Summary of a proposal submitted for the ESA M4 Mission Programme

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This proposal is the result of the merging of the ASTROMEV and GAMMA-LIGHT groups that submitted two separate LoIs. The proposal is presented on behalf of the ASTROGAM Collaboration by:

M. Tavani (INAF and University of Rome Tor Vergata, Italy)
V. Tatischeff (CSNSM, France)
P. von Ballmoos (IRAP, France)
C. Budtz-Jorgensen (DTU Space, Lyngby, Denmark)
A. Bykov (Ioffe Institute, St. Petersburg, Russia)
L. Hanlon (University College Dublin, Ireland)
D. Hartmann (Clemson University, USA)
M. Hernanz (ICE/CSIC-IEEC, Barcelona, Spain)
J. Isern (ICE/CSIC-IEEC, Barcelona, Spain)
G. Kanbach (MPI, Garching, Germany)
P. Laurent (APC, France)
J. McEnery (NASA, USA)
S. Mereghetti (INAF-IASF, Milano, Italy)
A. Morselli (INFN, Italy)
K. Nakazawa (The University of Tokyo, Japan)
U. Oberlack (Univ. of Mainz, Germany)
R. Walter, (Univ. of Geneva, Switzerland)
A. Zdziarski (NCAC, Poland)
A. Zoglauer (UC Berkeley, USA)

1 INTRODUCTION

ASTROGAM is a space mission dedicated to the observation of the Universe with unprecedented sensitivity in the mostly unexplored energy range 0.3 MeV - 100 MeV (extending up to GeV energies). It has been proposed for the 2014 ESA M4 Call. ASTROGAM is designed to achieve:

1. the best gamma-ray sensitivity (by a factor of 10-30) ever obtained in the range 0.3 MeV - 100 MeV;
2. an exceptional angular resolution for gamma-rays in the range 50 MeV – 1 GeV (0.15 deg at 1 GeV);
3. a very large field of view (2.5 sr);
4. polarization capability for both steady and transient sources;
5. sub-millisecond trigger, fast processing, and alert capability for cosmic and terrestrial transients.

This performance is to be obtained by Silicon detector technology with analog readout, a technique already successfully employed in space. ASTROGAM is based on the AGILE, *Fermi*, PAMELA and AMS heritage, and has mostly readiness > 6 for the space and ground segments.

ASTROGAM will focus on the 0.3-100 MeV energy range. This energy window is unique for studying matter evolution, antimatter generation and very energetic phenomena in compact objects and massive black holes. ASTROGAM's wide field of view opens up the transient sky, rich with the prospect of unanticipated discoveries. Until now, instruments in this energy range lacked the sensitivity for a breakthrough. The ASTROGAM sensitivity will improve that of previous detectors by a factor of 10-30 in the 0.3-30 MeV range, it will explore for the first time the 30-100 MeV range, and will substantially improve the *Fermi* sensitivity in the 100 MeV – 1 GeV range by a combination of excellent angular resolution and optimized pointing strategy. Polarization can be very effectively measured in the MeV range and above.

Definite answers about fundamental questions regarding our Universe can be provided only by high-sensitivity observations in the 0.3-100 MeV range. ASTROGAM is ideally equipped to focus on three main themes:

1. matter and antimatter in our Galaxy and beyond;
2. accelerators in the close and far Universe;
3. fundamental physics and new messengers.

A large number of fundamental issues are still unsolved from previous and current high-energy astrophysics missions (X-ray missions, CGRO, Integral, AGILE and *Fermi*) in the energy range from hard X-rays up to tens or hundreds of 100 GeV. Planned or to-be-developed detectors/telescopes in other wavelengths for the next decade (including SKA, advanced LIGO and VIRGO, CTA, Athena, possibly GAMMA-400) will not be able to significantly address the ASTROGAM science drivers. On the other hand, working in synergy with the aforementioned instruments, ASTROGAM will be absolutely crucial and unique in the next decade.

The 0.3-30 MeV energy range is notoriously difficult to study. It requires an efficient instrument working in the "Compton regime" with an excellent background subtraction: since COMPTEL, no space instrument obtained extra-solar gamma-ray data in the 2-30 MeV range. ASTROGAM resolves the technical issues regarding on-board Compton event detection and background subtraction by an optimal instrument configuration based on Silicon technology, state-of-the-art analog readout, and efficient data acquisition.

ASTROGAM will open a new window of opportunity for discovery in the high-energy Universe. It will work in full synergy with space and ground detectors including radio and optical telescopes, TeV instruments, gravitational wave detectors and neutrino experiments. ASTROGAM data, to be distributed to the community through a Guest Observer Programme, will have a huge impact on a broad variety of topics including baryogenesis and fundamental physics, nucleosynthesis and cosmic rays, compact objects, AGNs, GRBs.

2 SCIENCE CASE

ASTROGAM will be optimized for the 0.3 MeV – 100 MeV energy range, extending up to GeV energies. It combines for the first time excellent angular resolution with optimal detection capability in both the Compton scattering and the pair production regimes. Furthermore, it opens up an entirely new observational window on the high-energy universe as the first gamma-ray telescope with fully characterized polarimetric capability. ASTROGAM will investigate the Universe in the mostly unexplored energy domain 0.3-100 MeV. The mission science drivers can be grouped into three main themes:

- **Theme-1: Matter and antimatter in our Galaxy and beyond**
- **Theme-2: Accelerators in the nearby and distant Universe**
- **Theme-3: Fundamental Physics and new messengers**

ASTROGAM data will be crucial to answer as yet unsolved basic questions in high-energy astrophysics and fundamental physics, with important contributions to solar and terrestrial physics. ASTROGAM will resolve a large number of outstanding theoretical issues regarding the most energetic processes of our Universe. We summarize here the main lines of investigation that will be addressed by the mission.

- **Theme-1: Matter and antimatter in our Galaxy and beyond**

    - *How is nuclear enrichment in our Galaxy related to SN activity and star formation? What is the physics of Type Ia and core-collapse supernovae?*

        ASTROGAM will study with unprecedented sensitivity radioactive nuclei in our Galaxy with an effective area for line emission in the MeV range that represents a significant advance over previous missions. ASTROGAM will observe in the MeV range star forming regions, massive stars, supernovae, AGBs, Galactic novae together with their occasional GeV emission. The recent detection of the 847 keV line from the Type Ia SN 2014J in the starburst galaxy M82 by INTEGRAL represents the first such measurement and raises a series of questions regarding the explosion mechanism and the scenario of Type Ia SNe. ASTROGAM is expected to detect several Type Ia SNe in the nearby universe in 3.5 years of operations. Optimal sensitivity to nearby core-collapse SNe will also be achieved.

    - *What is the cosmic-ray density in our Galaxy? What is the role of sources vs. propagation? Are SNRs responsible for cosmic-ray acceleration up to PeV energies?*

        The MeV-GeV mapping of our Galaxy with unprecedented angular resolution and exposure will allow a direct comparison with the star forming regions and molecular clouds traced by multi-frequency observations. ASTROGAM will finally resolve the MeV-GeV emission profile for several crucial young and middle-aged SNRs, with the capability of detecting the pion spectral feature near 100 MeV. ASTROGAM's energy band in conjunction with TeV data (from CTA and other experiments) will determine definite hadronic signatures for the identification of the origin and propagation of Galactic cosmic rays.

    - *What is the structure of the Galactic Center in the MeV - GeV range? How is the central black hole powering the surrounding regions? Is the engine powering mass outflows (e.g. Fermi bubbles)? What is the role of compact objects in the region? What is the source of the puzzling antimatter in the Galactic Center?*

        ASTROGAM's excellent angular resolution and potentially very large exposure of the Galactic Center will resolve the region much improving our knowledge of MeV-GeV emitters. In addition, ASTROGAM's sensitivity at 511 keV, will provide an unprecedented view of the Galactic plane and Center regions and can resolve source and diffuse contributions to the annihilation line emission.

- **Theme-2: Accelerators in the nearby & distant Universe**

  - *Polarization studies.*

    The exquisite polarization capability of ASTROGAM will be a key tool in addressing the scientific questions posed in this Theme. ASTROGAM will be capable of detecting polarization in the MeV range and above 100 MeV. This information will be crucial for a variety of investigations including the study of compact objects, the magnetic field structure in jets and the emission mechanism during the different phases of GRBs. Polarization will also be crucial to obtain information on the existence of UHECRs in extragalactic jets.

  - *How are relativistic jets launched? How does the disk/jet transition occur? How and where is the high-energy emission produced in jets?*

    The simultaneous exploration of the 1-10 MeV and 10 MeV - GeV ranges with ASTROGAM's sensitivity and angular resolution will allow to accurately probe the transition between accretion disks and relativistic jets in microquasars and AGNs for the first time. ASTROGAM will provide definitive data to discriminate between hadronic and leptonic jet emission mechanisms.

  - *Are new types of acceleration mechanisms at work in Galactic and extra-galactic sources? Is magnetic field reconnection at work in high-energy sources?*

    A wealth of recent data on Galactic and extragalactic sources suggest the existence of particle acceleration mechanisms more efficient than Fermi-like diffusive processes. ASTROGAM will investigate the signatures of magnetic field reconnection at the crucial transition between quasi-thermalized and non-thermal accelerated distributions. The puzzling gamma-ray flares from the Crab Nebula and similar rapid phenomena in extra-galactic jets require non-ideal MHD mechanisms in need of crucial data in the MeV range. Studies of rotationally-powered pulsars, magnetars, and pulsar wind nebulae will also greatly benefit from data collected in the 1-100 MeV range.

  - *How is the MeV extragalactic background produced? Are high-redshift AGNs a significant source population at MeV energies? Where do ultra-high-energy cosmic rays (UHECRs) originate? Can baryon asymmetry at cosmological distances be detected?*

    One of the main scientific objectives of ASTROGAM is improving our knowledge of the extragalactic background at MeV energies. We will explore for the first time the most massive objects in the far universe with relativistic jets emitting in the MeV range, and will assess their contribution to the extragalactic cosmic background. Evidence for the presence of UHECRs can be obtained from MeV-polarization measurements of AGN jets. Deep ASTROGAM pointings of extragalactic fields can reveal pion emission redshifted to MeV energies resulting from nucleon-antinucleon annihilations at the boundaries of matter-antimatter cosmological regions.

  - *Are relativistic jets in gamma-ray bursts optically thick?*

    Relativistic jets are found in a variety of astrophysical objects and there is evidence that in some cases the jets are optically thick in the launch region. The foremost examples are the ultra-relativistic jets responsible for producing gamma-ray bursts (GRBs), which are optically thick up to distances several order of magnitude larger than the jet base. As the jets expand and become transparent, they release internally trapped photons as photospheric emission. Such a mechanism produces a distinctive polarization signature. ASTROGAM's broad energy range and polarization capability will render it uniquely capable of answering this fundamental and long-standing question in GRB astrophysics.

  - *What is the physics of acceleration and transient nuclear spectroscopy in solar flares?*

    Continuum and line sensitivity in the 0.1-100 MeV energy range will provide a crucial diagnostic for acceleration physics in solar flares with simultaneous information at GeV energies. MeV-polarization will add important information on the in-situ magnetic properties.

- *How are Terrestrial Gamma Ray Flashes (TGFs) generated? What is their high-energy spectrum and maximum energy? What is their impact on the Earth environment and connection with global climate?*

  ASTROGAM data will be very important for terrestrial studies. The instrument will detect thousands of TGFs within its 3.5 year lifetime. Atmospheric lightning and thunderstorms can produce particle acceleration in TGFs up to energies of 100 MeV. The optimal sensitivity of ASTROGAM in the MeV-GeV range will contribute towards understanding the physics and many implications of this puzzling atmospheric phenomenon.

- **Theme-3: Fundamental Physics and new messengers.**

  - *What is the nature of Dark Matter?*

    Resolving the inner region of our Galaxy at high-energies remains one of the outstanding problems of modern astrophysics. ASTROGAM will add the as yet unexplored MeV – GeV range to Dark Matter investigations with excellent angular resolution and exposure. Models will be tested in a spectral range not currently studied.

  - *Are MeV-GeV sources related to the emission of gravitational waves? Are MeV-GeV sources related to the emission of neutrinos? What is the connection of gamma-ray bursts (GRBs) to gravitational collapse?*

    ASTROGAM will operate in the presence of next-generation detectors of gravitational waves and neutrinos. The multi-messenger nature of the emission will provide unique diagnostics for the study of gravitational collapse, particle acceleration and emission at the highest energies. Among the most interesting sources, GRBs will be copiously detected by ASTROGAM. Simultaneous data in the MeV and GeV ranges fill the transition between different emission mechanisms for the prompt and afterglow/delayed emission phases. The aftermath of gravitational collapse can produce different patterns of emission depending on physical conditions and the nature of the compact source and environment. The MeV-GeV energy range can be strongly coupled with gravitational waves and/or hadronic acceleration and interaction producing neutrinos. The excellent MeV-polarization capability of ASTROGAM for GRBs will add uniquely important information on the nature of the emission and on its connection to the gravitational collapse and its aftermath.

Besides these three main themes, ASTROGAM will be ideal for the study of high-energy sources in general, both Galactic and extragalactic, including pulsars and pulsar wind nebulae, accreting neutron stars and black holes, SNRs, soft gamma-ray repeaters, magnetars, GRBs, AGNs. A dedicated program for a very fast detection of transients will be implemented with emphasis on Target of Opportunity observations.

3 THE SCIENTIFIC INSTRUMENT

3.1 Measurement principle and payload overview

Interactions of photons with matter in the ASTROGAM energy range is dominated by Compton scattering from 0.1 MeV up to about 15 MeV in silicon, and by electron-positron pair production in the field of a target nucleus at higher energies. ASTROGAM maximizes its efficiency for imaging and spectroscopy of energetic gamma rays by using both processes. Figure 3-1 shows representative topologies for Compton and pair events.

For Compton events, point interactions of the gamma ray in tracker and calorimeter produce spatially resolved energy deposits, which have to be reconstructed in sequence using the redundant kinematic information from multiple interactions. Once the sequence is established, two sets of information are used for imaging: the total energy and the energy deposit in the first interaction measure the first Compton scatter angle. The combination with the direction of the scattered photon from the vertices of the first and second interactions generates a ring on the sky containing the source direction. Multiple photons from the same source enable a full deconvolution of the image, using probabilistic techniques. For energetic Compton scatters (above ~1 MeV), measurement of the track of the scattered electron becomes possible, resulting in a reduction of the event ring to an arc, hence further improving event reconstruction. Compton scattering depends on polarization of the incoming photon, hence careful statistical analysis of the photons for a strong (e.g., transient) source yields a measurement of the degree of polarization of its high-energy emission.

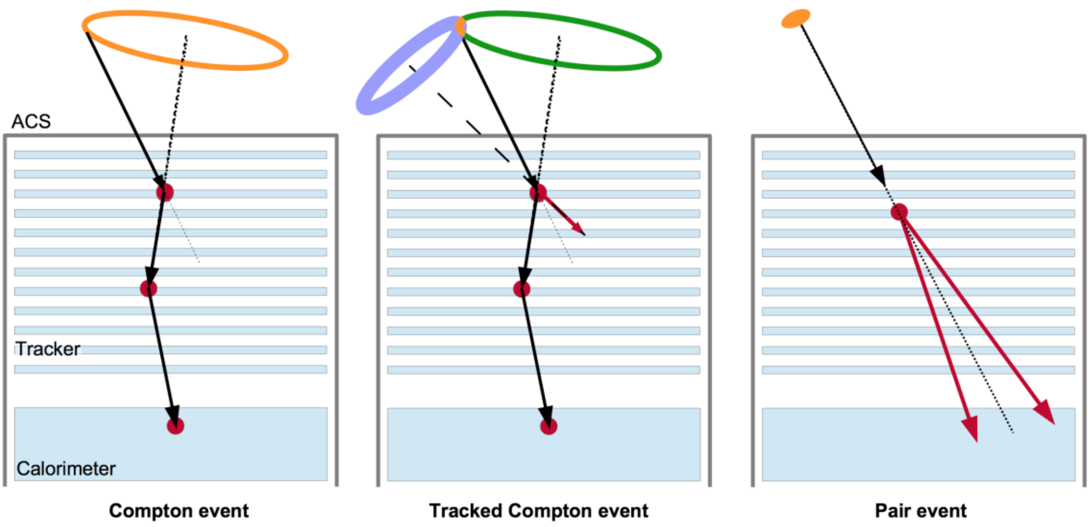


Figure 3-1 *Representative event topologies for Compton events without (left) and with electron tracking (center) and for a pair event (right panel).*

Pair events produce two main tracks from the electron and positron at small opening angle. Tracking of the initial opening angle and the plane spanned by electron and positron enables direct back-projection of the source. Multiple scattering in the tracker material (or any intervening passive materials) leads to broadening of the tracks and limits the angular resolution at low energies. The nuclear recoil taking up an unmeasured momentum results in a small uncertainty, usually negligible compared to instrumental effects. The energy of the gamma ray is measured using the calorimeter. Polarization information in the pair domain is given by the azimuthal orientation of the electron-positron plane.

The ASTROGAM payload is shown in Figure 3-2. It consists of three main detectors:

- A **Silicon Tracker** in which the cosmic gamma rays undergo a first Compton scattering or a pair conversion, based on the technology of double sided Si strip detectors to measure the energy and the 3D position of each interaction with an excellent energy and spatial resolution;
- A 3D-imaging **Calorimeter** to absorb and measure the energy of the secondary particles, which is made of an assembly of small scintillation crystals (12,544 CsI (Tl) bars of 5×5×50 mm^3) readout by silicon drift photodetectors to achieve the required energy resolution (4.5% at 662 keV);
- An **Anticoincidence** (AC) system to veto the prompt-reaction background induced by trapped, solar, or cosmic-ray charged particles, design with plastic scintillators covering the instrument to detect single charged relativistic particles with an efficiency exceeding 99.99%.

The payload is completed by a Data Handling and Power Supply Units located below the Calorimeter inside the platform together with the back-end electronics. The PDHU is in charge of the payload internal control, the scientific data processing, the operative mode management, the on-board time management, and the telemetry and telecommand management. The total payload mass and power budget are 300 kg and 524 W, respectively.

Especially for the Compton mode at low energies, but also more broadly over the entire energy range covered by ASTROGAM, it is important to keep the amount of passive materials on the top and at the sides of the detector to a minimum, to reduce background production in the field of view and to optimize angular and energy resolutions. In addition, the passive materials between the Tracker layers, and between the Tracker and the Calorimeter must be minimized for best performance. This enters the considerations for both the mechanical design, weighing minimal mass vs. mechanical stiffness, and the electronics layout, where a balance must be found between signal amplification and analog/digital conversion in the front-end electronics (FEE) close to the detector, and trigger and event selection decisions further away, ideally below the telescope in back-end electronics and on-board computers. The instrument harness is also optimized in this regard.

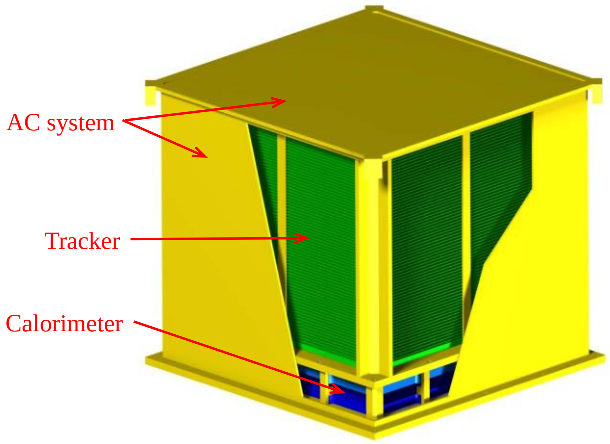


Figure 3-2 *Overview of the ASTROGAM payload showing the Silicon Tracker, the Calorimeter and the Anticoincidence system.*

3.1.1 Silicon Tracker

The gamma ray Tracker is the heart of the ASTROGAM payload. It is based on the silicon strip detector technology widely employed in medical imaging and particle physics experiments (e.g., ATLAS and CMS at LHC), and already applied to the detection of gamma rays in space by the AGILE and *Fermi* missions. The ASTROGAM Tracker will employ double sided strip detectors (DSSDs) to work also as a Compton telescope. The Tracker configuration is based on 70 planes of Silicon DSSDs; each plane is 60 x 60 cm^2 large, and each detector is made of 9.5 x 9.5 cm^2 Silicon tiles.

3.1.2 Calorimeter

The ASTROGAM Calorimeter is a pixelated detector made of a high-Z scintillation material – Thallium activated Cesium Iodide – for an efficient absorption of Compton scattered gamma rays and electron-positron pairs. It consists of an array of 12,544 parallelepiped bars of CsI(Tl) of 5×5×50 mm^3 dimension, read by silicon drift detectors at both ends. The Calorimeter thickness – 5 cm of CsI(Tl) – makes it a 2.7 radiation-length detector having an absorption probability of a 1-MeV photon of 72%.

3.1.3 Anticoincidence

The ASTROGAM Anticoincidence (AC) system is made of segmented panels of plastic scintillators covering the top and four lateral sides of the instrument, with three plastic tiles per side. The top plastic scintillators are 6 mm thick, whereas the lateral panels are 5 mm thick. All scintillator tiles are coupled to silicon photomultipliers (SiPM) by optical fibers. The architecture of the AC detector is fully derived by the successful design of the AGILE and *Fermi*/LAT AC systems. The AC particle background rejection is designed to achieve a relativistic charged particle detection inefficiency lower than 10^{-4} (a standard value already realized in current space experiments).

3.1.4 Data Handling

The ASTROGAM payload is completed by a Payload Data Handling Unit (PDHU) and a Power Supply Unit (PSU). The PDHU is in charge of carrying out the following principal tasks: (i) payload internal control; (ii) scientific data processing; (iii) operative modes management; (iv) on board time management; (v) Telemetry and Telecommand management. The main functions related to the scientific data processing will be: (i) the BEEs interfacing through dedicated links to acquire the scientific data; (ii) the real-time software processing of the collected Silicon Tracker, Anticoincidence and Calorimeter scientific data aimed at rejecting background events; (iii) the formatting of the selected good events into telemetry packets.

3.1.5 Trigger logic and data flow architecture

The ASTROGAM on-board scientific data processing will be composed of two main trigger pipelines, the gamma ray acquisition mode and the Calorimeter Burst search. The simultaneous data set provided by the Silicon Tracker, the Calorimeter and the AC constitutes the basis for the gamma-ray detection and processing. The gamma-rays trigger logic will be structured on two main levels: Level-1 (fast: 5-10 μs logic, hardware); and Level-2 (asynchronous, 50 μs processing, software).

3.2 Performance assessment

The scientific performances of the ASTROGAM instrument were evaluated by detailed numerical simulations, using two different sets of software tools: MEGAlib and Bogemms. The MEGAlib package was originally developed for analysis of simulation and calibration data related to the Compton scattering and pair creation telescope MEGA. It has then been successfully applied to a wide variety of hard X-ray/gamma-telescopes on ground and in space, such as COMPTEL, NCT and NuSTAR. MEGAlib contains a geometry and detector description tool for the detailed modeling of different detector types and characteristics, and provides a Monte Carlo simulation program based on Geant4, together with specialized Compton event reconstruction algorithms.

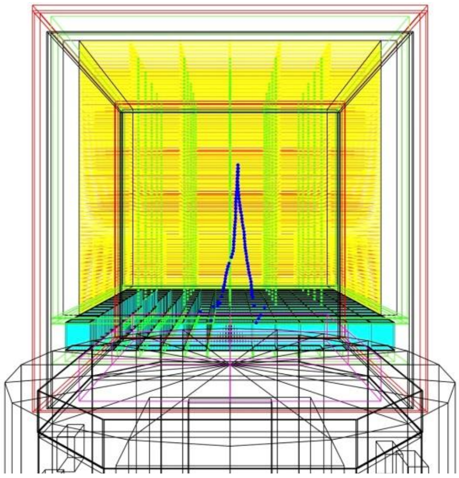


Figure 3-35 *Geant4/MEGAlib mass model of the ASTROGAM telescope on the platform, with a simulated pair event produced by a 30-MeV photon.*

Bogemms is a Geant4-based simulation tool specialized on the reconstruction of pair creation events. It was initially developed to reproduce AGILE data accumulated during the pre-launch testing and post-launch commissioning phases and was then validated from in-flight data from the AGILE gamma-ray imager detector. The results of Bogemms and MEGAlib were crosschecked in the gamma-ray energy range between 10 and 100 MeV.

Figure 3.5 shows the mass model of ASTROGAM used for these simulations. An accurate mass model that includes passive material in the detector and its surroundings, true energy thresholds and energy and position measurement accuracy, as well as a roughly accurate S/C bus mass and position are crucial to the modeling. In particular, care was taken to include all passive materials close to the Si and CsI(Tl) detectors.

All these components were carefully modeled using the MEGAlib environment tools. In the pair domain above 10 MeV, the background is mainly induced by fast particles (mainly leptons) impinging the S/C, as well as by the cosmic diffuse radiation and the atmospheric gamma-ray emission.

3.2.1 Angular and energy resolutions

ASTROGAM will achieve an unprecedented point spread function (PSF) above 50 MeV and a very good angular resolution in the Compton scattering domain as well, e.g. better than that of COMPTEL by a factor of 4 at 5 MeV (Figure 3.7). In the latter regime, the $\delta\theta$ values reported in Figure 3.7 are the FWHM of the optimal ARM obtained after selection on the reconstructed energy ($\pm 2\sigma$ on the full-energy peak) and the Compton scatter angle (e.g. ϕ between 0° and 40° at 500 keV). In the pair production domain, the ASTROGAM Tracker properties are ideal for a very accurate determination of the event topology, which include the vertex determination and the particle tracking. The absence of heavy converters and a ultra-light mechanical structure makes very probable the gamma-ray conversion in the Silicon detectors. At this point, the PSF above 30 MeV is dictated by the combination of multiple scattering in Silicon detectors and the tracking reconstruction algorithm. The ASTROGAM PSF above 30 MeV is therefore expected and simulated to be substantially better than those of Fermi and AGILE, as represented in Figure 3-5.

The right panel of Figure 3-5 shows the ASTROGAM spectral resolution in the Compton domain. Above 30 MeV the spectral energy resolution is expected to be within 20-30 %.

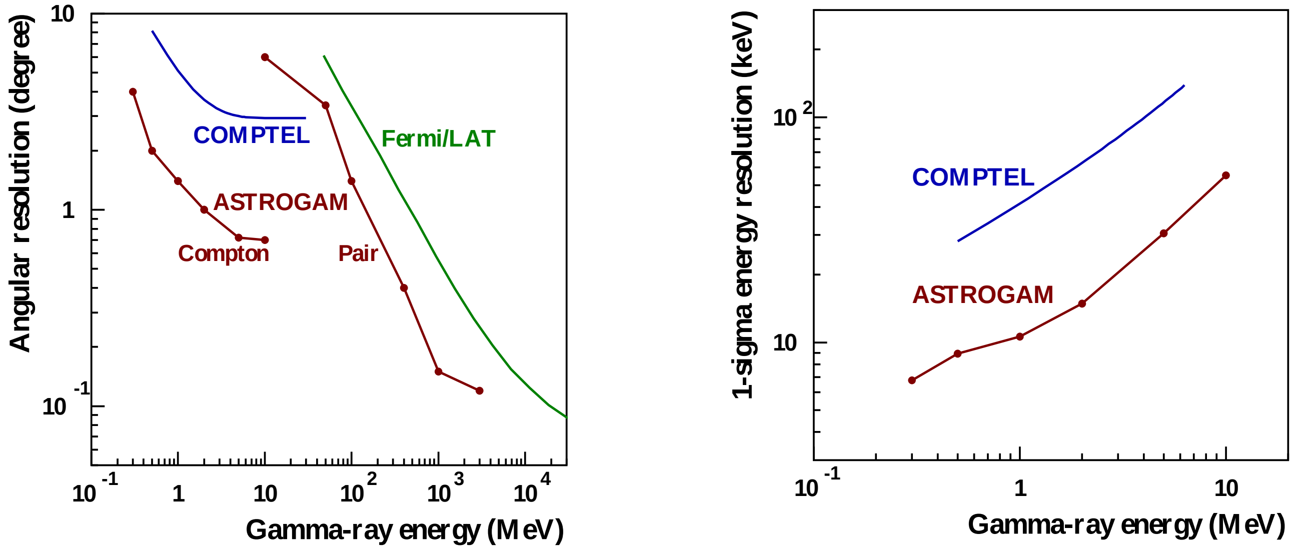
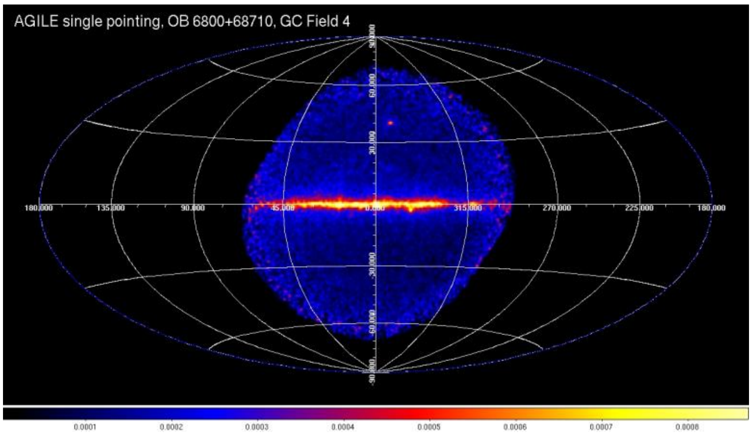


Figure 3-5 - *Left panel* – *ASTROGAM on-axis angular resolution compared to that of COMPTEL and Fermi/LAT. In the Compton domain, the presented performance of ASTROGAM and COMPTEL is the FWHM of the angular resolution measure (ARM). In the pair domain, the point spread function (PSF) is the 68% containment radius. The Fermi/LAT PSF is from the Pass 7 data.* ***Right panel*** – *1σ energy resolution of COMPTEL and ASTROGAM in the Compton domain after event reconstruction and selection on the ARM.*

3.2.2 Field of View



The ASTROGAM field of view (FoV) was evaluated from detailed simulations of the incident angle dependence of the sensitivity. It amounts to 41° HWHM at 1 MeV, with a fraction of sky coverage in zenith pointing mode of 21%, corresponding to Ω = 2.6 sr. In the pair production domain, the field-of-view assessment is also based on in-flight data from the AGILE and Fermi-LAT gamma-ray imager detectors. The consolidated FoV is 2.5 sr, but ASTROGAM characteristics (size, Si plane spacing, overall geometry) make possible an even larger FoV.

***Figure 3-6** shows the FoV of a 1-month AGILE pointing of the Galactic Center region. The ASTROGAM FoV will be similar or larger than that of AGILE and Fermi-LAT, 2.5 sr.*

3.2.3 Effective area and continuum sensitivity

Table 3.1 compares the effective area of ASTROGAM with that of INTEGRAL/SPI, CGRO/COMPTEL, Fermi/LAT and AGILE. Below 10 MeV, the reported values correspond to the detection of full-energy gamma rays from a monochromatic source on axis. We see that the effective area of ASTROGAM at low energies will be about two times larger than that of SPI and 7.5 times larger than that of COMPTEL (at 1 MeV). However, the gain in sensitivity of ASTROGAM will be much higher (see below), thanks to its unprecedented background rejection capability.

Table 3-1 *Effective area (in cm²) for the detection of a point source on axis.*

E (MeV)	ASTROGAM	SPI	COMPTEL	Fermi/LAT front	AGILE
0.3	207	110	-	-	-
1	119	65	16	-	-
30	302	-	26	50	50
100	514	-	-	1100	380
1000	635	-	-	4000	510

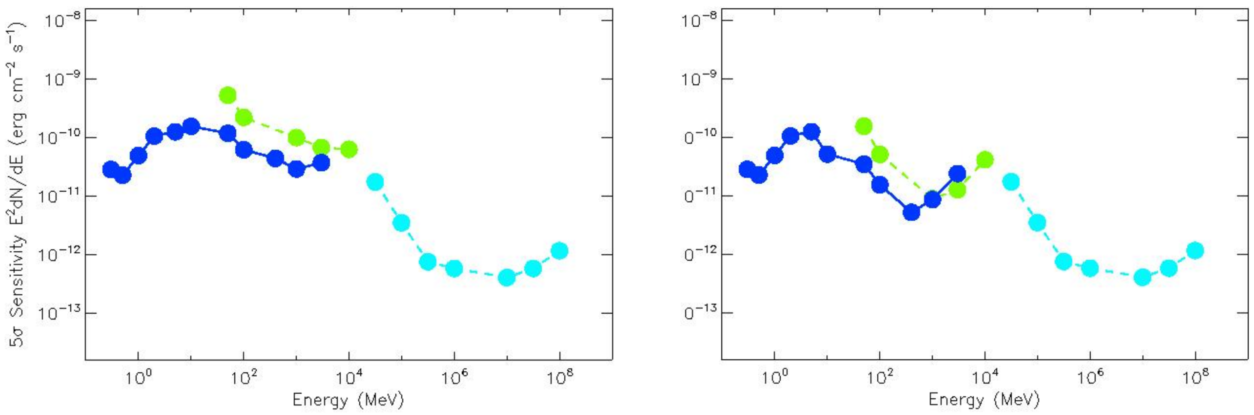


Figure 3-7 *- ASTROGAM source 5-σ sensitivity in pointing mode (dark blue curves) for a 1-month observation of a source at 30 degrees off-axis in the inner Galaxy (left panel) and for a high-latitude source (right panel). Also shown are the Fermi-front-LAT Pass7V_6 sensitivity (green curves) and CTA sensitivity for 15 hr integration (cyan curves). Sensitivies in the MeV up to nearly the GeV energies are background dominated. At higher energies, sensitivities are photon limited: here we show the limit sensitivities assuming at least N=5 high-energy photons detected within the 99% confidence radius. ASTROGAM is assumed to be pointing in a LEO orbit with an overall exposure efficiency of 0.6 similar to AGILE's (checked with real data). Fermi-LAT is assumed to be in sky-scanning mode with an overall exposure efficiency per single source of 0.16 (as checked with real data).*

In Figure 3-7 we compare the ASTROGAM source sensitivity in pointing mode for a 1-month integration in the inner Galaxy and in an extragalactic field. Also shown are the sensitivities of Fermi-front-LAT in sky scanning mode (the standard mode for Fermi) and for CTA (15 hr integration). ASTROGAM will have a better sensitivity than INTEGRAL and COMPTEL in the range 0.3-20 MeV by a factor of 10-30. A better sensitivity compared to Fermi up to 1 GeV is obtainable by a combination of pointing strategy and much improved angular resolution.

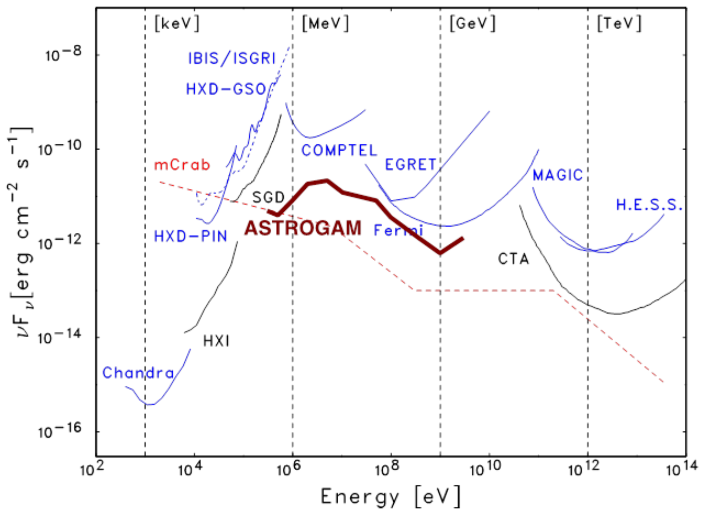


Figure 3-8 *- Point source continuum sensitivity of different X and γ-ray instruments (adapted from Figure 1 in Takahashi et al. 2013). The curves for Chandra/ACIS-S, Suzaku/HXD (PIN, GSO), INTEGRAL/IBIS and ASTRO-H (HXI, SGD) are given for an observing time T_{obs} = 100 ks. The COMPTEL and EGRET sensitivities are given for the observing time accumulated during the whole duration of the CGRO mission (T_{obs} ~ 9 years). The Fermi/LAT sensitivity is for a high Galactic latitude source and T_{obs} = 1 year (Atwood et al. 2009). For MAGIC (Aleksic et al. 2012), H.E.S.S. (Aharonian et al. 2006) and CTA (Actis et al. 2011) the sensitivities are given for T_{obs} = 50 hours. The ASTROGAM sensitivity is for an effective exposure of 1 year of a high Galactic latitude source (see text). Sensitivities above 30 MeV are given at the 5-sigma confidence level, whereas those below 10 MeV (30 MeV for COMPTEL) are at 3-sigma.*

Figure 3.8 shows the ASTROGAM continuum sensitivity (at 3σ below 10 MeV and 5σ above, assuming a spectral bin width $\Delta E = E$) for a 1-year effective exposure of a high Galactic latitude source, on a plot from Takahashi et al. (2013) compiling the sensitivity of various X and gamma-ray instruments. Such an effective exposure will be reached for broad regions of the sky after ~3 years of operation, given the very large field of view of the instrument (see Fig. 3.8). We see that ASTROGAM will provide an important leap in sensitivity in a wide energy band, from about 300 keV to 100 MeV. At higher energies, ASTROGAM will also provide a new vision of the gamma-ray sky thanks to its unprecedented angular resolution.

3.2.4 Line sensitivity

Table 3-2 shows the ASTROGAM 3σ sensitivity for the detection of key gamma-ray lines from pointing observations, together with the sensitivity of the INTEGRAL Spectrometer (SPI). The latter was obtained from the INTEGRAL Observation Time Estimator assuming 5×5 dithering observations. The reported line widths are from SPI observations for the 511 and 847 keV lines (SN 2014J), and from theoretical predictions for the other lines. Noteworthy, the neutron capture line from accreting neutron stars can be significantly redshifted and broadened (FWHM between 10 and 100 keV) depending on the geometry of the mass accretion.

Table 3-2: *ASTROGAM line sensitivity (3σ in 10^6 s) compared to that of INTEGRAL/SPI.*

E (keV)	FWHM (keV)	Origin	SPI sensitivity (ph cm^{-2} s^{-1})	ASTROGAM sens. (ph cm^{-2} s^{-1})
511	1.3	Narrow line component of the e+/e- annihilation radiation from the GC region	5.2×10^{-5}	8.0×10^{-6}
847	35	^{56}Co line from thermonuclear SN	2.3×10^{-4}	8.7×10^{-6}
1157	15	^{44}Ti line from core-collapse SN remnants	9.6×10^{-5}	8.4×10^{-6}
1275	20	^{22}Na line from classical novae of the ONe type	1.1×10^{-4}	1.1×10^{-5}
2223	20	Neutron capture line from accreting neutron stars	1.1×10^{-4}	1.2×10^{-5}

ASTROGAM will achieve a major gain in line sensitivity compared to SPI, e.g., by factors of 26 and 11 for the 847 and 1157 keV lines, respectively, which will enable the detection of several SNe Ia during the 3.5 years of mission duration, as well as a significant number of young, ^{44}Ti-rich SN remnants.

3.2.5 Polarization response

Both Compton scattering and pair creation partially preserve the polarization information of incident, linearly polarized photons. In a Compton telescope, the polarization signature (polarization angle and fraction) is reflected in the probability distribution of the azimuthal scatter angle. In the pair domain, the polarization information is given by the azimuthal orientation of the electron-positron plane. *ASTROGAM will be able to perform unprecedented polarization measurements throughout its bandwidth*, thanks to the light mechanical structure of the Si Tracker, which is devoid of any heavy absorber in the detection volume, and to the fine 3D position resolution of the Tracker and the Calorimeter.

Polarized radiation is generally expected from sources in which the phase space distribution of the radiating particle population is restricted by external forces. In ordered magnetic fields this leads to polarized synchrotron or curvature radiation; in beams and jets it can lead to polarized bremsstrahlung or inverse Compton emission; non-isotropic scattering of photons will also polarize the emissions. Polarization therefore allows unique insight into the geometry of high-energy sources. ASTROGAM has a great capability of detecting polarization in the MeV range as well as near 100 MeV employing the characteristic response of Compton scattering and pair creation to polarized gamma photons. Figure 3.9 shows the polarization detection capability of ASTROGAM.

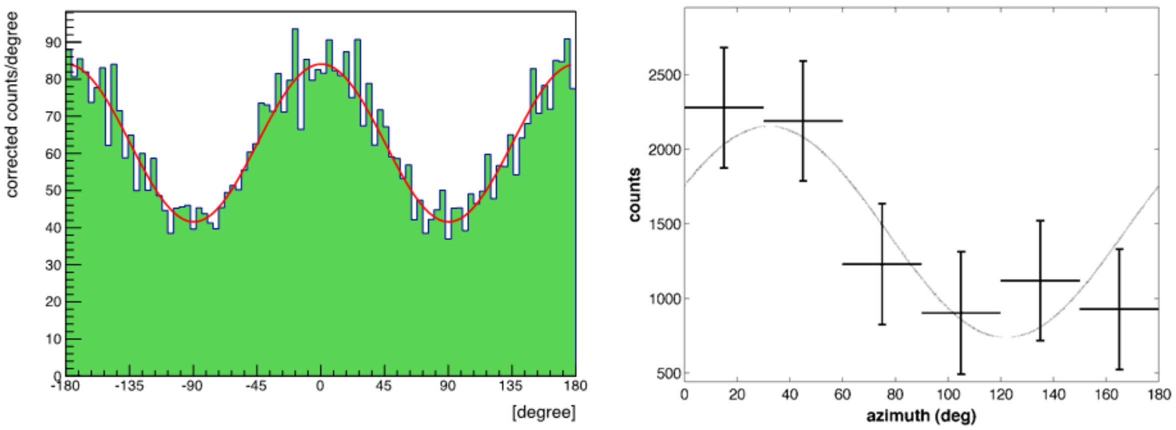


***Figure 3.9 - Left panel** – ASTROGAM polarization response (polarigramme) in the 0.2 – 2 MeV range for a 100% polarized, 10 mCrab-like source observed on axis for 10^6 s. The corresponding modulation is μ_{100} = 0.34. **Right panel** – Polarigramme measured with INTEGRAL/IBIS (1σ error bars) for the Crab emission between 200 and 800 keV in the off-pulse and bridge phase intervals (Forot et al. 2008). The measured polarization fraction is >88%.*

The left panel of Figure 3.9 shows an example of a simulated polarigramme for a 100% polarized emission from a 10 mCrab-like source. The comparison with the Crab polarization data recorded by the INTEGRAL/IBIS telescope (right panel) clearly illustrates the quantum leap in polarization capability that ASTROGAM will perform. Thus, ASTROGAM will be able to achieve a 3σ Minimum Detectable Polarization (MDP) as low as 1.1% for a Crab-like source in 1 Ms (statistical uncertainties only). After one year of effective exposure of the Galactic center region, the achievable MDP for a 10 mCrab source will be 17%. ASTROGAM will thus enable the study of the polarimetric properties of many black hole systems in the Galaxy. In addition, ASTROGAM will detect the polarization of several dozen extragalactic GRBs and AGNs.

4 MISSION CONFIGURATION

4.1 Orbit and launcher

The ideal ASTROGAM orbit is an equatorial LEO of altitude 550-600 km. Particle background properties are ideal for this orbit as already determined by the AGILE mission (which has a LEO orbit of altitude 520-550 km and 2.5 degree inclination with respect with the equator). An equatorial orbit (required to have an inclination of < 2.5 deg, and eccentricity $e < 0.01$) will make use of the ESA ground station at Kourou as well as the possible use of the ASI Malindi station in Kenya. The foreseen launcher for ASTROGAM is VEGA.

4.2 Spacecraft

The ASTROGAM system is composed by a satellite in a Low Earth Orbit and a ground segment that includes the stations of Kourou (French Guiana) and Malindi (Kenya) (in charge of performing the spacecraft control, monitoring, and the acquisition of scientific data). The ASTROGAM spacecraft has the purpose to observe the sky according to a predefined pointing plan uploaded from ground. Different pointing profiles can be selected in order to observe selected sky regions or to perform a scanning that, thanks to the wide P/L field of view, can cover almost the whole sky at each orbit.

The spacecraft platform is made of a structure that mechanically supports the ASTROGAM instrument and hosts internally the payload electronic units and all the platform subsystems. Deployable and steerable solar panels are required to minimize the satellite envelope during launch and to allow the maximum flexibility for the payload observation profile. Figure 4-1 shows the spacecraft configuration with deployed solar arrays. In order to guarantee the tolerance to a single failure and to increase the reliability, the platform is fully redundant as well as the PDHU and PSU. The P/L detector modular design ensures that a single failure of one element will cause only a small reduction of the overall performances.

The total satellite dry mass (with system margin) including payload and platform is 860 kg. The required peak total power (with system margin) is about 1000 W. The average telemetry budget is 1202 kbps.

A precise timing of the payload data (1 μs at 3σ) is required to perform a proper on ground data processing able to guarantee the scientific performances of the mission. As already implemented in current missions, the required timing performance can be obtained by a GPS unit directly connected with the PDHU in order to allow a fine synchronization with the time reference.

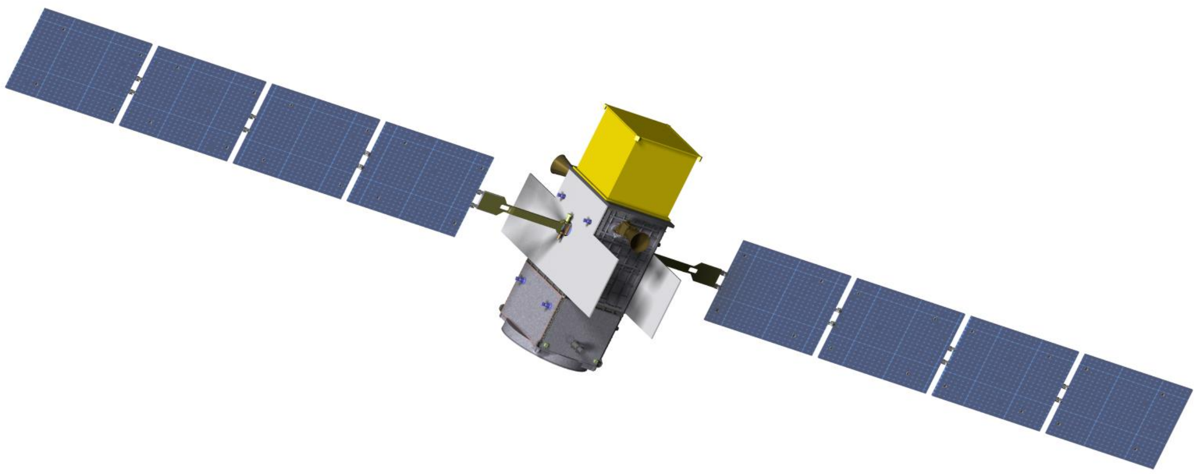


Figure 4-1 *– The ASTROGAM satellite configuration with deployed solar panels and radiators.*

The spacecraft is able to provide the following attitude pointings to support the payload observation requirements:

- nearly inertial pointing (with the possibility to slowly rotate around the payload boresight) to observe continuously a selected area of the sky;
- zenith pointing to perform at each orbit a scan of the sky;

- fast P/L repointing during eclipse periods to avoid the presence of the Earth in the payload FoV (allowing 2 pointings per orbit).

The required pointing accuracy (± 1 deg), stability (0.01°/s), and attitude knowledge of 1 arcmin (to be reached after ground processing) can be obtained using standard class sensors and actuators. The 3-axis stabilized attitude control is achieved mainly using a set of 4 reaction wheels used in zero momentum mode ensuring the possibility to perform fast repointing manoeuvres. Magnetic torquers are provided to perform wheels desaturation and to support a safe attitude pointing based on a basic subset of ACS items.

Attitude reconstruction is based on star trackers outputs; no gyros are required. Three star trackers are provided in order to guarantee the single point failure tolerance and to ensure the availability of at least one star tracker almost in any attitude condition. In addition to the star trackers, magnetometers and coarse star sensors are available.

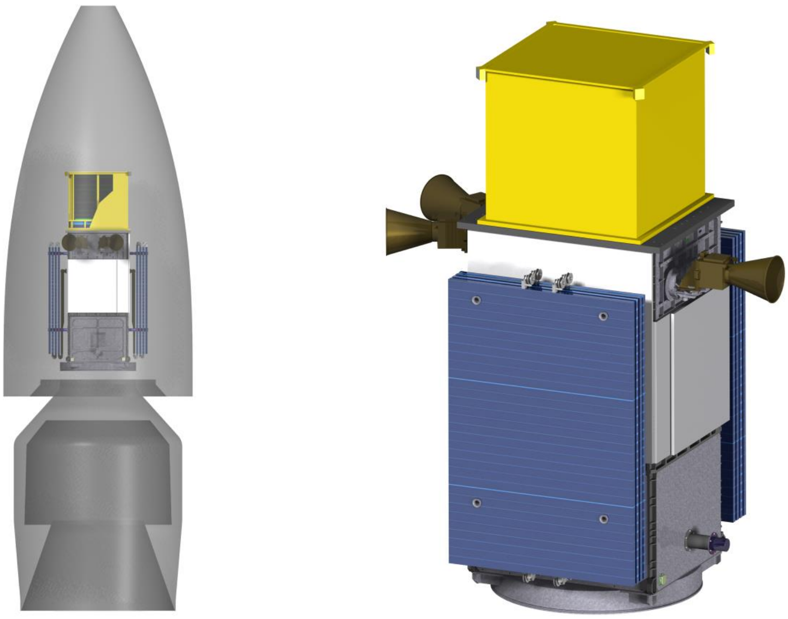


***Figure 4-2** – (Left panel:) the ASTROGAM satellite in stowed configuration on top of the adapter and within the VEGA launcher. (Right panel:) the satellite with the solar arrays and deployable radiators in launch configuration.*

A deployable and steerable solar array, composed by two wings, is provided to guarantee sufficient power generation in all the expected payload pointing scenarios. For the solar array, the power required at EoL is about 1900 W including a margin of 20%. The average orbital contact time with the ground stations of Kourou and Malindi is about 20 minutes for an orbit altitude of 550 km. In order to download all data, a minimum downlink data rate of about 5.7 Mbps is required. These values are compatible with the resources provided by the spacecraft platform of 10 Mbps of downlink data-rate, and 1 Gbyte of mass memory.

5 GROUND SEGMENT

5.1.1 Mission Control Center and ground stations

The ASTROGAM satellite will be managed by an ESA Mission Control Center (MOC). Standard operations and activities will be performed by the MOC (satellite control, flight dynamics, mission planning). The ESA ground station in Kourou will be the standard communication base with the possible support of the ASI Malindi ground station in Kenya.

5.1.2 Scientific Ground Segment

Science Operations Center (SOC)
The SOC is to be located in an ESA facility under ESA supervision. It is the official interface among the MOC, SDC, and the scientific users and guest observers. The SOC will be in charge of: TM acquisition from the MOC; scientific mission planning; running data pre-processing (from L0 to L1); running quick-look analysis; ToO management; issuing scientific alerts (GRBs, transient sources, TGFs); Guest Observer Programme (including scientific tool delivery); science data archive. The SOC will be coordinated by ESA who will enact the planning/operational decisions regarding the mission.

Science Data Center (SDC)
The SDC, under ESA management with support from national agencies, will be based on ESA and Science Team contributions. The SDC is in charge of: L1 data acquisition; Instrument calibration & calibration archive; instrument monitoring & support to P/L diagnostic; running data pipeline and data reduction (from L1 to L2); final stage of scientific SW development & testing; scientific products & data analysis (imaging, lightcurves, spectral & temporal analysis, etc.); tools for quick-look analysis and alert generation; Guest Observer analysis tool production and validation; Guest Observer analysis tool production and validation.

The variability aspect of the gamma-ray sources is a key factor for ASTROGAM and the study of the variability of the gamma-ray sky above 300 keV requires special focusing and resources. An automated Science Alert System will be implemented. Target of Opportunity observations (ToOs) are required to follow particularly important transient events that need a satellite repointing. The ASTROGAM mission requirement for ToO execution is within 6-12 hours.

5.2 Data policy, Guest Observer Program, Scientific Mission Planning

The ASTROGAM scientific program will be open to the international community through a Guest Observer Programme. A Science Management Plan will regulate the programmatic activities between ESA, the ASTROGAM team and the scientific community. ASTROGAM will operate as an observatory, and standard guidelines will be applicable. The mission will be operated by ESA following its standard rules in term of AO, data right, data distribution, etc. Hundreds of sources will be made available for GO investigations, following the operational examples of INTEGRAL, AGILE and *Fermi*. We envision the implementation of a Core Science Program that should guarantee that the Mission key objectives are met. In particular: (1) a performance verification phase is foreseen at the beginning of the operations, then a fraction of the observing time will be routinely reserved for in-flight calibrations. All these data will be available to the community after they have been validated by the Collaboration and the SOC. (2) Mission planning (regular pointings, ToO's) will be regulated by a Mission Planning Committee following the indications of a Users' Committee. (3) All data will become public after 1 year of proprietary right. (4) Guest Observers will be supported by the ASTROGAM Science Data Center with data and analysis SW.

6 APPENDIX 1: THE ASTROGAM COLLABORATION

The proposal has been prepared on behalf of the ASTROGAM Collaboration by:

Marco Tavani	(INAF and University of Rome Tor Vergata, Italy)
Vincent Tatischeff	(CSNSM, France)
Peter von Ballmoos	(IRAP, France)
Lorraine Hanlon	(University College Dublin, Ireland)
Margarita Hernanz	(IEEC-CSIC, Spain)
Philippe Laurent	(APC, France)
Aldo Morselli	(INFN, Italy)
Uwe Oberlack	(Univ. of Mainz, Germany)
Roland Walter	(Univ. of Geneva, Switzerland)
Andrea Argan	(INAF, Italy)
Andrea Borgna	(Univ. of Mainz, Germany)
Andrea Bulgarelli	(INAF Bologna, Italy)
Andrei Bykov	(Ioffe Institute, St. Petersburg, Russia)
Riccardo Campana	(INAF IASF Bologna, Italy)
Martina Cardillo	(INAF, Roma, Italy)
Immacolata Donnarumma	(INAF Roma, Italy)
Valentina Fioretti	(INAF, Italy)
Andrea Giuliani	(INAF Milano, Italy)
Manuela Giusti	(INAF-IAPS, Italy)
Dieter Hartmann	(Clemson University, USA)
Gottfried Kanbach	(MPI, Garching, Germany)
Juergen Kiener	(CSNSM, France)
Jordi Isern	(CSIC-IEEC Barcelona, Spain)
Claudio Labanti	(INAF-IASF Bologna, Italy)
Olivier Limousin	(CEA/Irfu, France)
Francesco Longo	(Univ. and INFN Trieste, Italy)
Martino Marisaldi	(INAF-IASF Bologna, Italy)
Sandro Mereghetti	(INAF-IASF, Milano, Italy)
Kazuhiro Nakazawa	(The University of Tokyo, Japan)
Jean Peyré	(CSNSM, France)
Giovanni Piano	(INAF-IAPS Roma, Italy)
Sabina Sabatini	(INAF-IAPS Roma, Italy)
Xin Wu	(Univ. of Geneva, Switzerland)
Andrzej Zdziarski	(NCAC, Poland)
Andreas Zoglauer	(UC Berkeley, USA)

We acknowledge contributions by G. Annoni (CGS), G. Babini (CGS), P. Lattanzi (CGS), B. Morelli (CGS), C. Vettore (CGS).

THE ASTROGAM COLLABORATION

ABOUDAN A. (INAF-IASF Bologna, Italy)
AHARONIAN F. (DIAS, Ireland)
AJELLO M. (Clemson University, USA)
ALAPHILIPPE V. (CSNSM, France)
ALVAREZ L. (ICE/CSIC-IEEC, Spain)
ANTONELLI A. (INAF, Italy)
ARGAN A. (INAF Roma, Italy)
ARTIGUES G. (ICE/CSIC-IEEC, Spain)
ATTIE D. (CEA-Saclay, France)
BALDINI L. (INFN Pisa, Italy)
BARBIELLINI G. (Univ. and INFN Trieste, Italy)
BARING M. (Rice University, USA)
BASA S. (LAM, France)
BECKMANN V. (APC, France)
BENVENUTI P. (Univ. Padova, Italy)
BERNARD D. (LLR, Ecole Polytechnique, France)
BERTUCCIO G. (Politecnico di Milano, Italy)
BLAY P. (University of Valencia, Spain)
BLOSER P. (University of New Hampshire, USA)
BOGGS S. (University of California, USA)
BONVICINI W. (INFN Trieste, Italy)
BOTTACINI E. (University of Stanford, USA)
BOUCHET L. (IRAP, France)
BRANDT T.J. (GSFC, USA)
BRÉELLE E. (APC, France)
BREGEON J. (LUPM, France)
BRIGGS M. (University of Alabama, USA)
BROGNA A. (Univ. of Mainz, Germany)
BUDTZ-JØRGENSEN C. (DTU SPACE, Denmark)
BULGARELLI A. (INAF-IASF Bologna, Italy)
BYKOV A. (Ioffe Institute, Russia)
CABEZON R. (University of Basel, Switzerland)
CABRUJA E. (IMB-CNM/CSIC, Spain)
CALIANDRO G. A. (University of Stanford, USA)
CAMPANA R. (INAF-IASF Bologna, Italy)
CARAVEO P. (INAF IASF Milano, Italy)
CARDILLO M. (INAF, Italy)
CAROLI E. (INAF/IASF Bologna, Italy)
CASARES J. (IAC, University of La Laguna, Spain)
CELESTIN S. (LPC2E, University of Orleans, France)
CHABOT M. (IPNO, France)
CHEN A. (Univ. Witwatersrand, South Africa)
CHEUNG T. (NRL, Washington, USA)
CHIPAUX R. (CEA-Saclay, France)
CHIPPS K. (Oak Ridge National Laboratory, USA)
CIPRINI S. (ASI ASDC, Italy)
CLARET A. (CEA-Saclay, France)
COHEN-TANUGI J. (LUPM, France)
COLAFRANCESCO S. (Wits University, South Africa)
COLLMAR W. (MPE, Germany)
CONNAUGHTON V. (University of Alabama, USA)
COPPI P. (Yale Univ., USA)
CORDIER B. (CEA-Saclay, France)
DAIGNE F. (IAP, France)
DE ONYA E. (ICE/CSIC-IEEC, Spain)
DE ROSA A. (INAF-IASF Bologna, Italy)
DE SEREVILLE N. (IPNO, France)
DEL MONTE E. (INAF-IAPS, Italy)
DEPAOLA G. (University of Cordoba, Argentina)
DI GIORGIO A. M. (INAF-IAPS, Italy)
DI GIULIO C. (INFN Roma Tor Vergata, Italy)
DIEHL R. (MPE, Germany)
DIETRICH S. (ISAC CNR, Italy)
DOGIEL V. (Lebedev Institute, Russia)
DOLGOROUKY Y. (APC, France)
DONNARUMMA I. (INAF-IAPS, Italy)
DUBUS G. (IPAG, France)
DWYER J. (University of New Hampshire, USA)
FEINSTEIN F. (LUPM, France)
FERRARA E. C. (University of Maryland, USA)
FERRARI A. (Univ. Torino, Italy)
FIORETTI V. (INAF-IASF Bologna, Italy)
FOGLIZZO T. (CEA-Saclay, France)
FRASCHETTI F. (University of Arizona, USA)
FUKAZAWA Y. (Hiroshima University, Japan)
FUSCHINO F. (INAF-IASF Bologn,a Italy)
GALLANT Y. (LUPM, France)
GALLI M. (ENEA Bologna, Italy)
GALVEZ J. L. (ICE/CSIC-IEEC, Spain)
GARCIA-SENZ D. (UPC and IEEC, Spain)
GEHRELS N. (GSFC, USA)
GENOLINI B. (IPNO, France)
GIEBELS B. (LLR, France)
GIOMMI P. (ASDC Frascati, Italy)
GIULIANI A. (INAF-IASF Milano, Italy)
GIUSTI M. (INAF-IAPS, Italy)
GOLDWURM A. (APC/CEA-Saclay, France)
GOMEZ-VARGAS G.A. (INFN Roma Tor Vergata, Italy)
GOSTOJIC A. (CSNSM, France)
GOUIFFES C.(CEA-Saclay, France)

GREINER J. (MPE, Germany)
GRENIER I. (CEA-Saclay and Univ. Paris Diderot, France)
GROS P. (LLR, Ecole Polytechnique, France)
GROVE E. (NRL, USA)
HAMADACHE C. (CSNSM, France)
HAMMACHE F. (IPNO, France)
HANLON L. (University College Dublin, Ireland)
HARDING A. (GSFC, USA)
HARTMANN D. (Clemson University, USA)
HAYS E. A. (GSFC, USA)
HENRI G. (IPAG, Grenoble Observatory, France)
HERMSEN W. (SRON, The Netherlands)
HERNANZ M. (CSIC-IEEC, Spain)
HEWITT J. W. (GSFC, USA)
HUNTER S. (GSFC, USA)
ICHINOHE Y. (ISAS/JAXA, Japan)
ISERN J. (CSIC-IEEC, Spain)
IYUDIN A. (SINP, Moscow State University, Russia)
JACHOLKOWSKA A. (LPNHE, France)
JEAN P. (IRAP, France)
JELTEMA T. (University of California, USA)
JOHANNESSON G. (University of Stanford, USA)
JOHNSON N. (NRL, USA)
JOSE J. (UPC and IEEC, Spain)
KANBACH G. (MPI, Germany)
KARKOUR N. (CSNSM, France)
KATSANEVAS S. (APC, France)
KHALIL M. (APC, France)
KIENER J. (CSNSM, France)
KNÖDLSEDER J. (IRAP, France)
KRETSCHMER K. (APC, France)
LABANTI C. (INAF-IASF Bologna, Italy)
LACHAUD C.(APC, France)
LARSSON J. (KTH, Sweden)
LAURENT P. (APC/CEA-Saclay, , France)
LAVALLE J. (LUPM, France)
LEBRUN F. (APC, France)
LEISING M. (Clemson University, USA)
LIMOUSIN O. (CEA/Irfu, France)
LIN L. (APC, France)
LINARES M. (IAC, University of La Laguna, Spain)
LINGET D. (CSNSM, France)
LIPARI P. (INFN Roma-1, Italy)
LONGO F. (Univ. and INFN Trieste, Italy)
LOTT B.(CENBG, France)
LOZANO M. (IMB-CNM/CSIC, Spain)
LUND N. (DTU SPACE, Denmark)
MADEJSKI G. (University of Stanford, USA)
MAMBRINI Y. (LPT, France)
MANNHEIM K. (University of Würzburg, Germany)
MARCOWITH A. (LUPM, France)
MARISALDI M. (INAF-IASF Bologna, Italy)
MARTIN P.(IRAP, France)
MARTIN-CARRILLO A. (Univ. College of Dublin, Ireland)
MASSARO F. (University of Stanford, USA)
MCBREEN S. (University College of Dublin, Ireland)
MCCONNELL M. (University of New Hampshire, USA)
MCENERY J. E. (GSFC, USA)
MEREGHETTI S. (INAF-IASF Milano, Italy)
MIRABEL F. (CEA, France)
MITCHELL J. W. (GSFC, USA)
MIZUNO T.(Hiroshima University, Japan)
MOISEEV A.(GSFC, USA)
MORRIS O. (University College of Dublin, Ireland)
MORSELLI A. (INFN Roma Tor Vergata, Italy)
MOSKALENKO I. (University of Stanford, USA)
MUNOZ C. (IFT-UAM/CSIC, Spain)
MURPHY R. J. (NRL, USA)
NAKAZAWA K. (The University of Tokyo, Japan)
NEGUERUELA I. (University of Alicante, Spain)
NERONOV A. (University of Geneva, Switzerland)
NEUBERT T. (DTU Space, Denmark)
OBERLACK U. (Johannes Gutenberg Universität, Germany)
OHNO M. (Hiroshima University, Japan)
OLIVETTO C. (APC, France)
ORLANDO E. (University of Stanford, USA)
ORLEAŃSKI P. (SRC PAS, Poland)
ØSTGAARD N. (Univ. Bergen, Norway)
OSTROWSKI M. (AO, Jagiellonian Univ., Poland)
PACCAGNELLA A. (Univ. Padova, Italy)
PADOVANI M.(LUPM, France)
PALUMBO G. (INAF/IASF Bologna, Italy)
PAREDES J. M. (Univ. Barcelona, Spain)
PARIKH A.(UPC and IEEC, Spain)
PAUL J. (CEA-Saclay, France)
PEARCE M. (AlbaNova University Centre, Sweden)
PELLEGRINI G. (IMB-CNM/CSIC, Spain)
PÉREZ GARCÍA M. Á. (Univ. de Salamanca, Spain)
PERKINS J.(GSFC, USA)
PESCE ROLLINS M. (INFN Pisa, Italy)
PEYRÉ J. (CSNSM, France)
PHLIPS B.(NRL, USA)
PIANO G. (INAF-IAPS, Italy)
PICOZZA P. (INFN Roma Tor Vergata, Italy)
PILIA M. (ASTRON, The Netherlands)
PIRON F. (LUPM, France)

PITTORI C. (INAF OAR and ASDC, Italy)
POHL M. (Univ. of Geneva, Switzerland)
PONS R.(IRAP, France)
PORTER T. (University of Stanford, USA)
PRANTZOS N. (IAP, France)
PUCELLA G. (ENEA, Italy)
RASHEVSKY A. (INFN Trieste, Italy)
RAZZANO M. (INFN Pisa, Italy)
REA N. (ICE/CSIC-IEEC, Spain)
REIMER O. (Leopold Franzens University, Austria)
RENAUD M. (LUPM, France)
RIBO M. (University of Barcelona, Spain)
ROBERTS M.(NYU, UAE)
ROBERTS O.(University College of Dublin, Ireland)
RODRIGUEZ F.G. (INFN Roma Tor Vergata, Italy)
ROMERO G. (IAR, Argentina)
RYAN J. (University of New Hampshire, USA)
RYDE F. (KTH, Sweden)
SABATINI S. (INAF-IAPS, Italy)
SALA G.(UPC and IEEC, Spain)
SAVCHENKO V. (APC, France)
SCHANNE S. (CEA-Saclay, France)
SGRO C. (INFN Pisa, Italy)
SIEGAL-GASKINS J. (Caltech, USA)
SILVA R. (LIP, Portugal)
SOLDI S. (APC, France)
STAWARZ Ł. (ISAS, Japan)
STEPHEN J. B. (INAF/IASF Bologna, Italy)
STRIANI E. (Univ. of Turin, Italy)
STRONG A. (MPE, Germany)
TAKAHASHI T.(ISAS, Japan)
TAKEDA S. (ISAS/JAXA, Japan)
TANAKA Y.(Hiroshima University, Japan)
TATISCHEFF V. (CSNSM, France)
TAVANI M. (INAF-IAPS, Tor Vergata Univ., Italy)
TERRIER R. (APC, France)
THOMPSON D. (GSFC, USA)
TORRES D. F. (ICE/CSIC-IEEC, Spain)
TOURRETTE T. (CEA-Saclay, France)
TROIS A. (INAF OAC Cagliari, Italy)
ULLAN M. (IMB-CNM/CSIC, Spain)
ULYANOV A. (University College of Dublin, Ireland)
URSI A. (University of Rome Tor Vergata, Italy)
VACCHI A. (INFN Trieste, Italy)
VASILEIADI G. (LUPM, France)
VENTERS T. (GSFC, USA)
VERCELLONE S. (INAF-IASF Palermo, Italy)
VERRECCHIA F. (INAF OAR and ASDC, Italy)
VERZI V. (INFN Roma Tor Vergata, Italy)
VILMER N. (LESIA-Paris Observatory, France)
VITTORINI V. (INAF-IAPS, Italy)
VON BALLMOOS P. (IRAP, France)
VUILLAUME T. (IPAG, France)
WALTER R. (University of Geneva, Switzerland)
WILSON-HODGE C. (University of Alabama, USA)
WU X. (Univ. of Geneva, Switzerland)
WULF E. (NRL, USA)
ZAMPA G. (INFN Trieste, Italy)
ZAMPA N. (INFN Trieste, Italy)
ZDZIARSKI A. (NCAC, Poland)
ZIETARA K. (AO, Jagiellonian Univ., Poland)
ZOGLAUER A.(University of California, USA)
ZURBACH C. (LUPM, France)

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