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COMPLIANCE OF THE POST-2000 SATELLITE-BASED COMPONENT OF GOS WITH REQUIREMENTS AND POSSIBLE APPROACH TO UP-DATE / UP-GRADE FUTURE SYSTEMS

Bizzarro Bizzarri, Scientific Advisor to the EUMETSAT Director

Note - This is a discussion paper prepared on request of EUMETSAT for CGMS-XXVII. The contents remain responsibility of the Author and do not imply EUMETSAT endorsement.

Two interleaved issues are addressed:

- whether important gaps exist in the post-2000 satellite-based component of GOS, and how they could be filled at best by minimal additional efforts
- how to prepare for the replacement of the elements currently in use or being developed, in view of next generation satellite systems to be used in the post-2010 era.

Recommendations are put forward for four missions to fill outstanding gaps of post-2000 GOS: a constellation of micro-satellites for atmospheric discontinuities by radio-occultation sounding, an advanced geostationary satellite for improved sounding and imagery, a dedicated mission for parameters needed to describe cloud and radiation interactions, and a dedicated mission for large-scale ocean salinity and soil moisture.

The purpose of submitting the paper to CGMS is to trigger discussion about possible cooperation for implementing these missions contextually with replacing the post-2000 system based on few large satellites by a post-2010 system based on more small-medium-size satellites. The scientific and programmatic advantages of this approach are shown.

CONTENTS

1. INTRODUCTION

This document addresses two interleaved issues:

- whether important gaps exist in the post-2000 satellite-based component of GOS, and how they could be filled at best by minimal additional efforts;
- how to prepare for the replacement of the elements currently in use or being developed, in view of next generation satellite systems to be used in the post-2010 era.

It is evident that, in spite of any effort deployed by CGMS members to enter the new millennium with an operational satellite system as advanced as possible, a number of required observations still are lacking or are carried out with insufficient quality. The reasons may be:

- lack of technology at the time when the system was designed;
- lack of financial resources which lead to descoping the system by privileging observations of highest priority (sometimes more because of continuity requirement than of scientific priority);
- new requirements emerged after the system was designed and entered development.

Depending on updated requirements and/or improved technology, it could be the case to make additional efforts to try to fill gaps as early as possible, possibly already in the 2000-2010 time frame.

In addition to this problem, there is the fact that, although the post-2000 satellite system leaves gaps, still is based on very large satellites (e.g.: MSG and GOES exceeding 2 tons; METOP/EPS about 4.5 tons). At the time when these will have to be replaced, three types of requirements will be concurring:

- to provide continuity and possible up-grading of the previous mission;
- to take over requirements previously left out for one or another reason, now become a priority;
- to implement observations associated to new requirements.

Since it is not conceivable to continue growing the size and complexity beyond that one of, e.g., METOP and MSG, another approach has to be envisaged, based on the assumption that, in the post-2010 era, the overall observing service from space will be split among a wider number of satellites of small-medium class. The advantage of this approach is manifold:

- scientific: if more satellites and orbits are used, each measurement will have more opportunity to be carried out under optimal observing conditions or in the most comfortable environment from the view points of, e.g., platform suitability or instruments synergy;
- financial policy: although the overall cost of a spread system may be higher, its distribution could be more fair, as more agencies could be involved and industry could realistically consider co-investing for development within a commercial approach (which is impossible with large satellites: too large investment, too long time to recover, too large risk of total failure, …); also, the time profile of costs could be smoother;
- coordinated development: due to the obvious national/industrial interests when large and complex systems are involved, and to different planning cycles in the CGMS partners, it has always been extremely difficult to synchronise the evolution of the different elements of GOS. A spread system would be much less sensitive to this problem.

On the contrary, if the new approach is not followed and the present practice of few/large satellites continue, at the time of replacing them a serious probability exists that the divergence between (conservative) space-provided services and (expanding) user requirements will increase.

In this document we will:

- identify the most serious gaps in the post-2000 GOS and propose missions to fill them, all based on small-medium size satellites;
- show the strategy leading to the eventual replacement of current/developing large satellites by smaller elements within a spread context.

2. GAP ANALYSIS IN THE POST-2000 SATELLITE-BASED COMPONENT OF GOS

This chapter is based on work previously done by the Author for EUMETSAT, as a follow-on of a CEOS initiative for a *Database of User requirements and Space capabilities*. The elaborations of the initial CEOS findings are reported in the following four documents, available from EUMETSAT:

- ***Geophysical parameters potentially retrievable from satellites*** **-** This report introduces those measurements which, at least in principle, can be carried out from space, and defines names of parameters (generally "*Level 2 products*") and quantities to specify their quality (*horizontal resolution Δx, vertical resolution Δz, accuracy r.m.s., observing cycle Δt, delay of availability δ*), including the physical units to be used. The definitions are essentially the same as agreed in CEOS, with very few changes stemming from experience in use. The number of parameters is 90.

- ***Synthetic user requirements for data from satellites*** **-** This report elaborates on the user requirement database collected in the framework of CEOS by selecting a limited number (eight) of representative applications and forcing the original data to fit typical generic requirements of each application. The following applications (a sort of "eigenvectors" of original 55 entries from WMO, WCRP, GCOS, IOC, IGBP, ICSU, UNEP, UNOOSA and the EC) were selected:
  -*Atmospheric physics and chemistry*
  -*Atmospheric energetics and dynamics*
  -*Global oceanography and glaciology*
  -*Coastal zone environment monitoring*
  -*Global land processes monitoring*
  -*Agrometeorology, hydrology, civil defence*
  -*Resources and territory management*
  -*Geology and solid Earth physics*.

- ***Synthetic performances of products from satellites*** **-** This report elaborates on the performances originally quoted by space agencies in the CEOS Database, by extracting quasi-objective correspondences between final product quality and technical instrument characteristics, and provides "harmonised" performance evaluations for all products from all instruments of most satellites in GOS (plus ENVISAT), also combining the performances of more instruments on a satellite, more satellites in a system and, finally, the overall GOS. Performances are evaluated for:
  - instruments: METOP (*ASCAT, GRAS, GOME-2, IASI, HIRS-4, AMSU-A, MHS, AVHRR/3*), POES (*HIRS/3, AMSU-A, AMSU-B, AVHRR/2, SBUV/2*), MSG (*SEVIRI, GERB*), GOES (*Imager, Sounder*), MTSAT (*Imager*) and GOMS (*TRS*); plus ENVISAT (*SCHIAMACHY, GOMOS, MIPAS, AATSR, MERIS, ASAR, RA-2+MWR, DORIS+LRR*);
  - missions: *METOP, POES, MSG, GOES, MTSAT* and *GOMS*, plus *ENVISAT*;
  - systems: *GEO = MSG + GOES/W + GOES/E + MTSAT + GOMS*, *POLAR = METOP + POES*, *MET = GEO + POLAR* and *ALL = MET + ENVISAT*.

- ***Compliance analysis of space system performances with user requirements*** **-** This report introduces the concept of an overall "data quality indicator" which combines different quality aspects (Δx, Δz, r.m.s. and Δt), equally applicable to both user requirements and product performances, and defines a methodology to evaluate compliance between performances and requirements in terms of fractions of one order-of-magnitude. Compliance steps are defined as:

- *good*: performance matches requirement within 1/4 order-of-magnitude;
- *acceptable*: performance matches requirement within 1/2 order-of-magnitude;
- *marginal*: performance fails to meet requirement but by less than 1 order-of-magnitude;
- *no compliance*: some capability exists, but compliance fails by over 1 order-of-magnitude;
- *no capability*.

It is stressed that the methodology developed and applied in the reports mentioned above has the advantage of being nearly-objective, but the results have to be seen in a broad context only.

In order to get useful results for specific problems, some "personalisation" of the context is necessary. For the purpose of CGMS, a main simplification is to focus on the terms of reference of the commonality of its members (it being understood that individual members may have extended terms of reference). The following are proposed:

- operational meteorology (weather prediction first, but also applied meteorology and some basic research needed to improve weather prediction models);
- climate monitoring (for diagnosis and climate change detection);
- environment (limited to those effects more closely associated to weather and climate).

On this basis, a sub-set or combination of the eight applications mentioned above can be selected. The following three are proposed:

- atmospheric physics and chemistry, global climate monitoring;
- atmospheric energetics and dynamics, weather prediction;
- hydro-agro-meteorology, coastal zone activities, civil defence, nowcasting.

Sparing the details of the follow-on elaboration, in ***Table 1*** the compliance rates of the post-2000 satellite-based component of GOS are reported. The following explanations stand:

- parameters relevant to solid Earth physics and high-resolution land observation have not been included; and, to stay within a single table, a few parameters closely related each other and with similar compliance rates have been put in the same box, and the rates of atmospheric profiles, generally different with the atmospheric volume (lower and higher troposphere, lower and higher stratosphere, and total column) have been averaged along the vertical;
- the compliance rates have been coded in a gray scale according to the five defined steps; "white" indicates that there is no requirement for one parameter in one specific application;
- the "remarks" either indicate limitations not evident from the overall compliance rate, or that, though the measurement is not provided by GOS satellites, the information may be available from other satellite programmes reasonably operationally-oriented (e.g. for land or ocean observation).

The Table is not conceived for detailed considerations, but provides a rather clear quick-look of gap areas. Net of "false" gaps (i.e. gaps of GOS which could be filled by cooperation with other programmes if needed), the following main gap areas can easily be identified:

- the problem of wind profiling, particularly at smaller scales; this requires technological developments (e.g., Doppler lidar), but could be mitigated by faster geostationary imagery and possibly stereoscopy between images from more satellites;
- the insufficient quality of temperature/humidity profiles at smaller scales (mainly because of the slow observing cycle provided by polar satellites); this requires high-vertical-resolution frequent sounding from geostationary orbit, which also would mitigate the problem of wind profiling and improve the quality of atmospheric instability indexes;
- the poor capability of detecting atmospheric discontinuities (height of tropopause and of PBL), which undermines the usefulness of temperature/humidity profiling at all scales; this gap could be mitigated by introducing constellations of GPS radio-occultation sounders;
- trace gases other than ozone are observed only as total columns, limited to few green-house species; other programmes could help, but some additional effort within GOS is probably needed;
- a most outstanding gap is in the area of atmospheric ice/liquid water and the associated radiative parameters; to fill this gap, measurements at many wavelengths across the e.m. spectrum, from UV to MW, with more polarisations and viewing geometries are needed (process study requires active instruments such as radar and lidar);
- for surface parameters, the most outstanding gaps are for ocean salinity and soil moisture, both requiring low-frequency micro-wave radiometry.

Table 1 - Compliance of post-2000 GOS performances with meteo-climate user requirements

Gray code	Good	Acceptable	Marginal	No compliance	No capability	No requirement

Geophysical parameter	Atmospheric physics & chemistry, global climate monitoring	Atmospheric energetics & dynamics, weather prediction	Hydroagrometeorology, coastal zones, civil defence, nowcasting	Remarks
Wind profile	Marginal	No compliance	No capability	
Temperature profile	Good	Acceptable	No compliance	
Relative humidity profile	Good	Acceptable	No compliance	
Atmospheric instability index	No compliance	No compliance	No compliance	
Height of tropopause	Marginal	No compliance	No capability	
Height of Planetary Boundary Layer	No capability	No capability	No capability	
Ozone profile	Good	Acceptable		
Trace gases profiles	No compliance			Total columns of a few
Cloud imagery		Acceptable	Marginal	
Cloud type	Good	Acceptable	Marginal	
Cloud cover	Acceptable	Good	Marginal	Problems with cirrus
Cloud top height	Acceptable	Good	Acceptable	Problems with cirrus
Cloud top temperature	Acceptable	Good		Problems with cirrus
Cloud ice content (at cloud top)	Marginal	Marginal		
Cloud drop size (at cloud top)	No capability	No capability		
Cloud base height	No capability	No capability	No capability	
Cloud water profile (< 100 μm)	No capability	No capability		
Cloud water profile (> 100 μm)	No compliance	No compliance	No capability	Total column only
Cloud ice profile	No capability	No capability	No capability	
Cloud optical thickness	Marginal	Acceptable	No compliance	
Short-wave cloud reflectance	Marginal	Marginal	Marginal	
Long-wave cloud emissivity	Good	Acceptable	Marginal	
Precipitation rate at the ground	No compliance	No compliance	No compliance	
Precipitation index (daily cumulative)	Acceptable	Marginal	No compliance	
Aerosol profile	Marginal	No compliance	No compliance	
Aerosol (total column) size	No capability	No capability	No capability	
Solar irradiance at TOA	No capability	No capability	No capability	From other programmes
Short-wave outgoing radiation at TOA	Acceptable	Marginal	Marginal	
Long-wave outgoing radiation at TOA	Good	Acceptable	Marginal	
Short-wave Earth surface radiation	Acceptable	Marginal	No compliance	
Short-wave Earth surface reflectance	Good	Acceptable	Marginal	
Long-wave Earth surface radiation	Good	Acceptable	Marginal	
Long-wave Earth surface emissivity	Good	Acceptable	Marginal	
Air pressure over sea surface	No capability	No capability	No capability	From sea-surface wind
Sea surface wind (vector and speed)	Acceptable	Marginal	No compliance	
Sea surface temperature	Acceptable	Good	Marginal	
Significant wave height, Wave period and direction	No capability	No capability	No capability	From other programmes
Sea level, Ocean topography	No capability	No capability	No capability	From other programmes
Ocean chlorophyll, suspended sediments, yellow substance	No capability	No capability	No capability	From other programmes
Ocean salinity	No capability	No capability	No capability	
Sea-ice cover	Acceptable	Good	Marginal	
Sea-ice type	Marginal			
Sea-ice surface temperature	Good	Good		
Ice-sheet elevation, Topography, Thickness	No capability	No capability	No capability	From other programmes
Icebergs (extension and height)	Acceptable		No compliance	
Snow cover	Acceptable	Acceptable	No compliance	
Snow melting conditions			No compliance	From other programmes
Snow depth	No capability		No capability	From other programmes
Snow water equivalent	No compliance		No compliance	From other programmes

Glacier cover	**Good**	**Good**	**Acceptable**	
Land surface temperature	**Good**	**Acceptable**	**Marginal**	
Soil moisture	**No compliance**	**No compliance**	**No capability**	
Apparent Thermal Inertia (ATI)	**Acceptable**	**Acceptable**	**Marginal**	
Normalized Differential Vegetation Index (NDVI)	**Good**		**Marginal**	From other programmes
Leaf Area Index (LAI), Vegetation hydric stress indexes	**Marginal**		**No compliance**	From other programmes
Photosynthetically Active Radiation (PAR)	**Marginal**		**No compliance**	From other programmes
Fractional Photosynthetically Active Radiation (FPAR)	**Marginal**		**No compliance**	From other programmes
Fires (extension and temperature)	**Good**		**No compliance**	

3. RECOMMENDED PRIORITY DEVELOPMENTS

The gap analysis has shown that considerable effort is still needed to bring the satellite-based component of GOS to meet user requirements in full. In certain cases progress is conditioned by the need to develop and demonstrate new technologies. These are, particularly, the cases of wind profile, requiring Doppler lidar, and height of PBL, requiring backscatter lidar. Although the enabling technology is available, there is a long way to go before these capabilities are brought to an operational status. In this section we will identify solutions which can be implemented on the base of technologies either consolidated or with a strong heritage.

In the field of wind profile, it is possible to considerably improve data quality by improving the imagery mission of geostationary satellites. The main improvements should be:

- much faster image cycle (e.g., 1-2 min instead of 15-30 min);
- somewhat improved resolution (2-3 km in IR instead of 4-8 km);
- more satellites to exploit stereoscopy.

In the field of temperature/humidity sounding, compliance with user requirements would substantially improve if high-vertical-resolution sounding is introduced in geostationary orbit. 4-D assimilation of frequent sounding also would mitigate the effects of the lack of quality of wind profile, and would enable improved monitoring of atmospheric instability, tropopause evolution and cloud and radiation. The main features should be:

- observing cycle in the range of 1 hour;
- data quality comparable with that one expected from IASI and AIRS from polar orbit;
- "image-like" operation to substantially contribute to accurate cloud and surface observation.

In the field of atmospheric discontinuities, the most promising technique to ensure the required vertical resolution is temperature/humidity sounding through radio-occultation of signals from navigation satellite systems (GPS and GLONASS). To be operationally attractive, the system should provide an observation density in the range of 200-300 km each 6 hours, which implies using a constellation of several tens of platforms (which could be micro-satellites).

In the field of trace gases other than ozone, it is too early to recommend anything exceeding the capability of GOME-2 and IASI. Experience from ENVISAT and EOS-Chem should be awaited for.

In the field of clouds and radiation, current plans for process study mission are based on active instrumentation unsuitable to be transferred into an operational environment for monitoring purpose. The alternative of using passive-only sensing techniques implies a number of features such as:

- contextual observation is required of many parameters (ice/liquid/vapour water, radiation at TOA, aerosol, precipitation, …);
- these observations require exploitation of wavelengths ranging from UV to MW, with more polarisations and more viewing geometries;
- if added to one of the multi-purpose platforms of GOS, the mission size would become explosive: a dedicated optimised satellite is therefore advisable.

In the field of ocean salinity and soil moisture, if global meteo-climate requirements are merged with those of coastal zone activities and agro-hydrology within a multi-purpose context, very large structures are required. However, the mission becomes affordable within a small-medium size satellite constraint if the purpose is limited to global ocean dynamics and large-scale air mass transformation monitoring.

In the next chapters, requirements and concepts are described for four missions intended to address the recommendations listed above. These missions have been studied to a different depth, first of all to establish requirements and concepts, then to assess the availability of technology and to estimate sizes.

4. ATMOSPHERIC DISCONTINUITIES BY RADIO-OCCULTATION

We have seen that temperature/humidity profiles from space seem to meet user requirements, at least for the larger scale applications, whilst for the smaller scale there is a big gap of quality. However, even at the larger scales, the impact of temperature/humidity profile on weather forecasting and climate models is limited by two "hidden" deficiencies:

- the vertical resolution is insufficient to catch atmospheric discontinuities, specifically the tropopause height and the height of the PBL: it should be noted that the predictive value of sounding, in the absence of accurate information on the constraints applied to vertical transport, is greatly reduced;
- the accuracy required for climate modelling and monitoring is impossible to be achieved instantaneously by any remote sensing system, thus integration or averaging over large areas and long time intervals is required: however, the error structure of IR and MW profiles is unfavourable to averaging and integration, as errors are correlated through their dependence on the same physical reasons (clouds, …) or biases (spectroscopy knowledge, …).

The radio-occultation technique implements sounding by measuring the characteristics of signals from navigation satellites (the American GPS and the Russian GLONASS) while undertaking occultation across the Earth's limb, setting or rising in respect of the horizon of a Low-Earth-Orbiting satellite (LEO) equipped with appropriate receivers. Other not-occulting GPS/GLONASS satellites (GPS + GLONASS = GNSS) help with establishing accurate location and velocities (see ***Fig. 1***).

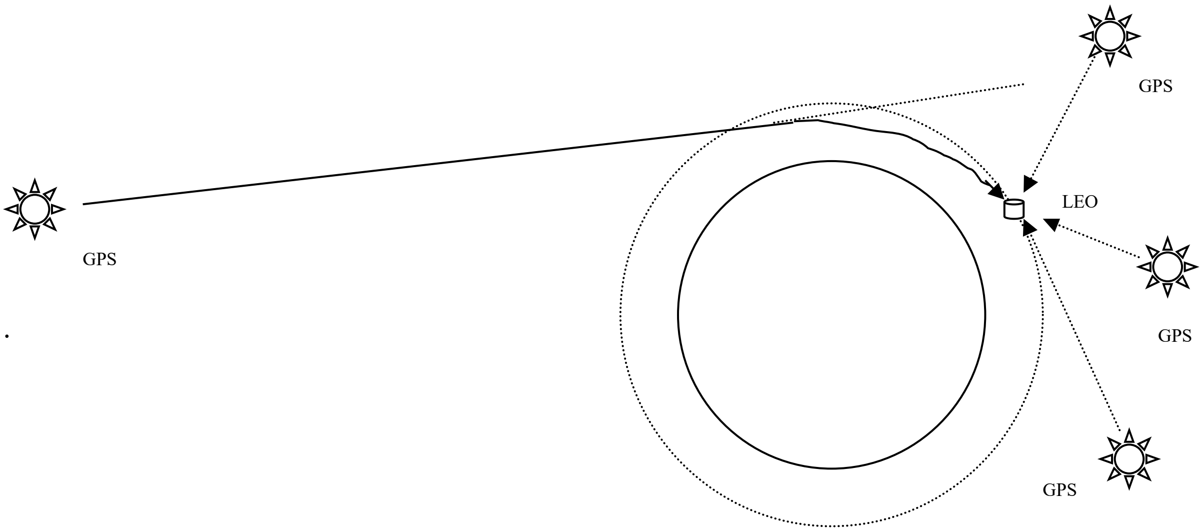

Fig. 1 - Observing principle of radio-occultation sounding

We see that, by using this principle, the vertical resolution is determined by the sampling rate of the carrier frequency. The temperature and humidity profiles determine the refraction index, which causes a ***bending angle*** which is accurately measured by monitoring phase or Doppler shift of the carrier frequency. All the observation is strongly relying on accurate geometry restitution. In this sense, it is an "absolute measurement", suitable to long-term averaging to achieve the sort of accuracy required for application to climatology. Due to the frequencies used by GPS and GLONASS, (1200-1600 MHz), the system provides ***all weather*** observations.

There are disturbing factors which impact on the measurement. One of this is the effect of the ionosphere on the propagation of the signal from the GNSS satellite to the LEO. This may be corrected by using two frequencies (both GPS and GLONASS are equipped with them). The amount of the correction may be used to infer ionospheric Total Electron Content (TEC) and electron density profiles, important information for ***Space Weather.*** Very precise orbitography is required for accurate geometry restitution. This information may also be used for ***Solid Earth physics.***

The radio-occultation technique is not proposed to replace IR and MW sounding. In fact, there are a number of limiting factors, such as:

- the horizontal resolution: due to the limb geometry, measurements are integrated over an effective path of some 300 km;
- the rarity of occultation events: each LEO, even by tracking both GPS and GLONASS, both in the rising and setting phases, and extending the azimuth field of view by ± 45° fore- and aft-, can undertake about 1000 occultations/day, corresponding to an average density of 700 km each 24 h;
- degrading accuracy in the lower troposphere (in GPS, this also is enhanced by artificial signal degradation in one of the two carrier frequencies);
- the fact that the refraction index is contextually sensitive to temperature and water vapour: this can be solved by direct 4-D assimilation of bending angles but this limits the usefulness of the profiles as self-standing observations of multi-purpose applicability.

Notwithstanding these limitations and difficulties, there is no other practical way of solving the problem of improved vertical resolution of temperature/humidity sounding to the extent necessary to accurately observe atmospheric discontinuities at global scale.

User requirements applicable to a radio-occultation sounding system are reported in ***Table 2.*** Since the most likely way of using the data will be direct assimilation of the bending angle, requirements for this parameter also are reported.

Table 2 - User requirements for a sounding mission by radio-occultation
(modified from ESA/EUMETSAT GRAS-SAG Report, Version 1.1, 5 January 1998)

		Temperature	Humidity	Bending angle
Horizontal domain		Global	Global	Global
Horizontal resolution (Δx)		< 300 km	< 300 km	< 300 km
Vertical domain		Surface to 1 hPa	surface to 100 hPa	surface to 0.01 hPa
Vertical resolution (Δz)	troposphere	0.5 km	0.5 km	time sampling consistent with $\Delta z < 0.5$ km
	stratosphere	1.0 km	n/a	
Accuracy (rms)	troposphere	< 1.0 K	< 10 % or < 0.2 g/kg, whatever is larger	< 1 μrad or < 0.4 %, whatever is larger
	stratosphere	< 2.0 K	n/a	
Observing cycle (Δt)		6 h	6 h	6 h
Delay of availability (δ)		< 3 h	< 3 h	< 3 h

Mission and system requirements are strongly conditioned by the need to meet the user requirement on observation density (< 300 km spacing, globally each 6 h). Considering that a certain oversampling has to be provided to minimise certain effects of the limb geometry (damping of horizontal gradients, inaccuracy due to field curvatures, …), it seems appropriate to require:

- target horizontal resolution: 200 km;
- threshold requirement (see Table 2): 300 km.

Recalling that each LEO provides ~ 1000 occultations/day, the corresponding number of satellites is:

- for the target requirement: 48
- for the threshold requirement: 24.

A satellite constellation is therefore needed. According to present technology, e.g. developed for METOP/GRAS, the radio-occultation payload may have a mass of < 10 kg, require < 25 W and provide < 20 kbps data rate for a total volume of < 15 MBy/orbit. It is therefore possible to think in terms of ***micro-satellites*** (i.e. with mass << 100 kg) to be launched in cluster of, say, 4-8 at a time.

A number of studies are being run to define the optimal configuration of such constellation. The number of satellites determined before is only valid if their distribution is such as to ensure even distribution of the observations across all latitudes (temperature profile is more valuable at higher latitudes, but water vapour is more important at lower latitudes; anyway, the tropopause in intertropical regions is an extremely important information for climate modelling). This is only possible if orbits with more inclination angles are used, including low inclinations for frequent observation of the intertropical regions. In addition, to exploit all of the GPS and GLONASS satellites spread across all longitudes, orbits with more Local Solar Times (LST) are required. The LST does not need to be steady across the year (e.g., the orbit does not need to be sun-synchronous); on the contrary, drifting orbits are more appropriate in order not to introduce seasonal biases in long-term integration for climatology. The orbital height is not critical, provided that it is > 500 km because of lifetime requirements, and < 1100 km because of the risky local radiative environment. An ***example*** of constellation configuration could be as follows:

- two orbital inclinations: 80° and 30°;
- four planes for each inclination;
- eight satellites in the 80° inclination orbits, four in the 30° inclination orbits; total: 48;
- all orbits 800 km high.

It is important to note that the concept of constellation has a number of attractive features:

- no criticality in respect of reliability: failure of one satellite in one cluster, or even one full cluster because of a launch failure, would only cause "graceful degradation" of the system performances;
- possibility to tune the implementation rate to actual user needs: it could be that, during the build-up phase, cost-effectiveness considerations invite to either reduce the launching rate to remain with a lower number of satellites in the constellation, or to increase the number if it is justified;
- possibility of implementing the overall constellation as envelop of more sub-constellations provided by different CGMS members or other agencies: this is feasible because the selection of orbits and payloads is not critical for inter-operability, and the "absolute" nature of the measurement principle alleviates problems of inter-calibration;
- feasibility of industrial involvement to pre-finance the design and development phases, and possibly to sell a "key-in-hand" service, since:

- massive production is foreseen on which to amortize the initial investment;
- relatively simple and consolidated technology is implied;
- risks of failures are distributed and a "threshold level of service" may be easily guaranteed.

It is worth elaborating more on the possibility of Industry to propose "key-in-hand" services up to the level of providing end products. For products derived from instruments such as a spectrometer (e.g. sounding from IASI) or too loosely linked to the instrument (e.g. winds from geostationary imagery) it is extremely unlikely that Industry can undertake to guarantee the quality of the end product. In the case of sounding by radio-occultation, the quality of a number of end products can be guaranteed, e.g.:

- the bending angle in all conditions;
- the temperature profile in conditions of null humidity (e.g., upper troposphere and stratosphere, winter arctic regions)
- the humidity profile in conditions of known temperature profile (e.g., lower equatorial troposphere).

As for heritage, apart from the *GPS/MET* mission flown by NASA in 1995 and the Danish *Oersted* presently being flown, radio-occultation missions are being developed for METOP (*GRAS*) and for the German *CHAMP*. ESA has collected proposals in response to various Calls (*ASTRO* and *APROCC/ACE*) and has awarded industrial contracts to define the concept of an *Atmospheric Profiling Earth Watch* (*APEW*). In the USA, industrial studies have been awarded in the NPOESS preparation framework and a joint NASA-Taiwan project (*COSMIC*) is being pursued. Therefore, ***times seem ripe to focus all these activities towards implementing an operational constellation !***

5. IMPROVED SOUNDING AND IMAGERY FROM GEOSTATIONARY ORBIT

5.1 Approach to an Advanced Geostationary Sounder

Our gap analysis has shown the need for an Advanced Geostationary Satellite to primarily provide frequent temperature and humidity sounding to meet user requirements from smaller scales application. Also, while waiting for technological development such as Doppler lidar, it is necessary to improve the quality of wind profiles as practicable within the limitations of what can be done by tracking image features. Contextually with better imaging for wind tracking purpose, improved monitoring of cloud development and mid-troposphere water vapour growth would be pursued. The instrumentation defined on the base of these driving requirements, also would provide (implicitly or by marginal additional effort) better cloud field characterisation, improved surface observation and enhanced contribution to Earth radiation budget observation.

Present or post-2000 geostationary satellites of GOS have been designed with imagery as driving requirement. Sounding capability is not present in MTSAT, GOMS, FY-2 and INSAT, or marginally present in MSG (a few absorption channels), or present with insufficient vertical resolution in GOES (a filter-wheel radiometer). If an advanced sounder is introduced in geostationary orbit, also provided with imaging capability, most products requiring a relatively slow observing cycle, say, 1 h, could better be provided by the sounder, enabling the imager to be designed in such a way as to better address those observations which really require fast observing cycle, say, 1 min.

Our approach to define an Advanced Geostationary Satellite concept, is therefore as follows:

- first, to define a concept of a future advanced sounder for geostationary orbit;
- then to identify the simplifications which can be introduced in the imaging mission, and define an imager which enhances those features of primary importance for wind and cloud development;
- further requirements are then addressed by marginal additional effort on the two basic instruments;
- the constraint of a small-medium size satellite will apply. By “small-medium” we intend something less than 50 % of the mass of MSG or GOES (about 2 tons at launch).

5.2 Mission objectives of an Advanced Geostationary Satellite

The primary objective of sounding from geostationary orbit is ***to measure frequent temperature and humidity vertical profiles***, for the purpose of NWP at scales ranging from Global to Regional and National (atmospheric wavelengths ranging from 10,000 to 1,000 and 100 km).

Temperature and humidity profiles, at middle-high latitudes and medium-large scales (i.e. small Rossby numbers), represent the mass field and also allow to infer most of the dynamic field through realistic balance equations, thus contain most of the information needed to initialise NWP models. At low latitudes and/or small scales (i.e. large Rossby numbers), balance equations become progressively less accurate, to the extent that independent measurement of the ***wind profile*** becomes necessary.

Unfortunately, wind profile is a difficult measurement (not only from space !). From space, the only "signature" of air motion in the electromagnetic field is the Doppler shift. This principle can be used by high-resolution spectroscopy of molecular lines (only applicable in the upper atmosphere in limb mode: see, for instance, WINDII on UARS) or by Doppler lidar to follow aerosol eddies, in clear air, both in troposphere and stratosphere. Development of Doppler lidar for clear-air wind is being pursued, but there is still a long way to go before the technology is developed, qualified, brought to affordability and entered into operational use. In addition, the technique can only provide rather sparse data, only suitable for large-scale NWP. Therefore, for a long time to go, the only operational technique will continue to be tracer tracking by frequent imagery from geostationary satellite.

It is therefore necessary to exploit as much as possible of the temperature/humidity observed fields also to mitigate the effect of insufficient availability and/or quality of wind profiles. In this context, frequent sounding is one interesting possibility. Direct observation of trends of the temperature profile, in certain conditions (e.g., far from heat sources), provides information on vertical motion, which could be retro-fitted in the dynamic domain through the ω-equation or derivatives. If sounding is observed with high vertical resolution, changes of atmospheric stability can be observed which are linked to the Reynolds number, possible to be retro-fitted in the dynamic domain. Also, high vertical resolution enables to better map tropopause patterns and evolution, very much significant of the dynamic field. Not to be forgotten that measurement of temperature and humidity profile in IR also implies observation of a ***gross ozone profile***, which could be assimilated to infer the dynamic field in the low stratosphere.

Obviously, frequent sounding is only possible from geostationary satellite, whose field of view is dominated by tropical regions. One traditional criticism to sounding from geostationary is that, in tropical regions, the temperature profile has little variance. If this is true for temperature, certainly is not true for water vapour profile. Frequent sampling of the vertical distribution of water vapour is a key information to predict convection development.

If an advanced sounder is embarked in geostationary orbit, and has a conveniently high horizontal resolution and an "imaging mode" scanning, a number of products presently being extracted by image processing could be instead extracted from the sounder with better quality. With reference, for instance, to the best geostationary imager in the post-2000, SEVIRI, and assuming an IR sounder similar to, e.g., IASI or AIRS, we can state the following:

- instability index - obviously, the quality from the sounder would be much superior, as it includes much more information on air temperature and water vapour, with high vertical resolution;
- sea surface temperature - much better quality because of much better atmospheric correction and of the availability of on-board absolute calibration of the sounder;
- land surface temperature - same as for sea surface temperature, plus the possibility of correcting for emissivity thanks to the large number of window channels in different parts of the spectrum;
- cloud classification - more accurate because of higher number of "signatures" in more windows and water vapour channels; as for ice/liquid discrimination, the differential signature between channels around 4 and 11 μm should be sufficient in daylight, and the SEVIRI "triplet" technique of channels 8.7/11/12 μm is more applicable with more, much narrower channels;
- cloud-top height - much more accurate as a by-product of profiles retrieval (more accurate information on top temperature + emissivity, and extended application of the 13.4 μm principle);
- tropopause evolution by ozone pattern monitoring - obviously, much more accurate (we have the full ozone profile); also possible ozone patches tracking, for which hourly intervals are sufficient.

The objection that all these products, if extracted from an imager, would have higher resolution is only partially correct. It is reminded that the superior horizontal resolution of the imager is generally associated to a much worse MTF value; that the radiometric accuracy in absorption bands is generally poor; and that the spectral resolution is much worse (few relatively broad channels against many thousands of narrow-band channels). As a consequence, products from an imager are generally extracted at level of large pixel arrays (typically 32 x 32, i.e. about 100 km) whilst, for a sounder, a number of products can be retrieved at level of pixel (it could be ~ 10 km) or 3 x 3 pixels (~ 30 km). The objection that products from an imager could be available more frequently is not relevant: none of the products listed above are required at 15 min intervals.

If a IASI-class sounder is there, the role of the imager could be enhanced in respect of the image cycle for the purpose of ***clouds early detection and development monitoring***, In addition, after experience with the Meteosat water vapour channel, the requirement for monitoring ***water vapour growth in the middle troposphere*** should be considered as fully consolidated.

Summing-up, the recommended ***driving objectives*** of and Advanced Geostationary Satellite are:

- frequent, high-vertical-resolution temperature and humidity sounding;
- improved quality of wind (by faster imagery);
- improved cloud detection and monitoring, and mid-troposphere water vapour growth observation.

As discussed, other observations on cloud and surface fields will implicitly be provided by the instrumentation to be developed in front of these driven objectives. However, a couple of observations presently carried out by MSG and/or GOES require to be continued. These are:

- spectrally-integrated Earth radiation from TOA to space (MSG/GERB);
- use of short-wave channels (0.6/0.8/1.6 μm as in MSG/SEVIRI and GOES/Imager) for:
    - improved contrast of clouds over different landscapes (including snow);
    - inference of cloud optical thickness;
    - inference of aerosol;
    - land observations (NDVI, ATI) which could benefit from sampling with changing solar angle.

These additional objectives could be pursued by marginal effort beyond the baseline instrumentation.

5.3 User requirements

To establish requirements for a geostationary sounding mission, we refer to the following scenario:

- geostationary satellites have to provide frequent sounding over a large fraction of the globe, at least in IR (i.e. accepting that gaps will occur in overcast areas: this is because observation in the MW field could not be practical for a long time to go);
- polar satellites will continue to ensure a regular all-weather data set by observation in the MW field, and to complete coverage at high latitudes in both MW and IR;
- a constellation of micro-satellites exploiting the radio-occultation sounding principle (see Chapter 4) will solve the problem of tropopause height observation (and height of PBL in certain conditions), and provide un-biased measurements suitable to long-term averaging for climate change monitoring.

With this scenario, we have to extract from the user requirements for the overall sounding mission, the fraction applicable to the geostationary component of the GOS system. We can derive the following:

- <u>horizontal resolution</u> (Δx) - in the lower troposphere: ***30 km*** in the majority of observing conditions (i.e. broken cloudiness), with possibility of ***10 km*** under favourable observing conditions (i.e. cloud-free areas); values relaxed by about 50 % in the higher troposphere;
- <u>vertical resolution</u> (Δz) - in the lower troposphere: ***1.0 km*** in the majority of observing conditions (i.e. broken cloudiness), with possibility of ***0.5 km*** under favourable observing conditions (i.e. cloud-free areas); values relaxed by about 50 % in the higher troposphere;
- <u>accuracy</u> (r.m.s.) - in the lower troposphere: ***1.0 K*** (temperature) / **20 %** (humidity) in the majority of observing conditions (i.e. broken cloudiness), with possibility of ***0.5 K*** (temperature) / **10 %** (humidity) under favourable observing conditions (i.e. cloud-free areas); values relaxed by about 50 % in the higher troposphere;
- <u>observing cycle</u> (Δt) - ***1 h*** , to meet the requirement of smaller scales, but also to reduce the effect of defective observation of the wind profile;
- <u>delay of availability</u> (δ) - ***1 h*** , to meet the requirement of smaller scales.

These ***user requirements for geostationary sounding*** are plotted in ***Table 3***. The ranges indicate the figures to be achieved under favourable observing conditions (cloud-free areas) and in most conditions (broken cloudiness). It should be noted that, in the regions observed from geostationary orbit, the "favourable" conditions are expected to be rather frequent.

Table 3 - Proposed user requirements for geostationary sounding

Atmospheric volume	**Δx**	**Δz**	**r.m.s.** (temperature)	**r.m.s.** (humidity)	**Δt**	**δ**
Lower troposphere	10-30 km	0.5-1.0 km	0.5-1.0 K	10-20 %	1 h	1 h
Higher troposphere	15-45 km	0.8-1.5 km	0.8-1.5 K	15-30 %	1 h	1 h

As regards user requirements for imagery, the best approach is to iterate on what we know from Meteosat and GOES experience. With reference to wind from tracers tracking, we know that:

- improving the image resolution is less efficient than one could expect, since we do not track individual clouds, but air cells which we can recognise from one image to the next when they are "signed" by a mesoscale cloud pattern or another tracer (e.g. water vapour patches): assuming that we need about 1000 pixels for pattern recognition (i.e. 32 x 32 pixels), better image resolution would increase the wind resolution but decrease its accuracy because of failure in using an appropriately significant motion scale;
- improving the observing cycle is absolutely necessary: it has been demonstrated (e.g. by Fujita) that the accuracy of 1 m/s can be achieved by using images taken at 1 min intervals;
- the other major error source of satellite-derived winds is the height assignment of the tracer: this could be very substantially improved by the contextual existence of the sounder, which has much higher capability of cloud characterisation. Another opportunity is that, if the satellite succeeds to be of the small-medium class, a larger number could be placed in orbit (say, 6), to enable stereoscopy to be carried out in overlapping regions.

For clouds and water vapour monitoring, we can say the following:

- substantially better observing cycle than the 15 min of MSG and GOES would be very beneficial, as shown by the GOES rapid-scan mode and, recently, by the Meteosat-6 MAP experiment;
- somewhat better horizontal resolution than MSG and GOES is desirable.

In ***Table 4*** reasonably up-dated user requirements are reported for an imagery mission in geostationary orbit, assuming that a sounding mission is implemented and thus the mission objectives are limited to monitoring cloud development and mid-troposphere water vapour growth, and to trace-motion winds.

Table 4 - Proposed user requirements for geostationary imagery additional to sounding

	Horizontal resolution	**Vertical resolution**	**Accuracy**	**Observing cycle**	**Delay of availability**
Imagery	2 km (1)	N/A	N/A	1 min (2)	5 min
Wind	100 km (3)	1 km (4)	1 m/s	1 h (5)	1 h

(1) 1 km resolution desirable in at least one channel
(2) for wind processing purpose: not necessarily to be distributed each minute
(3) with gaps in the absence of suitable tracers
(4) accuracy of height assignment: only few levels in the troposphere, none in the stratosphere
(5) estimated time interval to get one observation in most cells, with the required accuracy and in a few levels

We do not fix user requirements for the following other products:

- those derived from the basic sounder and imager in addition to the driving parameters;
- those to be measured by adding short-wave channels to the basic sounder and imager;
- Earth radiation budget from additional broad-band channel.

We simply require that these products have quality at least as good as from the MSG SEVIRI+GERB, and the GOES Imager+Sounder.

5.4 Mission, instrument and system requirements for sizing an Advanced Geostationary Satellite

A rather detailed sizing exercise has been carried out for a possible geostationary sounder. The full documentation has been prepared for EUMETSAT, consisting of three studies:

- *Study of a geostationary sounding mission - GIASI, Geostationary Infrared Atmospheric Sounding Interferometer;*
- *Study for a geostationary imagery mission as simplified and improved as a consequence of the existence of an independent geostationary sounding mission (GIASI) - VIRIR, Visible-Infrared Rapid-Imaging Radiometer;*
- *Follow-on comments on the results of the studies on GIASI and VIRIR: possible sizing of Meteosat Third Generation, MTG.*

In this section, the main background elements (mission, instrument and system requirements) used for the sizing exercise are provided. Obviously, other solutions may be envisaged to meet the same mission objectives and user requirements, but the one presented here is thought to be sufficiently representative for carrying out a significant sizing exercise.

5.4.1 The sounder

***Selection of the spectral bands* -** The practicability of MW or Sub-mm sounding was ruled out for the following reasons:

- the only possible frequency bands to achieve the required resolution and cycle with reasonable antenna size are 425 GHz for temperature and 380 GHz for water vapour;
- unfortunately, at this frequencies, not only precipitating clouds would interfere, but also clouds of relatively small droplets (and ice, whose signal is re-enforced by scattering);
- furthermore, in this range, a spectral continuum is present which practically prevents observation of atmospheric layers lower than about 5 km;
- in addition, the technological state-of-the-art at these frequencies is such that it would be problematic to achieve the radiometric accuracy required for atmospheric profiling (or, conversely, very long integration times would be needed, incompatible with the required 1 h observing cycle).

Finally, an IR spectral range similar to IASI and AIRS could be adopted:

- ***4.0 - 15.4 μm , or 650 - 2500 cm^{-1}***

(the reasons for starting from 4.0 μm is to reserve shorter wavelengths for an embedded imager).

***Spectral resolution* -** Since the driving requirement is temperature/humidity sounding (no trace gases), the value adopted is somewhat relaxed in respect of, e.g., IASI:

- ***spectral resolution: $\Delta\nu = 0.5$ cm^{-1} (unapodised).***

***Radiometric accuracy and absolute calibration* -** Essentially the same as in IASI and AIRS:

- ***radiometric accuracy: NEΔT = 0.2 K @ 280 K for 0.5 cm^{-1} channel width ;***
- ***accuracy of absolute calibration: 0.5 K @ 280 K.***

***IFOV* -** From the user requirements in Table 3 we see that, in order not to preclude the possibility to have 10 km horizontal resolution at least in best conditions, the IFOV must be in the range of 10 km. This would allow to meet the requirement of 30 km in broken cloudiness conditions by co-processing 3 x 3 IFOV's to filter clouds. The same value of IASI is adopted:

- ***IFOV = 12 km.***

Sampling – Unlike IASI, continuous and contiguous IFOV's must be sampled, both to ensure that there are 3 x 3 samples in a 36 km processing box, and to provide ***imaging capability*** as to enable simplification of the imagery mission. The requirement is:

- ***pixel = IFOV = 12 km .***

***Observing cycle and delay of availability* -** Table 3 leaves little latitude:

- ***observing cycle: 1 h ;***
- ***delay of availability: 1 h .***

***Embedded imager* -** As in IASI and AIRS, an embedded imager is foreseen. The purposes are:

- to monitor possible changes in the scene during interferogram dwelling, either because of clouds crossing the IFOV, or because of satellite attitude change;
- to improve monitoring the sounder pointing status (a critical issue from geostationary orbit) by:
    - horizon detection, for localising the Earth disk
    - data location, by cross-correlation with coastlines
    - boundaries between the (nominally) contiguous FOV's of the interferometer;
- to provide cloud information at level of sub-IFOV of the interferometer:
    - cloud amount in the interferometer IFOV
    - first-guess cloud top height
    - evaluation of solar reflected radiation (as for channels 20 of HIRS/4 or 19 of GOES/Sounder).

The embedded imager requirements can be met by a ***two-channel radiometer*** as follows:

- IR: 3.5-3.9 μm (preferred over a 11 μm channel because of higher sensitivity to coastlines);
- VIS: 0.68-0.70 μm (same as HIRS/4 and GOES/Sounder);
- NEΔT < 0.1 K @ 300 K (at 3.7 μm), SNR > 1 @ 0.1 % albedo (at 0.69 μm);
- absolute calibration (in IR only): 0.5 K at 280 K;
- IFOV = pixel: 1.2 km ; MTF > 0.3 at the Nyquist spatial wavelength;
- cycle: three "instantaneous" images (< 1 s) at the extremes and in the middle of the dwell interval.

To define an ***instrument concept for sizing purpose*** a representative reference can be identified in IASI. Thus the name of this instrument: ***GIASI*** *(Geostationary Infrared Atmospheric Sounding Interferometer)*. The main instrument requirements could be as follows.

***Size of the primary optics* -** Determined by the limit of diffraction and by a required high MTF value:

- ***L = 20 cm*** corresponding to $\mathrm{MTF}_{\mathrm{diffraction}} = 0.85$ at $\lambda = 15.4$ μm .

Dwell time – It can be evaluated by scaling the IASI values. The result is:

- ***dwell time: t = 12 s*** (short enough to allow neglecting scene changes during dwelling due to clouds carried by wind across the IFOV contours. With a 50 m/s wind, the cloud displacement would be 600 m, i.e. 5 % of the IFOV).

Sampling strategy* -** To comply with the requirement of 1 h observing cycle and the estimated need for 12 s dwell time, 300 measurements have to be performed in 1 hour. Obviously, the number of IFOV's to be viewed in the Earth disk is much higher. Therefore, ***detector arrays are required, to view more IFOV's in parallel. The following sampling strategy may be adopted:

- ***viewed Earth disk: 18.4° covered by 15 x 15 FOV's***
- ***FOV: 1.23° = 21.5 mrad or 768 km at s.s.p.***
- ***number of pixels or IFOV's in one FOV: 64 x 64***
- ***12 s dwell time, 15 s dwell+step+others, 56 min Earth observation, 4 min retrace+calibration.***

***Instrument type* -** A laborious trade-off analysis was carried out. The final outcome is:

- ***interferometer*** is preferred over grating spectrometer, for many reasons including the essential possibility of viewing more IFOV's in parallel by detector matrix arrays;
- ***dual port interferometer*** to drastically improve the accuracy of calibration. The second input port permanently views deep space, for improved calibration; the two output ports are both equipped with detectors, for improved calibration, increased signal and improved reliability;
- ***dual side interferometer*** for easy phase error correction and zero-path-difference determination;
- ***phase shift handling*** based on minimising later shift errors by using coupled back-to-back cube-corner reflectors and, if necessary, by addressing the laser beam to more focal plane positions.

A possible scheme of a Fourier Transform Spectrometer (FTS) with dual ports and coupled back-to-back cube-corner reflectors is shown in ***Fig. 2.***

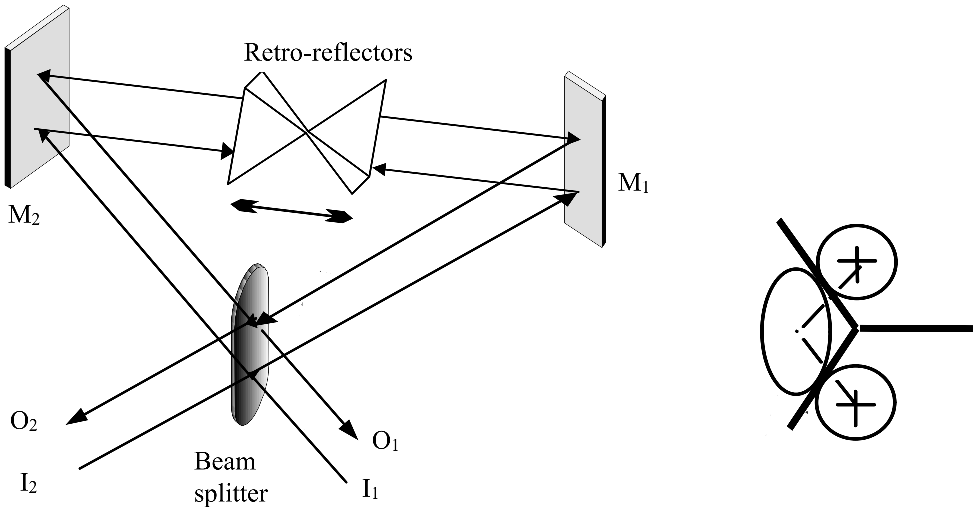

Fig. 2 - Schematic principle of the GIASI FTS and beam cross-sections at retro-reflector

As for the ***embedded imager,*** the concept is based on a detector's matrix array covering the FTS FOV (768x768 km^2 at s.s.p.) with ample margins, say:

- ***embedded imager FOV = 920 x 920 km^2 covered by 768 x 768 detectors matrix.***

The size of the ***primary optics*** is determined by the need to have an IFOV of 1.2 km at 3.9 µm with an MTF > 0.3 at the Nyquist frequency. The result is:

- ***L = 20 cm,*** i.e. the same optics as the interferometer.

Therefore the signal for the embedded imager must be acquired by removing the shorter wavelengths from the beam addressed to the interferometer, by means of a dichroic mirror: this is the reason why the spectral range of the interferometer starts from $\lambda = 4.0$ µm.

The available ***integration time*** may be computed by scaling the values of the 3.7 µm channel of AVHRR, which has the same central wavelength and bandwidth ($\Delta\lambda = 0.40$ µm). The results is:

- ***t = 80 ms,*** which allows with ample margins taking 3 pictures in the 12 s dwell time of the FTS.

The ***instrument type*** may be very simple: the imager gets the signal by separation from the input beam by means of a dichroic soon after the primary GIASI optics. The short-wave beam is separated into an IR and a VIS channel by a second dichroic. A detector matrix is placed in each of the focal planes. Best co-registration between imager and FTS IFOV's is ensured, and calibration mechanism is shared.

One main ***system requirement***, obviously, is ***three-axes stabilisation.*** One classical problem of using three-axes stabilisation for remote sensing from geostationary altitude is the ***pointing accuracy and stability.*** In the GIASI concept the problem of pointing accuracy is solved because pixels to be co-processed are geometrically consistent, as they belong to the same detector array simultaneously viewing one FOV (64 x 64 pixels covering an area of size 768 km). Pixels from different FOV's will not be co-processed. Positioning of the total array is not critical. It should be in the range of 5-10 % of the FOV. The main requirement concerns attitude stability during dwelling (12 s). This should be established in terms of fraction of an IFOV (say, 10 %). The results are:

- ***pointing accuracy: 50 km at s.s.p. (1.4 mrad = 0.08°)*** (location knowledge after processing: 1 km)
- ***pointing stability: 0.1 km/s at s.s.p. (2.8 μrad/s).***

A critical item associated to the use of interferometers is ***data rate.*** Associated to this, the requirement for on-board processing may arise. One problem that does not exist for a geostationary system is the requirement for on-board storage (except for holding data to be processed on-board, if any). The data rate for direct transmission of raw interferograms is prohibitive: 500 Mbps, which clearly indicates the case for on-board processing. Assuming that spectra are calibrated and processed on-board, we have:

- the number of spectral channels of 0.5 cm^{-1} width in the 650-2500 cm^{-1} spectral interval is 3700;
- 64 x 64 spectra are taken each 15 s (including use of the time spent for stepping);
- 768 x 768 pixels in 2 channels are taken 3 times each 15 s (imager);
- with a 12 bit digitisation we have a data rate of ***15 Mbps*** (12.2 interferometer, 2.8 imager).

5.4.2 The imager

Spectral channels - Since the only objective is to detect clouds and other possible atmospheric tracers, relying on GIASI for vertical structure information (specifically, height determination and implied emissivity estimate), it is relatively easy to identify the necessary (and sufficient) channels:

- an IR window channel for day and night cloud detection: the 11 μm window is preferred over the 3.7 μm because sensitive to most clouds in most atmospheric layer;
- a WV channel for water vapour growth monitoring and patches tracking to provide clear-air winds in the middle troposphere: the 6.3 μm band is the only practicable alternative, as the 18 μm band would be blind to the lower troposphere (and would place problems of detectors availability);
- a VIS channel to detect clouds difficult to be discriminated in IR (e.g. low stratocumulus), at least in daylight; also, since it will be feasible to get higher resolution in VIS than in IR, the VIS channel is required to monitor cloud development in the earliest stages.

Without having to re-discover the wheel, it is natural to select the three channels of present Meteosat:

- ***VIS: 0.4-1.0 μm***
- ***WV: 5.7-7.1 μm***
- ***IR: 10.5-12.5 μm.***

Geometric resolution - The user requirements (see Table 4) clearly indicate the wish for 2 km resolution. However, a great progress over SEVIRI and the GOES imager would already be achieved if a 3 km sampling is adopted, associated to a comfortable MTF value of > 0.3 at Nyquist. For the VIS channel we can require 1 km. The correct specification of the requirement is:

- ***for the IR and WV channels: MTF > 0.3 at the spatial wavelength of 6 km***
- ***for the VIS channel: MTF > 0.3 at the spatial wavelength of 2 km.***

Radiometric accuracy and absolute calibration - Rather severe requirements are necessary:

- ***IR channel: NEΔT < 0.1 K at 300 K; absolute calibration accurate to 0.5 K at 300 K***
- ***WV channel: NEΔT < 0.3 K at 250 K; absolute calibration accurate to 0.5 K at 300 K***
- ***VIS channel: SNR > 10 at 1 % albedo; absolute calibration not required.***

Observing cycle and delay of availability **-** The requirements in Table 4 leave little latitude:

- ***observing cycle: 1 min***
- ***delay of availability: 5 min .***

These mission requirements can be used to define an ***instrument concept for sizing purpose.*** Because of the driving requirement of short observing cycle, we name this instrument as ***VIRIR*** *(Visible-Infrared Rapid-Imaging Radiometer).*

Size of the primary optics **-** The minimum possible optics aperture L is dictated by the diffraction law and the required MTF. The result of a trade-off analysis is:

- ***L = 20 cm*** corresponding to $MTF_{diffraction} = 0.50$ at $\lambda = 12.5$ μm .

IFOV, FOV, integration time **-** The required observing cycle of 1 image/min leaves little margins to the instrument concept: it is certainly necessary a camera-like scheme where a very large area (FOV) is electronically scanned by a matrix of detectors; and a 3-axes stabilised satellite ! Since the 3-axis stabilisation from geostationary orbit makes accurate pointing and pointing stability difficult, there is an interest to see in the same FOV an area as large as possible (say, over 1000 km), in order to keep good image quality internally to this area. This implies the use of very large detector matrixes. Omitting details, the following concept is adopted:

- ***viewed Earth disk: 19.7° covered by 8 x 8 FOV's***
- ***FOV: 2.46° = 43 mrad or 1536 km at s.s.p.***
- ***number of pixels or IFOV's in one FOV: 512 x 512 (IR and WV), 1536 x 1536 (VIS)***
- ***600 ms integration time, 100 ms step + others, 45 s Earth observation, 15 s retrace + calibration.***

One driving ***system requirement*** for imaging from geostationary orbit is ***satellite pointing accuracy and stability.*** Internally to the FOV, the relative geometry of the 512 x 512 pixels covering areas of 1536 km, is ensured by the "hard" structure of the detector matrix array. In between FOV's, linkage will be ensured by cross-correlation of overlapping pixels (by about 10 %). The pointing accuracy is therefore not critical: we assume a value in the range of 5 % of the FOV or, more simply, 50 km. The pointing stability could be assumed as 10 % of the IFOV during the integration time. The results are:

- ***pointing accuracy: 50 km at s.s.p. (1.4 mrad = 0.08°)*** (location knowledge after processing: 1 km)
- ***pointing stability: 0.1 x 3 / 0.600 = 0.5 km/s (14 μrad/s).***

The ***data rate*** is computed assuming that all data are digitized to 10 bit and that the transmission is stretched over the full time available for a FOV (observation + stepping). We get the figure:

- *(512 x 512 + 512 x 512 + 1536 x 1536) x 10 / 0.700 =* ***41 Mbps.***

5.4.3 Additional observations

The ERB mission (continuation of MSG/GERB) could be added to GIASI as a separate optical chain fed by a 4 cm telescope imaging the Earth through the same scanning mirror. In addition, a sun diffuser installed to calibrate the short-wave broad-band channel also enables the VIS channel of the GIASI embedded imager to be calibrated. As in GERB, the main features would be:

- two broad-band channels: 0.3-4.0 μm and 4-30 μm
- horizontal resolution: 48 km,

with the following advantages in terms of synergies, as compared to MSG/GERB:

- sub-pixel components of the long-wave radiation budget (from the GIASI FTS)
- sub-pixel information on cloud type and top height/pressure/temperature (from the GIASI FTS)
- fine spatial structure of reflectors and emitters (from the VIS/IR channels of the GIASI imager)
- full time and geometry co-registration between broad-band information and sub-pixel components
- improved radiometric accuracy, thanks to the 3-axes stabilisation.

The last items are the short-wave channels 0.6, 0.8 and 1.6 µm available on SEVIRI, GOES/Imager and also in AIRS. If incorporated in VIRIR, these channels would drive the data rate unnecessarily (nobody requires these data at 1 min intervals). If incorporated in the GIASI embedded imager, the cycle (1 h) would be appropriate, and also the resolution (1.2 km). Also, they would fit with the cloud analysis production, and with the Earth radiation budget mission.

The present concept of the GIASI embedded imager is based on two channels (0.68-0.70 µm and 3.5-3.9 µm) taking three images during the FTS dwell interval. The data rate of this sub-system is not negligible (2.8 Mbps out of a total of 15 Mbps of GIASI). In order to maintain the same data rate, we could assume that the three images are only taken by the 3.7 µm channel, and that the VIS channel is split into three channels, each one only taking one image during the FTS dwell interval. With this, the impact of implementing the three short-wave channels within the GIASI embedded imager is estimated as marginal. To be noted that, if the three short-wave channels are incorporated in GIASI, assuming that also the option for the ERB channels is adopted, these channels will have absolute calibration (drawn from the calibration mechanism installed for the short-wave broad-band ERB channel). This is important for cloud optical thickness and aerosol observations.

5.5 Evaluation of the possible size of an Advanced Geostationary Satellite

On the base of the instrument concepts defined in Section 5.4 as representative of what might be envisaged to fulfil mission requirements, a sizing exercise was carried out. ***Table 5*** reports the results.

Table 5 - Overview of resource requirements for GIASI + complements and VIRIR

GIASI + ERB + S.W.	Volume	90x60x55 cm^3 (optics) + 20x30x30 cm^3 (electronics)
	Mass	130 kg
	Electrical power	165 W (net of telecommunications)
	Data rate	15 Mbps (on-board processed data)
VIRIR	Volume	60x30x40 cm^3 (optics) + 20x15x30 cm^3 (electronics)
	Mass	50 kg
	Electrical power	45 W (net of telecommunications)
	Data rate	41 Mbps (raw data) or 15 Mbps (compressed)

The satellite concept and the size evaluation were studied by using a representative small-medium size platform (*PRIMA*, being developed in Italy). In the course of the analysis, the following features and critical issues were singled out:

- detectors matrix arrays as large as requested for the GIASI FTS (64 x 64) are not yet commercially available, but can be developed by a reasonable amount of effort; anyway, active cooling to some 50 K is likely to be necessary (which is not a very serious problem);
- the VIRIR IR detectors do not need to be cooled (micro-bolometers); however, arrays of the required size (512 x 512) are not yet commercially available (but are expected to be shortly);
- the most critical system problem is the combination of satellite attitude control actuation with the requirement of pointing accuracy stability during the GIASI FTS dwelling: since these cannot occur simultaneously, appropriate operations strategies must be developed;
- there is a data rate problem if direct read-out at local user stations is required (which is very likely to be the case): this is only possible at reasonable cost of the station if the data from VIRIR are compressed by a factor over 2.5, to reduce the data rate to about 15 Mbps (as mentioned in Table 5), and the transmission is spotted to an area as large as, say, 10 % of the earth disk;
- although the satellite appears rather complex, enabling technologies are not required and the level of developmental risk in the various aspects seems to be reasonable.

Table 6 reports the results of the sizing exercise, which includes provision for a Data Collection System, a Low-Rate Information Transmission system in S-band (LRIT) and a new Very High Rate Information Transmission system in X band (VHRIT). It is assumed that VIRIR data are compressed to reduce the rate to 15 Mbps.

Table 6 - Preliminary sizing exercise for an Advanced Geostationary Satellite

Volume	Satellite in orbit (with deployed solar panels)	1.5 m, 1.7 m, 9.5 m
	Satellite stowed (without LAE and fuel tank)	**1.5 x 1.7 x 1.7 m^3**
Mass	Payload	180 kg
	Telecommunications (including DCS, X-band VHRIT, S-band LRIT)	80 kg
	Service module including power system	220 kg
	Total "dry" mass in orbit (including 10 % margin)	**530 kg**
	Fuel for geostationary orbit maintenance	70 kg
	Total mass at launch in case of direct injection in geostationary orbit	600 kg
	LAE and fuel for geostationary orbit by a transfer orbit	350 kg
	Total mass at launch in case of use of transfer orbit	950 kg
Power	Payload	210 W
	Telecommunications	150 W
	Internal services	230 W
	Total electrical power (including 10 % margin)	**650 W**
VHRIT (LRIT & DCP unchanged)	Antenna size at local stations	< 5 m (X-band)
	Required G/T at local receiving stations	< 23 dB/K
	Data rate	**30 Mbps**

Fig. 3 provides an outlook of the satellite.

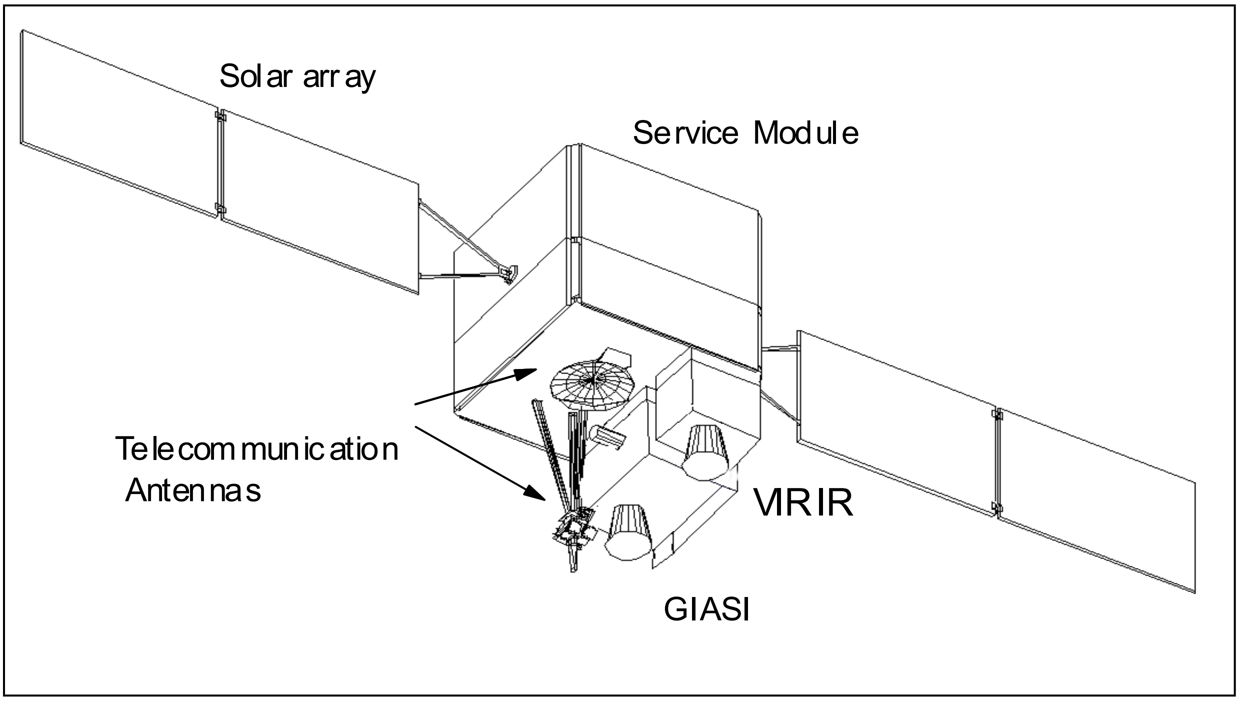

Fig. 3 - Schematic view of an Advanced Geostationary Satellite

The comparison of AGS (Advanced Geostationary Satellite) with MSG and GOES is as follows:

- AGS - payload mass: 180 kg, dry mass: 530 kg, mass at launch: 950 kg, power: 650 W
- MSG - payload mass: 281 kg, dry mass: 1074 kg, mass at launch: 2042 kg, power: 800 W
- GOES - payload mass: 298 kg, dry mass: 977 kg, mass at launch: 2105 kg, power: 1100 W.

It can be seen that the dry mass and the mass at launch of AGS is about one half of both MSG (which does not have a sounder) and of GOES, whose performances are inferior. Another advantage is that, in case a new satellite is built, the opportunity exists to design it for a direct injection in geostationary orbit. The mass at launch, in this case, would be only ***600 kg*** (to include fuel for orbit maintenance), and the increasing problems with launching geostationary satellites through a transfer orbit would be avoided. Launchers for direct injection in geostationary orbit already are available (*Proton, Zenith*) or considered (*Ariane-5/ESV*).

5.6 Possible performances of an Advanced Geostationary Satellite

In ***Table 7*** an overview is given of the possible products from an Advanced Geostationary Satellite as proposed in this document. The parameters driving the mission definition are in bolt characters. Great improvement in respect of what will be available from MSG and GOES can easily be appreciated.

Table 7 - Possible performances from an Advanced Geostationary Satellite

Geophysical parameter	Horizontal resolution	Vertical resolution	Accuracy (rms)	Observing cycle
Temperature profile	50 km	1 km	1 K	1 h
Humidity profile	50 km	1 km	10 %	1 h
Cloud detection and monitoring	3 km	n/a	n/a	1 min
Mid-troposphere water vapour growth	3 km	n/a	n/a	1 min
Wind profile (by 1-min imagery)	100 km	3 km	1 m/s	1 h
Ozone profile	50 km	2 km	10 %	1 h
Tropopause evolution (from total ozone)	12 km	n/a	n/a	1 h
Atmospheric instability index	50 km	n/a	16 classes	1 h
Cloud cover	100 km	n/a	1 %	1 h
Cloud type	12 km	n/a	8 classes	1 h
Cloud top temperature	12 km	n/a	1 K	1 h
Cloud top height	12 km	n/a	0.5 km	1 h
Cloud optical thickness	12 km	n/a	10 %	1 h
Precipitation at ground (index)	12 km	n/a	8 classes	1 h
Short-wave radiation at TOA	50 km	n/a	0.5 W/m^2	1 h
Long-wave radiation at TOA	50 km	n/a	0.5 W/m^2	1 h
Sea surface temperature	12 km	n/a	0.5 K	1 h
Land surface temperature	12 km	n/a	2 K	1 h
Vegetation index (NDVI)	12 km	n/a	2 %	1 h
Thermal inertia (to infer soil moisture)	12 km	n/a	1 K^{-1}	1 h

In addition to these “Level 2” products, higher level products would be available from real time 4-D assimilation. Short-term forecast of derived fields (e.g. ***precipitation rate***) would be possible with resolution and accuracy today difficult to conceive, so as to be applicable to small hydrographic basins and coastal zones activity. Continuous monitoring of cloud fields and water vapour vertical motion would allow fine control of forecast against actual weather conditions. The contextual availability of Earth radiation budget and its components as derived from cloud and surface observation and temperature/humidity profile would allow to build a dynamical climatology comprehensive and accurate beyond any level conceivable today.

6. CLOUD AND RADIATION FIELDS

Information on clouds from current and post-2000 GOS satellites is very much confined to the cloud top as observed in VIS and IR, unsuitable to be quantitatively used in numerical models. Very little is observed concerning the cloud interior, which requires MW observation, only available at coarse resolution from temperature/humidity sounders and from SSM/I. For radiation, information has to be collected from a number of instruments being flown on different satellites as a matter of opportunity.

The situation is totally unsatisfactory, since the role of ***clouds*** in the atmosphere is extremely active. Only a fraction of the energy available to the thermo-dynamical mechanisms in the atmosphere derives directly from the primary energy source of the Earth system (the short-wave solar radiation). A major part of the energy input into the atmosphere occurs when the water vapour condenses, therefore releasing, at different altitudes, the latent heat originally captured from the oceans (evaporation) and from land/vegetation (evapotranspiration). As soon as drops of liquid water, or ice crystals, are generated, the incoming short-wave solar ***radiation*** is affected, and the primary energy available to the Earth system changes. The outgoing long-wave terrestrial radiation also is affected, and the balance between short and long wave radiation changes with height as well as horizontally. The radiation *divergence* (in the volumetric sense) affects in turn the cloud structure. The intensity of the interaction between clouds and radiation critically depends on the cloud water being liquid or ice, and on the size distribution of drops or crystals (crystal orientation also impacts).

The lack of information on cloud internal structure and contextual radiation field is such that it is presently considered as probably the major limiting factor of long-term weather prediction and eventually climate prediction. Insufficient information exists to feed the development of appropriate cloud-radiation models and to tune the parametric representation in Numerical Weather Prediction (NWP) and General Circulation Models (GCM). To this end, ***process study missions*** are requested from space. A few are running (e.g., *TRMM*), or planned (e.g., the NASA *Picasso-Cena* and *CloudSat*), or considered (e.g., the ESA *Earth Radiation Mission*). However, for an operational follow-on, i.e. to routinely *initialize* actual forecasting models, long-term ***monitoring missions*** are necessary. Obviously, a monitoring mission also uses to strongly contribute to improve the knowledge of basic processes.

The ***mission objectives*** of a Cloud and Radiation monitoring satellite would include observation of:

- the ***cloud "classical" parameters*** mostly referring to the top surface, with emphasis on ice/liquid discrimination and size;
- the ***cloud interior,*** specifically water phase (ice or liquid) and whether drop size is likely to produce precipitation;
- the ***outgoing radiation*** from Top of Atmosphere to space;
- the main parameter impacting with both clouds and radiation in the 3-D atmosphere, i.e. ***aerosol***;
- the primary source of clouds, i.e. ***water vapour,*** also primary factor of radiative processes in the 3-D atmosphere;
- the indicator of final removal of water from the atmosphere, i.e. ***precipitation.***

In order to advise CGMS about what could and should be done in this field, use is made of a study presently being run under EC sponsorship: ***CLOUDS - a Cloud and Radiation monitoring satellite.*** The *short statement of objectives* of the CLOUD project sounds very stringent:

"*The CLOUDS objective is to study the mission of a new satellite to provide accurate, comprehensive, consistent and frequent information on cloud structures and the associated radiative parameters, to be used by operational and research centres for improved climate and weather forecasting*."

The ***user requirements*** of the CLOUDS project (see ***Tables 8 and 9***) are driven by two applications:

- ***climate monitoring and research***
- ***weather prediction and research meteorology.***

Table 8 - Reference user requirements for the CLOUDS mission

Geophysical parameter	Horizontal resolution (1)		Vertical resolution (2)	Accuracy		Observing cycle (5)	Delay of availability (6)		Priority
	weather	climate		r.m.s. (3)	bias (4)		weather	climate	
BASIC (mostly from CLOUDS)									
Cloud water (< 100 µm) total column	30 km	100 km	N/A	5 g/m^2	1 g/m^2	3 h	3 h	3 d	1
Cloud water (< 100 µm) gross profile	30 km	100 km	3 km	30 %	5 %	3 h	3 h	3 d	2
Cloud water (> 100 µm) total column	30 km	100 km	N/A	5 g/m^2	1 g/m^2	3 h	3 h	3 d	1
Cloud water (> 100 µm) gross profile	30 km	100 km	3 km	30 %	5 %	3 h	3 h	3 d	2
Cloud ice total column	30 km	100 km	N/A	0.5 g/m^2	0.1 g/m^2	3 h	3 h	3 d	1
Cloud ice gross profile	30 km	100 km	3 km	30 %	5 %	3 h	3 h	3 d	2
Cloud drop size (at cloud top)	30 km	100 km	N/A	5 µm	1 µm	3 h	3 h	3 d	3
Cloud ice content (at cloud top)	30 km	100 km	N/A	30 %	5 %	3 h	3 h	3 d	1
Cloud optical thickness	30 km	100 km	N/A	30 %	5 %	3 h	3 h	3 d	3
Water vapour total column	30 km	100 km	N/A	500 g/m^2	100 g/m^2	3 h	3 h	3 d	2
Precipitation rate at the ground	30 km	100 km	N/A	3 mm/h	0.5 mm/h	3 h	3 h	3 d	3
Precipitation index (daily cumulative)	30 km	100 km	N/A	1 mm/d	0.2 mm/d	3 h	3 h	3 d	4
Short-wave outgoing radiation at TOA (*)	30 km	100 km	N/A	3 W/m^2	0.5 W/m^2	3 h	3 h	3 d	1
Long-wave outgoing radiation at TOA (*)	30 km	100 km	N/A	3 W/m^2	0.5 W/m^2	3 h	3 h	3 d	1
Aerosol total column	30 km	100 km	N/A	30 %	5 %	3 h	3 h	3 d	2
Aerosol gross profile	30 km	100 km	3 km	30 %	5 %	3 h	3 h	3 d	3
Short-wave cloud reflectance	30 km	100 km	N/A	5 %	1 %	3 h	3 h	3 d	2
Long-wave cloud emissivity	30 km	100 km	N/A	3 %	0.5 %	3 h	3 h	3 d	2
(*) Under the same geometry as for clouds									
BASIC (also available from METOP)									
Cloud imagery	3 km	10 km	N/A	N/A	N/A	3 h	3 h	3 d	4
Cloud type	30 km	100 km	N/A	3 classes	15 classes	3 h	3 h	3 d	3
Cloud cover	30 km	100 km	N/A	5 %	1 %	3 h	3 h	3 d	1
Cloud top height	30 km	100 km	N/A	1 km	0.2 km	3 h	3 h	3 d	1
Cloud top temperature	30 km	100 km	N/A	1 K	0.2 K	3 h	3 h	3 d	2
SUPPORT TO BASIC									
Temperature gross profile	30 km	100 km	3 km	3 K	0.5 K	3 h	3 h	3 d	3
Relative humidity gross profile	30 km	100 km	3 km	30 %	5 %	3 h	3 h	3 d	2
Ozone total column	30 km	100 km	N/A	30 DU	5 DU	3 h	3 h	3 d	4
ASSUMED TO BE AVAILABLE									
(Accurate) **Temperature profile**	30 km	100 km	1 km	1 K	0.2 K	3 h	3 h	3 d	-
(Accurate) **Relative humidity profile**	30 km	100 km	1 km	10 %	2 %	3 h	3 h	3 d	-
Solar irradiance at TOA	N/A	N/A	N/A	0.5 W/m^2	0.1 W/m^2	3 h	3 h	3 d	-
Short-wave outgoing radiation at TOA (flux)	30 km	100 km	N/A	3 W/m^2	0.5 W/m^2	3 h	3 h	3 d	-
Long-wave outgoing radiation at TOA (flux)	30 km	100 km	N/A	3 W/m^2	0.5 W/m^2	3 h	3 h	3 d	-
Short-wave Earth surface radiation	30 km	100 km	N/A	5 W/m^2	1 W/m^2	3 h	3 h	3 d	-
Long-wave Earth surface radiation	30 km	100 km	N/A	5 W/m^2	1 W/m^2	3 h	3 h	3 d	-

(1) Logarithmic centre of a range between a target value and a threshold of interest one order of magnitude worse.
(2) Intended as inference of a gross vertical structure, i.e. 3-4 layers in the troposphere.
(3) Logarithmic centre of a range between a target value and a threshold of interest half order of magnitude worse.
(4) Required as < 20 % of rms, so that the requirement for climate use is met after integration over < 1 week.
(5) Requirement set to account for diurnal variations. For climate use data will be integrated over longer periods.
(6) Referred to products. Raw data are requested to be available in real time.

Table 9 - User requirements for parameters not part of the CLOUDS objectives

Geophysical	Horizontal resolution (1)		Vertical	Accuracy		Observing	Delay of availability (6)		Prio-
parameter	weather	climate	resolution (2)	r.m.s. (3)	bias (4)	cycle (5)	weather	climate	rity
Wind over sea surface	30 km	100 km	N/A	3 m/s	0.5 m/s	3 h	3 h	3 d	5
Sea surface temperature	30 km	100 km	N/A	1 K	0.2 K	3 h	3 h	3 d	5
Ice/snow imagery	3 km	10 km	N/A	N/A	N/A	3 h	3 h	3 d	5
Sea-ice cover	30 km	100 km	N/A	5 %	1 %	3 h	3 h	3 d	5
Sea-ice type	30 km	100 km	N/A	2 classes	10 classes	3 h	3 h	3 d	5
Icebergs	30 km	100 km	N/A	50 %	10 %	3 h	3 h	3 d	5
Snow cover	30 km	100 km	N/A	30 %	5 %	3 h	3 h	3 d	5
Snow melting conditions	30 km	100 km	N/A	2 classes	10 classes	3 h	3 h	3 d	5
Soil moisture	30 km	100 km	N/A	30 g/kg	5 g/kg	3 h	3 h	3 d	5
Apparent Thermal Inertia (ATI)	3 km	10 km	N/A	3 K^{-1}	0.5 K^{-1}	3 h	3 h	3 d	5
Vegetation hydric stress index	30 km	100 km	N/A	30 %	5 %	3 h	3 h	3 d	5

Same notes as in Table 8.

In Table 8, "basic" requirements are distinct from "support", both to be fulfilled by the same satellite for co-registration reasons; some of the basic could be redundant with a GOS satellite as METOP/EPS, but actually need to be measured under the same conditions for co-registration reasons. In Table 9, requirements are listed for measurements not part of the CLOUDS objective, but actually carried out by the instrumentation primarily designed for cloud and radiation (particularly MW sensors).

The ***mission requirements*** established for CLOUDS are strongly conditioned by the monitoring objective, which implies compliance with *long-term sustainability requirements*, and the requirement for an observing cycle consistent with routine use. The main consequences of these requirements are:

- only passive instruments can be used, to ensure a swath of at least 1400 km for a daily global coverage of measurements essentially derived from long-wave channels, or 48-hours coverage for products implying the use of short-wave channels; use of passive instruments only also enables achieving long life-time and reducing power/weight requirements;
- to mitigate the lack of active instruments, all other means are allowed: e.g., use of a greatest number of observing channels covering a widest spectral range, measurements of polarisations in more planes, and observation under more viewing angles;
- synergy with METOP is envisaged, in order to enable framing the CLOUDS information within basic meteorological fields, specifically accurate temperature and water vapour profiles, and high-resolution imagery for detailed cloud pattern and derived surface radiative parameters.

The key aspect of the CLOUDS mission is the exploitation of a widest range of the e.m. field to collect as many "signatures" as possible of the different parameters to be measured. ***Fig. 4*** provides a view of the spectral coverage of the CLOUDS channels assembled in six instruments, extending from ~ 0.3 µm to ~ 4 cm, i.e. spanning over 5 orders of magnitude ! ***Table 10*** lists the mission requirements for all channels.

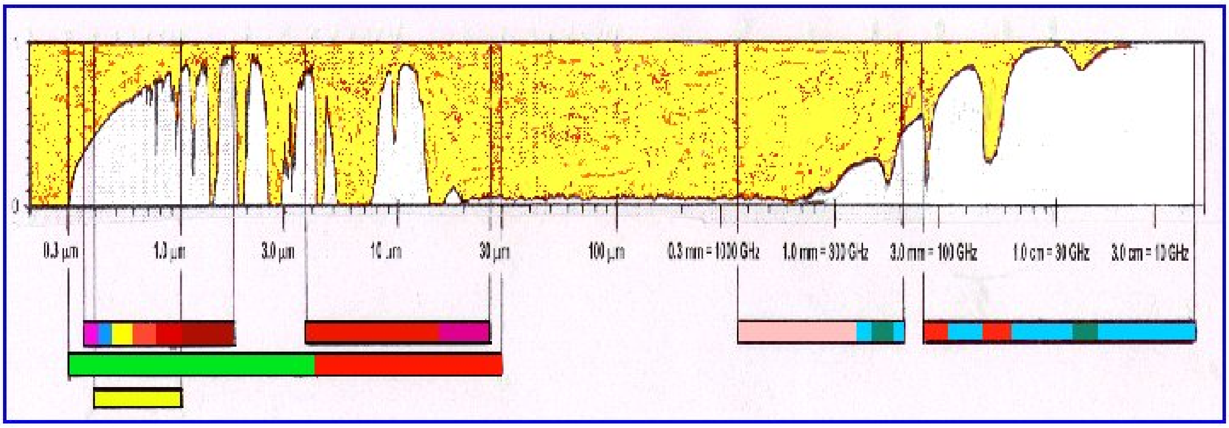

Fig. 4 - Spectral range covered by CLOUDS instruments

An outmost important ***instrument requirement*** to note is that all channels in CLOUDS must have consistent scanning mechanism, so as to ensure compatible viewing geometry and make possible accurate co-registration, for a true multi-spectral approach, as necessary when dealing with fractal fields. Since most channels require differential polarisation, ***conical scanning*** is most suitable. The geometry of conical scanning is shown in ***Fig. 5***, which also shows the possibility to view each area twice, fore- and aft-. Six instruments have been defined, to comply with the mission requirements as set up in Table 10. The four optical instruments will have conical scanning at 1 scan / 8 s, the MW and Sub-mm instruments at 1 scan / 2 s. ***All instruments will have in-flight calibration.*** Co-registration and intercalibration requirements are rather stringent.

Table 10 - Mission requirements for CLOUDS channels

Channel	Bandwidth (half-power)	Radiometric accuracy (1)	Absolute accuracy	Polarisations	Dual view	IFOV
334.5 nm	5 nm	1000 @ 10 % albedo	5 %	not required	required	20 km **(2)**
388.0 nm	5 nm	500 @ 10 % albedo	5 %	not required	required	10 km **(2)**
443.0 nm	20 nm	200 @ 10 % albedo	5 %	not required	required	5 km
555.0 nm	20 nm	200 @ 10 % albedo	5 %	three	required	5 km
670.0 nm	20 nm	200 @ 10 % albedo	5 %	three	required	5 km
865.0 nm	20 nm	200 @ 10 % albedo	5 %	not required	required	5 km
910.0 nm	20 nm	200 @ 10 % albedo	5 %	not required	required	5 km
1,240.0 nm	30 nm	200 @ 10 % albedo	5 %	three	required	5 km
1,380.0 nm	30 nm	200 @ 10 % albedo	5 %	not required	required	5 km
1,610.0 nm	30 nm	200 @ 10 % albedo	5 %	not required	required	5 km
3.74 μm	0.40 μm	0.50 K @ 300 K	1 K	not required	required	5 km
6.25 μm	1.00 μm	0.30 K @ 250 K	1 K	not required	required	5 km
7.35 μm	0.50 μm	0.30 K @ 250 K	1 K	not required	required	5 km
8.70 μm	0.50 μm	0.10 K @ 280 K	1 K	not required	required	5 km
9.66 μm	0.50 μm	0.30 K @ 250 K	1 K	not required	required	5 km
10.8 μm	1.00 μm	0.10 K @ 300 K	1 K	not required	required	5 km
12.0 μm	1.00 μm	0.10 K @ 300 K	1 K	not required	required	5 km
13.4 μm	0.50 μm	0.30 K @ 280 K	1 K	not required	required	5 km
18.2 μm	1.40 μm	0.20 K @ 220 K	1 K	not required	required	40 km **(2)**
24.4 μm	0.80 μm	0.20 K @ 220 K	1 K	not required	required	40 km **(2)**
Total short-wave	0.3-4.0 μm	0.5 $Wm^{-2}sr^{-1}$	1.0 $Wm^{-2}sr^{-1}$	two	required	40 km
Total long-wave	4-30 μm	0.5 $Wm^{-2}sr^{-1}$	0.5 $Wm^{-2}sr^{-1}$	not required	required	40 km
$\alpha = 21°$, $\zeta = 23.9°$ $\alpha = 33°$, $\zeta = 38.1°$ $\alpha = 45°$, $\zeta = 53.2°$ $\alpha = 57°$, $\zeta = 71.7°$	0.4-1.0 μm	200 @ 10 % albedo	5 %	not required	required	5 km
874.38 ± 6.0 GHz	3.0 GHz	1.0 K @ 240 K	1.5 K	two	required	10 km
682.95 ± 6.0 GHz	3.0 GHz	1.0 K @ 240 K	1.5 K	two	required	10 km
462.64 ± 3.0 GHz	2.0 GHz	1.0 K @ 240 K	1.5 K	two	required	10 km
220.50 ± 3.0 GHz	2.0 GHz	1.0 K @ 240 K	1.5 K	two	required	10 km
183.31 ± 1.0 GHz	1.0 GHz	1.0 K @ 240 K	1.5 K	not required	required	10 km
183.31 ± 3.0 GHz	2.0 GHz	1.0 K @ 260 K	1.5 K	not required	required	10 km
183.31 ± 7.0 GHz	4.0 GHz	1.0 K @ 280 K	1.5 K	not required	required	10 km
150 GHz	4.0 GHz	1.0 K @ 300 K	1.5 K	two	required	10 km
118.75 ± 1.0 GHz	1.0 GHz	0.5 K @ 230 K	1.5 K	not required	required	10 km
118.75 ± 1.5 GHz	1.0 GHz	0.5 K @ 250 K	1.5 K	not required	required	10 km
118.75 ± 2.0 GHz	1.0 GHz	0.5 K @ 270 K	1.5 K	not required	required	10 km
118.75 ± 4.0 GHz	1.0 GHz	0.5 K @ 290 K	1.5 K	not required	required	10 km
89.0 GHz	3.0 GHz	1.0 K @ 300 K	1.5 K	two	required	5 km
55 GHz	0.5 GHz	0.5 K @ 230 K	1.5 K	not required	required	10 km
54 GHz	0.5 GHz	0.5 K @ 250 K	1.5 K	not required	required	10 km
53 GHz	0.5 GHz	0.5 K @ 270 K	1.5 K	not required	required	10 km
50 GHz	0.5 GHz	0.5 K @ 290 K	1.5 K	not required	required	10 km
36.5 GHz	1.0 GHz	0.7 K @ 300 K	1.5 K	two	required	10 km
23.8 GHz	0.4 GHz	0.6 K @ 250 K	1.5 K	two	required	20 km
18.7 GHz	0.2 GHz	0.5 K @ 300 K	1.5 K	two	required	20 km
10.6 GHz	0.1 GHz	0.4 K @ 300 K	1.5 K	two	required	40 km
6.9 GHz	0.3 GHz	0.3 K @ 300 K	1.5 K	two	required	40 km

(1) *Radiometric accuracy* is intended as the random component of the error budget. The quoted quantities represent:

for broad-band channels: NEΔR [W / ($m^2 \cdot$ sterad)]
for short-wave narrow-band channels: SNR [specified for a certain scene albedo]
for long-wave channels: NEΔT [K specified for a certain scene temperature]

(2) Sampled at 5 km for co-registration purposes

The main ***system requirements*** of CLOUDS are:

- orbit: sun-synchronous, to chase METOP de-phased by 30 min (H = 840 km, ε = 98°, T = 101.7 min, LST = 10 h);
- design lifetime: 5 years, to ensure a total mission duration of 15 years by 3 successive satellites;
- both direct read-out and global acquisition to be provided;
- commonality of ground segment with METOP/EPS.

After one year of studies (*Phase 0* and *pre-Phase A*) a ***system baseline*** has been defined. ***Fig. 6*** provides a sketch idea of how the satellite could appear in orbit. Preliminary ***size estimates*** as resulting from a pre-Phase A industrial study are as follows:

- satellite mass: 750 kg;
- electric power requirement: 1000 W;
- data rate for local read-out (S-band): 1.1 Mbps;
- data rate for global acquisition at CDA (X-band): 30 Mbps.

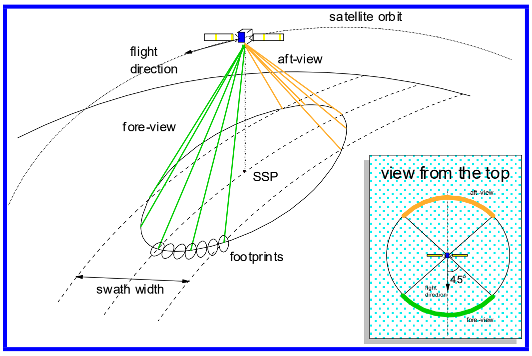

Fig. 5 - Geometry of conical scanning

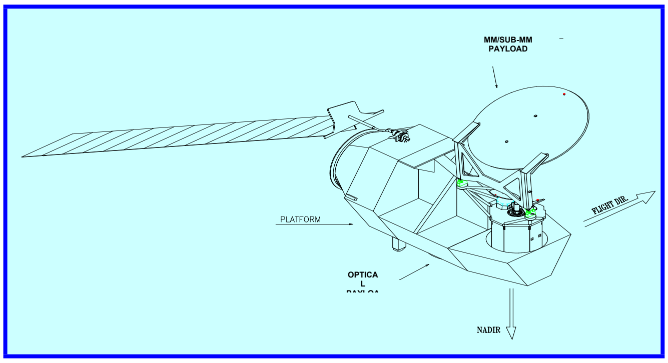

Fig. 6 - Sketch of CLOUDS in deployed configuration

The EC-funded CLOUDS study is demonstrating that, for monitoring purpose, it is possible to implement a sustainable satellite system which only makes use of passive radiometry suitable to large-swath observation as frequent as needed. Clearly, cloud radar as in the NASA *CloudSat* or backscatter lidar as in the NASA *Picasso-Cena* or a combination of both as in the ESA *ERM*, and rain radar as in *TRMM* and possible follow-on, are more suitable instruments to inspect cloud interior or rain, and accurate top height and aerosol. However, their role can only be limited to process study, since their swath is very narrow (if any). In addition, a payload complement capable of synergistically observe all the parameters contextually needed, as in CLOUDS, would require an extremely large satellite. The mass of CLOUDS, instead, is estimated as < 20 % of METOP/EPS.

A system based on the CLOUDS concept should be installed ***in parallel with METOP/EPS and POES*** to fill the gap of the post-2000 GOS as concerns cloud and radiation observation. In future, if the trend to split the mission of presently large satellites among more small-medium size missions prevails, CLOUDS could be one element of the split scenario. It is important to note that the quality of the imagery mission of CLOUDS as defined, apart from the horizontal resolution, is much superior to that one of the post-2000 GOS satellites to the extent that, by limited up-grading, could enable simplifying the mission of, e.g., post-METOP satellites. Also, a marginal improvement of the MW radiometer (full polarimetry) could allow sparing the wind scatterometer. These aspects will be further discussed in Chapter 8.

7. OCEAN SALINITY AND SOIL MOISTURE

As regards ***surface parameters***, the post-2000 GOS is sufficiently equipped for most needs of operational meteorology and climate monitoring (examples of observed parameters: *sea surface temperature*, *sea ice*, *land surface temperature*, *land albedo* and *vegetation index*). Further parameters, specifically on ocean, are expected to be available from non-GOS programmes, yet near-operational (*ocean topography, ocean-colour* derived observations). For *sea-surface wind* there is METOP/ASCAT, and others. *Air pressure on sea surface* would be a task for GOS, but requires technological development of doubtful potential, so that, at present, it is safer to rely on derivation from other measurements (specifically, sea-surface wind by scatterometry) through 4-D assimilation.

The most dramatic gap is for ***ocean salinity*** and ***soil moisture.*** These two measurements have one very important link, of technological nature: they both require low-frequency MW radiometry, which place demanding constraints for a space mission, also difficult to be re-conciliated with constraints from other instruments. A dedicated mission seems therefore appropriate.

The reason why ocean salinity and soil moisture are difficult measurements is that good sensitivity for these parameters only is achieved at frequencies such as 1.4 GHz. Since the strongest requirement for salinity measurements comes from coastal zone activities (river discharges in the sea) and, for soil moisture, from agriculture and hydrology, it is popularly believed that the horizontal resolution should be in the range of very few kilometers. The law of diffraction ($IFOV/H < 1.2\ \lambda/D$) shows that, for, say, a 3 km IFOV from $H = 500$ km (the minimum for a decent life time in orbit) an antenna diameter $D > 43$ m would be required ! Systems have been proposed to synthesize this sort of antennae by correlation interferometry, where the antenna is made of an array of thin antennae, still, however, very long (and probably missing too much radiometric accuracy because of very low efficiency).

In the context of CGMS, however, a limited scope is probably sufficient. We propose to limit the ***mission objective*** to physical climate at global scale, and to address the following applications:

- **ocean dynamics** as determined by, and traced through, the distribution of ***salinity.*** The main addressed phenomena are the evolution of the polar ice cap, and the input of water of different density from large basins into the ocean (example: flow of denser Mediterranean water into the Atlantic ocean, which determines a bi-static circulation in North-East Atlantic). Apart from the interest of evaluating polar ice cap reduction, which is so important in the context of Global Change, distribution and changes of salinity (which affects density) are one of the very few indicators which allow to infer the three-dimensional ocean dynamics;
- **large-scale air mass transformation** when crossing continents affected by variable ***soil moisture.*** Present parameterization of large-scale soil moisture for the purpose of representing humidification processes in Global NWP is extremely brutal, and constitutes one of the present limiting factors in weather predictability. The lack of knowledge of soil moisture (which is very difficult to be measured even in-situ) is such that climate characterisation is very defective in this aspect, thus climate modelling and model performance evaluation also are affected.

These objectives could correspond to the following ***generic user requirements*:**

- motion scale to be described: 500-1000 km wavelength
- required sampling to describe target wavelengths: 100-200 km
- required observing cycle: one global coverage each 2 days.

Being this range of MW frequency totally insensitive to clouds, the instrument resolution at 1.4 GHz could be 100 km for ocean salinity, possibly reduced to 50 km for soil moisture. This makes antenna sizes becoming affordable. However, the measurement is affected by other effects, which must be properly sampled and measured in order to enable correct and safe use of the data in all circumstances.

Observation of water salinity at 1.4 GHz is affected by ***surface roughness*** and, to a minor extent, ***surface temperature.*** The evaluation of surface roughness (or wind) requires frequencies exceeding 10 GHz, which also are affected by temperature: thus an additional frequency around 6 GHz, more sensitive to temperature, is required. Signals at these frequencies, however, are affected by water vapour, thus a channel at about 23 GHz is required, as well as a nearby window around 19 GHz. These channels provide a comprehensive set of measurements which synergistically re-enforce the value of salinity and moisture observation. Specifically, the 19 GHz channel allows to observe sea ice boundaries and type which are closely related to the salinity field. In addition, if the 19 GHz channel is equipped with full polarimetric capability, wind direction will be measured as well as speed. This is important, in so far as ocean surfaces exhibit azimuth brightness temperature asymmetry due to wind direction effects: the detection of such azimuth asymmetry through the measurement of the Stokes vector will significantly contribute to characterise the surface geometry and to improve accuracy in salinity retrieval. Heavy precipitation (e.g. from the monsoon) also will be detected (over the sea), which impacts on salinity.

Unlike salinity, which is sensed nearly exclusively at 1.4 GHz, information on soil moisture is achieved also at higher frequencies. A 2.7 GHz channel would have stabilising effect on the simultaneous retrieval of salinity/moisture and temperature (by providing more regular sampling of the surface emissivity through the frequency range); in addition, it would provide better horizontal resolution for the moisture measurement.

Table 11 shows the sensitivity of typical frequencies to the various geophysical parameters whose signals are convoluted when observing the Earth in this frequency range.

Table 11 - Sensitivity of MW channels to various geophysical parameters of convoluted effects

	1.4 GHz	2.7 GHz	6.8 GHz	10.6 GHz	18.7 GHz	23.8 GHz
Ocean salinity	****	*				
Soil moisture	****	***	**	*		
Surface temperature (ocean and land)	**	***	****	***	**	*
Wind (ocean) and roughness (land)	*	*	**	***	****	**
Precipitation (ocean)			*	***	****	**
Sea ice boundaries and type				*	****	**
Total column water vapour				*	**	****

One conclusion from this discussion is that ocean salinity and soil moisture need to be measured contextually with other interfering parameters. Whilst a broad resolution has been accepted for salinity and moisture, the interfering parameters need to be measured with a resolution compatible with their field structure (which is more detailed). ***Table 12*** suggests "reasonable" ***user requirements.***

Table 12 - Possible user requirements for ocean salinity, soil moisture and associated parameters

Geophysical parameter	Horizontal resolution	Accuracy	Observing cycle	Delay of availability
Ocean salinity	100 km	$0.3\ ^{0}/_{00}$	2 d	1 d
Soil moisture	50 km	30 g/kg	2 d	1 d
Sea surface temperature	20 km	1 K	2 d	1 d
Land surface temperature	20 km	1 K	2 d	1 d
Sea surface wind	10 km	3 m/s	2 d	1 d
Precipitation rate (on ocean)	10 km	1 mm/h	2 d	1 d
Sea ice boundary	10 km	1 km (*)	1 d	1 d
Sea ice type	10 km	0.3 classes^{-1}	1 d	1 d
Total column water vapour	10 km	500 g/m^2	2 d	1 d

(*) accuracy of boundary positioning on monthly maps.

Mission requirements obviously call for a MW radiometer equipped with channels as from Table 11. Not shown in Table 11, there is a dependence of the “signatures” from the various geophysical parameters on polarisation: thus each channel should be doubled for differential polarisation (the 23 GHz channel could be not doubled, if resources are critical). Double polarisation also is useful for dealing with Faraday rotation effects in the ionosphere, which affects low frequency radiation from Earth: a source of errors, especially for daytime observations. These errors may be insignificant for soil moisture measurement, but are important for the retrieval of ocean salinity. So it may be convenient to retrieve ocean salinity using the first Stokes parameter (sum of V and H polarisations) which is invariant to Faraday rotation. Alternatively, only night time data should be used. Finally, as already mentioned, it is convenient to infer not only sea-surface wind speed, but also direction, by carrying out full polarisation measurement for the 18.7 GHz channel.

As for the orbit selection, both ocean salinity and soil moisture are affected by diurnal variation (because of sun-induced evaporation). However, monitoring at more times in the day would preclude global coverage: specifically, the sub-arctic regions, which are a primary target for salinity measurement, would not be observed. Therefore, a near-polar orbit is adopted, sun-synchronous at 500 km height. In order to reduce the effects of ionospheric Faraday rotation, it would be convenient a 6 am / 6 pm orbit, since the electron content of the ionosphere is minimum at local sunrise.

The requirement for differential polarisation implies conical scanning. Both fore- and after- arcs should be sampled, to improve roughness filtering on land or improved wind determination on sea. With a 45° off-nadir conical scanning the useful swath would exceed the 700 km required to get one global coverage each 2 days (it would be each 1 day at high latitudes).

A ***sizing exercise*** has been carried out on the base of ***instrument and system requirements*** as follows:

- orbit: sunsynchronous, LST 06/18, 500 km height
- conical scanning 45° off-nadir, fore- and aft- viewing
- antenna size: 2.5 m
- dual polarisation in all channels, triple in one
- swath 700 km, observing cycle 2 days
- radiometric channels: as specified in ***Table 13.***

Table 13 - Suggested channel for a global ocean salinity and soil moisture radiometer

ν	Δν	NEΔT	abs.cal.	polariz.	viewing	IFOV	sampling
1.4 GHz	27 MHz	0.1 K	1 K	V & H	fore & aft	120 km x 80 km	14 km x 40 km
2.7 GHz	10 MHz	0.1 K	1 K	V & H	fore & aft	60 km x 40 km	14 km x 20 km
6.8 GHz	0.2 GHz	0.2 K	1 K	V & H	fore & aft	25 km x 16 km	14 km x 10 km
10.6 GHz	0.1 GHz	0.2 K	1 K	V & H	fore & aft	16 km x 10 km	14 km x 10 km
18.7 GHz	0.2 GHz	0.2 K	1 K	three	fore & aft	9 km x 6 km	14 km x 5 km
23.8 GHz	0.4 GHz	0.3 K	1 K	V & H	fore & aft	7 km x 5 km	14 km x 5 km

The results of the sizing exercise are:

- ***mass: ~ 500 kg, electric power: ~ 300 W, data rate: ~ 30 kbps.***

A global ocean salinity and soil moisture mission tailored to the needs of meteorology and addressing a total gap of GOS, also limiting factor for long-term weather and climate prediction, is therefore feasible within the constraint of a small-medium size satellite. It would not meet requirements from coastal zones and agro-hydrology, for which large structures are needed (synthetic or inflatable antennae). It should be mentioned that large systems designed for high horizontal resolution would not meet meteorological requirements, because of insufficient accuracy and lack of contextual information required for information retrieval (large systems have low sensitivity, cannot be calibrated and cannot include the number of channels required for a reasonably self-standing data set).

8. CONCLUSIONS: A TRANSITION STRATEGY TO POST-2010

In this document the major gaps of the post-2000 satellite-based component of GOS have been identified. Four missions were studied, to fill these gaps contextually with making preparation for replacing the large-size satellites foreseen for the 2000-2010 time frame.

Of these missions, there is one, the ***constellation of radio-occultation micro-satellites***, which does not need to wait for the years 2010. There is little linkage, from the technological view point, between this constellation and the basic satellite system in polar and geostationary orbit, certainly limited to few satellites, even if their size is reduced to small-medium. Also, there is no technological development envisaged in the IR/MW cross-nadir sounding, beyond IASI and AIRS, which could provide observation of atmospheric discontinuities as accurate as by radio-occultation. This system represents therefore an ***add-on*** to be implemented as early as possible.

The ***Advanced Geostationary Satellite*** for frequent high-vertical resolution sounding and fast imagery capability represents a ***replacement*** of those to be operated in the years 2000-2010. The study reported in this document indicates that a very advanced mission could be possible by a small-medium size satellite. This is extremely important, because it provides the opportunity to install a higher number of satellites in the equatorial belt, which is required because of the limited zenith angle for useful sounding, and to have a larger area where to improve wind quality by better height assignment through stereoscopy. The ideal number would be in the range of eight, including contingency margin.

The ***clouds and radiation mission*** is needed as a matter of urgency, since the poor description of cloud-radiation interaction is already a limiting factor of long-range weather and possibly climate prediction. Initially it could be an ***add-on***, e.g. to follow METOP/EPS in orbit. Eventually, it could constitute ***one of the components of a possible split scenario*** in the post-METOP and NPOESS era. The mission as defined, e.g., in the CLOUDS project, represents a great improvement (except for the horizontal resolution) in respect of the METOP/POES imagery mission based on AVHRR. With some up-grading, e.g. a high-resolution channel in a single band, could represent the imagery mission of the post-2010, leaving to METOP the limited task of supporting the sounding mission (e.g., by up-grading the IASI embedded imager). By up-grading the MW radiometer (by more polarisations) the wind scatterometer could be spared. Thus, the post-METOP EPS satellites could be substantially smaller, focusing on the sounding mission and perhaps enhancing the chemistry mission if needed. In case the NPOESS concept tends to grow beyond sustainability (due to growth of requirements by the US user community), it could be envisaged that the coarse-resolution imagery mission is allocated to a CLOUD-like satellite, allowing NPOESS focusing on other requirements (in this case, 2-3 orbital planes would be needed, which is conceivable, given the small size of CLOUDS).

The ***global ocean salinity and soil moisture mission*** implies technical solutions which are not compatible with being hosted by other satellites, even if larger than METOP (which is a very unlikely case !). It therefore requires a dedicated ***add-on*** effort. The requirement is presently less urgent than for clouds and radiation, but it could be the next limiting factor for long-range NWP and GCM. It is stressed that it cannot be expected that high-resolution systems based on correlating interferometry or inflatable antennae, being pursued by other user communities, meet meteorological requirements.

It is reminded that the assumption has been made that other satellite programmes of near-operational status are expected to fill further gaps in fields with are not a priority for meteorology. Particularly, ocean topography, wave field and derivatives from ocean colour; and high resolution land observation.

In conclusion, it is stressed that there is still a long way to go before GOS meets user requirements. The approach presented, based on small-medium-size satellites first to be added and then to replace current large satellites within a split scenario, has i.a. the advantage of being easier to be implemented ***by a cooperative effort within CGMS.***