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Guy Cerutti-Maori

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Space Technology

Study Report

Prepared by Guy CERUTTI-MAORI

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CHAPTER 1
INTRODUCTION

The Study Report is done in accordance with the Annex B of the Letter Agreement and deals with:

- Telecommunications satellites,
- Meteorological satellites,
- Earth observation satellites,
- Scientific satellites.

For the purpose of this study, the previous satellite families have been split in different subfamilies.

Space Technology are the technologies necessary to design, to built, to test and to operate satellites, taking into account their evolution in the next 5,10 and 20 years. The time to develop space segment for a new mission was considered for this study, since it is an important parameter.
The development of future space segment and ground segment needs the availability of:

- Manpower with good knowledge,
- System, design and engineering tools,
- High performance data processing including advanced software, new architecture and EEE parts,
- Means including industrial and environmental facilities,
- Adequate technologies with free access.

The selected approach in this study is “Technology Push”, i.e. a survey of the usual technologies is given, since the objectives of INPE are not known. The identified technologies are presented like a menu for the sake of clarity. A selection of the adapted technologies has to be done by INPE in a “User Driven” approach after identification of the future missions and the associated satellites and payloads.

Results of this study are support of the INPE Strategic Plan: the INPE future mission selection has to take into account the correspondent technologies according to:

- Technology development in Brazil
- Technology purchase with the risk of export limitations
- Technology purchase within the framework of cooperation agreement

For each selected technology, a roadmap must be established in a near future.

CHAPTER 2
GENERALITIES

2.1 Technology Readiness Levels

Technology Readiness Levels (TRLs) are a systematic metric/measurement system which enables both to assess the maturity of a particular technology and to compare efficiently the degree of maturity between different kinds of technology. The TRL approach has been used on-and-off in NASA space technology planning for many years and was incorporated in the NASA Management Instruction (NMI 7100) addressing integrated technology planning at NASA.

In July 2005, NASA, ESA, JAXA and CNES have decided to be in accordance on the definition and on the use of TRL which are hardware and software applicable.

CNES recommend the identification of the TRL during the establishment of roadmaps.

A summary of the 9 TRLs is given hereinafter:

TRL1 Basic principles observed and reported
TRL2 Technology concept and/or application formulated
TRL3 Analytic and experimental critical function and/or characteristic proof-of-concept
TRL4 Component and/or breadboard validation in laboratory environment
TRL5 Component and/or breadboard validation in relevant environment
TRL6 System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL7 System prototype demonstration in a space environment
TRL8 Actual system completed and “flight qualified” through test and demonstration (ground or space)
TRL9 Actual system “flight proven” through successful mission operations

Levels 1 to 3 are relative to technological survey. Levels 2 to 5 deal with doctorate thesis or post doctorate in universities or Research & Technology activities in agencies or space companies. Levels 6 to 9 concern the development of project desmonstrators for system evaluation.

2.2 Technology push or User driven

The lower levels are “technology push”, that means a monitoring of all the possible technologies is done with the objective of not forget one.

On the other hand, the upper levels are “user driven”. In this case, a choice concerning the adapted technologies for a given space mission is made and only the suitable technologies are retained.

2.3 Technology procurement

For the development of a space program, an important factor for schedule and cost respect is the free access to the needed technologies.

An important point to notice is that the procurement of some technologies coming from the US may be problematic due to export limitations (ITAR). In particular, it concerns the technologies dealing with a powerful and fast data processing, advanced architecture, software, and EEE components.

2.4 Commercial or agency market

Telecommunication satellite application is a commercial and mature market, which offers many services. In the past, the agencies developed the technologies for the telecommunication satellites as well as the satellites themselves; today their contribution is limited to some R&T developments that increase the competitiveness of some selected companies.

On the other hand, Meteorology, Earth Observation and Scientific satellites are not in an open commercial market but remain an agency market, except for high spatial resolution satellites, where a pseudo-commercial market is appearing through the sale of image products.

2.5 Development time of a space mission

This duration is an important factor for the availability of the needed technologies; this duration is the addition of the mission definition duration and of the satellite development duration.

The duration of the mission definition lasts between 2 to 5 years.

For the satellite development duration, it is necessary to separate the Telecommunication satellites from the others:

- For a standard Telecommunication satellite, which does not need technological development, the time gap between order and launch is 2 or 3 years for an orbital life better than 15 years.
- A new generation of Telecommunication satellite is prepared when technologies are available, and the development time is 5 to 6 years. This new generation generally allows more power and more payload capacity.
- For Meteorology, Earth Observation and Scientific satellites, the time between order and launch is 5 to 10 years for an orbital life time of 5 years. Suited technologies are generally developed in parallel with the satellite development.

2.6 Brazil location

Brazil is an equatorial country, whose location offers the following advantages:

- Equatorial or low inclination low altitude Earth orbit give the opportunity of more than 10 revisits per day,
- Brazil is permanent in visibility of the geostationary orbit. Images can be acquired without significant geometrical deformations and with a low atmospheric transmission disturbance.

These advantages could give some opportunities for the future INPE missions.

CHAPTER 3
MISSIONS AND SATELLITE ARCHITECTURES

3.1 Telecommunication satellites

To-day, Telecommunications missions from low altitude Earth orbit (Globalstar and Iridium) were not proved to be attractive for users and the most important user is the US DoD (Department of Defense). For preserving the Globalstar constellation, orders for a new set of satellites are initialized by the operator. Since this domain of low Earth orbit is not a mature one, so this paragraph will be limited to market adapted satellites, i.e. satellites flying on geostationary orbit.

Up-to-date, telecommunication satellites are 3-axis satellites, located on the geostationary orbit at 36000 km altitude. The satellite is injected on the transfer orbit by the launcher (elliptical orbit 200-36000km), apogee motor of satellite is used for having the circular orbit. So the satellite dry mass is half of satellite full mass with its bi-propellant.
A telecommunications satellite is the assembly of 2 modules: platform and payload modules, each of them with independent development.

The platform module provides the following functions:

- Power with the 2 wings solar array and batteries,
- Propulsion with the apogee motor and the bi-propellant tanks,
- Attitude and orbit control, with sensors, reaction wheels, thrusters,
- Data handling,
- Launcher interfaces,
- Primary structure.

The payload module is a structure, equipped with thermal components, where all equipments of the telecommunication payload are assembled and tested before being integrated on the platform module.
The platform module is able to embark different kinds of payloads, which use a lot of common equipments, for the different Telecommunications commercial services:

- TV Broadcast/video application-HDTV (high definition), DTH
- Broadband access
  - Internet/intranet, other multimedia applications and services
  - Transition of VSAT systems from narrow band to broadband
  - Secure communications
- Mobile services- Mobile multimedia (3G), Future nomadic system (4G)
- Backhaul/Trunking
  - Internet Backbone
  - Backhauling for terrestrial systems:3G, 4G, WIFI, WiMax

For better services, and for a given satellite mass (mass is a prominent driver for telecommunications satellite), the future improvements will concern:

- Power enhancement, with impact on solar array and on batteries,
- Bit rate enhancement.

For power enhancement (to-day objective is 12 to 20 KW), the solar array must be more efficient, 2 ways are possible to reach this aim:

- Use of multiple junction GaAs solar cells,
- Increasing the solar array area, by the use of 2-axis deployment mechanisms. This can be done either by augmenting the number of panels with solar cells or introducing a concentrator.

The power enhancement needs, at the same time, availability of high efficiency batteries (if not available, the platform module mass will increase).

Bit rate enhancement could be achieved by 2 ways:

- Increasing the number of channels. However, to maintain the mass of the satellite constant, the platform module mass must decrease since the payload module mass raises due to the augmentation of channels.
- Development of flexible payload technologies (C/Ku/Ka).

In the 2 previous cases, thermal control of payload module needs advanced technologies for better passive and active thermal control.

A mass reduction of platform module, and also for payload module, could be achieved by:

- High performance structures for primary structure, solar array, tanks, antennas, thermal protection, ...
    - Stiffness, low mass, thermal properties, electrical properties,
    - Thermal/mechanical stability, moisture insensitive property,
    - Functional coatings,
- Use of electrical propulsion (to-day, insurance policies are very expensive for satellite equipped with electrical propulsion, so satellite operators do not buy this kind of satellites)
- Use of highly integrated avionics.

Today, for satellites with a 15-year life time, reaction wheels with mechanical bearings are closed to the technological limit.

3.2 Meteorological satellites

In the Meteorology satellite family, it is necessary to separate the geostationary orbit satellites from the low Earth orbit satellites.
A close coordination exists between agencies, particularly between NOAA and Eumetsat.

3.2.1 Geostationary orbit satellites

According to an agreement, 5 geostationary satellites assume the operational coverage of the Earth equator: 2 of them are US (NOAA-GOES), 2 of them are European (Eumetsat-MSG/Meteosat) and the last one is Japanese; these satellites collect raw image data 24 hours per day and provide the distribution of corrected image data to the users.
In addition, others satellites from India, China and Russia collect data too.

The first generation (1975-2000) of NOAA's and Eumetsat's satellites were spin satellites and gave each 30 minutes images of the Earth in the visible (1 channel, spatial resolution around 2.5 km) and in the infrared (2 channels: 10.5-12.5 µm and water channel around 6 µm, spatial resolution 5km). The satellites were cylindrical and their diameter was imposed by the electrical power needed for the mission. The spin axis was parallel to the Nord-South direction; the satellite rotation allowed the Earth analysis along East-West direction. In order to scan in the other direction, the Imager needed a Nord-South scan mechanism (rotation of a flat entrance mirror or rotation of the telescope). Raw image data were transmitted to ground by an electronically de-spin antenna. Infrared detectors were cooled by passive cooler seeing the Nord or the South direction, in the opposite side of the de-spin antenna. The spin of 100 revolutions per minute gave high satellite stability and simplified the thermal control, principally for the telescope Imager.
First generation Japan satellite is a spin one with a de-spin platform for the antenna.

With the second generation (1995-2020) of NOAA's and Eumetsat's satellites the quality of the collected data could be strongly improved:

- Full Earth image in 15 minutes instead of 30 minutes,
- Better spatial resolution,
- More channels mainly in the infrared,
- Pseudo vertical sounding of atmosphere by the use of the new infrared channels.

The Eumetsat choice is a spin satellite: the Meteosat Second Generation (MSG) is a big Meteosat Operationel (MTO) with a new Imager.
The NOAA choice is a 3-axis satellite: the GOES-Next satellite architecture is similar to the Insat satellite, the India satellite (see later). However, this configuration has 2 drawbacks:

- 3-axis satellite stability is worse than spin satellite stability,
- Thermal control of the flat entrance mirror is difficult around the equinox, during Earth night. The permanent solar power light on this mirror, during more than 1 hour, can induce mirror deformation (loss of instrument MTF and Geometric

Image Quality) and increase mirror temperature (loss of Radiometric Image Quality).

Second generation Japan satellite is a 3-axis satellite.

The third generation (after 2015) shall be based on 3-axis satellites. The improvement shall be not the Imager but the sounding capabilities of the atmosphere: the satellite will embark an infrared sounder and a microwave sounder, which are not easily compatible with spin satellite architecture. The study of the satellite configuration shall be difficult due to:

- The Imager with its 2-axis mechanism and its passive cooler,
- The Infrared sounder with its 2-axis mechanism and its passive cooler,
- The Microwave sounder with its 2-axis mechanism and its large antenna,
- The Telecommunication payload,
- The apogee motor,
- The solar array.

In the future, this "weather" satellite could also embark some environmental optical instruments for missions which need a permanent observation of the Earth.

China satellite is a spin one too.

Insat, the India satellite, has 2 functions relative to India country:

- Telecommunications,
- Meteorological observation.

The satellite is a 3-axis one, similar to a Telecommunications satellite, and not a spin one. This configuration is a good one for Telecommunications mission but the Meteorological observation dictates some constraints:

- The Imager has a flat entrance mirror with a 2-axis mechanism,
- The passive cooler, which needs a free half-space FOV, is not compatible with the classical 2 wings Solar Array. As a consequence, one of the 2 wings was suppressed and replaced, for AOCS needs, by a mass on the extremity of a mast (to keep the center of gravity at the same location) and a Solar sail (same radiation pressure torque than with the suppressed wing).

Russia satellite is a 3-axis one with a non-classical architecture, it never work well and Eumetsat has moved a Meteosat satellite on the Indian Ocean, near the nominal Russia meteorological position but in direct visibility of Darmstad station, for holding data collects on this area.

3.2.2 Polar orbit satellites

For the low Earth orbit, data are collected by polar satellites. To-day, the operational coverage is assumed by the satellites of 2 US agencies:

- One POES satellite of NOAA (NOAA is under responsibility of Department of Commerce), [POES=Polar-orbiting Operational Environment Satellite],
- Two DMSP satellites of US Army (US Army is under responsibility of Department of Defense), [DMSP=Defense Meteorological Satellite Program], with NOAA access to the data of some instruments.

Before the end of this year, the first Eumetsat METOP satellite will complete this operational coverage; the 3 METOP satellites will assume 14 years weather mission.

In a near future, these 2 previous US programs shall be superseded by the NPOESS program [NPOESS=National Polar-orbiting Operational Environment Satellite System]. It is a decision of President Clinton administration and on October 3, 1994, NOAA, Department of Defence, and NASA created an Integrated Program Office to develop, manage, acquire, and operate NPOESS. The IPO is located organizationally within NOAA and is headed by a System Program Director who is responsible to the NPOESS Executive Committee. This new system, operational in 2013, shall have 3 constellations of satellites on the same polar orbit but with 3 different local times at the equator crossing:

- The 5.30 and 13.30 satellites embark all the instruments,
- The 9.30 satellite embarks a few number of instruments, this “light satellite” will complete METOP satellite.

NPOESS shall be not an “advanced weather satellite” but an “environmental observing system”.

The NPOESS approach announces the end of large satellite in low altitude Earth orbit: a constellation of small satellites shall replace a large satellite. This approach imposes the connection capabilities of data coming from the different satellites but it has 2 advantages:

- If a payload is late, only a satellite is late; the other satellites could be launched at the nominal date,
- In the case of the failure of one of principal payloads, only a small satellite must be launch for mission recovery.

For example, the 4.1 ton METOP satellite shall be replaced by a constellation of 3 satellites in the range 1.1 to 1.4 tons.

For Polar orbit satellites, the mission approach is similar to the Geostationary orbit satellites. For improving the weather predictions:

- In the first step, a lot of imagers give image data,
- In the second step, passive sounders in the infrared and the microwave give vertical information of the atmosphere,
- In the third step (not compatible with geostationary orbit), Doppler Wind Lidar will give wind fields versus Earth location and altitude,

To-day, the prototype of the third step is in development: it is the Aeolus program of ESA, for a flight beginning 2008, the Lidar is 0.355µm wavelength in direct detection. An operational satellite could be envisaged not before 2020.

3.3 Earth observation satellites

In the Earth Observation satellite family, it is necessary to consider the subfamilies hereinafter:

- Very high spatial resolution satellites in the visible,
- High spatial resolution satellites in the visible (CBERS 3/4 class),
- Multi spatial resolution satellites in the microwaves (SAR),
- Environment satellites, with platform and some instruments similar to those of low Earth orbit Meteorology satellite.

3.3.1 Very high spatial resolution satellites in the visible

It is the domain of spatial resolution around 1m; this spatial resolution is not compatible with the classical push broom observation used on Spot or CBERS satellites:

- The instrument TFOV is small, only a few kilometers (long focal length and limited number of detectors),
- The instrument radiometry is bad, use of TDI detectors is not enough,
- Use of flat de-pointing mirror is scrapped.

Like interesting scenes with this resolution are not so numerous on Earth (only towns, industrial areas are concerned), a large part of the orbit is devoted to each scene recording:

- Instrument Line of Sight (LOS) is oriented to the scene before satellite vertical passage on the scene, for example at +30° of zenith direction,
- Push broom observation begins with a small satellite rotation in view to reduce the on-ground relative satellite speed, this operation increase integration time and give a better radiometry,
- After recording of a narrow spatial band of the scene, the instrument LOS is quickly oriented in the aim to record an adjacent band,
- A new observation begins and, at the end, a new instrument LOS direction is achieved for recording a third band,
- These operations are made since the satellite being up to -30° of zenith direction.

The raw image of the scene is an assembly of multiple bands, each band having a specific resolution (coming from the satellite-scene distance) and specific shadow (coming from the satellite direction versus zenith).

Such satellite needs agility which is not compatible with classical Earth observation satellite composed of a platform module and some instruments fixed on the platform. Satellite agility imposes:

- Compact instrument,
- Satellite built around the instrument,
- Use of control moment gyros (CMG),
- Control of micro-vibrations generated by the spacecraft equipments which induce jitter on the instrument LOS.

After the launching of US satellites like Ikonos, CNES is developing PLEIADES family (dual use: civil use and military use), which will replace the SPOT family.

3.3.2 High spatial resolution satellites in the visible

The architecture is very classical and well known: a platform module and some instruments fixed on the platform, with eventually specific data transmission equipments. Spot and CBERS satellites are good examples of satellite design compatible of 3/5 m spatial resolution.

With some platform improvements and new instruments, it is possible to have a family of satellites for more than 15 years duration; the platform could be a common one, after power enhancement, with high spatial resolution satellite in the microwave.

In the future, with the current technological development, a significant mass and size reduction of the platform and of the instruments will appear, and the large satellite will be replaced by a constellation of mini-satellites (same approach than polar orbit meteorological satellites).

3.3.3 Multi spatial resolution satellites in the microwaves

SAR is an active microwave remote sensing instrument, enabling an all-weather imaging i.e. during night or under cloudy scene. It was first a military instrument.

The SAR operation is periodic: emission of microwave pulses during a short time around the observed scene and reception of the backscattered signal of each impulsion. Due to the SAR power cycle, all the needed power comes from the battery; when the battery is flat, SAR is stopped and solar array has to recharge the battery. Since SAR consumes a lot of energy and produces a large amount of data which cannot be all stored on board, it is only used regionally for periods of a few minutes per orbit.

In the classic design, SAR antenna is a deployable rectangular multi sources antenna, the long direction of the antenna being parallel to satellite orbital velocity. ESA has developed ERS 1/2 satellites in the past and, more recently Envisat satellite where SAR is one of the principal instruments. Envisat was the first SAR satellite to be equipped with a full active array antenna equipped with distributed transmit/receive modules which provides distinct transmit and receive beams.

Several SAR satellites will be launched in the near future. Canada has developed the Radarsat1 satellite and will launch the Radarsat2 satellite in 2007. Germany will launch Terrasar-X in a few months. Italy is developing the Cosmo-Skymed satellites but have some problems with US part procurement and with the launch from Baïkonour.

The architecture of such satellite is very classical and well known since the SAR is mounted on a classical platform module. For example, ERS 1/2 have used the same platform than the SPOT 1/2/3 satellites (with minor modifications).

Since a few years, a new concept, well adapted to mini or micro satellite platform, appears but with limited operational modes. The deployable rectangular active antenna is replaced by a reflective off-axis parabolic antenna with a few horns at the parabola focus.

With this concept, Germany is developing the SAR Luppe satellite and Israel the TechSAR satellite.

SAR is a very versatile instrument, which enables to cover many missions and a multi-mode operation:

- multi-resolution imaging with the spotlight mode, sliding mode, stripmap mode, and scan-SAR mode (from the highest to the lowest resolution but with a increasing imaged area)
- interferometry between 2 antennas separated in the across-track dimension (single-pass interferometry) or between 2 single antenna passes (two-pass interferometry) to get digital elevation maps of the Earth and to measure the terrain altitude variation i.e. for volcanoes, and after an earthquake…
- polarimetry in order to analyse the soil, forests, crops, …
- detection of moving targets or measurement of sea currents with 2 (or more) antennas separated in the along-track dimension

Furthermore, the choice of the carrier wavelength (from m to cm) has a strong influence on the mission since radar waves have different ground penetration characteristics according to the wavelength.

A limiting factor for DEM generation (Digital Elevation Map), and for detecting object and surface motion is the short distance between the antennas, which is restricted by the satellite dimension. In the future, some formation flying missions are envisaged to overcome this limitation. These constellations are composed of 2 satellites which are following each other such as the German TanDEM-X mission (combining 2 TerraSAR-X satellites) and the Canadian Radarsat2-3 mission (combining 2 Radarsat2 satellites), or of 3 satellites with are rotating around each other such as the French project Cartwheel from CNES.

3.3.4 Environment satellites

Since the end of 80s, the approach was to develop in parallel:

- A big platform module,
- A big payload module composed of some instruments make fast on payload structure module and data transmission equipment.

After ERS1/2, ESA has developed Envisat which is the last of this approach; this large satellite Envisat presents many drawbacks:

- Expensive platform and payload modules,
- Long schedule with some critical instrument developments,
- If an instrument is late, the launch is delayed,
- Difficult arrangement of instruments on payload module,
- In the case of the failure of one of principal instruments, mission recovery asks for the launch of a new satellite.

Some instruments developed for ERS1/2 and Envisat are now embarked on METOP, these experimental satellites have prepared “weather” operational satellites; this way will continue in the future.

The current approach is very different. One or a few number of instruments is integrated on a generic mini-satellite platform; if necessary, a constellation of satellites is launched instead to develop a specific big satellite with a lot of instruments.
For example, the Proteus multi-mission platform is used on:

- Jason 1/2 , mission devoted to the sea-level study with radar altimeter, microwave thermal imager (NASA-CNES cooperation),
- Calypso, mission devoted to the study of atmosphere with a Rayleigh lidar and an infrared imager with micro-bolometers (NASA-CNES cooperation),
- SMOS, mission devoted to the study of soil moisture and ocean salinity with a passive microwave synthetic aperture instrument (ESA-CNES-CDTI cooperation).

Furthermore, Calypso is part of a constellation of satellites devoted to the study of atmosphere; the 2 others satellites are:

- Cloudsat (NASA), mini-satellite with a cloud radar,
- Parasol (CNES), micro-satellite with Polder, a visible instrument for study of atmosphere BRDF.

This new approach presents cost and schedule reduction in the development of satellite.

Environment satellites have many use, some of them have been discovery after the launch. A list of satellites as well as the associated environmental applications is presented below:

- Grace, Goce: gravity, ocean circulation, water stock fluctuations in continental tanks, deep impact of earthquake
- OErsted, Champ, SWARM: magnetic field variation at the Earth nucleus surface
- Jason ½: sea steams, sea surface levels, knowledge of the ocean bottoms, sea surface temperatures
- Metric resolution satellite: seismic break observation on a long distance
- Cryostat: ice-caps variation
- Fuegosat: forest fire detection
- Calypso, Earth care: study of atmosphere with a Rayleigh lidar
- SAR satellites: ground deformation around epicenter

After missions using Rayleigh lidar, missions using DIAL lidar are envisaged:

- WALES: water vapor concentration with high accuracy versus location and altitude,
- CARBOSAT for a complete description of CO2 cycle.

3.3.5 Coordination between agencies

The Earth observation domain offers an important number of activities. At the exception of NASA, the others space agencies cannot cover all activities, in particular for application operational satellites.

To-day, CNES is developing Pleiades (metric resolution in the visible) and do not plan to develop SAR satellites. Exchange of French visible data with SAR data have been negotiated with:

- Germany (SAR Luppe data),
- Italy (SAR Cosmo Skymed data).

European community is developing GMES (Global Monitoring for Environment and Security) with the support of ESA. The GMES venture is aimed at integrating the various aspects and themes of environmental surveillance, from global climatic changes to risk management, with a view to maintaining European sovereignty.
In a first step, GMES will buy data, for example data from Info Terra- TerraSAR.
In a second step, ESA will develop the Sentinels family:

- Sentinel1, a SAR satellite,
- Sentinel2, an hyperspectral satellite,
- Sentinel3, an oceanography satellite.

3.3.6 GEO observation
All Earth observation satellites are on low earth orbit (LEO) and the most of them are heliosynchronous ones for 2 reasons:

- For visible, the scene must be sun illuminated,
- The solar array must be sun illuminated for power production without the need of a 2-axis solar array orientation mechanism.

These orbits pass 14 times per day over the poles but cross 14 times per day the equator, the revisit time of an interesting scene varying from 3 days to 26 days (dependence with the satellite altitude). Furthermore, the scene will have nearly the same solar illumination.
This kind of orbit does not allow the permanent control of a scene.

Today, the use of the geostationary orbit (GEO) is envisaged by some agencies for satellites with passive instrumentation. However, the observation at medium and high latitude will not be so good.

For high resolution, the 36000 km altitude instead 800 km could impose the use of complex instrument (large entrance, long focal length). Instrument and satellite definition is not evident and should need the use of deployable mirror and telescope in space.
Furthermore, small satellite missions are easily feasible like a forest fire satellite.
For detection of launch of strategic missiles, military early warning satellites are operational on GEO since more than 25 years and detect flame during propelled phases.

3.4 Scientific satellites

Science of the Universe could be cut in 6 domains:

- Fundamental physics,
- Astronomy and astrophysics,
- Planet study,
- Solar physics and ionized media,
- Microgravity,
- Exobiology.

For Scientific satellite, it is not possible to identify satellite families like in the previous topics. If we consider the different missions, 3 sizes of satellites can be distinguished:

- Micro-satellite size (example: Picard, Microscope,), mass range: 50 to 200 kg,
- Mini-satellite size (example: Corot,), mass range: 300 to 800kg,
- Large satellite size (example: Herschel & Planck, GAIA, JWST, Lisa,).

Micro- and mini-satellites can be fully financed by national agencies such as France, Germany or Italy. However, due to their important cost, large satellites are reserved to NASA, ESA, or international cooperation between agencies.

Unmanned exploration missions of Mars, Mercury and Moon will have important development in the future and need Re-Entry, Descent, Soft landing, Rover and Ascent technologies to:

- Carry out remote sensing of planet environment,
- Achieve robotic exploration and surface analysis,
- Implement sample return missions.

In the next 10 years, formation flying will change the approach of some missions which need large satellite to-day; the size of such satellite result of the need of an important focal length for the instrument.
For example, it is the case for Chandra (NASA) and Newton (ESA), 2 satellites working in the X-rays; their axial length comes from the distance between the mirrors and the focal instrumentation. It will be difficult to increase the axial length of unique satellite without introduction of deployable structure or assembly in orbit with the support of ISS. The formation flying approach offers no limitation to the axial length, a mini-satellite embarks the mirrors and a second one embarks the focal instrumentation, the difficulty is the position control, on 6 degrees of freedom, of the second satellite versus the first one.
Formation flying approach is also applicable in:

- solar physics, for example an UV/visible coronograph,
- nuclear astrophysics, for example a gamma telescope,
- discovery of planets like Earth, for example infrared interferometer.

The Darwin Mission (ESA), scheduled for 2020, is an ambitious mission with 7 infrared cryogenic satellites in formation flying at L1 Lagrange position, for the discovery of planets like Earth.

Use of electric propulsion is very attractive for interplanetary mission, but it has an important drawback: the cost of operations; each day, a team must control the spacecraft and at the end of the mission, the associated cost is high. On the ESA Smart1, electric propulsion has worked well, but ESA prefers chemical propulsion on “Bepi Colombo” Mercury mission for cost reduction.

CHAPTER 4
PAYLOADS

Like we have seen in the previous chapter, the number of possible missions is very important, at each mission is associated a specific payload. In general payload is the assembly of different instruments, so in this chapter, the presentation will be limited to generic payloads or instruments.

4.1 Telecommunication payload

The telecommunication payload architecture is optimized for the high power dissipation. The best satellite faces for thermal control are the North and the South faces where the solar illumination is very low (a face is in shadow, the other face have solar illumination with high incidence). These 2 faces are OSR fully covered (OSR: Optical Solar Reflector) in the objective to radiate the heat produced by the payload. The surface of these faces is maximized.
During the launch, the panels of each solar array wing are stowed on the North and South faces.

The payload structure is a U shape structure composed by the assembly of 3 satellite faces: the North face, the South face and the Upper face.
All payload dissipative equipments are located on the North and South faces. For temperature homogenization, each face has a heat pipe network between the face structure and the equipments. Due to the variation of solar illumination versus seasons, a second heat pipe network links the North and South faces and passes through the Upper face. Ground thermal tests need heat pipes being in the horizontal plane, this is a design constraint for the network geometry and for the test definition.

Telecommunication payload includes a lot of antennas. The limited place between the launcher and the satellite imposes that most of the antennas are deployable. During launch, they are stowed on the Upper face and on the 2 other satellite lateral faces. Arrangement study of all the antennas in stowed position and in deployed position is complex. Deployment mechanisms are done accordingly to the antennas.

The different kinds of antennas are:

- fixed reflective antenna (parabola reflector with sources)
- steering reflective antenna (parabola reflector or cassegrain reflector, with sources)
- fixed active antenna
- steering active antenna

Payload works with in the C, Ku and Ka bands with different frequency and different polarization. Reflector figuring shall be more difficult in Ka band than in C band.

In the past, a complex spot beam was achieved by a set of sources with parabolic reflector. Today, the same complex beam is achieved by a source and a deformed parabolic reflector.

Payload is the arrangement of a lot of existing equipments or elements which can be procured in advance for schedule reduction.

4.2 Earth observation payload
The instruments used on the different payloads for meteorology, earth observation, environment and also science missions are very similar so this paragraph will present the instruments after grouping in families.
The identified instrument families are:

- Very high and high spatial resolution imagers in the visible,
- Medium spatial resolution imager in the visible and the infrared,
- Imaging spectrometer in the visible and in the near infrared
- Passive atmospheric sounder in the thermal infrared and in the microwave,
- Active and passive microwave instruments,
- SAR with active phased array and with classical antenna (SAR Luppe design),
- Lidars for wind speed measurements and atmosphere analysis,
- Radiofrequency instruments for atmosphere sounding.

Specific instrumentation for field measurements (gravity, electric, magnetic…) or for particle measurements (mass spectrometer…) will not be presented.

4.2.1 High spatial resolution imager in the visible
This LEO family covers the spatial resolution from 3m to 20m in association with panchromatic or multi spectral observation and an instrument FOV of 50 to 120km on ground. In some mission, a de-pointing mirror is mounted in front the instrument for across track observation.
CCD detectors allow push broom instrument.

In the past, the available detectors had some limitations:

- Linear array of silicon photodiodes CCD
- Pixel size 13 µm
- Line of 1728 photo-elements
- Large size encapsulation
- Commercial detector

The complex detector assembly in the focal plane gave optical transmission losses and resulted in the development of large telescopes. The HRV instrument of the French SPOT 1/2 satellites is an example of this first generation, the entrance pupil diameter was 33cm and the spatial resolution was 20m in multi spectral and 10m in panchromatic in a FOV of 60km.
For this kind of instrument, telescopes are Schmidt type (spherical mirror associated with an entrance dioptric corrector) or TMA (three mirror anastigmat in off-axis configuration)

New generation detectors change the situation, their characteristics are:

- Pixel size 13 µm
    - Quadric linear array
    - 4 lines of 6000 photo-elements each with small separation between lines
    - Adapted unique encapsulation for the 4 lines
    - Use of 4 strip filters in front the detector
    - Space detector
- Pixel size 6.5 µm
    - Linear array
    - Line of 12000 photo-elements
    - Adapted encapsulation (same IF than the quadric linear detector)
- Pixel size 6.5 µm
    - Double linear array
    - 2 lines of 12000 photo-elements each with small separation between lines
    - Lateral translation of 3.25 µm between the 2 lines(in the line direction)
    - Adapted encapsulation (same IF than the quadric linear detector)

With the same telescope, on SPOT 5, use of linear arrays of pixel size 6.5 µm instead of previous 13 µm give spatial resolution of 10m in multi spectral and of 5m in panchromatic. The double linear array of pixel size 6.5 µm is also used for panchromatic observation, the spatial resolution in panchromatic becomes around 2.5m.

For a fixed spatial resolution, the pixel size reduction conducts to a focal length reduction, so the telescope could be replaced by dioptric system (lenses) which allows a better FOV on ground. Use of dioptric system in space needs a good thermo-optical design for control of lens glass index variation versus temperature.
For CBERS 3/4, INPE has selected the following design for MUXCAM:

- Dioptric system
- Quadric linear array with pixel size 13µm, in association with 4 strip filters
- Spatial resolution 20m in multi spectral in a FOV of 120km

After some limited improvements of the dioptric system, use of linear array with pixel 6.5 µm would conduct to a spatial resolution of 10m in panchromatic, use of double linear array would conduct to 5m.

The Focal Plane Assembly is more and more complex with video processing entirely integrated on the focal plane, the video processing being link to digital processing (outside the instrument) by a high speed digital link. This “photon in- bit out” concept may be resumed by radiometric performance optimization at lowest costs.
The digital processing is mainly an elaborate data compression.

4.2.2 Very high spatial resolution imager in the visible
It is a push broom LEO instrument which need satellite agility.
The spatial resolution is around 1m in panchromatic. Radiometric resolution imposes the use of multi linear array CCD in TDI mode in association with satellite rotation in view to reduce the apparent satellite speed on ground. The number of used detector lines is programmable, it depends of scene radiometric conditions and the integration time must be adjustable.

For CCD in TDI mode, the pixel size is around 13µm, and the photo-element is photoMOS. Limited by the focal size and data rate, the FOV is around 10 km on ground.

The instrument must use a telescope, 2 types are possible:

- Ritchey- Chrétien telescope with dioptric corrector (Cassegrain telescope family),
- Korsch on-axis 3 mirrors telescope (Cassegrain telescope with a concave elliptic mirror)

These optical designs give a long focal length with a limited axial mechanical length, so the instrument is very compact. The entrance pupil diameter is about 50-60 cm, the mirrors are lightweighted and mounted on telescope structure by elaborate mirror fixation device.
The Focal Plane Assembly is an integrated one (see previous paragraph).

The important data rate imposes a very efficient data compression and important data storage.
The satellite is built around the instrument which needs a very stable structure. A crucial point for the mission is that the satellite structure does not have to introduce in the telescope structure micro-vibrations coming from reaction wheel, CMG, or solar array during agility operations.
The instrument and telescope optical test must be done in a vacuum tank.

4.2.3 Medium spatial resolution imager in the visible and the infrared,
It is a scanner instrument which use a few number of detectors in each spectral channel, the instrument covers the visible spectral range (0.4 to 1µm) and also the near infrared spectral range (1 to 2.5µm), the medium infrared spectral range (2.5 to 4µm) and the thermal infrared spectral range (4 to 14µm).
The 2 first spectral ranges observe the solar signal reflected by the ground or by the atmosphere and the last observe the temperature dependence signal (thermal signal) emitted by the ground and the atmosphere. The medium infrared spectral range observes a mix of the previous signals in the daytime, and it observes thermal signal during the night. This large spectral range imposes the use of a telescope.

By an appropriate choice of instrument spectral channels, the instrument will collect:

- Data from ground,
- Data from atmosphere
- Data for atmospheric transmission corrections of previous data

This instrument need mechanism(s) for scene analysis, the complexity of mechanism(s) depends of the orbit and of AOCS subsystem. The infrared channels need a passive cooler, so that the detector temperature is around 90 K. Filters and also some IR lenses have to be cooled too. Introduction of cooler is an important design driver for the study of the instrument and satellite architectures.

Scanners are used on meteorological satellite in geostationary orbit. They give Earth global view (covering nearly half of Earth).

For a spin satellite, satellite rotation around North-South axis gives image analysis along East-West direction. Image analysis along North-South direction is given by 1-axis scan mechanism which drives:

- A flat mirror at telescope entrance level (GOES first generation, Meteosat Second Generation-MSG/Seviri instrument)
- Or the telescope (Meteosat Operationel-MTO/ Meteosat Radiometer)

For the spin satellite, the telescope diameter is around 40 to 50cm and the cooler sees the North or the South direction.

For a 3-axis satellite, imaging along North-South and East-West directions needs a 2-axis mechanism with a flat mirror at telescope entrance level which can be realized in 2 ways:

- 2-axis mechanism driving the flat mirror
- Or 1-axis mechanism driving the flat mirror plus 1-axis mechanism driving the telescope

For the 3-axis satellite, the telescope diameter is around 30cm but 2 difficult problems must be solved (see paragraph 3.2.1):

- Flat mirror thermal control
- Cooler implementation on satellite

In low Earth heliosynchronous orbit, scanners are used to. Satellite displacement gives along track image analysis, the across track image analysis is given by 1-axis mechanism. The Earth vicinity imposes a more complex design for the passive cooler. For a small FOV (lower than 100km), the telescope is afocal and this 1-axis mechanism drives a small flat mirror located at the telescope exit pupil.
In the other cases, this 1-axis mechanism drives a flat mirror at telescope entrance level, the telescope diameter varies from 10cm to 40cm.
Different kinds of mechanism are used:

- AVHRR (Metop instrument):
  - mirror incidence 45°,
  - mechanism in constant rotation around the satellite velocity, giving a linear scan
  - telescope axis parallel to satellite velocity,
  - large FOV +/- 45°,
  - spatial resolution variable in the FOV (bad at the FOV edges), 1km at nadir
- AATSR (Envisat instrument)
  - Telescope axis parallel to zenith direction
  - Mirror incidence 22.5°
  - Mechanism in constant rotation around the zenith direction, giving a conical scan
  - Large FOV +/-45°
  - Spatial resolution constant in the FOV, 1km
- Thematic mapper (NASA)
  - Telescope axis perpendicular to satellite velocity and to zenith direction
  - Mirror mean incidence 45° (variable)

- Oscillating mechanism around satellite velocity
- Small FOV
- Spatial resolution 30m

The previous 3 examples indicate that scanner design is open to a lot of solutions.

Today, the situation is changing in low Earth orbit with the technology evolution. If the instrument spectral range is limited to the visible and the near infrared, it is possible to use push-broom instead of scanner. The French Vegetation instruments of SPOT 4/5 satellites are one example, the WFI camera of CBERS 3/4 is another example. Another example is the Polder instrument which uses an area array CCD.

With a micro-bolometer array which is an infrared thermal detector at ambient temperature, it is possible to develop a very simple thermal imager. For example, Calypso satellite embarks this kind of instrument.
In the Fuego project, the use of micro-bolometer thermal imager is selected for the detection of forest fire from a constellation of LEO satellites. From geostationary orbit, it will be easy to develop equivalent instrumentation for forest fire detection.

4.2.4 Imaging spectrometer in the visible and in the near infrared

This instrument family is used for doing thematic studies and classification. Many domains are concerned, it is possible to cite:

- Ocean color (phytoplankton, turbidity, costal zone…)
- Vegetation (farming, forest, vegetal cover, dryness…)
- Atmosphere (atmosphere transmission and polarization, water vapor…)
- Mineralogy (need bare soil: ore identification, erosion identification…)

Imaging spectrometer is a push broom instrument with the following elements:

- Photon collector (telescope or dioptric system) with a narrow slit in its focal plane, this slit selects a line in the image,
- A spectrometer is placed after the photon collector, the previous slit being the spectrometer entrance slit, dispersive element being prism or grating,
- The spectrometer output gives spectral images of the slit,
- An area array detector is placed in the spectrometer output: detector lines give spectral information and detector columns give spatial information.

So, this instrument analyses finely all the instrument spectral range with a good spectral resolution.

A good example is the Meris instrument on Envisat satellite which covers the spectral range 400-1000 nm with the use of Silicon CCD. It is mainly devoted to ocean color.

Another example is the Prism instrument with some developments under ESA contracts. It covers most of the solar spectral domain, from 450nm to 2.3µm with a spectral resolution close to 10nm. It provides reasonably high spatial resolution 50m over 50km swath when looking at nadir. In the 450-1000nm spectral domain, the detector is a

Silicon CCD; in the 1-2.3µm spectral range, the detector is a cooled CdHgTe infrared CCD.

The use of CCD detectors imposes the reading of the spectral information. So the data rate is very high. By signal processing the pertinent lines are selected and then transmitted to ground.

It is possible to envisage others concepts:

- Instrument with filter before the area array CCD, the filter being made of prismatic coatings. This simpler concept is sensitive to satellite AOCS,
- Instrument with field compensation interferometer before the area array CCD. This concept is also sensitive to satellite AOCS.

4.2.5 Passive atmospheric sounder in the thermal infrared and in the microwave,

By selecting narrow spectral channels in some thermal absorption bands of the atmosphere, it is possible to evaluate the vertical temperature profile or the vertical vapor water profile...

Since atmosphere is opaque between 14µm to 1mm, measurements are done in the thermal infrared or in the microwave.

In meteorological scanners (see paragraph 4.2.3), some infrared channels are devoted to these measurements. The filter large channel bandwidths do not allow a good vertical resolution.

Reduction of filter bandwidth is not compatible to the needed radiometric resolution.

Only multiplex design allows very narrow bandwidth and radiometric resolution.

IASI instrument (Infrared Atmospheric Sounding Interferometer), developed by CNES for Metop satellite, is a multiplex instrument using a Michelson interferometer with a moving cube corner reflector mounted on linear mechanism.

An entrance flat mirror on a de-pointing mechanism selects the observed point on ground. Cube corner displacement codes the optical signal collected by a set of individual detectors cooled by a passive cooler.

A specific processing (inverse Fourier transform) gives both the spectral emission of atmosphere and the vertical profiles (temperature, vapor water, altitude of inversion layer…).

Presence of clouds limits the observation.

It is not the case in the microwave where radiofrequencies pass trough clouds.

Microwave atmospheric sounders are scanners. They use RF components and technologies. Their architecture is comparable to a mechanical scanner.

MHS (Microwave Humidity Sounder) is an example. In the past, INPE delivered such an instrument to NASA. Today, MHS flies on Metop with AMSU-A, a NOAA atmospheric microwave sounder.

The 5 channels of MHS give atmospheric humidity vertical profile, cloud cover, atmospheric ice, rain, snow, hail-storm…

Microwave atmospheric sounder will require a large antenna associated to a 2-axis scan mechanism.

4.2.6 Active and passive microwave instruments,
The previous microwave sounder is a passive instrument. In atmospheric transmission bands, it gives sea surface, ground or cloud temperatures.
Passive instruments are similar to optical one. They are said to have quasi-optics techniques.

An example is the SMOS payload which is a microwave aperture instrument composed by an array of small antennas mounted on 3 long arms. This design gives a spatial resolution equivalent to those of unique antenna of same size than the arms.

Active microwave instruments use radar techniques.
The Radar Altimeter embarked on Jason gives the sea level.
The 2 antennas Radar Altimeter embarked on Cryosat measure both the ice-cap variations and the slope of ice-caps.

ASCAT (Advanced SCATterometer) embarked on Metop is an improvment of those of ERS 1/2 satellites. Its 6 linear antennas allow sea surface wind measurement, ground and sea ice monitoring, soil humidity and thaw, and snow characteristics.

4.2.7 SAR with active phased array and with classical antenna
SAR satellites enable to image the Earth with a resolution ranking from several tens of meters down to one meter such as with the future SAR satellites Radarat2 and TerraSAR-X. The area of the illuminated scene varies from several hundred of kilometers down to a few kilometers in the high resolution mode.

SAR using a classical antenna (SAR Luppe) are similar to a Radar Altimeter instrument with some classical horns at the parabola focus. The used technologies are the same but the signal processing is specific to this SAR design. This SAR has limited operational modes.
This kind of SAR will be used on the small satellites in formation flying around a classical satellite. The bi-static mode allows suppression of the emission function.

The new generation of SAR systems such as Envisat, TerraSAR-X, and Radarsat2 are equipped with an active array antenna. The T/R modules are organized in networks which provide flexibility and multi-mode operation.
After deployment, the deployable panels must give a precise geometry to the array. Each panel is equipped with an important number of T/R modules and therefore the failure of one T/R module is not critical. The T/R modules assume the pulse emission and the reception of the reflected signal.

SAR generates a high data rate. Raw data are sent to ground. From the raw data, images, interferograms, and other data products are processed on Earth after a heavy signal processing.

4.2.8 Lidars for wind speed measurements and atmosphere analysis

Lidar is optical radar (LIght Detection and Ranging).

The today lidar source is a solid state laser for space use. For near-term uses, the rod is Nd-YAG glass which emits 1.06µm pulses. With the help of non linear crystals, the 1.06 µm wavelength becomes 0.53µm (green) or 0.355µm (ultra violet).

The laser is laser-diode pumped and the emitted power is a few % of consumed power, most of the energy is transferred in heat. So, the thermal control of laser head is complex and the emitted pulses have impacts on power supply.

Lidar operational mode is the following:

- Short duration pulse emitted by laser (0.1 µs pulse duration is equivalent to 30m)
- Laser divergence reduction with a beam expender
- After propagation in vacuum, light arrives in the upper atmosphere
- During pulse propagation in atmosphere, backscattered light comes back to the satellite,
- A telescope collects this backscattered light,
- An optical filtering eliminates the optical background
- A photon counting detector, for example a photomultiplier tube, transforms the backscattered photons in electrons
- Electron number measurements versus time give altitude analyzed by the lidar
- Electrons are summed during a short duration time, this short duration time giving the vertical resolution of atmosphere analysis.

A simpler optical filter function collects all the atmosphere backscattered signal, this signal comes from the Rayleigh diffusion of atmosphere molecules and from the Mie diffusion of atmosphere particles. Examples of such atmospheric lidar are the Calypso lidar (NASA) and Atlid (ATmospheric LIDar –ESA).

A complex optical filter function using interferometer associated to a multi-channel detection gives the Doppler shift induced by the horizontal wind on the instrument line of sight. Knowledge of bidirectional wind needs wind measurements on 2 orthogonal directions.

Example of such Doppler wind lidar is Aladin (ESA). Its development is in progress for the AEOLUS satellite.

4.2.9 Radiofrequency instruments for atmosphere sounding

GRAS (GNSS Receiver for Atmospheric Sounder) embarked on Metop is a GPS receiver which gives atmospheric temperature and humidity by radio occultation technique.

CHAPTER 5
SYSTEM ENGINEERING

In the space manufacturing sector, simulation, modelisation, system design, engineering and verification activities are core processes: they represent a key know how. In general, industry intends to master them in-house for risk mitigation purposes. They also require hardware and software tools with significant investment effort.
As testing opportunities in real space conditions are a very rare resource, due to the limited launch opportunities for technology validation, space system and equipment development rely heavily on ground test and simulation equipment as well as on design and modelisation software tools.
Modeling is first required of the space environment where the system is required to operate. The ability to accurately simulate a variety of space conditions is the first key to optimized design; inaccurate models lead to more expensive over-designed system in order to reduce risks.
The spacecraft itself can be accurately simulated (the virtual spacecraft concept) to assess system issues and equipment interfacing. The virtual spacecraft will simulate all phases of the spacecraft's lifetime, from the early development stages to the end of operational life.
Design, engineering, testing and validation tools are needed at equipment and system level. They have to be interfaced and require commonly shared protocols.

The 2 axes of system design processes are:

- Virtual spacecraft
- Concurrent engineering

Virtual spacecraft is used from the preliminary design to the orbital lifetime, it is also use during AIT activities.
With concurrent engineering, all design tasks are done in parallel instead in serie.
At these previous activities must be associated:

- Multi disciplinary software tools
- Enhanced software tools for thermals, mechanics, optics, propulsion …

GPS sensor offers some opportunities:

- Availability of high precision time
- Satellite localization
- Coarse attitude restitution (in no multi runs)

The modeling of space environment and the effects on materials must be available, in particular for some components of payloads and for the COTS part use (see chapter 10).
A better knowledge of radiofrequency propagation in the atmosphere (particularly Ka band) is needed for margins reduction.

Better modelisation of mechanical shocks is mandatory:

- Carbon fiber structures allow mass reduction but lead to shock propagation in structure,
- Launcher stage separation generates high level socks,
- Large solar array deployment generates socks on structural ligthweighting elements.

Some domains need a special attention for the future:

- Satellite agility for metric resolution (compact architecture, CMG use…)
- Formation flying (the concept is applicable for many missions)
- New platform and instruments design to increase resolution in GEO observation (quasi-continuous observation)
- Next generation LEO platform (taking into account the future technologies presented in chapter 10)
- Constellation concept (replacement of a large satellite by a constellation of mini-satellites)

Today, formation flying is linked to a top-down approach, future missions have given the requirements for the needed equipments to be developed. A bottom-up approach shall be also done, from the equipments to the possible missions.

Space software needs well defined requirements taking into account the software testability; in the future, a possible way is:

- Simultaneous software/hardware co-design.

Around the computer, there are some associated circuits, the objective of S/H co-design is schedule optimization with identification of functions made by software and those made by hardware. A choice has to be done between:

- ASICs circuit (after manufacture, impossibility to change anything but the recurring cost is low),
- FPGAs circuit (reprogrammable circuit but the recurring cost is high).

Satellite autonomy has to be set up.
To day, autonomy is the simplification of the ground station interfaces by on-board automatic operations without ground intervention, it must be improved.
True autonomy, e.g. capability to solve unexpected failure, does not exist today. Such approach is quasi mandatory for interplanetary flight.

CHAPTER 6
PLATFORM MODULE SUBSYSTEMS

This chapter is relative to the technologies to be developed in the future for the platform module subsystems.

6.1 Power subsystem

This subsystem is very important for telecommunications and SAR satellites, the technology axes are:

- Solar array
    - Multiple junction GaAs cells (>3)
    - Solar array concentrator
    - Composites for low mass solar array
    - 2-axis deployment mechanism
- Battery
    - Supercapacitors
    - Higher efficiency Li-ion battery
    - Next generation high efficiency battery
    - Regenerative fuel cells with life time improvement
- Aluminium harness for high power transmission

6.2 Structure and mechanisms subsystem

Composite materials have shown great versatility to substitute other materials on satellites; properties of satellites can be tailored to support the needs of a wide range of equipment, such as antennas, solar arrays, tanks, satellite structures, telescopes (in this case, structure stability versus temperatures or loads or moisture is very important).

- Composites for low mass structures
    - Carbon fibers production
    - Matrix/Carbon composites
    - Carbon-carbon composites (for very high stability structure)
    - Industrial and manufacturing processes: curing, non destructive inspection...
- Innovative materials
    - High performance metals like gossamer technologies
    - Ceramics
- Deployable telescope structure
- Telescope structure for assembly in space
- Low socks pyrotechnic components
- Functional coatings on carbon fiber structure, for example for a better thermal conductivity

6.3 Thermal control subsystem

In the vacuum of space, thermal exchanges are made extremely difficult, in particular with the power dissipation and mass increases of telecoms satellites.
Scientific or Earth observation payloads have also specific requirements like stringent temperatures stability, thermal dissipation of laser sources or radars, cryogenic temperatures for detectors and sometime for mirrors.

- Fluid loop
  - Single phase using loop mechanical pumping (miniaturization)
  - Two-phase loop using mechanical pumping for high power rejection
- Passive technologies
  - High efficiency radiators, deployable radiator
  - High efficiency multi layer insulation (MLI)
  - High capacity heat pipe
  - Cryogenic heat pipe
- Cryomachines
  - Stirling (down to 4K)
  - Pulse tube & adiabatic

6.4 Propulsion subsystem

This activity will continue in the future:

- Composites for low mass tank

The principal effort in Europe will concern the next generation very high power electric propulsion for Telecommunications satellites.

- Engines (P>5; throttability)
  - Plasmic thruster
  - Ion thruster
- Power processing technologies
  - Power supply(dependence only on some components: e.g. MOSFETs, HV components…)
- Propellant technologies: gas formulation
- Test bench

For formation flying, activities in Micro/Mini propulsion are essential.

- Coarse actuation: cold gas, HET, ion
- Fine actuation: FEEP
- Fine actuation: Micro-ionic propulsion

Due to possible launcher failure, Europe intends to develop propellants with lower toxicity. As soon as new propellants for launcher are available, they may be envisaged.

- Green/low toxicity propellants and thrusters
  - Replacement of MMH/NTO
  - Replacement of hydrazine

6.5 Avionics subsystem

In the past, spacecraft had 2 computers:

- One was devoted to AOCS subsystem,
- The other was devoted to OBDH subsystem.

With the computer improvement, a centralized approach appears with unique computer on board.

The Avionics subsystem results from the fusion of the AOCS subsystem and of the OBDH subsystem; hence the new platform module has only one computer. The TTC subsystem is also included in the Avionics subsystem.

The future will be a highly integrated avionics.

- Miniature MEMS sensors
- Data processing/software: Smart FDIR S/W, advanced S/W techniques
- Star sensor with APS
- Earth sensor with micro-bolometers
- Hybrid sensors: GPS, inertial, star sensor, sun sensor…

New actuators will be:

- Control moment gyro (CMG) for satellite agility
- Reaction wheel with magnetic bearings for improvement of telecommunication satellite lifetime

In the avionics domain, formation flying needs development of adapted equipments for system control and GNC.

- RF and laser measurements
- Optical sensing and metrology
- Integrated optics
- Fringe measurements (delay line)
- MEMS based sensors: optical, inertial
- Formation acquisition & control algorithms

6.6 Data processing, software and components

Data processing tasks perform critical operations on a spacecraft.

Increased data processing power and speed are required at all levels of space systems, to perform control tasks on the platform and the associated payload, or to perform data processing, transfer and storage tasks related to the mission.

Processing architectures will vary, from distributed to centralized, but the main building blocks will share the common characteristics needed to perform in the space environment.

Critical requirements are the ability to withstand space radiations, and to operate in the peculiar thermal environment of space.

Today, most of these technologies are procured in the United States where they are covered by export limitations (ITAR).

Europe will intend to develop a lot of technologies for achieving technological non dependence on critical items.

The non dependence on critical items needs development on the 3 axes below.

Advanced EEE components: Electronic and Microwave parts

- Digital electronic components
  - Processors, high speed memories
  - Rad-hard DSP (1 Gflops)
  - FPGAs (reprogrammable over 1 Mgates)
  - ASICs (below 0.1 µm with high speed serial link > 3 Gps)
- Microwave components
  - LNAs and frequency devices (high frequency filters) and transistors
  - ADC/DAC (high speed and low power consumption)
  - MMIC
  - SiGe
  - GaN
  - Phase lock loop
- Generic components
  - Mixed ASICs and power transistors (Power Mosfets)
  - MEMS
- Packaging of devices
  - Thermal management, heat transfer issues
  - High density printed circuit board (BGA, CSP packaging)
  - Hybrids (RF and non microwaves), MCM (multi-chip module) and Flip ship

Advanced software technologies

- Improved processing capabilities basis on On-board software modularity
  - Software definition, design, development and test tools
  - Advanced software technologies for high criticality or high integrity applications
- Facilitate usage of COTS software
  - Requirements procedures and supporting tools for use of COTS software
- Low cost of maintenance
  - Develop or/and adapt automatic code generation tools developed for non-space ultra-reliable systems

High performance data processing technologies

- Architecture and technologies for next generation compact data systems, which emphasizes high performance processing capability
  - Develop high performance data reduction capability to support raw data refinement and processing
  - Assure architecture and technologies for next generation compact data systems

CHAPTER 7
PAYLOAD TECHNOLOGIES

This chapter is relative to the technologies to be developed in the future for the different payloads.

7.1 Telecommunication payloads

For being in accordance with the market, commercial company priorities are the availability of a "tool box" of payload equipments for the next generation of telecommunication payloads. This next generation will be a flexible payload with active antenna, high performance processing and Input-Output agile section.

- Antennas for in-orbit re-configuration
    - Passive antennas such as steerable zoomable spot beam, beam forming network (BFN) with switches or variable power dividers
    - Composites for low mass passive antennas
    - Active reconfigurable antennas with analog or digital BFN, either direct radiating array (DRA) or FAFR
- Switching devices for channel-to-beam allocation with fine granularity
    - IF processor, medium bandwidth Digital Transparent processor, RF/IF/BB converters, optical technologies for large bandwidth…
    - Wideband Digital Transparent processor, regenerative circuit or paquet OBP, ADC/DAC at IF or RF…
- RF power flexibility
    - Multi-port amplifier (MPA), flexible traveling wave tube amplifiers (TWTA) with medium dynamics, SSPA
    - Flexible TWTA with high dynamics

For optical links, see the paragraph "laser systems technologies" below.

7.2 Earth observation payloads

This paragraph concerns passive and active optical instruments, and the SAR active microwave instrument.
Some SAR technologies are common with those of telecommunication payloads.
Many optical technologies are common at the 3 generic families of optical instruments.

7.2.1 High resolution wide swath SAR

The objectives are to increase the accuracy of the instrument, enlarge the field of view, and enable a multi-mode operation

- Polarimetric / interferometric / multi-resolution SAR
    - SAR architecture

- Antennas: active phased array with large front end integration, parabolic antenna with horns at the parabola focus,
    - Advanced generic TR modules
    - Generic power supply units (converter)
    - Arrays technologies and architecture
    - Radiators
- Data storage, Processing and Transmission (Modular Control Electronics)
    - Advanced core radar processing electronics
    - Data compression algorithms
    - Solid state mass memory
    - Advanced modulation (for high data rate)
    - Signal processing

7.2.2 High resolution visible imager

These technologies are mandatory for the respect of Image Quality requirements (MTF, S/N ratio, registration…)

- Mirrors
    - Very low mass/ large diameter /new materials (ceramic,..)
    - Deployable mirror for GEO observation
    - Mirror grinding and polishing
    - Mirror fixation device
    - Active optics (sensors, actuators, mirrors)
    - Mirror coating
- Lenses
    - Radiation resistant glass
    - Lens barrel
    - Lens coating
- Telescope structure
    - High stability structure
    - Deployable structure
- Detectors
    - 2 line linear array
    - TDI linear array
    - Highly integrated focal plane assembly (FPA)
    - Linear filters
- Focusing mechanism
- Wavefront sensor for active optics
- Data compression (DCT, wavelet ..)
- Mass memory
- Data transmission to ground station

7.2.3 Hyperspectral instruments and spectrometers (visible and infrared)

These instruments have a large FOV with a good spectral resolution. Infrared channels need cryogenic temperatures for detectors and some optical components (filters, lenses, mirrors. Optical design is complex with some critical elements.

- Optical components

    - Mirrors with its coatings
    - Lenses (visible and infrared) with its coatings
    - Cooled optical components
- Focal plane Assembly (ambient temperature and/or cryogenic temperature)
    - Area array detectors (visible and infrared)
    - Active pixel sensors (APS)
    - Micro-bolometers
    - Radiators
    - Cryo-cooling devices
    - Filters
- Interferometry technologies and specific components
    - Beam splitters, filters, wide band antireflection,…
    - High precision linear mechanism
- Transmission of light through electro-optical systems
    - Optics to fibers coupling system
    - Integrated optics
- Calibration sources

7.2.4 Laser systems

Today lidar missions are new missions which could be operational in the future. High energy space laser development is difficult, the need is the increase of laser power and stability and a better lifetime.

- Nd-YAG lidars
    - High efficient laser pump source
    - Innovative highly resolving filters
    - Scattering Attenuation Meter (SAM) detectors, array detectors
    - Space qualification of solid state lasers (lifetime)
- Future DIAL lidars
    - 0.94 µm solid state laser for water vapor study
    - 2 µm solid state laser for CO_2 cycle study
- Optical communications, optical metrology, opto-electronic components
    - High power single mode laser sources
    - High power amplifier
    - Secure optical communication technologies through atmosphere

CHAPTER 8
GROUND SEGMENT

In the future, ground station will use more and more commercial equipments.
The virtual space craft gives directly a precise satellite representation to be included in the ground station tools.
Better satellite autonomy will simplify satellite operations.

CHAPTER 9
SATELLITE ASSEMBLY, INTEGRATION and TEST

Today, spacecraft, platform, and payload modelisations are more and more representative.
The virtual spacecraft shall be used during all the AIT operations and for the definition of GSE.
With all the available enhanced software tools, the design margins have been reduced, so for the Telecommunications satellites markets:

- Tests are more stringent for enhancing the satellite design reliability,
- Tests are more numerous for demonstrating the robustness of satellite concept.

CHAPTER 10
DISRUPTIVE TECHNOLOGIES

Space has been at the leading edge of technology for decades. Advances in computing and materials were driven by space research as much as it was benefiting from them. Today space is rarely a leading sector in terms of integrating new technological advances, especially since technologies to be used in space need to undergo costly qualification processes, and customers usually prefer proven technological solutions.

Advances in some technologies exhibit very high potential of benefit if applicable to space systems. Mass and power constraints are major driver of space system design and act as mission limiting factors.
Disruptive technologies may allow rethinking the way space systems are conceived with potentially major leaps for both scientific missions and operational missions.
Due to the difficulty of reducing significantly launch costs, and the limits in spacecraft mass and volume put by the available launcher supply, the optimization of spacecraft volume and mass budgets is, with power budget, at the heart of mission and spacecraft efficiency.

10.1 Micro-nanotechnologies

Today development of carbon nanotubes, with their promising characteristics, allows 4 attractive uses.

- Heat pipe for micro applications, for example processor cooling
- Smart structures
- Micro-propulsion for formation flying in the future
- Power storage in a wheel with magnetic bearings (only nanotubes could allow high angular speed for being mass competitive with next generation batteries)

Nota: Skeleton company introduces nano-structured carbons into supercapacitor.

10.2 MEMS sensors

MEMS (Micro-Electro-Mechanical Systems) are designed for a wide range of applications like sensors, switches, micro-shutters, beam deflectors, micro-deformable mirrors… The main advantages of micro-optical components are their compactness, scalability, and specific task customization using elementary building blocks. As these systems are easily replicable, the price of the components is decreasing dramatically when their number is increasing.
MEMS technology is closely linked to the micro-electronics fabrication process. Various materials are deposited on the surface of a substrate, and using masks, their localization on the substrate is precisely defined in order to ensure their specific tasks. In micro-systems, they are two kinds of layers: structural layers and sacrificial layers. The structural layer materials are polysilicon or metal. The sacrificial layers are silicon

oxides or organic materials which are chemically dissolved at the fabrication process in order to create air or vacuum gap between the remaining structural layers. A great level of sophistication in the micro-electronics technology ensures excellent tolerances on layer thickness and pattering precision.
Micro-mechanical actuation is obtained using electrostatic, magnetic or thermal effects.
MEMS technology could have a lot of application in space.

- In telecommunication payload, MEMS associated to reflective array antennas could offer flexibility for in-orbit re-configuration.

- Among the technologies available for gyroscopes usable in space, solid state MEMS gyroscope technology appears to be the most suitable: no moving parts, very good lifetime, low power consumption, very good behaviour in radiations and vacuum, easy manufacture. Today in Europe, Safran and BAe Systems are developing MEMS gyroscopes (2 possible procurements in the future).

- Micro-bolometers, a MEMS technology product, are infrared area array detectors at ambient temperature. With micro-bolometers, it is possible:
    - To develop an infrared imager (for example for forest fire detection)
    - To develop an Earth sensor
    - To develop a sun sensor

- Micro-mirror array, another MEMS technology product, can be use for multi-object spectroscopy, image slicer…

10.3 APS star sensor
APS = Active Pixel Sensor
Today, star sensor detectors are area array CCD. The CCD detectors lay down to read all the pixels and the signal processing selects the pertinent pixels for extracting the spacecraft attitude.
Use of CMOS detectors allows direct access to the pertinent pixels so the time for extraction of spacecraft attitude is smaller than CCD detectors. CMOS detectors allow:

- High dynamic range
- Programmable window
- High speed read-out

In some applications, this sensor could be assembled in 2-axis or 3-axis star sensor (assembly of 2 or 3 optical head on a common structure).
With the CMOS detectors, it is possible to manufacture a sun sensor too.

10.4 GPS sensor
GPS sensor offers some opportunities:

- Availability of high precision time
- Satellite localization
- Coarse attitude restitution (if no multi runs)

The high precision time can be use for the fine adjustment of spacecraft clocks, so the clock precision could be relaxed.

Good satellite localization is important for an Earth observation satellite, in particular for very high resolution satellite with a small instrument FOV:

- Predictive location allows observation of expected scene without the need of important margins,
- Restitution location allows good geometrical image processing.

Coarse attitude restitution (1 to 2°) could be achieve with specific location of GPS antennas and adapted satellite geometry; this coarse attitude could be acceptable for some missions or some spacecraft operations.
In the future, GPS sensor will be a GNSS sensor compatible of US GPS and European Galileo.

10.5 COTS

COTS = components on the shelf
Instead to develop a devoted to space Hi-Rel part, the idea is to use commercial part with some limitations.
Since the use of COTS parts requires part screening, the final cost for procurement is similar to the procurement of Hi-Rel part.

In general, COTS part use is acceptable for some months in LEO orbit. CNES Demeter micro-satellite uses COTS parts; SSTL spacecrafts use COTS parts too.
COTS part use need a revision of electronics circuits design which must be able to accept more noise, in this case Product Assurance rules have to be adapted.

For long duration mission like Telecommunications, COTS part use is not possible. Due export limitations, since 3 years, Europe develops European sources for the most essential Hi-Rel parts.

10.6 Power storage devices

During the last twenty years, satellite power increase by a ratio of 10. Today some missions need important or specific power storage:

- Telecommunication satellite during eclipse,
- SAR satellite where SAR is alimented on batteries,
- Earth observation satellite with lidar,
- Metric resolution satellite which cannot use solar array during the observation operations (platform agility),
- Earth observation satellite with functional infrared instrument during eclipse.

Old NiCd battery had limitations which induce high mass for batteries:

- Low efficiency,
- Limited deep of discharge for LEO orbit

NiH2 batteries (50 Wh/kg, deep of discharge 75% in GEO and 30% in LEO) replaced the previous ones. First generation of Li-ion batteries (100 Wh/kg) are used now in spite of its thermal problems.

With the envisaged power of 20 kW in orbit, the use of a new generation of power storage devices will allow a mass reduction or a better satellite duty cycle. Some possibilities are:

- Higher efficiency Li-ion battery (140 Wh/kg)
- Next generation high efficiency battery
- Super capacitors
- Regenerative fuel cells with life time improvement
- Power storage in a wheel with magnetic bearings

The super capacitor is a recent development in energy storage technology. Super capacitor is a trade name, which was given to the first Electric Double Layer Capacitor (EDLC), this type of capacitor is also known as an Ultra capacitor and by various other trade names.
NASA has approved super capacitors for use in space and it is now within the ISS as part of the portable electronic equipment kit.

The characteristics of super capacitors are in essence complementary of those of batteries:

- Batteries
  - Low power density (around a few hundred of W/kg)
  - High energy density (50 to 100 Wh/kg)
  - Low life time (around 1500 cycles)
  - High temperature dependence (around 20°C)
- Super capacitors
  - High power density (1000 W/kg)
  - Medium energy density (5 Wh/kg)
  - High lifetime (> 50 000 cycles)
  - Low temperature dependence (-20°C,+100°C)
  - No memory effect (no eclipse reconditioning process)

Batteries could be damaged if forced to supply high power peak and they should be protected from power surges. It is the case on SAR satellites where battery delivers high power peaks.
From literature, for the future, it is proposed the use of a battery (which is a high energy density device) in parallel with a super capacitor (which is a high power density device), this assembly creates a device with high power and energy density; this results in:

- Reduction of stress on the battery
- Increase in the battery life time,
- Mass and volume saving

10.7 Power supply

In the satellite, there is different kind of power supplies.

Power supply converter

In the past, it was a centralized approach: the power supply subsystem distributes all the needed tensions.

Today, it is a decentralized approach: the power supply subsystem distributes only bus tension, and equipment must generate its needed tensions. So, on-board satellite, they are many power supply converters. Rationalization of some converter circuits is in progress.

High power supply converter

Some equipment or instrument (e.g. laser sources, radars) generate today large amounts of heat which needs to be managed or to be reduced.

Recent advances have allowed silicon semiconductor technology to approach the theoretical limits of the silicon material for power supply, in term of higher blocking voltages, switching frequencies, efficiency, and reliability. To overcome silicon limitations, new semiconductor materials for power device applications are needed. For high power requirements, wide-band semiconductors like AsGa, SiC and GaN, with their superior electrical properties, are likely candidates to replace Si in the near future.

AsGa gives limited improvement versus silicon use.

SiC and GaN have similar characteristics and gives significant improvements versus silicon use.

Application of GaN devices have mainly focused on optoelectronics and radiofrequency uses because of the material's direct bandgap and high-frequency performance, respectively. GaN also have a potential for use in high-power electronics applications, growing GaN on SiC wafers increases the overall thermal conductivity.

Application of SiC devices is found only for high-power electronics.

High voltage power supply

SAR and Lidar are active instrument which deliver impulsions.

Lidar source is a laser, the lidar operation is periodic: emission of laser pulses during a short time around the observed point, reception of backscattered signal, and after signal processing, summation of signal for enhancement of S/N ratio. No emission is done since the next observation point is reached (stand-by period).

Due to the laser cycle, in general a battery is integrated after the DC-DC converter to regulate the power consumption. Use of battery with super capacitor will be an opportunity in the future.

In a laser, most of the energy is changed in heat; the emitted light is a few % of laser consumption.

18.8 Optics on board satellite

Beside optical instruments, a lot of optical devices are in progress for space use. Optical links between satellites and from space to ground have been developed (ESA SILEX experiment).

In chapters 6 and 7 are listed a lot of optical devices in some applications like:

- Formation flying,
- Telecommunication payload
- High resolution visible imager
- Hyperspectral instruments and spectrometers
- Laser systems

Most of these devices come from micro-electronic domain and integrated optics domain where important technology developments had been done for optical communications on ground. With these technological bases (similar to a tool box), it is possible to design and manufacture many kind of sensors.

For example, CNES has done in the past, the feasibility demonstration of an interferometer in integrated optics to measure 3 degrees of freedom (relative position of space telescope mirror), which requires the use of 3 measuring heads. Each head is a Michelson interferometer in a compact chip compatible with a space use, the interferometric function is performed by integrated optics made by ion exchange on a glass substrate. This technology allows the procurement of an optical circuit of small size (compared with a bulk optics device) without optical misalignment (alignment being done by the mask design itself). The expected performances were: measuring range from 0 to 3m, accuracy 0.2 µm, maximal displacement speed 150 mm/s.
This interferometer is departure point for the design of distance measurement sensor for formation flying.

Optical aperture synthesis interferometry could use integrated optics technologies for the beam combinig and cophasing function instead of a complex bulk optics device.

Appendix to Space Technology Study Report

Response to questions and clarification requests

Final version

This appendix gives the responses to the different questions coming from INPE.

Section 2.3 Technology Procurement

What is your suggestion to deal with the international restrictions related to the procurement of the technologies mentioned on your report, especially those coming from ITAR?

Due to ITAR, you must try to use technologies available outside the USA and to have contacts with others suppliers from Europe, Russia, Japan, China, India…
For parts, a solution is the use of COTS.
In a first step, selection of parts must to be done for keeping parts able to withstand space radiations eventually with the help of shields.
In the second step, use of many selected parts instead of one Hi-Rel part leads to an acceptable circuit but with lower performances, higher mass and higher power consumption.

Section 2.6 Brazil's location

In your opinion, which are the opportunities for future INPE space missions due to Brazil geographic location?

For a LEO sun-synchronous polar satellite, the revisiting time of a scene is between 3 days and 26 days and the observation is always done at the same local time.
This so long revisiting time is not compatible with some applications which need quasi permanent observation (GEO satellite) or 5 to 10 observations per day (LEO equatorial satellite).
Today, meteorological satellite system is designed for good weather prediction over North America and Europe. Do tropical/ equatorial regions need specific instrumentation for a better weather prediction in GEO satellite or in LEO equatorial satellite?
Forest fire detection is another opportunity. Today Europe should develop LEO Fuego constellation, similar mission is possible with one LEO equatorial satellite for Brazil or a small payload on a GEO satellite.
Precision farming is a mission devoted to the monitoring of agriculture production: irrigation control, plant illness, dryness stress, offer estimate for setting the prize in advance, fertilizer use. Brazil location allows the use of LEO quasi-equatorial satellite.
Another application is GEO data relay satellite for LEO satellites over South America, ground or sea beacons, government links…

Section 3.1 Telecommunications satellites

List the foreseen technologies that will be necessary to design the higher data rate modulators required for the on board future systems (greater than several Gbps)

For RF transmission, the frequency is lower than 1 Gbps, the origin of this limitation is the driver circuit which allows to converter the numerical signal in analog signal to be introduced in the modulator. Two modulations could be envisaged:

- First modulation in intermediate frequency, then RF frequency conversion.
- Direct RF modulation which allows more band-pass.

In space telecommunications, the need is about 10 to 30 Mbps per channel so the driver circuit is not a limitation.

For image data transmission to ground in the future, some requests are around 1 Gbps. In this case, we need to use optical transmission. Some developments have been initialized, for example a mock-up with data rate of 50 Mbps in association to a study for possible extension to 1 Gbps. Wavelength multiplex could increase the data rate. To-day, the state-of-the-art for optical modulation is 40 Gbps in laboratories.

Section 6.1 Power Subsystems

Give more details on:

- *Battery charge and discharge electronic management topologies;*
- *Power subsystem new topologies and architectures;*
- *New methods applied to power supply subsystem design and analysis;*
- *New technologies applied to power supply electronic components, manufacturing and process.*

Li-ion batteries are space qualified and offer for this application 100 Wh/kg with an objective of 140 Wh/kg in a near future (180 Wh/kg for ground applications). Their advantages are:

- Low mass,
- High open circuit voltage,
- No memory effect,
- Low self discharge rate.

A unique drawback of the Li-ion battery is that its life span is dependent upon aging from time of manufacturing (shelf life) regardless of whether it was charged, and not just on the number of charge/discharge cycles. So an older battery will not last as long as a new battery due solely to its age, unlike other batteries.

At a 100% charge level, a typical Li-ion laptop battery that is full most of the time at 25 °C, will irreversibly lose approximately 20% capacity per year. The capacity loss begins from the time the battery was manufactured, and occurs even when the battery is unused. Different storage temperatures produce different loss results: 6% at 0 °C, 20% at 25 °C, 35% at 40 °C. When stored at 40% charge level, these figures are reduced to 2%, 4% and 15% for the previous temperatures.

A stand-alone Li-ion cell must never be discharged below a certain voltage to avoid irreversible damage. Therefore all on-ground systems involving Li-ion batteries are equipped with a circuit that shuts down the system when the battery is discharged below the predefined threshold; this is one of the reasons Li-ion cells are never sold as such to consumers, but only as finished batteries designed to fit a particular system.

It is very difficult to give recommendations for Li-ion battery space uses without to speak of a particular application, furthermore I need to respect industry knowledge.

Section 6.2 Structures and Mechanism Subsystem

- *Give more details on high performance metal like gossamer technologies.*
- *Which kind of metals would be of interest to be used in this kind of technology?*
- *What are the pros and cons of using inflatable structures in space?*
- *Which are the promising manufacturing processes in composites?*
- *Which are the promising ceramics materials?*
- *Which are the design alternatives for low shock pyrotechnic components?*
- *Explain what you mean by "2-axis deployment mechanisms"*
- *Add in your report comments on space application of:*
    - *a. Shape Memory Alloys (SMA)*
    - *b. Cold welding coating technologies (like Diamond Like Carbon – DLC)*
    - *c. Hinge mechanism bearing coatings*
    - *d. Satellite appendixes deployment control*
    - *e. Among the deployable structures, which would be of major interest (boom, mast, lattice, ...)*
    - *f. Nanocomposites*

Choice of promising technology needs to know firstly the application and secondly the selected architecture and available manufacture means.
Many composite types are used in space industry, each of them for specific applications:

- PMC (polymer matrix composite) like CFRP (carbon fiber) or GFRP (glass fiber) or AFRP (aramid fiber),
- MMC (metal matrix composite),
- CMC (ceramic matrix composite),
- CC (carbon-carbon composite).

For example, if we want to manufacture a high resolution telescope, many solutions are possible:

1. Mirrors in Zerodur (glass ceramic with very low thermal expansion) associated with a structure in CFRP with epoxy resin (epoxy is the main resin used for space applications).
2. Mirrors in Zerodur (glass ceramic with very low thermal expansion) associated with a structure in CFRP with cyanate ester resin.
3. Mirrors in Zerodur (glass ceramic with very low thermal expansion) associated with a structure in CC.
4. Mirrors in SiC (isotropic ceramic with medium thermal expansion) associated with a structure in the same SiC.

The 4 solutions give same telescope performances but each induces specific constraints:

1. This solution needs monitoring of CFRP thermal expansion, of CFRP moisture expansion and of the structure moisture state during ground and space lifetime.

2. This solution needs monitoring of CFRP thermal expansion, with a relaxed monitoring for CFRP moisture expansion and structure moisture state during ground and space lifetime, the cyanate ester resin manufacturing process is more difficult that of epoxy resin.
3. This solution is the best for thermo-elastic but CC use is not so easy (CC procurement, CC mechanical characteristics lower than CFRP, mechanical links between elements).
4. This solution needs the same temperature on all telescope elements (mirrors and structure), use of SiC is not so easy (SiC procurement and machining and assembly, high stiffness and brittle material, complex thermal control).

C-SiC is a CMC which presents anisotropic characteristics, it could be used too for telescope structure but its future main use should be hot structures (for re-entry), hot control surfaces, thermal protection structures.

Classical pyrotechnic devices induce shock. For shock reduction, different solutions are space qualified or in development.

1. The fused release nuts of NEA are easy to use.
2. For solar generator, Fokker has developed a device using a Kevlar cable tightened on a thermal knife, when the knife is warmed up, the cable makes longer then breaks.
3. CNES is developing 2 devices, the first uses heated solder (at higher temperature, solder breaks) and the second uses pyrotechnic device with a calibrated hole.
4. Another solution is the use of Shape Memory Alloys but such materials is limited to ambient temperature, it is good for satellite internal equipment but not for external equipment like a solar generator. It is necessary to do attention to the storage temperature on ground too.

For hinge mechanism bearing, the coating is MoS2, another solution is the selection of Carpentier joint which uses springs for a deployment mechanism.

In the report, 1 axis deployment mechanism corresponds to a classical solar array. If we consider 3 panels with dimensions 4x2 m, in folded configuration, the SA size is 4x2 m and after deployment, its size begins 12x2 m. In the case of a solar array with 9 panels, with a 2 axis mechanism, in folded configuration the SA size is 4x2 m but after deployment, its size begins 6x12 m.

Concerning deployment control, at the stroke departure, energy is given by springs. At the stroke end, it is necessary to introduce a brake:

- With a mechanical brake, a shock appears at the stroke end,
- With an electrical motor, it slows down the moving mass and stops its, then it carries the moving mass to its final position without shock.

Inflatable and rigidization structure correspond to disruptive technology enabling new space applications due to their low mass, their low volume in folded configuration and their low manufacturing cost. Their major applications are relative to orbital assemblies and manned missions today, and to high resolution Earth observation from geostationary orbit in the future.

Some technological developments have been done on the below equipments:

- 1 dimension structure
  - Deployable mast
  - Aerobraking sail

- 2 dimension structure
    - Sunshield
    - Solar sail
    - Reflect array
    - Solar array
- 3 dimension structure
    - Solar concentrator
    - Parabolic antenna

Section 7.1 Telecommunication payloads

Present a trade-off analysis comparing the mechanically steerable antenna (for example, using gimbals) versus the active phase array antenna, focusing the analysis for the Earth Observation Satellite case.

Present a trade-off analysis comparing TWTA x SSPA high power amplifiers for the Earth Observation Satellite image data X-band downlink.

It is difficult to separate antenna trade-off from high power amplifier trade-off.

The antenna trade-off is application dependant.
At the end of 90s, during the definition phase of LEO Skybridge constellation in K band, a trade-off between active phase array antenna and mechanically steerable antenna using gimbals has been done. The best solution was the mechanically steerable antenna and this choice is still valid today. The mechanically steerable antenna is a passive one and presents a better power efficiency (advantage to TWTA versus SSPA in this band). In the case of active antenna, the beam forming array commands are more complex than the steerable antenna commands.
The Globalstar constellation in S band (2GHz) uses array antenna with sharing out SSPA high power amplifier. The antenna beams are fixed and the SSPA efficiency is not so critical versus TWTA).
For Earth observation image data transmission in X band, the trade-off must take into account 3 antenna architectures: stationary antenna, mechanically steerable antenna and active phase array antenna:

- The first architecture concerns a low gain passive antenna (gain 5 to 6 dBi) with isotropic radiated power; this architecture needs very high power amplifier (around 100W) so TWTA must be selected.
- The second architecture concerns a mechanically steerable high gain passive antenna (gain > 21 dBi) with SSPA power amplifier (a few watts); this is an exchange between TWTA mass/power and mechanism complexity.
- The third architecture concerns a co-shaped active antenna and is attractive for a space satellite very sensitive to mechanical disturbances induced by a steerable antenna. In the past a demonstrator has been developed for remote sensing satellite in X band (8 GHz). The radiant elements are a set of lines on a conical surface. Commutation of lines gives azimuth pointing, elevation pointing is given by phasing command of radiant elements. This design uses SSPA power amplifier.

Like we have seen in the previous paragraph, choice of TWTA versus SSPA is not independent of antenna choice.
The advantages of TWTA high power amplifiers are:

- Better efficiency (around 70%) which induces
  - Low power consumption,
  - Low thermal dissipation.

The advantages of SSPA high power amplifiers are, for efficiency half of TWTA one:

- Lower cost,
- Lower mass,
- Lower volume.

The 2 solutions are equivalent in term of reliability and procurement (TWTAs are produced by Thalès, SSPAs are produced by some European manufacturers).
Choice between the 2 solutions must be done at system level and must take into account antenna choice.

Chapter 8 Ground Segment

- *How do you see, in practice, standards like CCSDS, ECSS, applied to space missions?*
- *How do you see light out operation for complex satellites?*
- *How do you see Ground Station equipment automations?*
- *How do you see operations of a multimission control center?*
- *According the ECSS_E_70, a way to ensure mission success in a cost-effective manner is to establish the coordination during all phases of the space system project, between space and ground segment and between ground segment entities. Some critical areas that shall be addressed are:*
  - *Commonality between processes and elements of the ground segment such as AIT and mission operations (e. g. commonality between EGSE and MCS);*
  - *Re-use, to maximum possible extent, of space segment operations data (e.g.: telemetry and telecommand list, procedures) between space segment design, AIT and mission operations.*
  - *How do you see this way in the future?*

ESA/ESOC approach is not the most efficient due to the complexity of European geographical return rules with the different actors: European agencies, national space agencies, space companies…

An efficient approach is those of Telecommunications satellite commercial market which uses multi-mission control center. Furthermore, the complexity of satellites is increasing with severe competition between the primes.

For each satellite, a specific control center is developed and it is based on a data base common to the different satellites manufactured by a same prime.
The architecture of this data base is very important for cost reduction between different programs and needed important manpower effort in the past by prime. The data base is filled up by the system team and is used by the AIT team and by the control center team, only a few persons are allowed to update the data base. The objectives of AIT

team and control center team are not the same so the commonality between EGSE and MCS is very low: the 2 teams could only use some common modules.
By conception, the control center is autonomous and does not need permanent presence of men, a small team is under compel, ready to do intervention 24 hours per day if needed. Presence of men is only needed for important maneuvers.

For another satellite, the control center is identical to the previous one (same architecture, same alarms in the same locations…), so an uique team could control easily different satellites. In the case where a satellite needs an improvement of its control center, the other control centers must be retrofitted.

In the future, the virtual spacecraft approach will introduce a common data base for all the satellites.

Section 10.2 MEMS sensors

The use of micro-bolometers for infrared cameras operating in the SWIR bands can be envisaged in a near future?

No, in the SWIR band, the infrared signal is too low for detection by micro-bolometers. Today for SWIR band, the best detector is Cd Hg Te linear or area array manufactured by Sofradir.