# SMALL SATELLITES CNES PROGRAMME MISSIONS FLOWN AND IN PREPARATION, LESSONS LEARNT, SUCCESS CONDITIONS

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# **1. INTRODUCTION**

MYRIADE is the name of the CNES (french space agency) small satellite Line of Product which development started in 1999.

It was an answer to the existing scientific, application or technological missions needs, and also an opportunity to develop international cooperation, technical or technological innovation, new management techniques, new organisations ...

MYRIADE had several objectives :

- provide low mission cost including launch cost
- provide short development time
- provide possibility to launch 2 missions/year
- provide high performances together with great flexibility

The MYRIADE system is a multi-missions system, with a common ground segment and a specific flight segment for each mission.

The first MYRIADE scientific mission has been launched on 29<sup>th</sup> june 2004., the second in december 2004 together with a constellation of 4 small satellites of the French Armament Agency developed by industry on a MYRIADE basis.

Other missions are under study or development at CNES or at industry .

MYRIADE is the result of a CNES in house development.

Lessons learnt and success conditions have been well identified from the beginning of the Line of Product development, with a lot if various difficulties.

The performances of this complete system are very well adapted to a great number of missions.

# 2. THE MYRIADE SYSTEM





The System components are (fig. 1):

# 2.1. THE GROUND SEGMENT

- the multi-missions Command Control Center (located in Toulouse-France) prepares and sends the programming messages, monitors the communication (RX/TX) with the satellite, process the TM for quick look, provides alarm generation, ...

- the ground stations network (with 3.1 m diameter antenna S band stations in Toulouse and northern Europe, and an X band station in Toulouse), operates automatically.

- another CNES stations network can be used for punctual tasks (localisation, ...).

- the Command Control Center interfaces with the scientific (or technological) Mission Center which send the payload programming messages and receives the payload data.

The Command Control Center can operate five satellite/missions at the same time, is operating during working hours only, but can perform automatic loading of messages

The availability is around 0.9

# 22.. THE SATELLITE

The satellite is based on a recurrent bus and a payload dedicated to the mission.

Typical performances of a recurring satellite :

- mass around 130 kg
- near 60 kg mass and 60 W continuous power (all along a classical low earth orbit with eclipse) offered to the payload
- payload data flow transmission : from 0.5 Gb/day with a single S band station to more than 24 Gb/day with a single X band station, for SSO type orbit.
- satellite availability : 0.92
- bus reliability : from 0.85 at 1 year to 0.61 at 3 years

# 2.3. GROUND/SATELLITE I/F

The communication between the ground segment and the satellite is performed through two links:

. the S band link is fully 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 housekeeping and technological telemetry, or for scientific missions with limited data transmission needs (up to 2 Gb/day). All the TC are transmitted through the S band, using a protocol which guarantees automatic re-transmission of TC frames detected as erroneous or lost by the board peer. For X band, maximum data coded rate is from 18 Mb/s to 175 Mb/s in near future. The modulation and coding used is a Multidimensional Trellis Coded Modulation Concatenated with Reed-Solomon bloc code (MCTMCRS).

#### 2.4. THE SYSTEM VALIDATION BENCH

It includes the computer, the flight software, the stellar sensor. All other functions are simulated. It is used for validation of performances, of Flight Softwares, of TM/TC ..., of procedures ...

#### 2.5. THE MYRIADE SUBSYSTEMS

Electronic components are commercial components which sustained a ground qualification to space environment radiations.

The design of the bus structure (fig. 2) is very simple (quasi cubic - 60x60x55 cm , aluminum and honeycomb aluminum, ...) to limit development and recurring costs. The X- panel includes the launcher adapter and the propulsion subsystem with its hydrazine tank. The payload is located on the X+ side of the bus.

The OBC (On Board Computer – in house development) has very few redundancies. As it is not fully immune to SEU nor SEL, a specific system (FDIR function), combination of hardware watchdogs and software function has been developed to overcome SEL, SEU, corrupted data, interrupted data transfers or dead processes. This FDIR function has been extensively tested and verified on dedicated ground test bench.



Fig 2 : MYRIADE bus top view, with lateral panels opened

The power subsystem is based on a single wing solar generator with 2 rigid panels with AsGa cells, rotated continuously by a Solar Array Drive Mechanism controlled by the OBC. After separation from launcher, hold down mechanisms are released in automatic sequence managed by the OBC.

A Power Conditioning and Distribution Unit (PCDU) is in charge of :

- launcher separation detection to connect the main non regulated bar to the battery
- battery regulation
- power distribution to equipment and payload (regulated voltages or voltages 22 to 37 V)
- thrusters and magnetoactuators commands
- pyro lines distribution

The battery is Li-ion type.

AOCS design is rather classic. It uses solar sensor, 3 axis magnetometer, high accuracy star sensor, gyros and GPS (option) as sensors, and magnetotorquers, reaction wheels and Hydrazine propulsion (4 x 1 N thrusters) (option) as actuators.

Four AOCS modes are used : acquisition/safe mode, transition mode, normal mode and orbit control mode.

	MYRIADE CHARACTERISTICS/I	BASIC PERFORMANCES
Structure	Al structure, honeycomb panels	600x600x800 mm, 130 kg total (with payload)
		payload 600x600x350 mm, 60 kg max.
Power	Solar panels ( <i>Alcatel and CONTRAVES</i> )	2 panels, 0.9 m2 total, rotating (200 W peak)
	AsGa cells (Spectrolab)	more than 90 W total permanent in SSO
	Battery Li-ion 14 Ah (AEA)	(60 W permanent-even during eclipse- for
	PCDU (Alcatel B)	payload)
AOCS	Sun sensors (Astrium)	Demonstrated Performances nominal mode:
	Magnetometer (IAI/Tamam-Israël)	1 axis, 3 axis, pointing capability
	Star sensor (TUD Denmark)	A priori pointing : $< 0.02^{\circ}$ (1 $\sigma$ ) each axis
	Gyros $< 6^{\circ}/h (Litef - D)$	Pointing stability : $< 0.02^{\circ/s}$
	Magnetoactuators (IAI/Tamam – Israël)	
	Reaction wheels $0.12 \text{ Nms} (Teldix - D)$	DeltaV available : 80 m/s for 120 kg satellite
	Propulsion : 4 x 1 N thrusters, hydrazine	
	system Isp 210 s (EADS Gmbh)	
Localization	Performed by Control Center	By Doppler measurements :
/Orbit		Position restitution/prevision at 3 $\sigma$ : ± 350 m
determination		/± 575 m along the track and less than ± 10 m $\perp$ to
		the track or in altitude (idem for prevision)
	Option GPS TOPSTAR 3000 (Alcatel)	Localisation by GPS : $< \pm 1 \text{ m}$
On board	μprocessor T 805	5 Mips, 1 Gb memory (EDAC)
data management	CNES design (STEEL manufacturing)	In-orbit reprogrammable
and		OS-link between OBC and payload 5 Mb/s
Command/Contr.	Flight software : (CSSI)	Payload has its own computer
		Datation : $\pm$ 15 ms/UT (at 700 km altitude)
Communications	TX link : CCSDS and coding	Error Bit Rate : 10 <sup>-10</sup>
S band	RX link : CCSDS and coding	Error Bit Rate : $10^{-10}$
	Emitter (QPSK modulation) THALES	10 or 400 kb/s to 600 kb/s - cold redundant
	Receiver (QPSK demodulation) "	20 kb/s – hot redundant
	2 antennas (SHELTON)	opposite sides, omnidirectional coverage
Payload data	Option : X band emitter for payload	18 Mb/s to 80 Mb/
downlink with X	(ALCATEL)	more than 100 Mb/s in development
band		
Payload	Performed by payload electronic	8, 16, 32 Gbits mass memory included in payload
management and	computer with µprocessor, solid state	electronic
data storage	memo ry, (STEEL)	

Table 1 : MYRIADE	procurement and basic	performances
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On board data management and control/ command perform the following main functions :

- satellite configuration management
- mission plan management
- storage of house keeping and payload data, and transmission to S band station
- implementation of AOCS

The architecture is centralized : processing is achieved by one single OBC with direct links with PCDU, Solar generator rotating system, AOCS equipment, RX and TX, payload.

The RX/TX includes two S band receivers (hot redundancy), two S band transmitters (cold redundancy) and two antennas on opposite direction to obtain quasi omni-directional coverage.

Thermal control is based on use of passive systems (paints, MLI, SSM coatings, ...) and heaters.

Satellite redundancies are limited to :

- 2 emitters in cold redundancy
- 2 receivers in hot redundancy
- 2 electric motors/electronics for solar generator rotating system
- internal OBC parts (controllers, flash EPROM memories, DRAM memories for central software, FRAM memories)

The Table 1 summarizes the main satellite performances.

#### 2.6. THE LAUNCH MEANS

MYRIADE mechanical design is compatible with several launchers environments:

DEMETER has been launched with DNEPR (Kosmotras) launcher (see figure 3)



Fig 3: DEMETER launch on DNEPR (29<sup>th</sup> june 2004)

This launcher is very performant in terms of high precision orbit injection, low cost, high volume offered (see figure 4), ...



Fig 4: DEMETER (center) inside DNEPR fairing

PARASOL and ESSAIM have been launched by ARIANE 5 (as passengers on ASAP plate – fig 5).



Fig 5; PARASOL and ESSAIM on Ariane 5 ASAP

For future missions, other launchers are available: SOYOUZ, VEGA and EUROCKOT.

#### **3. THE MYRIADE ORGANIZATION** CNES is prime for MYRIADE.

Satellite AIT is performed by CNES or industry. There is also a partnership between CNES, ALCATEL and ASTRIUM :

ASTRIUM has participated to system test bench development, software specification and validation, some of the AOCS modes development, ...

ALCATEL has participated to PCDU (Belgium) and system bench development.

This partnership gives to these companies the possibility to use MYRIADE design and products for their own applications (defense, commercial market, ...). Finally, a high level of standardization (analysis tools, data bank, ...) has been reached which allowed good efficiency developments.

# 4. IN FLIGHT CNES MYRIADE MISSIONS

# 4.1 The DEMETER mission

DEMETER (figure 6) is a scientific mission proposed by CNRS agency (LPCE laboratory was prime) [1]. It is dedicated to the detection and the characterisation of electro magnetic waves signals associated with telluric activities (earthquakes, volcanic) or issued from human activities (Power lines, VLF, HF broadcasting). These signals disturb the ionosphere and high atmosphere. These perturbations occur between a few tens of minutes and a few hours prior to the seism. The scientific payload is constituted by a 3 axis magnetic search coil instrument, 4 Electrical sensors, a Langmuir probe, a Plasma analyzer, a Particles detector and an Electronic unit.

To limit bus perturbations, the magnetic sensors are set at the end of a 2 m length deployable boom, while the 4 electric sensors are set at the extremity of four 4 m length expendable booms.



Fig 6 : The DEMETER small satellite

The secondary mission of DEMETER is technological. The purpose is to perform in flight validation of i) an advanced system of payload telemetry incorporating a solid state mass memory of 8 Gbits and an X band transmitter at 16,8 Mbits/s, ii) a system of autonomous orbit control relying on a GPS and a navigator, iii) a pyro device firing by laser, iiii) a thermal protections aging test.

The main challenge of DEMETER bus was the necessity to procure to payload the lowest possible electric and magnetic perturbating levels (1000 Hz range). The magnetic satellite emission is limited to -24 dBpT from 1 to 7 kHz (some streaks are over but there are few). This has been done by specific wirings, active filtering, magnetic shields on wheels, connectors, ITO on solar generator, ...

# Status :

DEMETER has been launched 29<sup>th</sup> june 2004 . The satellite and the payload work well after 2 years in orbit.

# 4.2 The PARASOL mission

PARASOL is the second mission developed by CNES within the frame of MYRIADE.

It has been proposed by CNRS agency (LOA laboratory was prime)[2].

It will be part of a swarm (the A train) composed by CALIPSO, AQUA, OCO, CENA, AURA and CLOUDSAT.

PARASOL addresses climatology, in particular measurements of clouds and aerosols properties, and radiative budget interaction(contribution to the global warming)

It will carry an instrument derived from POLDER, instrument already flown aboard the Japanese ADEOS-I and ADEOS-II satellites.

PARASOL bus design (figure 7) is nearly <u>similar</u> to DEMETER/MYRIADE design.

Minor modifications concern:

The solar generator cant angle has been set to 0° to avoid disturbances not compliant with the pointing stability requirements of the mission (< 0.01°/s over 5s) while the solar generator is in rotation.</li>



Fig 7: The PARASOL s mall satellite

A yaw steering capacity will be implemented in order to compensate for the earth rotation when the payload is taking images.

Concerning the payload, mass memory capacity is extended to 16 Gbits.

PARASOL is the first demonstration of recurring mission developed within less of three years with a low recurring cost.

#### <u>Status :</u>

Integration of PARASOL was initiated in June 2003. Launch was in december 2004, aboard ARIANE VASAP.

#### 5. OTHER IN FLIGHT MYRIADE MISSIONS



Fig 8 : The ESSAIM constellation mission

ESSAIM is a French Armament Agency mission developed by EADS/ASTRIUM company on a MYRIADE basis. It is a demonstration mission in view of operational mission. It is based on a constellation of four small satellites, enabling localisation of ground electromagnetic sources.

#### ESSAIM development was conducted <u>as close as</u> <u>possible to DEMETER development</u>, but\_ with simplifications:

The Solar Array Drive Mechanism was suppressed, leaving a fixed solar array.

The nominal AOCS mode was suppressed, the normal operational mode becoming the gross transition mode, compatible with the required pointing performances., with suppression of star sensor and X-axis and Z-axis reaction wheels.

Except for the suppression of these equipment the structural architecture is not changed. The on board software needed to be adapted to the dynamics of the satellite, with sun pointing in the regions of North and South pole to increase electrical power.

All these modifications resulted in a <u>cost reduction</u>, particularly efficient in case of a constellation.

#### Status :

Launched in December 2004, the ESSAIM constellation is presently operated nominally by French Armament Agency.

# 6. IN DEVELOPMENT CNES MISSIONS

#### 6.1. The MICROSCOPE mission

It is a scientific mission proposed by ONERA agency (as payload prime). MICROSCOPE is dedicated to the demonstration of the EP (Equivalence Principle). This principle states that the gravitational mass and the inertial masses should be equal. The payload will be based on 2 differential accelerometers of high performance  $(10^{-12} \text{ m.s}^{-2} \text{ precision})$  developed by ONERA.

Detection of an acceleration on the second accelerometer, using a proof mass with a different density, will bring evidence of a violation or not of the equivalence principle at a  $10^{-15}$  precision level.

In order to measure such differential accelerations, the accelerometers have to operate in proper conditions : - the satellite (fig 9) has to be controlled drag free with residual linear acceleration less than  $3.10^{-10} \text{ m.s}^{-2}$ . Hz<sup>-1/2</sup>.



Fig 9 : The MICROSCOPE small satellite

- the satellite has to be spinned at  $10^{-3}$  Hz. MICROSCOPE requires important adaptations of the

basic MYRIADE design : - payload accelerometers have to be located precisely at the satellite CoG, with very high thermal decoupling from spacecraft structure

- dedicated AOCS modes have to be developed, using low thrust electric thrusters (Field Emission Electric Propulsion thrusters) as actuators. These thrusters are developed under ESA responsability.

- bus architecture is specific ; a new solar generator (symmetric) has been designed Main mission performances are :

Orbit 700 km, SSO 6 am/18 pm Pointing ٠ spin axis ^ to orbit plane new modes for drag free at 3.10<sup>-10</sup> AOCS ٠ Power 2 deployable then fix solar panels • Propulsion 12 FEEP thrusters on 4 pods ٠ 150 mN thrust each Weight Total: 190 kg. ٠

Status :

The program is starting phase B. Launch is scheduled in 2007/2008.

# 6.2 The PICARD mission

PICARD is a scientific mission proposed by CNRS agency, Belgium and Switzerland laboratories. Service Aéronomie/CNRS is the prime.

It is dedicated to the sun observation (diameter, irradiation, differential rotation, UV) in relation with the earth climatology, together with solar physics measurements (oscillations, UV).

The payload has three instruments (fig 10):

- a high resolution and high thermomechanical stability telescope (SA/CNRS) with CCD detector, for diameter and oscillations measurements : precision a few milliarcseconds

- a radiometer (IRMB) for total irradiation measurement - a UV radiometer (WRC/PMOD)

The payload main sizing requirement is linked to bus pointing : the need is absolute sun pointing precision of less than  $\pm 0.01^{\circ}$  and pointing stability less than  $0.01^{\circ/s}$ .



Fig 10 : The PICARD s mall satellite

The satellite design is based on MYRIADE bus (fig 10).

Main mission performances are :

Orbit	•	700 km, SSO 6 am/18 pm
	•	sun pointing $< \pm 0.01^{\circ}$
	•	stability < 0.01 °/s.
AOCS	•	new sun pointing mode using payload telescope
Propulsion	•	not necessary
Weight	•	Total: 140 kg.

Status :

The program is in phase C development. Launch is planned end 2008.

#### 7. IN DEVELOPMENT DEFENSE MISSIONS

#### 7.1. The SPIRALE mission

SPIRALE is a French Armament Agency mission developed by EADS/ASTRIUM company on a MYRIADE basis. It is a demonstration mission in view of operational mission. It is based on a constellation of two small satellites on GTO orbit.

It is an\_Early Warning mission. The constellation will collect infrared images of terrestrial backgrounds. EADS/ASTRIUM (prime contractor and integrator), work with ALCATEL/ALENIA Space (satellites engineering).

The two MYRIADE satellites are adapted to cope with GTO orbit (first use of MYRIADE in GTO orbit).

#### Status :

The programme is in phase C development. The launch is scheduled in 2008 on an ARIANE 5 (piggyback with a geostationnary satellite).

#### 7.2. The ELINT mission

ELINT is a French Armament Agency mission developed by EADS/ASTRIUM and THALES companies on a MYRIADE basis. It is a demonstration mission in view of operational mission. It is based on a constellation of 4 small satellites, enabling localisation and characterization of radars.

Status :

The programme is in phase A development. The launch is scheduled in 2010.

# 8. CNES MISSIONS IN STUDY (Phase 0 or A/B)

A lot of missions have been studied or are in study on MYRIADE basis.

# 8.1 Solar/fundamental physics/univers missionsThe TARANIS mission :

This mission, proposed by CEA agency (payload prime) and other laboratories (F, USA), is dedicated to the measurement of coupling phenomena (sprites, particles) between upper atmosphere, ionosphere and magnetosphere during storms. The payload is constituted by electric and magnetic antennas, Langmuir probe, 2 cameras, photometer and X,  $\gamma$  and electrons sensors.

A satellite (fig 11) phase 0 study (teamX type) has demonstrated a good feasability: Main mission performances are :

Orbit	•	700 km, SSO 6h/18h
Pointing	•	earth pointing
SL EMC	•	DEMETER design reused to limit SL EMC perturbations
Propulsion	٠	MYRIADE recurrence
Weight	•	Total: 120 kg. Payload weight: 45 kg.

#### <u>Status :</u>

Phase A will end soon. Launch possible for 2008.



Fig 11 : The TARANIS small satellite

# 8.2 Earth Observation missions

# - The ALTIKA mission (pre-operational or operational mission)

This mission has been proposed by several french oceanographic institutes (LEGI, LEGOS, SHOM, IFREMER, CLS).

It is dedicated to the study of the mesoscale oceanic variability (50/500 km wavelength, days/year period, amplitude < 30 cm), of he cost and land altimetry, of continental waters and ices, ), of the rain, and contributes to MERCATOR.

The payload (fig 12) is constituted by :

- a Ka monofrequency (35.75 GHz) altimeter (full deramp), with antenna, horn and electronic

- a radiometer (24 and 37 GHz) for humid tropospheric correction

- DORIS system for orbitography

- a laser retroreflector mirror

Target performance : 4 cm vertical resolution for ocean waves less than 6 m height.

Constellation : Interest of 3 satellites for post-ENVISAT operational mission is underlined.

#### Status :

This mission is now studied in a cooperation with India.





Main mission performances are :

Orbit	•	800 km, SSO 6am,18 pm
Pointing	• •	nadir pointing ± 0.2 ° stability 0.02° over 25 ms
Attitude restitution	•	satellite attitude restituted by radar payload
Localisation and datation	•	by DORIS system
Weight	• •	Total: 125 kg. Payload weight: 40 kg.
launch	•	Possible for 2007 (overlapping with ENVISAT)

Status:

After CNES in house phase A/B study with MYRIADE small satellite (fig 12), the mission could be performed in cooperation with India (in discussion).

#### - The HRG mission

This mission has been studied by CNES in order to assess a mission in continuity to the HRG/SPOT 5 earth observation mission, but based on a MYRIADE microsatellite.

The HRG/SPOT 5 images are 60 km x 60 km, with 2.5 m resolution in panchromatic and 10 m resolution at 480, 550, 660, 850 nm wavelengths.  $\pm$  30° off nadir pointing and 160 images/day are possible. The payload is constituted by : - a new (and small) instrument with 3 mirrors (TMA type), 110 mm aperture, 650 mm focal length, with 2 x 12000 pixels (6.5 x 4.5  $\mu$ ) panchro detectors, and a quadrichromic detector (4 x 6000 pixels 13 x 13  $\mu$ ). - a detection box, a video electronic box, a compressor, a memory and command electronic box

- a high rate TM box and antenna and a GPS. Target performance is 3 m resolution and images

number around 70 / day.

The payload has been fitted up on the MYRIADE bus as presented in the following figure 13. The feasability was demonstrated, but the study has pointed some weak points :

- the reliability of MYRIADE (few redundancies) is around 0.5 for a 5 years mission, i.e. a low value when total mission cost is considered.

- a constellation of 4 satellites is too expensive. For these reasons, it was decided to study an option with more performant instrument, implementation of redundancies for each bus equipment, manœuvre performance of 2.5 °/s (gyroscopic actuators, rigid solar generator, new gyros...).



Fig 13 : The MYRIADE HRG microsatellite

Main mission performances are :

Orbit	•	500 km, SSO 10:30 am descend. node
SCAO	٠	X wheel : 1 Nms
	•	MagnetTorquer Bars : 25 A.m2
Attit. point.	50 j	urad (X) to 180 µrad (Y)
Pointing	٠	2 µrad at 7 Hz with new gyros or
stability		with 0.01 Hz SCAO band
Localisation	٠	20 to 40 µrad with SST and Gyros
Agility	•	1.5 °/s max.
Propulsion	•	hydrazine
Weight	•	Total: 126 kg.(Payload: 44 kg)
launch	•	Possible for 2007

The total satellite mass for this option was around 220 kg, giving possibility to achieve around 150 images/day, with better than 2.5 m resolution and satellite reliability around 0.8 for 5 years.

# Status :

Pending CNES decision.

# 8.3 Operational missions

# - The ARGOSµSAT mission

The existing ARGOS constellation is based on satellites from NOAA (POES) and EUMETSAT. These satellites are on three SSO polar orbital planes (around 14 h, 18 h and 22 h local times).

NOAA and CNES are discussing the possibility to replace NOAA-K in 2008 (planned end of life), by a small satellite named ARGOSµSAT. This option should be based on a MYRIADE system with an already existing ARGOS 3 instrument.

This mission has been extensively studied during phases 0 and A at CNES.

Simplicity and reliability were the driving parameters. The detailed studies have concluded on the main following characteristics:

- a low altitude orbit (around 660 km) compatible with the mission and enabling a natural deorbitation after the end of the mission (no propulsion system necessary)
- a 17h30 (ascending node local time) orbital plane
- a fixed solar generator
- a simple attitude control system with magnetometer, solar sensors, inertia wheel and magnetotorquers (no stellar sensor, no gyro)
- a simple communications system (MYRIADE S band)

The following figure 14 shows the global layout with the UHF antenna, the L band antenna and the 2 S band antennae.



Fig 14 : The ARGOS $\mu$ SAT small satellite

The main performances are:

- satellite reliability: 0.76 at 7 years
- data (around 0.5 Gb/day after compression) available
  3 hours after beacon signals reception with data
  downloading at every orbit (S band stations available
  in Kiruna-Sweden, Toulouse-France and Fairbanks-USA).

Status:

Pending results of discussions between NOAA and CNES.

# 9. MISSIONS DEVELOPED BY INDUSTRY

#### - The ALSAT 2 mission

After international competition, ASTRIUM won a contract from Algeria for the development of an Earth Observation system based on two small satellites and the associated ground segment.

The satellites are based on MYRIADE design (fig ), with a mass of 130 kg.



The payload telescope will provide images 2.5 m ground resolution and 17 km swath, with MYRIADE mass memory extended to 64 Gb and X band telemetry rate extended to 70 Mb/s.

Up to 100 images/day will be taken.

The ground segment will be developed by ASTRIUM, the Control Center and the Mission Center being located in Algeria.

Launch of first satellite is planned beginning 2009. This is the first MYRIADE export contract.

# **10. LESSONS LEARNT FROM DEVELOPMENT**

MYRIADE design was based on some innovative technologies, providing high performances at low costs.

High level performances:

It was a good choice, because it is easier and more cost effective to degrade some performances for a dedicated mission, rather than enhancing the design.

Low costs:

Off the shelf equipment have been procured every time it was possible.

# **OBC and Central Software:**

The On Board Computer has been developed internally at CNES with support of R&D programme. The design drivers were:

- low mass, low consumption, low cost, but reliable

- use of commercial components
- risks accepted

- manufacturing in small local company CNES has allowed to delegate development responsibility to a unique person. No big pressure was put on the development planning (development duration was around 5 years).

Ground solutions were often selected (I2C bus, µprocessor T805) together with FPGA and PIC µcontrollers. Only few critical devices had redondancy (converters, oscillators), and Failure Detection and Recovery was implemented by central software use. The FDIR system was deeply qualified on a test bench. OBC characteristics:

- less than 3 kg, 6 W

- 5 Mips, 1 Gb memory, in orbit reprogrammable, ...

#### AOCS

The AOCS is a classical design, but estimated performances were very good: pointing accuracies lower than 0.05°, due to good performances of Star Tracker. Satellite guidance and pointing has been optimised to avoid Moon inside the field of view of the Star Tracker (which generates satellite safe mode).

# Payl oad:

# DEMETER:

Scientific payload is managed by a dedicated computer (similar to OBC) with OS-link communication between the two. Associated dedicated software has been developed..

High rate X band telemetry has been developed by R&T programme in parallel to MYRIADE development. The performances obtained were very good: from 17 Mb/s to higher than 100 Mb/s (2 kg box, 36 W). This performance is very attractive for payload data downloading.

Mass memory and High rate X band telemetry used CCSDS format.to transmit all scientific data. The different laboratories or industrial companies which have developed these payloads followed roughly the same development philosophy as for MYRIADE, with one exception: High Rel components were sometimes used.

# 11. LESSONS LEARNT FROM FLIGHT

The in flight operations (on the three missions) have been completely successfull till now. No hardware failure has occurred. The On Board Software and its FDIR function have successfully recovered many problems (SEU on wheels, on Star Tracker, on DRAM memory). Capacity to reload On Board Software has been used extensively to correct bugs or optimise functions. DEMETER has demonstrated very good Autonomous Orbit Control function performance (satellite position maintained at  $\pm$  50 m wrt on board command) thanks to performant GPS and propulsion subsystem (1 N hydrazine thrusters providing reproducible 62 ms pulses generating less than 1 cm/s deltaV). Payload Computer and payload X band telemetry have been in flight qualified with DEMETER mission.

No problem was encountered with these equipment.

The PARASOL OCXO has an important drift not explained, necessitating monthly adjustment TC from ground.

PARASOL Star Tracker behaviour:

The Star Tracker working temperature (around  $9^{\circ}$ ) associated to the working frequency (4 Hz) induced apparition of great number of hot spots (due to high energy protons), and consequently false stars images on the CCD and loss of star tracker data.

The solution consisted to install morphological filters inside the star tracker software.

After this installation, the star tracker has recovered a 100 % availability.

The aging of the solar generator and the battery induced losses of efficiencies from -0.5 % to -8% after 15 months of in flight operation.

All the in flight MYRIADE missions payloads (6 satellites) are working perfectly.

# Availability performances

Some events (equipment resets due to SEU or software bugs/tunings), have induced satellite safe mode on the three in flight missions (around fifteen in total). The overall system availability was around 86% during the first 12 months, and around 95% for the satellite. From mid 2005, the system and satellite availability are well above 95%.

These figures are completely satisfactory. MYRIADE has been designed for a one year lifetime, two years being a plus. It appears today that the probability is high to demonstrate real in orbit lifetime higher than 3 years.

#### Lessons learnt from on-board operations

After definition and validation of Flight Operations, the DEMETER and PARASOL operations were complicated by a lot of satellite anomalies. The satellites operations team had to cope with. Due to good operations preparation, rigorous organisation and adapted methodology, the team acquired a level of knowledge enabling to conduct operations securely and autonomously [4].

#### **12. SUCCESS CONDITIONS**

We now identify what we can consider as the necessary conditions or needs to reach this present successfull status.

. all specifications were well targeted towards small missions, lifetime limited to 1 or 2 years (in consequence redundancy was not absolutely required), and simplicity was a design driver.

. efficient/performant FDIR function was an absolute and priority necessity. Experience has shown that it was probably one of the main success condition.

. the CNES internal development was not easy. At a given time, it was necessary to increase internal CNES human resources and set a priority to the MYRIADE project.

. one top requirement was to design as simple as possible, lifetime being not the priority.

. risks philosophy: from the beginning of the programme, risks concerning development delays, costs update, in orbit failure, ... have been accepted. This was new for our agency. In reality, nobody like to have a failure or a delay in its work, and each people gave the best of himself in this development programme.

The development of MYRIADE being an agency in house development allowed probably to initiate excellent relationships between different teams (project, development, operations, ...). A team spirit was present which also explains the success achieved.

# **13. CONCLUSION**

DEMETER, PARASOL and ESSAIM missions, 6 SL in orbit at total, are flying today.

Demonstrated lifetime is 2 years (june 2006 status) for DEMETER.

PARASOL mission has made demonstration of the possibility to develop a new mission within less than three years, with a launch 6 months after DEMETER launch.

MICROSCOPE and PICARD (CNES scientific missions) are in development.

SPIRALE, ELINT and ALSAT 2 missions (8 satellites at total) are in development by EADS/ASTRIUM. All these in development missions (10 satellites at total) are based on MYRIADE design and will use MYRIADE ground Segment.

Concerning launch capabilities, the present russian market offers several launchers at low cost (DNEPR, STRELLA, START, ROCKOT) with a good reliability The high level of performance (pointing, TM/TC, power, ...) of MYRIADE design and its flexibility are such that many mission needs can be fulfilled, while overall cost is maintained at an attractive level.

Also the development duration is limited and launch opportunities are many.

CNES and french industry have now to complete the demonstration by increasing the rate of new decided/operating missions.

# Perspectives :

- MYRIADE design has demonstrated its performances and its adaptation to many missions needs, either scientific or operational.
- Use of high recurrence induces short development durations and limited costs.
- Opportunity of several small missions is believed more attractive than costly flagship missions.
- Some ambitious scientific missions (like MICROSCOPE) are still possible with adaptations of MYRIADE design..
- Operational missions are possible. If necessary, it is possible to increase operational lifetime, by implementation of equipment redundancy, or in orbit satellite redundancy (launch of several generic satellites can sometimes compensate development costs).

# Commercial perspectives:

This is the task of french industry (ALCATEL and ATRIUM are CNES partners on the MYRIADE development). These companies have presently contracts with the french Defense Agency, and are prospecting the commercial market (issuing proposals).

#### Cooperation perspectives:

MYRIADE system appears to be an excellent space missions cooperation tool. New possibilities of scientific or operational missions in cooperation with CNES can be investigated and discussed in the coming years.

# **14. REFERENCES**

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