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ORIGINAL ARTICLE

SIMBOL-X: An hard X-ray formation flying mission

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Abstract In 2004 and 2005 CNES decided to perform phase 0 studies on 4 scientific missions: ASPICS (Solar physics), MAX (γ-rays Laue lens), PEGASE (hot Jupiter study by an interferometer in the 2 μm to 4.5 μm range) and SIMBOL-X (hard X-rays telescope). This last mission had already undergone a feasibility study in 2003 (ref. [4]), however a complementary study was necessary to take into account the possibilities of increasing the payload mass allowance, as well as the developments in the payload design and science goals (see ref. [1]). The output of this new detailed study is described hereafter.

1. SIMBOL-X scientific mission

The SIMBOL-X project is a high energy new generation telescope covering by a single instrument a continuous energy range starting at classical X-rays and extending to hard X-rays ie from 0.5 to 80 keV. It is using in this field a focalizing payload which until now was only used at energy below 10 keV, via the construction of a telescope distributed on two satellites flying in formation. SIMBOL-X permits a gain of two orders of magnitude in sensibility and spatial resolution in comparison to state of the art hard X-rays instruments.

The energy range targeted by SIMBOL-X is the one where thermal emissions leave place to harder emissions which are due to particles acceleration or which are due to accretion phenomena on a massive central object. The study of these phenomena is the heart of SIMBOL-X scientific objectives.

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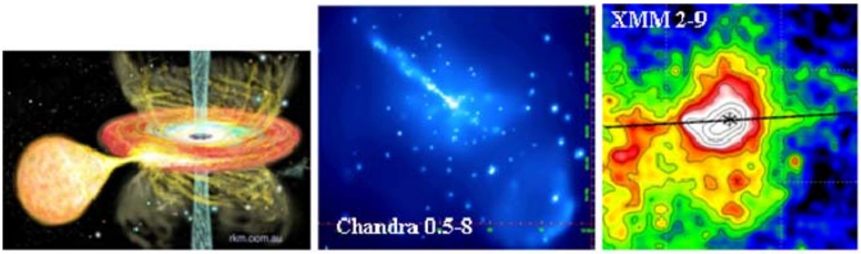


Systèmes binaires avec trou noir de masse "stellaire" | Galaxies à noyau actif (trou noir supermassif actif) | Le centre de notre Galaxie (trou noir supermassif inactif)

1.1. Why hard-X rays?

Non thermal emissions in X and γ rays are unique signatures needed to answer fundamental questions in modem astrophysics:

- How works the dynamics of the universe at all scales? From star formation to cosmological large structure formation, this is driven by accretion power, particularly on Black Holes, and violent non thermal phenomena (as jets)
- How good are our physics laws in extreme conditions, of gravity, pressure, magnetic field? Do we need new physics?
- How and where are accelerated the cosmic rays at the highest energies?

2. SIMBOL-X mission

SIMBOL-X orbit has been revisited during the 2005 study. It has permitted to define an orbit giving more mass allowance at launch, as well as a very good flexibility in the mission scheduling.

In particular the mass impact linked to the major drivers (redundancy, collimator) revisit have been absorbed and left intact a comfortable system margin (>30%).

This mission should allow for observations during 2 years (cumulated observations). It means that the total space system life duration would be about 3 years (taking into account some months for "In flight formation acquisition, reacquisition and checking" and a provision for servicing operations and accidental safe mode).

Scientific observations have to be performed outside the Van Allen belts (no instrument background noise): that is to say an altitude greater than 73 000 km. Nevertheless it has been accepted to pass very high in these belts once every week.

The telescope is implemented with a "mirror spacecraft" and "detector spacecraft" in formation flying.

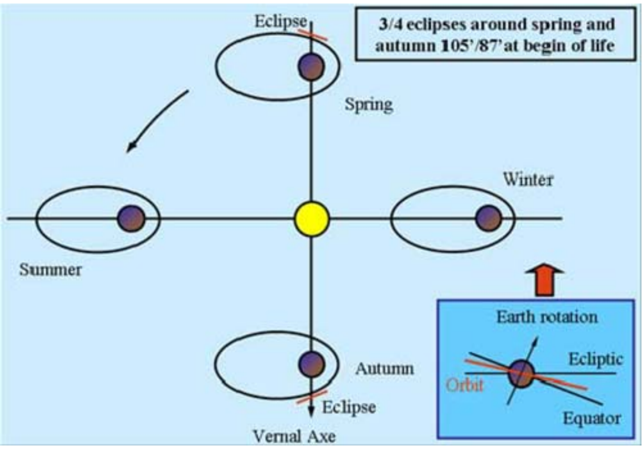
Optimizing the global resources of both spacecrafts led then to select a scientific orbit with a 44 000 km perigee altitude/a 253 000 km apogee altitude/a 7 sidereal days period /Low initial inclination. This orbit is subject to significant luni solar effect.

It has been chosen to give 90% time above 73 000 km which maximizes the science return.

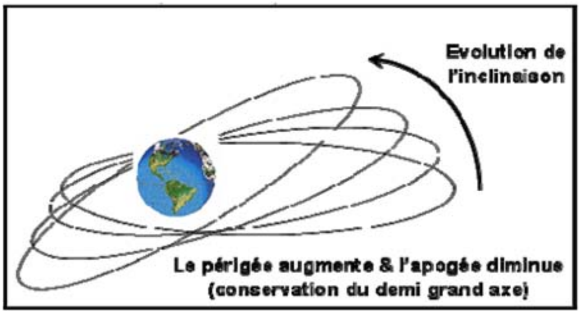
The satellites ΔV is around 500 m/s and can be achieved with a classical and robust hydrazine system.

The daily visibility are ~12 hours per station with a maximum of 2 hours gap.

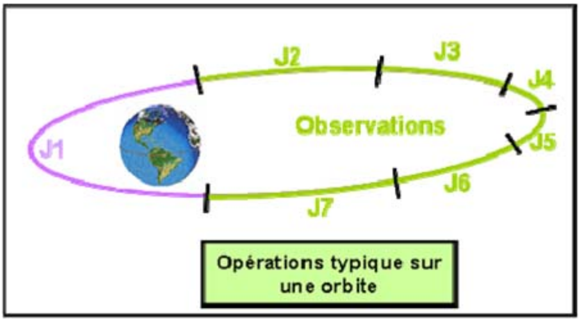
At perigee the visibility is permanent (24 hours) for the chosen station.



During mission there is no need to maintain exactly the orbit parameters. The important point is to keep the correct orbit period and the phasing with the ground segment to facilitate the operations with the Ground at perigee pass (maximization of telemetry rate). In that perspective roughly one manoeuvre per month is expected to maintain the semi-major axis. The result is that orbit parameters evolution are constrained by luni-solar effects and the perigee will increase to ∼70 000 km after 2 years due to lunar effects combined to semi major axis conservation (see below).



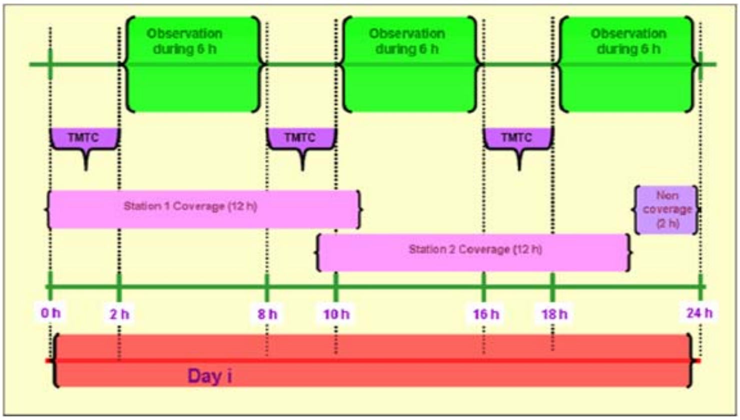
Typical operations on such an orbit consists in performing science during 6 days (out of perigee) and to use permanent perigee visibility to download the bigger part of the telemetry. Outside perigee a daily contact of one to two hours is sufficient for Status of Health and/or monitoring of the formation repointing to a new target.



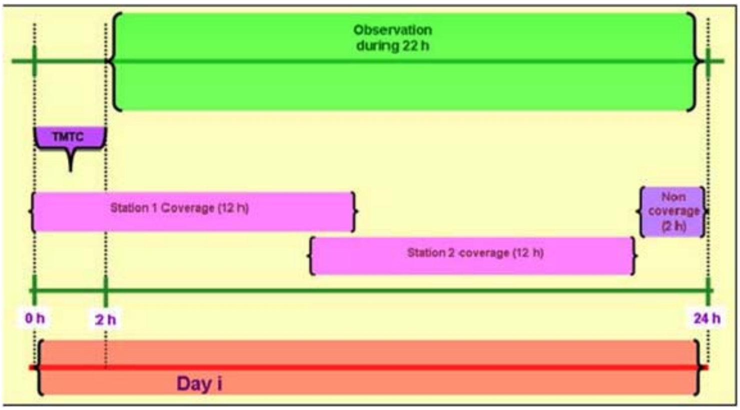
The distributed instrument ("mirror spacecraft" and "detector spacecraft") would be able to observe a great variety of astrophysical sources. Depending on them the observation time varies a lot. As an example a bright source like the "Crab" one needs an observation time in the range of an hour, on the contrary a faint source or a deep field observation could need several days of continuous observation. In the satellite design 500 observations per year have been taken into account.

The following schemes are giving examples of operation for different sources.

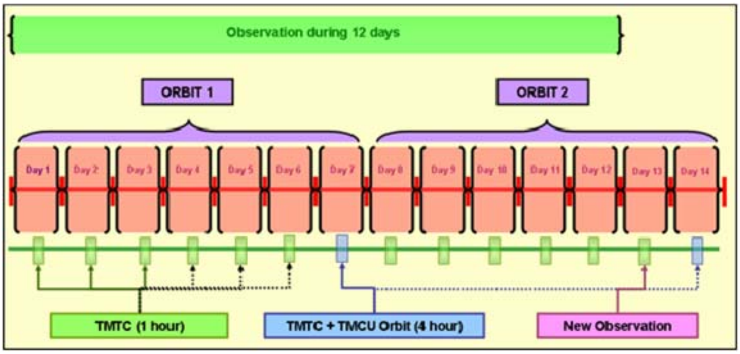
Example 1. Several bright sources on one day (22 ks each; >1m Crab)



Example 2. One weak source (79 ks; $<50\mu$ Crab)

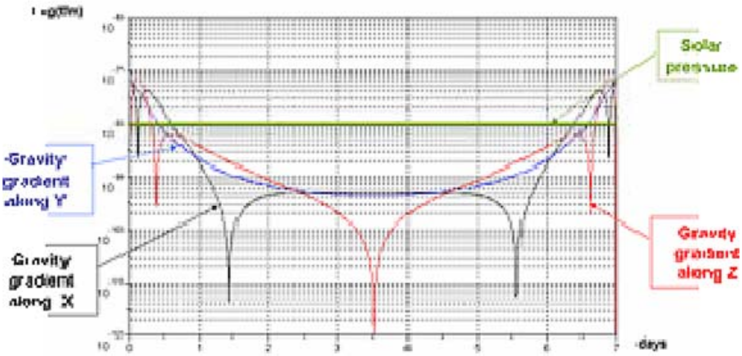


Example 3. Deep field ($\sim$1 Ms)



3. GNC & formation flying constraints

On the pre-selected orbit the conditions are very favourable for the formation flying as it can be seen on the following scheme:



Variation of the gravity gradient on an orbit period along the different axis

The solar pressure is the main contributor to the perturbations except around the perigee. Nevertheless, gravity gradient perturbations being low, the system will be designed to keep formation around perigee and thus avoid to break/reconstruct itself once per orbit.

The instrument field of view is equal to 6 arc min in the design studied in phase 0. The angular resolution must be better than 20 arc sec and the telescope line of sight measurement accuracy better than 3 arc sec. This last requirement is rather demanding. The mirror attitude control accuracy shall be better than 10 arc sec during scientific observation.

The following summarizes the main constraints due to formation flying:

Relative positioning:

- lateral/L.O.S.:+/− 1 cm
- longitudinal: +/− 10 cm
- lateral position knowledge: 0.5 mm (or 3″ LOS)
  Constraint on inertial and relative metrology lateral sensor + star tracker with 1 arc sec accuracy range

Mirror attitude control:

– Pointing: 10 arc sec
– Stability: no constraint

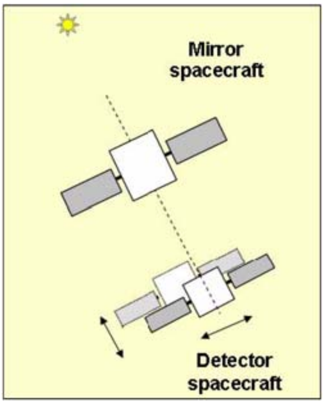
Detector attitude control:

– Pointing: 5 arc min
– Stability: 5 arc min

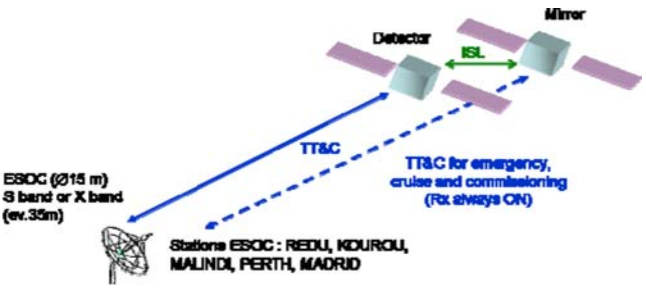
In the following paragraph, we summarize the main choice relative to the GNC functions.

– **G.N.C. concept**: The selected philosophy for Formation Guidance Navigation and Control consists in having all the functions on one spacecraft (the detector satellite). Then, the "detector spacecraft" is position controlled with respect to the "mirror spacecraft". This last one stands on its natural orbit and performs the fine pointing. The relative position is measured with respect to the "mirror spacecraft" reference frame. This ensures good performances by decoupling position and fine attitude control. Moreover, this concept simplifies in flight operations and improves system safety.
– **Metrology system**: For the deployment and safing phases, a RF localization system based on GPS metrology constitutes the baseline. Each spacecraft is equipped with a Rx/Tx terminal (Receiver/Transmitter) plus a set of antennae and the 3D position is reconstructed from the range and line of sight measurements. This system permits moreover to fulfil the observation phases requirements for the relative longitudinal position knowledge.

For observation phases, the requirement of relative position knowledge is driving the use of a lateral sensor, including a laser source, which measures the line of sight of the beam reflected by a corner cube with a 1″ precision. This sensor is installed on the "detector spacecraft".



Formation guidance is located by choice on the detector spacecraft which directly communicates with the Ground Station. This strategy is still to be confirmed but by this way during routine science phases the formation could be seen by the Ground Segment as a "single satellite". For non nominal phases or for commissioning or positioning, each satellite is independent and communicates directly with the Ground (see figure below):



Then to summarize, 2 communications modes are foreseen:

- Housekeeping mode (TC + HKTM + ranging)
- TMCU download (TC + TM high rate, detector only).

The access to the mirror will be done through the inter satellite link (ISL) in nominal phase. There will be direct access to the mirror (parallel communications) for:

- Cruise & positioning
- Commissioning
- Emergency

Considering all this a list of equipment set can be given for each satellite:

-	*Mirror Spacecraft*
Metrology	standard SST (x2) + 1gyrobloc **- RF terminal + 1 antenna** **- corner cubes or diodes**
Actuation	Reaction wheels (x4) > 1 Nm.s 5 N Hydrazine thrusters (orbit transfer & maintenance; wheels off-loading)

-	*Detector spacecraft*
Metrology	Fine SST(1'') + standard SST or standard SST + precise gyrometers **- RF terminal RF + 3 antennas** **- Lateral sensor**
Actuation	Cold gas thrusters (8 x 2) for attitude & fine position control 1 N Hydrazine thrusters (orbit transfer & maintenance; formation slew)

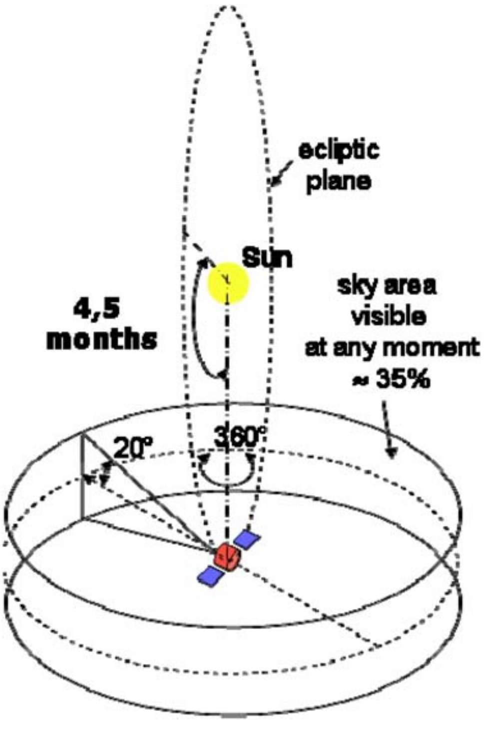
There seems to be no critical technology in metrology (currently in development or R&D studies) and propulsion (already available).

4. Satellites configuration

Two main topics are sizing for the satellites configurations:

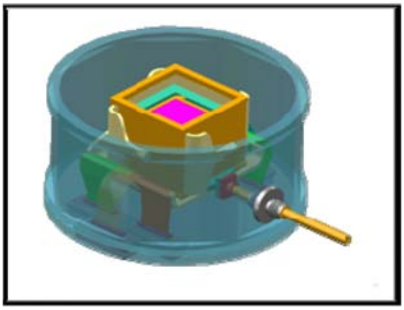
– The observations constraints (as described below),
– The payload protection against the X-ray background thanks to a collimator.

The "distributed telescope" L.O.S. (X-axis on Figure 5) shall be "quasi-orthogonal"(+/−20°) to the Sun direction. This quasi-inertial pointing allows to have fixed solar generators and then simplifies "mirror spacecraft" and "detector spacecraft" architecture. This hypothesis allows access to ∼35% of the entire sky at any given time (excluding short eclipses by the Earth). Thus, the entire sky coverage could be performed within 4, 5 months:



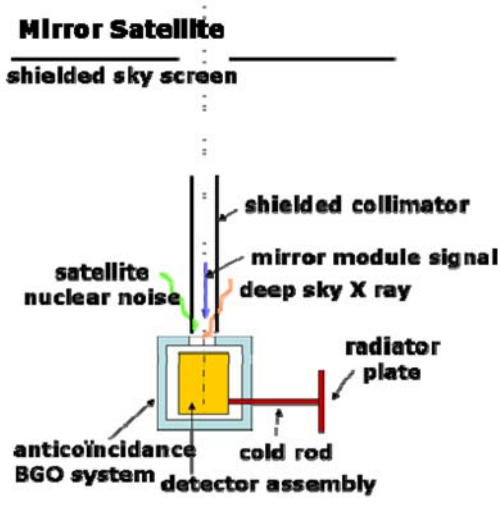
As described in the here after scheme, the detector satellite focal plane shall be protected against the satellite nuclear noise and the deep sky X-ray background, in such a way that it sees only the targeted object signal focalized by the mirror module.

Detection payload



The satellite nuclear noise will be measured and taken into account thanks to an active anticoincidence system which surrounds the detection payload.

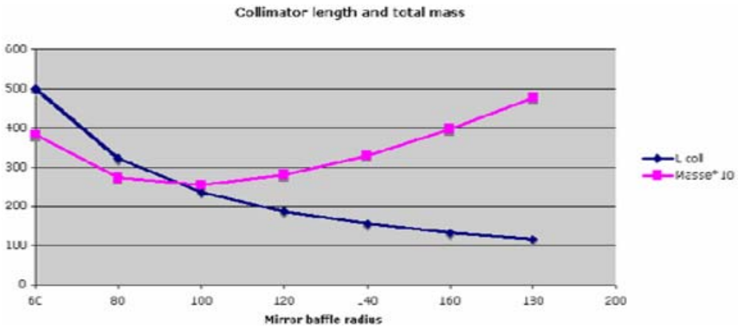
COLLIMATION CONSTRAINTS



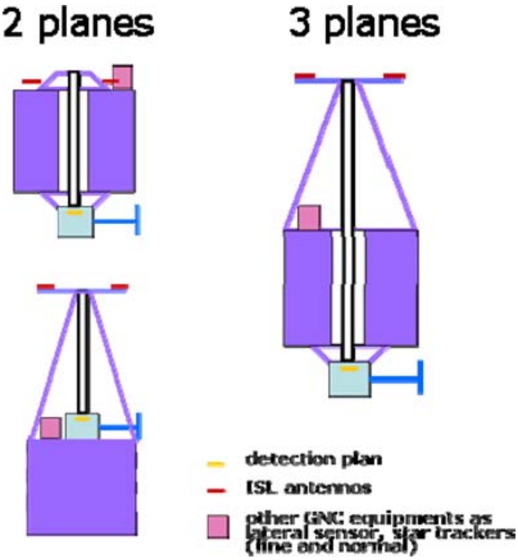
For the deep sky X-ray background a shielded collimator is foreseen. A sharing was to be done on the protections between both satellites. The “mirror satellite” can use a shielded sky screen which blocks the X-rays and the “detector satellite” uses a collimator.

In the hypothesis where no sky screen equips the “mirror satellite”, the collimator is very long and heavy (several meters). The sky screen permits to reduce the collimator lengths and a good balance was found with a collimator of roughly 1,5 meter and a sky screen of about 3 meters diameter.

The following scheme shows that an optimum in mass exists for the sharing of both equipment among the two satellites.

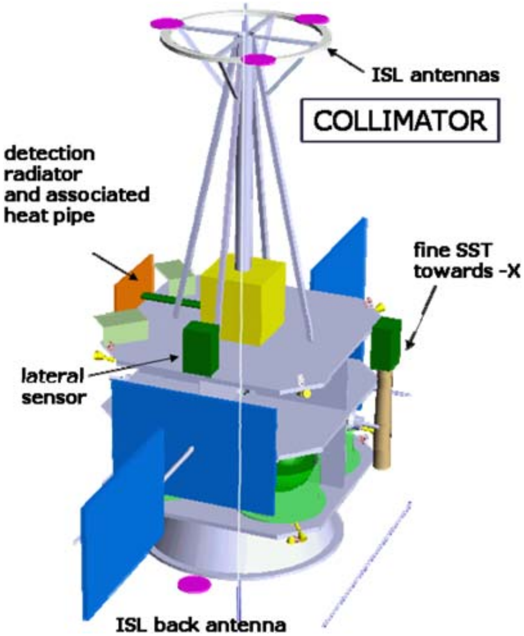


Given that several options can be pursued to implement the detector payload (as shown below)

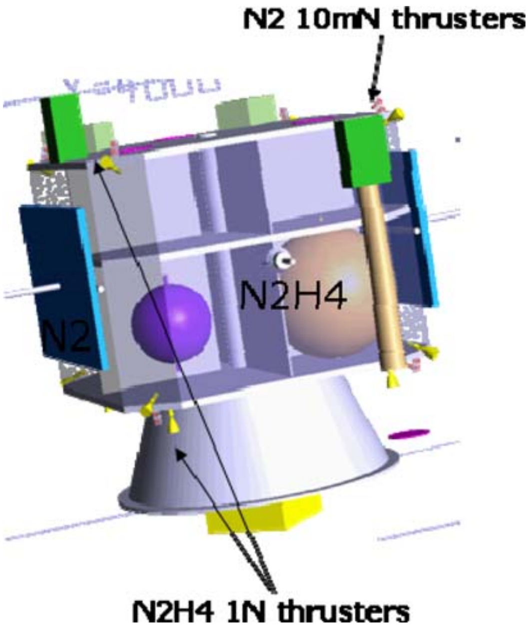


Depending on the one chosen, several reference planes are needed to mount the sensors needed to perform the formation flying and relatively to the payload. To optimize the global pointing accuracy management, GNC sensors and detection plan must be nearby one to each other as much as possible to avoid all possible structural deformations. This is why the solution with 3 planes has been rejected and only two options remained opened.

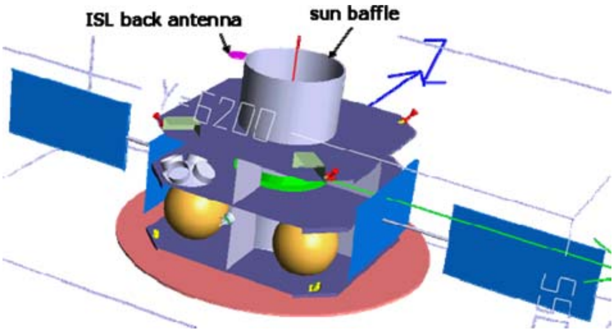
The following figures present the "detector satellite" for a payload mounted on top of it. In that case the interfaces between the payload and the platform seems less intricate. On another point, the satellite is higher and ISL antennas need to be mounted on top of the collimator.



On the following scheme showing details of the propulsion system, the collimator crosses the whole platform.



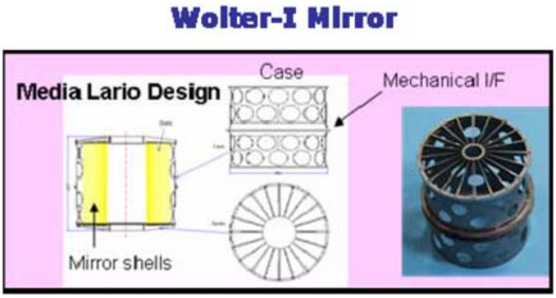
The "mirror satellite" is carrying the mirror module. As it is already naturally quite large, the implementation of the sky screen can be done with a small mass impact (see figure below).



The mirror module itself consists in a set of roughly 100 Wolter-I mirror shells which are embedded and structurally maintained thanks to two spiders one at entrance and one at exit. For this two apertures a very thin kapton film is foreseen to regulate homogeneously the shells thermally and reduces dramatically the power needs.

Such films obviously reduce the X-ray transmission on the low energy side, but it is anticipated that transmissions of at least 20% around 1 keV can be achieved, resulting in negligible impact of the performances for the science objectives of Simbol-X.

An X-baffles at entrance completes the module.



Launch configuration: There are several possibilities for this, the two extremes are:

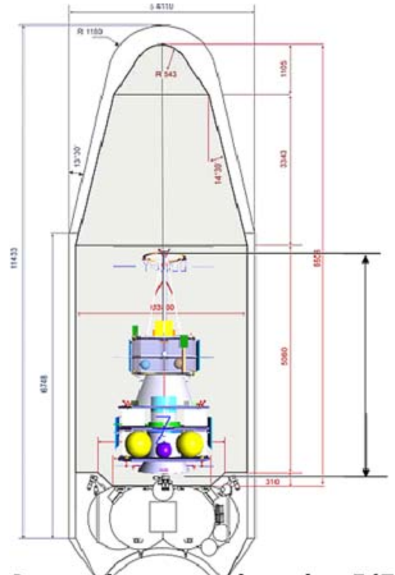
– 2 independent satellites with their own interface and separated by the new Soyouz SYLDA. Then each of them performs individually the positioning on the scientific orbit.
– Two satellites attached during launch, cruise and positioning maneuvers (some weeks).

The 1st solution is the most mass constrained. It has also the advantage to maximize the uncoupling of the satellites development. In addition the interfaces are simpler.

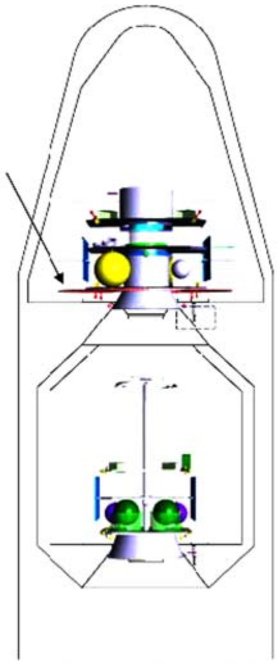
The 2nd solution is the best for mass and permits to minimize the propulsion on the carried satellite thus allowing the reuse of existing platform (mostly structure, thermal & propulsion subsystem). Even if it has mass penalty and if the launch cost would be slightly greater. (we have to note that the dispenser is currently under study by STARSEM for development, independent from the project).

On another hand the carrying satellite structural design is importantly impacted (composite would be 5 meters high !) and the satellite development & interfaces are intricate (which should be the source of over cost).

Finally, we have to consider that the composite will be really a third satellite with its own modes during quite a long time (positioning phase) and this is another complexity increase of the mission.



Composite on one launcher I/F



2 independent I/F with SYLDA

Due to those considerations the most favoured option is the "independent satellites" one. An intermediate solution (if mass were to be a problem), would be to couple the satellites during launch (to avoid the SYLDA) and to separate them at injection by Soyouz.

5. Conclusions

SIMBOL-X is a "permanent observatory" which propose a great number of observations (∼500 per year) and a great variety of these sources. The short duration of the observation times (less than a day in general) authorizes a great scheduling flexibility or a short term redefinition of the objectives.
The substantial spacecraft mass margins allows to envisage several mirror options (with adapted focal between 20 m and 30 m):

– Mirror thickness similar to XMM mirror,
– Thinner mirrors with Platinum coating,
– Mirrors with multilayer

These options shall have to be studied during phase A and the choice confirmed at the end of this one.

The decrease of the transmission at low energy (20% at 1,5 keV) should permit to decrease the necessary resources for the mirror module thermal control (addition of insulating layers at the entrance & exit), it is an important simplification with respect to XMM constraints. The necessity of including a collimator in front of the detector (perturbations due to diffuse X-ray emission), led to deep modifications of the detector satellite configuration and at a lower level of the mirror satellite one. Nevertheless, a broad space for optimization of the satellite configurations exists.

In addition, a fairly detailed definition of the detector payload and a strong technical support by CEA allowed to identify suitably the constraints imposed by this one on the space segment. The result of this is that the mission and space system are, then, strong & robust (detection function).

Acknowledgments We would particularly like to thank Mrs. Paul Duchon & Emmanuel Hinglais (CNES Toulouse) and all the team in CNES and CEA and of the Observatory of Brera which participated to the 2005 phase 0 study for SIMBOL-X.

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