INVITED SESSION

Wednesday 10 May 9:30-10:15

Chaired by :

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Future Satellite Earth Observation Requirements and Technology in Millimetre and Sub-Millimetre Wavelength Region

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Abstract
Satellite observation of Earth's atmosphere in the millimetre and sub-millimetre wavelength region is complementary to those in the visible and infrared spectral region. The emission and opacity of the atmosphere, and scattering by ice particles are all exploited for sensing various layers of the atmosphere in terms of water vapour content, temperature, molecular composition, precipitating water and ice content. Future observation requirements for limb sounding, ice cloud imaging/sounding and meteorological observations are summarized, and corresponding instrument/system concepts meeting those requirements are described.

Keywords: Atmospheric measurements, millimetre wave and sub-millimetre wave radiometry, Earth observation, meteorology, satellite remote sensing

1. INTRODUCTION

Satellite observation of the Earth's atmosphere in the millimetre and sub-millimetre (mm/sub-mm) wavelength region is complementary to those in the visible and infrared (IR) spectral region. The emission and opacity of the atmosphere, and scattering by ice particles are all exploited for sensing various layers of the atmosphere in terms of water vapour content, temperature, molecular composition, precipitating water and ice content.

Limb sounding of the atmosphere enables observation of molecular composition with high vertical resolution, which is required for understanding the global exchange and chemical processes in vertical, and the transport in horizontal direction. The exchange processes in the upper troposphere and lower stratosphere, including the formation of ice clouds, are the least well-understood area of the global atmospheric circulation and mixing. The next generation of limb sounders shall focus its observation in this atmospheric region in terms of water vapour, temperature, aerosols, ice clouds and key minor molecular components.

Observation of ice clouds in the mm/sub-mm is complementary to IR observations, and exploits their scattering property which modulates the upwelling background water vapour signature. Due to the longer wavelength as compared to the latter, the signal is more sensitive to larger ice particles and to those at lower atmospheric layers. Global distribution of ice clouds and their role on the Earth's radiative properties are two of the major uncertainties in predicting the future climate evolution. Existing general circulation models are known to fail in correctly predicting the quantity of ice in the atmosphere. Thus, global and continued observation of ice clouds represents a high priority for future satellite missions.

For meteorological applications, the definite advantage of the mm/sub-mm is its potential to provide observations under cloudy conditions. For the numerical weather prediction, the observation can be performed from low Earth orbit, whereas for nowcasting applications, high temporal resolution (e.g. 15 min.) observation from geostationary Earth orbit (36000 km) would be required. The latter applications call for a very large sensor aperture, which needs to image the Earth with a sufficient spatial resolution.

2. LIMB SOUNDING OF UPPER TROPOSPHERE AND LOWER STRATOSPHERE

The Atmospheric Composition and Upper Troposphere/Lower Stratosphere Exchange Processes mission (ACECHEM) [1], proposed as an Earth Explorer Core candidate in 2000, was studied at pre-phase A level. A further study [2] to consolidate the observation requirements confirmed the instrument complement of ACECHEM: a set of mm/sub-mm-wave and IR limb sounders with high vertical resolution, combined with the IR nadir observation by MetOp (IASI). For further consolidation of the mission objectives and demonstration of its capabilities, an airborne demonstrator MARSCHALS to be flown on the Russian Geophysica aircraft, as shown in Fig. 1, has been developed at Rutherford Appleton Laboratory [3]. The principal and most innovative objective of MARSCHALS is to simulate the capability

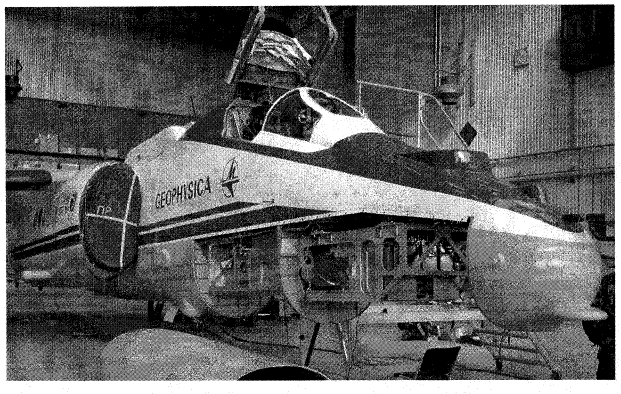

Fig. 1. MARSCHALS instrument mounted in the nose of Geophysica aircraft

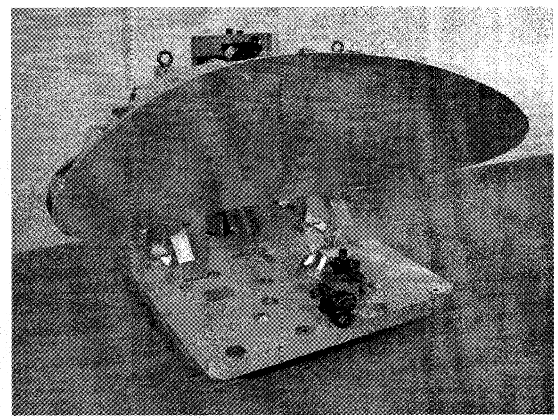

Fig. 2. ADMIRALS full-sized antenna breadboard (2200 mm × 800 mm)

of MASTER, a mm-wave limb-sounder payload of ACECHEM, for sounding O_3, H_2O and CO at high vertical resolution in the upper troposphere/lower stratosphere (UT/LS) at bands around 300, 325 and 345 GHz. Spectra are recorded in these bands with a resolution of 200 MHz. MARSCHALS is the first limb-sounder to be explicitly designed and built for the purpose of sounding the composition of the UT/LS. A particular attribute of mm-wave measurements is their comparative insensitivity to ice clouds. However, to assess the impact on the measurements of cirrus in the UT, MARSCHALS also has a near-IR digital video camera aligned in azimuth with the 235 mm mm-wave antenna. In addition to the capability to be fitted within an aircraft, MARSCHALS can also be flown on a stratospheric balloon platform when fitted with a 400 mm antenna.

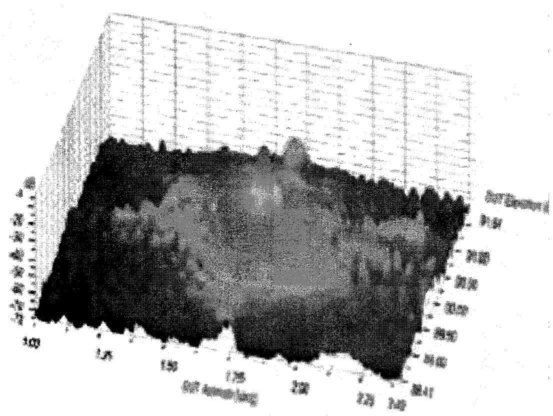

Fig. 3. Measured antenna beam-pattern at 322 GHz

Several hardware developments have been carried out for demonstrating the antenna performance for a "MASTER"-like instrument. The five-channel (203 – 503 GHz) quasi-optical demuliplexer had been breadboarded previously [4], and an aluminium full-sized reflector breadboard was manufactured by HTS in Switzerland. The complete breadboard assembly was then tested at the EADS Astrium Ottobrunn facilities. Fig. 2 shows the ADMIRALS antenna with the Quasi-optical feedbox mounted behind the main reflector, and Fig. 3 the measured beam-pattern at 322 GHz.

3. SUB-MILLIMETRE WAVE OBSERVATION OF ICE CLOUDS

CIWSIR was proposed in 2001 as an Earth Explorer Opportunity mission [5]. It is aimed at observing distribution of ice clouds, quantifying the total ice content in the atmosphere, and understanding their impact on the Earth's climate. The proposed instrument is a 5-channel, conical scanning sub-mm-wave radiometer (see Fig. 4) on a low Earth orbit satellite including channels at 183, 325, 448, 683 and 874 GHz. Two separate antennas are used for the high and the low frequency channels, respectively, providing a footprint of 10 km at all frequencies.

At this point, activities are being finalised to improve the theoretical basis for a CIWSIR type mission such as the refinement of radiative transfer models for accurate scattering calculations by ice clouds at sub-mm-wave frequencies. The latest model features [6]:

- Polarised radiative transfer
- Spherical geometry
- Many different crystal shapes, sizes & orientations
- All particle mixtures and profiles

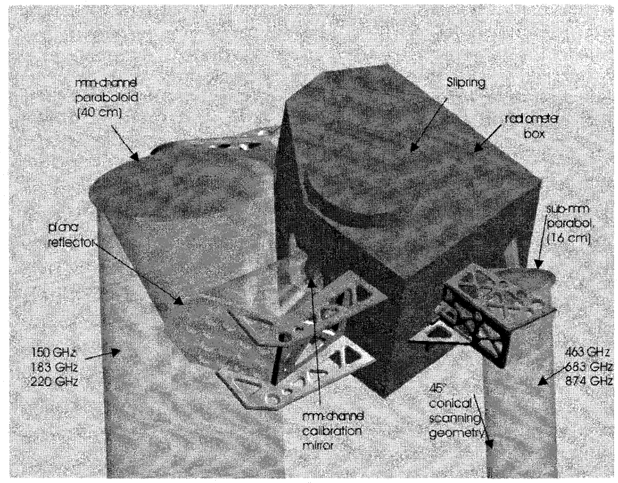

Fig. 4. CIWSIR conically scanning instrument concept consisting of separate mm- and sub-mm-wave antennas

In addition, an activity to consolidate the mission and instrument requirements for such a mission has been started. A near future activity foresees a development of an airborne demonstrator in order to gather experimental data. The technology for the 874 GHz room temperature receiver is seen as critical and would require an early development.

4. METEOROLOGICAL OBSERVATIONS FOR NUMERICAL WEATHER PREDICTION

In cooperation with EUMETSAT, the preparation for the next generation polar orbiting meteorological satellite mission (post-EPS) has been initiated in 2005, with a projected start of services in 2018. The system shall provide all-weather observation of temperature and water vapour profiles, as well as of precipitation and ocean surface wind for numerical weather prediction. The future MW sounder and imager shall provide better spatial and temporal resolution, better coverage and higher radiometric quality than the current instruments on-board the upcoming MetOp satellites. A number of candidate concepts have been developed. Among these are AMSU type cross-track scanners as shown in Fig. 5, including higher frequency channels up to 229 GHz, and conically scanning instruments reaching up to sub-mm-wave frequencies [7]. The cross-track scanner has an antenna aperture of 360 mm, resulting in a spatial resolution of 40 km at the sub-satellite point at 23 GHz. It is a compact instrument (1245 mm × 625 mm × 740 mm), which combines the capability of AMSU-A and AMSU-B with better radiometric sensitivity.

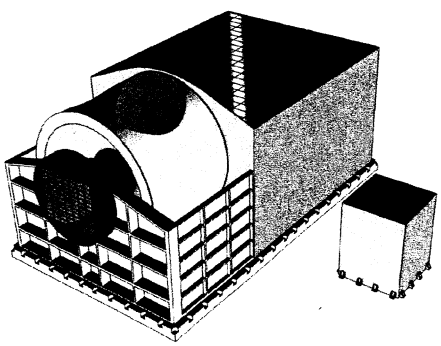

Fig. 5. AMSU type cross-track scanner

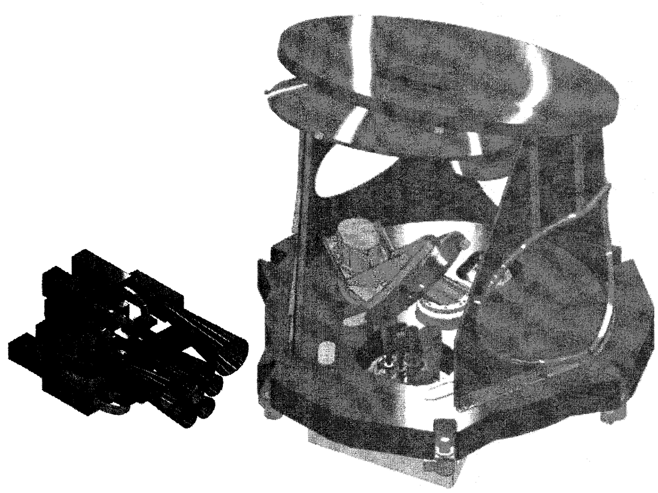

Fig. 6. Combined imaging/sounding radiometer with push-broom receivers at 54 GHz sounding band – Feed cluster shown separately on the left with 7 parallel dual-polarisation horns (the central horn is 54/118 GHz dual-frequency)

A combined imaging/sounding instrument is shown in Fig. 6, which makes use of push-broom technique with 7 parallel dual-polarisation horns in the 54 GHz sounding band, resulting in 14 parallel receivers, for achieving a very high radiometric sensitivity. For accommodating a large number of channels, two reflectors (700 and 360 mm diameter) are used to separate the low and high frequency feed clusters. The sounder/imager concepts were developed at pre-phase A level instrument studies.

As a part of early technology developments, a long-life scan mechanism, 54/118 GHz dual-frequency horn and 89 GHz direct-detection receiver are objects of breadboarding at this stage. 10 years in-orbit life is aimed for a conically scanning radiometer such as the one depicted in Fig. 6, which represents a challenging requirement. Fig. 7 shows the design of a 89 GHz direct-detection receiver frontend. A more compact, mass-efficient receiver can be built as no local oscillator is required for down-conversion. The low noise amplifier MMIC was processed at Fraunhofer Institute in Germany, and the frontend block was integrated at EADS-Astrium SAS, and is undergoing a detailed characterisation test.

5. NOWCASTING OBSERVATIONS

Millimetre and sub-mm-wave imager/sounders are considered for future meteorological and climate observation satellites. In coordination with the EUMETSAT's Meteosat Third Generation (MTG) preparatory activities, ESA is conducting studies of future microwave imager/sounder in geostationary (GEO) and medium Earth orbits (MEO) [8]. The primary advantage of a GEO orbit for remote sensing, compared with a Low-Earth (LEO) orbit, is that continuous monitoring is possible over a large area of the Earth's surface and atmosphere. This is desirable for the observation of rapidly evolving meteorological phenomena such as convective systems, precipitation and cloud patterns, enabling nowcasting.

The principal emphases in all of the concepts are the observations of precipitation, ice clouds, atmospheric motion vectors and temperature and humidity sounding with high temporal resolution (15 – 30 min.) and a horizontal resolution of better than 10 km. The proposed frequencies range from 54 to 875 GHz, out of which the bands around 54GHz, 118GHz, 183GHz, 380GHz have the highest user priority followed by the corresponding window channels 110GHz, 150GHz, 340GHz and, finally 424GHz, 683GHz, 875GHz.

The main technical challenges are the very large antenna aperture for achieving the required spatial resolution (40 folds increase in the distance to the Earth as compared to the LEO) and the necessity for imaging using two-dimensional scanning due to the absence of a relative spacecraft-Earth movement. Furthermore, other challenges are the wide frequency and the optimisation among radiometric accuracy, geographical coverage and repeat cycle. Fig. 8 shows a imager/sounder concept based on the use of a 4 m diameter reflector antenna.

A two-dimensional mechanical scanning of the reflector is limited within an area of 5000 km × 5000 km centered on Europe every 15 min. This limitation is a result of the trade-off among temporal sampling, radiometric sensitivity and coverage, and it takes into account of achievable reflector acceleration during the scan.

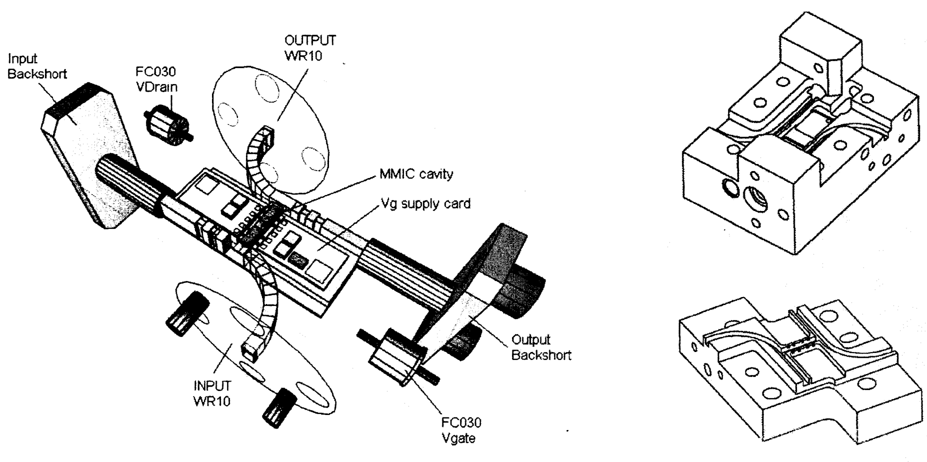

Fig. 7. 89 GHz direct-detection receiver frontend in split-block technique

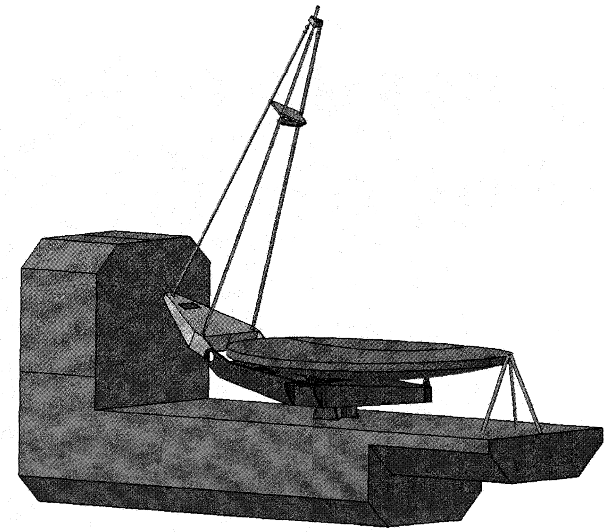

Fig. 8. GEO imager/sounder concept based on 4 m diameter mechanically scanned reflector

An alternative to the GEO concept is the use of an elliptical MEO such as 8 hours Molniya orbit with apogee at 27000 km altitude [9]. It has a repeat cycle of 24 hours and enables observation of successively Europe, North America and South-East Asia, each with 6 hours imaging period. Fig. 9 shows the satellite path over such a 24 hours period and demonstrates an optimum observation geometry (low incidence angle) for the northern hemisphere. Due to the lower altitude of the apogee with respect to the GEO, a smaller antenna can be used for a same spatial resolution, hence easing the design of the scan mechanism. From the technology point of view, radiation shielding, precise orbit analysis, scan pattern and scan mechanism are issues to be investigated in detail. For ensuring a 24-hour coverage, a total of 4 satellites would be required.

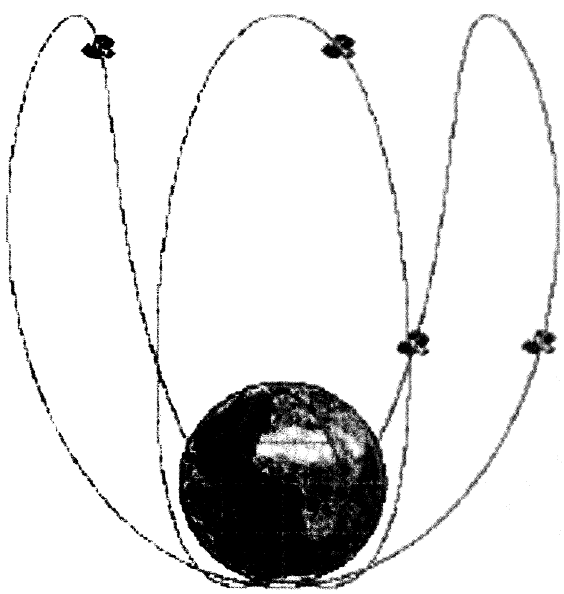

Fig. 9. MEO imager/sounder in 8-hour Molniya orbit - Satellite path over 24 hours period

The technological challenge represented by such instruments is now addressed by an ambitious demonstrator programme. Two competing concepts were investigated: a conventional, large scanning reflector antenna concept and an interferometric aperture synthesis concept. The interferometric concept showed most potential to meet the required spatial resolution from geostationary orbit, and was thus selected for a concept demonstration. In this concept, approximately 500 receivers in total are distributed to form an effective aperture of 8 m diameter. The instrument covers the highest priority frequency bands as indicated above.

6. CONCLUSION

A review of possible instrument concepts for future satellite missions in mm and sub-mm-wave spectral region was presented. For each of the application areas, the corresponding observation requirements lead to a specific radiometer design. The general trend for the future is marked by a better radiometric sensitivity and accuracy, higher spatial resolution and higher number of channels for enabling better observation quality. Very low noise receivers are required with compact volume and light weight. Receiver backends must offer high number of channels with sharp frequency cut-offs. The antenna size needs to be increased with very high mechanical stability and thermal properties, and it must be at the same time light weight. For applications requiring very large aperture, the new interferometric concept will compete against the classical reflector-based instruments. Nevertheless, such a concept still requires substantial developments in the areas of miniature frontend design, local oscillator signal generation and distribution, stable IF-signal transmission over long distances, receiver calibrations, very large number of signal-correlators, etc. A dedicated technology development has recently been started by ESA.

7. REFERENCES

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