, it was strongly supported by the ESA Earth Science Advisory Committee who recommended further works on the measurement and the interpretation of radiometric brightness temperatures from an airborne demonstrator (see Section 5).

Table 1
List of the proposed European space missions and frequencies.

Name	Orbit	Frequency in GHz (V and H stand for Vertical and Horizontal polarization respectively)
CIWSIR	LEO	183.31 ± 1.5 (V), 183.31 ± 3.5 (V), 183.31 ± 7.0 (V); 243.2 ± 2.5 (V & H); 325.15 ± 1.5 (V), 325.15 ± 3.5 (V), 325.15 ± 9.5 (V); 448 ± 1.4 (V), 448 ± 3.0 (V), 448 ± 7.2 (V); 664 ± 4.2 (V & H)
GOMAS	GEO	54 (11 sub-bands); 118.75 (10 sub-bands); 183.31 (7 sub-bands); 340 (optional); 380 (6 sub-bands); 424 (8 sub-bands)
MIRACLE	LEO	183.31 ± 1.5 (V or H), 183.31 ± 3.5 (V or H), 183.31 ± 7.0 (V or H); 243.2 (V & H); 325.15 ± 1.5 (V), 325.15 ± 3.5 (V), 325.15 ± 9.5 (V or H); 448 ± 1.4 (V or H), 448 ± 3.0 (V or H), 448 ± 7.2 (V or H); 664 (V & H)
CloudIce	LEO	183.31 ± 0.2 (V), 183.31 ± 1.0 (V), 183.31 ± 3.0 (V), 183.31 ± 5.0 (V), 183.31 ± 7.0 (V), 183.31 ± 11.0 (V); 243.2 ± 2.5 (V & H); 325.15 ± 1.5 (V), 325.15 ± 3.5 (V), 325.15 ± 9.5 (V); 448 ± 1.4 (V), 448 ± 3.0 (V), 448 ± 7.2 (V); 664 ± 4.2 (V & H)
Boitata	LEO	243.2 (V & H); 325.15 ± 1.5 (V), 325.15 ± 3.5 (V), 325.15 ± 9.5 (V or H); 448 ± 1.4 (V or H), 448 ± 3.0 (V or H), 448 ± 7.2 (V or H); 664 (V & H)

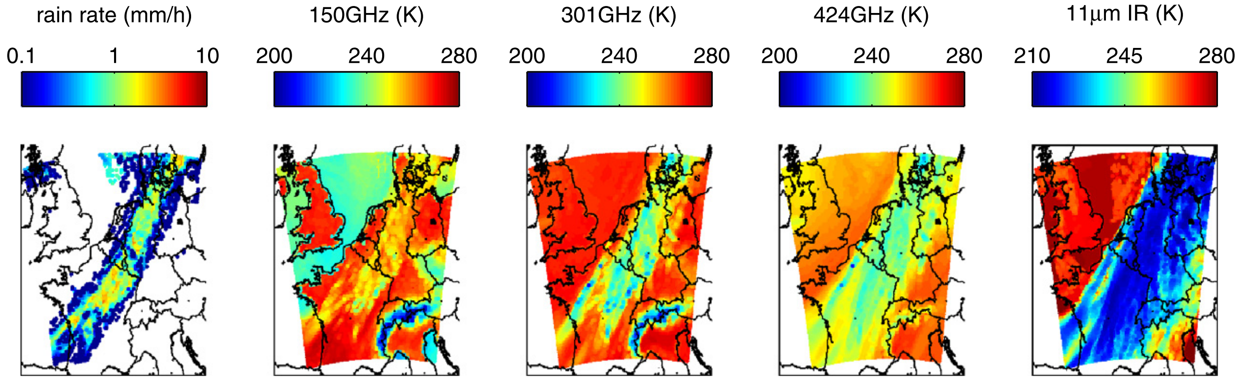

Fig. 3. Example of cloud and radiative simulations like rain rate as provided from the cloud model MESO-NH (left panel), and brightness temperatures computed at nadir from the atmospheric cloud profiles at 3 sub-millimeter wavelengths and in the infrared.

Following the proposal of the MIRACLE mission [11] to the French space agency CNES in response to the call of ideas in 2009, the phase 0 of French–Brazilian project Boitata elaborated an SMMW radiometer concept for the characterization of the ice cloud properties over the Tropics.

Millimetre and sub-millimetre radiometers are now suggested to equip the next generation of European operational satellite (Post-EPS) to be launched in 2021, for again a better characterization of the cloud ice phase. The MicroWave Imager (MWI) is currently studied in phase-A for Post-EPS, with a decision regarding implementation of the millimetre/sub-millimetre channels due in 2012/2013.

4. Retrieval of atmospheric geophysical parameters

In the following, we summarize the main results obtained during different studies aiming at assessing the performances of the SMMW radiometry for ice cloud and rain characterization. The work performed for the evaluation of the relevance of SMMW radiometry for ice cloud characterization helped in the design of the CIWSIR mission [5] and more recently of the CloudIce mission [10]. The work summarized on the rain characterization was performed to evaluate the performances of a GOMAS-like mission to detect and quantify the rain from a geostationary location [12].

4.1. Method

The technique employed, so far, to evaluate the potential of SMMW radiometry is based on simulations. Realistic atmospheric profiles are first created either from in situ airborne measurements of the cloud microphysics [6] or from microphysics profiles obtained from cloud resolving model simulations [13]. Radiative transfer computations for the atmospheric profiles and the different frequencies to be investigated are then carried out [6,12]. Fig. 3 presents an example of radiative simulations at 150, 301 and 424 GHz and 11-μm (IR channel) at nadir performed for a frontal system over Europe simulated with the cloud-resolving model MESO-NH [13]. Fig. 3 clearly shows that according to the frequency different regions of the clouds are sampled and that simultaneous measurements at multiple frequencies should be used to retrieve the atmospheric properties such as rain rate or vertically integrated content along the atmospheric column. But one should keep in mind that the relationships between the frequency responses and the hydrometeor profiles are complex, non-linear, and (cloud and/or rain) regime dependent [14,15]. At the end, a database of cloud profiles and simulated brightness temperatures is generated. Such database is then used to train retrieval algorithms mainly neural-network-based [6,12]. Because

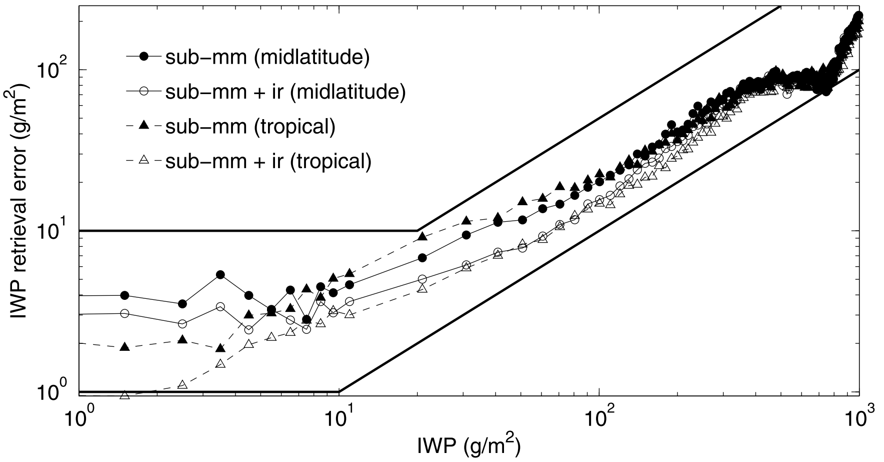

Fig. 4. Retrieval performance for IWP as a function of the true IWP [5]. Retrieval results are shown with and without additional infrared channels, as available from METOP. Also are shown the results for two different atmospheric scenarios (mid-latitude and tropical). Solid black lines indicate the scientific mission requirement ranges.

the quality of statistical retrieval algorithms is directly related to the realism of the simulated database, an evaluation of the quality of the simulations is required and can be performed by comparing the cloud and radiative simulations to coincident space-based observations for example (e.g. [14]).

The neural-network-based retrieval algorithms are then evaluated to identify the most suitable frequency set to be operated from space with the best performances in the description of the parameters to retrieve [6,12]. The test consists in applying the retrieval algorithms on part of the simulated database, the other part of the database being used to train the retrieval algorithms. Realistic instrument noise is also added to the simulated brightness temperatures used to train and to verify the retrieval algorithms. The performances are then evaluated in terms of retrieval errors as determined from the difference between the retrieved and the original values of a given atmospheric parameter. The retrieval errors are usually estimated per range of the atmospheric parameter to retrieve.

4.2. Retrieval of ice cloud properties

The use of passive SMMW measurements to retrieve cloud ice water content and ice particle size was suggested several years ago by [16] and following articles (e.g. [17]). As already mentioned in Section 3, the CIWSIR proposal was not selected directly for a pre-phase-A study, but there was a strong recommendation to continue preparatory activities. The subsequent ESA study, Establishment of Cirrus Cloud Mission and Instrument Requirements at Submillimetre Wavelengths [18], further refined the mission concept. More recently the CloudIce mission, proposed in 2010 to ESA, was designed based on the CIWSIR mission concept. It was proposed to equip the CloudIce mission with a passive SMMW radiometer designed to measure cloud Ice Water Path (IWP), ice particle size and cloud altitude. The proposed instrument was a conically scanning 15-channel radiometer with channels between 183 and 664 GHz (Table 1), proposed to fly in tandem with one of the METOP satellites.

As introduced above, retrieval simulations were used to test different channel combinations and other instrument options for both CIWSIR prototype instrument concept and CloudIce mission. The simulations used a neural network, together with a stochastic training dataset of atmospheric states and associated radiances. The training data contained random cloud profiles, including random sizes and shapes of ice particles, with statistics consistent with radar and in situ aircraft data. The methodology and results of these simulations are discussed in detail in [6].

Retrieval results were shown to be highly robust against small changes in radiometer noise level and channel configuration, allowing some freedom for trade-offs with technical and programmatic mission aspects [6]. Fig. 4 from [5] shows the retrieval performance of the CIWSIR/CloudIce instrument concept for IWP as a function of the true IWP. The retrieval results are shown with and without additional simulated infrared channels, as available from METOP. Also are shown the results for two different atmospheric scenarios (mid-latitude and tropical). The relevant scientific mission requirements specified in [5] are also included in the figure as black solid lines. In summary, appropriate SMMW channels can measure IWP with a relative accuracy of approximately 20% and a detection threshold of approximately 2 $\mathrm{g\,m^{-2}}$. [6] reports that a median mass equivalent sphere diameter of the ice particles can be measured with an accuracy of approximately 30 μm, and the median IWP cloud altitude can be measured with an accuracy of approximately 300 m. All the above accuracies are median absolute error values; root mean square error values are approximately twice higher, due to rare outliers.

4.3. Retrieval of rain properties

Observations from geostationary satellites can provide the revisiting time necessary to monitor extreme weather events. However, from these orbits, passive microwave measurements at currently used frequencies require large antennas to

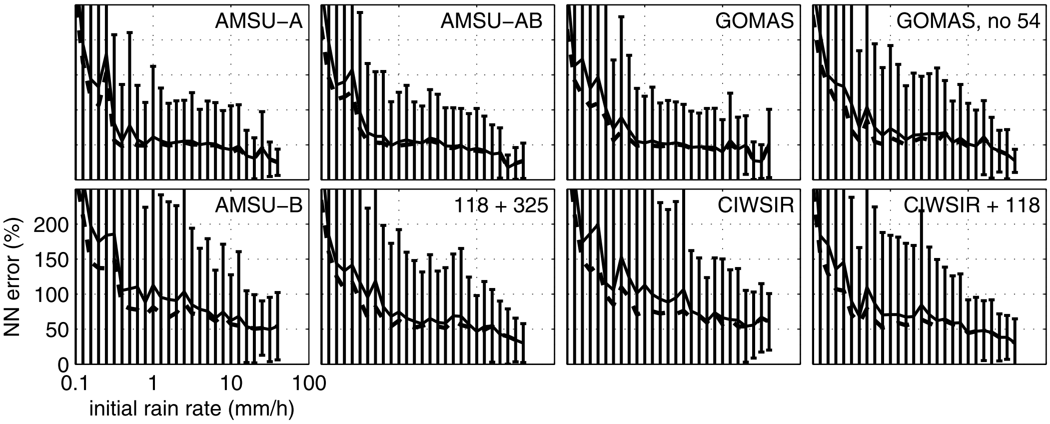

Fig. 5. Rain rate retrieval errors for different frequency sets (see Table 1 for the list of frequencies for a given mission). The mean absolute relative error e_m (solid lines) ± the standard deviation (vertical segment) and the r.m.s. errors e_{rms} (dashed line) are computed per 0.1 bin – X-axis is in decimal logarithmic scale – for pixels over ocean at 19° incidence.

achieve adequate spatial resolution. To overcome this problem, the use of passive SMMW observations should be considered. Radiometry at these wavelengths is predominantly sensitive to the cloud ice particles and rain detection/quantification is mainly derived from correlation with the ice particles above the rain. The GOMAS project proposed to operate multiple O_2 and H_2O channels (Table 1) on a GEO platform.

To evaluate the performances of the GOMAS mission, a series of mid-latitude cloud simulations were performed [13] in addition to radiative simulations for up to 36 different frequencies spanning the SMMW domain [14,12] for different viewing configurations and surface types. Retrieval schemes were then built according to the technique described in Section 4.1. Rain detection for different frequency sets was also investigated with the use of supervised classification (not detailed in the following; see [12] for more details on the classification). The retrieval performances of the GOMAS-like mission were evaluated relatively to the User Requirements [19]. The User Requirements table basically lists the values below which the applied technique brings significant information. For example, for hydrology application and for a rain rate above 10 $\mathrm{mm\,h^{-1}}$, the applied technique needs to be accurate with an error below 20%, 10% and 5% at the threshold, breakthrough and objective levels respectively.

Fig. 5 shows the r.m.s. of the retrieval error (e_{rms}) and the mean absolute relative error (e_m) along with the standard deviation around the error e_m (vertical segments) for the retrieval of the rain rate at different frequency combinations such as the ones for the operational AMSU-A, AMSU-B and AMSU-AB missions or for the proposed GOMAS and CIWSIR missions. The errors usually decrease when the rain rate increases. At AMSU-A, AMSU-AB, or at the frequency set selected for GOMAS (Fig. 5), the errors are within 50% for a rain rate above 0.5 $\mathrm{mm\,h^{-1}}$, i.e. well within the threshold values of 100% requested for NWP (Numerical Weather Prediction) application and below the breakthrough values of 50% (based on User Requirements table [19]). However, all the frequency combinations presented in Fig. 5 are clearly not suitable for land surface hydrology applications given the required accuracy specified in [19]. Strong precipitation events (rain rate above 10 $\mathrm{mm\,h^{-1}}$) can be quantified with errors around 50% for all frequency configurations.

A frequency combination similar to one of the CIWSIR/CloudIce mission does not provide the requested accuracy but the addition of the 118 GHz channel does improve the results and provides similar performances to a GOMAS mission without the 54 GHz O_2 channels (Fig. 5). A simple instrument combining the 118 GHz O_2 and the 325/380 GHz H_2O sets yields performances close to the specifications for rain rate above 1 $\mathrm{mm\,h^{-1}}$. Results for the GOMAS-like frequency set over ocean and land are comparable for different incidence angles (not shown, [12]). Adding the thermal infrared has almost no impact, except for the configurations that originally suffered from large errors (not shown, [12]). Introducing noise in the treatment induces small variations in the retrieval performances for most frequency sets (not shown, [12]).

The potential of SMMW radiometry to retrieve vertically integrated hydrometeor content was also investigated [12]. Using a GOMAS-like frequency configuration, the average error for total-ice retrieval is below 40% and for most of the total-ice content range close or below 20% (not shown). This is within the threshold of 50% specified by the user requirements for this quantity and close to the 20% breakthrough value [19].

In summary, the potential of SMMW observations for precipitation detection and quantification has been demonstrated from theoretical calculations. The skills of a frequency set such as planned for the GOMAS mission, with and without the 50 GHz O_2 channels, fully satisfy the requirements up to the User Requirements threshold level for NWP and nowcasting applications in terms of rain detection as well as for rain rate retrieval above 1 $\mathrm{mm\,h^{-1}}$. The retrieval of other hydrometeor quantities (e.g., ice, snow, graupel[1]) has also been tested with success, as well as the possibility of estimating the vertical

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[1] Also called soft hail.

Table 2
List of the ISMAR radiometers (V and H stand for vertical and horizontal polarization respectively; B, UC, TB stand for built, under construction and to build respectively).

Type	O_2	Window	Window	H_2O	O_2	H_2O	Window	Window	Window	Window
Frequency (GHz)	118	243	243	325	424	448	664	674	874	874
Number of sub-channels	5	1	1	3	3	4	1	1	1	1
Polarization	V	V	H	V	V	V	V	H	V	H
Status	UC	UC	UC	B	TB	UC	UC	UC	TB	TB
Scanning	Long track, downward and upward looking with 5° beam									
Calibration	Frequent in-flight calibration on two dedicated loads									

hydrometeor profiles [12,15]. This opens new perspectives to detect, quantify and track precipitation at high visiting time (compared to LEO missions) on future geostationary missions.

5. The International Sub-Millimetre Airborne Radiometer

To validate experimentally the pertinence of SMMW instrumentation and proposed space-based SMMW mission concepts, a passive instrument, the International Sub-Millimetre Airborne Radiometer (ISMAR) is under construction [20] to be initially operated on the FAAM (Facility for Airborne Atmospheric Measurements) BAe-146 research aircraft within the EUFAR (European Facility For Airborne Research) fleet. The instrument is designed from the main conclusions of a feasibility study of an airborne demonstrator performed for ESA [21]. In [21], different aircrafts, different instrument configurations (i.e. full brand new radiometer or high frequency radiometer operating in conjunction with already existing airborne radiometers), frequency selection and associated theoretical retrieval performances, flight altitude, instrument size and weight, auxiliary measurements were evaluated to provide the most valuable SMMW radiometer for both demonstration and future operations for research flights.

The modular and portable ISMAR instrument includes a number of heterodyne receivers, with space to add additional channels as the technology becomes available (Table 2). ISMAR channels were identified in different studies [5,6,12,14,15,18] as the optimum frequencies for ice cloud and rain measurements with passive SMMW radiometry. Some ISMAR radiometers are currently under construction based on UK Met Office and ESA financial supports. The scientific community in Europe will then benefit from a unique SMMW airborne instrument for scientific field campaigns and for validation campaigns for future space-based missions.

6. Summary

Passive SMMW radiometry has recently been evaluated through different studies and instrument/mission proposals for ESA [5,6,12–14,18,21], EUMETSAT [15] and CNES [3] on its potential to provide new remotely sensed measurements for the characterization of clouds and rain. For Earth observation applications, passive SMMW radiometry for cloud/rain characterization consists in recording the up-welling radiation at frequencies ranging from 200 to 800 GHz (for comparison the highest frequency used in Earth observation operational missions so far is 183 GHz from AMSU-B or SAPHIR[2] onboard the Megha-Tropiques mission). At these frequencies the radiation measured onboard satellites over ice clouds is dominantly affected by the scattering from the ice particles. Vertically integrated ice and water contents and hydrometeor properties can then be retrieved from multi-frequency radiometric observations using retrieval schemes based on inversion databases simulating the observed brightness temperatures from in situ or modelled atmospheric microphysics profiles. Sub-millimetre wave radiometry on space missions could then characterize the ice phase in clouds [5,6] at global scale for the validation of climate models, which are still suffering from poor parameterization of the high altitude clouds. Sub-millimetre wave radiometry could also be used for rain detection and quantification mainly because of the correlation between the precipitation and the ice content above [9,12]. In addition sub-millimetre detection technology is becoming more and more mature and offers new perspectives for new instruments for Earth atmosphere characterization: for instance a deployment of sub-millimetre wave radiometers from geostationary satellites will offer the possibility to monitor and track severe weather events with a better vertical sounding of the clouds than IR imagers only, and at a spatial resolution compatible with the average size of a thunderstorm; or new scan and observation strategies with the operation of multi-pixel radiometers [22]. Finally the ISMAR instrument is currently under construction on the UK FAAM BAe-146 research aircraft based on UK Met Office and ESA supports [20,21], and should validate experimentally both mission/instrument concepts and retrieval methodologies for a future deployment of SMMW radiometers on space-based Earth observation missions. The scientific community in Europe will then benefit from a unique SMMW airborne instrument for scientific field campaigns and for validation campaigns for future space-based missions.

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[2] SAPHIR, a six-channel 183 GHz microwave radiometer for water–vapor profile retrieval built by CNES for the French–Indian weather satellite Megha-Tropiques. Megha-Tropiques was successfully launched on October 12, 2011.

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