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New CNES Microsatellite product for science applications

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By

C. BOUZAT (head of Microsatellite division-CNES) and the project team
M. PARROT (DEMETER Principal Investigator-LPCE)
L. DAME (PICARD Principal Investigator-IPSL/SA)

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• Abstract

Taking into account the capability given by the low cost launch opportunities, specially with the ARIANE5 ASAP structure, and the evolution of technology and low cost industrialization development, CNES with a strong support of national scientific community, has decided in continuity of the PROTEUS product to develop a new Microsatellite product line.

This new product is built to be compatible with a secondary payload launch configuration on ARIANE 5 or PSLV (indian launcher) and on the mid-term with the others launchers like STARSEM/SOYOUZ ROCKOT, LEO-LINK… The goal corresponds to a cost objectif of 50 MF per mission, launch included, and a average capability of two missions per year.

A selection process of scientific missions initiated in early 97 showed the existence of a large request and lead the Scientific Program Committee of CNES (CPS) to choose last March 98 eight missions among 26 proposals corresponding to various thematic areas like Earth Sciences (Solid Earth, Atmosphere, Biosphere) and Science of Universe (Astronomy, Planetology, Physics of Plasma, Fundamental Physic). Feasability studies have been performed on these eight missions and CPS has finally selected two of these missions by end of 98 :

- *the first one called DEMETER, of which launch is scheduled end of 2001 with the indian launcher PSLV and which concerns the study, by observation of magnetic and electromagnetic effects, of ionospheric disturbances potentially linked to volcanic or seismic activities. This interaction underligned in the 50's has been observed in orbit in 1983 and is considered to be a potential short-term forecast signal of seism activity. But these observations are still fortuitous and unadapted. It is not possible to establih undoubtly their sismotectonic origin. While measuring this phenomena on ground, within the same frequency bands, these data will allow to improve modelization of the propagation modes of the signal towards the upper atmosphere and also to study the dynamics of energetic particles inside the radiation belt in correlation with the solar activity.*

- *the second one, called PICARD, launched before mid-2003 by ARIANE 5, concerning the Sun observation (precise measurement of the solar diameter, of the solar constant and of their variations and variability). These measurements will be analyzed to improve the knowledge of the solar factors influencing on the Earth climate evolution (in particular its warming) and of the internal structure of the Sun (diameter oscillations).*

Here are described the first missions which have been used to size the Microastellite product, the organization and methods used for suitable answer to the various missions needs while keeping inside a limited budget, as well as the technical characteristics of the developped microsatellite system.

At last, one is presented the first applications DEMETER and PICARD which crystallize the generic developments and, beyond the only needs of the scientific missions, allows to develop all the equipments necessary for the following applications.

1 - INTRODUCTION

Over the past 2-3 years CNES has studied the possibility to develop a microsatellite product line for scientific, technology demonstration or even for some radio-communication and earth observation mission. The success of microsatellite development in SSTL and DLR and the various experimentations undertaken by other countries wishing to develop a space activity show the growing interest for low cost mission taking benefit from opportunity like ASAP and PSLV or other launchers. These launchers offer now capability for designing a microsatellite class that covers a satellite mass range up to 120kg. Besides the technology improvement permits to perform application missions or high interest scientific missions, including even propulsion capability.
Considering that small mission fast turn around allows validation of latest technologies and experimentations and pushed by a high demand from the scientific community, CNES decided to develop an active policy in the field of small satellites. After PROTEUS developped in partnership with ALCATEL SPACE, CNES decided to create a microsatellite project organization as a prime for controlling the industrial organisation and setting up the methods and tools which allow to adapt the product to each mission in low cost objective and short time schedule.

A reference system has been designed covering most of the identified missions (see table 1) coming from call for ideas and associated selection performed by scientific workshop. In parallel, studies have been performed to adapt the microsatellite design to experimental mission coming from the ministery of Defense.

Low cost and new methodology are the major keys to allow the realization of approximately 2 scientific or technology demonstration missions each year since 2002.

MISSION	ORBIT	POINTING	MASS	CONSUMPTION	DATA GENERATION
DEMETER	LEO (≈ 800 km) Circular Incl. ≈ 70°	Geocentric Attitude restitution : 0,2°	20 kg	20 W	16 Gbits/day
DORIS	LEO (≈ 800 km) Circular Incl. ≈ 70°	Geocentric Accuracy : 1° Stability : < 0,01 °/s	15 kg	20 W	5 Mbits/day
µ-SCOPE	LEO (≈ 600 km)	Inertial	30 kg	25 W	100 Mbits/day
[illegible]	LEO (800 km) Circular Incl. : [illegible]	Geocentric Accuracy : 1° Restitution : 0,2° Stability : < 0,05 °/s	13 kg	28 W	1,0 Mbits/day
ORAGES	LEO (≈ 800 km) Circular Incl. : [illegible]	Géocentrique Accuracy : 1° Restitution : 0,2°	20 kg	28 W	90 Mbits/day
[illegible]	LEO (400 à 1000 km) High Incl.	Inertial Accuracy : 0,1° [illegible]	25 kg	20 W	3,4 Mbits/day
PICARD	GTO ou LEO (> 1000 km)	Sun and Inertial (calibration) Accuracy : 0,05° Stability : < 0,01°/s	30 kg	30 W	1,4 Mbits/day
[illegible]	Héliosynchronous	Geocentric Accuracy : 0,1°	30 kg	30 W	30 Gbits/day

Synthesis of typical scientific missions

2 - THE CNES MICROSATELLITE PRODUCT LINE

The CNES microsatellite product line development is characterized by a high performance design in terms of capability offered to the payload (mass, power, pointing accuracy, telemetry and processing) but with low cost objective given by COTS (parts and equipments) utilization and use of innovative methods of engineering and management (risk management, quality management, internal or external customer/supplier processus, design and manufacturing tool standardization). In particular, the objective is to settle concurrent engineering process by associating selected industrial companies in the design process. This interactivity shall be exercized in the frame of an engineering workshop developped by CNES. The computer structure, in which are centralized the system modelizations, will allow to make design iterations with industry taking into account manufacturing constraints and defining technically and costly optimized requirements.

Considering also that microsatellite is a good way to develop cooperation with foreign countries willing to develop space activites CNES decided to ensure the prime role but with an industrial partnership as this product could be largely used by industrial main prime contractors.
The CNES microsatellite program is based on :
- a reference subset of functinal chains fully developped and qualified on the occasion of the first mission DEMETER,
- options fully studied and available for new missions, most of them flying on DEMETER even if not required by the mission,
- models and simulations, mostly but not exclusively software, allowing fast study of any new mission in the frame of the Engineering Center,
- a ground system for multimission control.

3 - THE PROBLEMATIC OF LOW COST

For the microsatellite development, the low cost objective has to be achieved in the following context :1) to develop innovation 2) preference to design-in house in order to control cost 3)use technical knowledge spreaded in a large technical organization 4) no financial incentives 5) try to find performance-cost optimum with targeted investment 6) no unique design and mission adaptability 7) use auxiliary payload configuration with associated strong constraints imposed by the main satellite (no rights only duties) 8) high performance system.

To deal with that context and offer maximum low cost reduction, the following principles have been considered:

- try to analyze in depth and freeze mission requirements during the feasability phase,
- design robustness but high performance avionics and powerful configuration (deployable and steerable solar array, 3-axes stabilization for fine pointing, CCSDS communication). No large margins are provided to ensure success and functional redundancy is used as much as possible with degraded mission modes in terms of performance. Reliability is not sacrified but relaxed. Single string design, which reduces cost, can be reliable of they are built robust, with good quality control and thoroughly tested. As the system is more complex when fully assembled, it must be heavily tested in that configuration with reasonable test margins. Minimization of upset effect and latch up is achieved by specific protections in order to offer better availability but no more.
- simplified mechanisms (for example Carpentier joint),
- reuse of design at maximum extent from one mission to the other (at least for avionics),

- use of commercial standard interfaces (RS422/RS485 data handling interfaces) which provide access to well debugged test equipments and parts,
- use of cots devices at part level and for standard equipment (as parts could be heterogeneous in quality custom screening process and qualification tests must be applied for validation through an appropriate balance between part test and system test),
- make strategic procurement to prevent obsolescence and develop futur equipment in parallel to follow technology evolution,
- on board autonomy to simplify ground operations but no complex strategy of FDIR and use of a robust and reliable safe mode(this is achievable by hardware and software systems capability but limits the mission availability),
- simplified and straight model philosophy (full qualification at equipment level, no satellite engineering model, thoroughly tested protoflight model),
- management alleviation to focus on key points and minimize paperwork (documentation is issued only when value is added). Extensive use of PC based software tools and interactive teams with co-localization and high communication inside the group.

4 - ORGANIZATION AND METHODS

4.1 Organization

For the development of the product line CNES is responsible for the design and development of generic items (those ones corresponding to the ground segment being derived from PROTEUS development). The CNES technical departments are deeply involved in the design and as far as possible R&D developments are considered if mature with respect to the scientific mission schedule. At the beginning, Cnes is also responsible for the selection and procurement of the equipment level items coming from small companies and will select an industrial company for the satellite integration. This organization will evolve in order to transfer to industry equipment procurement and allow industry to commercialize the product, CNES keeping in charge the system and satellite engineering and the scientific laboratories being responsible of the development of the payload and scientific data treatment ground segment.

In order to achieve various missions in a short schedule and limited cost, it is necessary to rely on competent and motivated teams. As this philosophy must be based on innovations outside the established norms, the team must be constantly aware of its limitations and adjust roles and responsabilities to best use of everyone's talent. In particular, with respect to the training objective of young engineers, it is necessary to pair such people with senior engineers having in mind the essential rules which avoid major troubles. Besides, the institution must also admit that the team defines its own management process if it respects the general approved guidelines defined for the program. At last it also must be clearly identified the level of acceptable risk and in the beginning of the project both parties must be aware of critical points and associated methods of control.

4.2 Method

This program will be the opportunity to test new design and management methods (as concurrent engineering) which are more often promoted in USA. As low cost and short time scale means :

- rapid mission assessment and feasability,
- improved understanding (from experience and product evaluation) of the quality of material and behaviour under life environment

it is necessary to make different competences work interactivally.

For answering to the required objective, several aspects have been identified:

- to organize multidisciplinary teams and facilitate their job in using informatic tools based on data banks of equipments relevant to all the differents skills,
- to favour development of modelisation approach and search for a global coherency between the different tools used by the various specialists,
- to allow the customer to participate in the definition of the system requirements.

In order not to overspecify the system, the project team must interact with the principal investigator to adjust the mission requirements to ensure the goals of the mission while taking into account ressources limitation.

Based on competent technical team, the concurrent engineering must be encouraged by project management contributing in ideas at higher level to stimulate the team's problem-solving capabilities and to facilitate communication. Conducted by a strong system engineer, the project team (which could consist in subsystem engineers belonging to different technical hierarchical structures) must avoid to perform individual optimisation. There must be also a strong communication between co-localized subsystem engineers while equipment engineers can stay near their technical structures where they have access to peer support and technical tools.

These necessary means are being developped in CNES and will constitute the Microsatellite Project Design Center as those used by GSFC or JPL for team-X sessions.

Another area esential in the low cost approach is the risk control management. Change in the project management method and use of COTS components require to adapt the product and quality assurance process to that context. The risk control process is based on identification, assessment and reduction of risks of not satisfying the mission (having in mind that : "mission is percieved as sucessful only if it meets a useful purpose at an affordable cost and within an acceptable period"). In the design phase, safety construction is based on a functional analysis which allows to identify nonfunctionning risks, to evaluate them and to define corrective actions. This process is helpfull to validate the design and focus quality effort only on critical functions.

Concerning COTS equipment, it is necessary first to evaluate the product in terms of performance and qualification status and also to evaluate the supplier in terms of quality assurance(this is achieved by qualification file analysis and audit of the supplier). The use of commercial parts leads to define a selection and evaluation methodology based on selection team including designers and parts experts. The risky part are identified and evaluation actions are settled to check their reliability.

Concerning management, in order to avoid major drift of cost and schedule due to technical difficulties, it will be necessary, by a close management, to take decision which performs the best compromise between requirements keeping or additional constraints applied to the product line and requirement relaxation.

5 - MICROSATELLITE SYSTEM DESCRIPTION

The Microsatellite system relies on an architecture including:

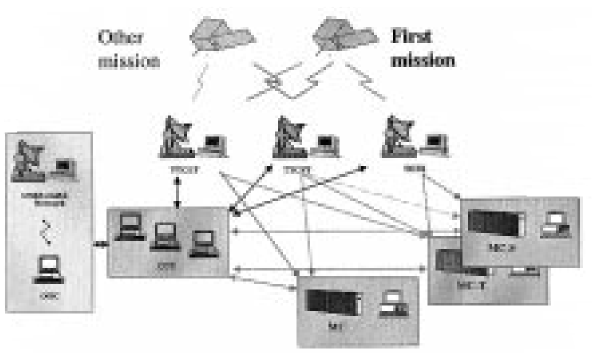
➜ A space segment composed of microsatellite based on a payload, and a set of on board functional chains.

➜ A command control ground segment with
- a Command Control Center (CCC),
- one Telemetry and TeleCommand Earth Terminal (TTCET),
- a Data Communication Network (DCN),
- an X band Telemetry Earth Terminal (TETX).

➜ Two Mission Centers (MC), one for the scientific part of the mission (MC-S) and the other for the technological one (MC-T).

In addition this system has the capability to use CNES multimission resources (the CNES S band stations network and the Orbitography Operational Center). This resources can be used for the station acquisition and in case of anomaly.

As described in the two following pictures the architecture of this system will evolve. Moreover, some components of this system are not dedicated to one mission but will be shared with other ones, when the next satellites will be launched.



Multi-mission system architecture

5.1 Satellite

MAIN ON BOARD FUNCTIONAL CHAIN (HARD CORE OF THE PRODUCT LINE DEVELOPMENT)

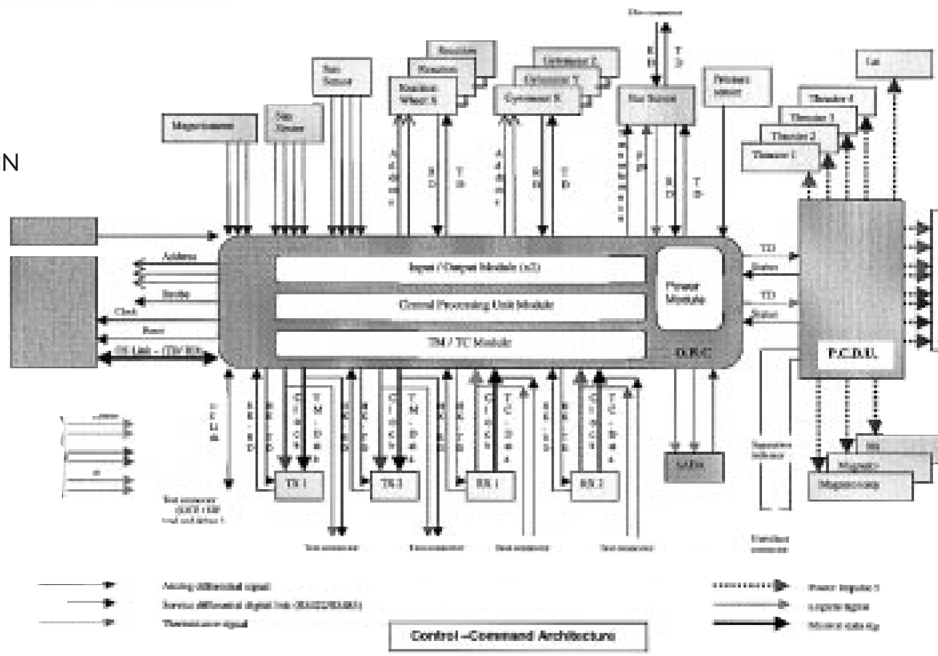
The satellite architecture is mainly based on the following product line functional chains:

<u>1 - an attitude and orbit control function which includes :</u>
- an attitude determination system based on 2 coarse Sun sensors (only used for the acquisition and the safe mode), a 3 axes magnetometer and a stellar sensor when precise attitude measurement is needed or when pointing accuracy must be better than few degrees. Three raw gyros (1 axis gyros) are added to the design to give attitude information during orbit manoeuvres.
- an attitude control system based on the use of up to 3 reaction wheels (fine attitude control and manoeuvrability) and 3 magnetotorquers, for reaction wheels unloading or coarse attitude control mode,
- and optionally an orbit control system assumed by an hydrazine propulsion subsystem with four thrusters corresponding to minimum configuration to have manoeuvre capabilities and 3 axes attitude control during manoeuvres.

<u>2 - An electrical power generation, regulation and distribution function</u> including one AsGa solar generator (with 2 deployable panels), one Li-Ion battery of 9 Ah and a power regulation and distribution system. The power is delivered to the payload equipment on up to 5 non-regulated bus. The solar generator could be fixed (Sun pointing mission) or oriented with a 1-axis mechanism around the -Y axis (earth pointing mission case as the DEMETER one). The cant angle of the deployed solar array will depend on the mission.

<u>3 - a control / command function which is implemented on:</u>
- a central On Board Computer (OBC), including a 1 Gbit memory, based on a transputer T805 and several micro-controllers (PIC 16C73) for interfacing with the equipment.
- two S band link transmitter and receiver chains, with two sets of antennas (Tx /Rx) used to have a quasi-omnidirectional coverage. The TM data rate is 400kbits/s in operational modes and 25kbits/s in safe modes.

The command control chain with its interfaces to the other satellite equipments are shown in the following figure.



These functional chains will be slightly adapted for each mission, depending on their specific requirements. For example, in addition to the X band telemetry chain, the following specificity are taken into account for the DEMETER mission:

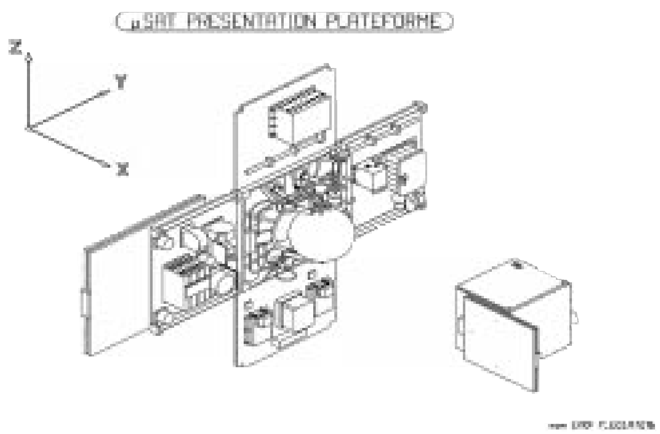
- high satellite inertia and low natural frequencies due to some large appendages,
- magnetotorquers activation limited to the period without scientific measurements (terrestrial high latitudes > 60° and <-60°),
- specific EMC requirements (solar generator covered with ITO coating, …).

SATELLITE MECHANICAL AND THERMAL ARCHITECTURE

The structure and the satellite thermal control will be customised for each mission, except in case the basic structure is able to accommodate the payload identified for the corresponding mission. The main drivers of the satellite architecture are:

- use of a generic rigid lower plate (interface with the launcher), including a shock damper system,
- design of a modular architecture with an independent propulsion module directly integrated on the lower plate,
- general design concept (mechanical, power generation and attitude control) allowing to systematically have a satellite face in the shadow. This face supports low temperature equipment (battery) and the stellar sensor which requires not only low temperature but also a field of view without any Sun parasitic illumination.

The following figure shows the basic structure, with the propulsion module and the lateral panels with the equipment of the 3 previously described functional chains. The 2 solar generator panels are folded on the -Y face, opposite to the battery and to the stellar sensor +Y face.



LAUNCHER

Apart from ASAP ARIANE 5 opportunities, the PSLV launcher is considered. It has a capacity to launch up to 2 micro-satellites in addition to the main passenger. The PSLV requirements are quite identical to the Ariane5 requirements for an ASAP micro-satellite launch, with lower environmental loads (shock and random).

ARIANE5 ASAP configuration.

SATELLITE MAIN BUDGETS

Mass budget: the DEMETER mass budget is approximately 110 Kg splitted in avionics (19 Kg including payload management/mass memory and X-band telemetry), structure and thermal (32 Kg), power supply (18 Kg), propulsion (8 Kg) and payload (33 Kg).

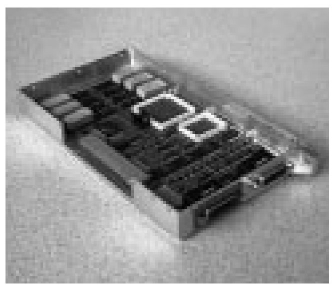
Power budget: the solar generator gives a 140W maximum power at 70°C after one year in orbit.
For DEMETER, the solar generator configuration (cant angle of 14°) and the local hour variations of the orbit ascending node lead to a maximum permanent available power higher than 75W for a satellite consumption of 59W in the survey or burst payload modes, up to 90W during the X band TM transmission.

Attitude control performances: the raw attitude control mode has an attitude control accuracy less than 5°.
With the use of the stellar sensor the attitude control and the attitude measurement accuracy is better than 0.2° worst case.

R&D DEVELOPMENTS FOR MICROSATELLITE PRODUCT LINE

Some R&D developments have started in 1997 concerning microsatellite equipments. They concern the OBC computer and the S-band reciever/transmitter(RX/TX). Others R&Ddevelopments are in progress in order to make available advanced technology equipments corresponding to the needs of the Microsatellite product line in terms of technical and cost goals.

For the OBC computer, the goal was to fulfill the low cost/low mass/low power optimum while having a computing and communication performance similar to the state-of-the-art computers used in current projects. A 3Kg/5w/2 liters/2 Mips/ 1Gbits/ 15Krads goal was assigned. Even if in the conservative space domain it is not so difficult to get performance using current technology (SPARCX processor,memory,rad-hard parts) the main challenge was to fulfill **all** the constraints together. Use of new architectural solutions was necessary.

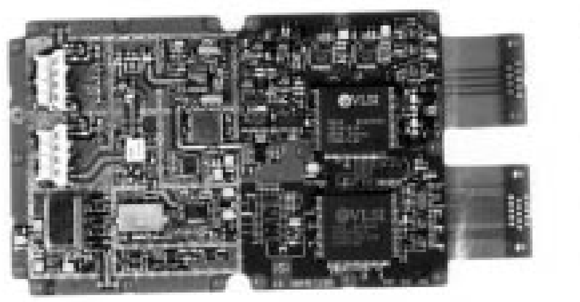


OBC processor board

In practise, mass budget requirement allows to use conventional printed circuit boards populated both sides with plastic surface mounted parts(except for FPGAs and processor using ceramic packages).The use of internal serial buses for connecting the four baseline modules (Power,TMTC,CPU and I/O) allows to follow a network paradigm and provides enough adaptation margins: this is a direct application of what everybody sees when he uses a PC connected to a network ! For external interfaces the opposite was done,avoiding buses to simplify software but using direct and dedicated RS485 links. As the processor is not latch-up immune, specific circuits protect and allow a reboot of the computer when non recoverable error occurs. With regards to COTS use, some "system hidden" redundancy scheme was implemented for each critical internal node(watch-dog and over-current protection against heavy ions effects, coded command against failure propagation).Besides a reduced number of rad-hard parts are used to build an internal safe management core.

For the RX/TX equipment, low cost was achieved by miniaturization and technology used on commercial markets.To achieve low cost/low power/low volume the driving idea was to find and use macro-parts for the heart of the equipment which belong to numeric TV or mobile phone electronic production (for example ASICs use for decoding and demodulation in TV receivers).These parts benefit from a very dynamic background in term of innovation and reliability. Of course these parts have undergone complementary tests(temperature, radiations…) but these targeted and simple tests do not change the cost efficiency in terms of integration,performance and global cost. Other functions are achieved in more conventional hardware but always with more advanced technologies (multi-layer circuits, CMS parts, automatic report as for radiotelephone devices).

Today, results are encouraging as with respect to a standard full space develoment a figure of 2 has been reached on the power consumption and volume, a figure of 5to 10 has been obtained on the recurrent cost. The constraints inherent to that type of development are nevertheless acceptable : more interaction with a industrial partner who has less knowledge of the space constraints, need to make a strategic active parts procurement, and full qualification tests campaign.



RX/TX board

The first mission DEMETER will also include some technological experiments as on board autonomous orbit control system, and pyrotechnic priming by a laser system.

5.2 Ground/satellite interface

The communication between the ground segment and the satellite is performed through two links : the S band, and the X band. The S band link is full compliant to the CCSDS standard, whereas the X band link complies with this standard at the packet level.

The X band is devoted to scientific telemetry, whereas the S band is used for the housekeeping and technological telemetry. However, it must be possible to transmit telemetry through the S band link, in the limit of the actual S band link capability. All the TC are transmitted through the S band, using a protocol, which guarantees automatic re-emission of TC frames detected as erroneous or lost by the board peer. For the S band, the specified performance objectives must be guaranteed for a minimum elevation of 10° with a system margin of 3 dB for the TM and 10 dB for the TC. The frequency, modulation and rate characteristics of the interface for LEO satellites are stipulated in the following table :

S band	SAFE MODE	NOMINAL MODE
• TM modulation and coding	QPSK (1/2 Nyquist filter) Viterbi + RS concatenated coding	QPSK (1/2 Nyquist filter) Viterbi+ RS concatenated coding
• TC modulation and coding	QPSK (1/2 Nyquist filter) Viterbi	QPSK (1/2 Nyquist filter) Viterbi
• Maximum telemetry rate	25 kbits/s	400 kbits/s
• Telecommand rate	20 kbits/s	20 kbits/s

For the X band, the specified performance objectives must be guaranteed for a minimum elevation of 15° with a TETX. The maximum data coded rate is 18 Mb/s. The modulation and coding used is a Multi-dimensional Trellis Coded Modulation Concatenated with Reed-Solomon bloc code (MCTMCRS).

5.3 Command control ground segment (MIGS)

The MIGS inherits of the Proteus Generic Ground System.
As far as the CCC is concerned, it is in charge of :
- preparing the programming messages taking into account the payload part which is built in the Mission Centers,
- preparing and monitoring the communication with the satellite using a TTCET,
- reconciling the TM for a quick look and for alarm generation,
- evaluating the functioning of the platform,
- orbit and attitude monitoring.

The CCC realizes the orbit restitution using Doppler measurements acquired by the TTCET on the down link.
The Data Remote Processing PC (DRPPC) is a PC which can be used in the CCC or outside, in order to treat the real time housekeeping telemetry, or to work on the archive stored in the CCC databases.
From an operational point of view, the operators work during administrative hours. This functioning requires :
- the capability of performing automatic loading of programming messages in the absence of any operator, using an agenda function,
- an automatic anomaly detection.

The TTCET are automatic S Band stations, in charge of :
- establishing and maintaining the satellite to ground radio-frequency link for all programmed visibility passes (transits),
- receiving and temporarily storing the received telemetry during a transit. This function concerns the House Keeping Telemetry to be Recorded, but also a part of the Payload Telemetry,
- receiving and transmitting to CCC the Passage House Keeping Telemetry during a transit,
- accepting the connection with CCC or a Mission Center for transmission of payload data and a part of the received platform data,
- transmission of telecommand to the satellite for the transit in progress,
- doing Doppler measurements during the transit, for orbit calculation and antenna positionning,
- compensating Doppler effect on telecommand link,
- contributing to the correspondence between on board and UTC time.

The TTCET has a 3.1 meters diameter antenna.
The last component of the MIGS is the Data Communication Network (DCN). Its main characteristics are :
- the interfaces of the MIGS are based on Internet Protocol (IP), for real time transfer via service sockets, or file transfer using ftp,
- the MIGS subsystems are connected to the IP network by standard routers.

6 - THE DEMETER MISSION

6.1 Scientific objectives

The main scientific objective of the DEMETER experiment are to survey the EM noise and to study the disturbances of the ionosphere due to the seismo-electromagnetic effects, and due to anthropogenic activities (Power Line Harmonic Radiation, VLF transmitters, HF broadcasting stations).

The seismo-electromagnetic effects are the electric and magnetic perturbations caused by natural geophysical activity such as earthquakes and volcanic eruptions. It includes: electromagnetic emissions in a large frequency range, perturbations of ionospheric layers, anomalies on the records of VLF transmitter signals, and night airglow observations [1]. Such phenomena are of great interest, because they start a few hours before the shock and can be considered as short-term precursors.

Electromagnetic emissions in the ULF/ELF/VLF range that are related to seismic or volcanic activity are known since a long time but their generation mechanism are not well understood. Many papers have presented ground observations of wave emissions during seismic events [2]. Examples can be found in [3]. Two types of emissions can be considered. First, precursor emissions occur a few hours before earthquakes, in a large frequency range from one hundredth Hertz up to several MHz. Second emissions observed after the shock generally are attributed to the propagation of acoustic-gravity waves [4]. However, all hypotheses concerning the generation mechanism of precursor emissions are also valid after the shock, when the Earth's crust returns to an equilibrium state. The emissions can propagate up to the ionosphere, and observations made with low-altitude satellites have shown increases of ULF/ELF/VLF waves above seismic regions. In contrast to ground experiments, satellite experiments cover most seismic zones of the Earth, and statistical studies become meaningful because of the much larger number of recorded events.

Since the great Alaskan earthquake in 1964, many evidence of electron density perturbations in the ionosphere after strong earthquakes have been reported. Ionospheric perturbations have been observed a few days before above the seismic zone. They are better detected during the night when the ionosphere is calm. Increases as well as decreases of the critical frequencies are observed in different regions of the ionosphere before earthquakes. Additional information provided by GPS measurement such as TEC (Total Electron Content) data will be used.

Wave emissions and electron density perturbations can be linked through various mechanisms in the ionosphere and the same hypotheses of generation mechanism of precursor are valid for the two perturbations. These hypotheses are mainly related to: wave production by compression of rocks, diffusion of water in the epicentral area, and redistribution of electric charges at the surface of the Earth and then in the Earth's atmospheric system. Only a statistical study with many events will show the general behaviour of such ionospheric perturbations and will help to define a signature of ionospheric perturbations prior to earthquakes [5]. This will be achieved with the data of the wave experiment.

In the interaction between the solar wind and the Earth's magnetic field, the ionosphere is the first protective layer around the Earth. Therefore the study of its evolution and its perturbations are of great interest. The second objective of the DEMETER experiment are related to perturbations coming from the Earth's surface either due to man-waves (PLHR, VLF transmitters, HF broadcasting stations).

The Power Line Harmonic Radiation (PLHR) is the ELF and VLF waves radiated by electric power systems at the harmonic frequencies of 50 or 60 Hz. Evidence of PLHR Propagation in the magnetosphere was first observed on ground. However direct observations by satellites are rather rare [6] and show in few papers (indirect effects are more reported). The observations show that the lines drift in frequencies and that it is most probably due to a non-linear interaction between electrons and the coherent waves. All the observations indicate that PLHR influences the atmosphere-ionosphere- magnetosphere coupling. On one hand, non linear interactions between electrons and PLHR can participate in the precipitation of electrons from the slot region in the radiation belts, on the other hand, main part of the PLHR energy dissipates in the lower ionosphere and modifies the ionospheric currents. This problem now requires serious attention because the electrical power consumption is always increasing in the world.

At VLF frequencies between 10 and 20 kHz, the ground-based transmitters are used for radio-navigation and communications. Their ionospheric perturbations include: the triggering of new waves, ionospheric heating, wave-electron interactions, and particle precipitation. At HF frequencies, the broadcasting stations utilise powerful transmitters which can heat the ionosphere and change the temperature and the density. All these wave dissipations in the ionosphere could participate to the global warming of the Earth because the change in global temperature increases the number of natural lightning discharges in the atmosphere. Then the supplementary lightning discharges produce more magnetospheric whistlers which could produce heating and ionization in the lower ionosphere.

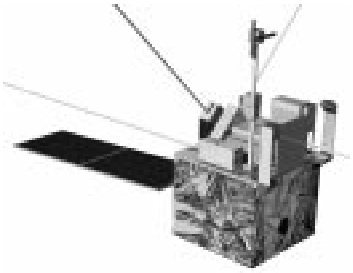
Furthermore, it is a feedback mechanism because two different processes could be involved. First, lightning is a source of NOx, and NOx affects the concentration of ozone in the atmosphere which contributes to the greenhouse effect. Second, precipitation of energetic electrons by man-made waves may trigger other lightning discharges. It explains the importance of the study of such man-made waves [7]. Ionospheric perturbations by natural geophysical activities have been made evident by two methods: the study of the electromagnetic waves, and the measurement of the electron density.

6.2 Scientific payload

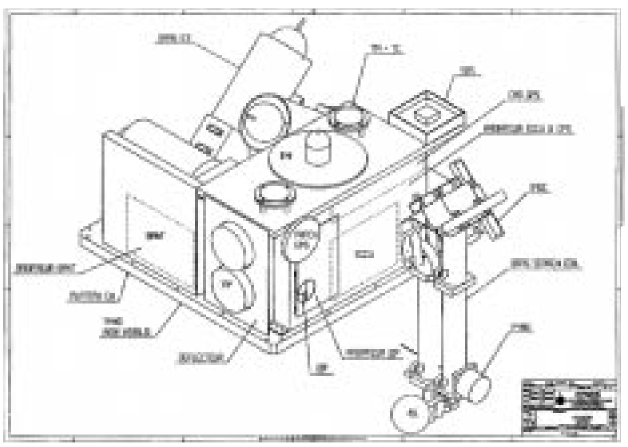
The scientific payload of the DEMETER micro-satellite is composed of several sensors:

- Three Electric and three magnetic sensors (6 components of the EM field),
- A Langmuir probe,
- An ion spectrometer, and,
- An energetic particle analyzer.

The payload is concentrated on an upper plate as shown in the next figure. The sensors and antennas layout is highly constraint by multiple requirements (thermal, field of view, booms deployment cinematic, EMC, …).



For this mission, the system is supplemented by a high data rate telemetry chain with an on board 8Gbits memory, a X band transmitter and a X band ground station needed by the high volume of scientific data produced during the payload burst measurement mode.



6.3 Onboard data processing and technical issues

There are two modes of operation: (i) a survey mode to record low bit rate data all around the Earth (concerning the EM waves, only spectra will be recorded), and (ii) a burst mode to record high bit rate data above seismic regions (waveforms)

Frequency range, B	10 Hz - 15 kHz
Frequency range, E	DC - 4 MHz
Sensibility B :	2 10^{-5} nT $Hz^{-1/2}$ at 1 kHz
Sensibility E :	0.2 • V $Hz^{-1/2}$ at 500 kHz
Particles: electrons	30 keV • 10 MeV
Particles: ions	90 keV • 300 MeV
Ionic density:	5 10^2 ? 5 10^6 ions/cm^3
Ionic temperature:	1000 K • 5000 K
Ionic composition:	H^+, He^+, O^+, NO^+
Electron density:	10^2 • 5 10^6 cm^{-3}
Electron temperature:	500 K • 3000 K

TABLE 2. Experiment capabilities.

In the survey mode the telemetry is of the order of 950 Mb/day, and in burst mode, it is larger than 1 Gb/orbit. The number of telecommands is estimated to be of the order of 600 octets/3 days.

6.4 Ground-based data processing

The telemetry will be received in Toulouse. The data processing center will be located in LPCE, Orléans. We will perform correlation with seismic activity using data from the GEOSCOPE network. The production of Quick-Looks will be available on our WEB site. The data processing center will be also in relation with ground-based experiments. It is expected to have collaboration with ground-based experiments performing measurements of DC fields, electromagnetic noise in various frequency bands, ionospheric parameters, optical parameters,…

7 - THE PICARD MISSION

PICARD mission will carry simultaneous measurements of the solar diameter, differential rotation, total irradiance and spectral irradiance in selected wavelengths. It will determine their relationships and variabilities experimentally and will study their consequences for Earth's climate and the internal structure of the Sun.

7.1 Scientific objectives

Since the solar energy is one of the major driving inputs for terrestrial climate and since it exists some correlations between surface temperature changes and solar activity, it appears important to know on what time scale the solar irradiance and other fundamental solar parameters, like the diameter, vary in order to better understand and assess the origin and mechanisms of the terrestrial climate changes.

7.1.1 Why the diameter? From 1666 to 1719, Jean Picard and his student Philippe de la Hire measured the solar diameter, observed the sunspots and determined the Sun rotation velocity. Fortunately, these measurements covered the Maunder minimum and some time after. The data were re-examined by Ribes et al. (1987) who, after removing the seasonal variation of the solar diameter, obtained the annual means at 1 AU. These values, averaged for the Maunder minimum period and after while the Sun recovered a significant activity, show a definitive difference of the order of 0.5 to 1 arcsec, corresponding to a larger Sun diameter during the Maunder minimum. As expected, few sunspots were observed. However, Picard's data also showed a slow down of the Sun rotation velocity at equator and more sunspots in the south Sun hemisphere than in the north.

7.1.2 Diameter and earth's climate. The solar constant measurements performed in space by the radiometers since 1978 were modeled using the sunspots number and faculae. This allowed to reconstruct the solar constant variation till 1610 (Lean, 1997). This shows that the solar constant experienced a significant decrease during the Maunder minimum. The temperature in the northern hemisphere has been also reconstructed for the same period. The cooling of this period is known as the Little Ice Age. The similarity of the temperature and solar constant variations strongly suggests the Maunder minimum as the cause of the Little Ice Age. To assess this suggestion, climate models were run by Sadourny (1994) that show the Maunder minimum as the possible cause of the Little Ice Age. However, volcanic eruptions (major ones) also play a certain role, but their effects do not extent more than a few years.

As during the Maunder minimum where, as suggested by Picard's data, the Sun radius experienced a significant change, the modern data of Sun diameter measurements and sunspots number, set together by Laclare etal (1996), reveal a relation between the Sun radius and solar constant variations corresponding to an increase of the Sun radius for a decrease of the solar constant. Therefore, in order to establish experimentally without ambiguity the Sun constant and diameter relationship, we propose to operate from space by measuring simultaneously both quantities from the same platform and in non-magnetic lines or continua. The importance of the measurements for climatology is straightforward taking into account the Little Ice Age and the Maunder minimum events.

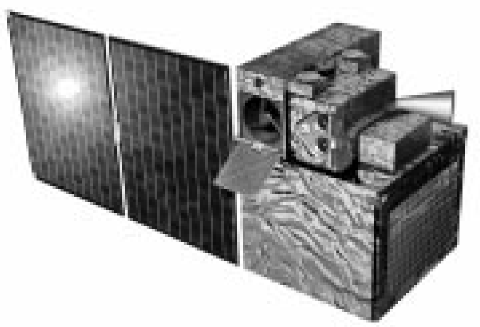
7.1.3 Lyman alpha monitoring. Lyman alpha irradiance has been monitored since 1977 and more recently by UARS since 1991. The EOS/SOLSTICE experiment will be launched in late 2002 and it will also monitor Lyman alpha irradiance. Since these irradiance monitoring experiments observe the Sun as a star, there is no information about the physical causes of the observed irradiance changes. To identify the causes of changes in Lyman alpha, one needs to compare the full disk irradiance data with images. PICARD will provide high resolution and continuous Lyman alpha images which will well complement the EOS/SOLSTICE measurements. These images will make it possible to better account for the observed Lyman alpha changes and also for a better reconstruction of a long-term Lyman alpha data set. Since Lyman-alpha irradiance is important for the ozone changes and the formation of the ionospheric D-region in the Earth's atmosphere, better understanding of the variations in Lyman alpha will also be important for atmospheric science and aeronomy.

7.1.4 Oscillations. Another objective of PICARD is to detect the gravity modes (g modes) of the Sun. These modes are of prime importance to understand the structure and dynamics of the solar core which cannot be studied by using solar pressure modes (p modes) alone. So far the g modes have not been discovered by any set of instruments onboard the SOHO spacecraft. The 1-σ upper limit of g-mode amplitude at around 200 µHz is typically 1 mm/s or 0.1 ppm (Fröhlich et al., 1998). Given a velocity amplitude of 1 mm/s at 200 µHz, the displacement of the solar surface would be of about 1.6 m p-p which is equivalent to a variation of solar radius of about 2 µarcsec. This level could be marginally detected by PICARD although this is not the method we are using for detecting the g modes with our instrument. Nevertheless, it is worth noticing that MDI/SOHO was able to — without an optimized, stable and distortion free telescope as SODISM/PICARD — to observe a 10 µarcsec high frequency p mode (5 min.) solar limb oscillation signal (Kuhn et al., 1997).

With PICARD we want to detect intensity fluctuations at the solar limb that will perturb the equivalent solar radius signal. Appourchaux and Toutain (1997) reported to have detected p modes using the limb data of the LOI instrument. In some case the amplification with respect to full-disk integrated data is about 4, i.e. it means that a p mode with an amplitude of 1 ppm in full disk is observed with an amplitude of 4 ppm at the limb (cf. Damé et al., 1999). This amplification factor was roughly predicted by theory (Appourchaux and Toutain, 1997). If we hope that the same amplification factor holds for the g modes, we may detect them faster with the limb data of PICARD than with the SOHO data. A pessimistic derivation gave 20 years for the detection of the first few g modes with SOHO (Fröhlich et al., 1998). With PICARD we can seriously envisage detecting them in 16 months with the amplification factor above.

7.2 PICARD INSTRUMENTS

To carry the proposed measurements PICARD has 3 instruments: SODISM, the "SOlar Diameter Imager and Surface Mapper", for the measure of the diameter and differential rotation (this is, therefore, a whole Sun imager), SOVAP (SOlar VAriability for Picard), for the measure of the total absolute solar irradiance (correlation with SODISM measurements) and UVSPM (UV Sun PhotoMeter), a package of 3 UV photometers at 230 nm. SODISM is realized by Service d'Aéronomie, France, in collaboration with the Space Science Department of ESTEC, SOVAP by the Royal Meteorological Institute of Belgium and UVSPM by the World Radiation Center of Switzerland.



7.2.1 SODISM/PICARD. SODISM is a simple telescope of useful diameter 110 mm (cf. Fig. 1). It forms a complete image of the Sun on a large, back thinned, CCD of 2048 x 2048 useful pixels. The pixel, 13.5 µm, corresponds to 1.05 arcsec (at 1 AU) and the effective spatial resolution is also about an arcsec (at the limb). SODISM observes in 4 wavelengths bands the whole Sun (230 nm, 538 nm, 160 nm and Lyman alpha) and 2 calibration channels (cf. Table 1) accessible through the use of 2 cascading filterwheels, each with 5 positions.

• UV nominal mode	230 nm
• Visible	538 nm
• Active regions	160 nm
• Prominences and ionosphere	Lyman alpha
• CCD Flat Field	“Diffusion”
• Scaling factor	“Star field”

Table 1 - Operational observing and calibration modes of SODISM/PICARD.

OPERATIONAL MODES

The main observing wavelength is 230 nm (5 to 9 nm bandwidth). It corresponds to a mostly flat UV continuum formed in the high photosphere. It is the best possible choice of wavelength since it is sensitive to UV variations (about half of the MgII index variability for instance), it corresponds to the ozone bands (and by chemical interaction in the stratosphere, the UV may affect the stratospheric dynamics and, consequently, the clouds coverage — which may be one of the paths of the Sun influence on the Earth's climate) and the limb darkening in this continuum is limited.

In addition, SODISM/PICARD observes 538 nm which is the center wavelength of the 100 nm bandpass used by Francis Laclare CERGA's group for the solar diameter measurement with the Astrolabe (and, in the near future, with the new DORAYSOL instrument). The 160 nm and Lyman alpha filters are used for identification and elimination of the active regions and prominences. This is essential to prevent activity manifestations to affect the "quiet" radius determination. By avoiding in the diameter computation the pixels at the limb affected by faculae, active regions, prominences, sunspots or pores, SODISM/PICARD has a reduced sensitivity in the ratio of a few diameters over 3000 or so but this does not add noise to the diameter measure.

The diffusion plates are simply used to monitor the CCD response and sensitivity (Flat Field). The CCD itself is a complete state-of-the-art system (EEV 42-80 2048x4096 pixels back thinned and with frame transfer) hopefully developed in parallel of our program for the COROT asteroseismology CNES/PROTEUS program.

Finally, specific to PICARD — and providing the ABSOLUTE diameter reference at the mas (milli arc second) level — is the “Star field” channel. It provides access to stellar fields in which (with a limit magnitude of 9) stars' triplets of the HIPPARCOS reference catalog are imaged, allowing to identify and to follow any structural change in the focus or CCD dimensions which could affect the diameter measure directly.

OPTICAL CONCEPT

SODISM has a sound optical concept allowing to achieve a distortion free and dimensionally stable image of the solar limb. It has a symmetry of revolution and a single telescope-detector-guiding telescope support structure for common referencing and stability. The telescopes mirrors (and, as well, those of the guiding telescope) are made of SiC without coatings. Advantage is indeed that the photometry will not change by aging and degradation of coatings since there will be no coatings. Further, the primary and secondary mirrors will help to remove 96 % of the visible solar flux, preserving the filters from degradation.

MECHANICAL/THERMAL STABILITY

To provide an ABSOLUTE measure of the diameter of 1 mas over the two years time period of the mission is the goal of SODISM/PICARD. The design selected achieves mechanical and thermal stability because of the choice of a single monolithic carbon-carbon structure linking the SiC mirrors of the telescope to the detector. As well the guiding telescope is in the same structure, its mirrors (same optical properties than the main telescopes) and 4-quadrant detector being linked to the carbon-carbon structure. This new type of structure allows to reduce the thermal regulation to ± 0.5 °C for an absolute tolerance of the diameter to 1 mas (1 thousand of a pixel). The isotropic property of carbon-carbon and a detailed knowledge of the experiment (interferometric calibration), will help to further gain, by modelisation, a factor 100 to 1000 on the diameter variations (useful for the solar limb oscillations).

POINTING

Image guiding and stabilization is provided by an off-axis telescope with the same optical properties than the main telescope and implemented in the same carbon-carbon cylinder structure. The 4-quadrant detector assembly is fine guiding the piezoelectrics which activate the primary mirror of the telescope. Fine guiding is used so that the image of the Sun on the CCD does not move by more than 0.1 arcsec, i.e. 1 tenth of a pixel (about 1 tenth of the Airy disk as well). The 4-quadrant detector will also provide (by access to the low frequency part of the control signal) accurate guiding to the microsatellite itself. In that case the coarse guiding of the stellar sensor is overruled by our sensor when the Sun acquisition is effective in the nominal ± 0.5° field of view. The 4-quadrant detector, the piezo electrics and the control loop will be provided by the Space Science Department of ESTEC.

7.2.2 SOVAP. To measure the solar constant, PICARD will use a SOVA 1 type radiometer, SOVAP, the "P" standing for PICARD. SOVA 1 is a differential absolute solar radiometer developed at the RMIB, Royal Meteorological Institute of Belgium (Crommelynck and Domingo, 1984). Its radiometric core is formed by two blackened cavities constructed side by side on a common heat sink. In between each cavity and the heat sink, a heat flux transducer is mounted. The difference between the two transducers' outputs gives a differential heat measurement, in which the common part of the thermal surrounding radiation seen by the two cavities is eliminated. By the symmetrical construction and good insulation thermal asymmetry is minimized.

Both cavity channels are equipped with a shutter in front of them. Equilibrium between the two cavity heat fluxes is maintained by regulating, using a servo system, the electrical power in one of the two cavities. In the default measurement sequence a constant electrical power is fed into one cavity, the "reference" cavity, while its shutter remains closed. The electrical power in the other cavity, the "measurement" cavity, is regulated continuously, while its shutter sequentially opens and closes (both open and close phases take 90 seconds). When the instrument is pointed to the Sun, the equilibrium electrical power in the measurement cavity drops proportional to the absorbed solar power when going from the closed to the open phase. The basic measurement of the solar radiative flux is the drop in the measurement cavity electrical power divided by the precision aperture area. To this basic quantity corrections have to be applied for the optical characteristics of the cavity (e.g. diffraction around the precision aperture borders, absorption coefficient of the cavity, …) and for the thermal emission of the shutters. The RMIB radiometers have been flown in Space 8 times from 93 to 98. SOVAP characteristics are summarized in Table 3.

Measured quantity	Total irradiance (Wm^{-2})
Number of channels	2
Number of reference voltages	6
Cavity type	Cylindrical, diffuse black
Diameter precision aperture	1 cm
Slope angle	2.5°
Solar sampling period	3 minutes
Duty cycle	50 %
Instrument noise	< 0.1 Wm^{-2}

Table 3 - Characteristics of SOVAP (default measurement mode).

7.2.3 UVSPM. This instrument is provided by the World Radiation Center, Davos, Switzerland. It consists in 3 "filter radiometers", based on the same principle than a radiometer (equilibrium of the flux inside a cavity) but with the preselection of a known and reduced spectral bandwidth. These photometers are observing in the UV, at the same wavelength, 230 nm and with the same bandwidth (5 to 9 nm) than SODISM. Having 3 of them — one is a reference — allows monitoring aging. They serve to estimate the UV flux in this ozone sensitive bandwidth and the CCD possible degradation.

Measured quantity	Spectral irradiance at 230 nm (Wm-2)
Number of photometers	3
FWHM bandwidth	5 to 9 nm (id. SODISM filter)
Cavity type	Cylindrical, diffuse black
Full view angle	2.5°
Slope angle	0.7°
Diameter precision aperture	3 mm
Accuracy of aperture area	<10-3
Cross-Talk	< 10-5

Table 4 – Characteristics of UVSPM.

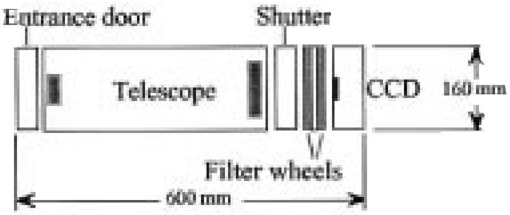


Fig. 1 — Concept of the SODISM/PICARD telescope assembly.

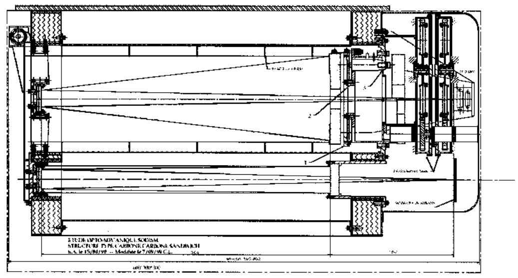


Fig. 2 – Mechanical layout of the SODISM/PICARD.

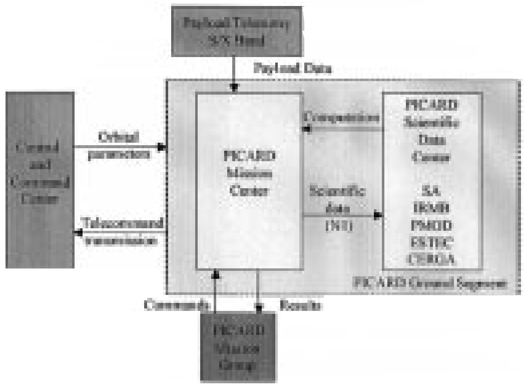


Fig. 3 – PICARD data handling summary. The PICARD Mission Center is in charge of evaluating the proper operation of the payload with quick-look and alarm generation, preparing the TC packets for the next transit and recording calibrated data on disk (N1 data). The PICARD Data Scientific Center (Laboratory) computes data of level 1', 2 and 3, and validates the algorithms to be installed at the Mission Center. On his side the PICARD Mission Group regulates changes to the software and determines the access rights to the Scientific Data base.

8 - CONCLUSION

The CNES Microsatellite program will be one of the opportunities for applying the trends of the strategic plan defined by CNES in testing new way of adaptation to the evolution of the space activity, either through use of other economical sectors or through search for innovative technology or methodology. The microsatellite product line defined as a subset of tools and functional chains (equipments, software, architectures, simulation test bench, engineering workshop) will be qualified in 2001 and first application for DEMETER mission will be flown beginning 2002. The CNES leadership in the industrial organization definition and the settement of partnership with industry should allow the best use of every competence to contribute to the success of this ambitious program.

Beyond the first applications and the scientific microsatellite program, it is foresen to extent the industrial organization for producing, and when needed, commercializing this product. This, in the long term, will allow CNES to concentrate on the main role of system and satellite prime responsability for its own scientific and technological applications or for cooperations,in which the developped engineering and management tools will allow CNES and its partner to design a system offering the best answer based on the CNES microsatellite product line.

- ***LIST OF DEMETER EXPERIMENTERS***

The experiment onboard the DEMETER microsatellite is proposed by a group of scientists involved in external and internal geophysics.

LPCE (France) D. Lagoutte, F. Lefeuvre, M. Parrot, B. Poirier, J.L. Pinçon - CESR (France) J.-A. Sauvaud, A. Cros - CETP (France) J.J. Berthelier, M. Menvielle
IPGP (France) J. Artru, P. Bernard, Y. Cohen, G. Hulot, J.F. Karcewzski, J.L. Le Mouël, P. Lognonné, J.P. Montagner - LDG/CEA (France) E. Blanc, J.L. Plantet
IDG Sophia (France) A. Deschamps - LPSH (France) A. Kerdraon - Univ. of Electro-Comm. (Japan) M. Hayakawa - SSD/ESTEC (ESA) J.P. Lebreton
CBK (Poland) J. Blecki, J. Juchniewicz.

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2. *M. PARROT, Electromagnetic noise due to earthquakes in Handbook of Atmospheric Electrodynamics, v.II, Ed. by H. Volland, CRC Press, Boca Raton, pp. 95-116, 1995.*
3. *O.N. SEREBRYAKOVA, et al., Electromagnetic ELF radiation from earthquake regions as observed by low-altitude satellites, Geophys. Res. Lett., 19, 91-95, 1992.*
4. *O.A. POKHOTELOV, et al., Response of the ionosphere to natural and man made acoustic sources, Ann.*

- ***LIST OF PICARD EXPERIMENTERS***

The PICARD mission team is based on the following group of scienti??? and engineers:

Luc Damé[1], Michel Hersé[1], Mireille Messonnier[1], Gérard Thuillier[1], Thierry Appourchaux[2], Thierry Beaufort[2], Dominique Crommelynck[3], André Chevalier[3], Steven Dewitte[3], Alexandre Joukoff[3], Claus Fröhlich[4], Hansjörg Roth[4], Francis Laclare[5], Christian Delmas[5], Jean-Pierre Rozelot[5], Patrick Boumier[6], Thierry Toutain[7], Michael Turmon[8], Judith Pap[9].
[1]Service d'Aéronomie, Verrières-le-Buisson, France
[2]SSD, ESA/ESTEC, Noordwijk, The Netherlands
[3]Institut Royal Météorologique, Uccle, Belgique
[4]PMOD/WRC, Davos Dorf, Switzerland
[5]OCA/CERGA, Grasse, France
[6]IAS, Orsay, France
[7]Dept. of Astrophysics, University of Nice, France
[8]Jet Propulsion Laboratory, Pasadena, USA
[9]Dept. of Astronomy, University of California at Los Angeles, USA

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