A NEW AIRBORNE SUBMILLIMETRE DEMONSTRATOR

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ABSTRACT

ISMAR (International SubMillimetre Airborne Radiometer) is a new aircraft remote sensing instrument, with heterodyne receivers from 118 to 664GHz. It has been funded by the Met Office and ESA, and has been designed to allow additional channels to be added, including 874GHz.

Submillimetre frequencies are very sensitive to ice clouds and can provide direct retrievals of Ice Water Path [1] which is an important parameter in General Circulation Models. ISMAR will be used as a satellite demonstrator as well as for investigating specific scientific case studies. It can be used in the preparation for the usage of Ice Cloud Imager (ICI) data on MetOp-SG and for calibration/validation post satellite launch.

The instrument has been certified on the FAAM BAe-146 aircraft and is currently undergoing a channel upgrade. This paper describes the instrument, its applications and the future aircraft campaign plans.

1. INTRODUCTION

ISMAR (International SubMillimetre Airborne Radiometer) is a passive remote sensing instrument with polarisation and multiple channels, designed to operate on an aircraft platform. It operates in the submillimetre and microwave frequencies which are particularly sensitive to ice clouds and other atmospheric properties.

Several submillimetre satellites have been previously proposed (including CIWSIR [2], GOMAS [3], and CloudIce [4]). Though not funded they had strong recommendations for an airborne demonstrator as proof of concept. The new airborne instrument, ISMAR, has been funded by the UK Met Office and ESA (European Space Agency) as a satellite demonstrator and for researching atmospheric case studies to improve weather and climate models. It can also be used in the preparation for the use of ICI (Ice Cloud Imager) data and for ICI's cal/val post launch on MetOp-SG in 2022.

ISMAR is a modular instrument such that additional channels can be added as funds become available. In this way it can also be used as a technology demonstrator. For example, ESA are planning to fund the development of European 875GHz receivers and ISMAR can be used to demonstrate the technology in a practical application.

The basic ISMAR instrument containing 325GHz channels, the scanning and calibration system is being upgraded with additional channels funded by ESA listed in section 3. These receivers have been designed and built by a consortium of RAL (Rutherford Appleton Laboratory), RPG (Radiometer Physics GmbH) and SEA (Systems Engineering and Assessment Ltd), and are currently being laboratory tested post instrument integration. ISMAR will be flown together with the existing microwave instruments MARSS (Microwave Airborne Radiometer Scanning System) and Deimos, which contain 23.8GHz, 50GHz, 89GHz, 157GHz and three 183GHz channels.

2. SCIENTIFIC APPLICATIONS

Measurements of ice mass and Particle Size Distributions (PSDs) are required to validate Global Circulation Model (GCM) simulations leading to improvements in weather and climate forecasting. There have been many studies on ice water cloud uncertainties [5-10] and their impact on climate prediction [11]. This has also been recognized by the World Meteorological Organization (WMO), which classifies ice mass as one of the essential climate variables in the framework of the Global Climate Observing System [12].

Currently active and passive instruments in microwave, infrared and visible wavelengths are used to determine ice cloud properties. Visible and infrared wavelengths are sensitive to thin ice clouds with particle diameters less than 50 microns, as illustrated in figure 1 for 10µm infrared radiation. However it is inherently difficult to relate these measurements to the bulk mass of ice. Microwave sensors for cloud applications currently use frequencies less than 200GHz and are only sensitive to particles much larger than 200 microns, as depicted in figure 1 for 176GHz.

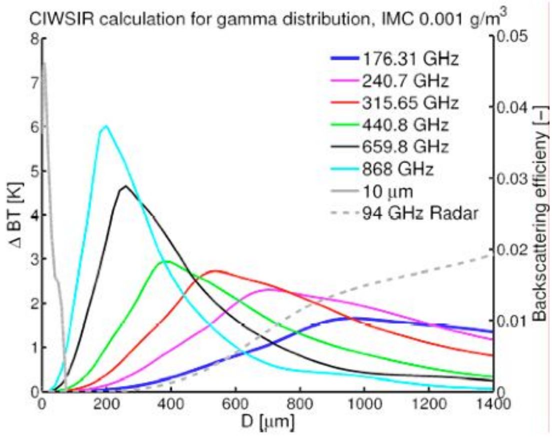

Figure 1: Simulations of a space borne instrument sensitivity (delta BT) at a range of frequencies (radar, microwave, submillimtere and infrared at 10 microns) to ice particle diameter (D) for a fixed Ice Mass Content cloud. [2]

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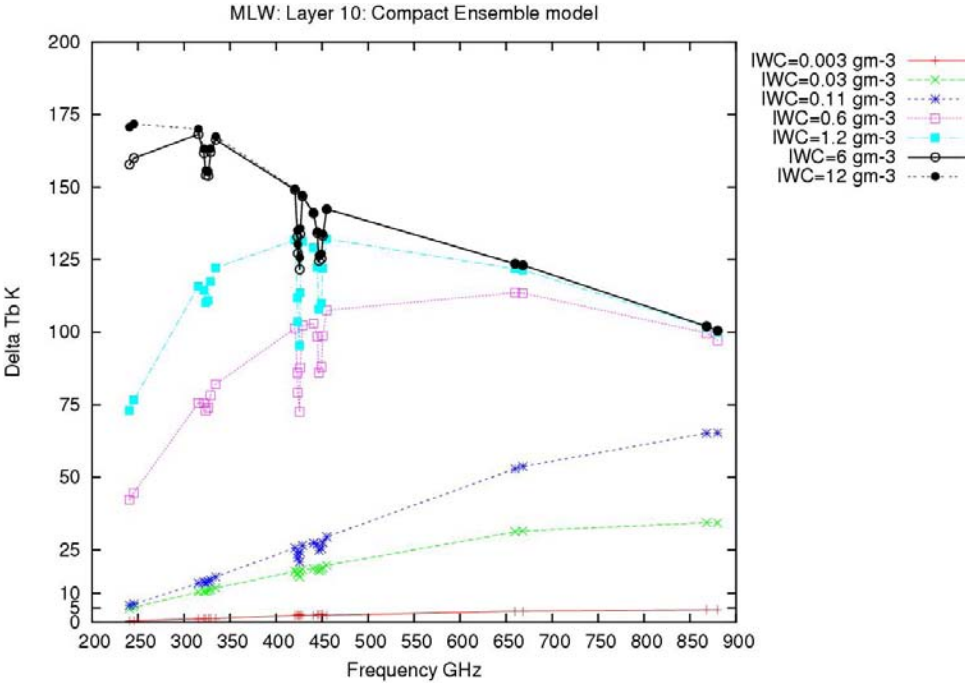

Figure 2: Simulations of the sensitivity (delta BT) to a range of Ice Water Contents (IWC) at each of the ISMAR frequencies in the submillimetre. Microwave frequencies are sensitive to only to higher IWC.

Submillimetre frequencies fill this gap. They are very sensitive to ice and water, and give a direct estimate of ice mass and mean ice particle size. Figure 2 shows the sensitivity to Ice Water Content (IWC), a fundamental GCM prognostic variable, at each of the ISMAR frequencies in the submillimetre. Note from the figure the sensitivity to narrow (low IWC) and broad (high IWC) PSDs at the higher and lower frequencies respectively.

By using the multiple frequencies and polarisation information from ISMAR, MARSS and Deimos it is possible to determine: ice mass, particle size and some shape information in ice clouds; mixed phase cloud properties; an indirect measurement of precipitation [3], snow surface emissivity and near source ash plume information [13]. ISMAR will be used to test retrieval algorithms, perform scientific case studies and provide calibration and validation of future satellites post-launch, e.g. ICI.

To obtain a full picture of the atmospheric state and ice cloud, ideally multiple wavelengths should be used simultaneously. On the FAAM research aircraft this is possible using the existing infrared, near infrared and visible remote sensing instruments in conjunction with the microwave and submillimetre radiometers.

3. ISMAR FREQUENCY SELECTION

The optimisation of the frequency selection for observations of cloud ice has been examined within ESA studies [2, 14-17]. These studies have been used to select the ISMAR frequencies which are shown in figure 3 on top of a simulated atmospheric spectrum with and without cirrus. The selected frequencies also match most of the ICI channels.

Some channels are positioned on water or oxygen lines, while others are in pseudo-window regions. They are listed in table 1 together with the complementary microwave channels from MARSS and Deimos. The window channels have dual polarisation which can provide some particle shape information.

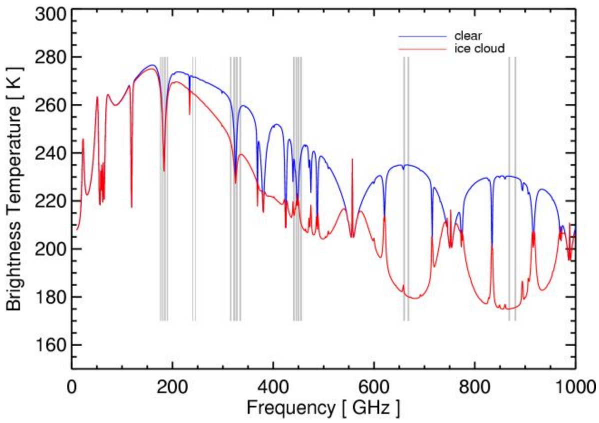

Figure 3: Simulated atmospheric signal (in Brightness Temperature) as a function of frequency as observed by the instrument looking down from high altitude [4]. The blue line shows the signal for clear skies. The red line shows the large reduction in signal for a cirrus cloud below the platform due to scattering.

Channels (GHz)		BW (GHz)	Polarisation	Feature	Aircraft Instrument
23.8	±0.07	0.127	V&H	Water vapour line	Deimos
50.1	±0.05	0.082	V&H	Oxygen line	Deimos
88.992	±1.1	0.65	V&H	Window	MARSS
118.75	**±1.1 ±1.5 ±2.1 ±3.0 ±5.0**	**0.4 0.4 0.8 1 2**	**V**	**Oxygen line**	**ISMAR**
157.05	±2.6	2.6	V&H	Window	MARSS
183.248	±1 ±3 ±7	0.45 1 2	V	Water vapour profile and snowfall	MARSS
243.2	**±2.5**	**3**	**V&H**	**Quasi-window, cloud ice retrieval, cirrus clouds**	**ISMAR**
325.15	**±1.5 ±3.5 ±9.5**	**1.6 2.4 3.0**	**V**	**Water vapour profile, Cloud ice effective radius**	**ISMAR**
424.7	±1.0 ±1.5 ±4.0	0.4 0.6 1	V	Oxygen line	ISMAR: Awaiting funding
448	**±0.8 ±2.0 ±4.5 ±11.5**	**1.2 2 3 3**	**V**	**Water vapour profile, Cloud ice effective radius**	**ISMAR**
664	**±4.2**	**3**	**V&H**	**Quasi-window, cirrus clouds, cloud ice water path**	**ISMAR**
874.4	±6.0	3	V&H	Quasi-window, cirrus clouds, cloud ice water path	ISMAR: ESA receiver development

Table 1: List of current ISMAR channels and their bandwidths, polarisation and atmospheric features (in bold). There are 2 unpopulated spaces in ISMAR which await development or funding. The microwave MARSS and Deimos instrument channels have been included for completeness. They were originally designed to match some of the AMSU A and B channels.

4. THE ISMAR INSTRUMENT

4.1. Aircraft Installation

ISMAR has been designed to fit on the FAAM BAe146-301 research aircraft, but could fit on other aircraft (e.g. HALO or Geophysika) for higher altitude measurements. It is approximately 1.1m long by 0.4m high by 0.5m deep, and weighs approximately 90kg. All of the electronics and data acquisition are housed with the instrument rather than on a rack inside the aircraft, and only aircraft power is required for operation. There is an Ethernet port such that an operator can monitor and control the instrument in flight from a laptop or rack computer when desired.

4.2. Scanning Geometry

The instrument is installed into the front bay of the blister on the side of the aircraft, as shown in figure 4. This location and the specially designed fairing allow it to have along-track scan views above and below the aircraft by use of a scan mirror. A conceptual image of the instrument is shown in figure 5 where the scan mirror directs the scene (hot or cold black body, or atmospheric zenith or nadir view) onto the detector array. In reality a large frameless servo motor is used to drive the scan mirror, which is mounted around the feedhorn cluster. The scan mirror is plain made of gold coated aluminium.
ISMAR can view scenes between +55 deg to -10 deg in nadir, and +10 deg to -40 deg in zenith, as shown schematically in figure 6. In the downward direction at high altitude the instrument acts as a pseudo satellite. The upward views provide added value by being able to study ice clouds from below with space as the background and to perform tip-curve calibrations.
The scan pattern and integration time is user defined through the software, dependent on the scientific requirement, but typically it will scan sequentially between several nadir and zenith scene views and the calibration targets, dwelling at each position for approximately 100ms.

4.4. Calibration

ISMAR has two on-board black body targets at different temperatures such that calibrations can be made in flight. The hot target is thermally controlled and its temperature is user defined up to 100°C, but it will typically be operated at 80°C. The cold target is at ambient temperature which will be slightly greater than the external temperature due to the blister environment. The targets are made from magnesium coated with Eccosorb CR-114 and have a pyramidal structure to increase absorption and emissivity through multiple reflections, as shown in figure 7. ISMAR has a wide range of frequencies and this geometry was optimum for maximising emissivity at each, whilst retaining a small size and low weight.

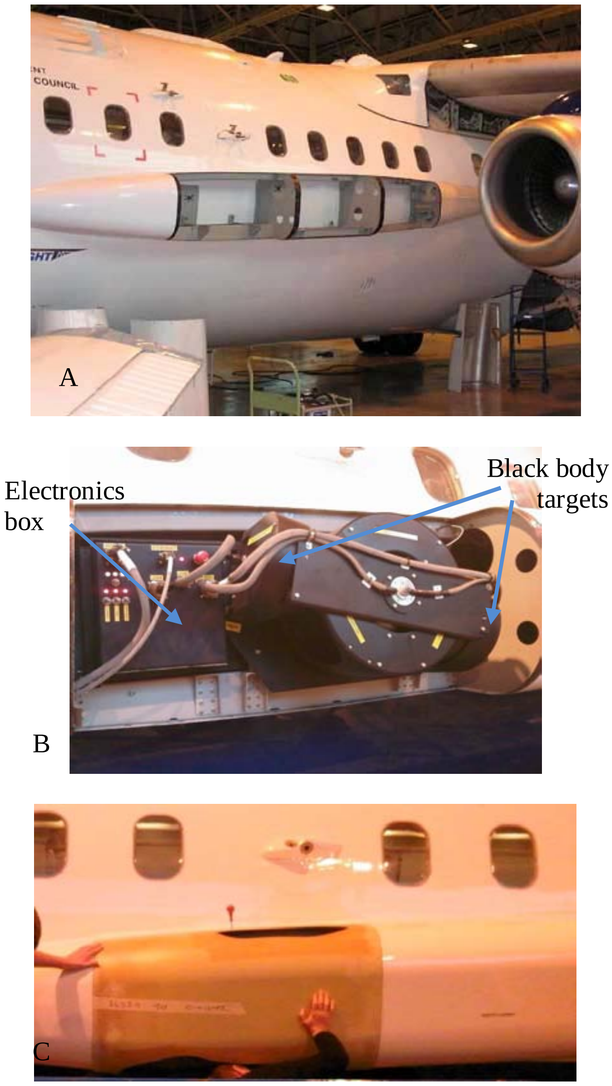

Figure 4: A) Aircraft blister on the side of the FAAM BAe146-301 aircraft which can house 3 instruments. B) ISMAR installed into the front bay. C) The front bay with the ISMAR fairing cover installed prior to painting.

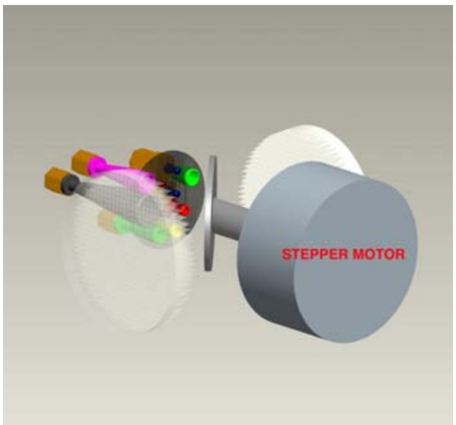

Figure 5: Conceptual image of ISMAR's receivers, two

black bodies (drawn white), scan mirror and motor.

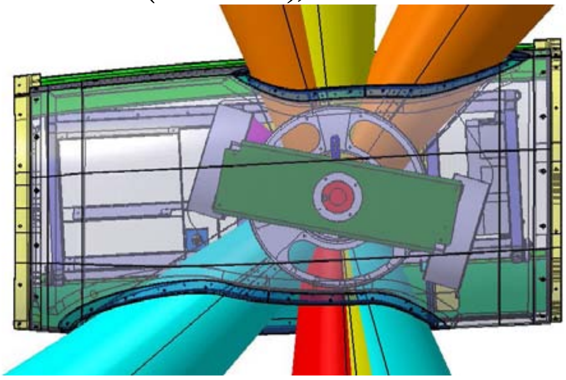

Figure 6: Schematic showing some of scan view angles of ISMAR.

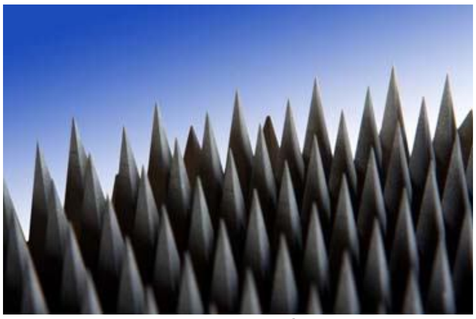

Figure 7: Pyramidal structure of the black body targets in ISMAR, designed and manufactured by RAL.

4.5. Detector System

ISMAR uses heterodyne receivers for each channel which have a direct view of the scene, via the scan mirror. This is in contrast to MARSS which uses quasi-optics to split the signal for each of its channels. Having a direct measure removes losses caused by quasi-optic components but requires the scan mirror and black bodies to be larger.

Each receiver is fitted into a “plug and turret” assembly with adjacent space available for the IF components and amplifiers. This design has allowed the instrument to be modular such that channels can be added when they become available.

Each receiver utilises a lens-feedhorn combination to produce a HPBW (Half Power Beam Width) of less than 5 degrees. The lenses are made of PTFE and blazed to minimise reflection for each frequency. The relative location of each mixer, receiver, feedhorn and lens are shown in figure 8. Figure 9 shows how the mixers (located behind the feedhorns) connect to the local oscillators via waveguides. A photograph of the fitted lenses is shown in figure 10. The 424 and 874 GHz missing channels are blanked off.

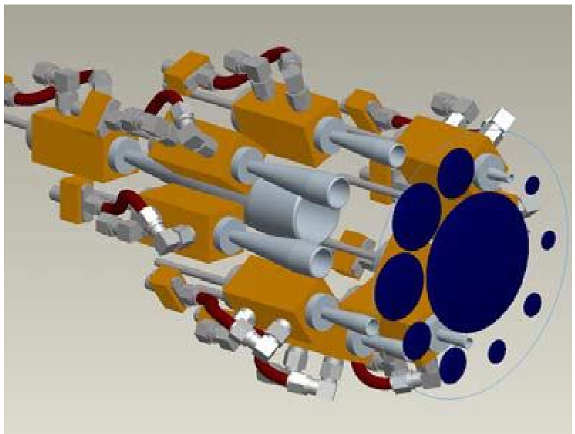

Figure 8: Drawing of the fully populated ISMAR receivers, feedhorns and lenses. The physical plug mounting is not shown for ease of visualisation.

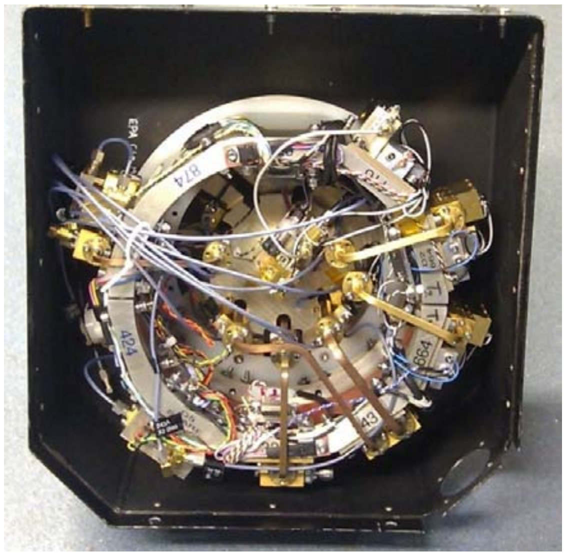

Figure 9: The rear view of the Front End receiver assembly, showing the local oscillators on the outer edge feeding into the mixers via waveguides.

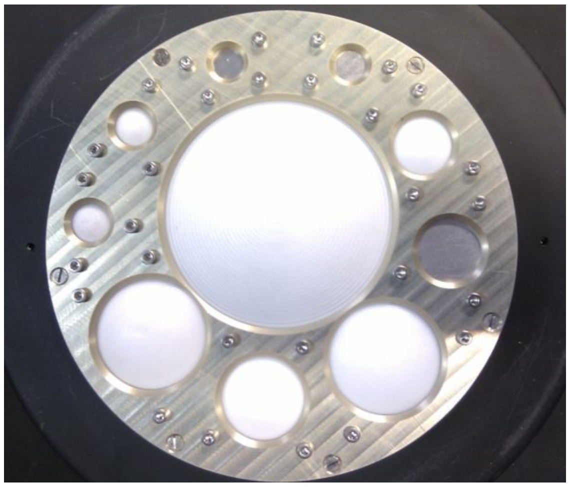

Figure 10: ISMAR’s lenses in the mounting frame. The missing channels are blanked off.

4.6. Data Collection

ISMAR uses National Instruments CompactRIO and FPGA hardware and LabView software to control the instrument and log the spectral signals, target temperatures and housekeeping. When connected to the aircraft Ethernet the instrument synchronises its time to the other aircraft instrumentation including those instruments that record GPS location, altitude, pitch and roll as well as the microwave instruments.

5. CAMPAIGNS

ISMAR in its basic form, without the channel upgrade, has already been installed and certified on the FAAM BAe146-301 research aircraft and has been test flown. For the upgraded channel instrument test flights will be performed in early November 2013, after laboratory calibrations and characterisation. An instrument performance campaign (STICCS – Submillimetre Trial In Cirrus and Clear Skies) will be operated out of Prestwick, Scotland in late November 2013. This campaign will concentrate on understanding the instrument performance in simple clear sky and cirrus cases. A scientific campaign in Canada will occur in April 2014, called COSMICS (Cold-air Outbreak and Sub-Millimetre Ice Cloud Study) to obtain further case study observations and start testing retrieval algorithms. Further campaigns are likely for more complicated case studies and in preparation for ICI.

5.1. Auxiliary instruments

The FAAM BAe146 aircraft can carry a large scientific payload (4000kg) and operate between 50 and 35000ft. This altitude range allows the aircraft to act as a pseudo satellite and the versatility of the altitudes between means that an in-situ “truth” can also be measured (including particle size distribution and ice water content), as long the conditions are not greatly varying. The large payload means that other complementary and auxiliary instruments can be flown simultaneously. For the ISMAR campaigns a range of instruments will be flown in addition to the microwave instruments (MARSS and Deimos) and the aircraft basic parameters (location, altitude, pitch roll, temperature, pressure, humidity, winds, etc). These will include an infrared spectrometer, a visible and near-infrared spectrometer, a downward facing backscatter lidar, and a range of cloud physics probes spanning the large variation in ice particle sizes. Drop sondes will be used to obtain in-situ vertical measurements of temperature, humidity and wind below the aircraft during high level runs.

6. CONCLUSIONS

ISMAR is a new submillimetre airborne radiometer which is currently undergoing an upgrade to add channels. Once upgraded it will be able to measure a variety of atmospheric parameters, in particular ice cloud mass and particle sizes. Flight testing will start in November 2013 with future scientific campaigns planned.

7. REFERENCES

1. Evans K.F., Walter S.J., Heymsfield A.J., McFarquhar G.M., (2002). Submillimeter-wave cloud ice radiometer: Simulations of retrieval algorithm performance. *J. Geophys. Res.*, **107,** D3.
2. Buehler, S.A., Jimenez C., Evans K.F., Eriksson P., Rydberg B., Heymsfield A.J., Stubenrauch C., Lohmann U., Emde C., John V., Sreerekha T.R., & Davis C.P. (2007). A concept for a satellite mission to measure cloud ice water path and ice particle size. *Q. J. R. Meteorol. Soc.* **133**(S2), 109–128.
3. Bizzari B. *et al.*, (2005). GOMAS: A Geostationary Observatory for Microwave Atmospheric Sounding. A proposal in response to ESA’s 2005 call for Next Earth Explorer Core Missions.
4. Buehler S.A., Defer E., Evans K.F., Eliasson S., Mendrok J., Eriksson P., Lee C., Jim´enez C., Prigent C., Crewell S., Kasai Y., Bennartz R., &. Gasiewski A.J. (2012). Observing ice clouds in the submillimeter spectral range: the CloudIce Mission proposal for ESA’s earth explorer 8. *Atmos. Meas. Tech. Discuss*., **5**, 1101–1151.
5. Baran A.J. (2012). From the single-scattering properties of ice crystals to climate prediction: A way forward. *J. Atmos Res*., **112**, 45-69.
6. Wendisch et al., 2005; Wendisch, M., Pilewskie, P., Pommier, J., Howard, S., Yang, P., Heymsfield, A. J., Schmitt, C.G., Baumgardner, D., & Mayer, B. (2005). Impact of cirrus crystal shape on solar spectral irradiance: a case study for subtropical cirrus. *J. Geophys. Res.*, **110**, D03202.
7. Penner, J. E. (2004). Climate change: The cloud conundrum. *Nature*, **432**, 962–963.
8. Waliser et al., 2009,; Waliser, D. E., Li, J.-L. F., Woods, C. P., Austin, R. T., Bacmeister, J., Chern, J., Genio, A. D., Jiang, J. H., Kuang, Z., Meng, 5 H., Minnis, P., Platnick, S., Rossow, W. B., Stephens, G. L., Sun-Mack, S., Tao, W.-K., Tompkins, A. M., Vane, D. G., Walker, C., & Wu, D. (2009). Cloud ice: A climate model challenge with signs and expectations of progress. *J. Geophys. Res.*, **114**, **D00A21.**
9. Waliser, D. E., Li, J.-L. F., L’Ecuyer, T. S., & Chen, W.-T. (2011). The impact of precipitating ice and snow on the radiation balance in global climate models. *Geophys. Res. Lett*., **38**, L06802.
10. Eliasson, S., Buehler, S.A., Milz, M., Eriksson, P., and John, V.O. (2011). Assessing observed and modelled spatial distributions of ice water path using satellite data. *Atmos. Chem. Phys*., 11, 375–391.

11. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., & Miller, H.L. (2007). *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK.
12. WMO (2006). Systematic Observation Requirements For Satellite-Based Products For Climate. vol. GCOS-107, WMO/TD No. 1338.
13. Baran A.J. (2012). A new application of a multifrequency submillimeter radiometer in determining the microphysical and macrophysical properties of volcanic plumes: A sensitivity study. *J. Geophys. Res.*, **117**, D00U18.
14. Charlton, J., Jarrett, M.L., Humphries, M.E., Child, R.K., Atkinson, N.L., Hewison, T.J., Slingo, A., Spilling, D.A.V., Higgins, J.M., Bray, M.A., Foster, P.R., & Matheson, D.N. (2002). Study on Future Microwave and Millimetre-wave Radiometer Requirements and Concepts, Final Report, Tech. rep., ESTEC Contract No. 14841/01/NL/MM.
15. Golding, B.W. & Atkinson, N.C. (2002). Study of Future Microwave Sounders on Geostationary and Medium Earth Orbits. Task 1 Report: Review of Preliminary List of Products and Corresponding Requirements, Tech. rep., ESA study STN/PR72/002, MGO-MET-RP-001.
16. Sreerekha et al., 2006; Sreerekha, T.R., Emde, C., Courcoux, N., Teichmann, C., Buehler, S.A., Loehnert, U., Mech, M., Crewell, S., Battaglia, A., Eriksson, P., Rydberg, B., Davis, C., Jim´enez, C., English, S., & Doherty, A. (2006). Development of an RT model for frequencies between 200 and 1000 GHz. Final Report, Tech. rep., ESTEC Contract No. 17632/03/NL/FF.
17. Jarret, M., Buehler, S., Child, R.K., Jim´enez, C., Courcoux, N., Emde, C., Heygster, G., Sreerekha, T.R., Eriksson, P., Rydberg, B., Foster, P.R., Rose, T., Davis, C., Evans, K.F., Heymsfield, A., Lohmann, U., & Stubenrauch, C. (2007). Establishment of Mission and Instrument Requirements to Observe Cirrus Clouds at Sub-Millimetre Wavelengths, Tech. rep., Final Report, ESTEC Contract No. 19053/05/NL/AR.

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