The DUAL mission concept

Peter von Ballmoos[*a], Jose Alvarez[b], Nicolas Barriere[c], Steve Boggs[c], Andrei Bykov[d], Juan Manuel Del Cura Velayos[e], Filippo Frontera[f], Lorraine Hanlon[g], Margarita Hernanz[b], Emmanuel Hinglais[h], Jordi Isern[b], Pierre Jean[a], Jürgen Knödlseder [a], Lucien Kuiper[i], Mark Leising[j], Benoît Pirard[k], Jean-Pierre Prost[l], Rui da Silva[m], Tadayuki Takahashi[n], John Tomsick[c], Roland Walter[o], Andreas Zoglauer[c] on behalf of the DUAL collaboration (see http://dual.cesr.fr/M3/collaboration)

[a] IRAP, 9 avenue du Colonel-Roche, F-31028 Toulouse
[b] IEEC/CSIC, Torre C5 Parell 2a Planta, E-08193 Bellaterra, Barcelona
[c] Space Sciences Laboratory, 7 Gauss Way, CA94720 Berkeley, USA
[d] Ioffe Physical-Technical Institute, 26 Polytekhnicheskaya, 194021 St Petersburg, Russia
[e] Sener: Calle Severo Ochoa, 4, E-28760 Tres Cantos
[f] Universita di Ferrara, Via Savonarola, 9, I-44121 Ferrara
[g] University College Dublin, Belfield, IE-Dublin4
[h] CNES, 18 Avenue Edouard Belin, F-31401 Toulouse
[i] Netherland Institute for Space Research, Sorbonnelaan 2, NL-3584 Utrecht
[j] Clemson University, 29634 Clemson, USA
[k] Canberra, 1, Chemin Roseraie, F-67380 Lingolsheim
[l] Thales Alenia Space, 100, Boulevard Midi, F-06156 Cannes la Bocca
[m] Universidade De Coimbra, Rua Larga, P-3000 Coimbra
[n] Institute of Space and Astronautical Science, Yoshinodai Sagamihara, 229-8510 Kanagawa, Japan
[o] Integral Science Data Center, 192, route de Vernier, CH-1214 Vernier

ABSTRACT

DUAL will study the origin and evolution of the elements and explores new frontiers of physics: extreme energies that drive powerful stellar explosions and accelerate particles to macroscopic energies; extreme densities that modify the laws of physics around the most compact objects known; and extreme fields that influence matter in a way that is unknown on Earth. The variability of these extreme objects requires continuous all-sky coverage, while detailed study demands an improvement in sensitivity over previous technologies by at least an order of magnitude.

The DUAL payload is composed of an All-Sky Compton Imager (ASCI), and two optical modules, the Laue-Lens Optic (LLO) and the Coded-Mask Optic (CMO). The ASCI serves dual roles simultaneously, both as an optimal focal-plane sensor for deep observations with the optical modules and as a sensitive true all-sky telescope in its own right for all-sky surveys and monitoring. While the optical modules are located on the main satellite, the All-Sky Compton Imager is situated on a deployable structure at a distance of 30 m from the satellite. This configuration not only permits to maintain the less massive payload at the focal distance, it also greatly reduces the spacecraft-induced detector background, and, above all it provides ASCI with a continuous all-sky exposure.

Keywords: nuclear astrophysics, gamma-ray optics : Compton-, Laue-, coded aperture-telescope

---

*pvb@cesr.fr; phone +33 561 55 66 47; www.cesr.fr/~pvb

UV, X-Ray, and Gamma-Ray Space Instrumentation for Astronomy XVII,
edited by Oswald H. Siegmund, Proc. of SPIE Vol. 8145, 81450E · © 2011 SPIE
CCC code: 0277-786X/11/$18 · doi: 10.1117/12.895419

1. SCIENTIFIC OBJECTIVE : THE EVOLVING VIOLENT UNIVERSE SEEN IN γ-RAYS

The γ-ray Universe is that of particle acceleration and nuclear physics, of cosmic explosions and non-thermal phenomena. Its observation allows the exploration of the most violent places in the Universe. These extreme conditions occur generally at the endpoints of stellar lives, when the relatively calm thermal evolution gives way to a more violent non-thermal evolution. Stellar explosions of all kinds and particle acceleration processes play a key role in this evolution, providing the conditions to synthesize new elements and providing kinetic energy to the interstellar and intergalactic media that are the seeds for new generations of stars and galaxies. Cosmic acceleration manifests itself most prominently in gamma-rays, which are best studied remotely in γ-rays, and takes place locally in solar flares, within our Galaxy in compact binary systems, pulsars and pulsar wind nebulae, supernova remnants, and in extremely distant objects such as active galactic nuclei and GRBs. Cosmic explosions are a site of prominent γ-ray emission, allowing examination of a wealth of radioactive isotope production, sources of antimatter, and accelerated particles at relativistic energies. Novae, supernovae and hypernovae are thus prime targets of γ-ray astronomy. The DUAL science case is presented in more detail in von Ballmoos et al (2010).

The exploration of the soft γ-ray band is complementary to the progress that is presently being made in neighboring energy bands. On the X-ray and Hard X-ray side, at the limit of the onset of non-thermal astrophysics, a large number of missions are underway (NuStar, Astro-H, eROSITA...) or under study (the Athena assessment study lead by ESA, to mention only one mission concept amongst many). Across the MeV-Gap (Figure 1), Fermi is presently revolutionizing the landscape in the high-energy γ-ray sky at GeV energies, and very high-energy γ-rays detected by ground based Cherenkov telescopes (such as HESS, MAGIC or VERITAS) have conquered this part of the spectrum for astronomy, with sources mainly belonging to the classes of pulsar wind nebulae, supernova remnants, blazars and micro-quasars.

Many of the most energetic compact objects in our universe (e.g. AGN) have their peak emission in the MeV range. Thus, only through observations in this range will we finally be able to fully test emission models for these sources. Understanding high-energy emission processes relies heavily on a broad spectral coverage, and combining DUAL observations with those achieved up to tens of keV on the one side, and the progress at GeV and TeV energies on the other side, will provide unique constraints on the underlying physics.

However, DUAL not only provides a vital bridge between X-ray and High Energy γ-ray astronomy, it will actually fill the sensitivity gap that has opened over the last decades in the nuclear range. Since the first generation of γ-ray telescopes in the early 1980's, three generations of space instruments (HEAO, Compton GRO, INTEGRAL) have consecutively observed the nuclear band, improving the sensitivities by a factor of roughly 7 (e.g., in the crucial ^{56}Co line at 847 keV). DUAL will provide the long awaited leap of a factor of 30, both for the ^{56}Co and ^{56}Ni (812 keV) lines of SN Ia, during focused pointings (10^6 sec) of its Laue lens, and for the long-lived radioactivity, e+e- annihilation radiation, nuclear excitation lines, etc. during its all-sky survey, through a very deep exposure (~ 10^{10} cm^2 s) of every source in the entire sky.

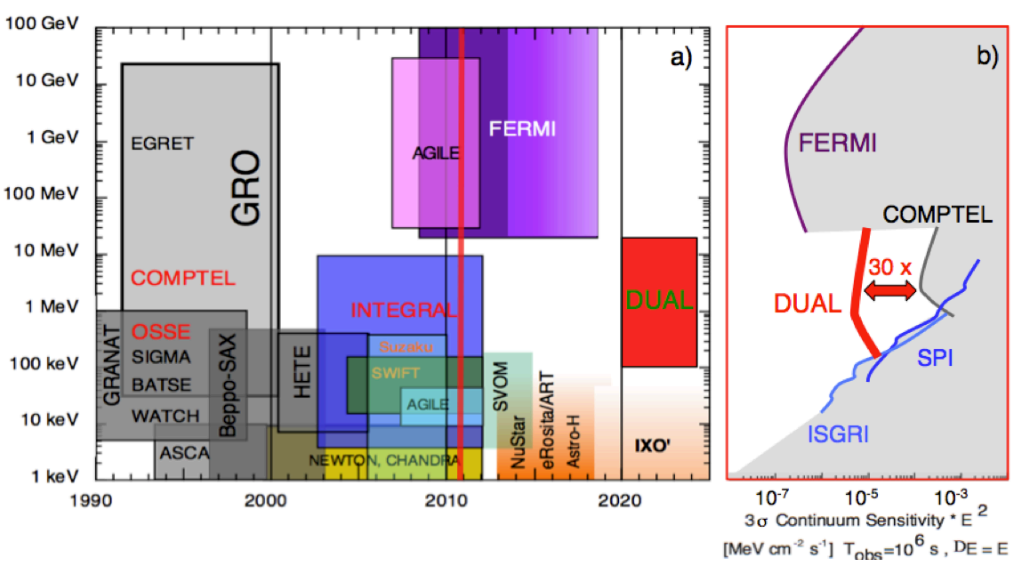

Figure 1: A bridge across the MeV-Gap. The roadmap of high energy astronomy shows a white spot on the future track of nuclear astrophysics – i.e. between 0.1-100 MeV **(a).** This not only is a concern for the future, there also exists a deep sensitivity gap **(b)** with on one side focusing X-ray telescopes, and on the other side, imaging tracking detectors in the GeV/TeV. With a sensitivity leap by a factor of 30, DUAL will bridge this gap, addressing a very wide range of fundamental astrophysical questions.

2. PAYLOAD

The DUAL payload is composed of an *All-Sky Compton Imager (ASCI)*, and two optical modules, the *Laue-Lens Optic (LLO)* and the *Coded-Mask Optic (CMO)*. Combining a Compton telescope with a Laue lens and a coded mask will permit to meet the requirements for a future γ-ray mission, i.e outstanding sensitivity for emissions with a wide range in angular extent. While the ASCI performs its "all-sky science" - i.e. map out large-scale distributions (e+e- annihilation radiation, long-lived radioactivities, excitation lines), detect GRB's on the entire sky and measure their polarization, monitor a large number of extragalactic and galactic compact sources - the optics modules simultaneously focus on specific key targets. The LLO concentrates on freshly produced radioactivity as a key to understanding Sn1a (LLO), and the CMO will disentangle the emission of compact objects in the Galactic Center, and map out the as yet unresolved bulge of e^+-e^- annihilation.

The *ASCI* serves dual roles simultaneously, both as an optimal focal-plane sensor for deep observations with the optical modules and as a sensitive true all-sky telescope in its own right for all-sky surveys and monitoring. It is situated on a deployable structure at a distance of 30 m from the satellite. The mass of the three payloads including the Collapsible Tube Mast (CTM) totals under 400 kg. The DUAL payloads have been studied by dedicated industry studies by Thales Alenia Space (lens, payload) and Canberra (detector).

But how can such small instruments (each one with m ≤ 100kg) achieve science goals that require a factor of 30 improved sensitivity compared to previous telescopes - some of them being an order of magnitude larger, i.e. more massive? Traditionally, realizing more sensitive γ-ray instruments is first of all associated with enhancing the source exposure (E), which then usually was translated with enhancing the instrument area (A_{eff}). However, larger photon detectors are not only more massive, they also have higher volumes and hence go along with higher instrumental background, so sensitivity improves at best with the square root of the size of the instrument. Two ground-breaking first-time ever concepts permit DUAL to overcome this impasse, resulting in performances that are worthy of much larger instruments :

ASCI – "time has no mass": as a true "whole sky telescope", ASCI will observe every single source in the sky during its entire mission lifetime (T_{life}) yielding extraordinary exposures for all those sources, even with the modest mean effective area ($\hat{A}_{eff}$) of a small instrument. Here a large exposure is produced by the very long observation time ($E=A_{eff} \cdot T_{life}$); and while the Compton condition keeps a background low, the sensitivity dramatically increases. In comparison with a 0.1 ster FoV instrument observing a source during 10^6 sec (like SPI), ASCI (FOV : 12 ster => $T_{life}=10^8$ sec) has an exposure (multiplex) advantage of 100, resulting in a sensitivity improvement of one order of magnitude*.

LLO - large area but low background: focusing source photons from the large collecting area (A_{lens}) of the LLO onto a small detector volume of the ASCI yields extraordinary exposures for the sources pointed, even for relatively short exposure times. Since the volume producing background noise is very small, SNR are extremely high and unprecedented sensitivities are achieved.

Remarkably both concepts, the whole-sky telescope (ASCI) and the γ-ray lens (LLO), are best realized by using a mast. A detector on the tip of a mast not only allows to maintain the less massive payload at the focal distance of a γ-ray lens, it also grants an unobstructed all-sky view to a true 4π-steradian imager. Here, the entire sky becomes available for simultaneous observation, resulting in a more than four times enhanced exposure for every source in the sky with respect to an equivalent instrument in LEO. Moreover, keeping the detector away from the platform cuts down background induced by cosmic-ray interaction in the spacecraft. This effect has been observed for the first time with a small γ-ray detector deployed on a 7,6 m boom from the Apollo 15 service module, resulting in background reduction of an order of magnitude due to the reduced solid angle subtended by the spacecraft (Trompka et al 1973). However, this solid angle effect can only be beneficial if albedo background radiation from the earth's atmosphere is avoided by observing from an L2 orbit, for example.

* back-of-the-envelope estimate for the sensitivity improvement, comparing the SPI sensitivity with ASCI

	mean $\hat{A}_{eff}$ at 1 MeV	T_{obs}	BGD at 1 MeV	sensitivity gain
INTEGRAL/SPI	65 cm^2	10^6 sec	~ 0.1 c/s·kev	
DUAL/ASCI	~ 51 cm^2	$9.5 \cdot 10^7$ sec	~ $7.3 \cdot 10^{-3}$ c/s·kev	
Improvement ~ √asci/spi	0.88	9.7	3.7	**32**

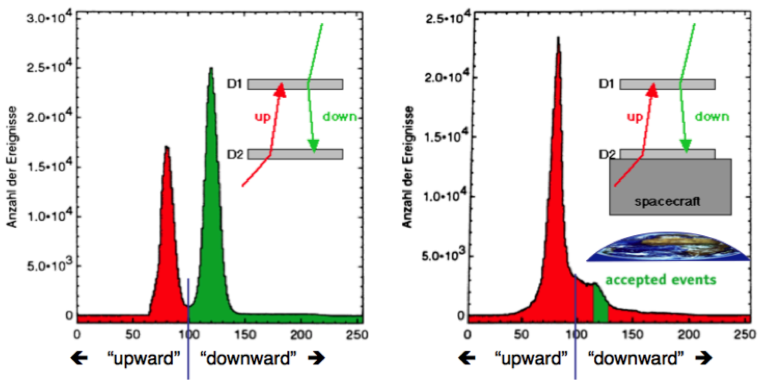

Figure 2: The time of flight spectra of CGRO-COMPTEL: left) time of flight for downward- and up-ward moving photons in during ground calibrations at Neuherberg. Discrimination seems evident. right) time of flight spectrum in low earth orbit: upward-moving photons from earth and spacecraft albedo are dominating the background.

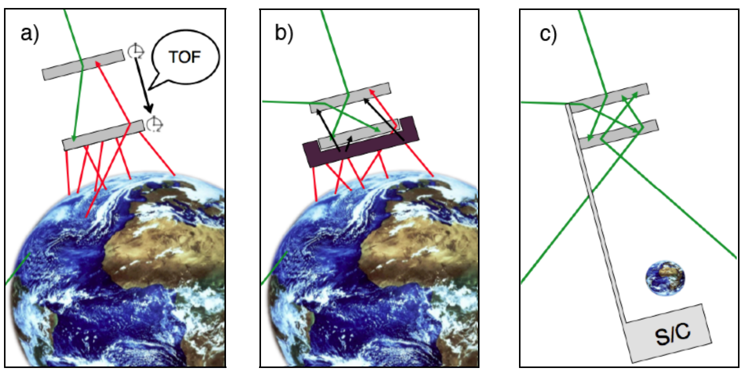

Figure 3: Options for suppressing earth and spacecraft albedo background:

a) Time of flight measurement: requires wide detector spacing resulting in low detection efficiency, leading to high instrument masses

b) anticoincidence shield: their mass is usually superior to the detector's, leading to very massive instruments

c) high orbit, on a mast: avoid earth and s/c background and benefit of a 4 times larger FOV, synonymous with 4 times more signal – this is **the DUAL choice** !

Figure 2 demonstrates the effect of upwards moving events in CGRO-COMPTEL and Figure 3 illustrates the various options for reducing this important background component. Besides avoiding albedo background from the earth's atmosphere, an L2 orbit minimizes gravity gradient disturbances, allows uninterrupted 4π-viewing, and permits simple passive cooling of the detector to 80-100 K.

In the DUAL concept, the combination of an All-Sky Compton Imager with a Laue Lens can therefore satisfy the stringent sensitivity requirements for a next gamma-ray mission. However, Compton telescopes have inherent limitations in angular resolution, fundamentally limited below a few hundred keV by the fact that the target electrons have an indeterminable momentum inside their atoms which introduces an uncertainty in the recoil energy of the Compton electron and the scattered photon (Zoglauer and Kanbach, 2003). For ASCI, this means that, e.g., the maps of GC annihilation radiation are limited to resolutions of 2.5° at best (strong source). This is the of same order of what is presently achieved by SPI, even though ASCI will provide a sensitivity improved by more than an order of magnitude. We therefore propose to improve considerably the imaging capabilities of DUAL by a coded mask optic that will be situated on the spacecraft. The important distance between S/C and ASCI result in spectacular angular resolutions (10-50 arcmin) and will be most valuable in the Galactic Center region.

2.1 All-Sky Compton Imager (ASCI)

Situated on a deployable structure at a distance of 30 m from the satellite, the ASCI is a compact array of cross-strip germanium detectors, with high spectral and 3-D spatial resolution to track γ–ray Compton-scatter interactions. The ASCI serves dual roles simultaneously, both as an optimal focal-plane sensor for deep observations with the optical modules and as a sensitive true all-sky telescope in its own right for all-sky surveys and monitoring. It will perform sensitive γ-ray spectroscopy and polarimetry in the energy band 100 keV-10 MeV Although weighting under 100 kg, ASCI's γ-ray line sensitivity after its nominal lifetime of 3 years is ~ 10^{-6} γ cm^{-2} s^{-1} at 1 MeV for every γ-ray source in the sky.

The most promising instrument design for fulfilling the sensitivity and wide-field requirements set forth above is a Compton telescope utilizing recent advances in semiconductor detector technologies to achieve significant improvements over the COMPTEL (Schönfelder et al. 1993) which pioneered this technique in the 1990s.

This technique also contributes to meeting scientific requirements through the ability to image both discrete sources and diffuse emission over a wide field-of-view (100% sky simultaneously), as well as the ability to perform simultaneous imaging and spectroscopy of line and continuum emission over a broad energy range (0.1–10 MeV). A detailed description of the Compton telescope principle and associated analysis methods is found in Zoglauer (2006).

Among modern-day Compton detector technologies, Germanium provides the highest spectral resolution, crucial to understanding source dynamics via Doppler shifts and/or broadening of nuclear lines from radioactive decays or positron annihilation. Germanium also has a moderate Z – low enough to allow significant Compton scatters, but high enough to stop the photons in the instrument once they scatter.

Instrument conceptual design and key characteristics : The baseline for DUAL's All-Sky Compton Imager (ASCI) is a stack of 45 highly segmented high-purity germanium (HPGe) detectors operating at cryogenic temperature, which combines the best performances to achieve the science objectives: high detection efficiency over a large field of view, excellent spatial resolution and high spectral resolution. The proposed technology and detector configuration have been studied in a close collaboration by CESR, Canberra France (HPGe detector manufacturer) and UC Berkeley. Figure 4 shows the DUAL focal plane detector. The sensitive part consists of 5 layers of 9 double-sided strip detectors (DSSD) made of HPGe. The 45 detectors are mounted on supporting frames specifically designed to be light and compact in order to maximize the instrument detection efficiency. This cold stage is sealed in vacuum within the cryostat box, and thermally isolated with thermal shield and MLI blankets. The overall thickness of materials will be minimized in the forward and backward directions (detector symmetry axis) so that shielding and scattering effects for incident γ-rays are limited.

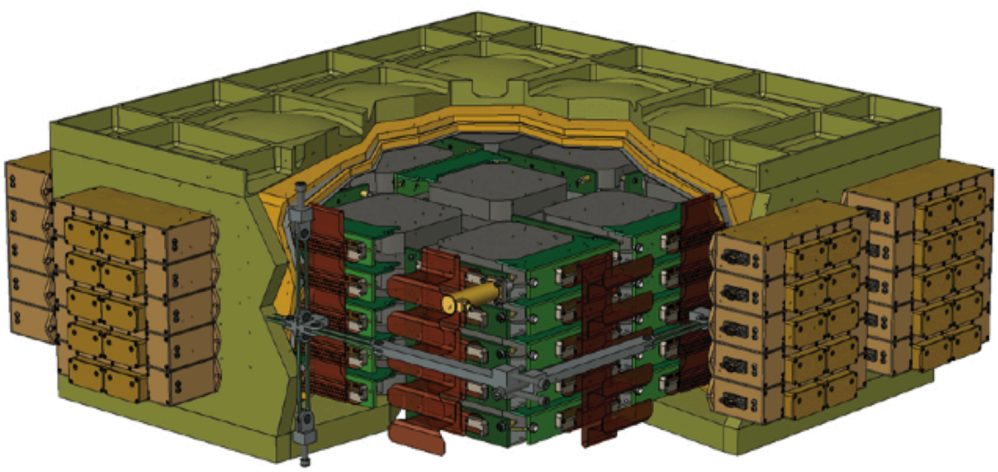

Figure 4:
The ASCI instrument

Germanium strip detectors : Each HPGe detector module has an active area of 100 × 100 mm^2 and a thickness of 15 mm, this large size is allowed by the extraction lengthwise from large grown HPGe crystals. The orthogonal X-Y strips on the two electrodes will be separated with a pitch of 2 mm and surrounded by a 1 mm thick guard ring. The double sided X-Y strip configuration is widely and exclusively used in applications using high resolution Compton imaging. It allows both excellent energy and position resolution when the full potential of signal processing is used (i.e. timing and pulse shape analysis on all the channels simultaneously, Vetter et al. 2000). The expected position resolution for a γ-ray interaction within the HPGe detector is 1.6 mm^3. Table 1 summarizes the main performance parameters for such HPGe strip detectors, comparing them with the Ge-strip detectors of the Nuclear Compton Telescope (NCT, Figure 5), a balloon telescope that has successfully flown and validated the entire proposed detector technology. The design of the DUAL detector modules is based on existing HPGe strip detectors already manufactured in the past by Canberra for γ-ray tracking and imaging applications. It relies in particular on robust processes such as thin contact and passivation technologies developed in the last decade. All the detectors, except the central position in the front layer, will be made

GeD/ parameter	DUAL	NCT
Strip pitch	2.00 mm	2.00 mm
Strip gap	0.25 mm	0.25 mm
Individual detector dimensions	100x100 mm^2	74x74 mm^2
	15 mm	15 mm
Guard ring thickness	1 mm	2 mm
Spectral resolution (FWHM) @ 662 keV < 0.1 MeV(noise limit)	1.6 keV 2.1 keV	1.6 keV 2.1 keV
Depth res. (FWHM)	0.4 mm	0.4 mm
Position resolution	1.6 mm^3	1.6 mm^3
Spectroscopy threshold	10 keV	12 keV
Depth threshold	25 keV	40 keV
total # strip channels	4500	912
Instrument volume	6750 cm^3	972 mm^3

Table 1: Comparison of DUAL and NCT GeDs.

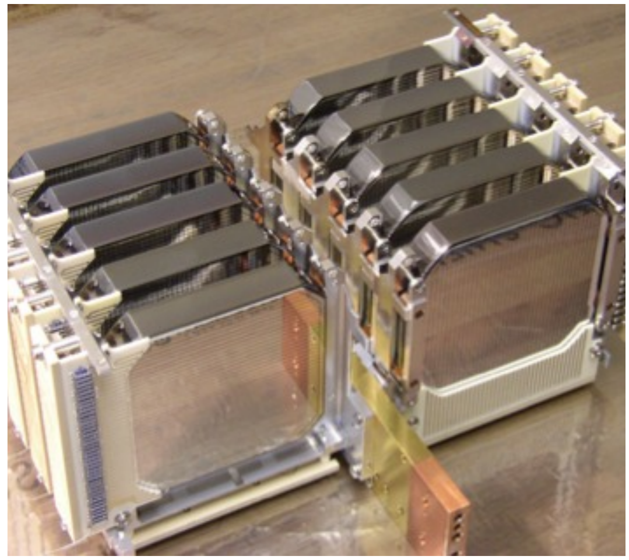

Figure 5: The Ge-strip detectors of NCT

the same in terms of shaping, surface process, mounting on the supporting frame, wire bonding and connection to flex ribbon cables.

The central detector in the front layer will be designed with an inner hole in order to allow γ-rays from the lens to hit directly the second layer; this configuration presents the best detection efficiency for the focused γ-rays. This central front detector will work the same way as for others, the strips in two parts from each side of the inner hole will be wire bonded together to create a single strip electrically.

Heritage : Germanium detectors have flown on several space missions during the last two decades : INTEGRAL/SPI, Mars Odyssey / GRS, RHESSI, KAGUYA/GRS, MESSENGER/GRS, etc. Canberra France not only manufactured a large fraction of those spaceborne HPGe detectors, but also played a leading role in developing key technologies for HPGe detectors, such as encapsulation and segmentation (Gutknecht, 1990). A design very similar to DUAL has already been realized with the NCT instrument of for UCB/SSL Berkeley. NCT's HPGe strip detectors have been tested on stratospheric balloon flights; on its 2005 flight NCT has successfully detected and imaged the Crab Nebula (Bandstra et al, 2011).

	Mass	Cont.	Mature	Power	Cont.	Mature
Ge detectors	35.9	10%	39.5	-	-	-
Mounting & contact boards	4.1	20%	4.9	-	-	-
Cryostat, cold fingers, structure, MLI	8.8	20%	10.6	-	-	-
Front-end/ASIC boxes & connectors	5.0	20%	6.0	16.2	20%	19.4
IDPU incl housing	9.3	20%	11.2	-	-	-
DIBs	-	-	-	16.2	20%	19.4
DCB & PCB	-	-	-	4.0	20%	4.8
Instrument Power Conv. & Controller	1.4	20%	1.7	16.7	20%	20.0
Plastic - housing, mounting, readout	6.0	20%	7.2	8	20%	9.6
HV power supplies and filters	5.4	20%	6.5	21.2	20%	25.4
Radiator Panels	12.0	20%	14.4	-	-	-
Harness	7.9	20%	9.5	-	-	-
TOTAL	95.8		111.5	82.3		98.8

Table 2: mass and volume resources of the ASCI

2.2 Laue-Lens Optic (LLO)

A Laue lens offers the unique possibility of concentrating gamma rays from a large collection area onto a small focal spot. The dramatically improved signal to background ratio leads to outstanding sensitivity. DUAL's Laue-Lens Optic (LLO) focuses in the 800 keV-900 keV energy band, relevant for the detection of the ^{56}Co line of SN1a. It is composed of 5800 crystals glued onto a CeSiC monolithic substrate. The total weight amounts to 80 kg, the outer diameter is 98 cm.

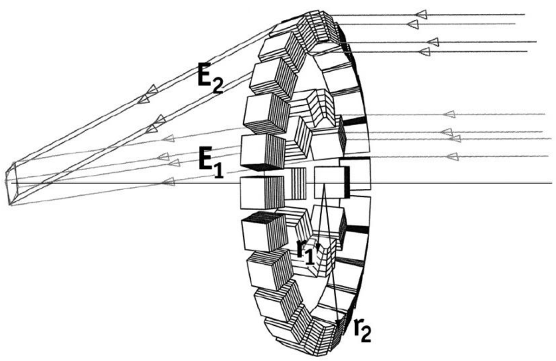

Figure 6 : Principle of the gamma-ray lens payload.

Instrument conceptual design and key characteristics : The Laue lens payload consists of a broad-band gamma-ray lens based on the principle of Laue diffraction of photons in mosaic crystals. Each crystal can be considered as a little mirror which deviates gamma-rays through Bragg reflection from the incident beam onto a focal spot. Each crystal diffracts an energy band proportional to its mosaic spread (also called mosaicity). Placing the crystals on concentric rings around an optical axis, and the careful selection of the inclination angle on each of the rings, allows then to build a broad-band gamma-ray lens that has continuous energy coverage over a specified band. Since large energies E_1 imply smaller diffraction angles θ, crystals diffracting large energies are located on the inner rings of the lens. Conversely, smaller energies E_2 imply larger diffraction angles and consequently the corresponding crystals are located on the outer rings (see Figure 6).

The LLO is composed of 5800 crystals arranged in 32 concentric rings. Each ring is populated by identical crystals, the axis of symmetry of the rings defining the optical axis of the lens. The characteristics of the LLO are presented in Table 3. The crystals are glued onto a CeSiC monolithic substrate that combines many properties. Beside being space qualified, this material have excellent mechanical stability and thermal conductivity, is lightweight and have an absorption lower than 6% at 850 keV (for a thickness of 3 mm). The effective area of the LLO is shown in Figure 7. It peaks at 340 cm^2 at 847 keV. At the focus, 62% of the signal is concentrated in a disc of 7 mm of radius (1.54 cm^2), which represents a concentration factor of ~ 220.

Parameter	*Value*	*Parameter*	*Value*
Focal length (m)	30.0	Mass of crystals (kg)	61.0
Inner radius (cm)	12.85	Crystal size (mm^2)	10 x 10
Outer radius (cm)	48.50	Crystal thickness (mm)	5.1 – 12.0
Crystal materials	Rh, Ag, Pb, Cu, Ge	Crystal mosaicity (")	45
Number of crystals	5800	inter Crystal spacing (mm)	0.5

Table 3: Characteristics of the LLO.

Measurement technique and pointing requirement : SNeIa are first discovered in visible light, most of the time within a few days after their explosion. At the time when the LLO will point towards them, they are point sources of known position. The observation strategy will consist in multiple (typically 4) pointed observations of 10^6 s, starting a few days after their discovery and distributed over about 6 months. The requirement for the lens pointing is ± 20'', with ±10 being the goal.

Interface and thermal stability : The LLO is attached to the spacecraft. The thermal stability requirement derives from the crystals that should keep their orientation within ± 10 arcsec with respect to the lens optical axis. During the MAX

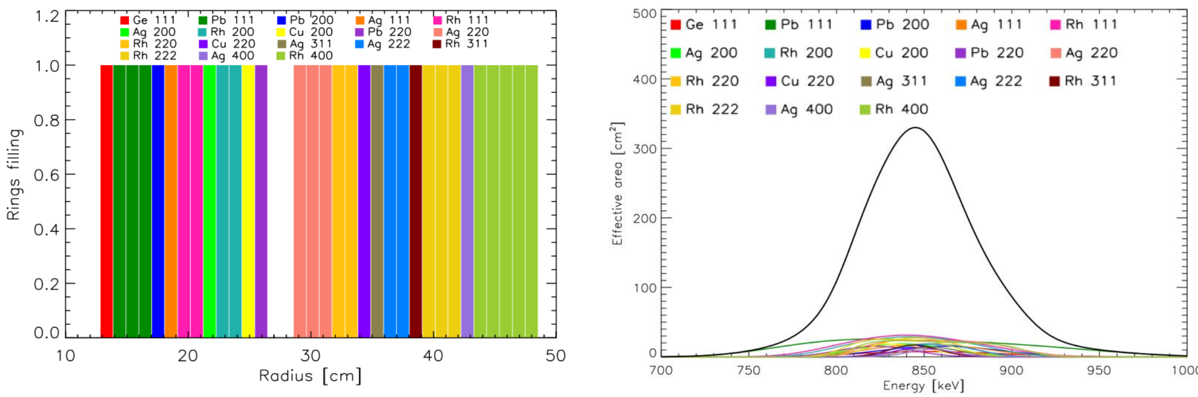

Figure 7 : Right: the color strips represent the crystal and reflection used for each ring. The lens is composed of the following crystals: 3193 Rh, 1662 Ag, 521 Pb, 348 Cu and 76 Ge. Left: Effective area of the LLO. This calculation assumes crystals oriented within 10 arcsec of their nominal angle (1 sigma, Gaussian distribution), and takes into account the absorption of the substrate (3 mm of CeSiC). The crystals are modeled using Darwin's model of mosaic crystals fed with experimentally determined parameters (Barriere et al, 2010).

pre-phase A study at CNES, the thermal control of the Laue lens was investigated (Hinglais et al., 2005). It showed that a cocoon of multilayer insulator (MLI) surrounding the lens, added to a few heaters and thermistors on the lens structure are sufficient to limit to 2ºC the thermal gradient across the lens for any sun exposition, which in the case of MAX would insure a crystal disorientation lower than 10 arced. The proposed LLO has a much simpler and smaller structure that MAX's, so it is believed that the thermal gradient permitted might be higher than 2ºC.

Current heritage and technology readiness level : The proposed lens is based on the experience gained in the Laue lens R&D work conducted during the last decade at CESR (France), UNIFE (Italy), and Argonne National Lab (USA), which culminated so far in the first detection of a gamma-ray source (the Crab nebula) using a gamma-ray lens during a stratospheric balloon flight (CNES funded CLAIRE project, von Ballmoos et al. 2004). We also benefit from the experience gained during the CNES assessment study of MAX (Duchon et al. 2005), the ESA Technical Reference Study on GRL (Brown 2005) and the GRI study proposed to ESA in the framework of CV07 (Knödlseder 2009). Technologically, the LLO can be split into 3 components: the crystals, their assembly onto a substrate, and the substrate (which all benefited from the recent CNES funded R&D, R-S09/SU-0002-025 R&T, R-S06/SU-0002-025 R&T and R-S06/SU-0002-026 R&T).

Crystals : The crystals used for the LLO (mainly Rh, Ag, Pb) have proved to exist with the required mosaicity (Barriere et al 2010). They are currently being investigated by our collaboration in a NASA-founded study aiming to demonstrate their availability in an industrial pattern. The complementary crystals (Ge, Cu) have already been used on Laue lens prototypes developed by CNES/CESR in France (von Ballmoos et al 2004) and ASI/University of Ferrara in Italy (Frontera et al 2008), and proved to be suitable for the realization of a Laue lens. Especially Cu was investigated in the framework of the successful ESA-founded Gamma–Ray Optics Development activity (ESTEC contract No. 20357/07/NL/NR).

Assembly method : Three different assembly methods have been investigated during the past 10 years in France and Italy. In particular, the latest investigated in a CESR/TAS collaboration (CNES contract n°70662/00 with TAS Cannes, ref DCT/SA/AB n°07-3202) led to the realization of a prototype module which showed outstanding results with 10 arcsec orientation accuracy obtained on several crystals. This module successfully underwent vibration and thermo-vacuum cycles tests. The requirements of the LLO does not show any particular difficulty, CeSiC large structure have already be proven in space.

2.3 The Coded Mask Optic

DUAL's Coded Mask Optic is adding high angular resolution to the All-Sky Compton Imager in a single region of highest importance for γ-ray astronomy : the Galactic Centre bulge. Coded aperture systems - consisting of masks or collimators - have been successfully used in high energy astronomy for over 20 years. Especially INTEGRAL has shown that it is possible to image with high efficiency both point and diffuse sources. Using the spatial modulation provided by the coded mask in combination with an optimized pointing strategy, the information on the source fluxes from different directions in the Field-of-View can be reconstructed and the systematic errors minimized.

Instrument conceptual design and key characteristics : The CMO will use the ASCI as focal plane detector placed 30 m apart. Its size is physically limited by volume and mass constraints. The design foresees the mask assembly to be 1 m^2 in size. A pattern of 9 mm thick tungsten blocks is used for spatial multiplexing of the γ-rays within a FoV of 2.5°full-width-at zero-response. Although the mask is modulating source photons over the entire energy range of the ASCI (100 keV-10 MeV), the CMO is optimized for sensitivity at 511 keV, in order to be able to map the diffuse emission from the Bulge with an accuracy better than one order of magnitude than the ASCI telescope resolution. With an angular resolution of 12' (54' at a focal distances of 7m), the CMO can measure the possible point source contribution at 511 keV when operating at the longer baseline, and map the Galactic Bulge diffuse emission for shorter mask-detector distance.

In the latter case, the FoV is 8x8 degrees for >50% coded area, i.e. significantly larger than the ASCI ARM. By filtering photon directions in the deconvolution or fitting process, it is then possible to improve the imaging capability and the SNR (by about a factor of 2). The mask pixel size chosen is 11.1 cm and the open fraction of the mask is 50%. In order to avoid periodicities in the mask pattern that would cause ambiguities in the reconstruction of the source fluxes, we have chosen a pseudo-random matrix of 9x9 elements as mask pattern. The mask will be placed on a carbon fiber support structure made of two flat panels and a CFRP supporting grid or honeycomb. The mask and support structure do not present particular risks and can be considered standard in view of the successful INTEGRAL masks, which has a factor ~2 heavier masks.

Performance assessment with respect to science objectives : The finite spatial resolution of the ASCI being ~20 times higher than the CMO element size, there will be no loss of sensitivity due to the discretization of the spatial information. The thickness of the tungsten elements provides an opacity of 90% at 500 keV and 53% at 2 MeV. In order to map the diffuse emission of the Galactic Bulge, the optimal configuration is the one at shorter distance (7m), for which it is possible to use the Compton event selection. However, should this option be not viable, the mapping of the 511 keV emission of the Bulge is still feasible at 30m by a survey of a ~50 square degrees region with a grid of pointings. In this case we exploit the modulation provided by the mask as a whole and the sensitivity is enough to provide a ~2° resolution map. The angular resolution of 12' at 30m is sufficient to exclude point sources contribution at 511 keV or conversely, to identify and locate them at a level of accuracy appropriate for identification.

An outstanding possibility could be to use a hybrid mask (two spatial scales) to provide fine imaging at lower energies, provided the ASCI has extended range down to ~20 keV. In this case it should be possible to reach an angular resolution as low as 30" by adding a thin (~0.5mm) tungsten layer on top of the coarse mask. The additional tungsten layer would not affect the sensitivity at 511 keV for an operational range of ~20-300 keV.

The CMO will have a total mass of 97 kg, with 9kg for the supporting structure (w/o contingency). For the W, a margin of 5% can be assumed. The required volume about 50,000cm3. No special mode or on-board data processing is required for the operation of the ASCI with the coded mask, if the telemetry is on an event-by even basis. The accuracy required by the CMO on the attitude and CMO-ASCI relative alignment is 0.2 arcmin.

2.4 The DUAL mast

A hybrid structure to support the ASCI at a distance of 30 m is proposed as an alternative to traditional rigid structures and Formation Flying technologies. For the relaxed requirements of DUAL (essentially the focal spot has to stay on the 30 cm wide detector), such a concept is advantageous in terms of mass and cost when compared with other solutions.

Instrument conceptual design and key characteristics : The Collapsible Tube Mast (CTM) is a concept already developed and flown by SENER as a deployment element used for space payloads. Stored in a box like a rolled stripe, once deployed outside the box, its section acquires a lentil shape which is stiff enough to be used as a mast with a mass on the other extreme. It is manufactured in two different materials (Carbon Fiber and Copper-Beryllium) and five different sizes with increased masses and stiffness (DUAL foresees caliber 5 : i.e. a section of 13x194 mm and a mass of 180g/m (CFRP) or 1070g//m (CuBe. The proposed hybrid concept is based on the use of CTM's for the deployment and separation of the detector and the lens. Two configurations with 3 CTM's arranged in a equilateral triangular shape have been analyzed, each with one of the different existing material options: Carbon Fiber and Copper-Beryllium. Carbon Fiber has a lower mass per unit length but is less rigid whereas the Copper-Beryllium is exactly the opposite and offers a higher rigidity but with a higher mass. For both structural configurations, a control system have been analyzed and designed, leading to feasible features, where special care has been taken to address the issue of the inherent structural flexibility of the system. A future trade-off will be performed where a more in-depth analysis will be performed regarding the stability and controllability with a large emphasis on the necessary robustness properties.

Performance assessment and pointing and alignment requirements : The main requirement for the mast is to maintain the detector soft spot (Ø 3 cm) in the focal spot of the LLO at a distance of 30±0.1m – the minimum requirement is to keep the 30 cm wide detector in the lens beam. For the observation with the LLO and CMO, the spacecraft maintains an inertial pointing towards the source, requiring an absolute accuracy of 20 arcsec for the lens only. This fine pointing is potentially jeopardized by the modes generated by the mast. SENER has therefore performed a dedicated modal analysis of the 3 CTM configuration with the detector mass at one end is performed where the eigen-frequencies and effective masses for translation and rotation of the flexible modes are computed leading to the following flexible modes' frequencies (1st mode): 0.041 Hz (Carbon fiber) and 0.054 Hz (Copper-Beryllium). It has been shown (see the results of the analysis on http://dual.cesr.fr/M3/mast) that the structural flexibility and its associated deformations do not impose a fundamental limitation on the control design feasibility.

The 3 CTM masts and containers have a total mass of 61.2 kg (w/o contingency). The single CTM's are already flight qualified, only the simultaneous deployment of the three CTM's has to be developed. A significant scientific benefit for consists in the possibility of retracting the mast to change its length (e.g. from 30 m to 7 m for observation with the CMO). The implementation of the focal length reduction of the telescope will be performed at the end of the mission for additional mask-based observations.

Alternatives : Possible alternative deployable structure systems which could be used for DUAL are rigid masts such as the ADAM (Able/ATK) or the Self Deploying Tube Structure (SDTS) currently being developed by Astrium in the UK. The ADAM mast has a very long record of success in space – in the case of an US involvement in DUAL, this mast would represent a substantial contribution. An ADAM mast will be used in 2012 as an optical bench with in the NuStar X-ray mission.

ASTRIUM's SDTS concept uses a series of panels attached via tape spring hinges which are folded flat in the stowed configuration to provide a packing efficiency of~ 1:20. The deployment is totally passive, with motorization achieved using the stored energy within the tape springs. Controlled deployment can be achieved through one of a number of damping systems. Astrium has demonstrated through analysis that this type of structure can provide excellent deployed stiffness (>2Hz) out to focal lengths of up to 80m. It can also be constructed entirely of carbon composite so will be both thermally stable and mass efficient. Astrium's preliminary breadboard has resulted in a current TRL of 3; the technology is expected to reach TRL 4 by 2012.

2.5 Performance assessment and science objectives

The ASCI, LLO and CMO payload performances have been evaluated by dedicated simulation software. The critical performance parameters for these payloads are the expected effective area and focal spot characteristics as function of energy. For the ASCI, the most critical properties are the instrumental background and detection efficiency (which is limiting the sensitivity) and the spectral resolution (which is limiting the energy resolution). An accurate mass model that includes passive material in the detector and its surroundings, true energy thresholds and energy and position measurement accuracy, and a roughly accurate S/C bus mass and position are crucial to this modeling. The ASCI simulations were performed using the MEGAlib package (Zoglauer, et al., 2006). Care has been taken to accurately include all passive materials close to the detector. The simulated background environment includes cosmic diffuse photons, cosmic-ray protons, electrons, and positrons, calculated using the MEGAlib environment tools. MEGAlib (and its predecessor MGGPOD) has been successfully applied to modeling the instrumental backgrounds of the TGRS, SPI, and RHESSI instruments, and the NCT balloon payload.
The relevant DUAL performances are summarized in table 4 and in figures 8 to 12.

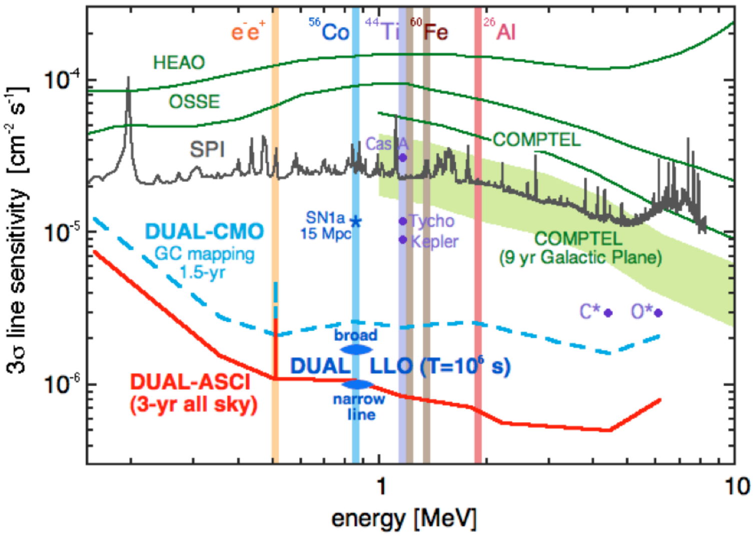

Figure 8 : **DUAL narrow line sensitivity**

After its 3 years of continuous sky survey, the sensitivity achieved by the All-Sky Compton Imager (**ASCI**) for any source on the sky is an improvement by a factor of 30 with respect to previous missions.

The same spectacular improvement is achieved by the Laue-Lens Optic (**LLO**) in 10^6s during deep observations of the broad ^{56}Co line from SNIa.

The Coded-Mask Optic (**CMO**) provides high angular resolution imaging (10'-40') in the Galactic Bulge region (FOV 2°-8°).

ASCI : All-Sky Compton Telescope		
Energy range		0.1 – 10 MeV
Spectral resolution (10 MeV - 0.1 MeV)		0.2 – 1 % FWHM
Field of view		4 π at all times
Angular resolution	511 keV 847 keV 1809 keV	2.7° (4.5° at sensitivity limit) 2.1° (3.5° at sensitivity limit) 1.6° (2.7° at sensitivity limit)
Narrow line sensitivity (any DC source after T_{obs}= 3 year)	511 keV 847 keV 1809 keV	$2.6\cdot10^{-6}$ ph·cm^{-2}·s^{-1} $1.1\cdot10^{-6}$ ph·cm^{-2}·s^{-1} $7.2\cdot10^{-7}$ ph·cm^{-2}·s^{-1}
Continuum sensitivity (any DC source, T_{obs}= 3 year)	500 keV 5 MeV	$4.2\cdot10^{-5}$ ph·cm^{-2}·s^{-1}MeV^{-1} $1.5\cdot10^{-6}$ ph·cm^{-2}·s^{-1}MeV^{-1}
Polarization sensitivity (MDP) 3 σ, any DC source, 200-500 keV T_{obs}=3 year	1 Crab 0.1 Crab 0.01 Crab	0.2% (statistical limit only) 2.4% 23.6%
GRB sensitivity (5 σ)		~ 10^{-6} erg/cm^2
Timing		1 μsec relative, 1 ms absolute
Laue Lens Optic (^{56}Co line from SN1a)		
Energy range		800-900 keV
Spectral Resolution		0.2 – 1 % FWHM
Field of view / Angular resolution		5 arcmin / 1 arcmin
narrow Line Sensitivity (dE = 3%, T_{obs}=10^6 sec) broad Line Sensitivity (dE = 0.5%, T_{obs}=10^6 sec)		$1.0\cdot10^{-6}$ ph·cm^{-2}·s^{-1} 1.8 $1.0\cdot10^{-6}$ ph·cm^{-2}·s^{-1}
CMO : Coded Mask Optic (Galactic Bulge high resolution imaging)		
Energy range		0.1 - 10 MeV
Spectral Resolution (10 MeV - 0.1 MeV)		0.2 - 1 % FWHM
Field of view (f = 30 m - 7 m)		2°12' - 8°54'
Angular resolution (f = 30 m - 7 m)		12' - 54'
Continuum sensitivity (any DC source in the Galactic Bulge, 1.5 year)	200 keV 500 keV 1 MeV	$3.1\cdot10^{-2}$ ph·cm^{-2}·s^{-1}MeV^{-1} $9.0\cdot10^{-5}$ ph·cm^{-2}·s^{-1}MeV^{-1} $3.1\cdot10^{-5}$ ph·cm^{-2}·s^{-1}MeV^{-1}
Narrow Line Sensitivity, T_{obs}=1.5 year any DC source in the Galactic Bulge	511 keV 1809 keV	$4.9\cdot10^{-6}$ ph·cm^{-2}·s^{-1} $2.6\cdot10^{-6}$ ph·cm^{-2}·s^{-1}
Polarization, T_{obs}=1.5 year 3 σ, any DC source, 200-500 keV	1 Crab 0.1 Crab	0.4% 4.5%
Timing		1 μsec relative, 1 ms absolute

Table 4. DUAL payload characteristics

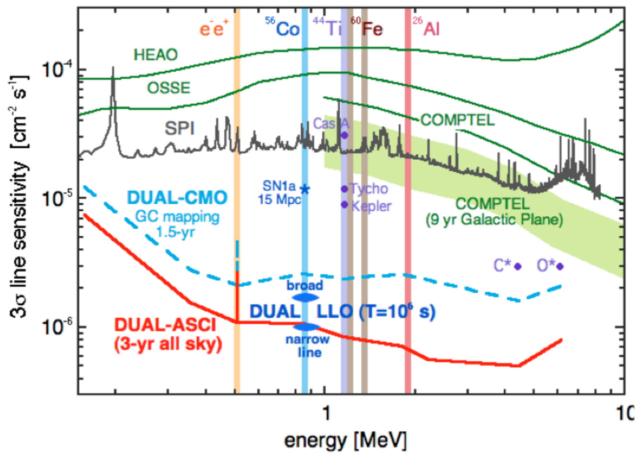

Figure 9 : DUAL line sensitivity : After its 3 years of continuous sky survey, the sensitivity achieved by the All-Sky Compton Imager (ASCI) - for any source on the sky ! The same improvement is achieved by the Laue-Lens Optic (LLO) in 10^6s during deep observations of the broad ^{56}Co line from SNIa.

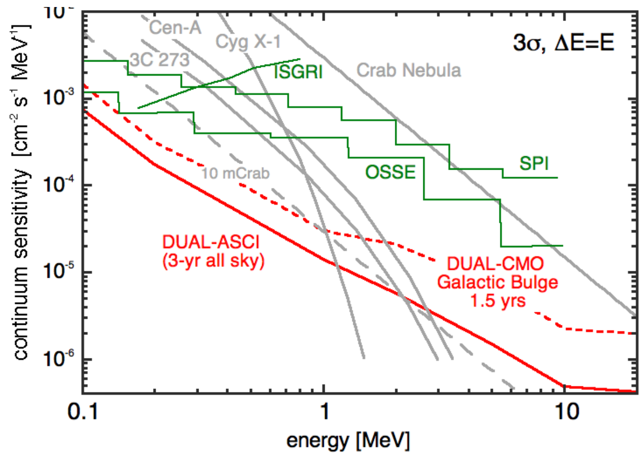

Figure 10 : DUAL continuum sensitivities
Sensitivity achieved by the All-Sky Compton Imager ASCI for any source on the sky after 3 years of continuous sky survey. The coded mask optics (CMO) provides high angular resolution imaging (12'-54') in the Galactic Bulge region (FOV 2°-8°).

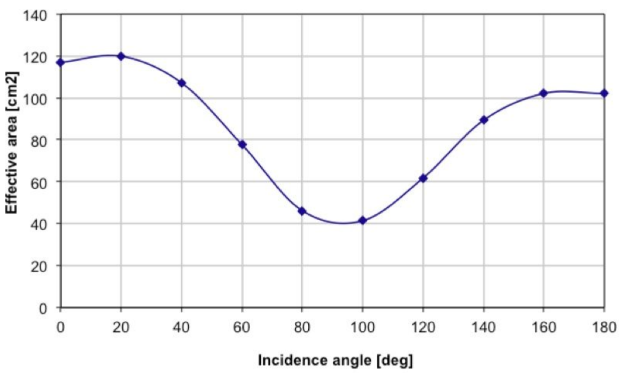

Figure 11: ASCI Effective area at 511 keV, as a function of incidence angle.

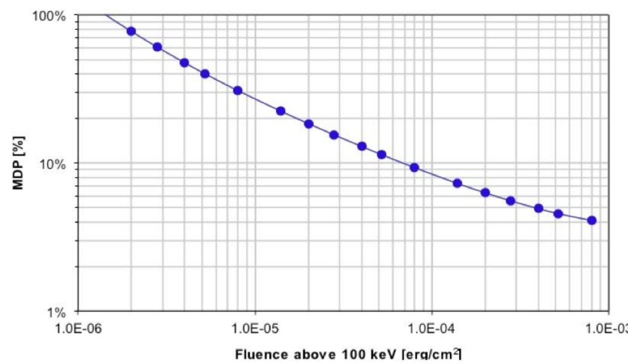

Figure 12: ASCI Minimum detectable polarization (MDP) for a gamma-ray burst characterized by broken power-law with a single break (a=-1.0, b=-2.5, break : 150 keV).

3. SPACECRAFT

The DUAL payloads consists of two optics modules, the LLO and the CMO that are deployed on the S/C after launch, and a detector (ASCI) on top of a 30 meters deployable mast. As a spacecraft for the above payloads, we propose the use of a Thales Alenia Space PROTEUS MARK 2 satellite class, a multi-purpose platform presently under development in the frame of the GOKTURK program. This platform is issued from PROTEUS mark 1 platform which is flight proven with the successful launch of the JASON-1, JASON-2, CALYPSO, SMOS and COROT satellites. The robust and reliable PROTEUS structure is composed of an aluminum rod assembly forming a cube (1.25 m long) stiffened by sandwich panels. It acts as primary structure and guarantees the transfer of main loads from payload to launcher through a fully machined aluminum frame. The PROTEUS MARK 2 structure is compliant with present estimated maximal payload mass of 404 kg. Adaptations will however have to be brought to this platform to deal with L2-orbit constraints, which are described hereafter.

Attitude and orbit control and reaction control system requirement : The PROTEUS MARK 2 AOCS provides a reliable and simple safe mode, an intermediate attitude acquisition mode, and a nominal operational mode based on stellar sensing and reaction wheels for actuation. To ensure a good pointing accuracy, the 3 Star trackers heads have been placed on the LAUE lens support plate. During the pre-assessment, this preliminary design will be re-assessed and traded against other accommodation possibilities.

The attitude is controlled through four reaction wheels with 20 Nms angular momentum capacity each. The sizing of the upper flap and of the solar arrays has been done to balance the differential solar radiation pressure at a maximum. The 20 Nms wheel capacity should thus be enough to interspace wheels de-saturations in compliance with Payload pointing duration requirements. It will have to be refined during the pre-assessment phase.

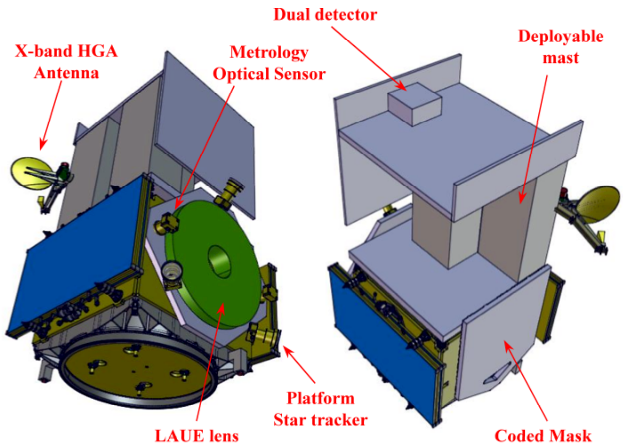

Figure 13: DUAL in folded configuration

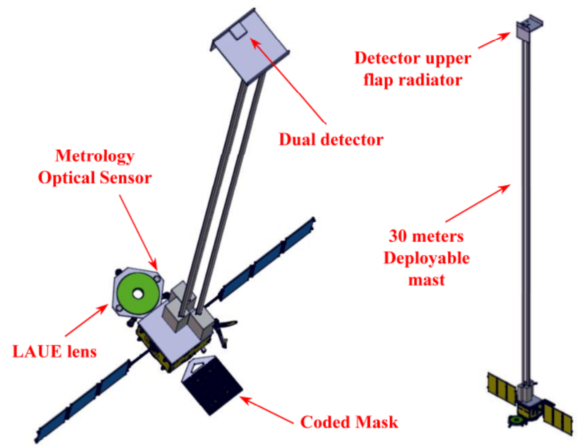

Figure 14: DUAL in deployed configuration

The orbit control and maintenance is done through a propulsion subsystem based on Hydrazine (N2H4) with 16 thrusters and a 50 kg tank. The exact thruster topology and thrust level will be thoroughly studied and determined during the pre-assessment phase to deal with the 30 meters mast constraints. L2-orbit specificity will lead to modify the PROTEUS MARK 2 AOCS, by removing the 2 magnetometers and the 3 Magnetic bars used for wheels de-saturation. The de-saturation maneuvers will thus be performed with the thrusters and optimized with payload re-pointing strategy. Control laws of nominal modes and safe modes will also be have to be adapted to the specific DUAL configuration, with high inertia values and the low Eigen frequencies of the mast-detector assembly.

Power Management and Distribution : Standard GaAs Solar Arrays can be used on DUAL satellite since the Solar Flux in L2 position is very near from the flux encountered near the Earth. Considering the power budget provided in Table 5, four 1 m^2 GaAs panels deliver enough power for the platform and the payload with comfortable margins. However, 2 other dummy 1 m^2 panels have been added to equilibrate the Solar radiation pressure imbalance generated by the detector thermal flap located at the end of the mast. The battery sizing is mainly driven by the platform consumption during launch. After separation, the Solar Arrays are released and continuously deliver power to the Satellite during the cruise and in L2 position. As a consequence, battery size on DUAL satellite has been greatly lowered wrt Low Earth Orbit configuration of the PROTEUS MARK 2 platform. A Power Conditioning and Distribution Unit (PCDU) will manage the power share between the Solar Arrays and the battery, and will distribute this power to the platform and payload units.

Thermal control : The passive thermal control uses only conventional and qualified components (radiators and MLI). The redundant active thermal control is based on a heating concept of regulation driven by the on-board computer. It can be noticed that L2 point induce a stable thermal environment, with no Earth albedo nor strong eclipse phases. As a consequence, the thermal control as described here above is suited to such conditions. A detailed thermal analysis of the detector will be performed during the pre-assessment phase to determine if the present passive thermal control (MLI, Sun shielding & radiator panel) is able to keep the detector at the required temperature in all operational conditions. If this is not the case, a cryo-cooler machine would be required at detector level. Considering present power margins, such a cooler would remain compatible with present platform design. It would however increase a little the global mass budget.

On-board data handling : The command & control sub-system is based on a centralized architecture and fully redundant. A central computer (SMU) controls the platform and the payload. The main CPU is an ERC32 processor to provide the DUAL satellite with the necessary mission autonomy. A mass memory is available within the SMU or in a dedicated unit, to allow satellite Housekeeping and Payload data storage between two Earth communication sessions. The TC&R subsystem provides an X-band ground link able to provide full duplex command, platform telemetry, payload data and ranging interfaces between the satellite and dedicated ground station according to ESA standards. The TC&R exhibits a high reliability thanks to its full redundancy. Two Low Gain Antenna ensures a permanent visibility with Earth ground stations whatever the satellite attitude. A mobile High gain Antenna is used in nominal conditions, providing a high download data rate and having enough degrees of freedom to deal with Payload re-pointing needs.

Mission operations concept : The mission operations for the DUAL mission will take place from ESA's European Space Operation Centre (ESOC). After Launch, ESOC will support the early IOT, the cruise to L2 point and the DUAL configuration setup.

Estimated overall resources : The DUAL satellite system level mass and power budgets are summarized in Table 5. All sub-systems are inherited from the PROTEUS family. The Technology Readiness Level (TRL) for all proposed sub-systems in this study is high (> 6).

Specific environmental constraints : The environment encountered by DUAL satellite during the cruise to L2 and once arrived at the operational point, is less constraining than for Low Earth Orbit missions. Radiation fluxes are much lower and while Solar flux is equivalent, the Earth albedo is removed. Moreover, the Solar illumination is far less variable than for LEO due to L2 orbit stability. As a consequence, the same PROTEUS MARK 2 platform architecture can be reused, particularly concerning equipment shielding and thermal control concepts.

Special requirements : Due to ASCI-LLO lens relative alignment requirements, a metrology system has been accommodated on the DUAL satellite. The proposed metrology for DUAL is based on optical sensors with two redundant optical heads on the lens and targets on the detector located at the top of the mast. An actuation part will also be added to achieve the required alignment between the DUAL payload parts. The metrology architecture addresses different trade-offs on each part: for optical sensors, targets choice between power LEDS or corner cubes with Laser illuminator installed on the Lens, and for actuation part choice between a movable mast root or a Lens rotation through a 2-DOF actuator.

Sub-system	*Mass (kg)*				*Power (W)*
	basic	margin		current	max.
AOCS/GNC	51	10%	5	56	53
TT&C	30	10%	3	33	156
Data handling	18	5%	1	19	67
EPS	80	10%	9	89	25
Propulsion including Hydrazine	59	10%	6	65	1
Thermal control	18	10%	2	20	115
Bus structure	151	10%	15	166	
Total service module budgets	407 kg		41 kg	448 kg	417 W
DUAL payload	337	20%	67	404	123
Total payload budgets	337 kg		67 kg	404 kg	123 W
Harness & PCU losses	39	10	4	43	21
System margins		20%	168	168	112
Total budgets (incl. margin)				1063 kg	673 W

Table 5: DUAL system level mass and power budget.

Current Heritage and Technology Readiness Level : The DUAL satellite reuses the PROTEUS MARK 2 platform having a strong heritage from previous PROTEUS MARK 1 missions and studies. Few adaptations will be made to comply with L2-orbit specificities. The most important modifications will concern the AOCS software related to the DUAL satellite configuration with high inertia and low mast Eigen frequency. However, the associated modifications do not jeopardize the platforms strong TRL. The TTC architecture will also be adapted, removing the S-band equipment and accommodating X-band equipment instead. All X-band parts foreseen for DUAL satellite have a high TRL. Only the mast will require a specific development, that should allow to achieve a TRL 5 in 2015.

Acknowledgment

We acknowledge the support of THALES ALENIA Cannes, SENER Madrid, CANBERRA Lingolsheim in the preparation of the technical part of this proposal. The proposal has also benefit from the results of the phase 0 study conducted by CNES in the context of the MAX project, and from the results of the Technical Reference Study conducted by ESA in the context of the GRL project. Technical developments in the context of DUAL are financially supported by ASI (contract I/088/06/0), CNES (lens R&D contracts 02/0551/01-DPI120 and DCT/SA/AB No 07-3202, R-S06/- and R-S09/SU-0002-025, and R-S06/SU-0002-026), ESA (ESTEC contract 20357/07/NL/NR) and the Spanish Ministry of Science and Innovation.

References

Bandstra, M.S., et al, to appear in ApJ., arXiv:1106.0323 (2011)
Barrière, N., et al., J. App. Cryst. **42**:5, p 834 (2009)
Barrière, N., et al., Proc SPIE **7732**, p. 773226 (2010)
Brown, C., GRL Technology Reference Study Final Report. ESA SCI-A/2005/058/GRL/CB (2005)
Duchon, P., Exp. Astron, **20**, p. 483 (2005)
Frontera et al., F., Proc SPIE **7011**, p. 70111R (2008)
Gutknecht, D., Nucl. Instr. and Meth. A **288**, 13 (1990)
Hinglais E., et al., Exp. Astron. **20**, p. 435 (2005)
Knödlseder J., et al., Exp. Astron. **23**, p. 121 (2009)
Phlips B., et al., IEEE Nucl. Sci. Symp. **2110** (2004)
Vetter K., et al, Nucl. Instr. and Meth. A **452**, 223 (2000)
Schönfelder, V., et al., ApJS 86, **657** (1993)
Trombka. J.I, et al., ApJ 181, **737** (1973)
von Ballmoos, P., et al., New Astron. Rev. **48**, pp. 243-249 (2004)
von Ballmoos, P., et al., the DUAL science case, http://dual.cesr.fr/M3/science.html (2010)
Weidenspointner G., et al., Nature **451** (7175), 159 (2008)
Zoglauer A., and Kanbach G., Proc. SPIE, 4851, 1302 (2003)
Zoglauer A., PhD thesis / MPE report No 289, TU Munich (2006)
Zoglauer, A., et al., NewAR 50, 624 (2006)