GAIA – Unravelling the Origin and Evolution of Our Galaxy

M.A.C. Perryman
Space Science Department, ESA Directorate of Scientific Programmes, ESTEC, Noordwijk, The Netherlands

O. Pace
Science Future Projects and Technology Office, ESA Directorate of Scientific Programmes, ESTEC, Noordwijk, The Netherlands

The GAIA Science Advisory Group

GAIA was the Greek goddess of Earth worshipped as the universal mother who had created the Universe. More recently her name was taken by James Lovelock for his theory on the interdependency of the Earth's atmosphere and biological organisms. Now it is the name given to an ambitious project to unravel the structure, origin and evolution of our Galaxy. GAIA is a Cornerstone candidate in ESA's Scientific Programme, proposed to carry out a stereoscopic survey of more than a billion stars – a detailed census of around 1 percent of the stellar content of our Galaxy. It will also detect upwards of 20 000 extra-solar planets, provide a comprehensive Solar System census of asteroids, and undertake tests of General Relativity with unprecedented accuracy. The extensive harvest from this revolutionary undertaking is expected to have enormous scientific implications.

Introduction

GAIA builds upon the observational techniques pioneered and proven by ESA's Hipparcos mission to solve one of the most difficult yet deeply fundamental challenges in modern astronomy – to create an extraordinarily precise three-dimensional map of our Galaxy and beyond. In the process, by combining positional data with radial velocities, GAIA will map the stellar motions, which encode the origin and subsequent evolution of the Galaxy. Through comprehensive photometric classification, GAIA will provide the detailed physical properties of each star observed, characterising their luminosity, temperature, gravity and elemental composition. This massive multi-parameter stellar census will provide the basic observational data required to quantify the origin, structure and evolutionary history of our Galaxy.

GAIA will achieve this by repeatedly measuring the positions and multi-colour brightnesses of all objects down to V = 20th magnitude (400 000 times fainter than the human eye can see). On-board object detection will ensure that variable stars, supernovae, transient sources, micro-lensed events and minor planets (including those that cross the orbit of the Earth) will all be detected and catalogued to this faint limit. Final accuracies of 10 microarcsec at 15 mag, comparable to the diameter of a human hair at a distance of 1000 km, will provide distances accurate to 10 percent as far as the Galactic Centre, 30 000 light-years away. Stellar motions will be measured even in the Andromeda galaxy more than 2.5 million light-years away, and tens of thousands of extra-solar planets will be discovered.

A Scientific Harvest of Enormous Extent and Implication

GAIA will pinpoint exotic objects in colossal numbers: many thousands of extra-solar planets will be discovered (see 'Extra-Solar Planets'), and their detailed orbits and masses determined; brown dwarfs and white dwarfs will be identified in their tens of thousands; some 100 000 extragalactic supernovae will be discovered, alerting ground-based observers to follow-up observations; Solar System studies will receive a massive impetus through the detection of many tens of thousands of new minor planets (see 'Asteroids and Near Earth Objects'); inner Trojans and even new trans-Neptunian objects, including Plutinos, will be discovered. In addition to astrophysical and Solar System studies, GAIA will contribute some surprising results to fundamental physics (see 'General Relativity').

Science with GAIA

The primary science goal of the GAIA mission is to clarify the origin and history of our Galaxy, quantifying tests of galaxy formation theories, and also dramatically advancing our knowledge of star formation and evolution. This is possible since low-mass stars live for much longer than the present age of the Universe, and retain in their atmospheres a fossil record of the chemical elements in the interstellar medium at the time of their formation. The orbits of these stars similarly encode their dynamical histories, so that the GAIA results will precisely identify relics of tidally-disrupted accretion debris, and probe the distribution of dark matter. The GAIA survey will establish the luminosity function for pre-Main Sequence stars, detect and categorise rapid evolutionary stellar phases, place unprecedented constraints on the age, internal structure and evolution of all stellar types, establish a rigorous distance-scale framework throughout the Galaxy and beyond, and classify the star formation, kinematical and dynamical behaviour across the Local Group of galaxies.

Stellar Astrophysics

GAIA will provide distances of astonishing accuracy and in remarkable numbers for all types of stars of all stellar populations, even the brightest, or those in the most rapid evolutionary phases, which are very sparsely represented in the solar neighbourhood. About 20 million stars will be measured with a distance precision of 1% (compared to a few hundred now), and about 200 million will be measured to better than 10% (compared to about 20 000 now). Some 10 million resolved binary systems will be detected within 250 pc. With the parallel determination of extinction/reddening and metallicities by the use of multi-band photometry and spectroscopy, this huge amount of basic data will provide an extended basis for reading in-situ stellar and galactic evolution. All parts of the Hertzsprung-Russell diagram will be comprehensively calibrated, including all phases of stellar evolution, from pre-Main Sequence stars to white dwarfs and all existing transient phases; all possible masses, from brown dwarfs to the most massive O stars; all types of variable stars; all possible types of binary systems down to brown dwarf and planetary systems; all standard distance indicators (pulsating stars, cluster sequences, supergiants, central stars of planetary nebulae, etc.). This extensive amount of data of extreme accuracy will stimulate a revolution in the exploration of stellar and galactic formation and evolution, and the determination of the cosmic distance scale.

Our Galaxy – the Milky Way

GAIA will determine the physical characteristics, kinematics and distribution of stars over a significant fraction of the Galaxy, with the goal of achieving a full understanding of the Galaxy's dynamics and structure and consequently its formation and history (Fig. 1).

The most conspicuous component of our Galaxy, or Milky Way, is its flat disc which contains nearly 10^{11} stars of all types and ages orbiting the Galactic Centre. The Sun is located at 27 000 light-years from the Galactic Centre. The disc displays a spiral structure and contains interstellar material, predominantly atomic and molecular hydrogen, and a significant amount of dust. The inner part of the disc also contains the bulge, which is less

Extra-Solar Planets

In the past five years, a huge programme of high-precision ground-based radial velocity (Doppler) measurements has led to the detection of about 40 extra-solar planets surrounding stars other than our Sun. These are all within a distance of about 100 light-years. The planets detectable by this method are rather massive, comparable to Jupiter (which has about 300 times the mass of Earth). The systems have some surprising properties: two thirds of these giant planets are orbiting their host stars much closer than Mercury orbits the Sun (0.39 astronomical units), some having periods as short as 3 days. More than one third have significantly elliptical orbits, with $e > 0.3$, compared with the largest eccentricities in our Solar System of about 0.2 for Mercury and Pluto, and 0.05 for Jupiter. The puzzle is how they can have formed or been displaced to such unexpected orbits. Theories of planetary formation developed to explain the formation of our own Solar System predicted that they would not form so close to the central star, where temperatures are high, and where the amount of protoplanetary disc matter was believed to be small. A transit across the face of the parent star has been observed for one system, and this leads to estimates of the radius, mass and density of the planet. One system is multiple, consisting of three massive planets, and theorists are involved in modelling its stability, and how it too might have formed. Over the next 5 years, a total of about 100 extra-solar planets may be known.

GAIA will completely revolutionise the field of extra-solar planetary physics. It is estimated that the remarkable precision of GAIA's positional measurements will lead to the detection and measurement of between 20 000 and 30 000 extra-solar giant planets out to distances of 300-500 light-years, corresponding to some 20 new planets per day, for each day of the 5-year mission. Masses and orbits will be determined for each, leading to a comprehensive inventory of planets near to our Sun. Theorists are currently estimating temperatures, radii, chemical compositions and other properties of extra-solar planets, aiming to predict which combination of physical parameters will lead to planets on which life may have developed: for example, as a function of stellar type and age, distance from the central star such that water will be in liquid form, mass and radius of the planet, etc. GAIA's survey will underpin future ambitious missions related to extra-solar planets, such as Darwin and Eddington.

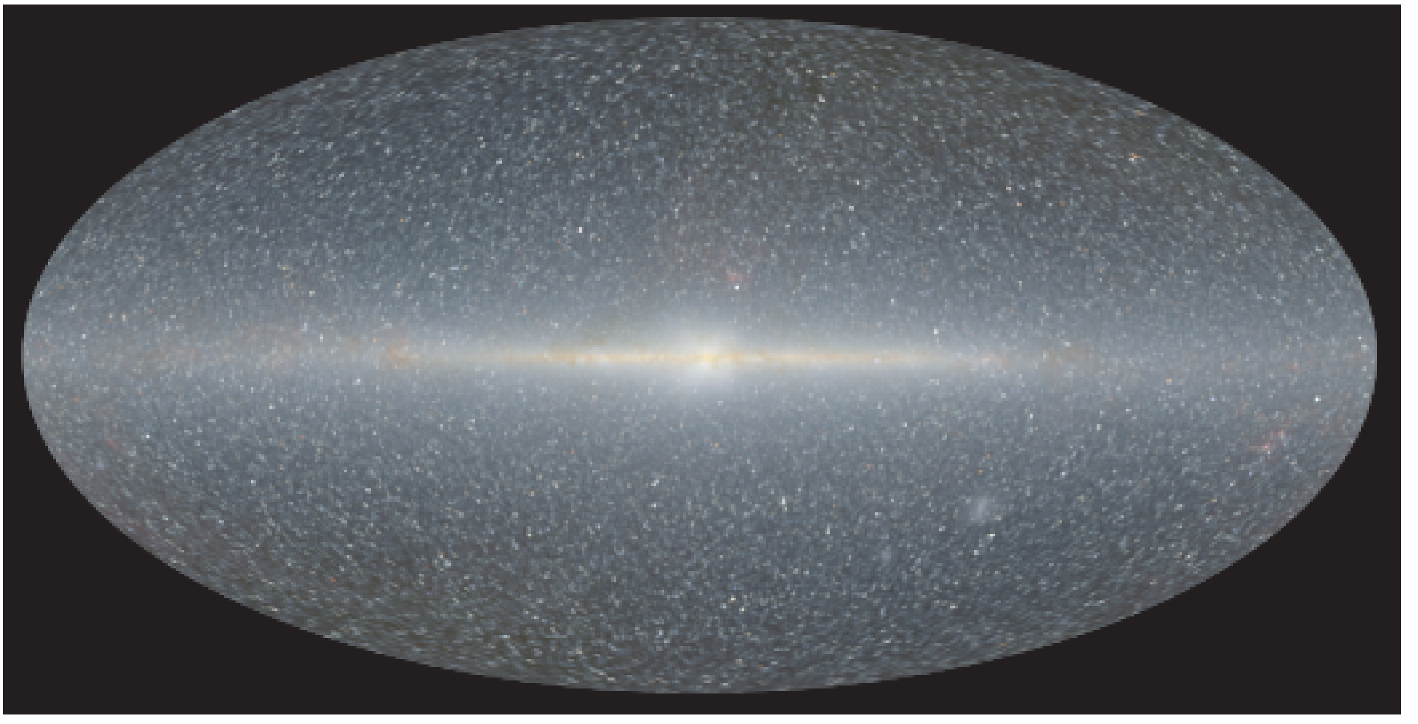


Figure 1. This composite near infrared (COBE) image of the Milky Way shows our Galaxy as it might be seen by an external observer. It shows red stars and dust in our Galaxy superposed against the faint glow of many dim stars in distant galaxies. Faintly visible as an S-shaped sash running through the image centre is zodiacal light – dust in our own Solar System. The thin disc of our Galaxy is clearly visible
(Courtesy of Edward L. Wright (UCLA), COBE, DIRBE, NASA, used with permission)

flattened and consists mostly of fairly old stars. At the centre lies a massive black hole of about 2.9 x 10^6 solar masses. The disc and the bulge are surrounded by a halo of about 10^9 old and metal-poor stars, as well as some 140 globular clusters and a small number of satellite dwarf galaxies. The entire system is embedded in a massive halo of dark material of unknown composition and poorly known spatial distribution. The various components of the Milky Way (stars, planets, interstellar gas and dust, radiation and dark matter) are distributed in age (reflecting their birth rate), in space (reflecting their birth place and subsequent motion), on orbits (determined by the gravitational force generated by their own mass) and with different chemical abundances (determined by the past history of star formation and gas accretion.) The history of the formation and subsequent evolution of our Galaxy is thus preserved in these complex distributions. Unravelling these complex patterns to trace the development of our Galaxy since its creation is the primary aim of the GAIA mission.

The Galactic Disc

Star formation has been reasonably continuous in the disc of the Galaxy over the past 12 billion years and, as a result, the disc contains stars with a range of chemical compositions, ages and kinematics. In the past decades, radio and millimetre observations, combined with kinematic models, have revealed the distribution and kinematics of the interstellar gas for nearly the entire Galaxy. They have delineated the spiral structure, and mapped a warping of the galactic disc outside the solar orbit. However, very little is known about the stellar disc beyond about 1000 light-years from the Sun. This is due to significant interstellar extinction towards the central regions of the Galaxy at optical wavelengths, and our inability to determine accurate distances and space motions. The GAIA parallaxes, proper motions, radial velocities and photometry will allow derivation of the structure and kinematics throughout the stellar disc for a large fraction of the Milky Way (Fig. 2).

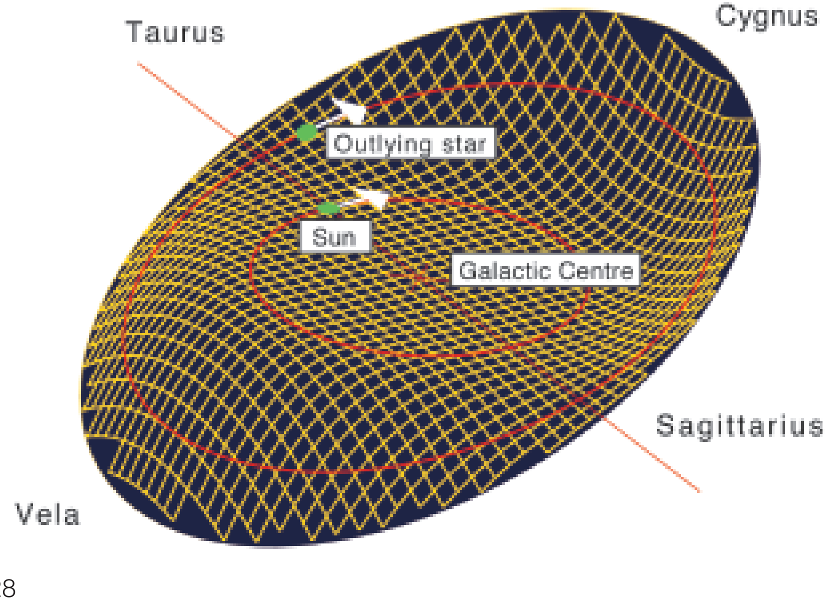


Figure 2. The disc of the Milky Way based on HI observations. The vertical axis is exaggerated by a factor of 10. The arrows show the motion of the Sun and an outlying star on their orbits in the Galaxy. The outlying star has an upward motion as seen from the Sun. Directions in the sky as seen from Earth, are indicated by their constellation names. GAIA observations will provide an enormous advance in understanding the structure of our galactic disc
(Courtesy of R.L. Smart et al.)

Spiral arms
Spiral arms are a distinguishing feature of disc galaxies with an appreciable gaseous component, and are clearly evident in the radio and far-infrared emission of our Galaxy. They are an important component, as they have associated streaming motions, redistribute angular momentum and are the primary locations of star formation, funnelling mass from one component (the gas) to another (the stars). Currently, our understanding of the large-scale dynamics and structure of the galactic disc derives mainly from 21-cm observations of HI, but these observations only provide the density as a function of radial velocity in any given direction, i.e. a single velocity component. To infer the actual distribution of the gas, and its kinematics, we rely upon the assumption of circular rotation. Even with this assumption, distances within the solar circle are ambiguous. GAIA will overcome these problems by providing a direct map of all of the major arms on our side of the Galaxy, using the location of young tracer populations. It will identify what constitutes an arm, its kinematic signature, and its stellar population mix.

Galactic disc warps
Galactic discs are thin, but they are not flat. Approximately one-half of all spiral galaxies have discs that warp significantly out of the plane defined by the inner galaxy. Remarkably, there is no realistic explanation of this common phenomenon, though the large-scale structure of the dark matter, and tidal interactions, must be important, as the local potential at the warp must be implicated. Neither the origin nor the persistence of galaxy warps is understood, and insufficient information exists to define empirically the relative spatial and kinematic distributions of the young (OB) stars, which should trace the gas distribution, and the older (gKM) stars, which define a more time-averaged gravitational field. At a distance of 50 000 light-years from the Galactic Centre, for a flat rotation curve, the systematic disc rotation corresponds to 6 milliarcsec per year. The kinematic signature from a 3000 light-year-high warp corresponds to a systematic effect of about 90 microarcsec per year in latitude and about 600 microarcsec per year in longitude. The study of the galactic warp will be well within the limits of GAIA's performance.

Galactic interstellar matter
The combination of GAIA parallaxes with GAIA photometry over a large part of the visual spectrum will provide a database of unprecedented size and accuracy with which to investigate the distribution of interstellar matter. The dust embedded in the gas causes extinction of starlight, both in terms of dimming, and as a colour change. These can then be used, through the known correlation of extinction and column density of neutral gas, to estimate the amount of gas along the path length to the star. The power of this method was demonstrated by the Hipparcos data. Important topics in this area that can be addressed with GAIA data are the optical thickness of the Milky Way disc, and the scale length of the dust distribution.

Dark matter in the disc
The distribution of mass in the galactic disc is characterised by two numbers, its local volume density and its total surface density. They are fundamental parameters for many aspects of galactic structure, such as chemical evolution (Is there a significant population of white dwarf remnants from early episodes of massive star formation?), the physics of star formation (How many brown dwarfs are there?), disc galaxy stability (How important dynamically is the self-gravity of the disc?), the properties of dark matter (Does the Galaxy contain dissipational dark matter, which may be fundamentally different in nature from the dark matter assumed to provide flat rotation curves, and what is the local dark matter density and velocity distribution expected in astro-particle physics experiments?), and non-Newtonian gravity theories (Where does a description of galaxies with non-Newtonian gravity and no

General Relativity

In 1919, Einstein's General Theory of Relativity was put to its first observational test – at the time of a total solar eclipse, the displacement of stellar images close to the Solar limb was measured, and demonstrated to be consistent with the deflection of 1.7 arcsec predicted by General Relativity. This was the first of many experimental tests that General Relativity has been subjected too, and all have been passed with flying colours. ESA's Hipparcos satellite measured light deflection from space – even 90 deg away from the Sun, starlight is still bent by 0.004 arcsec due to the Sun's gravitational field. Hipparcos was able to place one of the best constraints on light bending, demonstrating the accuracy of General Relativity to 1 part in 10^3.

GAIA achieves such extraordinary measurement accuracies that a number of other key fundamental physical constants will be measured with unprecedented precision. The light-bending term, γ, will be measured with an accuracy of 5 parts in 10^7. Another important number in 'Parameterised Post-Newtonian' formalism of gravity is a quantity referred to as β, which GAIA will measure with a precision of about 1 part in 10^4. These numbers are important since deviations from General Relativity are predicted in scalar-tensor theories of gravity, which are being considered in view of recent developments in cosmology (inflation) and elementary particle physics (string theory and Kaluza-Klein theories). GAIA will accurately measure the solar quadrupole moment from the perihelion precession of minor planets. It will be able to place the best constraints on any change in the value of the constant of gravitation, G, over cosmological time scales, based on models of the cooling times of white dwarfs. Even gravity wave detection is in principle possible, although unlikely. All of these remarkable measurements are consequences of the exquisite measurement capabilities of GAIA. Not only one billion stars in our Galaxy, but even space itself, will be seen to move.

Asteroids and Near-Earth Objects

As it sweeps the sky, GAIA will observe everything that crosses its sensitive fields of view. Supernovae will be seen in huge numbers, gravitational micro-lensed events will be detected, and variable stars of all descriptions will be detected as they oscillate in brightness throughout the mission lifetime. Also within our Solar System, GAIA will provide a whole range of spectacular results. Because of its accurate positional measurements, anything that moves will be noted immediately. Simulations show that GAIA might detect up to a million minor planets, or asteroids (about 60 000 are known at the present time). The Edgeworth-Kuiper Belt objects, now known to move around the Sun beyond the orbit of Neptune, will also be detectable. GAIA could even discover objects like Pluto if they exist and if they are moving on orbits inclined to the ecliptic plane where they will not have been detected up to now. Detection and classification of these objects is of tremendous interest for studies of the formation and evolution of our Solar System: they are relics of this formation process, and their physical properties as a function of distance from the Sun will reveal important clues about the Solar System's origin.

A particular class of objects which will also not escape the satellite's sensitive vision are the Near-Earth Objects, of significant interest due to the fact that they may impact the Earth in the future, with potentially catastrophic results, albeit with a very low probability. The Barringer Meteor Crater in New Mexico probably resulted from the impact of a 40 m diameter object. The object that is believed to have ended the Cretaceous period probably had a diameter of about 10 km. By April 2000, the Minor Planet Centre had recorded 75 Atens-class objects, 455 Apollos, and 442 Amors (these classes reflecting their orbital characteristics). Many objects so far undetected with sizes from tens of metres up to 1 km will be detected and measured by GAIA.

In a related field, GAIA will measure the trajectories of stars that have passed close to the Sun in the (geologically) recent past, and will identify those that will come close to the Sun in the future. These close stellar passages are believed to be responsible for disruptions of the Oort Comet Cloud, which may lead to the diverting of swarms of objects into Earth-impacting orbits. The Hipparcos results have already shown that the star called Gliese 710 is approaching our Solar System at about 14 km/s, and will pass through the Oort Cloud in about 1 Myr. But the trajectories of many other, fainter stars, will be probed by GAIA.

dark matter fail?). The most widely referenced and commonly determined measure of the distribution of mass in the galactic disc near the Sun is the local volume mass density, i.e. the amount of mass per unit volume near the Sun, which for practical purposes is the same as the volume mass density at the Galactic Plane. Its local value is often called the 'Oort limit'. The contribution of identified material to the Oort limit may be determined by summing all local observed matter – an observationally difficult task. The uncertainties arise in part due to difficulties in detecting very low luminosity stars, even very near the Sun, in part from uncertainties in the binary fraction among low-mass stars, and in part from uncertainties in the stellar mass/luminosity relation. All of these quantities will be determined directly and with extremely high precision by GAIA.

The second measure of the distribution of mass in the solar vicinity is the integral surface mass density, the total amount of disc mass in a column perpendicular to the Galactic Plane. It is this quantity which is required for the deconvolution of rotation curves into 'disc' and 'halo' contributions to the large-scale distribution of mass in galaxies. If one knew both of these quantities, one could immediately constrain the scale height of any contribution to the local volume mass density that was not identified. In other words, one could measure directly the velocity dispersion, i.e. the temperature, of the 'cold' dark matter.

The Bulge

At the centre of our Galaxy is a more extended, roughly spherical agglomeration of stars, the bulge. The distance to the bulge is so immense that studies of its composition, dynamics and age are very difficult. Bulge stars are predominantly moderately old, unlike the present-day disc they encompass a wide abundance range, peaking near the Solar value, as does the disc and they have very low specific angular momentum, similar to stars in the halo. Thus the bulge is, in some fundamental parameters, unlike both disc and halo. There are many open questions about the origin of the bulge: What is its history? Is it a remnant of a disc instability? Is it a successor or a precursor to the stellar halo? Is it a merger remnant? It is not clear whether the formation of the bulge preceded that of the disc, as predicted by 'inside-out' models of galaxy formation; or whether it happened simultaneously with the formation of the disc, by accretion of dwarf galaxies; or whether it followed the formation of the disc, as a result of the dynamical evolution of a bar. Large-scale surveys of proper motions and photometric data inside the bulge can cast light on the orbital distribution function. Knowing the distance, the true space velocities and orbits can be derived, thus providing constraints on current dynamical theories of formation. GAIA data for bulge stars, providing intrinsic luminosities, metallicity and numbers, can be inverted to deduce star-formation histories.

There is substantial evidence that the bulge has a triaxial shape seen nearly end-on. Indications for this come from the asymmetric near-infrared light distribution, star counts, the atomic and molecular gas morphology and kinematics, and the large optical depth to micro-lensing. The actual shape, orientation, and scale-length of the bulge, and the possible presence of an additional bar-like structure in the disc plane, however, remain a matter of debate. The reason why it is so difficult to derive the shape of the galactic bar is that three-dimensional distributions cannot be uniquely recovered from projected surface brightness distributions such as the COBE/DIRBE maps. GAIA proper motions to faint magnitudes, in particular in a number of low-extinction windows, will allow unambiguous determination of the shape, orientation, tumbling rate mass profile and star-formation history of the bulge.

The Halo

The stellar halo of the Galaxy contains only a small fraction of its total luminous mass, but the kinematics and abundances of halo stars, globular clusters, and the dwarf satellites contain imprints of the formation of the entire Milky Way. In fact the halo is likely to be the most important component that may be used to distinguish among competing scenarios for the formation of our Galaxy. The classical picture of inner monolithic collapse plus later accretion in the outer Galaxy predicts a smooth distribution both in configuration and velocity space for our solar neighbourhood, which is consistent with the available observational data. Currently popular hierarchical cosmologies propose that big galaxies are formed by merging and accretion of smaller building blocks, and many of its predictions seem to be confirmed in high-redshift studies. These merging and accretion events leave signatures in the space and velocity distribution of the stars that once formed those systems. Recent work has considered the present-day signature that could be observed arising from the debris of a precursor which was disrupted during or soon after the formation of the Milky Way. These studies show that while there are no strong correlations after 10 billion years of evolution in the spatial distribution of a satellite's stars, there are strong correlations in velocity space. These correlations manifest themselves as a very large number of moving groups each having a small velocity dispersion and containing several hundred stars. To detect individual streams would require accuracies of less than a few kilometres per second, requiring measurement precisions of microarcseconds. GAIA will be able to achieve this (Fig. 3).

The Outer Halo

GAIA will find several million individual stars in the outer halo, at distances of more than about 50 000 light-years from the Galactic Centre. These will mostly be G and K giants and red and blue horizontal branch stars. G and K giants are intrinsically bright, they form in all known old stellar population types, they have easily measurable radial velocities, and they are historically well studied because they are the most easily accessible stars in the globular clusters. Horizontal branch stars have been the preferred tracer stellar type for the outer halo to date, because they can be much more easily identified amongst field stars than G and K giants. In particular, blue horizontal branch stars have been very easy to locate. However they are a biased tracer of the halo population in the sense that they do not always form in old metal weak populations. Redder horizontal branch stars and G and K halo giants are drowned out by the huge numbers of foreground turnoff and dwarf stars in the galactic disc.

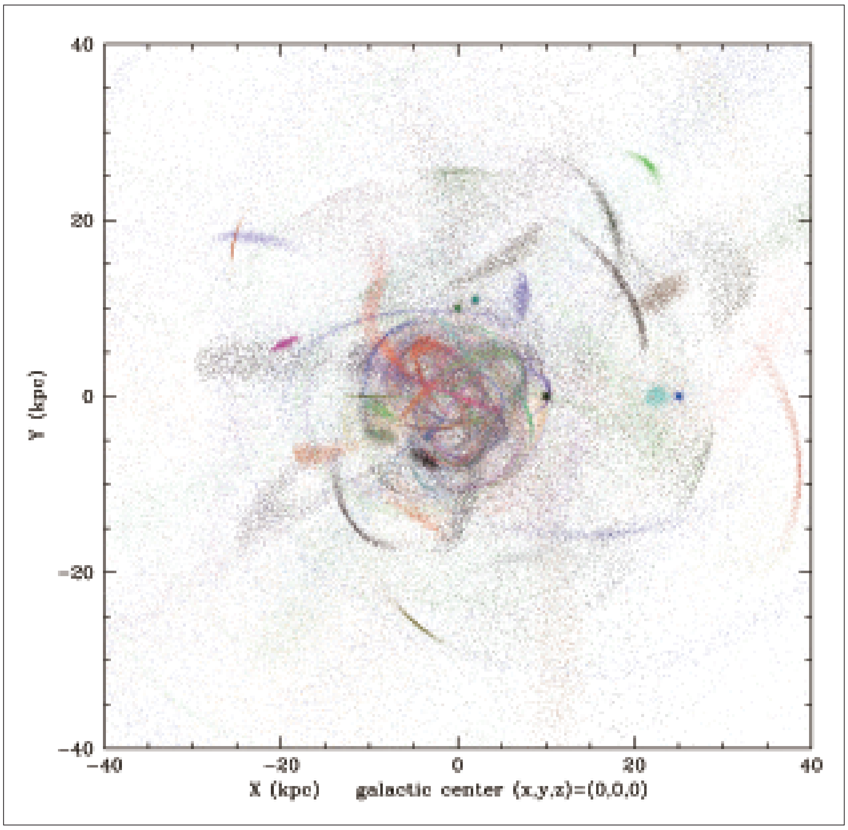


Figure 3. This simulation shows how a galaxy halo, like our own, may have been built up by the accretion of 50 dwarf galaxies colliding with the galaxy at various times during the last 10 billion years. The unit of distance is the kpc, or kiloparsec, where 1 kpc is a little more than 3000 light-years. GAIA would be able to detect the fossil streams of these ancient merging events (Courtesy of Paul Harding)

GAIA will circumvent all these difficulties. The late-type foreground dwarfs are much closer than the background late-type giants, so that even at the faintest magnitudes the dwarfs have a measurable parallax while the background giants do not. It will be possible to lift the veil of foreground stars and reveal millions of background halo stars, on the giant branch, and the red and blue horizontal branch.

The GAIA observatory

GAIA will do more than just record huge volumes of positional data on a vast number of astrophysical targets. GAIA will also provide a complementary range of data, with a diversity of applications. Every one of the 10^9 GAIA targets will be observed typically 100 times, each time with a complementary set of photometric filters, and a large fraction also with a radial velocity spectrograph. The available angular resolution exceeds that available in ground-based surveys. Source detection happens on-board at each focal-plane transit, so that variable and transient sources are detected. All these complementary data sets, in addition to the superb positional and kinematic accuracy derivable from their sum, make GAIA a powerful and revolutionary observatory mission: every observable object will be scrutinised every time it crosses the focal plane.

These data allow studies from asteroids to distant supernovae, from planets to galaxies, and naturally interest almost the entire astronomical community. Because of this enormous interest, GAIA will be an open observatory mission, directly making available its rich scientific resource to the sponsoring communities. The scale of the GAIA data is such that some analyses can be undertaken during operations, while others must await final data reduction. The GAIA observatory will provide exciting scientific data to a very wide community, beginning with the first photometric observations, and rapidly increasing until the fully reduced GAIA data become available. The resulting analyses will provide a vast scientific legacy, providing a wealth of quantitative data on which all of astrophysics will build.

The payload

To access a very significant fraction of the Galaxy requires accuracies of 10 micro-arcseconds at 15th magnitude (this was also a requirement specified by the Horizon 2000+ Survey Committee in 1994). The limiting magnitude and the number of objects that can be observed with GAIA follow from this accuracy requirement. The current technical design allows meaningful observations to 20th magnitude; this implies that important galactic tracers that only become accessible at 17-18th magnitude will be observed in significant numbers. A global sky-surveying mission such as GAIA must also be complete to well specified limits: this can be achieved by the on-board detection of all objects crossing the field-of-view.

There are three motivations for considering the parallel acquisition of radial velocities with GAIA: (i) the astrometric measurements supply only two components of the space motion of the target stars. The third component, the radial velocity, is required for proper kinematic or dynamical studies; (ii) radial velocity measurements are a powerful astrophysical diagnostic tool; (iii) at GAIA accuracies, perspective acceleration must be accounted for.

GAIA photometric measurements will provide essential diagnostic data, allowing the classification of all objects observed on the basis of luminosity, effective temperature, mass, age and composition. A wide separation of two individual viewing directions is a fundamental pre-requisite for the payload, since this leads to the determination of absolute trigonometric parallaxes, and thereby circumvents the problem that has plagued ground-based parallax determinations, namely the transformation of relative parallaxes to absolute distances.

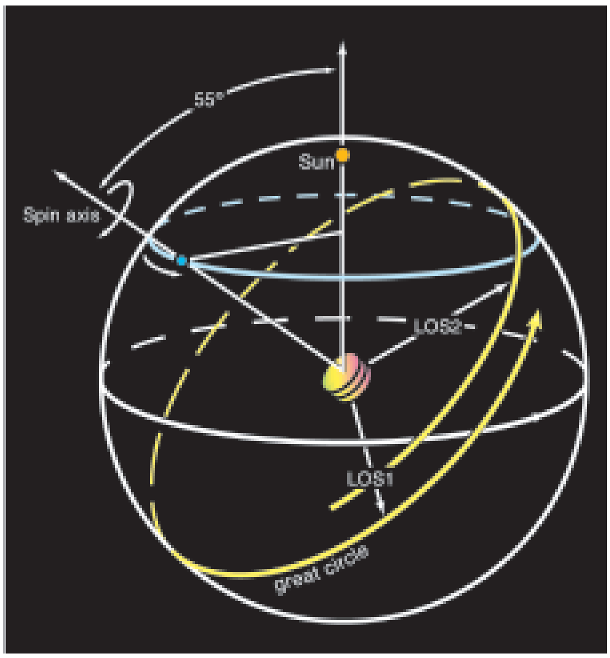


Figure 4. Characteristics of the observing strategy. The satellite rotates slowly about its spin axis, which itself precesses at a fixed angle of 55 deg to the Sun. LOS 1 and LOS 2 indicate the lines of sight for the two viewing angles which scan the same great circle on the sky

The measurements conducted by a continuously scanning satellite can be shown to be almost optimally efficient, with each photon acquired during a scan contributing to the precision of the resulting astrometric parameters (Fig. 4). Pointed observations cannot provide the overriding benefit of global astrometry using a scanning satellite, which is that a global instrument calibration can be performed in parallel, and the interconnection of observations over the celestial sphere provides the rigidity and reference system, immediately connected to an extragalactic reference system.

Quantifying and generalising from these basic design considerations, the general principles of the proposed mission can be summarised as follows:

(i) it is a continuously scanning instrument, capable of measuring simultaneously the angular separations of thousands of star images as they pass across a field of view of about 1 deg diameter. Simultaneous multi-colour photometry of all astrometric targets is a necessary and integral part of the concept; (ii) high angular resolution in the scanning direction is provided by a monolithic mirror of dimension ~1.7 m; (iii) the wide-angle measuring capability is provided by two viewing directions at large angles to each other and scanning the same great circle on the sky; (iv) the whole sky is systematically scanned in such a way that observations extending over several years permit a complete separation of the astrometric parameters describing the motions and distances of the stars.

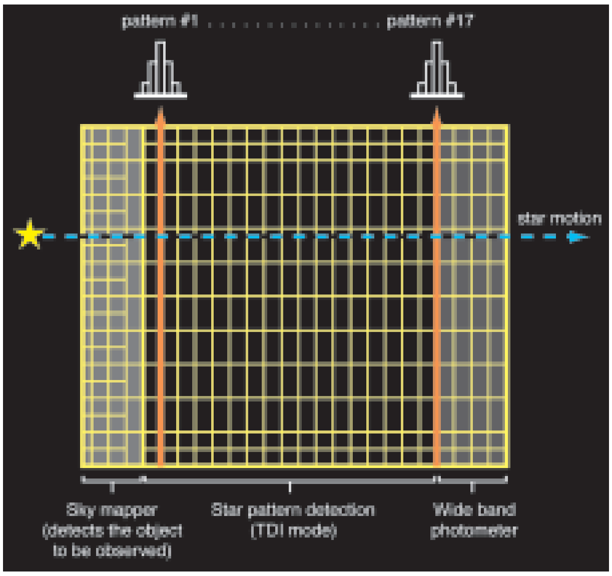


Figure 5. Overview of the astrometric focal plane (identical for Astro-1 and Astro-2). Star images cross the field, are detected by the astrometric sky mapper (left), observed in windowing mode across the main CCD arrays, and finally across the broad-band photometric field

The resulting payload design consists of:
(a) Two astrometric viewing directions. Each of these 'Astro' instruments comprises an all-reflective three-mirror telescope with an aperture of 1.7 x 0.7 m^2, the two fields separated by a basic angle of 106 deg (Fig. 5). Each astrometric field comprises an astrometric sky mapper (providing an on-board capability for star detection and selection, and for the star position and satellite scan-speed measurement), and the astrometric field proper, employing CCD technology, with about 250 CCDs and accompanying video chains per focal plane, a pixel size of 9 µm along scan, TDI operation, and an integration time of ~ 0.9 s per CCD. There is also a broad-band photometer, providing multi-colour, multi-epoch photometric measurements for each object observed in the astrometric field.

(b) An integrated radial velocity spectrometer and photometric instrument, comprising an all-reflective three-mirror telescope of aperture 0.75 x 0.70 m^2 (Fig. 6). The field of view is separated into a dedicated sky mapper, the

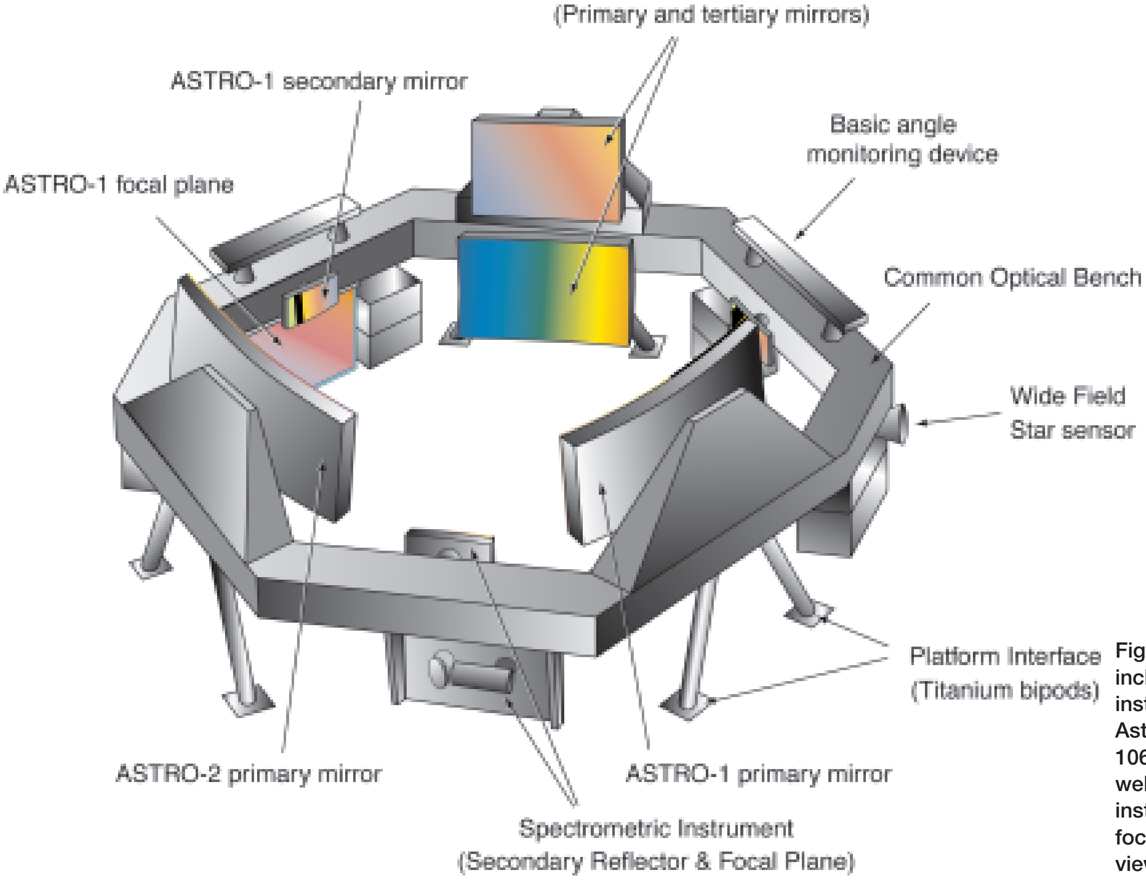
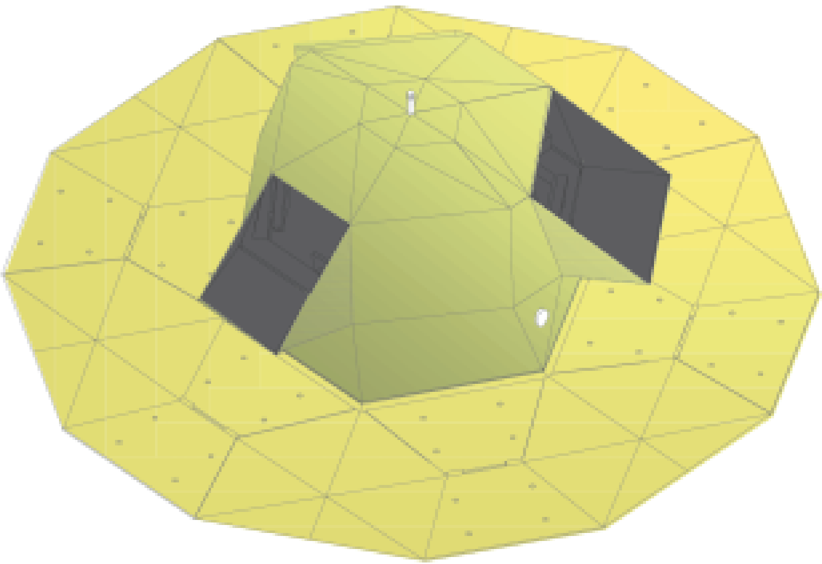


Figure 6. The GAIA payload includes two identical instruments (Astro-1 and Astro-2) separated by the 106 deg basic angle, as well as a spectrometric instrument which shares the focal plane of a third viewing direction

radial-velocity spectrometer, and a medium-band photometer with 11 filters. Both instrument focal planes are also based on CCD technology operating in TDI mode. The 11 medium spectral bands have been provisionally selected to optimise the scientific content of these photometric measurements.

(c) The opto-mechanical-thermal assembly comprising: (i) a single structural torus supporting all mirrors and focal planes, employing SiC for both mirrors and structure; (ii) a deployable sunshield to avoid direct Sun illumination and rotating shadows on the payload module, combined with the solar-array assembly; (iii) control of the heat injection from the service module into the payload module, and control of the focal-plane assembly power dissipation in order to provide an ultra-stable internal thermal environment; (iv) an alignment mechanism on the secondary mirror for each astrometric instrument, with micron-level positional accuracy and 200 μm range, to correct for telescope aberration and mirror misalignment at the beginning of life; (v) a permanent monitoring of the basic angle, but without active control on board.



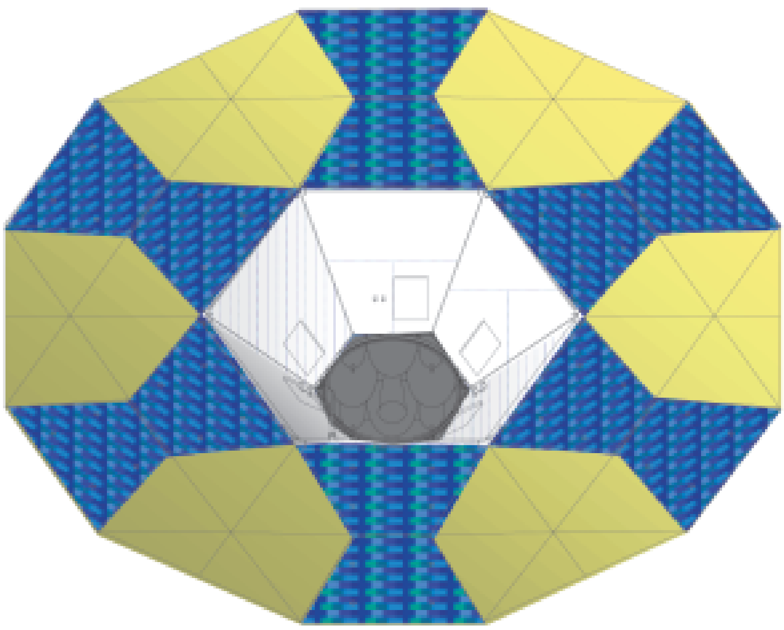


Figure 7. The GAIA satellite in orbit, with solar panels and sunshield deployed, viewed from above (top) and below (bottom)

Spacecraft design, launch and orbit

The GAIA spacecraft has been designed to take advantage of a dual/multiple launch with the Ariane-5 launcher (Fig. 7). The satellite consists of a payload module and a service module, which are mechanically and thermally decoupled. The solar array/sunshield assembly has a span of 9.50 m when deployed. The optical covers are removed from the instrument entrance apertures in orbit.

The service module has a conical shape to avoid any turning shadows falling onto the solar array/sunshield assembly. It interfaces on one side with the standard 1666 mm adapter of the Ariane-5 launcher, and on the other with the payload module. The service module structure is made of aluminium, with CFRP shear walls. All units accommodated in the module are thermally coupled to the lateral panels of the module, which are used as radiators and covered with optical solar reflectors. The temperature of the service module in orbit is around 20°C, and the payload module temperature about 200 K, with a temperature stability of the order of tens of μK. The system therefore provides a very quiet and stable thermal environment for the payload optical bench.

The solar array/sunshield assembly includes six solar-array wings, which are stowed during launch against the six lateral panels of the service module. Each wing is made of two solar panels based on Ga-As cells on CFRP structure. Hinges, based on a shape-memory-alloy construction, are foreseen between the panels, as well as between the wings and the service module core structure. The solar panels are insulated from the payload module with multi-layer insulation (MLI) on their rear face. Additional MLI sheets, reinforced with kevlar cables, are spread between the solar-array wings to complete the sunshield function. They are deployed together with the solar panels. The communications to ground are provided by an X-band link, with 3 Mbps science data rate, RF on-board power of 17 W, and a high-gain, electronically-steered phased-array antenna. The Perth 32 m diameter ground station is foreseen to be used for GAIA, with around 8 hours of visibility per day. The satellite telecommand (2 kbps) and housekeeping telemetry (2 kbps) is provided by a low-gain antenna system with omni-directional coverage. The present design concept includes an autonomous propulsion system with a 400 N motor, to take the satellite from geostationary transfer orbit to its final orbit around L2. This propulsion system could be deleted, thereby simplifying the satellite's design, if availability of the planned re-startable Ariane-5 launcher stage is confirmed before GAIA project activities start.

If selected as the next ESA Cornerstone mission, GAIA would be launched from the European spaceport at Kourou in 2009. The operational orbit selected for GAIA is a Lissajous-type, eclipse free orbit around the L2 Lagrangian point of the Sun-Earth system (at 1.5 million kilometres from the Earth). This particular orbit offers many advantages, including a very stable thermal environment, a very high observing efficiency (Sun, Earth and Moon are always outside the instrument field of view), and a low-radiation environment. An operational lifetime of five years is foreseen.

Conclusion

GAIA addresses science of enormous general appeal, and will deliver huge scientific impacts across the whole of astrophysics from studies of the Solar System, and other planetary systems, through stellar astrophysics, to its primary goal, the origin and evolution of galaxies, out to the large-scale structure of the Universe, and fundamental physics. In this article we have presented just some of the scientific questions that will be addressed by GAIA. A more detailed discussion of the scientific case, including results from specific GAIA simulations, can be found on the GAIA web site at http://astro.estec.esa.nl/GAIA/.

GAIA is timely as it builds on recent intellectual and technological breakthroughs. Current understanding and exploration of the early Universe, through microwave background studies (e.g. Planck) and direct observations of high-redshift galaxies (HST, NGST, VLT) have been complemented by theoretical advances in understanding the growth of structure from the early Universe up to galaxy formation. Serious further advances require a detailed understanding of a 'typical' galaxy, to test the physics and assumptions in the models. The Milky Way and the nearest Local Group galaxies uniquely provide such a template.

While challenging, the entire GAIA design is within the projected state-of-the-art, and the satellite can be developed in time for launch in 2009. With such a schedule, a detailed stereoscopic map of our Galaxy will be available within 15 years. By providing a quantitative census of the Milky Way, GAIA will provide a huge advance in unlocking its origins.

Acknowledgements

This summary of the GAIA mission is based on the GAIA Study Report, which is the result of a large collaboration between ESA, the European scientific community, and European industry. The study has been supervised by the Science Advisory Group Members, chaired by M. Perryman (ESA), comprising: K.S. de Boer (Sternwarte Universität Bonn), G. Gilmore (University of Cambridge), E. Høg (Copenhagen University Observatory), M.G. Lattanzi (Osservatorio Astronomico di Torino), L. Lindegren (Lund Observatory), X. Luri (Universitat de Barcelona), F. Mignard (Observatoire de la Côte d'Azur) and P.T. de Zeeuw (Sterrewacht Leiden).

The work of the Science Advisory Group has been supported by a Science Working Group, chaired by P.T. de Zeeuw and G. Gilmore (18 members) and responsible for quantifying the scientific case; a Photometry Working Group, chaired by F. Favata (18 members); an Instrument Working Group, chaired by L. Lindegren (16 members); and 52 other European scientists directly supporting the GAIA study.

ESA scientific involvement includes contributions from S. Volonté (ESA Paris), and from scientists within the Astrophysics Division (F. Favata, K.S. O'Flaherty, W. O'Mullane, M. Vannier and A. Colorado-McEvoy).

Technological activities have been led by the Study Manager, O. Pace (SCI-PF), and supported by M. Hechler (ESOC Study Manager), and a number of D-TOS engineers: J. Doutreleau (data processing), H. Evans (radiation), C. Gomez (thermal control), J. Gavira (structure), A. Martin Polegre (antenna), A. Mohammadzadeh (CCD CTE), R. Morgan-Owens (communications), P. Nieminen (radiation), C. Philippe (attitude and orbit control system), A. Popescu (basic angle monitoring), and I. Zayer (CCD operations). The satellite design was contracted to Matra Marconi Space (F), under Study Manager P. Mérat, and involving EEV Ltd (UK), and Alcatel Space (F). An Alenia Study Team, under Study Manager S. Cesare, evaluated the performance of an interferometric design, with the involvement of the Istituto di Metrologia 'G. Colonnetti', EICAS Automazione, the Osservatorio Astronomico di Torino, Matra Marconi Space (F), and Alcatel Space. Other industrial studies have been carried out by SIRA UK (CCD CTE), and TNO-TPD Delft (basic angle monitoring).