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MICROWAVE ATMOSPHERIC SOUNDING FROM GEOSTATIONARY ORBIT: THE CASE FOR A COOPERATIVE DEMONSTRATION MISSION

The need for early demonstration of MW/Sub-mm technology in GEO for the purpose of frequent all-weather temperature/humidity sounding and precipitation was identified in previous sessions of CGMS. The purpose of this paper is to inform CGMS about current/planned activities on this subject and prepare the agencies concerned to receive, in due time, a proposal for an implementation programme.

The paper briefly reminds of the status of definition of user requirements for future geostationary meteorological satellites in Europe and the USA. Those implying the use of MW radiometry (all-weather temperature and humidity sounding and precipitation) require a new approach, since the techniques used in LEO would lead to extremely large antennas.
The principle of MW sounding applicable from GEO implies the use of very-high-frequency microwave and sub-millimetre wave, to reduce antenna size. Absorption bands of O_2 and H_2O are used, at several different frequencies differently affected by liquid and ice water, hence precipitation. The principle is equally applicable over sea and land, and to convective rain as well as frontal rain, light rain and snowfall.

Projects in the USA (GEM) and in Europe (GOMAS) are being elaborated, closely coordinated. With current-state technology it should be possible to cover an area of about 1/12 of the disk each 15 min. For a demonstration mission, a dedicated satellite is thought, of the “smallsat” class, possible to be drifted along the equator for experiencing over more areas.

Current activities aim at preparing, within a couple of years, a consolidated proposal for implementing a demonstration mission. There will be technological activity to clear certain critical items, and scientific activity of modelling clouds and rain at these very-high frequencies and collecting experimental data by airborne campaigns.

Note: this document has been prepared by Dr. Bizzarro Bizzarri on request of the EUMETSAT Director General as an input for possible discussion at CGMS XXX (Bangalore, 11-14 November 2002). This does not imply EUMETSAT endorsement of the content, which remains responsibility of the Author.

MICROWAVE ATMOSPHERIC SOUNDING FROM GEOSTATIONARY ORBIT: THE CASE FOR A COOPERATIVE DEMONSTRATION MISSION

1. Introduction and purpose of document

This document reports about an activity undertaken in compliance with the concepts and proposals contained in the following WP's presented to previous CGMS sessions by the same Author:

- CGMS XXVII EUM/WP-06 - *Compliance of the post-2000 satellite-based component of GOS with requirements and possible approach to update/upgrade future systems*.
- CGMS XXVIII USA/WP-08 - *Requirements and possible approach to update/upgrade the satellite-based component of GOS*.
- CGMS XXIX EUM/WP-06 - *Towards an updated/upgraded Global Observing System.*

Specifically, the third document introduced a table of recommended developments paving the way to future advanced operational systems. A wide-scope recommendation was for CGMS to coordinate the plans for the definition of geostationary meteorological satellites of the next generation. One specific recommendation was focusing on the need for early demonstration of MW/Sub-mm technology in GEO for the purpose of frequent all-weather temperature/humidity sounding and precipitation.

On this subject, intensive activity has taken place in the past 1-2 years, conducted by a few (connected) groups in Europe and the USA. A scientific and experimental programme is being defined (and, in part, already undertaken) aimed at preparing, within a couple of years, a consolidated proposal for a demonstration mission to be implemented by R & D space agencies with endorsement and support by operational agencies responsible, thereafter, of sustaining long-term continuity within the Global Observing System.

The role of CGMS in this undertaking has been, i.a., identified by the ITWG. In CGMS XXX USA-WP-33 (*Report from the International TOVS Working Group*), under section 4.4.1 (*New initiatives for geostationary sounding*) we find the following "***Recommendation (CGMS):*** *ITWG recommends that a geostationary millimetre/sub-millimetre radiometer mission should be pursued as a technology demonstrator, with priority towards measurement of precipitation, cloud water/ice and humidity at high temporal frequency in support of nowcasting and short-range forecasting, and as a potential future contribution to the Global Precipitation Mission.*"

In addition, the subject has been addressed by the IPWG. In CGMS XXX WMO WP-14, under the heading "*Report of the Research Activities Working Group*", sub-heading "*Future Sensors*", it is reported that IPWG adopted "***Recommendation 1:*** *Indications for future sensors should emerge from the work of the IPWG research group based on the identified scientific outstanding areas*" and has undertaken the following "***Actions:*** *i) Generate a framework for the development of a multi-frequency simulator, orbit configurations, required to optimise future sensors with respect to different application areas; and ii) Definition and provision of experimental data sets*."

The purpose of this paper is to inform CGMS about current/planned activities and prepare the agencies concerned to receive, in due time, a proposal for an implementation programme.

2. Towards the definition of the mission of future geostationary meteorological satellites

The establishment of user requirements for the next generation of meteorological geostationary satellites has started in both Europe and the USA. *Applications Expert Groups* worked in EUMETSAT throughout 2001. Their work culminated with the "1st post-MSG User Consultation Workshop" (13-15 Nov 2001). In the USA, a "1st GOES Users' Conference" was held on 22-24 May 2001 and the "2nd GOES Users' Conference" on 1-3 October 2002.

Table 1 reports a free assessment of the Author on the feasibility of meeting the user requirements emerging from both processes. Only the main requested parameters are considered, driving the system design. The Table reports, for each parameter, the possible physical principles to be exploited, both from GEO and from LEO. Principles leading to a typical instrument are listed in the same column. The last two rows identify the instrument type and provide a statement of their technological maturity. The colours provide an evaluation of the degree of compliance of the derived products with user requirements expressed in terms of horizontal resolution, vertical resolution, accuracy and observing cycle. These change with application (Global NWP, Regional NWP, Nowcasting, ...): the Table reflects a reasonable blend of them.

Table 1. Qualitative assessment of the feasibility of complying with user requirements

PARAMETER	OBSERVABLES FROM GEO				OBSERVABLES FROM LEO	
Temperature and humidity profile	IR emission from different atmospheric layers by spectroscopy.		Emission from different layers by MW/Sub-mm radiometry.		IR/MW emission from different atmospheric layers by spectroscopy.	Occultation of signals from GPS received by a LEO satellite.
Wind profile	Motion of water vapour patches by IR spectrometers with frequent observing cycle. Derived by 4-D assimilation of frequent temperature / humidity profiles.	Tracers motion (clouds, water vapour and ozone patches) measured by VIS/IR image sequences.			Tracers motion (clouds, water vapour and ozone patches) measured by overlapping VIS/IR images at high latitudes.	Backscattered light from aerosol eddies or molecules by Doppler lidar.
Cloud pattern, type and evolution; water vapour growth		Frequent measurement of scattered and emitted radiation in several VIS/IR channels in atmospheric windows and water vapour absorption bands.			Scattered and emitted radiation in several VIS/IR channels in atmospheric windows and water vapour absorption bands.	
Precipitation rate	Derived by 4-D assimilation of frequent temperature / humidity profiles.	Correlation with cloud top ice as observed by VIS/IR radiometry.	MW/Sub-mm radiation in absorption bands - Gross profile possible.	Correlation with lightning intensity and flashes/time in a given area.	Correlation with lightning intensity and flashes/time in a given area.	MW backscattering from raindrops by radar - Profile provided. MW radiation in atmospheric windows.
INSTRUMENT	**IR sounding spectrometer.**	**VIS/IR imaging radiometer.**	**MW/Sub-mm radiometer.**	**Lightning mapper.**	**LEO technique also applicable to GEO.**	**LEO technique not applicable to GEO.**
FEASIBILITY	**Demonstration mission being developed in US.**	**Current practise. Improvements feasible.**	**To be demonstrated.**	**Demonstrated in LEO.**	**Current, or demonstration occurred.**	**Demonstrated or planned.**

Colour code	Marginal compliance	Poor compliance	Fair compliance	Good compliance	Excellent compliance

The Table shows that, by developing the appropriate instrumentation and exploiting an appropriate blend of GEO and LEO satellites, it is possible in principle to observe "Temperature and humidity profile" and "Cloud pattern, type and evolution; water vapour growth" with an excellent degree of compliance, whereas the observation of "Wind profile" and "Precipitation rate" can reach a good degree of compliance. The bottom part of the Table shows that the feasibility of achieving these targets relies on a blend of: i) natural evolution of current techniques (VIS/IR imaging radiometers), ii) exportation to GEO of technologies experienced in LEO (IR sounding spectrometers), iii) additional demonstrated payloads (lightning mapper) and iv) new developments to be demonstrated (***MW/Sub-mm radiometry)***.

3. The principle of MW atmospheric sounding from GEO

The purpose of MW/Sub-mm sounding from geostationary orbit, according to Table 1, would be:

- nearly-all-weather temperature and humidity sounding
- precipitation rate.

The driving parameter is precipitation rate, since it is required at short intervals, say, each 15 min. Unfortunately, the technique used in LEO, making use of atmospheric windows at frequencies as low as 6, 10, 19, 37 and 90 GHz and requiring differential polarisation, are not applicable, since the antenna diameter implied by a typical resolution of, say, 10 km, would need to be 15 m at 90 GHz, 35 m at 37 GHz, 70 m at 19 GHz, etc. ! In addition, polarisation differentiation at the low zenith angles proper of observing from the geostationary orbit would be impossible. A different observing principle needs therefore to be exploited.

The approach proposed for the geostationary orbit is to use higher frequencies to reduce antenna size and absorption bands instead of atmospheric windows: direct observation of raindrops is not attempted. "Slicing" absorption bands of O_2 by several channels in areas of different absorption strength enables retrieving the atmospheric temperature profile; channels in bands of H_2O enable retrieving the humidity profile. This technique is operationally used on NOAA satellites: AMSU-A, for temperature, exploits the 54 GHz band of O_2; AMSU-B, for humidity, exploits the 183 GHz band of H_2O. The primary purpose of AMSU is to retrieve nearly-all-weather temperature and humidity profiles, since at 54 and 183 GHz clouds are rather transparent, except when generating heavy precipitation. The sensitivity to clouds increases within a band for channels moving from the peak of absorption to the wings, so that a set of channels in a band performs "slicing" of the vertical structure of the cloud. For bands at increasing frequencies, sensitivity to clouds increases. These two effects (increase of cloud impact both moving to higher frequency and moving from peak to windows) are shown in ***Fig. 1***. See, for instance, the increasing cloud area moving from the peak 183 ± 1 GHz to 183 ± 3 GHz and then 183 ± 7 GHz (nearly window); or from 325 ± 1 GHz to 325 ± 3 GHz and then 325 ± 9 GHz (nearly window); and moving across windows from 90 GHz to 150 GHz, 183 ± 7 GHz, 220 GHz and 325 ± 9 GHz.

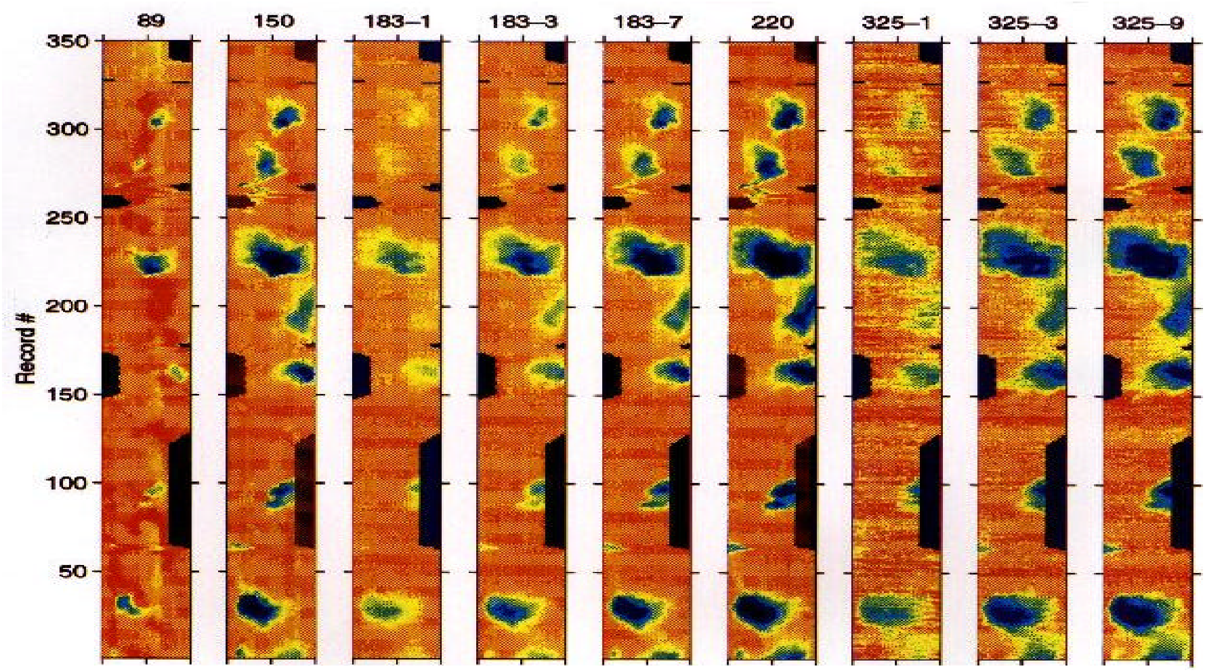


Fig. 1 - Image strips of convective precipitation cells over ocean obtained by a multi-channel airborne radiometer. Scenes of 40 km (width) x 200 km (length) (from Gasiewski et al., 1994).

Channels in absorption bands have already been used to retrieve precipitation, as shown in ***Fig. 2***, from the operational NOAA/AMSU sounder.

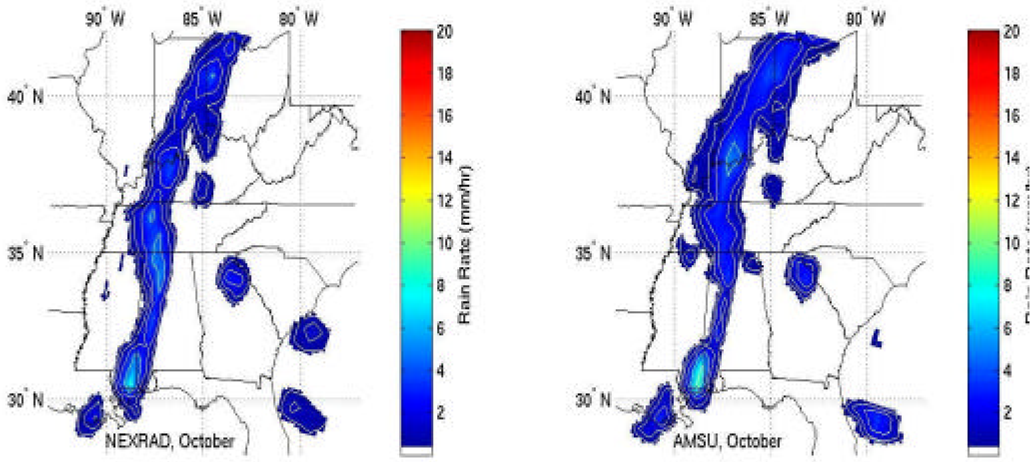


Fig. 2 - Precipitation images from a cold front on October 7, 1998. Left: NEXRAD map smoothed to 15 km resolution; right: NOAA/AMSU map obtained using a neural net retrieval technique (from Staelin and Chen, 2000).

Higher frequencies strongly respond to scattering and emission from convective cells with substantial ice content aloft, which is correlated with cloud particle size distributions and rainfall rates. ***Fig. 3*** shows an exercise based on the operational AMSU B.

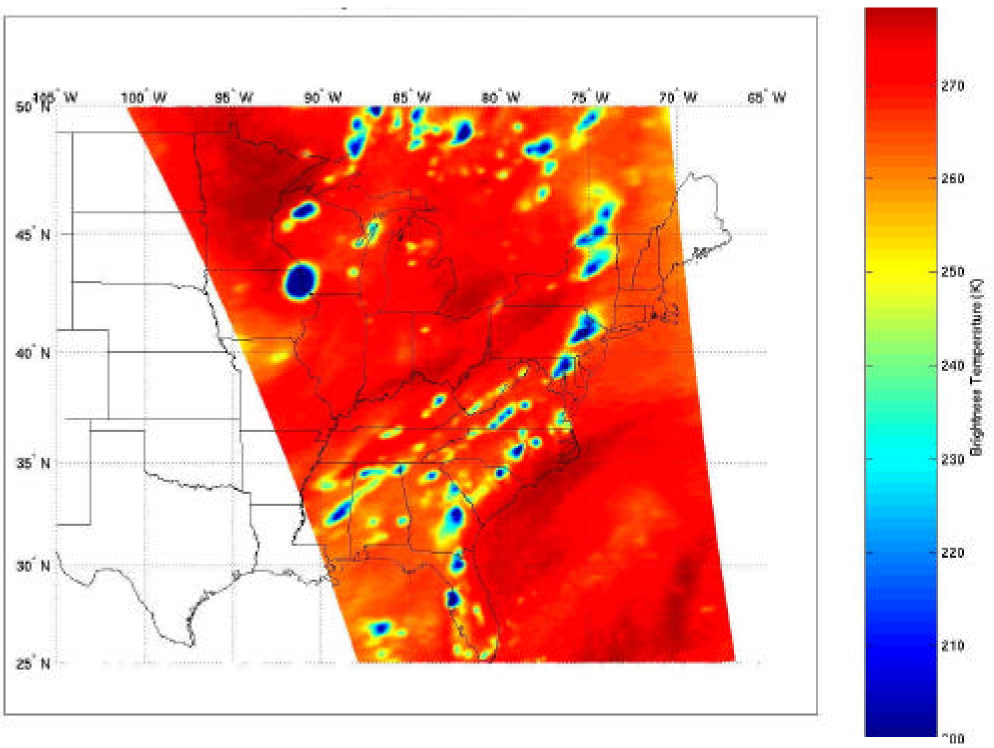


Fig. 3 - NOAA-15 AMSU-B 183+/-7 GHz 15-km resolution imagery of small rain cells over the Eastern U.S on August 2, 2000 (from Staelin and Chen, 2000).

With increasing frequency of the absorption band utilised, sensitivity to cloud increases. The next absorption band of O_2 is centred close to 118 GHz. “Slicing” that band again enables retrieving atmospheric temperature profile: however, now the profile is more disturbed by a rainy cloud. ***Fig. 4*** shows what can be inferred by exploiting differential information from the 54 and 118 GHz bands. In the top figure the ratio between temperature profiles obtained independently from the 118 and the 54 GHz bands is reported, as the aircraft travels. If there is no precipitation the ratio of the two temperature profiles is unity throughout the entire vertical range. When precipitation is present the ratio becomes less than unity below the altitude of the precipitation cell due to higher attenuation at 118 GHz than at 54 GHz. The effect is the result of the use of “similar clear-air weighting functions” along with the difference in ice scattering characteristics for the two wavelength regions (Gasiewski and Staelin, 1990; Gasiewski, 1992). The bottom part of Fig. 4 reports the precipitation profile simultaneously recorded by the Doppler radar onboard ER-2 (EDOP). The agreement is striking. A glance to the horizontal maps of Fig.’s 2 and 3 and the vertical cross section of Fig. 4 invites to infer that, if MW sounding in several bands of different frequency is possible to be implemented in geostationary orbit to perform observation at, say, 15 min intervals, meteorologists will have ***a proxy rain radar operating over continental field of view, and particularly over oceans and mountainous terrain.***

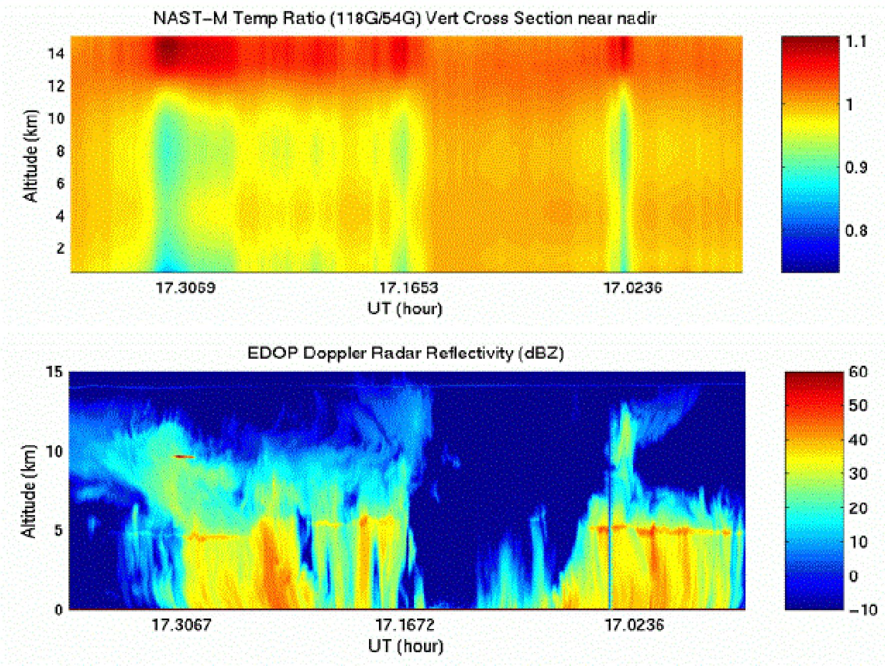


Fig. 4 - Comparison between the 118/54 GHz profile ratio from the NAST-M microwave radiometer on the NASA ER-2 aircraft and simultaneous EDOP Doppler radar reflectivity observation. Hurricane Bonnie at 17 GMT on August 26, 1998 (from Tsou et al., 2001).

With frequencies such as 54, 118 and 183 GHz, however, we are still far from meeting the requirement for antennas of affordable size. From the geostationary orbit, a 10-km resolution still requires diameters of 25, 11 and 7.3 m, respectively. We must move to substantially higher frequencies. ***Fig. 5*** shows the atmospheric absorption spectrum in the range 2 to 1000 GHz. It can be observed that the next useful O_2 band is around 425 GHz, and the next H_2O bands are around 325 GHz and (preferred) 380 GHz. It is noted that, from the geostationary altitude, a resolution of 10 km at 380/425 GHz is achieved by means of a ***3-m antenna***, which is thought to be feasible and affordable.

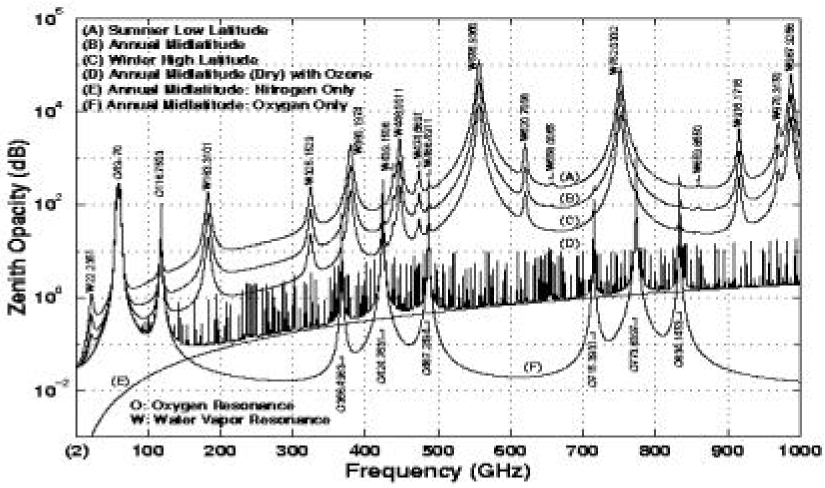
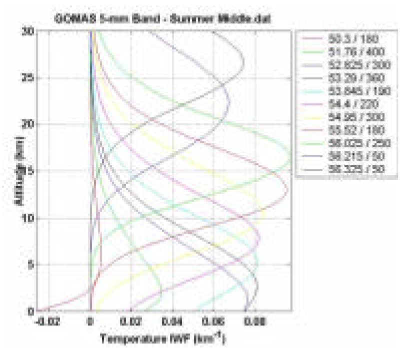


Fig. 5 - Atmospheric spectrum in the MW/Sub-mm ranges (from Klein and Gasiewski, 2000).

Incremental weighting Functions (IWF) of selected channels in the bands 54, 118, 183, 380 and 425 GHz are shown in ***Fig. 6***. It is observed that, in the bands 380 and 425 GHz, the lower troposphere is badly observed, whereas bands 54, 118 and 183 GHz can be used to observe down to the Earth surface.



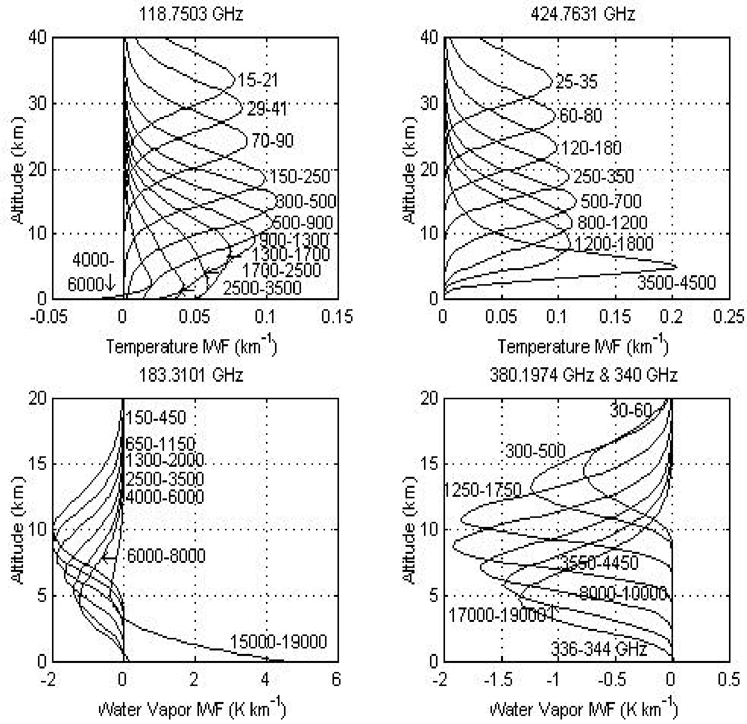


Fig. 6 - Incremental weighting functions (IWF) for temperature and humidity in the bands 118, 183, 380 and 425 GHz. The numbers attached to the curves indicate the distance (in MHz) from the frequency of the peak (from Klein and Gasiewski, 2000). The IWF's relative to the 54 GHz band, more familiarly used, also are plotted (courtesy of A. Gasiewski).

Temperature and humidity profiling is not the primary objective of MW in geostationary orbit; however, the expected results are rather interesting. ***Fig. 7*** shows simulated retrieval errors for temperature and humidity. It may be observed that, for temperature, 118 + 425 GHz as stand-alone are rather good for the Higher Troposphere and Lower Stratosphere (UT/LS). When added to an IR sounder of the class of IASI or AIRS ("GAIRS") the performance is as good as for the reference AIRS + AMSU/A + AMSU/B of EOS-Aqua, except in the lower troposphere. The 54 GHz band therefore continue to be necessary. For humidity, the 380 GHz band (helped by 425) performs better than the 183 GHz band (helped by 118) in the UT/LS, worse in the medium and low troposphere. The full set 118, 183, 380 and 425 is optimal. The accuracy of water vapour profile in the UT/LS (better than 10 %) is very valuable for <u>climatology</u> and difficult to be achieved by any other technique including IR spectroscopy, except lidar.

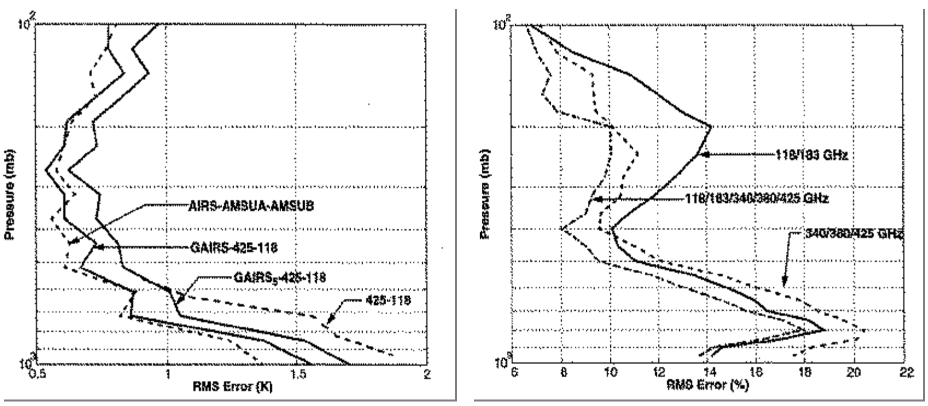


Fig. 7 - Retrieval errors for bands 118, 183, 380 e 425 GHz, stand-alone or associated to an IR sounder of the IASI or AIRS class ("GAIRS"). Temperature on the left hand, humidity on the right. On the left hand, GAIRS + 118 + 425 is compared to GAIRS alone and to 118 + 425 alone. For reference, the EOS/Aqua AIRS + AMSU/A + AMSU/B complex also is shown (Blackwell and Staelin, 1996).

4. Current projects: GEM and GOMAS

Two proposals for MW/Sub-mm sounding are being pursued: in the U.S., ***GEM (Geostationary Microwave observatory)***, in Europe, ***GOMAS (Geostationary Observatory for Microwave Atmospheric Sounding)***. GOMAS entirely builds on GEM, the main difference being that GEM is somewhat smaller (2-m antenna) because of the attempt to embark it on GOES-R, whereas GOMAS (3-m antenna) has a resolution more suitable to European latitudes and is conceived as a stand-alone mission. Short description of GEM is given by *Staelin et al.*, 1998, of GOMAS by *Bizzarri et al.*, 2002. Both concepts exploit the five bands 54, 118, 183, 380 and 425 GHz, with a total of about 40 channels.

Although temperature and humidity profiling is not the primary objective, the principle exploited to measure precipitation passes through full profiling. Profiles from different bands are differently affected by liquid and ice water of different drop size and shape, and finally by precipitation, so that simultaneous retrieval of all these quantities is necessary. One consequence is that the number of channels in each band (6 to 11), their width (< 1 ‰) and the radiometric accuracy (SNR > 100) must be sufficient for accurate profiling.

Preliminary studies have shown that this is possible by current technology in 15 min only if the scanned area is limited to about 1/12 of the Earth visible disk, e.g. the sector shown in ***Fig. 8***. In addition, although sampling is performed at 10 km s.s.p. for all channels and bands, pixels are averaged in software (at ground) so that the final product has a resolution resembling the IFOV size and, contextually, the radiometric resolution is recovered, necessary for profiles retrieval.

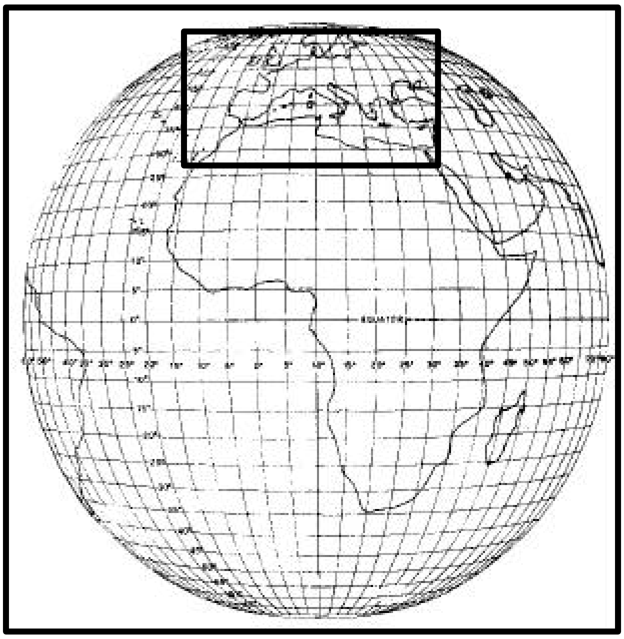


Fig. 8 - Earth's disk observed by Meteosat and reference coverage in 15 min from GOMAS

The sector of Fig. 8 is defined only for radiometric computation purposes. As a matter of fact, it will be possible to move it everywhere in the disk, and also change its shape and extend it up to the full disk, accepting that the observing cycle will change accordingly (it would be 3 h for full disk scanning). If implemented as a stand-alone satellite for a demonstration mission, it will be possible to drift the satellite across longitudes to cover from USA to India, according to the experimentation programme.

The observations to be performed are listed in ***Table 2***. The product resolution, quoted at the sub-satellite-point (s.s.p.), refers to antenna sizes of 3 m (GOMAS) and 2 m (GEM).

Table 2 – List of observation from GEM/GOMAS and expected resolution

Observation	Resolution at s.s.p.	
	3-m antenna	2-m antenna
Temperature profile, all-weather and inside clouds	30 km	45 km
Humidity profile, all-weather and inside clouds	20 km	30 km
Cloud liquid water, columnar content and gross profile	20 km	30 km
Cloud ice water, columnar content and gross profile	20 km	30 km
Precipitation rate	10 km	15 km
Each 15 minutes, over ~ 1/12 of the disk covering sea and land		

A sketch view of the instrument is shown in ***Fig. 9***. Its sizing features, in the GOMAS configuration, are:

- antenna: ∅ = 3 m, 40 kg, 40 W
- radiometer: $30 \cdot 50 \cdot 50$ cm^3, 67 kg, 95 W
- total: 107 kg, 135 W, 115 kbps.

A sketch view of the satellite, in the GOMAS configuration (i.e., as a stand-alone mission), is shown in ***Fig. 10***. Its sizing features are:

- mass: 860 kg ("dry": 430 kg)
- electrical power: 500 W
- volume: $3.0 \cdot 3.0 \cdot 3.0$ m^3 (stowed)
- data rate: 128 kbps (S-band, compatible with direct reception at the low-cost MSG LRIT stations).

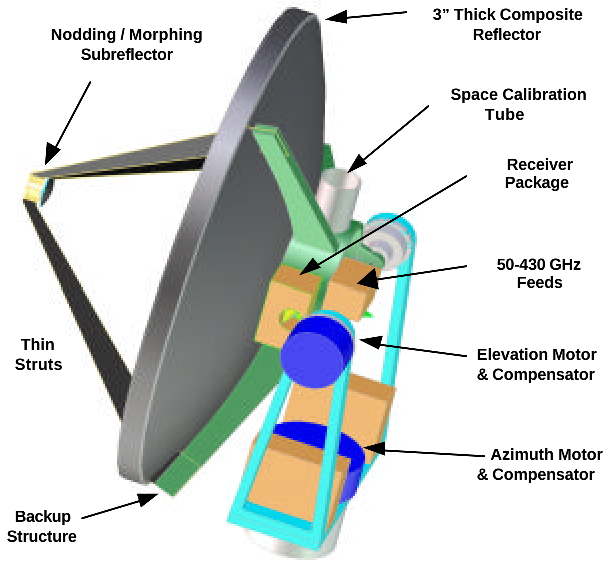


Fig. 9 - Sketch view of the instrument.

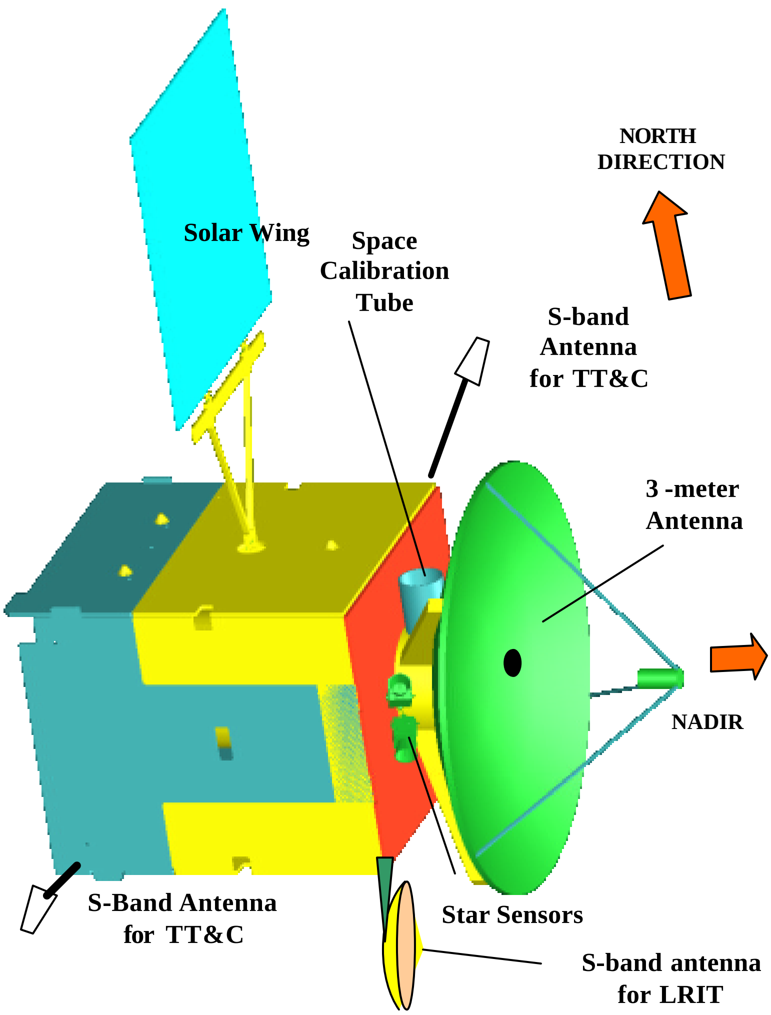


Fig. 10 - Sketch view of the GOMAS satellite.

5. Current and planned activities. Conclusions

GOMAS is proposed as a demonstration mission. It would be a precursor for future operational applications. From the technical standpoint, and building on the studies conducted in the U.S. on GEM, it is believed that no enabling technology is currently missing, provided that scanning in 15 min is limited to a regional area. The satellite could be developed in time for a launch before 2010, i.e. in synergy with the early phase of GPM and the late phase of GIFTS (Geostationary Imaging Fourier Transform Spectrometer). However, a number of short-term activities need to be completed before a consolidated proposal for implementation is put forward (say, within a couple of years).

In the area of technology, certain identified critical areas (for example, the scanning mechanism) need to be cleared. To this end, a "GEM" proposal has been submitted to the NASA Instrument Incubator Program. The result is pending. In the scientific area, further modelling of the signature of clouds in the Sub-mm range is necessary, both to better support the case for a demonstration mission, and for fine tuning of the instrument specifications. In addition, it will be necessary to collect experimental data to support model development and validation. In this context, it is worth mentioning that airborne campaigns are being planned, based on the use of the NOAA/ETL PSR (*Polarimetric Scanning Radiometer*, equipped with frequencies from 6 to 500 GHz), to be flown across Europe first by the NASA WB-57F aircraft and then by the European M-55 Geophysica aircraft.

Impetus on these activities is expected to come from an Advisory Working Group established within NOAA/NESDIS after the 2nd GOES Users' Conference, from a MW/Sub-mm Workshop to take place in EUMETSAT on 6-7 November 2002, and from the IPWG definition of its scientific programme.

In conclusion, the initiative of introducing MW/Sub-mm technology in GEO for the purpose of frequent rain observation propagated from the USA to Europe and now is spreading over a worldwide scientific community. A roadmap to prepare a fully supported and consolidated proposal is being defined and certain activities are already under way. ***CGMS is looked at as the reference body to coordinate a near-future implementation programme within a genuine international context.***

References

Bizzarri B. et al. (the 40 GOMAS proponents), 2002: "Requirements and perspectives for MW/sub-mm sounding from geostationary satellite". *EUMETSAT Meteorological Satellite Conference*, Dublin, Ireland, 2-6 September 2002.

Blackwell W.J. and D.H. Staelin, 1996: "Comparative performance analyses of passive microwave systems for tropospheric sounding of temperature and water vapor profiles". *GOES-8 and Beyond, Denver Co., August 7-9 1996 - SPIE Proceedings Series*, vol. 2812, p.472-478.

Gasiewski, A.J. and D.H. Staelin, 1990: "Numerical Analysis of Passive Microwave O_2 Observations Over Precipitation". *Radio Science*, vol. 25, no. 3, p.217-235.

Gasiewski, A.J., 1992: "Numerical Sensitivity Analysis of Passive EHF and SMMW Channels to Tropospheric Water Vapor, Clouds and Precipitation". *IEEE Trans. Geosci. Remote Sensing*, vol. 30, no. 5, p.859-870.

Gasiewski A.J., D.M. Jackson, J.R. Wang, P.E. Racette and D.S. Zacharias, 1994: "Airborne imaging of tropospheric emission at millimeter and submillimeter wavelengths". *Proc. of the International Geoscience and Remote Sensing Symposium*, Pasadena, Ca., August 8-12, 1994, p.663-665.

Klein M. and A.J. Gasiewski, 2000: "The Sensitivity of Millimeter and Sub-millimeter Frequencies to Atmospheric Temperature and Water Vapor Variations". *J. Geophys. Res., Atmospheres*, vol. 13, p.17481-17511.

Staelin D.H., A.J. Gasiewski, J.P. Kerekes, M.W. Shields and F.J. Solman III, 1998: "Concept proposal for a Geostationary Microwave (GEM) Observatory". *Prepared for the NASA/NOAA Advanced Geostationary Sensor (AGS) Program*, MIT, Lexington Mass., pp.23.

Staelin, D.H. and F.W. Chen, 2000: "Precipitation Observation near 54 and 183 GHz using the NOAA 15 Satellite". *IEEE Trans. Geoscience Remote Sensing*, vol. 38, no. 5, p.2322-2332.

Tsou J.J., W.L. Smith, P.W. Rosenkranz, G.M. Heymsfiels, W.J. Blackwell and M.J. Schwartz, 2001: "Precipitation Study Using Millimeter-wave Temperature Sounding channels". *Specialist Meeting on Microwave Remote Sensing*, Boulder, CO, November 2001.