RECENT DEVELOPMENTS IN A PASSIVE SUB MILLIMETRE-WAVE RADIOMETRY MISSION FOR OPERATIONAL METEROLOGY AND CLIMATOLOGY

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Abstract

Passive Microwave Radiometry has provided an important contribution to global Numerical Weather Prediction and climatology since the mid-seventies using data using instrumentation such as AMSU-A&B and MHS. It is now widely considered that further improvements can be made by addressing the uncertainties associated with ice clouds for which there is a lack of suitable global observations. Sub millimetre-wave radiometry has the potential to make an important contribution to this range of observations.

Now that the scientific communities are addressing the Post EPS Mission requirements, several studies have been undertaken by ESA to investigate the feasibility of developing a sub millimetre-wave ice cloud mission. These studies have addressed retrieval processes and simulations, mission requirements as well as instrument design and technologies, an airborne demonstrator and the definition of an early EO Technology Demonstration mission. This paper presents a summary and the conclusions of these studies.

BACKGROUND

The use of passive sub millimetre-wave measurements to retrieve cloud ice water and ice particle size was first suggested 12 years ago by Evans and Stephens (1995) and refined in subsequent publications (e.g. Evans et al 1998). Since then scientists have submitted several mission proposals to either ESA or NASA that focus on this techniques including Kunzi (2001) and Ackerman et al (2005, 2006). The last submission to the European Space Agency was proposed by Buehler (2005), which was made for the 2005 Earth Explorer call. The proposal was called 'Cloud Ice Water path Sub Millimetre Imaging Radiometer' (CIWSIR). The mission was not selected, but was highly placed with strong recommendations to continue preparatory activities, including the collection of more data with aircraft prototypes. This paper reports on the progress of these ESA led preparatory studies which have covered mission definition based on extensive retrieval simulations, an airborne demonstrator design and campaign plan, an Earth Observation Technology Demonstration study and several sub millimetre-wave technology development programmes.

ESTABLISHING THE SUB MILLIMETRE-WAVE ICE CLOUD MISSION

The study to Establish the Cirrus Cloud Mission and Instrument Requirements at Sub Millimetre Wavelengths ran from 2005 to 2007, led by Sula Systems and supported by the University of Bremen, Luleå Technical University, Chalmers University, RPG GmbH and MAAS. The objectives were to (a) derive a comprehensive and accurate set of scientific requirements to observe cirrus clouds that will provide improvements in the understanding of cirrus clouds and their statistics and which will lead to improvements in the ice cloud schemes in numerical climate models; (b) derive a complete set of mission and instrument requirements for a sub millimetre-wave wave radiometer which meet those scientific requirements; (c) to establish a preliminary mission and instrument concept that is complementary to existing and planned operational spaceborne missions and (d) to demonstrate clearly the link between the scientific requirements and the mission and instrument specifications.

Scientific mission requirements were derived by a three stage process: first existing requirement estimates were gathered from the Committee on Earth Observation Satellites (CEOS) of the World Meteorological Organization (WMO) and from earlier studies. Next, additional requirements for cloud ice observations for different applications were formulated. Finally, the concept of break-through ranges was used to derive a comprehensive set of scientific mission requirements from the pure scientific requirements for the different applications (Table 1).

Retrieval simulations were used to test different channel combinations for a proposed instrument. The methodology and results of these simulations are discussed in detail in Jimenez (2009). Retrieval results were shown to be very robust against small changes in radiometer noise level and channel configuration, allowing considerable freedom for trade-offs with technical and programmatic mission aspects. Figures 1, 2, and 3 show retrieval performance for ice water path (IWP, top), particle size (D_{me}, middle), and cloud altitude (z_{med}, bottom), all as a function of the true IWP. Shown are retrieval results with and without additional infrared channels, as available from MetOp. Also shown are results for two different atmospheric scenarios (mid-latitude and tropical). Solid red lines indicate the scientific mission requirements.

	Horizontal Resolution	**Accuracy**	**Threshold**
IWP	5 -20km	10-50%	1 -10gm^2
z_{med}	5 -20km	100-500m	n/a
D_{me}	5 -20km	10-50µm	n/a
Spatial Coverage :	Global /Near Global		
Diurnal Sampling :	Fixed Local Time (±0.5h)		
Observation Time Period:	7 years- 1 year		
Data Time Delay :	4h (NWP only) None for Climate Research		
Observation Cycle :	6-24h		

Table 1: **Scientific Mission Requirements**

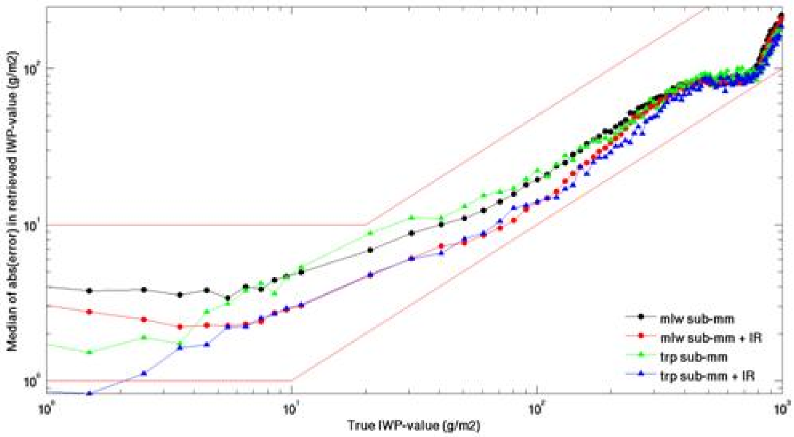


Figure 1: **Retrieval Performance for Ice Water Path (IWP).**

The resulting instrument concept was therefore based on a channel set encompassing 183GHz-664GHz with a single polarization as the simulations had not provided sufficient evidence for the upper channel, 874GHz or dual polarization as suggested in the original CIWSIR proposal. Table 2 summarises the selected channel set and estimated radiometric performance.

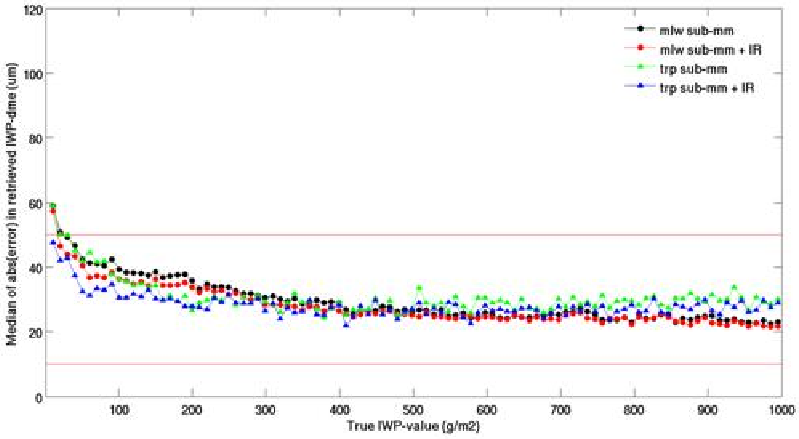


Figure 2: **.Retrieval Performance for Ice Particle Size (D_{me})**

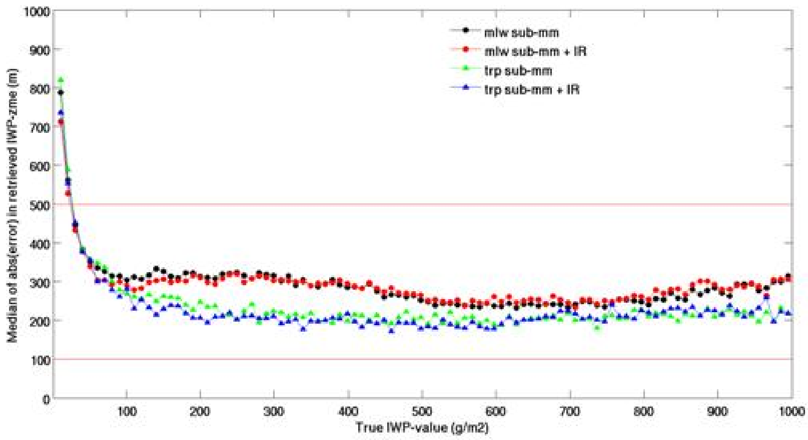


Figure 3: **Retrieval Performance for Cloud Altitude (z_{me})**

Frequency Bands (GHz)	NeΔT (K)
183GHz ±1.5, ±3.5, ±7.0	0.4-0.6
243GHz ±2.5	0.5
325.15GHz ±1.5, ±3.5, ±9.5	0.7-1.0
448GHz ±1.4, ±3.0, ±7.2	1.2-1.9
664GHz ±4.2	1.5

Table 2: **Derived Channel Set and NeΔT Performance**

The initial mission concept was therefore based on a single instrument mounted on a small satellite, flying in tandem with MetOp to allow the use of complementary data from the MetOp IR instruments. The key design features of the proposed sub millimetre-wave radiometer included a single aperture antenna concept, conical scanning, a quasi-optical antenna feed and an internal switching calibration mirror to allow views to cold space and an ambient internal calibration target. The proposed configuration and functional diagram is shown in Figure 4. This instrument would provide twelve channels all with a spatial resolution of 15km, excepting 664GHz at 7.5km. All the antenna beam efficiencies should be better than 95%.The mass was estimated as 51kg with a power requirement of 70W.

The study demonstrated that the selected mission and instrument concept was well within the scientific mission requirements range for all the critical requirements. It was concluded that the mission is scientifically justifiable with recommendations for the airborne demonstrator, a suite of technology development programme and continuation of the retrieval study to enhance the cloud. A thorough presentation of the scientific background and mission derivations can be found in Buehler et al (2007) as well as Jarrett et al (2007).

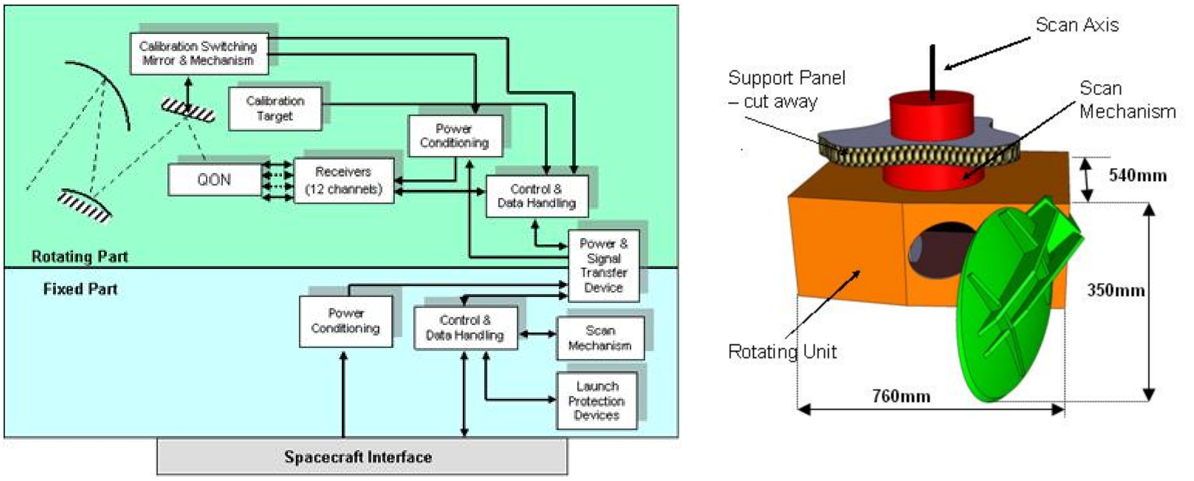


Figure 4: **Proposed Instrument Configuration**

A POTENTIAL EO TECHNOLOGY DEMONSTRATION MISSION

As ESA's missions become more complex and challenging, technology qualification through simulation and ground testing is not always sufficiently representative. Mainstream missions tend to require low-risk and therefore evolutionary technology development. For revolutionary techniques and technologies, demonstration in the space environment is essential prior to adoption for major missions and this is one of the most important roles of small satellites. While there are relatively frequent opportunities for secondary passengers to Geosynchronous Transfer Orbit (GTO), such opportunities to Low Earth Orbit (LEO) are rarer. Such an opportunity to demonstrate novel Earth Observation (EO) technologies in LEO is offered by the Vega Research and Technology Accompaniment (VERTA) Programme. The objective of ESA's EO Technology Demonstrator Study was therefore to investigate in-orbit demonstrations of spacecraft and EO technologies on a small mission within the 150 kg range exploiting the lessons learned with PROBA-1 and GIOVE-A and taking into account the near term flight opportunities.

Eight payload concepts, including the CIWSIR concept, were initially considered and this was down selected to three major payloads at the study mid-point based upon a number of criteria : (a) feasibility within the smallsat demonstration constraints i.e. typical payload mass 35-80kg, and power <50W (b) in-orbit demonstration of unproven technologies or components (c) demonstration of retrieval algorithm and processes for future missions (d) relevance to important EO current or future data needs. The CIWSIR sub millimetre-wave payload was one of the three payloads retained for study in the second phase: the opportunity to demonstrate sub millimetre-wave technologies and assess the associated retrieval algorithms was very attractive and the emerging importance of cirrus cloud was well recognised. The projected mass of the CIWSIR sub millimetre-wave payload is within a smallsat capability (e.g. such as SSTL 100 or 150 platforms), the available power is more limited but on further examination, momentum compensation was the most difficult characteristic for smallsats to manage. A conical scan had been identified in an earlier ESA study, Jarrett at al (2007) in order to provide global maps of ice cloud parameters with a constant footprint and constant polarisation mix. However this ESA EO Technology Demonstration Study concluded that a CIWSIR sub millimetre-wave payload was still viable as a technology and retrieval demonstration mission even though the global extent could not be provided. The fulfilment of these objectives alone would still be highly regarded and meet the required criteria. A fuller description of this study can be found in Chalkley et al (2009). Hence the study concluded with the recommendation that a pre-phase A study is initiated at the earliest opportunity in order to close out these remaining open points and to address some of the design issues.

THE ESA SUB MILLIMETRE-WAVE AIRBORNE DEMONSTRATOR

This ESA study considered a broad range of demonstrator requirements, based on the preliminary studies that led to the proposals for two sub millimetre-wave missions : CIWSIR (Buehler, 2005) and GOMAS (Bizarri et al. 2005) to ESA under the Earth Explorer call, with the objective of providing a design and development plan for a sub millimetre-wave airborne demonstrator for both ice cloud and precipitation observations which will be able to prove the feasibility of the scientific principles of both the CIWSIR and GOMAS (The Geostationary Observatory for Microwave Atmospheric Sounding) missions. This study also strongly benefited from the other ESA and EUMETSAT studies initiated to further analyse the observation characteristics of the two missions and optimise their performances in terms of accuracy of the retrieved geophysical variables (Jimenez et al 2007, Mech et al 2007, Defer et al 2007, Evans et al 2002, 2008).

By considering the use of existing instrumentation, upgrading or adapting that instrumentation as well as completely new instrumentation, a large number of design options were available for consideration. The down selection process considered compliance with the design and operational requirements as well as a cost benefit analysis. The outcome of the down selection process resulted in the selection of a design based upon a suite of upgraded, existing FAAM aircraft instruments: Deimos, MARSS and the most recent, the 325GHz ISMAR, the UK Met Office International Sub-Millimetre Airborne Radiometer. FAAM is the UK Facility for Airborne Atmospheric Measurements.

Table 3 summarises the spectral scope of the proposed demonstrator. Channels at 118 GHz, 243 GHz, 424 GHz and 664 GHz are to be added to the 325GHz ISMAR. The channels between 50 GHz and 54 GHz will be realized by receiver upgrades to the Deimos instrument on the FAAM, while the 183 GHz channels are already provided by MARSS on the FAAM.

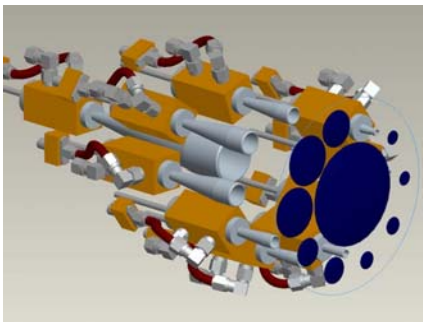
Frequency Bands (GHz)	Polarisation	NeΔT (K)	Existing Instrument
50.3, 52.825, 53.845, 54.4	V	0.3	New to Deimos
118.750GHz ±1.1, ±1.5, ±2.1 ±3.0, ±5.0	V	0.5	New to ISMAR
183GHz ±1.5, ±3.5, ±7.0	V	0.5	Existing (MARSS)
243GHz ±2.5	V and H	0.5	New to ISMAR
325.15GHz ±1.5, ±3.5, ±9.5	V	1.0	Existing (ISMAR)
424GHz ±1.0, ±1.5, ±4.0	V	1.0	New to ISMAR
664GHz ±4.2	V and H	1.5	New to ISMAR

Table 3: **.ESA Sub Millimetre-wave Airborne Demonstrator: Instrument**

Deimos and MARSS have been well reported elsewhere e.g. Hewison (1995) and McGrath et al, (2001) but ISMAR is the most recent addition to the Met Office suite of airborne instruments.

In July 2008, The Met Office succeeded in securing investment for Phase 1 of the development of ISMAR – the International Sub Millimetre Airborne Radiometer. The requirements have a considerable degree of commonality with the requirements of the ESA Airborne Demonstrator and ISMAR has been adopted as a component of the proposed ESA Demonstrator instrument suite. Based upon a modular concept, a strong design feature of ISMAR is the capability to incrementally add to the complement of radiometers. The final frequency coverage of the fully populated ISMAR will extend to 874GHz and include 448GHz but Phase 1 will result in 325GHz alone being implemented and this is designated the “325GHz ISMAR” onto which the ESA elements will be added.

ISMAR is an along-track scanning radiometer and will be mounted in the front bay of the large radiometer blister on the FAAM aircraft. Coverage of the required frequency range is implemented by an array of heterodyne receiver Front Ends mounted such that their Fields of View are parallel and oriented horizontally to port at right angles to the flight direction. Each receiver utilises a lens-feedhorn combination to produce a HPBW of 5 degrees. The instrument Field of View is directed along-track via a rotating scan drum which contains a plane mirror (Figures 5 and 6). During each scan, the instrument Field of View can be directed to a range of nadir and zenith views and either of the onboard calibration loads, which are maintained at temperatures of 230K and 370K respectively. Upgrades presently underway of the MARSS and Deimos scan electronics will permit the scan sequence of each instrument to be synchronized to the other two.



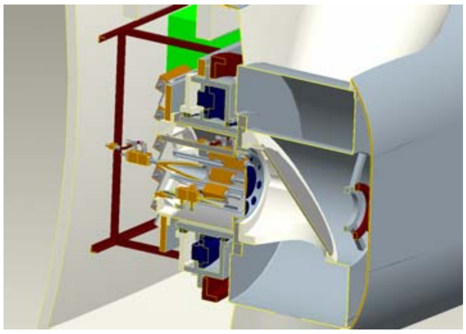
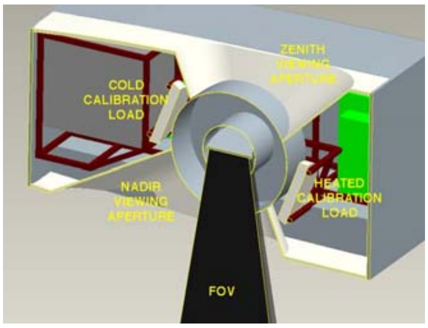


Figure 5: **ISMAR Receiver Cluster (left), cutaway view of mirror & scan drum (right)**



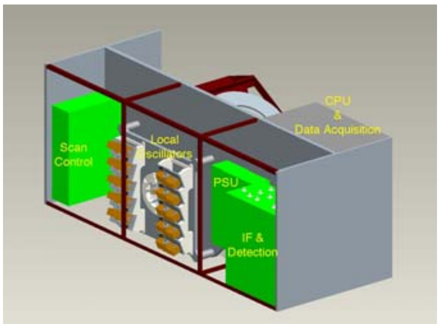
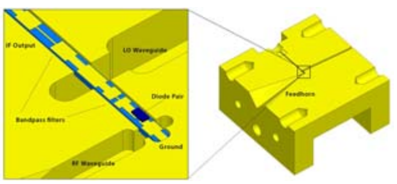


Figure 6: **ISMAR calibration loads (left) and LO & IF components mounted in inboard compartment (right)**

The study also developed a proof of concept campaign plan and this is reported in more detail in Charlton et al (2009). Further details of the ESA Sub Millimetre-wave Demonstrator design can be found in Charlton at al (2009).

RECENT SUB MILLIMETRE-WAVE TECHNOLOGY DEVELOPMENTS

A number of complementary ESA Technology Development Programmes have been started to support a new sub millimetre-wave mission. One ESA technology development initiative currently underway, funded through the General Support for Technology Programme (GSTP), aims to realise the design and manufacture of a 664GHz mixer. A novel fixed-tuned sub-harmonic mixer operating with a central frequency of 664 GHz using a discrete anti-parallel pair of Schottky diodes fabricated at STFC Rutherford Appleton Laboratory (RAL) and flip-chipped onto a quartz based microstrip circuit has been designed and manufactured (Figure 7). Simulations show a double-sideband (DSB) conversion loss of better than 10dB was achieved with 4.2mW of Local Oscillator (LO) Power across an RF range of 650-690GHz with a peak of 8dB at 663GHz.



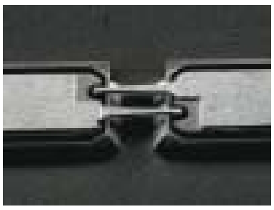


***Figure 7*:** **664GHz Mixer design (left), RAL diode chip (centre) and machined block (right)**

Other recent developments include the design and manufacture of low mass, large blackbody calibration targets at RAL (Figure 8) as well as ABSL. A pair of targets is presently being manufactured for ISMAR, each of diameter 245mm. To meet the stringent mass requirements for the aircraft instrument, the metallic core of the targets is being manufactured in magnesium alloy. The same technology would also be applicable for space instrumentation requiring large area lightweight calibration targets.

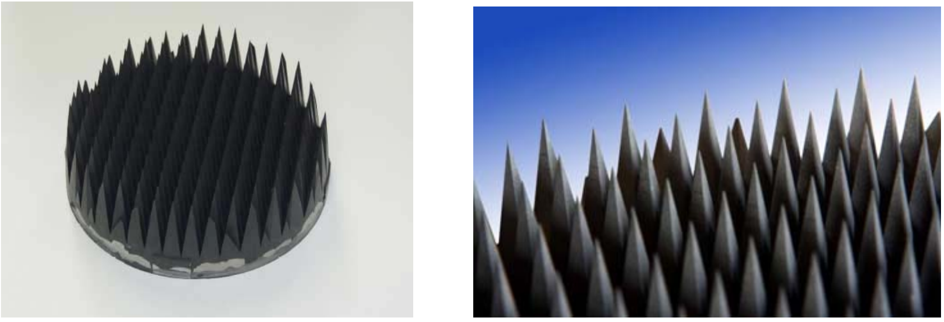


***Figure 8*: RAL Calibration Target (left) and Close-Up of Tip Geometry (right)**

Other technology development programmes include the development of Frequency Selective Surfaces as reported by Dickie et al (2009), a generic conical scan mechanism, and a contactless signal power transfer device.

CONCLUSIONS

This paper has reported on the progress of these ESA led preparatory studies which have covered mission definition based on extensive retrieval simulations, an airborne demonstrator design and campaign plan, an Earth Observation Technology Demonstration study and several sub millimetre-wave technology development programmes. In conclusion, all the ESAC recommendations made after the 2005 proposal for CIWSIR are in the process of being fulfilled while the start of manufacture of the ESA Airborne Demonstrator is expected in 2010. The next steps will be to allow the spaceborne instrument to develop in line with the rapidly maturing technology development programmes for either a EO technology mission albeit with a reduced coverage capability, or a dedicated scientific mission as in the Earth Explorer Call or in support of the Cloud Imaging Mission within the Post EPS framework.

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