# GAIA: THE SATELLITE AND PAYLOAD

**Oscar Pace**
European Space Agency, ESA-ESTEC, Keplerlaan 1, 2200AG Noordwijk, The Netherlands

## ABSTRACT

This paper summarises the main features of the Gaia technical baseline as of mid-2004. The Gaia spacecraft, to be put in a Lissajous-type orbit around the Sun–Earth Lagrangian point L2, was redesigned in 2002 to be launched with a Soyuz–Fregat launcher. The satellite, with a 'wet' mass of 1428 kg and 1331 W of power, consists of a payload and a service module, which are mechanically and thermally decoupled. The sun shield assembly has a span of 11.50 m when deployed, with a fixed solar array of annular type, installed on the bottom side of the service module, like Planck. While the temperature of the service module is $\sim 20°$C, the payload module is at $\sim$ 160 K, with a temperature stability requirement of $\sim$50 $\mu$K. The payload, thermally insulated, is composed of two astrometric instruments and an integrated radial velocity spectrometer and photometric instrument, with CCDs as detectors and mirrors made all by SiC, mounted on a single structural torus ($\sim$3 m diameter), also made by SiC. The system, together with the very quiet L2 orbit, provides a stable environment for the payload optical bench. The science data, dumped on ground by an X-band TM link at a rate of 5 Mbps, will be retrieved by a single ground station (Cebreros), with a minimum visibility of 6–8 h per day. The nominal stellar data acquisition time is 5 yr, extendable to 6 yr.

To reach Gaia's scientific objectives, comprehensive technology activities have been identified and a Gaia Technology Plan has been established and implemented. This Plan aims at developing the identified technology to a breadboard readiness level, tested in the relevant environment before the start of Phase B. This paper summarizes the current mission technical concept and introduces the technological developments required to make the Gaia mission feasible.

Key words: ESA; Gaia; Space astrometry.

## 1. SCIENTIFIC AND MISSION OBJECTIVES

The Gaia mission objectives are to build a catalogue of $\sim$ 1 000 000 000 stars with accurate positions, parallaxes, proper motions, magnitudes and radial velocities. The catalogue will be complete up to $V = 20$ mag. The overall mission can be split in three parts: a) astrometry, with the measurement of stellar position, parallax and proper motion; b) photometry, with measurements in different spectral bands; c) radial velocity measurements up to $V =$ 17 mag.

The accuracy targeted for the astrometry mission is 10 $\mu$as in positional and parallax accuracy and 10 $\mu$as yr$^{-1}$ for proper motion accuracy, for $V = 15$ mag stars. The parallax accuracy is equivalent to an accuracy of 10% on the distance of a star at 10 kpc. The proper-motion accuracy is equivalent to an accuracy of 1 km s$^{-1}$ on the velocity of a star at 20 kpc. The photometry mission must be multi-colour and multi-epoch. Magnitudes will be obtained in 5 wide spectral bands for all stars up to $V = 20$ mag, complemented with measurements in (provisionally) 11 narrow bands for stars up to $V = 17$ mag. The multi-epoch aspect is performed by a regular observation of the stars throughout the mission. The radial velocity measurements will provide a velocity accuracy of 1 km s$^{-1}$ for $V = 15$ mag stars. The radial velocity is derived from the Doppler shift of particular spectral lines within the 848–874 nm spectral domain.

## 2. MEASUREMENT PRINCIPLE

The main objective of the mission is to perform global or wide field astrometry as opposed to local or narrow field astrometry. In local astrometry, the star position can only be measured with respect to a neighbouring star in the same field. Even with an accurate instrument, the propagation of errors is prohibitive when making a sky survey. The principle of global astrometry is to link stars with large angular distances in a network where each star is connected to a large number of other stars in every direction.

Global astrometry requires the simultaneous observation of two fields of view in which the star positions are measured and compared. Therefore, the payload will provide two lines of sight, obtained with two separate telescopes, but, like Hipparcos, the two images will be focalised, slightly spaced, on a unique focal plane assembly. The angle between the instrument lines of sight defines what is called the basic angle.

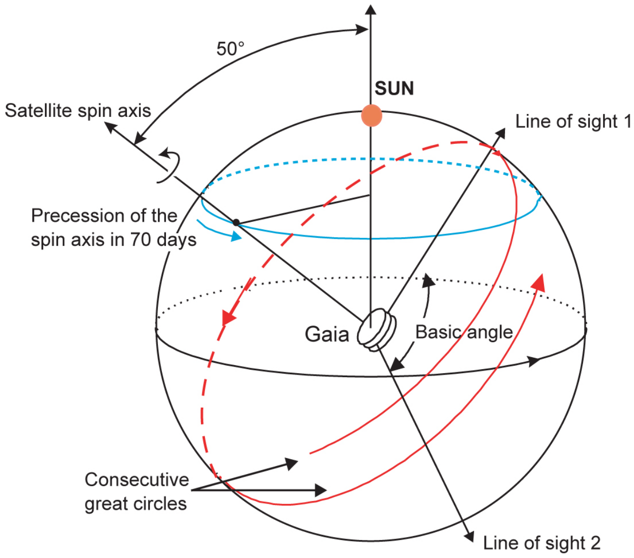


*Figure 1. The Gaia scanning law.*

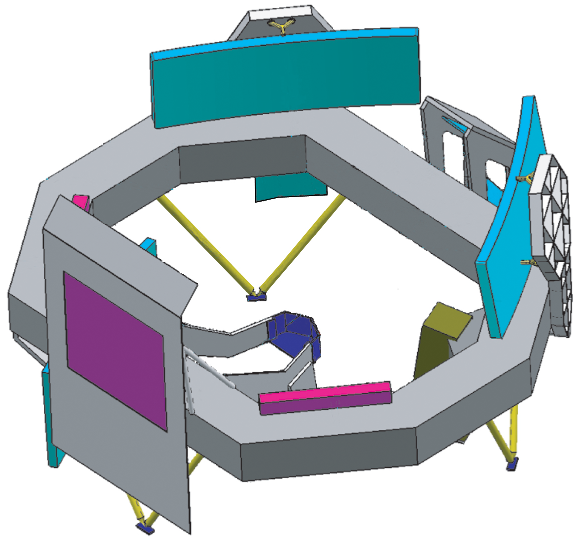

*Figure 2. Gaia payload configuration.*

A dedicated scanning law (Figure 1) does the coverage of the sky to build up the star network. The scanning law for Gaia is similar to the one of Hipparcos. A spin motion of the spacecraft with a 6-h period performs the scan of great circles. The lines of sight of both instruments are perpendicular to the spin axis, and the two instruments successively scan the same sky area, which can be viewed as a band whose height is equal to that of the field of view. From the instrument standpoint, the stars are crossing each field of view in a regular motion. As for Hipparcos, the scan direction is a privileged direction and the star position measurement is only performed in this direction.

A slow precession of the spin axis about the satellite–Sun axis slowly moves the great circle allowing a full coverage of the sky within a few months. For Gaia, the optimisation of the scanning law, having now a value of $60'' \ \mathrm{s}^{-1}$ (it was $120'' \ \mathrm{s}^{-1}$) has led to an orientation of the spin axis at 50° from the Sun direction and a precession of this axis about the Sun direction in 70 days. This scanning law ensures optimal sky coverage and a great rigidity in the data reduction (each star is measured on several great circles — 90 observations on average over 5 yr — with nearly isotropic orientations). The slow precession of the spin axis generates a line of sight motion across scan of $\sim$0.25° over a spin period, while the field of view height is 0.66°. This provides an overlapping between the consecutive bands observed by each field of view, which allows a calibration of some instrument parameters such as the basic angle using the same stars. The data reduction performed on ground starts with a processing of the star data on each great circle (great circle reduction): the stars are located relative to each other on the circle. Then, the reduction process has to orient and phase the different circles with respect to each other in what is called the sphere reduction. A more general global approach for the data reduction is also being considered. Large amounts of information from the instruments are derived from the data reduction. In particular, the distortion, the basic angle and the chromaticity can be calibrated as well as their low frequency variations, which make the variations of these parameters less critical. The self-calibration of fixed or slowly variable biases is a crucial advantage of the global measurement concept, which has been unambiguously demonstrated by Hipparcos, and without which the Gaia accuracy goal of 10 $\mu$as would be difficult to reach. The final catalogue is built from the best estimate of all star positions and of instrument parameters computed from the total amount of data collected during the mission. The final accuracy is only reached at the end of the mission, i.e., after 5 yr of operation, and after complete processing of all the data.

## 3. ASTROMETRIC INSTRUMENT

### 3.1. Optical Design

The optical design of the astrometric telescopes is represented in Figure 2. Each telescope, separated by a basic angle of 99.4°, consists of a Three Mirror Anastigmatic (TMA) configuration (M1, M2, and M3), with images combined and focalised by three flat mirrors (M4, M5, and M6), on the same focal plane, slightly staggered in space of one CCD row.

The design features a diffraction limited flat field larger than 0.4 deg$^2$, a large focal length (46.7 m) in comparison to the inter-mirror distance (less than 3 m), and a low optical distortion compatible with a time delayed integration of the star pattern over $\sim$ 3.3 s. The entrance pupil is located on the primary mirror and is rectangular: 1.4 m $\times$ 0.5 m. It is elongated in the scan direction, so as to provide the narrowest point spread function in the measurement direction, while being compatible with the optical quality, available volume, field size and radiometric needs. The pupil collecting area is such that the total number of collected photons per star over 5 yr of operation in orbit is compatible with the 10 $\mu$as positioning accuracy at magnitude 15. The large focal length of 46.7 m

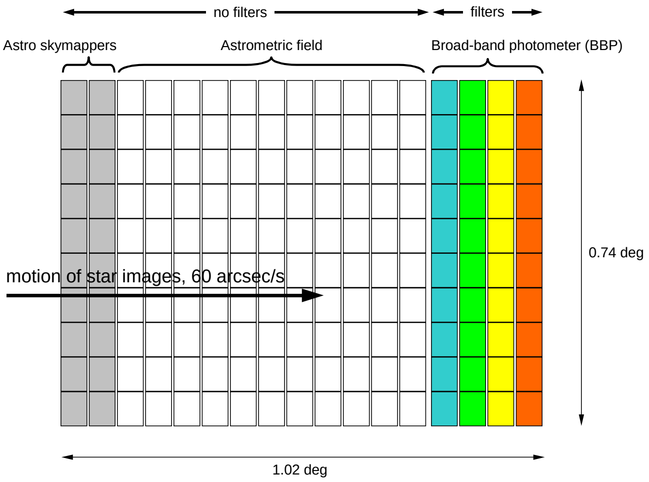


*Figure 3. Schematic layout of the astrometric focal plane, comprising 170 identical CCDs in three regions: the skymappers and the astrometric field (without filters), and the broad-band photometer with interference filters in front of the CCDs.*

allows a proper sampling of the diffraction pattern (4 pixels) along the scan direction, with a pixel size along scan of 10 $\mu$m, which is compatible with the available CCD detector technology. The astrometric instrument consists of two identical telescopes, rotated one with respect to the other by an angle equal to the basic angle, fixed at 99.4°. The optical design allows a mounting of the mirrors and focal planes of both telescopes on the same torus structure (Figure 2). This provides a high symmetry and dimensional stability of the system and simplifies its overall integration.

### 3.2. Focal Plane Design

The astrometric focal plane layout is represented in Figure 3. An observed object follows a nearly horizontal line on this figure, with a speed of $\sim$ 13.6 mm s$^{-1}$ given by the scan law, and therefore successively crosses all the columns of CCDs. All the CCDs are backside illuminated and work in time-delayed integration mode over their whole width. Therefore, for every observed star, each CCD provides the star pattern corresponding to the optical point spread function sampled by the CCD pixels. All the detectors are physically identical, with a pixel size of 10 $\mu$m along scan and 30 $\mu$m across scan. The columns of detectors are functionally grouped in three parts: the sky mapper, the astrometric field, and the broad band photometric field. The sky mapper and the astrometric field work in white light, the wavelength band being defined by the CCD quantum efficiency. Although the CCD detectors are physically identical, a different smart analogue binning process is implemented for the three focal plane parts, depending on the data to be extracted. The sky mapper is made of the first column of CCDs (ASM1 for the 1st FOV and ASM2 for the 2nd FOV) and by the first column of the Astrometric Field (AF1) and fulfills several functions:

– Object detection function: no catalogue is implemented on board, and the system will be autonomous for the object detection. Simulations performed by the Gaia Science Team (GST) showed that the detection process is efficient up to $V = 20$ mag, for which $\sim$ 300 e$^-$ per star are detected per second.

*Table 1. Summary of the astrometric instrument performances. CCD options refer to different thinning possibilities*

| | Astrometric accuracy ($\mu$as), $V$ =15 mag | | |
|---|---|---|---|
| | B3V | G2V | M8V |
| CCD #1 | 11.3 | 13.5 | 13.1 |
| CCD #2 | 12.7 | 12.0 | 12.0 |

– Windowing function: once the object is detected by the first column of the sky mapper, a detection window is defined for the following CCDs for this object, so as to reduce the readout noise and data rate.

– Attitude control function: a centroiding process is applied to two consecutive CCD columns for deriving the star speed measurement in both directions. Note that the speed measurement does not require any catalogue.

The astrometric field is made of the 11 columns of CCDs following the sky mapper. Since only the star position along scan is measured, the pixels are binned across scan in this area, and each CCD provides 6 samples per star representing the star pattern profile along scan. For avoiding any unrecoverable loss of information, these profiles are sent to the ground station without applying any further processing on board, aside from lossless compression techniques. The star dynamical range is managed by an appropriate gating of the CCDs, which allows to perform the star profile measurement up to $V$ = 6–7 mag.

The broad band photometry area is made of the five last columns of CCDs, and provides colour information for all observed objects in four spectral bands of $\sim$ 100 nm width. Such colour data are used for astrophysics science, and also for the calibration of star chromaticity effects.

In summary, the focal plane assembly is constituted of 180 CCDs of the same type, with 10 $\mu$m pixels along scan and 30 $\mu$m across scan. Out of 180, the 110 CCDs of the astrometric field have a physical array size of 49 mm $\times$ 60 mm (4500 $\times$ 1996 pixels), while the remaining 70 CCDs (20 for the Sky Mapper and 50 for the broad band photometer BBP) have half along-scan size, i.e., 30 mm $\times$ 60 mm (2600 $\times$ 1996 pixels). The total dimension of the focal plane, encompassing the two FOVs, will be $\sim$ 600 mm $\times$ 750mm.

### 3.3. Astrometric Performance

The final astrometric performance is not only given by the star localisation accuracy for one passage, but is driven by the total number of photons collected by both telescopes over the total observation time in orbit. Table 1 presents the astrometric accuracy versus magnitude for a yellow star (G2V), assuming 5 yr of observation in orbit. Similar results are obtained for blue stars, while the accuracy improves for red stars. The noise floor for bright stars is evaluated at $\sim$3 $\mu$as RMS and is driven by the CCD full-well capacity estimated at 250 000 e$^-$. Even under pessimistic evaluations of the saturation level, the noise figure for bright stars ($V < 12$–13 mag) will be better than 4 $\mu$as RMS.

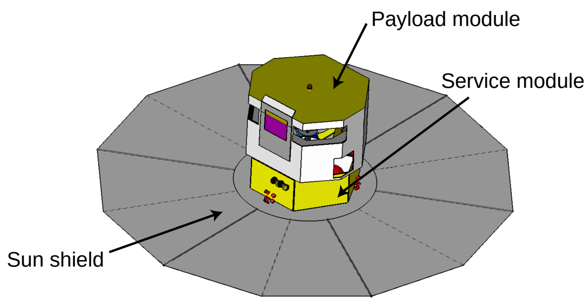


*Figure 4. Gaia in orbit – top view.*

## 4. SPECTROPHOTOMETRIC INSTRUMENT

The spectrometric instrument works up to $V = 17$ mag and is composed of the medium band photometer (MBP) and the stellar radial velocity measurement instrument (RVS). The two functions share the field of a common TMA telescope, including a classical three mirror telescope plus a dioptric spectrometer working at 1:1 magnification. The spectrometric telescope provides a diffraction-limited field of 4.8° across scan by 2° along scan, with a focal length of 2.1 m and a rectangular entrance aperture of dimensions 0.5 × 0.5 m. The mirrors and the shared focal plane are mounted on the same optical bench, with the telescope deployed in a horizontal configuration (deployment perpendicular to spin axis), while the dispersion direction of the spectrometer is along the scan. The MBP focal plane is constituted by two dedicated detection areas (MBP#1 and MBP#2), separated by the RVS focal plane, having each an optical field of view of 2° (along scan) and 1.6° (across scan). Each field is composed of 2 modules of 8 CCDs with each 5.5 s integration time. The CCDs are constituted of 336 × 3930 pixels, with 10 $\mu$m × 15 $\mu$m pixel dimensions and an active area of 3.36 mm × 59 mm. The total number of MBP CCDs is 32. The star measurement is performed in 11 different bands (sky mapper excluded) by means of filters located in front of the CCDs, with an integration time of 5.5 s per CCD.

Initial concepts for the radial velocity instrument baselined a classical configuration assembly of collimator/disperser/imager, working at unit magnification. More recently, an Offner-type spectrometer design has been considered. Although in evolution, the RVS focal plane assembly is at present constituted of 6 RVS detectors and a RVSM (RVS Sky Mapper), located in the telescope focal plane, in the vignetted field. The RVSM detects the stars and determines the windows for the RVS detectors. The detection area is formed by 6 CCDs , of the same type of the MBP CCDs (10 $\mu$m × 15 $\mu$m pixel, 10 mm × 59 mm active area).

The major characteristics of the RVS spectrometer are the following: Wavelength range: 848–874 nm; Pixel size: 10 $\mu$m × 15 $\mu$m; Number of spectral samples per star: 670; Spectral sampling: 0.375 Å per pixel; Available integration time, per star passage: 100 s; Total integration time (5 yr lifetime): 10 200 s.

## 5. PAYLOAD CONFIGURATION

Although fixed or slowly variable biases are self-calibrated by the great-circle or sphere reduction process, line-of-sight variations at a frequency higher or equal to the spin frequency (6 h) cannot be retrieved. It is therefore mandatory for the astrometric instrument that the design ensures a short-term basic angle stability (or at least knowledge of the basic angle variations) significantly below 10 $\mu$as RMS over the spin period of 6 h.

The proposed design was shown to actually meet this stringent requirement with a passive thermal control. The major design features for that purpose can be summarised as follows:

– The payload is protected from Sun radiation by means of a sun shield (Figures 4 and 5). The sun shield is obtained by connecting deployable booms with thermal foils.

– The payload module, in particular the torus, is also radioactively decoupled from the sun shield, by means of a thermal tent closing the payload completed with baffles on the optical apertures.

– The payload module is radioactively and conductively decoupled from the service module.

– The payload module is also mechanically decoupled from the service module by releasing in orbit two of the three bipods connecting one module to the other.

– A single low-expansion, high-conductivity and homogeneous material, namely Silicon Carbide (SiC), is used for the reflectors, the mounting plates and the torus structure.

The payload temperature is passively stabilised at $\sim$160 K. Although the basic angle stability requirement is passively met, a device was designed by Astrium for continuously monitoring the basic angle variation in-orbit with accuracy better than 1 $\mu$as RMS and therefore guaranteeing the mission performance. It basically consists of an artificial star on board (laser source) illuminating simultaneously the two astrometric telescopes.

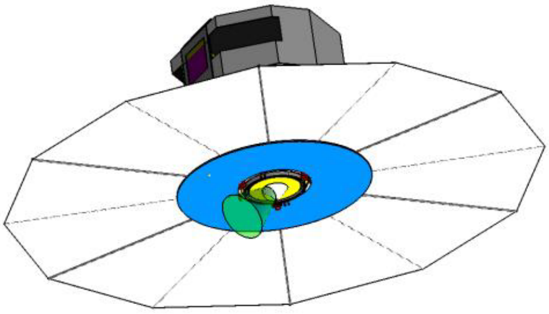

*Figure 5. Gaia in orbit – bottom view.*

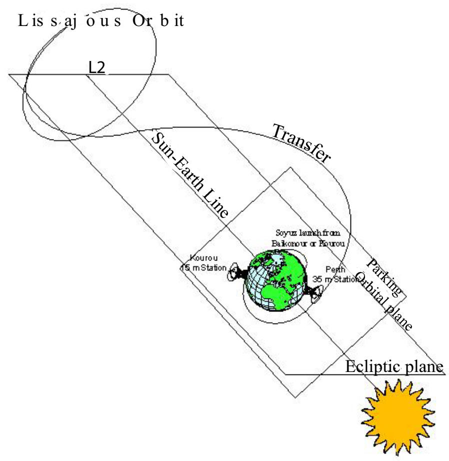


*Figure 6. Typical transfer orbit to L2.*

## 6. SATELLITE CONFIGURATION

The payload module is mounted on the service module (SVM) by means of three bipods in order to have an isostatic interface between the two structures. The SVM structure is built around a stiff and stable primary structure, composed of a cylindrical central tube, 6 shear walls and 6 external panels, supporting the electronic units, and upper panel for payload mechanical interface, all made by CRFP to fulfill the stability requirements. The SVM interfaces on one side with the standard 1194-mm adapter of the Soyuz–Fregat launcher and on the other side with the payload module. All units accommodated into the module are thermally coupled to the lateral panels of the module, which are used as radiators and covered with optical solar reflectors.

The solar array assembly, of an annular shape like Planck, fixed and installed under the Service Module bottom platform, is based on Ga–As cells and has a total surface of $\sim 10$ m$^2$. Figure 4 shows the satellite configuration in orbit. The sun shield assembly is deployed with a span of 11.50 m. The optical covers are removed from the instrument entrance apertures in orbit.

## 7. SCIENCE DATA PROCESSING

Because of the very large number of CCDs within each astrometric focal plane, the data rate at the output of these focal planes is huge. A strong filtering of the data flow is mandatory on board in order to minimise the quantity of data to be stored and then transmitted to ground. This on-board filtering process includes several steps:

– A star detection/discrimination function, using the sky mapper implemented within each astrometric focal plane, allows to detect all stars up to $V = 20$ mag. The detection process includes a background evaluation and suppression function, a cosmic hit discrimination function and a connectivity test, which allows to discard noise and extended objects. The payload operates without the support of any pre-loaded star catalogue.

– A windowing function propagates in real time the address of each detected star as it crosses the astrometric focal plane. It allows to read only the CCD-pixels that include the star signal.

– Finally, a compression function reduces the data rate, with minimum or no impact on the data quality. Thanks to this on-board filtering process, the data flow at payload output does not exceed an average value of 1 Mbps.

## 8. SERVICE MODULE

A simple and secure spin stabilisation approach is selected for this transfer phase, making use of standard Sun sensors and one gyroscope. The satellite is launched by a Soyuz–Fregat, from Baikonour or Kourou, into a 200 km, circular transfer orbit, by using the Soyuz stage. The satellite transfer from the circular orbit to the final L2 orbit (Figure 6) is done by means of the Fregat stage, with transfer time from 70 to 110 days, depending on the day of launch along the year. The selected operational orbit is a Lissajous orbit, providing at least 6 yr of observation with no eclipse, and even more than that assuming a limited correction manoeuvre after a few years of observation. A redundant set of Hydrazine 10 N thrusters is used for orbit correction during the transfer phase, for the final insertion into the operational orbit at L2 and in case slew manoeuvre in operations are required. The total $\Delta$V for a 6 months launch window is 326 m s$^{-1}$, for a 10° Lissajous orbit, while the total fuel mass, including AOCS fuel, is 242 kg.

Very stringent pointing stability and rate stability requirements have to be met during the observation phase (e.g., 10 mas s$^{-1}$ $3\sigma$, over 1 s, for the absolute rate error) in order to follow adequately the pre-defined satellite scan law without blurring the star image at focal plane level. This is achieved thanks to a set of microthrusters (field emission electric propulsion thrusters; FEEP) with a thrust in the range of 1 mN) controlled in a continuous proportional mode. They are used combined with the wide field star sensors of the astrometric instruments (sky mapper fields) as attitude and rate sensors. Thanks to the high specific impulse of the FEEP microthrusters and because of the very low level of dynamic perturbations to be controlled, only a few kg of Cs propellant are needed.

The satellite power demand, in observation phase, is $\sim$ 1331 W, including margins. This power is provided by $\sim$ 10 m$^2$ of Ga–As cells, with 40$^\circ$ Sun aspect angle, having available power of 1476 W (20% cell efficiency EOL, 0.92 absorptivity, at 70$^\circ$C and 90% packing density). A small Lithium-ION battery provides the required energy during the launch phase. No eclipse is expected during the transfer orbit or in operational orbit.

The satellite electrical architecture is split in two main parts: (i) science data chain including all the units required for the acquisition, discrimination and compression of the payload data. A solid state recorder of 300 Gbits ensures the temporary storage of the compressed science data between two consecutive transmission periods with the ground station; (ii) more standard set of equipment, connected to a central computer, provides all the general services to the spacecraft and payload (power, data transmission, attitude control, etc).

The communication between the spacecraft and the Earth (the ESA ground station located in Cebreros, Madrid, is today considered for the control of the spacecraft) is done via two sets of equipment: (i) classical telemetry and telecommand (TT&C) link with an omni-directional coverage provides a permanent control of the spacecraft whatever the mission phase and the spacecraft attitude. Both transmission and reception are done in X-band. A solid state power amplifier provides the 17 W of RF power required to transmit safely the 6 kbps of telemetry data over the $\sim$ 1.5 million km between spacecraft and Earth; (ii) dedicated telemetry link, also in X-band, provides the transmission to the Earth of the scientific data. The 'high' transmission rate (5 Mbps, taking into account a minimum of 6 h of ground station visibility per day), the large distance between the spacecraft and the ground station and the wide antenna field of view induced by the spacecraft spin and orbit motions impose altogether the use of a 'high' gain, high power phased array antenna.

## 9. SATELLITE INTERFACE AND BUDGETS

In the launch configuration, the sun shield is stowed against the service module structure. The optical covers are closed against the payload module thermal tent. The satellite envelope, with an overall diameter of 3.80 m and a height of $\sim$3.10 m is then compatible with the Soyuz–Fregat fairing, being developed for the Metop project with a launch in 2005. Use is made of the standard Soyuz–Fregat 1194 mm diameter adapter. Five years of total observation are necessary to finally reach the targeted 3–10 $\mu$as astrometric accuracy. The satellite has been designed for 6 yr of operation.

The spacecraft dry mass, including margins, is 1136 kg, while the launch mass, including the launcher adaptor (50 kg) and the propellant (242 kg), is 1428 kg, with 212 kg margin with respect to the lift-off capability of the Soyuz–Fregat, version 2-1a (planned to be available in 2005 for the Metop launch).

## 10. THE GAIA TECHNOLOGY PROGRAMME

The main objectives of the Gaia Technology Programme are to ensure effective technological preparation of the Gaia Project by the development of critical technologies, by demonstrating their feasibility and timely availability at flight standard. Such a demonstration is an essential prerequisite enabling the planned mission at an acceptable level of risk in terms of maturity, cost and schedule. The technology activities have been identified in conjunction with industry, in the context of the system level study performed in the past for Gaia.

The Gaia Technology Programme has been approved by ESA and it is now being implemented. Furthermore, all the activities have to fulfill the requirements identified at system level, i.e., at payload and at spacecraft levels. In order to help ESA to perform these activities, ESA has selected in open competition two parallel Technology Assistance/Definition Study Contractors, at Prime Contractor level, starting with a Technology Assistance activity of $\sim$ 1.5 yr duration and followed by a Definition Study activity of 12 months duration within the period 2002–2005. Although the Gaia Technology programme schedule has been established having in mind a Gaia launch date in mid-2011, the planning assumptions would not change in case of Gaia launch date put forward to the 3rd Quarter of 2010, by anticipating selected Phase B tasks during the definition phase.

## 11. CONCLUSION

A complete design of the Gaia spacecraft, including the payload instruments, consistent with the scientific goals specified by ESA and demonstrating the feasibility of the 10 $\mu$as astrometric accuracy target, has been established by ESA with the help of industry. A comprehensive Technology Programme has also been conceived, approved, and is being implemented, leading to a complete verification of the technology required by Gaia quite in time for the Gaia Project implementation, with a launch in mid-2011.

It is recalled that detailed features of the payload are subject to continuous design changes as the studies proceed, so that the parameters given here will not necessarily be the latest or definitive values.

## ACKNOWLEDGEMENTS

I would like to express my thanks and recognition to M.A.C. Perryman, the Gaia Project Scientist at ESA, to G. Colangelo, System Engineer from the ESTEC Technical Support, to the members of ESA's Gaia Science Team, and to ESA's industrial partners in the Gaia programme.