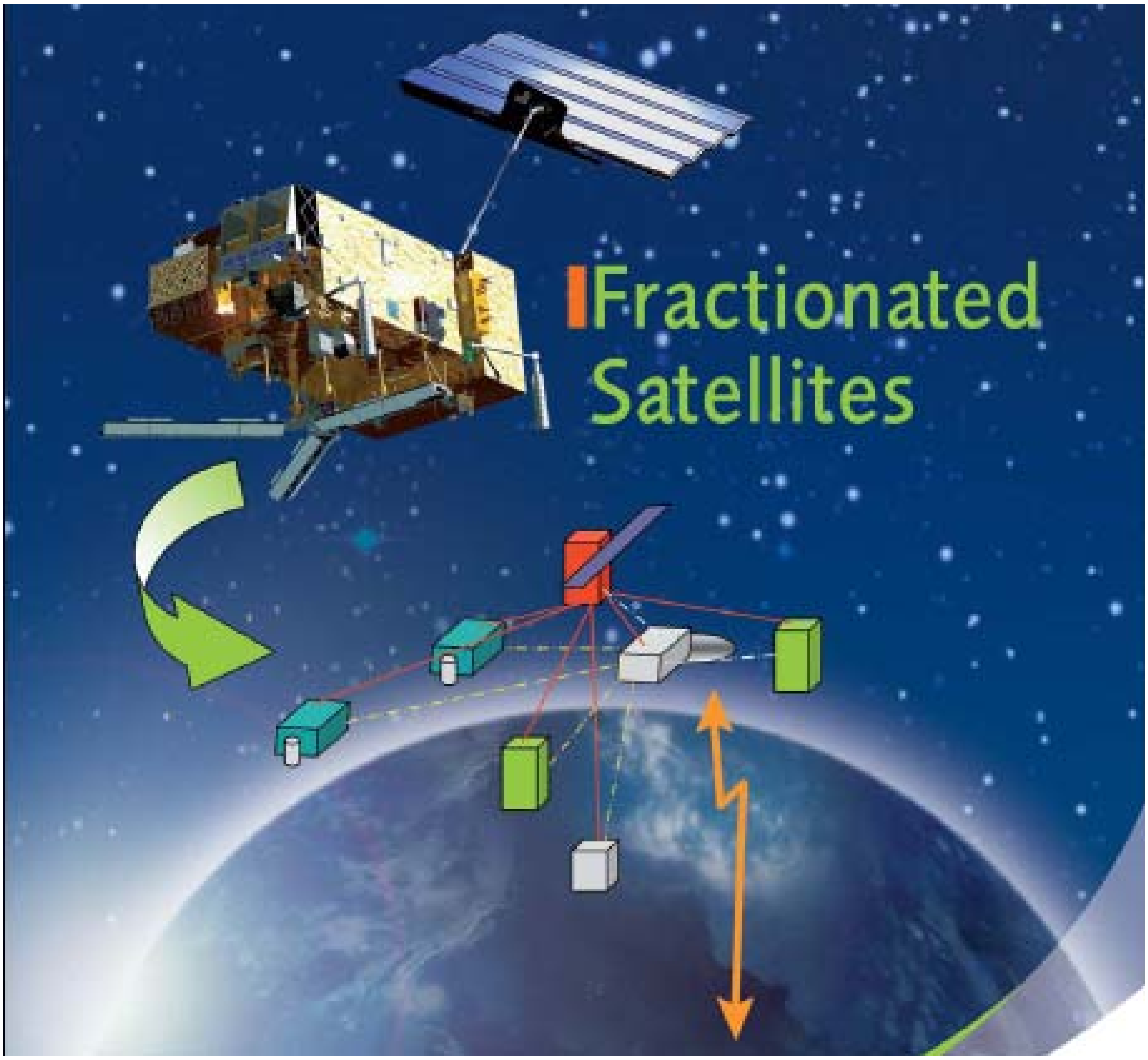
FRACTIONATED SATELLITES



EXECUTIVE SUMMARY

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1. INTRODUCTION

The fractionated satellites approach is a step towards more responsiveness, more flexibility, and more scalability for the space system. Such an approach has already been studied in USA for several years, and contract was recently awarded to industry for an in-orbit demonstration.

The fractionated satellite is a space system sharing its functionalities over multiple spacecraft modules.

This study aimed at defining the fractionated architecture, at determining its level of interest for various types of application and its added value and benefice for the customers.

2. SYSTEM ARCHITECTURE

Once in orbit, the fractionated satellite is a cluster of free flying modules, each fulfilling one or several functions of the space system, such as payload, communications, computing capability, cluster safety, etc. It relies on wireless transmission between the modules.

The functions or resources that can be fractionated includes the payloads, the functions specific to the operational phase, like high data rate communications with ground, data storage, etc, and some functions also used during the transfer of the free flying module to the cluster, when the way to fulfil the function may be different in operational phase.

The type of technology of the wireless transmission between the modules is a key driver of the fractionated architecture. The wireless data transmission is the basic system. It is sized by the distance and data rate, but the use of WiMax in S or K band will be adapted to most of architectures, allowing a data rate of up to 100Mbps at 5km. Wireless power transmission is a step further, still not technologically mature, for sharing the power supply.

Other drivers of the architecture are the data networking (central router or point-to-point network), to be selected as function of the application, and the distance between modules. This minimum distance shall be a compromise between the data rate between module (and data transmission performance), and the safety of the cluster.

The functional candidate architectures are characterised by the shared resources, and the number of modules housing these shared resources (1 to 3). They are illustrated on Figure 1. The resources subject to fractionation are the communications with ground, the data storage, the data processing, the cluster management and FDIR, the relative navigation computation, the relative navigation measurements, the power.

The redundancy approach will drive the final number of modules. Thus, the preferred approach is a redundancy at system level, with a spare module in orbit, but no internal redundancy in the module itself.

The applicability of the functional architectures to the different types of applications are synthesised in the Figure 2.

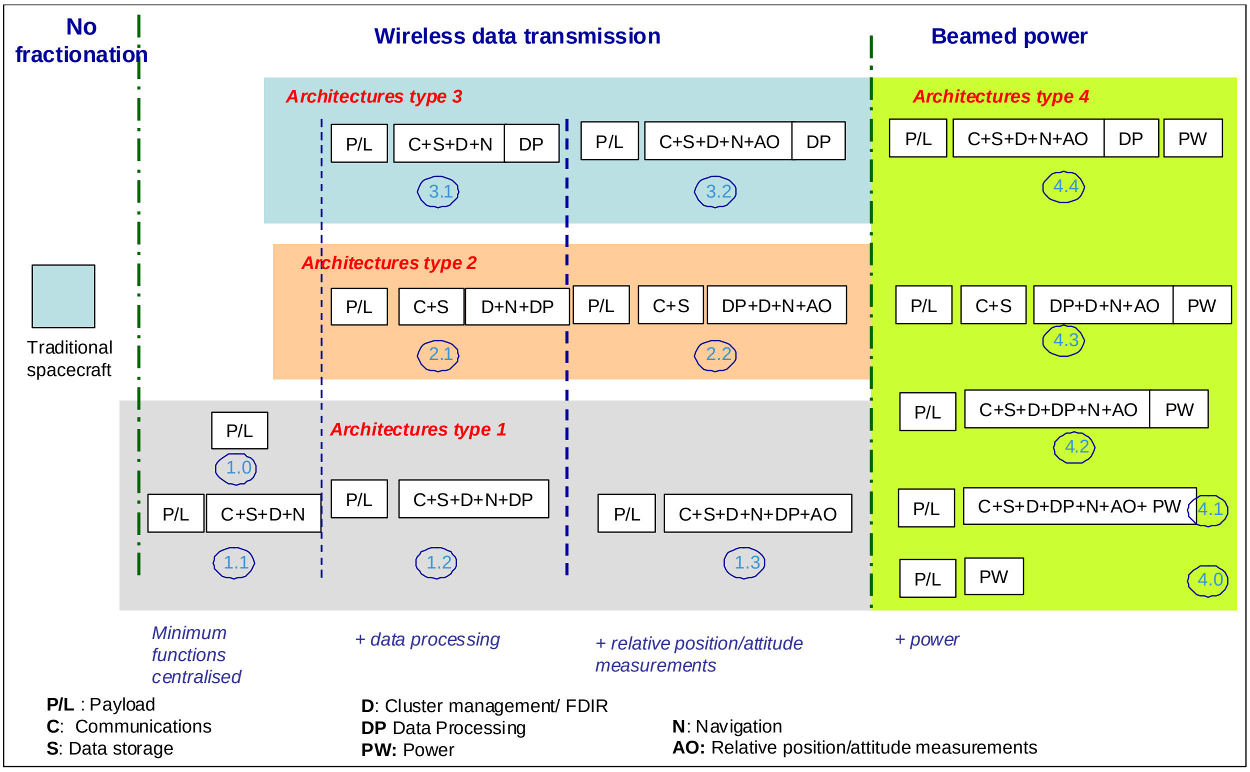

Figure 1: Possible functional fractionated architectures

	central router								point-to-point				
	1.0	1.1	1.2/ 1.3	2.1/ 2.2 (A1/ A2)	3.1 / 3.2	4.0/4.1/4.2	4.3 A2	4.4	1.0	1.1/1.2/1.3	2 / 3	4.0	4.1 to 4.4
LEO mission		low data rate		Low, high & mixed data rate			X						
GEO coms									X			X	
GEO obs		X	X	X			X						
Scientific Lagrange				X			X if shielding						
Planetary		low data rate		Low, high & mixed data rate			X						

Figure 2: Applicability of functional architectures to different types of application

3. COMPARATIVE ASSESSMENT

A comparative assessment between the monolithic satellite and the fractionated satellite has been carried out for four reference missions: LEO Observation (METOP), GEO telecommunications, scientific in L1 (SOHO), and planetary (BEPI-COLOMBO).

3.1 LEO MISSION: METOP

METOP is operational over 14 years with 3 satellites. Each satellite brings 12 payloads, which are operating permanently.

The fractionation of the payloads has taken into account the primary mission, the co-registration and the interactions between payloads. The payloads have been divided into 4 payload modules. On resource point of view, only communications with ground has been shared, and implemented on a communications module (Comms) with data storage, central router, cluster management and FDIR, cluster modules navigation computation and mission management. The proposed architecture is shown on Figure 3. It includes 6 modules, with a spare comms module. Due to the low data rate, the wireless data transmission relies on WiMax in S band, with a distance of 10 km between comms module and other modules, except module 1 (6km).

To define orbital position of each module while keeping the distance is a key point of the architecture. In the METOP case, three modules (comms module, Payload modules 1 and 3) are aligned along the nominal orbit. The other modules will be placed on concentric orbits around the comms module, that means orbit with the same energy (and period) as the nominal orbit (see Figure 4). These orbits shall be defined to avoid any risk of collision and, in that aim, a minimum distance between modules (typically 10 kms) is a key parameter. Alternatively, forced orbits could be considered for safety, but at the penalty of propellant consumption and mass impacts.

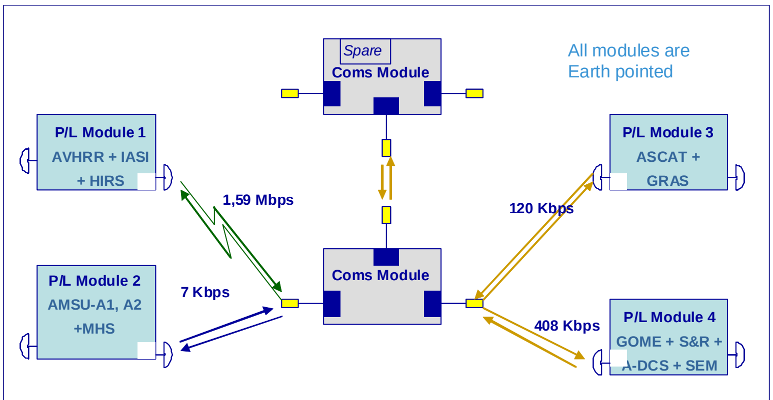

Figure 3: Fractionated satellite architecture for METOP

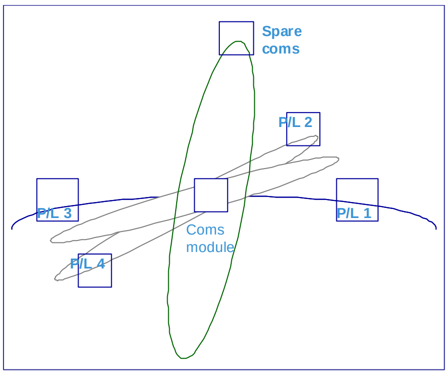

Figure 4: cluster orbits

This architecture leads to identify three standard modules: the comms module (400 kg), the medium module (800 kg, 1100 W, 170 Kg payload) applied to payload modules 2 and 4, and a large module (1100 Kg, 1300 W, 300 Kg payload) for payload modules 1 and 3.

Beyond the METOP mission, it appears that using fractionation in LEO is attractive when there are few instruments with different requirements in terms of field of view, pointing accuracy, agility, when there is a periodic utilisation of the instruments, and when there is a communications module with possibly computing capability.

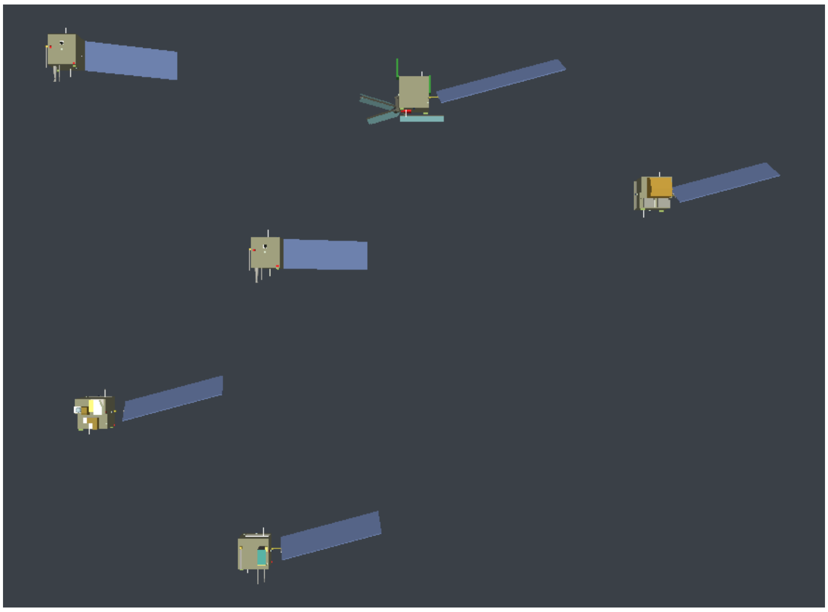

Figure 5: Illustration of METOP cluster of modules

3.2 GEO COMMUNICATIONS MISSION

The GEO communications satellite is characterised by a high power demand from payload and a permanent utilisation of the payload.

The drivers for the payload fractionation are to separate the payloads of different frequencies (C, Ku, Ka, etc) and to keep on the same module the payload elements linked by waveguide. Therefore, a possible approach consists in separating the reception function on one module, the amplification/transmission function on another module. On resource point of view, only the power could be fractionated. The architecture is based on a point-to-point network.

The analysis of a fractionated architecture with power modules has been done, as illustrated in Figure 6 for a mission with 64 channels. However, the low efficiency of the power transmission between modules (around 10%) is very penalising: the mass of the fractionated satellite for the mission case is about 370 to 450 % the mass of the monolithic satellite due to the five power modules. In addition, the laser beam requires an accurate pointing towards the receiver modules and a steering capability depending on the type of its orbit.

The proposed architecture includes two reception modules (one nominal, one spare) and two amplification/ transmission modules (Figure 6). The inter-module link relies on RF omni directional transmission. The total mass of the system is slightly higher than the monolithic satellite (125%). In a further step, the approach consists in having standard transmission modules with TBD channels, a few kW and one transmission antenna. The management of the cluster, including safety aspect and module localisation, will be done on ground so that the modules will be separated by 10 km.

The fractionated architecture brings advantage in terms of maintainability (case of failure), especially to minimise the mission outage and revenue degradation, development and mission flexibility. In particular, it is attractive in case of an emerging market, with a reduced number of modules at the beginning to test the market, or in case of established market with several co-located reception and transmission modules providing spare capabilities.

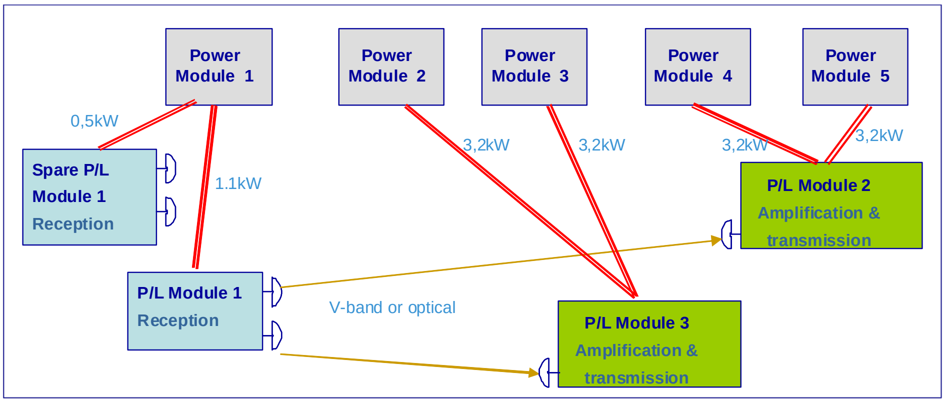

Figure 6a: Fractionated architecture with power modules

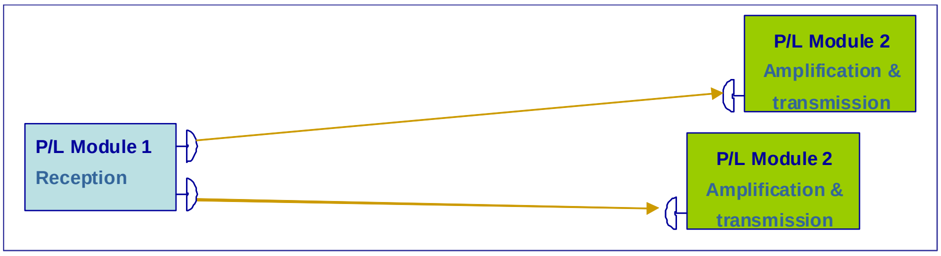

Figure 6b: Fractionated architecture without power modules

Figure 6: Fractionated architectures for GEO communications mission

3.3 SCIENTIFIC MISSION AT L1 (SOHO)

The SOHO satellite covers three types of mission.

It is proposed to fractionate the payload per type of mission, and within a type of mission to fractionate according the complementarities of payloads. That leads to four payload modules. On resource point of view, communications with ground are fractionated, and implemented on two comms modules (nominal and spare). The inter-module link relies on WiMax S band due to low data rate between comms module and payload modules. The architecture relies on a central router network. The distance between the central router and the payload modules is 10 km.

The mass of the modules vary between 450 and 900 Kg. The total mass of the fractionated satellite is about the double of the SOHO mass, taking the same strategy for launch and transfer to L1. The fractionated architecture is interesting for maintainability, development and mission flexibility. For instance, additional instruments could be integrated in the cluster if the first results of the mission identify the need for such a new instrument. That favours the growth capability of the mission.

Beyond SOHO, other types of scientific missions at L1 or L2 could benefit from the fractionated architecture while having slightly different needs. For instance, GAIA has several telescopes, some of them requiring a very high stability so that no mobile part can be implemented; it has also a very high processing capability that could be implemented in the comms module, at least as a spare capability.

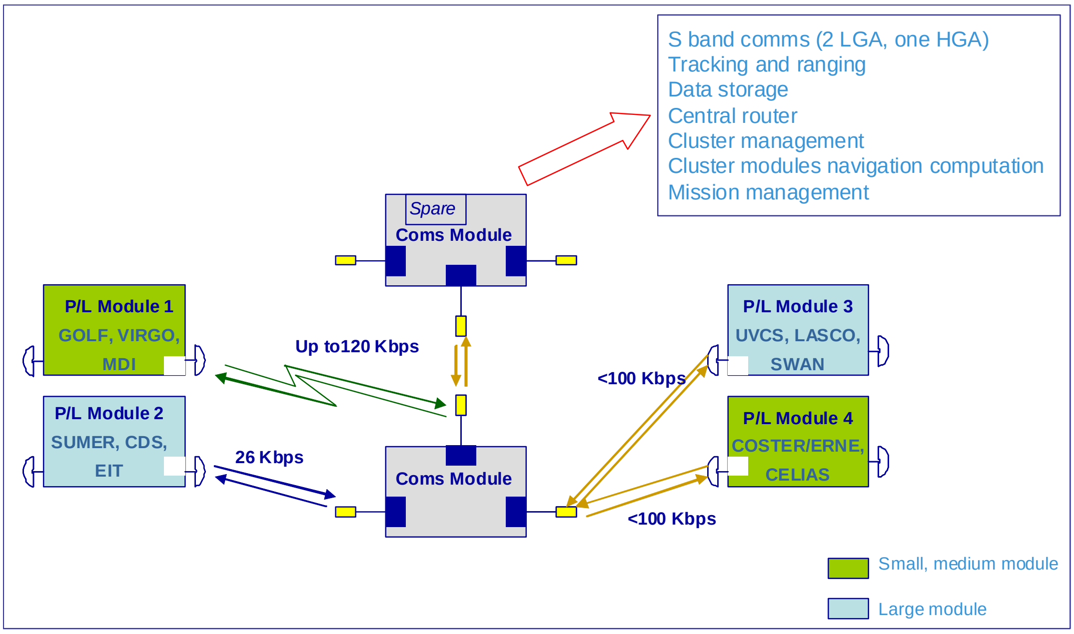

Figure 7: Fractionated architecture for SOHO

3.4 PLANETARY MISSION: BEPI COLOMBO

The objective of Bepi Colombo is the observation of Mercury. It is an assembly of two orbiters and a transfer module.

The main driver is the transfer duration, 6 years, due to the high energy required to go to Mercury. The mission duration around Mercury is one year. The proposed fractionated architecture is composed of 3 modules: two payload modules and one comms module hosting also some payloads. The spare approach will probably not be retained for BepiColombo due to transfer duration: in that case, the comms module will have redundancy. A standard transfer module will be used by each of the three modules. For this application, the fractionation has a low interest in terms of maintainability and flexibility, due to the duration of transfer compared to operational lifetime.

But, for other planetary missions, the fractionated architecture could be interesting if the operational phase duration is much longer than the transfer duration, as in the case of Mars or Venus observation.

Here, new payload module could be launched to complete the initial set o instruments, or to ensure the continuity and evolution of the mission.

Nevertheless, all the cluster modules are sized by the propellant need for the transfer; even with a standard platform, this propellant penalised the mass of the fractionated satellite. In addition, the rendezvous with the cluster shall be done autonomously. The distance between modules will be of several km (typically 10 km).

3.5 SYNTHESIS

The fractionated concept is well adapted when:

- There are several payloads, each having different drivers for the satellite sizing (accurate stability/pointing for some ones, thermal constraints for others, etc) leading to oversize the satellite
- There are several different suppliers of the payloads
- The mission or the market is susceptible of evolution during the satellite development and operational lifetime.

Therefore, the fractionated architecture appears:

☺☺☺ Interesting for Earth observation in LEO (comms and computing module, few payload modules, periodic use of instruments), for communications in GEO (cluster of standard payload modules, a new approach for the service), and other missions in GEO (combined mission with communications, meteo, observation, technology).

☺☺ Attractive for scientific mission in L1/L2, in particular if standard modules could be defined so as to be reused for other missions or for mission flexibility.

☺ Of low interest for planetary mission, due to the transfer phase and associated propulsion. It can be considered only when the operational phase is much longer than the transfer phase, and when the transfer phase is at low energy.

4. TECHNOLOGY ENABLERS

The assessment of the reference missions has led to identify the enabling technologies of these missions and their impacts on the system.

All these technologies have been reviewed per function:

In data management, the key technology will be the distributed computing over two modules. It will apply to missions highly demanding in computing. Although it is operational for ground commercial application, the TRL for space is low. Other technologies concern the payload data processing capability, the shared data base and the cluster FDIR that will depend on the application needs.

The architecture networking relies on two options: either a central router network, which has a high TRL for ground applications, or a point-to-point network that will require the development of a space communication transceiver in the adequate frequency band.

The wireless data transmission is based on WiMax. The WiMax controller works on ground and shall be space qualified, or the WiMx software could be integrated in a qualified FPGA. The RF part is already existing (S band) or in development (Ka band, TRL 6).

In terms of **AOCS**, the sensors for relative navigation are not completely available. It remains to consolidate the reachable accuracy. The rendezvous manoeuvres are feasible as there is no final approach (only rendezvous down to 5 km). The key point is the cluster dynamics, with the definition of the orbits of each module, in particular the concentric and/or forced orbits. This definition is important as driving the safety of the cluster (avoidance of risk of collision).

The **power transmission**, by laser or RF, is at its beginning with no in orbit demonstration so far. The technology will be available much later than the previous ones.

The Figure 8 summarises the time at which the technologies could be available, provided the requirements are known and the development started.

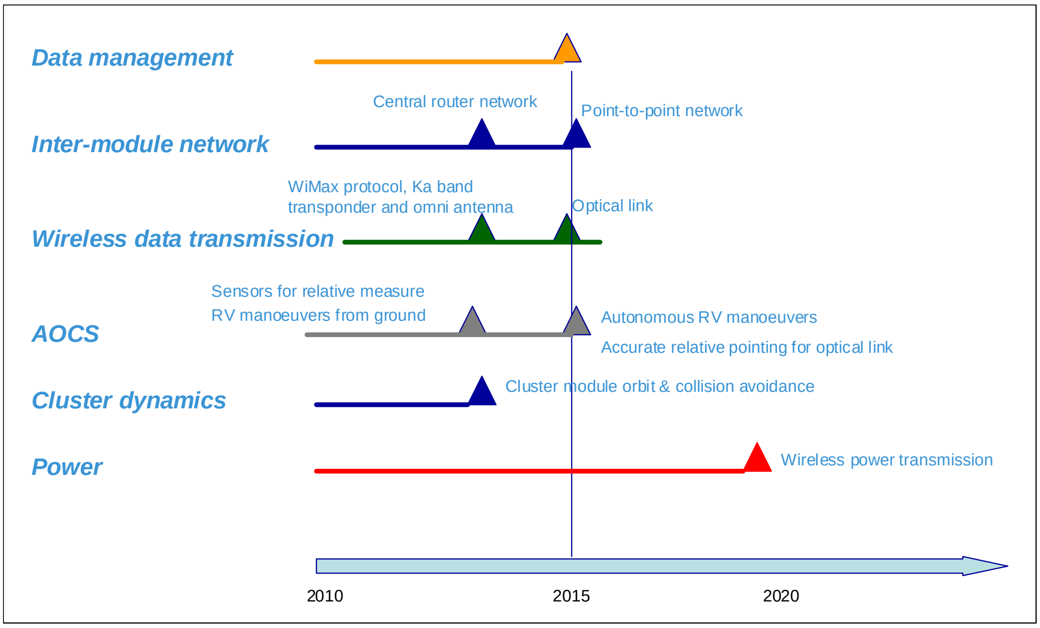

Figure 8: Availability of technologies

From this assessment, it appears that the fractionated architecture could apply to the applications in several successive steps (Figure 9). In a first time, a basic set of technologies could be available (central router, WiMax Sband, Cluster FDIR, cluster dynamics with limited number of modules, relative navigation computation, RV manoeuvres), so that the fractionated concept could be applied to LEO mission and scientific mission at L1/L2 with low data rate, and GEO observation.

In a second step, all other technologies except power transmission could be available, increasing the number of applications. Finally, power transmission will be available much later.

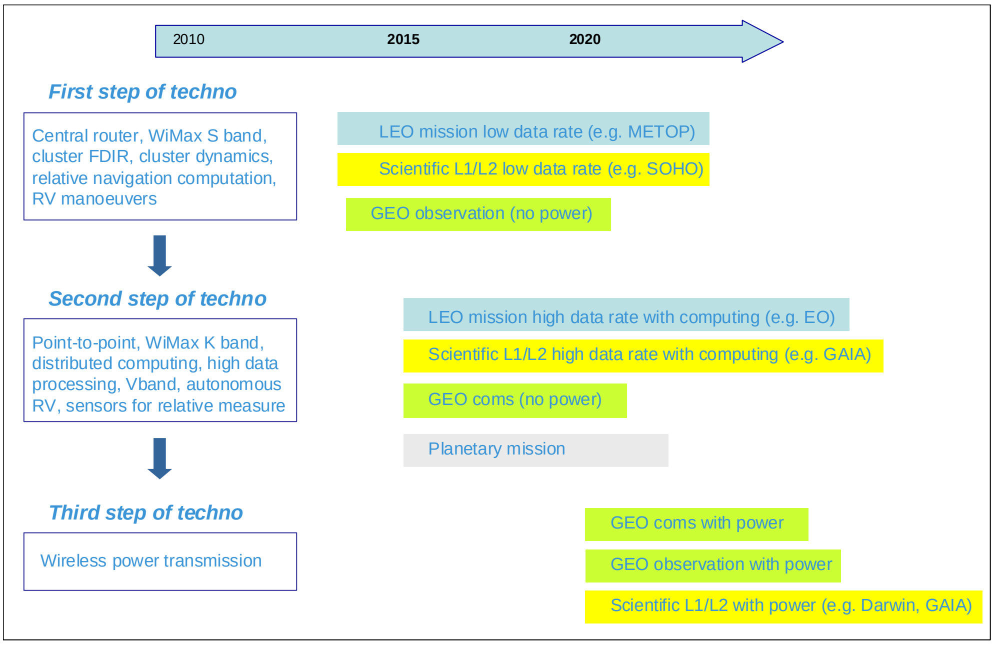

Figure 9: Successive steps of applicability of the fractionated concept

5. ADDED VALUE OF FRACTIONATION

An evaluation of the added value of the fractionation architecture has been carried out in the case of the METOP reference mission with respect to traditional (mass, cost) and non traditional (maintainability, scalability, flexibility, responsiveness) criteria. These non traditional criteria show the ability of the system to be adapted to uncertain internal or external changes affecting its functionality and performances, in a timely and cost effective manner.

Assumptions have been taken for the evaluation of the costs and to define a revenue model.

The METOP system consist in three satellites over 15 years, so that the fractionated architecture includes three sets of payload modules and a total of four comms module, not duplicating the spare in orbit. The total cost of the fractionated system, including launches, is about 10% higher than the total cost of the monolithic system. This is due to the high cost contribution of the instruments that is similar in both cases.

The maintainability criterion evaluates the effects of a failure on the system. Several scenarios have been analysed: launch failure, loss of a solar array panel, bad behaviour of an instrument. In the fractionated satellite, the exchange of the failed module allows to recover the nominal mission, and revenue within one year for a cost between 120 and 190 M€ including the loss of revenue. In the case of monolithic satellite, there is a degradation of the mission and a loss of revenue until the launch of the next model; if the service continuity is required, a new satellite has to be launched, so that the cost of the recovery is between two and three times the one of the fractionated satellite.

The scalability criterion deals with the obsolescence of the technology (computer, payload processing), the improvement of performances (detectors, payload pointing, etc) and the addition of payloads. That will generate a higher cost impact on the monolithic satellite (and it could be applicable mainly to the third satellite) while there will be a limited cost impact on fractionated concept as only a module will be modified.

The flexibility concerns the adaptation of the satellite design to changes occurring during development phase (requirements changes, late delivery of a payload that has been the case on Metop, etc), or operational phase (need for a new function, payload). The fractionated concept is better adapted to the development on demand. In the case of late delivery of one of the main instrument, the launch scenario of the modules would have been modified, so that the cost impact of this delay would have been about four times lower than in the monolithic concept case. The fractionated concept is also better adapted to the evolution of the market.

Finally, in terms of responsiveness, the fractionated concept relies on several small launchers, so that the time necessary to launch a new module could be limited to one year while at least two years will be necessary for monolithic concept. The fractionated concept allows minimising the duration of service interruption in case of failure.

Finally, the added value evaluation has highlighted the following points:

- The overall over cost of fractionation is small.
- The fractionation attractiveness is reinforced if there is an attractive revenue model requiring minimisation of outages.
- The development approach takes into account the non traditional criteria since the beginning, allowing a sharing of risk between modules, a progressive in orbit installation for earlier market capture and a progressive investment.
- The maintainability criteria is a major cost driver if the service continuity is required.
- The flexibility is also a great advantage.

6. CONCLUSIONS

It is difficult to compare fractionated concept and monolithic concept on an existing mission already fulfilled by the monolithic concept, as the mission requirements are adapted to the monolithic concept.

Therefore, we should **think differently** with fractionated satellite as primary drivers are not mass and cost, but **responsiveness to uncertainties**.

The fractionation concept allows the fulfilment of a mission in the time:

- The cluster of modules is not frozen, but can be modified to follow the evolution of the mission.
- Development approach and module implementation are adapted to the time evolution of the mission: investment may be spread in the time accordingly.
- Each module may be upgraded to cope with technology obsolescence and improved performances.

It also ensures the reliability and availability requirements at system level with additional modules.

It gives more freedom on payload development as any delay will not endanger the full mission and relies on the standardisation of the modules.

The level of fractionation of the resources is limited by the autonomous phases of the module (launch, transfer, rendezvous, removal) for which a minimum resources is necessary. Besides, the number of modules within a cluster is linked to their orbital position within the cluster, the distance between modules, the safety aspects and the network.

The fractionated concept allows also to reduce the vulnerability of the satellites to the impacts of debris.

Finally, the fractionated concept appears particularly attractive for applications requiring continuity of mission, that means for applications driven by the responsiveness to uncertainties like commercial missions (LEO observation, GEO communications) for which responsiveness is linked to a business model.