# GAIA

## Global Astrometric Interferometer for Astrophysics

A Concept for an ESA Cornerstone Mission

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# Contents

## Summary

GAIA is a proposed concept for an ESA cornerstone mission, building on the experiences of the highly successful Hipparcos space astrometry mission, but aiming at a considerably more powerful facility addressing a wide range of topics in astrophysical research.

GAIA will gather astrometric data (proper motions, trigonometric parallaxes) for some 50 million objects, as faint as 15-16 mag, with an accuracy of 5-20 micro-arcsec. Multi-wavelength, multi-epoch photometric information is also accumulated on all these objects.

Scientific goals extend to all areas of stellar structure and evolution, the dynamics of stellar systems, double and multiple stars, and stellar variability. At the proposed level of accuracy, motions and direct distances will be measurable for objects throughout our Galaxy, and beyond.

GAIA will be able to screen some 100,000 nearby stars for possible planetary and brown dwarf companions. Another subsidiary objective will be to map the gravitational light bending, including a possible determination of the PPN parameter Gamma to 1 part in a million.

The GAIA payload consists of three Fizeau interferometers with a baseline of 2.5 m and apertures of about 0.5 m diameter.

The European Space Agency (ESA) is presently considering its medium-term scientific programme (*Horizon 2000 Plus*), and the Survey Committee charged with assessing priorities for this programme has identified an interferometric mission as a leading contender for the next "cornerstone mission". The first aim of such a mission would be to perform global astrometry at the 10 microarcsec accuracy level. The GAIA concept could be considered a starting point for the definition of such a cornerstone mission.

## Preamble

During the meetings of the Topical Teams and Survey Committee associated with the formulation of plans for ESA's Horizon 2000+ scientific programme, a variety of questions were raised about the scientific goals, technical feasibility and timeliness of the various possible cornerstone concepts.

One of the outcomes of the Survey Committee reviews was a request, to ESA and in particular to the ESTEC Future Projects division, to prepare a concise technical appraisal for each identified concept—thus providing a top-level view of the system aspects of each possible cornerstone mission. In the case of the GAIA report, the document prepared by the Future Projects group does not, therefore, enter into details of the scientific objectives nor its international context (Action I.1 on the Topical Teams requested by H. Schnopper, as contained in the action item summary distributed by G. Cavallo on 4 July 1994); it does not provide an assessment of noise-level determinations (Action I.2, as requested by the Survey Committee Chairman); nor does it permit the presentation of the results of the major effort which has been dedicated to the study of the GAIA concept during the summer (Action III.1, placed on ESTEC by the Survey Committee Chairman).

This document has therefore been prepared as an appendix to the Future Projects division's report. It provides a more detailed scientific rationale for a future astrometric mission, and it includes further details about the possible way in which the payload could achieve the proposed scientific goals. In addition, some preliminary ideas about the scientific and management organisation are provided, along with a summary of known astrometric missions under consideration by other agencies, and appendices supplying additional indications of scientific support and goals.

One important remark must be offered. The Survey Committee's intention was that, at this stage, only a mission 'concept', not necessarily a specific 'project', should be studied. The work conducted on GAIA does not follow precisely this approach; there is the opinion among the proponents of a follow-up astrometric mission that the scientific objectives of a possible future mission cannot be discussed confidently without a very specific instrumental concept in mind—in order to assess the scientific goals, an accuracy assessment is needed; such an assessment is quite impossible without an instrumental concept. Conversely, the scientific appeal of *sub*-microarcsec astrometry could be discussed at length (it would, for example, provide direct distance indicators within the local group of galaxies, dynamical information related to cosmological evolution beyond the local group, etc). However, such deliberations will remain speculative unless a mission concept which can achieve such goals can be identified.

With GAIA, therefore, we address both the scientific importance of microarcsec astrometry, along with a proposed technical solution for achieving these goals within the boundary constraints of the Horizon 2000+ exercise.

It is demonstrated that a follow-up astrometric mission could now be embarked upon with some confidence. Building on the Hipparcos experiences, a mission with dramatically enhanced scientific goals could be undertaken. Many tens of millions of objects, including Solar System and extra-galactic objects, could be observed. Astrometric accuracies of the order of 10 microarcsec (better for brighter stars) seem achievable. This would yield distances and luminosities to objects within 10 kpc, and motions individually significant *throughout* our Galaxy. Information on double and multiple systems (including stellar masses), a truly immense data base of multi-colour, multi-epoch photometry, valuable information on the space-time metric, and angular diameters of thousands of stars, would become available.

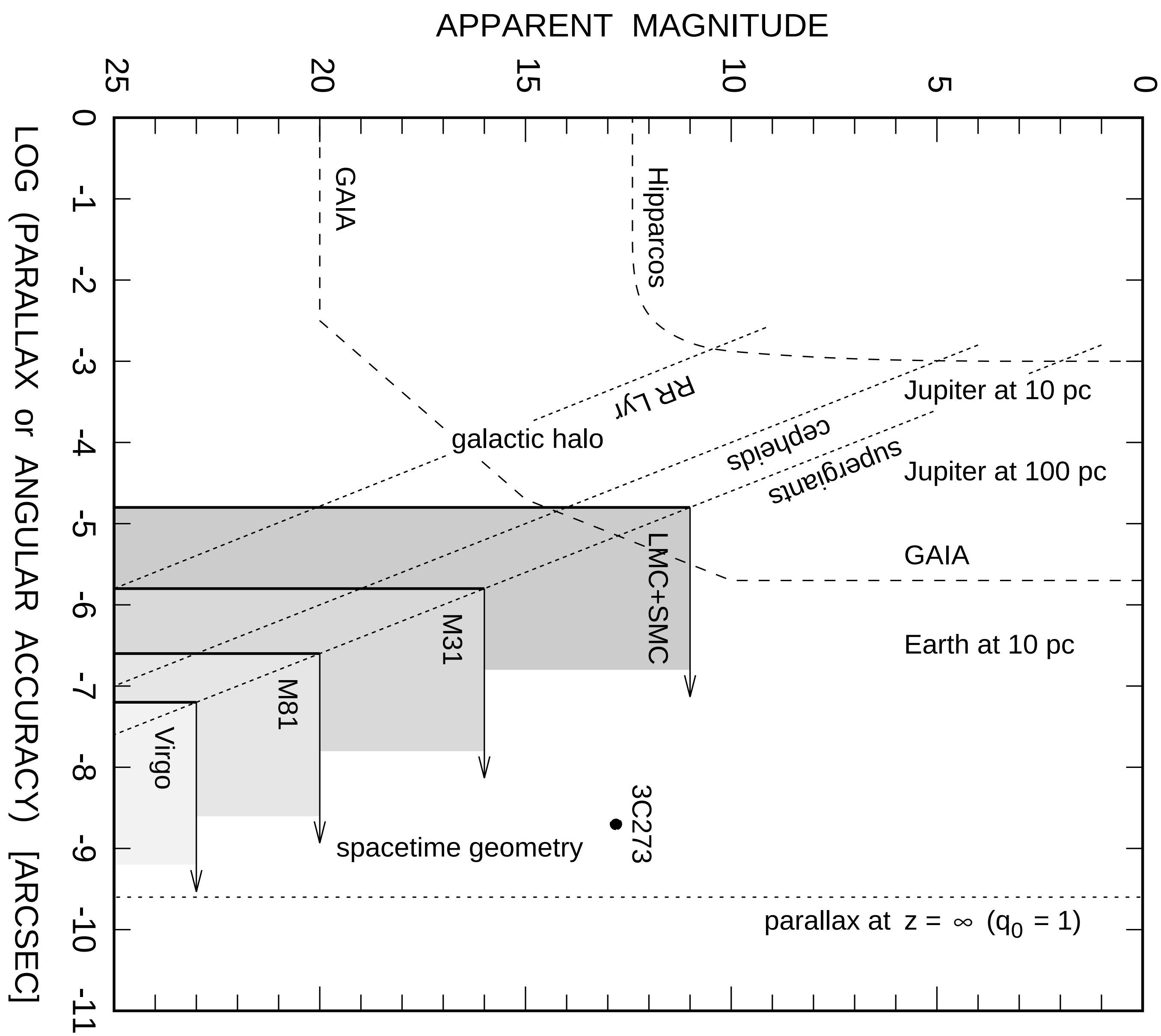
Initial system studies indicate that such a mission could be comfortably accommodated within the (dual-launch) Ariane 5 envelope, and within the financial envelope of the cornerstone mission (even on the assumption that the payload would be developed and built under ESA management), as a purely European mission. The mission is baselined for 5 years of operations, and could be positioned in either a geostationary, or L5 (Earth-Moon Lagrangian point) location. The mission could be undertaken rather rapidly. It would be a first in space interferometry, would strengthen European leadership in an important scientific discipline, and seems to involve an acceptable balance between overall feasibility and required technological development.

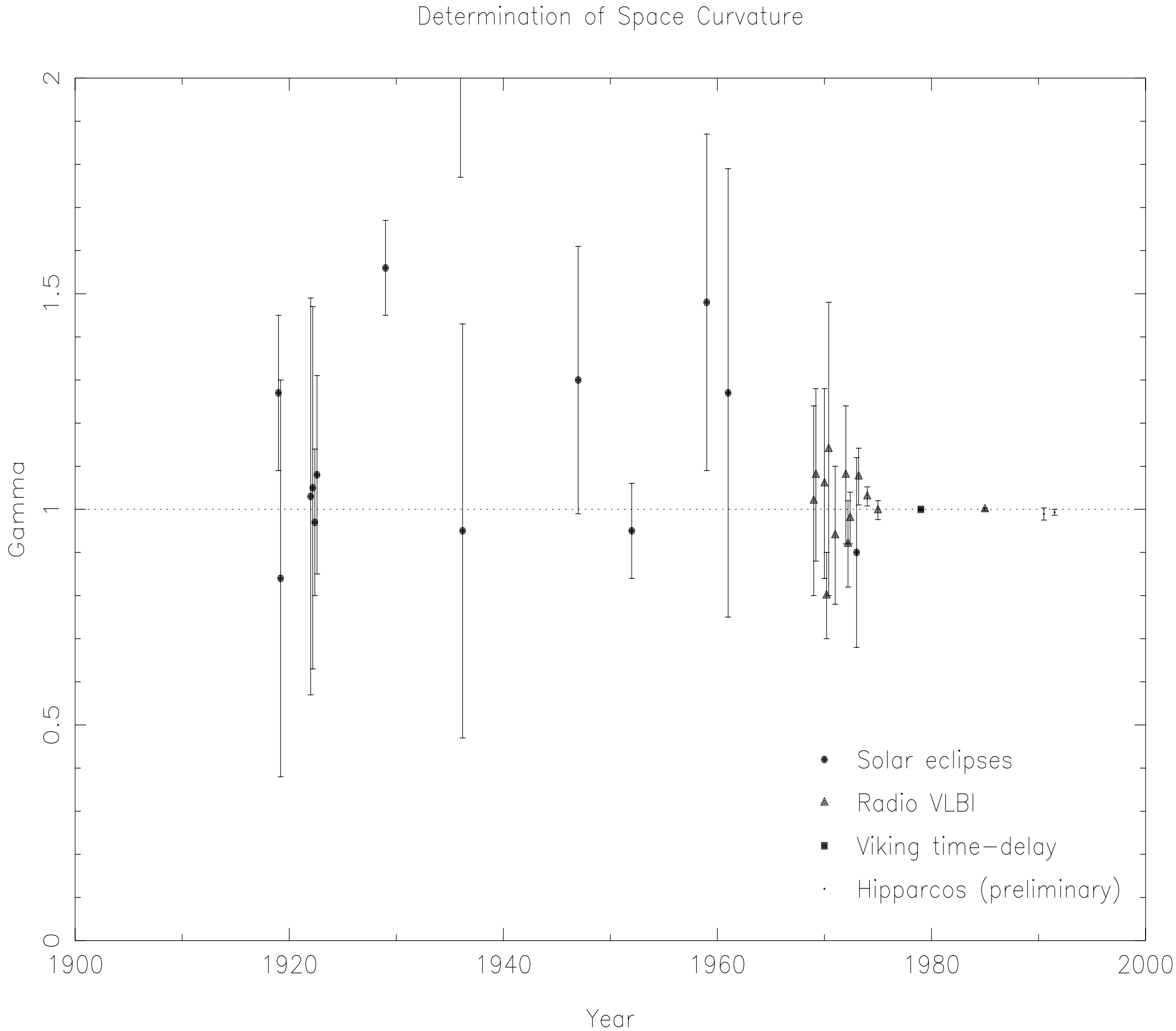
# Figures

## Figure 1: Scope of Parallax Measurements

Schematic overview of some objects and phenomena that can be studied by optical astrometry at various levels of accuracy and sensitivity.

The region probed by Hipparcos (limited by 0.001 arcsec accuracy and magnitude 12.5) is indicated


APPARENT MAGNITUDE
LOG (PARALLAX or ANGULAR ACCURACY) [ARCSEC]
25
20
15
10
5
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
GAIA
Hipparcos
RR Lyr
galactic halo
cepheids
supergiants
Jupiter at 10 pc
Jupiter at 100 pc
GAIA
Earth at 10 pc
LMC+SMC
M31
M81
Virgo
3C273
spacetime geometry
parallax at z = ∞ (q0 = 1)




by the dashed curve at the upper left corner.

The parameter region of interest for GAIA is also sketched. It includes direct (trigonometric) distances to all galactic supergiants and cepheids visible from the sun, RR Lyrae stars and bright halo stars within 10 kpc from the sun, as well as the brightest stars in the Magellanic Clouds (LMC+SMC). Jupiter-like planets can be detected from the photocentric motions of stars out to a few hundred parsecs.

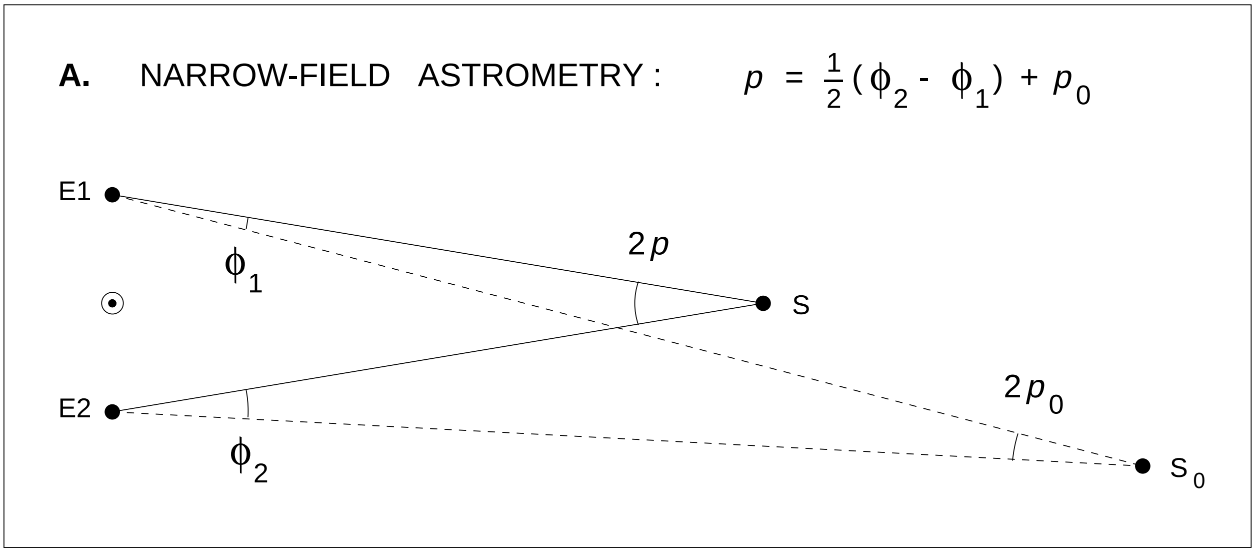
## Figure 2: Determination of Space Curvature

Determinations of the post-Newtonian parameter Gamma ($\gamma$), representing the deviation of the gravitational light-bending from Newtonian theory. According to general relativity, Gamma = 1.

The figure illustrates the very preliminary determination of Gamma derived from the first 12 months of the Hipparcos data:

$$\gamma = 0.989 \pm 0.014$$

along with other determinations. These include the original observations of Dyson, Eddington &




Davidson (1920), and other optical determinations made at times of total solar eclipse, including the most recent published determinations of Jones (1976) based on the 1973 Mauritanian eclipse. All such metric determinations have been based on observations within a few solar radii of the solar limb. Other determinations based on VLBI observations and the Viking spacecraft (Shapiro) time-delay, also restricted to measurements made close to the solar limb, are also illustrated. The data are taken from Soffel (1989).

A key subsidiary objective of the GAIA mission will be to map the light-bending in the gravitational fields of the sun and planets over most of the sky. The parameter Gamma could possibly be determined to one part in a million.

## Figure 3: The Measurement of Absolute Parallaxes

This figure illustrates why global (wide-angle) astrometry is required to determine *absolute* parallaxes, i.e., without a zero point error depending on the properties of background stars.

**A:** The principle of parallax measurement in traditional ground-based, narrow-field astrometry. The target star S is measured with respect to a background star S0 when the Earth is at opposite positions (E1 and E2) in its orbit around the sun. Half the difference of the angular distances gives the *relative* parallax p - p0.

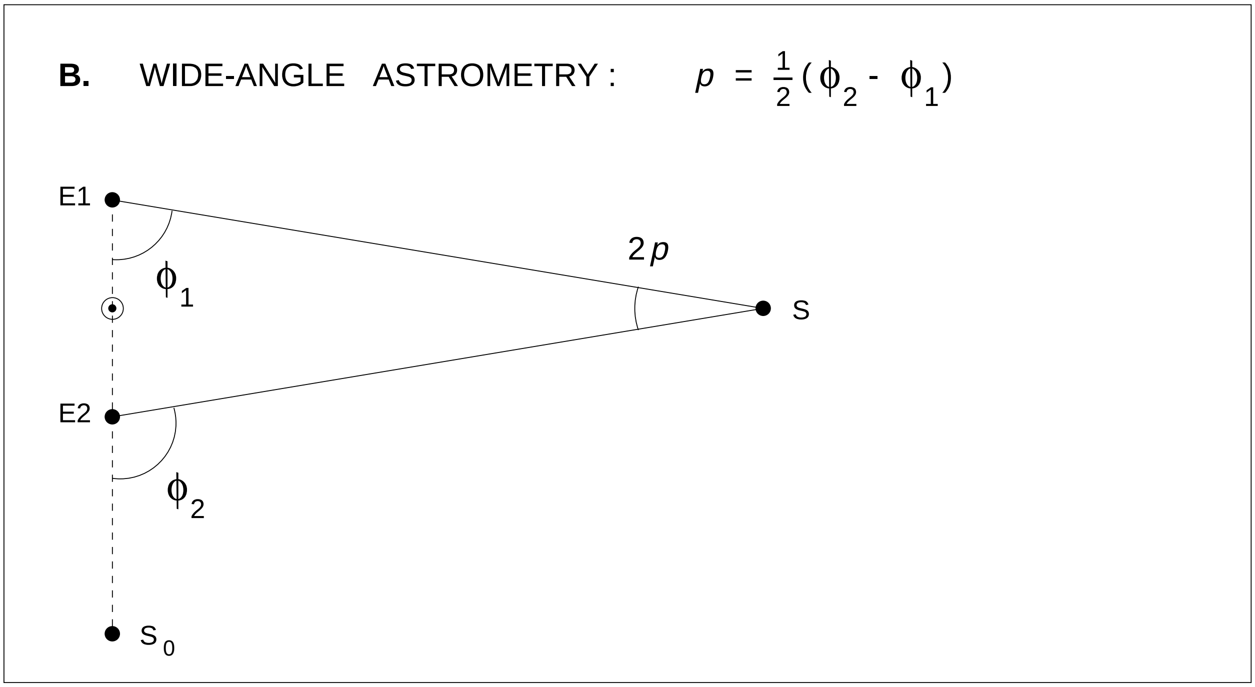
To obtain the absolute parallax (p), the mean parallax of the background stars must be added. The estimation of the mean background parallax is a major limitation to the ground-based technique.

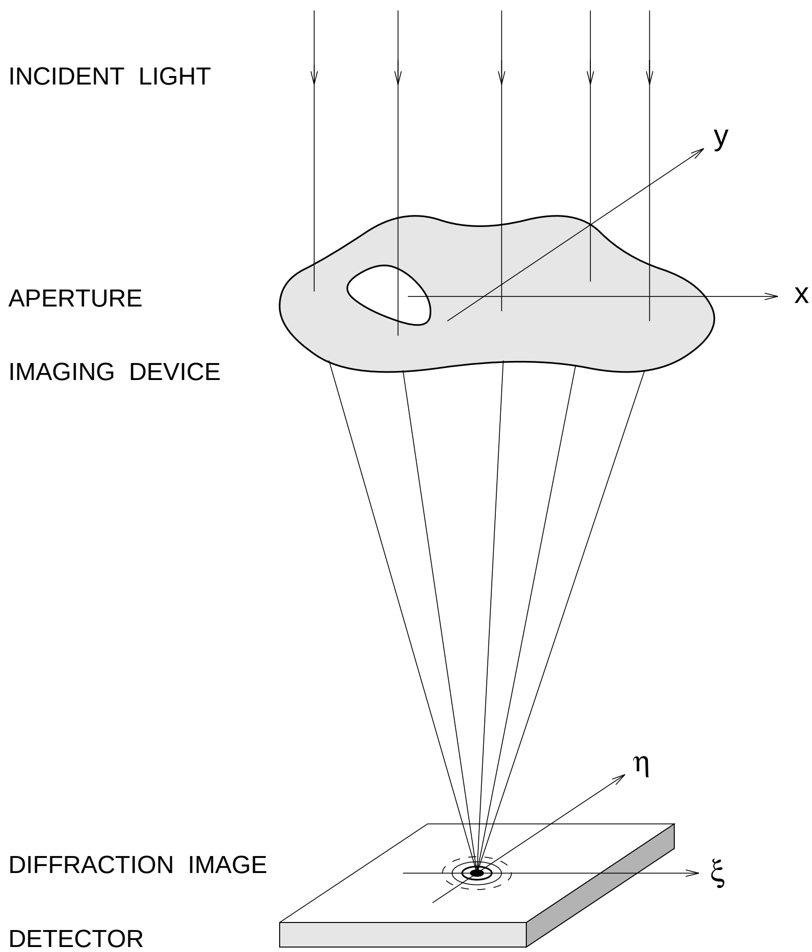
**B:** In global space astrometry, such as performed by Hipparcos and GAIA, the *absolute* parallax of S is directly obtained from wide-angle measurements.

## Figure 4: Fundamental Limit of Optical Astrometry

This figure illustrates the fundamental limit of the accuracy of optical directional measurements, as set by the dual wave/partical nature of light.

The diffraction pattern of the instrument aperture defines the probability density of the photon detection process. Given a limited number of detected photons, N, the centroid of the diffraction


B. WIDE-ANGLE ASTROMETRY : $p = \frac{1}{2}(\phi_2 - \phi_1)$
E1
$\phi_1$
$2p$
S
E2
$\phi_2$
$S_0$


INCIDENT LIGHT
y
APERTURE
x
IMAGING DEVICE
η
DIFFRACTION IMAGE
ξ
DETECTOR

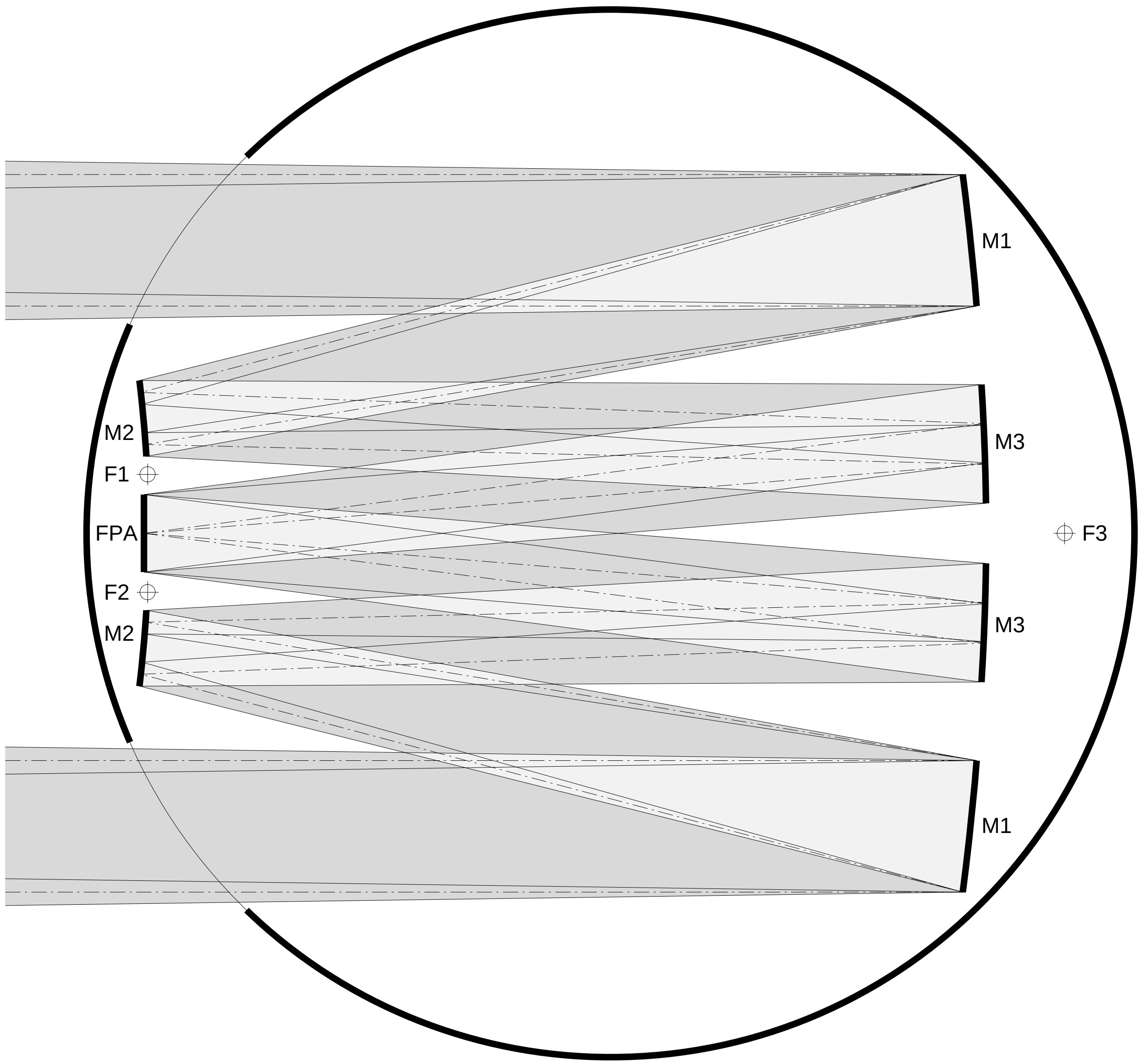



image can only be located to a certain precision given by the equation

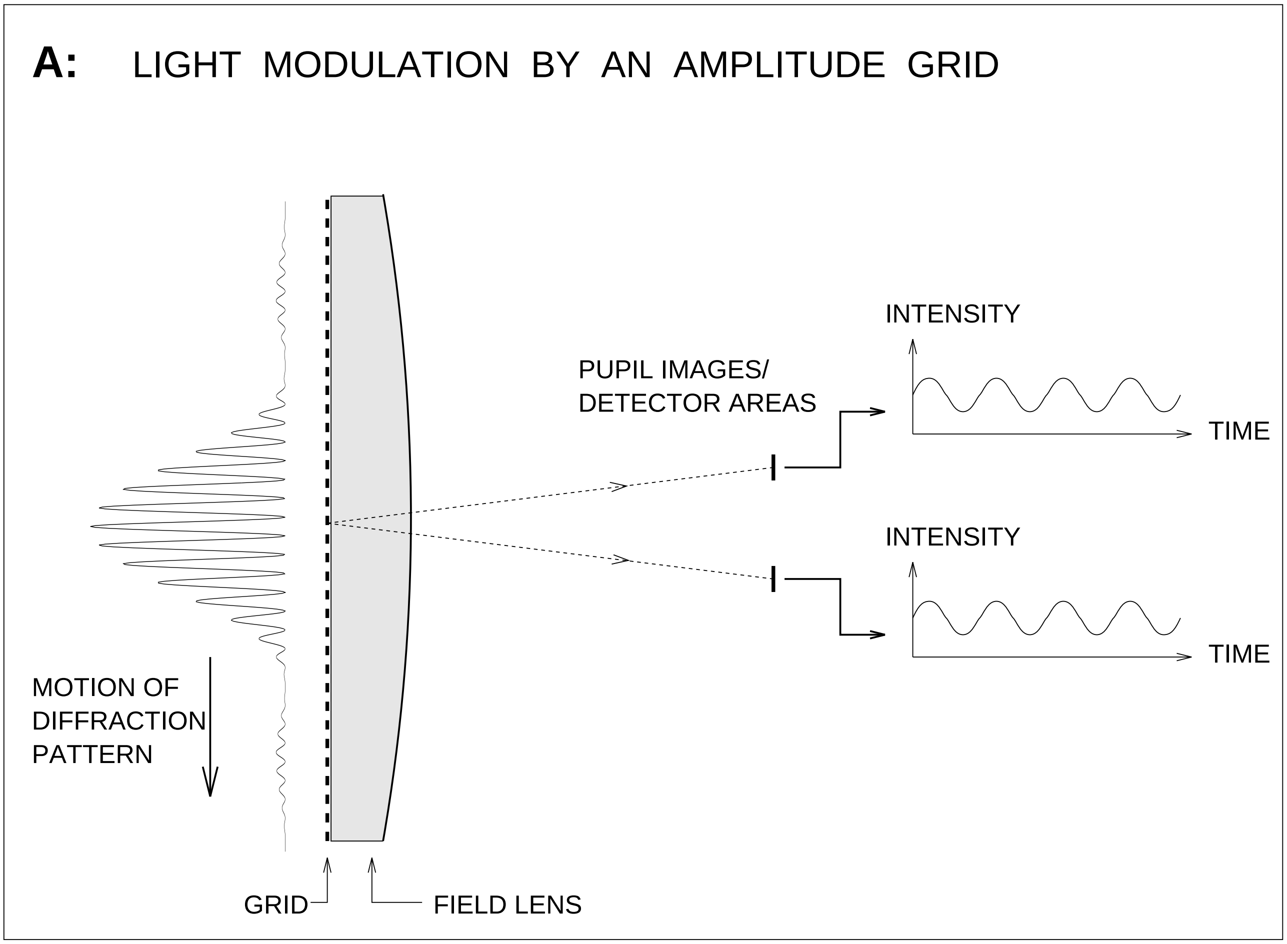
$$\sigma_\xi \geq \frac{\lambda}{4\pi x_{\rm rms}\sqrt{N}}, \quad \text{where}$$

$$\begin{aligned} \lambda &= \text{effective wavelength} \\ x_{\rm rms} &= \text{RMS extension of aperture in measuring direction} \\ N &= \text{number of detected photons} \end{aligned}$$

## Figure 5: Optical Layout of a Fizeau Interferometer

GAIA contains three identical Fizeau interferometers, pointed in different directions. The baseline of each interferometer is 2.5 m, and the aperture diameter is about 0.5 m.

Each interferometer is optically equivalent to a three-mirror telescope (M1, M2, M3) preceded by




a double aperture. FPA = focal plane assembly. F1, F2, F3 indicate three fiducial points for controlling the mirrors and focal plane assembly.

The interferometer fits into a cylindrical envelope of 4.4 m diameter, as shown in the figure.

This optical configuration results from a ray-tracing solution using the Code V package.

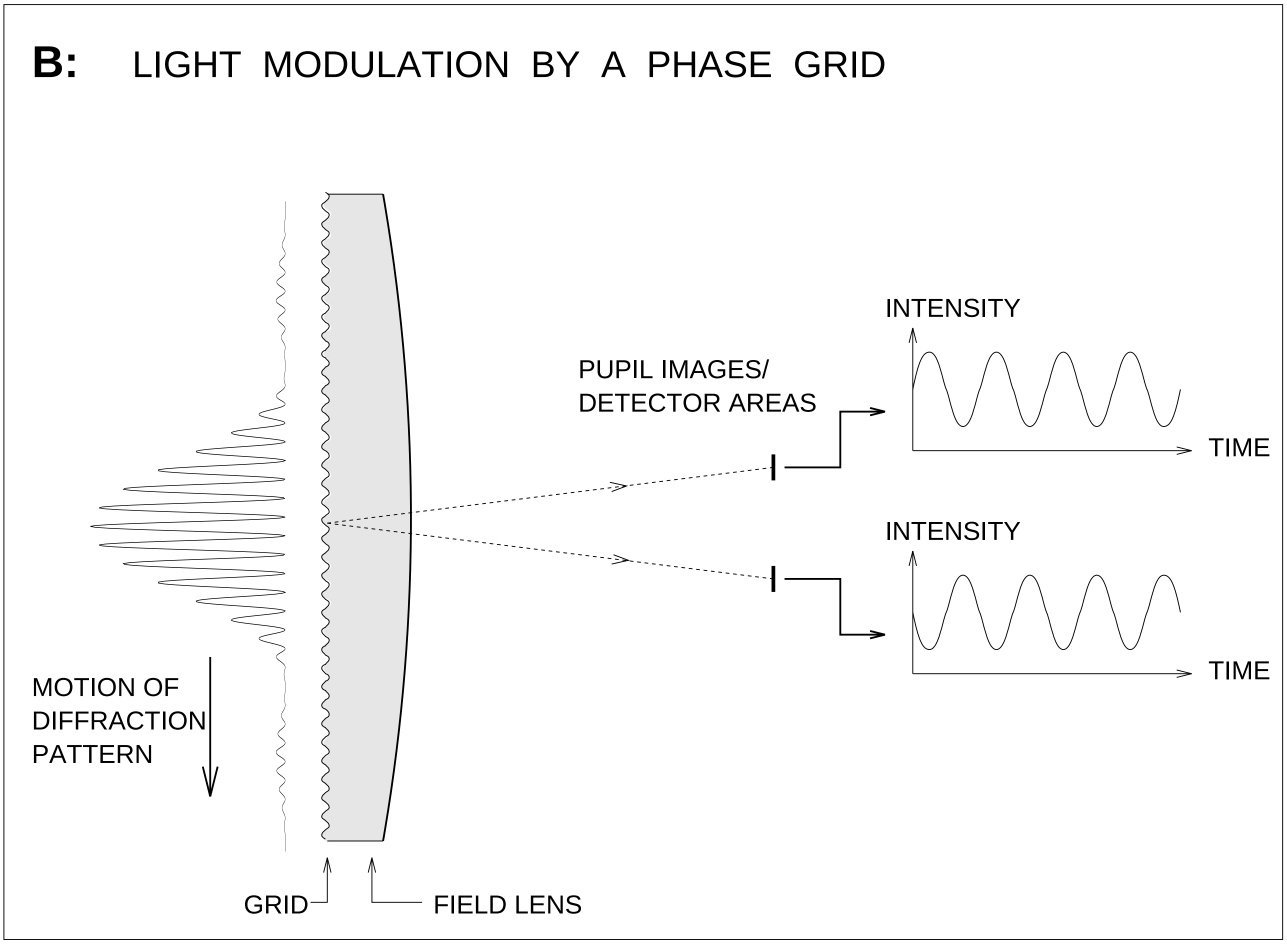
## Figure 6: The Principle of Light Modulation

The maximum efficiency of the focal plane measurements would be obtained with a detector of sufficient resolution to register the individual fringes of all star images in the 1 degree field of view.

Since no such detector is available at the moment, the baseline focal plane assembly for GAIA includes a system of modulating grids, followed by low-resolution CCDs to record the modulated light. This figure illustrates two methods of light modulation.

**A:** Principle of light modulation by means of an *amplitude grid*, consisting of alternatingly opaque and transparent bands having the same spatial frequency as the interference fringes. A major drawback of the amplitude grid is that only half the light is utilized.

**B:** Light modulation by means of a *phase grid*. This grid transmits all the light but introduces a periodic modulation of the phase; in other words, it corrugates the wavefront. The phase grid not only transmits twice as much light as the amplitude grid, the degree of modulation is also stronger; both factors impove the accuracy of the astrometric measurements.


B: LIGHT MODULATION BY A PHASE GRID
INTENSITY
PUPIL IMAGES/
DETECTOR AREAS
TIME
INTENSITY
TIME
MOTION OF
DIFFRACTION
PATTERN
GRID
FIELD LENS

For a phase grid the two images of the interferometric pupils are modulated in anti-phase, requiring separate detection of the two images.

### Figure 7: Layout of Grids and Detectors in the Focal Plane

This figure gives an example of how the focal plane could be disposed in terms of wavelength bands and type of detection.

The inner part of the field, used in the interferometric mode, is covered by a mosaic of phase grids, using different passband filters (A, B, ..., F) and a separate CCD behind each grid. The grids are divided in subfields with field lenses as shown in Fig. .

The outer part of the field is used for incoherent imaging, using CCD detectors placed directly in the focal plane and operated in drift scanning mode. The detectors labelled w, u, v, b, y, I, Bw and Bn are preceded by colour filters for intermediate and narrow band photometry. Each CCD has a two regions that are read out separately to increase the dynamic range. The pixels are long and narrow.

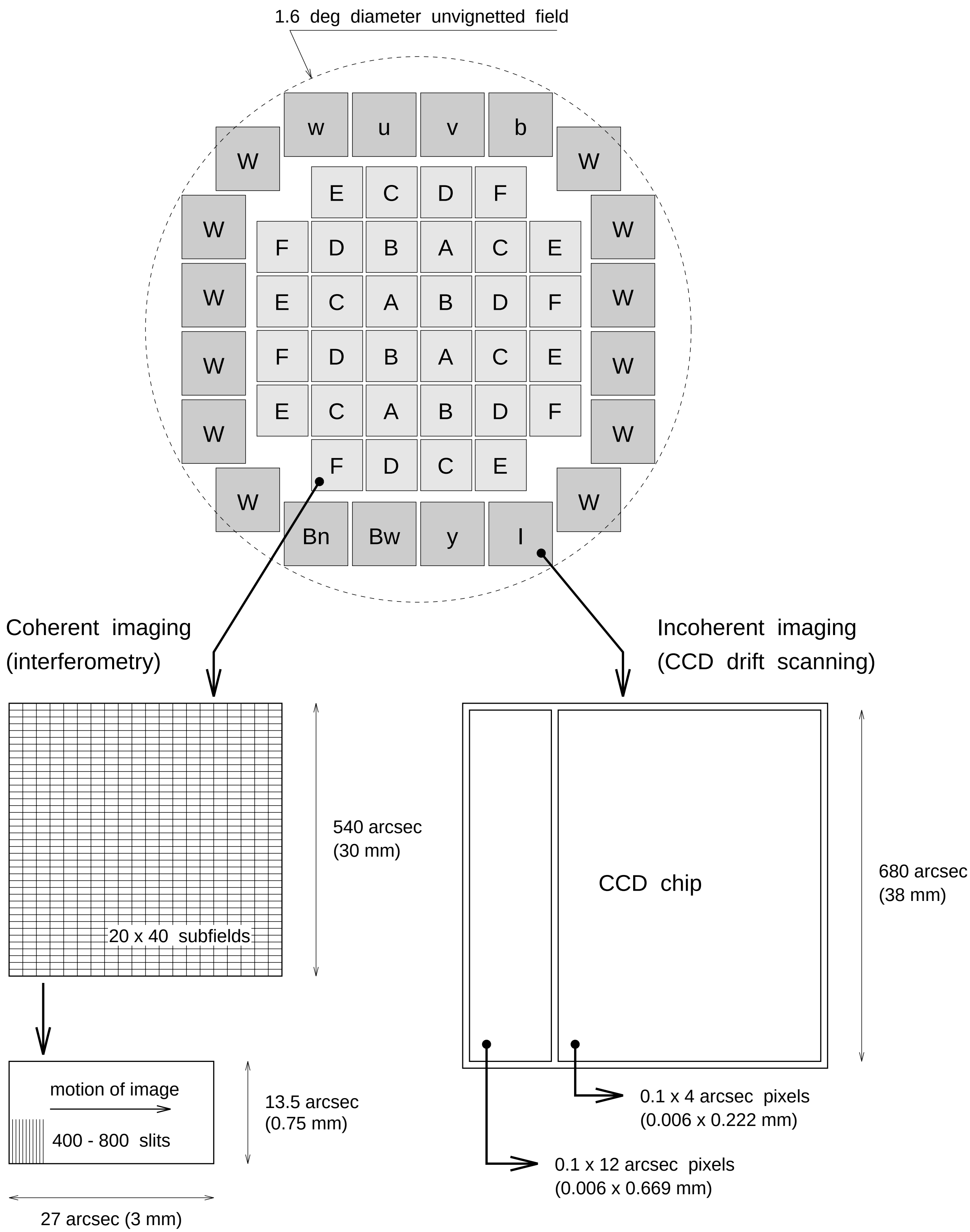
# 1 Introduction

## 1.1 Historical Context

The measurement of celestial angles, and in particular the angles between stars, is a branch of astronomy known as astrometry. It is one of the oldest branches of science, and one which has been a particular preoccupation of astronomers for the last few hundred years. Within the last century, developments in astrometry have been largely eclipsed by rapid and dramatic advances in many other areas of astronomy. Indeed, today, astronomy has many active observational and theoretical branches, and the Universe is being probed at all parts of the electromagnetic spectrum. But until the advent of astrophysics a century ago, astronomy consisted only of astrometry, and its theoretical counterpart, celestial mechanics. Practically all that was known about the Universe had been obtained by astrometric techniques. Increasingly precise angular measurements provided celestial mechanics with the data needed for its growth as an inductive science, and provided cosmology with the foundations necessary to take it beyond mere speculation. The development of angular measurements has resulted not only in a major and sustained contribution to the understanding of our place in the Universe, but in very fundamental changes in scientific belief.

A concise history should make these developments clearer. Angular measurements first led the ancient Greeks to conclude that the Earth was a sphere, and by 120 BC Hipparchus had calculated the distance to the Moon. Discussions of the Earth's motion were not re-opened until Copernicus demonstrated that accurate planetary predictions could be made by postulating a heliocentric system—the planets orbiting the Sun, rather than the entire Universe circling around the Earth. Tycho Brahe's sixteenth century astrometric observations provided the basis for Kepler's laws of planetary motion, the formulation of which had been prompted by observed discrepancies in the motion of Mars—these achievements resulted from improved methods of sub-dividing engraved scales and, in the process, making one minute of arc a 'sensible quantity' in astronomical measurement.

During the sixteenth century, one of the principal scientific problems was understanding the motion of the Earth. Before 1600, astronomers had reached an agreement that the crucial evidence needed to detect the Earth's motion through space was the measurement of stellar parallax. And even at that time, considerable speculation still existed about the nature of the stars. Were they simply points of light, as implied by the infinite Universe of Thomas Digges and supported by the more daring Copernicans, or did they have clearly measurable diameters?


1.6 deg diameter unvignetted field
w
u
v
b
W
E
C
D
F
A
B
Bn
Bw
y
I
Coherent imaging
(interferometry)
Incoherent imaging
(CCD drift scanning)
540 arcsec
(30 mm)
20 x 40 subfields
CCD chip
680 arcsec
(38 mm)
motion of image
400 - 800 slits
13.5 arcsec
(0.75 mm)
27 arcsec (3 mm)
0.1 x 4 arcsec pixels
(0.006 x 0.222 mm)
0.1 x 12 arcsec pixels
(0.006 x 0.669 mm)

The measurement of stellar distances was a task which preoccupied the early Astronomers Royal in England, amongst others, but it was to take a further 250 years until this particular piece of observational evidence could be secured. This search led to the detection, in 1725, as a by-product of James Bradley's unsuccessful attempts to measure the distance to the bright star Gamma Draconis, of stellar aberration, an effect correctly attributed to the vectorial addition of light to that of the Earth's motion around the Sun. This provided the first direct proof that the Earth was moving through space, and thus a confirmation both of the Copernican theory, and also Ole Roemer's discovery of the finite velocity of light. Soon afterwards, Edmund Halley detected the 'proper motion' of three stars, thereby demonstrating that stars move through space.

Parallaxes were first determined in the 1830's. The first confirmation that the stars lay at very great, but nevertheless finite, distances, represented a turning point in the understanding of the stars.

Astrometric measurements also led to William Herschel's discovery of the existence of double stars as actual physical pairs, or binary systems. They led to Nevil Maskelyne's demonstration of gravitational attraction between bodies of astronomical dimensions (and hence to a revised mass and mean density of the Earth), and thus to a confirmation of Newton's law of universal gravitation. Observations of the transit of Venus across the solar disc led to an estimate of the distance between the Earth and the Sun, and represented one of the most elaborate scientific undertakings of the eighteenth century. The predicted presence of the eighth planet Neptune as a result of orbital perturbations of Uranus, independently by Adams and Le Verrier, was widely considered to be a triumph of nineteenth century science. And it was Bessel's suggestion in 1844 that the motion of Sirius was perturbed by a faint companion, which led to the discovery of white dwarfs in 1915. The confirmation of Einstein's theory of General Relativity, from the perihelion motion of Mercury's orbit and the gravitational light deflection during solar eclipse, was also based on astrometric measurements of the very highest accuracy available at the time.

Over the last hundred years, with only relatively small advances in astrometric precision made possible by measurements from the Earth's surface, the most important applications of astrometry have been the continuing determination of stellar distances by measuring trigonometric parallaxes, the estimation of stellar velocities by measuring proper motions, and the setting up of a reference frame for the study of Earth, planetary and galactic dynamics.

The resurgence of interest in astrometry today is dramatically illustrated by the fact that, in 1989, ESA developed and launched a satellite entirely dedicated to high-accuracy astrometry. This elaborate mission has been an unprecedented success. Astrometry, in the words of a speaker (not involved with the Hipparcos project!) at the 1994 IAU General Assembly, has suddenly become a 'fashionable and respectable pursuit'. The realisation of the fundamental importance of astrometry, and its potential for the future, has inspired the proposal of three astrometric missions within the former Soviet Union, elaborate (wide-angle) ground-based astrometric facilities and a variety of proposed space programmes in the United States, the recent commencement of studies of an astrometric space mission in Japan, and the proposal for an astrometric mission (Roemer) within the ESA M3 round.

## 1.2 Timeliness of a Second Astrometric Mission

In his assessment of success in space science, Freeman Dyson expressed his view that 'A successful mission will raise new questions as often as it answers old ones'. Thus, in all areas of space science, the successful opening up of a new discipline has, without exception, resulted in follow-up missions; this can be seen in the infrared, optical/UV, X-ray, and gamma-ray domains. This logical development applies with equal force to astrometry: the imminent availability of the Hipparcos data has focussed much attention on wide-ranging problems in areas such as stellar structure and evolution, galactic structure, galactic dynamics and evolution, which will become accessible with angular measurements of an even greater accuracy, number, and limiting magnitude than those provided by Hipparcos.

Thus, the Roemer proposal was submitted in 1993 in response to ESA's Call for Proposals for the M3 mission within the Horizon 2000 programme (Høg *et al.* 1993). The proposal was rated very highly by the ESA advisory committees — scientifically it was given the highest rank of all medium-sized missions by the Astronomy Working Group. Other considerations led to its referral to a possible Horizon 2000+ Cornerstone Mission.

The interferometric GAIA concept was duly proposed as part of ESA's Horizon 2000+ scientific programme. It builds on the experience gained within the Hipparcos programme, and on ideas developed within the Roemer proposal. The concept of a free-flying astrometric interferometer has also emerged as an attractive and important development resulting from the deliberations of the various ESA scientific teams charged with the studies of a possible space-based interferometer. A long-baseline Michelson interferometer was identified as a long-term goal by the Space Interferometry Study Team (the SIST) but with requirements for a more modest precursor mission (Noordam *et al.* 1990). The lunar surface was considered as a location for such an interferometer by the Lunar Interferometry Study Team (the LIST); however, the LIST considered that a free-flying interferometer, of modest baseline, and dedicated to astrometry rather than imaging, was a natural, attractive, and scientifically highly-important precursor mission (Dainty *et al.* 1994).

The scientific goals and technical feasibility of the GAIA proposal constitute the main part of this report. To end this section we address a miscellany of items which we consider may clarify considerations of the timeliness of a future astrometric cornerstone mission:

(a) first and foremost, the scientific importance of the mission is considered overwhelming (see Section 2). Although the Hipparcos results have not been finalised and distributed, a series of more than 20 papers detailing the data quality and providing some indications of the scientific value of the data, will shortly be submitted to *Astronomy & Astrophysics*. The finalised data are to be made available in less than two years, with detailed exploitation and interpretation of these data expected to take place over the next 2–5 years;

(b) consultation within the scientific community confirms that it is quite inappropriate to wait until the Hipparcos data have been fully or even partially exploited before a follow-up astrometric mission is considered. The reasons for this are three-fold (i) the technical objectives of a future mission fall simply within the classification of accuracy, number of objects, and limiting magnitude. GAIA provides orders of magnitude improvement in all of these parameters, and thus *guarantees* its capability to provide the astrometric data that are needed after the exploitation of the Hipparcos results; (ii) the Horizon 2000+ cornerstone programme will be finalised shortly, and will essentially freeze the potential domains of space science addressable by an ESA cornerstone mission over the next two decades—if space astrometry is to have a future in Europe, now is the time to embrace it; (iii) the leadership, momentum, and capabilities—both scientific and engineering—are now in place within Europe to capitalise on the Hipparcos successes. This is true both for astrometry and interferometry;

(c) GAIA is expected to be achievable as a pure ESA mission, within the financial, schedule and technological constraints imposed by the Cornerstone mission concept. Preliminary system studies suggest that the GAIA satellite could be incorporated within an Ariane 5 envelope, without the requirement for payload element deployment. An astrometric interferometer achieves an excellent balance between achievability and an advance in technological capability (and thus attractive to industry) demanded by the Cornerstone concept. The mission performances summarised here are achievable with current detector technology, although potential detector development programmes over the coming years could provide a further enhancement in scientific capability, coupled with the technological challenge of new detector development, in line with the spirit of the Horizon 2000+ concept;

(d) we note that the level of technical studies permitted within this very earliest phase of feasibility assessment cannot yet permit the scientific community, nor ESA, to guarantee the

> performances claimed in this report. Nevertheless, there is a strong scientific indication that astrophysics can be revolutionised by astrometric measurements reaching the 10–20 microarcsec accuracy level, or better—this accuracy presently appears entirely realistic with a free-flying scanning interferometer adhering to the GAIA concepts.

This report aims to satisfy two, perhaps superficially conflicting, requirements. It focuses on a specific instrumental configuration, and by doing so is intended to indicate that the scientific goals identified here could be achieved without a very great demand on improved technological capabilities. But at the same time, focusing on a specific instrumental configuration is not intended to preclude developments which may occur, or may be encouraged to occur, within the time schedule of the Horizon 2000+ programme. In a sense, therefore, the identified accuracies and scientific goals may be considered as a 'minimum' objective. If considered appropriate, technological developments could permit enhanced scientific performances: in particular we may identify the following as areas in which improvements might occur: (i) improved (more efficient, energy sensitive) detectors, including detectors sensitive in the near infra-red; (ii) enlarged optical elements (if, for example, mirror weights can be decreased); (iii) larger interferometric baselines (if, for example, a large stable deployable structure could be foreseen).

## 1.3 Main Characteristics

The main scientific goals which would be achievable with such a mission are as follows:

- number of objects: ¿ 50 million
- limiting magnitude: V ¿ 15.5 mag
- completeness of catalogue: V ¿ 15.5 mag
- *a priori* observing list/object selection: not required
- positional accuracy: 10 microarcsec at V = 15 mag
- parallax accuracy: 10 microarcsec at V = 15 mag, i.e., 10% distance accuracy at 10 kpc
- proper motion accuracy: 10 microarcsec/year at V = 15 mag, i.e., 1 km/s at 20 kpc
- multi-colour (e.g., 6-band, sufficient for spectral type and luminosity class classification), multi-epoch photometry (at each of several hundred epochs) throughout the five year mission.

Further details of the expected astrometric accuracies, for both the interferometric and incoherent imaging modes, are given in Section 3.6, along with the assumptions entering into these accuracy estimates. At V = 10 mag, the astrometric accuracies are improved by a factor of 3 or so. The above goals are compared with those of Hipparcos in Table 1.

Table 1: A comparison between the scientific capabilities of Hipparcos with those of GAIA.

| | Hipparcos | GAIA |
|---|---|---|
| Limiting magnitude ($V$) | $\sim 12$ | $> 15 - 16$ |
| Completeness ($V$) | 7.3–9.0 | $> 15 - 16$ |
| Number of objects (main mission) | 120 000 | 50 000 000 |
| Accuracy (for all five parameters) | 1–2 mas | 5–20 microarcsec |

The main instrumental characteristics of a technically feasible configuration achieving the above goals are as follows:

- three independent Fizeau interferometers, stacked at angles of (for example) 54 deg (A-B); 78.5 deg (B-C); and 132.5 deg (A-C). A detailed study (from the rigidity and redundancy point of view) would be needed in due course;
- each interferometer consisting of two 50 cm (or larger) aperture mirrors, with a baseline separation of 2.5 m, such that each interferometer could be contained (without the need for in-orbit deployment) within the Ariane 5 envelope;
- each interferometer equipped with CCD detectors.

# 2 Scientific Objectives

Astrometric measurements provide model-independent estimates of basic geometrical and kinematical properties of astronomical sources. Traditionally the most important applications are the determination of stellar distances, motions and masses. GAIA will provide an immense quantity of extremely accurate astrometric and photometric data from which ultimately all branches of astrophysics will benefit. In the areas of the physics and evolution of individual stars and of the Galaxy as a whole the impact will be immediate and profound. On a much more modest scale this process will begin already with the availability of the Hipparcos results. However, while Hipparcos could probe less than 0.1% of the volume of the Galaxy by direct distance measurements, GAIA will encompass a large fraction of the Milky Way system within its parallax horizon, including much of the halo, and even touching on the nearest companion galaxies such as the Magellanic Clouds (Fig. ).

Another goal of astrometry is the establishment of an accurate set of reference directions for dynamical interpretation of the motions of the Earth and other planets and of the Milky Way system, i.e., an optical reference system. The importance of having access to a dense and accurate inertial reference frame is easily overlooked in comparison with the more direct benefits of, say, parallaxes. However, the ability to establish small systematic deviations in the patterns of motions, whether it concerns the search for transneptunian planets or dark matter in our galaxy, crucially depends on the accuracy of the reference system. Through its global survey nature, GAIA is ideally suited to provide an extremely dense and accurate reference system. The limiting magnitude is sufficiently faint to allow a direct link with the extragalactic system by observation of quasars.

In the following scientific survey, emphasis is given to topics where the estimated astrometric accuracies lead to clearly identifiable applications. In addition to these, the multi-colour, multi-epoch, sub-millimagnitude photoelectric photometry will open up vast areas for study related to stellar stability over the entire Hertzsprung-Russell diagram. Other possible topics have not yet been carefully assessed, but appear highly promising—amongst these one may note the detection of MACHOs (Alcock *et al.* 1993; Aubourg *et al.* 1993), and the possible determination of the angular diameters of many thousands of (nearby, giant) stars.

A 5-year mission is baselined, not only because of its resulting improvement in the achievable astrometric accuracy, but also because of the importance of such a temporal baseline for the dynamical studies of asteroids, for the determination of the parameters (including orbital motion) of double and multiple stars, for the detection of possible planetary and brown dwarf companions, and for the photometric variability studies.

In compiling the following survey of scientific capabilities of a micro-arcsec class astrometric mission we have drawn heavily from existing material describing the rich scientific capabilities of such an improvement in astrometric accuracy. In particular, we acknowledge the use of ideas and in some cases specific examples from Kovalevsky & Turon (1991), from the report of the ESA Interferometry Review Panel under the chairmanship of Dr. C. Dainty, and from the NASA report on the capabilities of an Astrometric Interferometry Mission, prepared by the Space Interferometry Science Working Group under the chairmanship of Dr. S. Ridgway. We have concentrated on scientific applications requiring an accuracy of the order of 20 microarcsec or 20 microarcsec/yr and a limiting magnitude around V = 15–16 mag, although GAIA may actually achieve even higher accuracy for brighter stars, and will reach fainter magnitudes at a reduced accuracy (cf. Fig. and Table 3).

## 2.1 Physics and Evolution of Stars

### 2.1.1 Stellar luminosities

Luminosity estimates are based exclusively on determinations of stellar distances, themselves determined directly only from measurements of trigonometric parallaxes. With Hipparcos, direct distance measurements are limited to 100 pc with, say, 10% precision, a distance horizon insufficient to include rare but astrophysically important categories of stars such as O stars, Cepheids, and RR Lyrae variables. From ground-based observations, distance determinations and luminosity calibrations have been restricted to the main sequence, with indirect distance estimates, for example based on statistical calibrations, used to estimate stellar distances and luminosities for rarer spectral types. Parallaxes with a precision of 20 microarcsec would reach to 5 kpc with 10% accuracy, or to 10 kpc with 20% accuracy. For the first time this would provide an extensive network of distance measurements throughout a significant fraction of our Galaxy, including the galactic centre, spiral arms, the halo, and the bulge.

### 2.1.2 Massive stars

Although only a small fraction of stars in the Galaxy are more massive than 20 solar masses, such stars, which spend most of their short lives as H-burning O-type stars, play an important role in galactic structure and evolution. Thus, accurate knowledge of the luminosity of these stars is important for comparing masses derived from stellar evolutionary models with those derived from stellar atmosphere models, for determining initial mass functions, and for studying stellar evolution in the high luminosity/high mass region of the Hertzsprung-Russell Diagram. The absolute magnitudes of O stars are presently poorly determined (no O star is sufficiently close to the sun to have a trigonometric parallax accurately measured), the absolute visual magnitudes coming primarily from O stars in clusters and OB associations whose distances are themselves uncertain, but are typically around 1–2 kpc. Typical apparent magnitudes are V = 4–6 mag.

### 2.1.3 Novae and nova-like variables

Distance determinations to novae are required to interpret the energetics of the outburst, and to place these objects more securely within the context of evolutionary models. Distance estimates can be made through modelling of the shell expansion velocity, but such applications are restricted to particular periods after outburst, and also suffer from modelling uncertainties. Most galactic novae are brighter than V = 12 mag at maximum, although measurements to V = 16 mag or fainter would also allow the determination of distances to galactic novae observed over the last few decades. Related objects, such as dwarf novae, AM Her stars, symbiotic stars, and cataclysmic binaries could be studied, providing accurate luminosities needed to distinguish among alternate possible energy generation mechanisms. Many such nova-like variables would lie within the distance horizon and the magnitude limit (say, brighter than V = 16 mag) necessary to provide distances to better than 5%.

### 2.1.4 Planetary nebulae

Planetary nebulae appear to present a very narrow mass range for the remnant star, and thus provide the possibility of being good distance indicators. However, because of their rarity, and therefore their typical distances, no satisfactory method yet exists for the their distance estimation. Parallax measurements of the central stars would lead to significant advance in the understanding of the formation and evolution of the shells, the status of the central stars, and the role of these objects as standard candles. Many tens of planetary nebulae would be measurable down to V = 16 mag.

### 2.1.5 Cepheids and RR Lyrae stars

In addition to the importance of these stars to models of stellar structure and evolution, Cepheids and RR Lyrae form the cornerstone of the extragalactic distance scale. Some 55 Cepheids and 26 RR Lyrae stars are known to lie within about 1000 pc, and already contained with the Hipparcos observing programme, but most of these lie beyond about 300–400 pc. Parallaxes at the 20 microarcsec level would yield distance estimates to better than 2% for these objects. In turn, the details of the period-luminosity-colour relationship for these objects would be significantly improved.

### 2.1.6 Stars in Open Clusters

Only two open clusters (Hyades and Coma Ber) lie within the 100 pc distance horizon yielding distances from Hipparcos (from individual objects within the clusters) to better than 10% accuracy. Cluster studies are important for numerous reasons, mostly related to the fact that they represent a co-eval population of stars with well-defined initial chemical compositions. They can thus be used to follow the development of the formation of our Galaxy, and as a testbed for theories of stellar evolution. For example, they are amenable to studies of their dynamical behaviour, for the calibration of stellar luminosities and distances via properties such as the Wilson-Bappu effect and the mass-luminosity relation for binary stars, and for the calibration of the main sequence as a function of age and metallicity. Some 30 open clusters are considered to lie within about 500 pc, sufficient to provide individual distances to 1% accuracy with parallaxes measured at the 20 microarcsec level.

### 2.1.7 Globular clusters

Little or no information will be provided by Hipparcos on the internal dynamics, and luminosity calibration, of stars within globular clusters, due to the faint magnitude and high central density of stars in these clusters. However, Hipparcos will provide a reference system with respect to which proper motions of cluster stars can be derived from ground-based observations acquired over long periods of time. Ages of globular clusters have indicated a possible discrepancy with the age of the Universe derived from present estimates of the Hubble constant. Many observational effects and theoretical complications make interpretation of globular clusters properties far from straightforward; but cluster age determinations essentially require absolute magnitude calibrations of the main-sequence and, in particular, the turn-off point as a function of chemical composition. For absolute ages to be accurate to a billion years, essential for a resolution of the age conflict, the distance of the cluster must be determined with an accuracy of better than 3%. An observing programme reaching 15 mag and 20 microarcsec accuracy on the parallaxes would include 20 or more globular clusters (such as 47 Tuc, omega Cen, M3, M5, and M15) lying between 5 and 10 kpc, and would yield *individual* distances accurate to better than 10–20%. Some 10 or more of the brightest stars per cluster would be observable, resulting in mean cluster distances at least a factor of three better than these individual accuracies.

### 2.1.8 Metal-poor stars and primordial nucleosynthesis

Recent determinations of boron abundances in the metal-poor star HD 140283 have raised important questions about the origin of this element: whether it originates from a high cosmic ray flux at the birth of the Galaxy, or primordial nucleosynthesis. If the former possibility is ruled out, it would seem to indicate that the standard Big Bang model is wrong, and that newer inhomogeneous models would be required. Cosmic ray spallation, in contrast, makes a specific prediction of the B/Be ratio, although the Be abundances turn out to be very sensitive to whether the star is a subgiant or a dwarf! A clear parallax determination (ground-based parallaxes are generally quite inadequate) would clarify this question. While the specific instance of HD 140283 should be resolved by the Hipparcos measurements, this example illustrates the importance of individual parallax determinations for astrophysical studies.

## 2.2 Dynamics of Stellar Systems

### 2.2.1 Visual and astrometric binaries

GAIA will be able to resolve binaries with an apparent separation exceeding 1–2 mas and a moderate magnitude difference. The astrometric and photometric characteristics of the components can be measured. For numerous systems with periods of a few years the absolute orbits can be determined and hence the individual component masses. Closer binaries, and systems with a faint companion, can in many cases still be detected from the non-linear motion of the photocentre. At the sensitivity level of GAIA some 25% of all stars may turn out to be non-single. This vast material on stellar duplicity will be essential for a correct interpretation of the astrometric and photometric parameters, as well as providing important constraints on theories of stellar formation.

### 2.2.2 Interacting binary systems

A rich variety of astrophysical problems related to interacting binary systems would become accessible with parallaxes in the 10–20 microarcsec range. The evolutionary history of interacting binary systems, and the origin of Type I supernovae, millisecond pulsars, low mass x-ray binaries, and globular cluster x-ray sources is intimately bound up with the behavior of compact binaries with mass transfer and loss. Accurate knowledge of the stellar masses and orbital separation can be derived from astrometric measurements (yielding the orbital separation and the orbital inclination) combined with estimates of the mass function determined by radial velocity measurements. Many specific questions about accretion rates, precursors, mass distributions, and kinematic behaviour could be addressed with these data, including studies of the black hole candidates. Galactic black hole candidates have bright secondaries (9 mag in the case of Cyg X-1, and 12 mag or fainter in the case of V404 Cyg) and wide orbits (with orbital periods of about 6 days), which should yield definitive black hole masses by determining orbital separation and inclination.

### 2.2.3 Be Star X-ray Binaries

Be star x-ray binaries are believed to consist of a recently formed neutron star and a Be star companion. The orbit has not yet circularized, and the eccentric motion produces periodic eruptions at periastron as the compact star passes through the mass outflow from the Be star. Measurement of the orbital parameters would yield information on the anisotropy of the supernova mass ejection. It is important to relate this to the kinematics of isolated pulsars, and to the physics of the explosion.

### 2.2.4 Dynamics of globular clusters

Accurate proper motions of stars within globular clusters are required to yield information on the cluster's internal velocity dispersion, and thus constrain dynamical models of their formation and evolution. Within 47 Tuc, for example, proper motions of 20 microarcsec/yr correspond to transverse velocities of 0.4 km/sec. In addition, spectroscopic binaries have been detected in globular clusters with amplitudes of tens of km/sec and periods of years, corresponding to separations of order 1 mas. Parallaxes and annual proper motions at the level of 50 microarcsec or better would provide distances and orbital data necessary to clarify the formation and evolution of these binary systems, and their role in the formation of the milli-second pulsars now know to exist in the cores of globular clusters.

### 2.2.5 Galactic dynamics

The huge number, impressive accuracy, and faint limiting magnitude of the GAIA mission would totally revolutionise the dynamical studies of our Galaxy, which are now understood to be capable of providing considerable advances in our understanding of the structure and motions within the spiral arms, the disc and the outer halo. It is still unclear, for example, whether spiral arms are density wave enhancements in the background stellar distribution, or whether they are regions of enhanced star formation. If a density enhancement exists, it will affect the stellar motions in a characteristic way, and this could be tested on the relatively nearby Perseus arm (about 2 kpc distant). Stellar motions would be determined for stars near the arm, both foreground and background (distinguished by their parallaxes), with proper motion accuracy requirements of some 100 microarcsec/yr, corresponding to about 1 km/sec in space velocity.

### 2.2.6 Dark matter within the disk

Two recent programs have attempted to determine the surface density of the Galactic disk in the solar neighborhood. One, led by Bahcall, finds evidence for dark matter in the disk, while the other (Gilmore & Kuijken) finds none. The issue is important because of the implications on the nature of dark matter—whether, if it exists, it admits matter in a baryonic or non-baryonic form. One source of uncertainty in the Bahcall result, based on the distribution of K giants perpendicular to the galactic disk, is the error in the distances to individual stars. These are relatively bright objects (apparent magnitudes 10 and brighter); their distance scale could be recalibrated and substantially improved by direct parallax measurements of K giants with a range of metallicities. Parallaxes at the level of 50 microarcsec would be required.

### 2.2.7 The mass of our Galaxy

The form of the rotation curve beyond the Sun, is very sensitive to the existence and amount of dark matter near to it. No very reliable determination of the rotation curve has yet been derived. In an extension of the programmes being undertaken with the Hipparcos data, measurements of the distances and motions of disk stars are required at a range of galactic longitudes, resulting in the rotation curve at distances out to 15 kpc determined from stars with V ¡ 12 mag. Parallaxes at the level of 20 microarcsec for an accuracy of 20% in individual distances, and annual proper motions of about 200 microarcsec/yr (or 10 km/sec), would be required.

### 2.2.8 Proper motions of the Magellanic Clouds, and active galactic nuclei

Different explanations for the dynamical behaviour of the LMC/SMC, in particular whether these systems are gravitationally bound to our own galaxy, implies systematic proper motions of below around 1 mas/yr, very much at the limit of the Hipparcos capabilities. Large numbers of stars measured in the LMC/SMC at the level of 50 microarcsec or better, would clarify their dynamical relationship with our own Galaxy. Further out, the nuclei of active galaxies are sufficiently pointlike that their absolute proper motions may be measurable. At a redshift of 0.03, a transverse velocity of 1000 km/sec corresponds to a proper motion of 3 microarcsec/yr. Thus, transverse velocities of nearby galactic nuclei due, e.g., to galaxy cluster potentials, might be detectable.

### 2.2.9 The role of quasars

Future astrometric missions, at levels of accuracy very much better than 1 microarcsec, could determine the transverse motions of external galaxies and quasars routinely, and determine their kinematic properties independently of a dynamical model of the Universe. In the meantime, an astrometric programme reaching 15–16 mag would include a number of quasars, and this in turn would allow a direct tie between the resulting reference system and an inertial reference frame, something which has not been possible (directly) in the case of Hipparcos. The considerable importance of this possibility is that the resulting proper motions of all the stars within the global observing programme would not be subject to arbitrary offsets in their proper motions, a fact critical for any dynamical interpretation of their motions.

## 2.3 Detection of Planetary Systems and Brown Dwarfs

The Hipparcos mission, due to its limited astrometric accuracy and mission duration, is unlikely to make any serious contribution to the possible detection of sub-solar mass planetary companions around nearby stars. The essential idea, that of detection of non-linear photocentric motions in the paths of nearby stars due to such 'planetary' companions, has been extensively studied and simulated, for example as part of NASA's TOPS (Towards Other Planetary Systems) and later as part of the POINTS programme. The probable size of the effect can be judged by considering the path of the Sun as seen from a distance of (say) 10 pc. The perturbation caused by Jupiter has an amplitude of 500 microarcsec and a period of 5 years, while the effect of the Earth is a one-year period with 0.3 microarcsec amplitude. With a mission length of 5 years and a target mission accuracy of 20 microarcsec, GAIA should be able to provide annual normal points with an accuracy of 50 microarcsec. This is sufficient to detect Jupiter-mass planets (at the 3 sigma level) out to 30 pc. This volume includes several thousand potential target stars, *all* of which can be monitored for possible companions. If the accuracy is instead 2 microarcsec, which may be feasible for bright stars (V ¡ 10 mag), then the detection horizon for Jupiter-mass planets is pushed beyond 100 pc and includes some 100,000 candidate stars. Screening all 50 million stars down to the survey limit of V = 15–16 mag for possible signatures of planetary and brown dwarf companions will provide a complete census of such bodies to well-defined detection limits.

## 2.4 General Relativity

The reduction of the Hipparcos data has necessitated the inclusion of stellar aberration up to terms of second order in v/c, and the general relativistic treatment of light bending due to the gravitational field of the Sun (and Earth). Light bending by the Sun amounts to 4 mas even at 90 deg (i.e., for light arriving perpendicular to the ecliptic). The astrometric residuals may be tested for any discrepancies with the prescriptions of general relativity; in principle this provides a constraint on the post-Newtonian light-bending term, Gamma, equal to unity in general relativity. Fig. illustrates the preliminary determination of Gamma derived from the first 12-months of the Hipparcos data, Gamma = 0.989 (standard error = 0.014), along with other determinations. These include the original observations of Dyson, Eddington & Davidson (1920), and other optical determinations made at times of total solar eclipse, including the most recent published determinations of Jones (1976) based on the 1973 Mauritanian eclipse. All such previous determinations have been based on observations within a few solar radii of the solar limb. Other determinations based on VLBI observations and the Viking spacecraft (Shapiro) time-delay, also restricted to measurements made close to the solar limb, are also illustrated (see Soffel 1989). The best available measurements to date are those from the Viking observations (Reasenberg *et al.* 1979), and provide a precision of about 0.001 in Gamma.

The GAIA measurements would provide a precision of about 1 part in a million or better in the determination of Gamma due to the Sun. Interestingly, this is close to the values predicted by those present theories which predict that the Universe started with a strong scalar component, and which is relaxing to the general relativistic value with time (e.g. Damour & Nordtvedt 1993). The importance of such theories is that they provide a possible route to the quantisation of gravity. For this reason, space experiments dedicated to the measurement of Gamma with a precision of about 1 part in a million have been proposed, and are being considered for the ESA M4 round.

We stress that GAIA would provide this precision as a simple by-product of its astrometric and photometric campaign.

Light deflection has also been observed, with various degrees of precision, on distance scales of 1E9 to 1E21 m, and on mass scales from 1E0 to 1E13 solra masses, the upper ranges determined from the gravitational lensing of quasars (Dar 1992). Light-bending by the Earth is at the level of 40 microarcsec, and GAIA could therefore extend the domain of observations by two orders of magnitude in length-scale, and six orders of magnitude in mass. (The Pound-Rebka experiment verified the general relativistic prediction of a gravitational redshift for photons, an effect probing the time-time component of the metric tensor, while light deflection depends on both the time-space and space-space components). Light bending at the Jovian limb is predicted to amount to 17 mas.

At the level of accuracy expected from GAIA, even more subtle effects will start to become apparent, such as the quadrupole components of the gravitational fields of the Sun and the planets, and the 'frame-dragging' effects of their motions and rotations (see, e.g., Soffel 1989). Light modulation effects due to gravitational lensing by MACHOs (Alcock *et al.* 1993; Aubourg *et al.* 1993), and the possible metric perturbations due to gravitational waves (Fakir 1994), must also be considered.

# 3 Technical Description

## 3.1 Significance of Global Measurements

A future space astrometry mission aiming at the widest range of astrophysical problems must be able to perform *global* measurements. This means that positions, and changes in positions caused by proper motion and parallax, are determined in a reference system consistently defined over the whole sky. Global astrometry is essential for determination of motions and distances that are independent of local kinematics and reference sources. In practice this requires direct and accurate measurement of large angles (of the order of 1 rad). The need for wide-angle astrometry in order to construct a distortion-free reference system around the sky is fairly self-evident and shall not be further elaborated here. But wide-angle measurements are also crucial for the determination of *absolute parallaxes*, which may require some explanation.

The trigonometric parallax is the most important and direct way for determination of stellar distances. The parallax, here denoted p, is defined as the angle subtended at the star by the mean radius of the Earth's orbit. If p is expressed in arcsec, then r =1/p gives the distance to the star in parsec (pc). The traditional (ground-based) method to determine p is to measure the annual oscillations of the star's apparent motion, as caused by the Earth's revolution around the Sun, against the background of distant stars. Because background stars can always be found sufficiently close to any star of interest, these measurements can be confined to the field of view of a long-focus telescope, usually within 10–20 arcmin. The situation is schematically illustrated in Fig. A. The target star S is measured with respect to the background star S0. However, the measurable quantity is the *relative* parallax

$$p - p_0 = \frac{1}{2}(\phi_2 - \phi_1)\,.$$

To obtain the true or *absolute* parallax of S one must add the (smaller) parallax of the background star, or more generally the mean parallax of the background stars. This correction from relative to absolute parallax is usually estimated simply from the magnitudes of the background stars. This procedure has been acceptable because the background stars usually have parallaxes of a few milliarcsec, which is less than or comparable to the measurement errors in classical parallax work. But when much higher accuracy is aimed at, this small-field technique is no longer useful because the uncertainty of the correction will be much too large.

The situation is radically different if wide-angle measurements can be made with the same accuracy as in a small field. As shown in Fig. B it is then possible to calculate the absolute parallax of S without making any assumption whatsoever regarding the distance to the reference star S0.

The principle of absolute parallax determination by wide-angle measurements was for the first time implemented in the Hipparcos mission, and has been demonstrated to be a complete success: several independent tests on preliminary Hipparcos parallaxes have shown that their zero-point errors are much less than 1 mas, and probably smaller than 0.1 mas. The same principle will apply to the GAIA mission, which therefore should produce in parallaxes that are absolute at the sub-microarcsec level.

## 3.2 General Considerations

GAIA could comprise three identical interferometers stacked on top of each other in a cylindrical body intended to fit into a dual-launch Ariane 5 envelope. While two interferometers are in principle sufficient to perform wide-angle astrometry, the addition of a third one provides full redundancy in the sense that any two instruments can be used and still achieve the mission goals. Mindful of the criticality of alignment of an operational interferometer, the design concept involves a further level of redundancy: by designing the system to yield coherent imaging (i.e., fringes) in the central part of the field; and incoherent imaging (equivalent to an enhanced Roemer mission) in the outer part, total failure of the interference capabilities would still yield an instrument providing overall astrometric accuracies degraded by only a factor of five or so.

The interferometers will perform a continuous scanning of the whole sky according to a pattern similar to the 'revolving scanning law' used with Hipparcos. Thus, the axis of rotation (perpendicular to the viewing directions) is kept at a nominally fixed aspect angle from the sun, and describing a precessional motion about the solar direction at constant speed with respect to the stars. For Hipparcos the solar aspect angle was 43 deg, but a slightly larger value (e.g., 55 deg) should be adopted for GAIA, if compatible with other requirements. The period of rotation is about 3 hours, corresponding to a speed of 120 arcsec/s for the motion of star images across the field. The rotation axis must be controlled to follow the nominal scanning law to within a few arcminutes in order to guarantee sufficient overlap between successive great-circle scans.

A baseline mission length of 5 years is proposed. Although the many advantages of the space environment permit very significant measurements to be made in a relatively short time, some of the more complex motions cannot be properly explored on a time scale of 2–3 years. As noted previously, this concerns in particular many binaries with periods up to several years and the detection of possible planetary and brown dwarf companions.

The GAIA concept, as described in subsequent sections, is the logical result of some fairly general considerations on the design of a future astrometric mission. The starting point is that we aim at a global, survey-type mission covering a very large number of objects, rather than a pointing-type mission as exemplified by the OSI and POINTS projects. The rationale for this very crucial choice can be summarized in the following points:

- it follows a proven concept, namely that of the Hipparcos mission;
- astrophysical research primarily oriented towards the physics of stars and of the Galaxy as a whole is best served by a survey-type mission encompassing large and well-defined samples of a wide variety of objects;
- from a technical viewpoint, a continuously scanning satellite appears to be particularly efficient, and perhaps optimal, in terms of instrument stability and calibration, and observing time utilization. This is due to factors such as the constant geometry with respect to the sun for a revolving scanning 'law'; that critical instrument parameters such as the 'basic angle', scale value and geometrical field distortion are obtained from the closure conditions on each complete rotation of a few hours; that these calibrations are part of the normal observations and therefore do not require any overhead time; that no overhead is required for re-pointing the telescope; and that many objects can be observed strictly simultaneously.

In this section we outline the main considerations that have lead to the proposed conceptual design of GAIA.

### 3.2.1 Theoretical limit on directional accuracy

The ultimate accuracy with which we can determine the direction to a point source of light is set by the dual nature of electromagnetic radiation, namely as waves (causing diffraction) and particles (causing a finite signal-to-noise ratio in the detection process). Consider an 'ideal' instrument (Fig. ) with an aperture of given size and shape, and aberration-free imaging onto a detector capable of recording the precise angular coordinates (xi,eta) of each photon event. In the absence of background radiation and other extraneous noise sources the limiting accuracy is given by:

$$\sigma_\xi \;\geq\; \frac{\lambda}{4\pi x_{\mathrm{rms}}\sqrt{N}}\,, \quad \text{where} \tag{1}$$

$$\begin{aligned} \lambda &= \text{effective wavelength} \\ x_{\mathrm{rms}} &= \text{RMS extension of aperture in measuring direction} \\ &\phantom{=} \text{relative to the aperture centroid} \\ N &= \text{number of detected photons} \end{aligned}$$

(Lindegren 1978). Two cases are of particular relevance here:

(i) For a single circular aperture of diameter D we have:

$$x_{\mathrm{rms}} = D/4 \qquad \Rightarrow \qquad \sigma_\xi \geq \frac{\lambda}{\pi D\sqrt{N}}\,. \tag{2}$$

Generally N is proportional to the square of D, so that

$$\sigma_\xi \propto D^{-2}\,.$$

(ii) For an interferometer consisting of two circular apertures, each of diameter D, with a central separation (baseline) of B we have to first order in D/B:

$$x_{\mathrm{rms}} = \sqrt{(B/2)^2 + (D/4)^2} \qquad \Rightarrow \qquad \sigma_\xi \geq \frac{\lambda}{2\pi B\sqrt{N}}\,. \tag{3}$$

In this case

$$\sigma_\xi \propto B^{-1}D^{-1}\,.$$

The relative merits of a single-aperture instrument and an interferometer obviously do not depend on these equations alone, as many other factors related to size, mass and complexity must be taken into account. However, if an overall size of several metres is contemplated, it appears that an interferometer is the obvious choice: a single filled aperture of similar resolution is out of the question and also unnecessary unless a very faint limiting magnitude is required. For a given maximum physical dimension W, as set for example by the launcher envelope, we should thus choose the maximum possible baselength (B + D = W), and then maximize D within the constraint set by the total mass and other factors. The optimum trade-off must await further technical studies; for the present report we have adopted B = 2.45 m and D = 0.55 m as representing a plausible interferometer compatible with the Ariane 5 launcher.

### 3.2.2 Integration time per object and field of view requirements

Equation (3) gives the limiting accuracy of a single angular measurement in the instrument frame. The positions, proper motions and trigonometric parallaxes of all the objects are eventually determined (in principle) by a least-squares combination of all such measurements collected over the whole mission. The accuracy of, say, the parallax of an individual star depends on the total weight of the measurements of the star, and a certain numerical factor determined by the geometry and temporal distribution of the measurements. The redundancy of the problem — that is, the ratio of the number of measurements to the number of unknowns — is sufficiently large that additional instrument and attitude unknowns can be determined without significantly weaken the solution. For the parallax accuracy we may write, by a slight generalisation of Eq. (3),

$$\sigma_p = F\frac{\lambda_{\rm eff}}{2\pi BR} \tag{4}$$

where F is a geometrical factor and R the total signal-to-noise ratio. Monte Carlo simulation of a Hipparcos-type scanning law shows that F = 2 (approx). Writing R instead of $\sqrt{N}$ allows the inclusion of certain other noise sources such as sky background.

For B = 2.45 m and an effective wavelength of 500 nm we have

$$F\lambda_{\rm eff}/(2\pi B) = 13 \text{ mas}.$$

However, we wish to reach 13 microarcsec rather than 13 mas, which requires a signal-to-noise ratio of 1000. Since $R \leq \sqrt{N}$ we need at least a million detected photons from the star. At 15 mag this translates into a total integration time of about 1000 s, assuming a throughput of 10 m2 nm. However, the total mission time (5 years) divided by the number of objects (35 million down to V = 15 mag) is only 4.5 s, so it is necessary to observe several hundred objects simultaneously. This, in turn, implies a large field of view of up to one degree diameter, and of course a matching detector system capable of the many simultaneous measurements.

Note that reducing the number of objects would not relax the requirement for a large field of view. In fact, for a continuously scanning instrument, the (average) total time spent inside the field of view by an arbitrary object is simply given by

$$\langle\tau\rangle = \frac{\Omega}{4\pi}L\,, \text{where} \tag{5}$$

$$\Omega = \text{solid angle of the field of view}$$
$$L = \text{effective mission length.}$$

To obtain a mean integration time per object of the order of 1000 s with L = 5 years thus requires

$$\Omega \gtrsim 0.3 \text{ deg}^2\,.$$

### 3.2.3 Spatial resolution of detector

Full utilization of the astrometric information of the diffraction images, as suggested in the previous paragraphs, in principle requires that the spatial coordinates (xi, eta) and — for a scanning instrument — the time are recorded to adequate accuracy for each detected photon. Let is briefly consider the option to place such an (ideal) detector directly in the focal plane. The period of the Young's fringes produced by the interferometer is

$$\lambda_{\rm eff}/B \simeq 40 \text{ mas}$$

at 500 nm wavelength. To be fully resolved, the diffraction pattern must be sampled at a quarter of the fringe period, or 10 mas. For a one-degree field this implies some 360,000 resolution elements (or pixels) across the detector. In the perpendicular direction a much lower resolution can be used, or about 30,000 pixels, because of the smaller aperture extent in the y direction. This is clearly beyond what can realistically be achieved with current technology such as CCDs.

We do not exclude that detectors of sufficient resolution and geometrical linearity will become available in the coming years as a result of ongoing or potential development programmes. Such a possibility might be provided by new developments in superconducting detectors, which may provide better efficiency, broader wavelength response (into the UV and infrared), lower noise, and energy resolution (see Lindegren & Perryman, 1994; Perryman *et al.* 1993). However, the present goals can be achieved by means of conventional detectors, if a *modulating grid* is used to encode the phase information of the fringes. The proposed modulation/detection scheme is outlined in Section 3.5.

### 3.2.4 Coherent and incoherent imaging mode

Operating the telescope as a Fizeau interferometer requires that the Airy disks formed by the two 0.55 m openings add coherently to form interference fringes. The condition is that the Airy disks fall at the same position in the focal plane (to within a fraction of the Airy radius), and that the optical pathlengths in the two interferometer arms are equal (to within a fraction of the coherence length $\lambda^2/\Delta\lambda$). For the nominal instrument these conditions are certainly met at the centre of the field and out to a certain field angle, where residual aberrations become significant. Preliminary calculations indicate that the maximum field angle for interferometry is about 0.5 deg. Outside of this angle the geometrical image is still very small (a few micron) and contains very substantial astrometric information, corresponding to the resolution of one of the D = 0.55 m openings rather than the B = 2.45 m baseline. Moreover, the potential *photometric* capacity is practically unaffected by this loss of resolution in the outer part of the field.

These considerations induce us to propose that the outer part of the field, roughly between 0.5 deg and 0.8 deg radius, be used in an *incoherent* imaging mode for additional astrometric and photometric measurements. The term 'incoherent' is here used to mean simply that the information is derived from the Airy envelope of the stellar images instead of the interference fringes. The theoretical loss of astrometric precision is given by the ratio of Eqs. (2) to (3), or 2B/D = 9, but in practice the ratio is smaller because of other design factors. For the incoherent imaging, CCD detectors can be used directly in the focal plane and operated in the drift scanning mode. That is, the charge images are shifted along with the optical images and read out as they arrive at one side of the array. The principle of operation in this mode corresponds exactly to that of a proposed non-interferometric astrometric mission, Roemer (Lindegren *et al.* 1993) or Roemer+ (Høg 1994), and the predicted performance is even slightly better than for Roemer+ (Section 3.6).

The addition of the incoherent imaging mode brings about some very significant advantages and a considerable strengthening of the overall mission performance:

- compared with the use of a modulating grid, the CCD directly in the focal plane gives better light economy and much more efficient suppression of background radiation and nearby images, resulting in a fainter limiting magnitude (V = 20), albeit at a reduced accuracy;

- the optimum wavelength bandwidth to be used with the grid is completely determined by the pupil geometry (Section 3.5). Thus, any attempt to tailor these passbands for photometric purposes will hamper the astrometric capability in the interferometric mode. In contrast, for the incoherent mode we are free to choose a number of passbands ranging from the widest possible (to obtain the best astrometry for faint stars) to intermediate and narrow bands (including, for instance, Stromgren and Hbeta photometry to V = 16 mag). The disposition of different detectors and passbands should be similar to what has been proposed for Roemer+ (see Høg 1994; for a general discussion of the design of overlapping filters necessary to permit transformability to other photometric systems, and for astrophysical interpretation, see Young, 1994);

- the incoherent imaging mode provides attitude information, especially on the orientation of the rotation axis, which is essential for proper interpretation of the modulation phases measured behind the grids. The three-axis attitude is needed, *a posteriori*, to a few mas accuracy in order to process the phase measurements to 10 microarcsec or better (the ratio of the phase error to the transverse attitude error is basically given by the field angle, i.e., ¡ 0.01 rad). At least some CCD detectors set directly in the focal plane would have been required even if they were not used for direct astrometry and photometry. The addition of the incoherent imaging mode is thus merely an extension of a system that is already an essential part of the GAIA concept;

- positions determined by the incoherent imaging can be used as starting points for a solution based on the interferometric data. This brings the latter solution into the linear regime (phase errors ¡¡ 1 rad), allowing considerable simplification of the processing and eliminating possible ambiguities and spurious solutions;
- the CCD detectors surrounding the interferometric field can be used for coarse focussing and control of mirror alignments, since the star images from the two pupils must overlap completely and in all parts of the field when the mirrors are correctly adjusted. Since this function does not depend on the formation of fringes, it should be particularly useful for the first phase of fringe acquisition. For this purpose it may replace some of the absolute laser gauging, thus possibly reducing the overall complexity of the interferometric system;
- finally, the incoherent imaging mode provides a reliable and useful backup facility in a scenario where one or more of the interferometers, for some technical reason, fails to produce fringes. In such a case the interferometric detectors do not produce any useful data at all (except a low-resolution, about 10 arcsec, photometric sky survey), whereas the incoherent mode still provides photometry at nearly the full accuracy and astrometry certainly at the sub-milliarcsec level.

## 3.3 Telescope

We have seen [Eq. (5)] that a large field of view, of the order of 1 deg diameter, is needed in order to accumulate sufficient integration time on each object. This implies that the interferometer is of the Fizeau type, i.e., optically equivalent to a single large telescope with two openings in the entrance pupil. The non-illuminated parts of the mirrors are removed, and we are basically left with two off-axis telescopes having a common focus.

In a first approximation we have considered the optical characteristics of the single 'underlying' 3 m telescope. An effective focal length of 10–15 m is desirable for a convenient linear size of the field (a few tens of cm). Diffraction-limited imaging over a large field implies good correction for spherical aberration, coma and astigmatism, which suggests a three-mirror system. Very preliminary optimization of such a system led to a design whose main parameters are given in Table 2. The mirror diameters are calculated for an unvignetted field of 0.8 deg radius. The resulting Fizeau system is shown in Fig. .

Table 2: Main parameters of the three-mirror telescope from which the Fizeau interferometer is derived. z = coordinate of the vertex of the surface, D = outer diameter of surface, d = inner diameter of surface, r = radius of curvature, K = conic constant. Light enters in the +z direction. All mirrors are concave towards +z (negative curvature). The focal surface is flat.

| Surface | $z$ | $D$ [m] | $d$ [m] | $r$ | $K$ |
|---|---|---|---|---|---|
| primary mirror | 3.52 | 3.00 | 1.90 | 11.47 | −1.39 |
| secondary mirror | 0.02 | 1.28 | 0.64 | 5.20 | −3.40 |
| tertiary mirror | 3.52 | 1.25 | 0.25 | 9.79 | −4.60 |
| focal plane | 0.00 | 0.33 | 0.00 | $\infty$ | — |

The nominal performance of the three-mirror telescope is diffraction limited out to a substantial field angle. A complete optimization, taking into account the actual aperture and the complex interaction with the grid system (cf. Section 3.5) remains to be done, but it appears that acceptable performance could be achieved within a radius of 0.45 deg. The outer part of the field, between 0.5 deg and 0.8 deg radius, is still unvignetted and the images are still much smaller than the Airy disk of the 0.55 m openings; consequently this part of the field can be used for the incoherent imaging mode (Section 3.2).

The Fizeau interferometer fits into a circular envelope of 4.4 m diameter, as indicated in Fig. , with the focal plane assembly conveniently located near the envelope for passive cooling of the detectors. The layout permits internal baffling so that, for instance, the tertiary mirror is invisible from the outside.

Three identical interferometers are stacked on top of each other in a cylindrical envelope, with baselines set at different angles (0, g1 and g2). The configuration thus has three different 'basic angles', g1, g2 and g3 = g2 - g1. These should be carefully chosen so that they are all 'large' (in the approximate range from 1 to 2 rad) and incommensurable pairwise as well as with respect to 360 deg. This means that any two interferometers, or all three of them, can be used to perform wide-angle measurements.

## 3.4 Alignment and Stability Requirements

For diffraction-limited performance the relative positions of all mirror elements need to be controlled, passively or actively, to within a fraction of a wavelength. In particular the superpositioning of the Airy disks from the two circular openings must be achieved over the whole one-degree field, which puts very stringent demands on the symmetry of the system. However, not all degrees of freedom need to be controlled to the same accuracy, and passive means should be used whenever possible. For instance, it would seem likely that the focal plane assembly and the two secondary mirror segments (M2) can be controlled as a single unit. The other mirror segments (M1 and M3) will probably have to be actively controlled, relative to the FPA+M2 block, at least in one dimension (along the optical axis). Active control must be based on error signals that can be derived from laser gauges, but also from the FPA detectors themselves. The metrology requirements for the optical alignment are modest (some nm) and may be achieved with commercial gauge technique.

Much more stringent requirements are set by the stability requirements, and in particular variations of the angles between the interferometer baselines (the basic angles). All variations on time scales longer than a few hours (equal to the rotation period of the spinning satellite), as well as the absolute values of the basic angles, can be deduced from the off-line data analysis by means of the closure conditions on each complete great-circle scan. Although *some* short-period variations can in fact be derived from the data analysis (as has been demonstrated for Hipparcos), basically one needs either extremely good short-term stability or a continuous monitoring of changes in the relative baseline orientations. On a 3-m baseline, 5 microarcsec corresponds to a linear shift of one end by 70 pm. Thus, monitoring at the 10–50 pm precision level is likely to be required, but only for *variations* occurring on time scales up to a few hours. The basic feasibility of differential laser gauging at the pm level has already been demonstrated in the POINTS and OSI projects (Noecker et al. 1993; Shao 1993).

The effective interferometer baseline is defined by an arbitrary fixed point on the focal grid in combination with all the mirror elements. The condition is that the optical path lengths through the two interferometer arms are equal, when measured from the central grid point to an incident plane wave front parallel with the baseline. The orientation of this baseline may be monitored with respect to three fiducial points, e.g., as indicated in Fig. (F1, F2, F3). The basic angle can then be monitored from the distances of the fiducial points of one interferometer with respect to the other. We do not claim that this is the best way to monitor the interferometer baselines, but merely point out that there is in principle no difficulty to incorporate such metrology in the proposed form of interferometer.

## 3.5 Focal Plane Assembly

### 3.5.1 Coherent imaging mode (interferometer)

As noted above, exploitation of the full astrometric information at the fringe frequency by means of a detector, such as a CCD, directly in the focal plane would require a prohibitively large number of pixels. This requirement, and the corresponding tolerances on the detector performances, can be relaxed dramatically with the inclusion of a modulating element (grid), resulting in a data collection somewhat analogous to that employed with Hipparcos.

In this concept the inner part of the focal surface, dedicated to the interferometric measurements, is covered by a grid consisting of many narrow bands parallel to the interference fringes of the stellar images. The spatial frequency of the bands match the fringe frequency, thus producing a sinusoidal modulation of the light intensity behind the grid as the images (and fringes) move across the field, perpendicular to the bands. The grid may be designed to modulate either the amplitude of the image (by means of alternatingly opaque and transparent bands, or slits, as was used for Hipparcos), or the phase (by means of a phase hologram). The relative merits of amplitude and phase modulation is discussed below.

Figure  shows a possible layout of the focal field. The inner part of the field is covered by a mosaic of 32 CCD detectors with corresponding grids, working at several different effective wavelengths. Each grid is divided into subfields of 27 x 13.5 arcsec to limit the background light and confusion from other stars. Some of the design considerations are outlined in the following paragraphs.

### 3.5.2 Fringe/grid matching

For a narrow wavelength passband the diffraction image of the nominal interferometer will consist of a set of Young's fringes having an angular period of

$$\lambda_{\rm eff}/B \text{ radians},$$

and with an outer envelope in the shape of an Airy disk corresponding to one of the pupils. The grid period s must equal the fringe spacing in order to produce light modulation at the detector. With effective wavelengths in the range from 350 to 800 nm (see below) and with a rotational speed of 120 arcsec/s, the frequency of light modulation will be in the range from 1800 to 4000 Hz. The phase of this signal provides the positional information (star image relative to the grid), while the amplitude contains photometric information. In order to allow an accurate determination of the phase, the intensity must be sampled at a rate of at least four times the modulation frequency, but preferably at eight times the frequency.

### 3.5.3 Optical bandwidth

The finite bandwidth reduces the fringe contrast as one moves away from the centre of the image. The mean intensity also drops off away from the centre, according to the Airy function. To get good modulation by the grid it is necessary that the fringe contrast does not drop off quicker than the mean intensity; in other words, that fringes are seen across the whole Airy disk. This condition is satisfied if

$$\Delta\lambda/\lambda_{\rm eff} \lesssim D/B\,.$$

Increasing the bandwidth increases the number of photons that can be used for the phase determination, but also reduces the modulation of the signal. More detailed calculation shows that the standard error on the phase measurement is minimized for

$$\Delta\lambda/\lambda_{\rm eff} \simeq 1.1D/B \simeq 0.25$$

for the present pupil configuration.

### 3.5.4 Size of subfields

The light of any (unresolved) source falling on the grid will contribute to the detector output by superposing a sinusoidal component on the signal. Although it is actually possible to disentangle many such superposed components in the data analysis, by a process analogous to aperture synthesis in radio interferometry, such a process is always accompanied by a reduction of the signal-to-noise ratio. It is in fact desirable to have a 'clean' signal for most observations, and only resort to the more complex analysis when necessary, e.g., in the case of a double star. This requires that the effective field of view covered by a single detector channel is restricted to a fairly small area on the sky, so that the probability of accidentally having a disturbing star within that area is small. At the limiting magnitude of about V = 15.5 mag we may consider any star brighter than V = 16.5 mag as a potentially serious disturber. The mean density of such stars is about 3000 per square degree (Allen 1973). For the probability of disturbance to be less than 10%, say, the area must then be smaller than about 400 square arcsec. The average sky background within this area is equivalent to one star of magnitude 16: this contributes an acceptable level of photon noise but no modulation. In the design schematically shown by Fig. the size of each 'subfield' is 27 x 13.5 = 365 square arcsec.

### 3.5.5 Detection of modulated light

An integrated 'light curve' of the modulation can be recorded by a CCD in which the electric charges generated by the photons are shifted back and forth at the (known) frequency of modulation. In principle eight pixels are sufficient to store the eight phases of the light curve. For each clock pulse the charge image is shifted one pixel forward, and after eight pulses it is quickly shifted eight pixels backward, immediately starting integration of the next modulation cycle. The pulse frequency must be accurately matched to the actual modulation frequency (depending on the grid period, the satellite rotation rate, and the image scale) to allow the light curve to be built up over many hundred modulation periods. A field lens (Fig. ) ensures that the illumination on the CCD is stationary during this process, by imaging the two circular openings of the interferometer at fixed points on the CCD.

Several hundred modulation cycles are integrated before the whole CCD is quickly read out, the relevant samples saved, and the next integration started. The multiple shifting back and forth of the charges requires a high charge transfer efficiency, but should be quite feasible with current performance figures. A similar use of multiple hidden, fast image buffers on a CCD chip is proposed for the second generation of the Zurich Imaging Stokes Polarimeter (ZIMPOL II; Stenflo *et al.* 1992).

The distance from the grid to the detector has to be at least some 5 mm to accommodate the grid substrate, the array of field lenses (one for each subfield), a filter for the wavelength passband, and a mask to shield off unwanted light on the CCD. The size of each illuminated spot on the detector, corresponding to one of the circular pupils, is then at least some 200 micron in diameter. If conventional CCD arrays are used, several pixels are needed to cover each spot; charges may still be added on the chip before readout to minimize readout noise. A limited spatial resolution across the pupil image of bright stars may provide information on the optical aberrations.

Alternative detectors such as photon-counting silicon avalanche photodiodes (APD) should also be considered. Although not yet available in arrays, commercially available discrete APD detectors have characteristics that are very well suited for the present application (size of sensitive area about 200 micron, high quantum efficiency over a very wide spectral range, low dark counts with moderate cooling, and high time resolution). The possible advantages of the more speculative superconducting tunnel junction detectors have already been noted.

### 3.5.6 Mechanism of light modulation

An alternative way of describing the light modulation is to regard the grid as a diffraction grating. The imaging of the entrance pupils through the grating and the field lens produces a whole series of spectral orders on the detector, in particular the images of order -1, 0, and +1. At precisely the wavelength where the fringe period matches the grid, it turns out that the separation of the successive spectral orders equals the separation of the pupils, so that the 1st order image of one pupil is superposed on the 0th order image of the other pupil, etc. The light modulation at the two illuminated detector spots can thus be understood as interference of the two pupil images superposed in different orders. In the Fraunhofer approximation the instantaneous monochromatic intensity in the detector plane can be written

$$I(x,y,t,\lambda) \propto \sum_{n=-\infty}^{\infty} \sum_{m=-\infty}^{\infty} c_n c_m^* \exp[i(n-m)\phi]\, A(x-n\lambda/s,y) A^*(x-m\lambda/s,y) \tag{6}$$

where

$$\begin{aligned} A(x,y) &= \text{complex amplitude in the pupil plane} \\ \phi &= \text{phase of the fringes relative to the grid at time } t \\ u &= \lambda/s \\ c_n &= \text{complex Fourier coefficients for the amplitude} \\ & \quad\ \text{transmittance of the grid along the } \xi \text{ axis.} \end{aligned}$$

[The (x,y) coordinates in the detector plane are defined by the geometrical imaging through the field lens of the pupil plane coordinates.] The complex amplitude transmittance of the grid is given by the Fourier series

$$g(\xi) = \sum_{n=-\infty}^{\infty} c_n \exp(i2\pi\xi/s)\,, \tag{7}$$

where, for a grid with transparent and opaque bands,

$$c_n = \frac{\sin(n\pi q)}{n\pi}\,. \tag{8}$$

Here, q is the ratio of the width of the transparent bands to the grid period s. The optimal value is q = 0.5, so that terms with —n— ¿ 1 can practically be neglected. Collecting together the terms in (6) with n - m = 0 yields the DC component of the signal, while n - m = -1 and +1 yield the amplitude and phase of the modulated component.

Inspection of Eq. (6) reveals that any (diffracted) light falling outside the geometrical image of the entrance pupil is unmodulated, and the signal-to-noise ratio is therefore improved by removing such light. This is done by placing a mask immediately in front of the detector, with two circular holes corresponding to the geometrical images of the interferometer openings. It is also seen that modulation is only obtained for wavelengths in the interval

$$(B-D)s < \lambda < (B+D)s\,.$$

Other wavelengths would still contribute to the DC component, and consequently increase the photon noise. As was already noted above, it is thus advantageous to restrict the bandwidth.

#### 3.5.7 Phase grid

The grid described by Eq. (8) has an average transmittance of q = 0.5, which means that at most half of the light is actually used. By regarding the grid as a diffraction grating and the modulation as a result of interference of the superposed pupil images of different order, it is easy to see that a *phase grid* could be used instead of the amplitude grid, resulting in a better utilization of the light. A pure phase grid introduces a phase shift that varies periodically with the xi coordinate. For instance, a sinusoidal variation of the phase, with an amplitude of p radians, gives instead of Eq. (9):

$$c_n = i^n \, J_n(p) \tag{9}$$

where Jn are the Bessel functions. Insertion in Eq. (6) shows that the intensity modulation is now 180 deg phase shifted between the two illuminated spots, so that the sum of the transmitted light is constant. The optimum performance is obtained with a phase amplitude of p = 1.35 radians. Compared with the amplitude grid the phase grid gives nearly twice as many photons (some are however diffracted into the wrong orders) and a higher degree of modulation. The combined effect is to reduce the photon-statistical phase errors by more than a third. Figure  illustrates the interaction of the diffraction fringes with an amplitude and a phase grid.

#### 3.5.8 Image synthesis

A practical problem with the use of a periodic grid is the ambiguity of image positions with respect to a multiple of the grid period. This can be solved if several different grid periods are used. However, this requires a separate CCD for each grid period, since the whole CCD must be operated at the same clock rate, as governed by the modulation frequency. Moreover, the effective wavelength and hence the colour filters must be chosen to match the grid periods. The use of several different grid periods endows the instrument with a certain imaging capability at its maximum resolution, as each scan across an object corresponds to the sampling of the origin and two conjugate points in the spatial frequency (uv) plane. This is a great help in dealing with double and multiple stars and the 10% cases when more than one star happen to fall in the same subfield.

#### 3.5.9 Possibility of direct fringe detection

The use of a modulating grid instead of direct fringe detection entails a significant loss of accuracy compared to Eq. (4), as well as a brighter limiting magnitude. While this approach is considered feasible with existing technology, and therefore retained as the baseline solution, we do not exclude the possibility that detectors may become available in the near future with sufficient spatial resolution to record the fringe phases without the use of a modulating grid. In the accuracy analysis (Section 3.6) we have therefore included a hypothetical option called 'Direct Fringe Detection'. In this option we assume a detector with similar characteristics as a CCD, except that the pixel width in the scanning direction is much smaller than the fringe period, say ¡ 0.5 micron The inclusion of this option may serve as an illustration of the improvement in accuracy that could result from using a nearly optimal detector.

#### 3.5.10 Incoherent imaging mode

The outer part of the unvignetted 1.6 deg field includes a number of CCD detectors (20 as sketched in Fig. ) placed directly in the focal plane and operated in continuous drift-scan mode. The pixel width, 6 micron = 108 mas, is matched to the size of the diffraction disk of the 0.55 m pupils (Airy radius = 160 to 360 mas) but completely damps out Young's interference fringes (period = 30 to 65 mas). Some of the CCDs are equipped with intermediate and narrow-band colour filters, e.g., corresponding to a modified uvbybeta+I system. These provide accurate and astrophysically important photometric information on all stars observed by the interferometer and for selected fainter stars. The remaining CCDs have no filters, and are used for complementary astrometric measurements and for attitude determination and coarse mirror control as explained in Section 3.2. The use of the outer CCDs for astrometry and photometry is very similar to what is proposed for the Roemer+ mission (Høg 1994).

## 3.6 Accuracy Estimates

### 3.6.1 Interferometric (coherent) mode

The light modulation recorded by the detectors can be evaluated by integrating Eq. (6) with respect to (x,y) over the relevant detector area, and with respect to wavelength weighted by the stellar photon flux, instrument and filter transmittances, and detector quantum efficiency. Such calculations have been carried out using realistic assumptions on all instrumental characteristics. The accuracy of the phase determination, and hence on the angular coordinate of the star in the scanning direction, is then computed for a maximum likelihood estimator. The resulting errors are finally transformed into global astrometric errors by assumptions similar to those used for the Hipparcos accuracy assessment.

Some results of a preliminary assessment of the astrometric accuracy of GAIA are given in Table 3. A mission length of 5 years is assumed, including 10% dead time. The columns headed 'baseline option' refer to the use of modulating phase grids and CCD detectors as described in Section 3.5. The columns headed 'direct fringe detection' refer to a hypothetical detector with sufficient spatial resolution to replace the modulating grid.

Table 3: Astrometric performance of the GAIA interferometer using a modulating grid (baseline option) and with a hypothetical high-resolution detector (direct fringe detection). Stars of spectral type G0 have been assumed. A dash means that the star is too faint to be measured against the background of faint stars and diffuse light within the 27 x 13.5 arcsec subfield assumed for the baseline option. Units: mas = milliarcsec for parallaxes, mas/yr for proper motions (p.m.).

| | Baseline option | | Direct fringe detection | |
|---|---|---|---|---|
| $V$ [mag] | $\pi$ [mas] | p.m. [mas/year] | $\pi$ [mas] | p.m. [mas/yr] |
| 10 | 0.002 | 0.001 | $<$0.001 | $<$0.001 |
| 12 | 0.003 | 0.002 | 0.001 | $<$0.001 |
| 14 | 0.006 | 0.004 | 0.002 | 0.001 |
| 15 | 0.011 | 0.006 | 0.003 | 0.002 |
| 16 | 0.020 | 0.012 | 0.005 | 0.003 |
| 18 | – | – | 0.012 | 0.007 |
| 20 | – | – | 0.030 | 0.018 |

### 3.6.2 Incoherent mode

Table 4 gives the photonstatistical limits on the astrometric and phootmetric precisions achievable in the incoherent imaging mode. The actual accuracy will be lower depending on how well the geometric and photometric properties of the CCDs can be calibrated, and how stable they are on time scales up to several weeks (the time period needed to achieve a complete mapping of irregularities). However, photometric accuracies better than 0.01 mag should be obtained for all survey stars (V ¡ 15.5 mag), as well as sub-mas astrometric accuracy for additional fainter stars.

Table 4: Predicted mean errors in astrometry and photometry, *due to photon noise only*, for a G0-star from a 5 year mission of GAIA, as obtained by the incoherent imaging on CCDs. Filter and CCD characteristics are given at the bottom. For faint stars, a dash means a signal-to-noise ratio ¡ 2.0 on a single CCD crossing. Units: mas = milliarcsec for parallaxes ($\pi$), mas/yr for proper motions (p.m.), and milli-magnitudes for the photometry.

| | Astrometry | | Photometry [milli-mag] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $V$ [mag] | $\pi$ [mas] | p.m. [mas/year] | W | w | u | v | b | Bn | Bw | y | I |
| 8 | 0.002 | 0.002 | 0.1 | 0.5 | 0.3 | 0.1 | 0.1 | 0.3 | 0.1 | 0.1 | 0.1 |
| 10 | 0.003 | 0.002 | 0.1 | 1.2 | 0.7 | 0.3 | 0.2 | 0.7 | 0.2 | 0.2 | 0.1 |
| 12 | 0.008 | 0.005 | 0.1 | 3.0 | 1.8 | 0.8 | 0.6 | 1.7 | 0.6 | 0.6 | 0.3 |
| 14 | 0.020 | 0.011 | 0.1 | 7.8 | 4.5 | 2.0 | 1.4 | 4.2 | 1.4 | 1.4 | 0.6 |
| 16 | 0.05 | 0.03 | 0.3 | 22.5 | 12.1 | 5.0 | 3.7 | 11.1 | 3.7 | 3.7 | 1.6 |
| 18 | 0.14 | 0.08 | 0.7 | – | 44.1 | 14.0 | 10.1 | 39.6 | 10.1 | 10.1 | 4.3 |
| 20 | 0.5 | 0.3 | 2.2 | – | – | – | 38.5 | – | 38.5 | 38.8 | 14.2 |
| Central wavelength [nm] | | | - | 320 | 350 | 411 | 467 | 486 | 486 | 547 | 800 |
| Filter FWHM [nm] | | | - | 20 | 30 | 25 | 25 | 3 | 25 | 25 | 140 |
| Peak transmission | | | - | 0.30 | 0.40 | 0.60 | 0.70 | 0.70 | 0.70 | 0.70 | 0.96 |
| QE of CCD | | | - | 0.64 | 0.68 | 0.74 | 0.78 | 0.78 | 0.78 | 0.76 | 0.62 |

## 3.7 Other Mission Characteristics

The principal spacecraft characteristics which would be needed to accommodate the goals identified here are described in the document ESTEC/PF/OP/962, and may be summarised as follows:

### 3.7.1 Spacecraft

Hipparcos-type scanning law, with an *a priori* pointing error requirement at the level of arcminutes.

### 3.7.2 Orbit

The satellite could be operated in geostationary orbit, or at the Earth-Moon triangulation libration point L5; the advantages of the latter (Companys *et al.* 1993) include a reduced particle radiation background, and absence of eclipses; but operation at L5 would demand at least two ground stations, and X-band for telemetry transmission.

### 3.7.3 Data Rate

A telemetry data rate of several hundred kbits/sec is foreseen, which is not considered problematic in view of the intended move to X-band telemetry systems. Telecommanding rate would be relatively low.

### 3.7.4 Mass

A first estimate indicates a payload mass of below 600 kg, a bus mass of 700–800 kg, a bi-propellant fuel mass of between 600 kg (L5) and 1100 kg (geostationary orbit); giving a total launch mass of between 2100 kg (L5) and 2700 kg (geostationary).

### 3.7.5 Power

The payload power requirements are estimated at around 400 W. The total spacecraft power demand is about 1100 W.

### 3.7.6 Deployable elements

These would include only a second antenna to ensure omnidirectional RF coverage, and the solar panels (arranged so as to minimise the dynamical perturbations due to solar radiation pressure).

### 3.7.7 Thermal control

Each interferometer would be contained within an actively-controlled thermal environment to ensure geometric stability. The CCDs at the focal surface are specifically arranged to lie close to the outer surface of the spacecraft (Fig. ) to allow passive cooling to deep space.

### 3.7.8 Alignment stability of mirrors

The structural stability, and the alignment of the mirror elements, is probably the most challenging requirement. Indications are already available that the design requirements could be achieved, although an appropriate technology programme within ESA would be recommended.

# 4 Programme Management and Scientific Organisation

## 4.1 Knowledge acquired from the Hipparcos Programme

All of the original scientific goals of Hipparcos have been met, and indeed in all cases, significantly exceeded. More target stars, higher astrometric accuracy, and a massive (originally unforeseen) photometric data base have been realised. The original cost envelope for the mission was exceeded by less than 15 per cent, a cost over-run itself largely attributable to a one-year launch delay imposed by the Ariane launcher programme. The immense and complex data analysis system—the global treatment of 1000 Gbit of data is considered as the largest data reduction problem ever undertaken in astronomy—is on schedule for completion according to the originally foreseen scientific time schedule.

These successes are attributable to a variety of factors some of which we consider it appropriate to identify here; these will be used to identify the manner in which the implementation of a mission following the GAIA concept could be undertaken:

(a) a clear set of scientific goals was established by the scientific community and endorsed by the ESA advisory bodies. These were considered as inflexible by the ESA Project Team and, in turn, by industry.

(b) responsibility for *all* scientific aspects was taken by a *single* committee, the Hipparcos Science Team, a non-political group committed to the mission goals and hence its scientific success. All other bodies involved in the scientific aspects—the Scientific Programme Selection Committee, the four scientific consortia, and a variety of working groups, all reported directly to this Science Team. The Hipparcos Science Team was in turn, responsible for all scientific decisions during the satellite development phase, and for overseeing the timely preparation of the observing programme catalogue, the data analysis software, and all other interfaces with ESA and ESOC having a potential impact on the scientific conduct.

(c) all of the scientific aspects of Hipparcos were entrusted to the scientific community, under their responsibility and financial authority. In turn, ESA took financial responsibility for the entire satellite (spacecraft and payload), and entrusted its entire development, manufacture and testing to the industrial prime contractor. The overall system approach to the satellite as a single entity, adopted by ESA and the prime contractor (MATRA)—including error analysis and allocation, and procurement, integration, verification and calibration of the payload—was a substantial and crucial factor contributing to the eventual success of the mission.

We have no hesitation in urging that a similar approach is adopted for the GAIA concept: the preparation of the observing programme, its execution, and the resulting data analysis and final catalogue preparation is to be seen as a single collective task. It calls for substantial commitments, both in terms of manpower, infrastructure, and eventually costs from the scientific community, to which this work could be entrusted by ESA. Further aspects of the proposed scientific organisation are detailed below.

Similarly, the achievement of a precise set of scientific goals implies that a system approach be adopted for the satellite. The accuracy analysis and error allocation budget for Hipparcos during the development phase was a highly complex activity, comprising diverse but inter-related aspects such as spacecraft attitude control and jitter, optical performance and stability, detector characteristics, spacecraft and payload thermal control, data rates, spacecraft and payload shielding (electromagnetic and particle/Cerenkov), straylight, satellite spin rate, scanning law, mission duration, and so on. Global missions like Hipparcos and GAIA demand that target accuracies are met and, in turn, that a minimum operational lifetime is achieved. We consider that entrusting the development of the spacecraft and payload to a single prime contractor is the most satisfactory and risk-free route to be followed.

## 4.2 Preparation of the Observing Programme

A very challenging problem for Hipparcos was to identify the desired subset of programme stars (about 100 000 could be accommodated) from amongst all those potentially observable (a few million). This required (a) an announcement of opportunity for observing proposals (600 000 objects were eventually proposed for study); (b) scientific assessment and priority allocation by an *ad hoc* (independent) selection committee; (c) extensive mission simulations covering scientific and operational considerations; (d) an extensive, laborious, and complex programme for the compilation of the requisite *a priori* astrometric and photometric data.

GAIA will survey the entire sky to a certain limiting magnitude (around V = 15 mag). All objects brighter than this limit will be observed, their data analysed, and their astrometric and photometric parameters eventually published. Thus, *a priori* target selection will not be needed, neither will an observing programme defined on the basis of scientific proposals. This will vastly facilitate preparations for the mission. The Hipparcos and Tycho Catalogues will supply the star catalogues necessary for real-time attitude control. The location of all stars to be observed are, in any case, expected to be available from the STScI's GSC-II plate measurement programme. If approved, this programme is expected to provide absolute positional accuracies, for 2 billion objects over the entire sky down to V = 18 mag, of 0.5 arcsec (worst case) at epoch J2000, and 0.59 arcsec at epoch J2025. Two-colour photometry with an accuracy of better than 0.2 mag would also be available (Jenkner, private communication).

In summary, the GAIA observing programme, despite its size, could be established relatively rapidly from (future) existing material, *without the great complexities and overheads created by a call for observing proposals*. Such a call for observing proposals could be considered for the question of 'data rights' allocation; this aspect is briefly addressed in Section refsec:rights.

## 4.3 Data Analysis

The data analysis problem for GAIA will be similar to that for Hipparcos: global and complex. It will, however, follow the precepts established by Hipparcos, but probably employing an even more rigorous approach to the global reduction problem than was possible with the Hipparcos data because of computing constraints. The Hipparcos reduction problem was broken down into a serious of three 'steps': (1) solving for one-dimensional positions on a 'reference great circle'; (2) reconstructing the origins of these reference great circles; and (3) back-substitution of the one-dimensional coordinates within the reference great circle system in order to estimate the astrometric parameters. This method introduces approximations in the projections onto the reference great circles, and to an extent decouples the solution of the astrometric parameters from the problem of the satellite attitude determination. Truly global reduction algorithms for the Hipparcos data have been studied; they could possibly lead to small improvements in the overall astrometric accuracies, but have not been adopted due to time, schedule and computer resource constraints.

The reductions for the GAIA data would therefore follow the established principles adopted for the Hipparcos reductions, but with certain improvements included. On the other hand, treatment of error sources such as chromatic terms, timing errors, relativistic (metric) effects, secular acceleration, effects of double and multiple stars (including astrometric binaries), will be considerably more complex. This, in turn, offers great intellectual and organisational challenges to the scientific teams that would be called upon to take charge of the data reductions.

The Hipparcos reductions were characterised by the unusual (and by some 'outsiders' poorly-understood) feature of two independent data analysis groups treating the entire data set in parallel. In brief, this proved to be a remarkably powerful method of cross-verification, identification of software coding errors or incorrect comprehension of interface specifications, etc, as well as providing important information on the final data quality, and the possible contribution of modelling terms to the final accuracy estimations. Many errors or imperfections were rapidly identified in this way.

A similar approach must be recommended for the global treatment of the GAIA data.

The data reduction tasks would be entrusted to the scientific community, at the very start of the mission studies, and these groups would need to be in place during the satellite Phase B development. The technical and scientific trade-offs encountered will only be possible if the software tools necessary to reduce the data, and estimate the associated accuracies, are available during the development phase.

## 4.4 Astrophysical Exploitation

In Section 4.2, it was explained that the observing programme, and with it the observations and satellite operations, would not require the same type of preparatory work undertaken for the Hipparcos programme. However, for the data analysis, and especially for the astrophysical exploitation, the situation is less clear. While this may be considered as outside of the responsibilities of the ESA scientific programme, some words of explanation are in order.

With the Hipparcos programme of 120 000 stars, many of the target objects were known, in advance, as objects of astrophysical or astrometric 'interest'. In many cases their spectral types and/or multi-colour photometry, and details of their multiplicity or (coarse) photometric variability, were known. Metallicities, luminosity types, and many radial velocities were known or are in the process of being acquired as part of dedicated support programmes. Nevertheless, it must be pointed out that much of this 'auxiliary' material is of very inhomogeneous quality: when the final Hipparcos Catalogue is published, two-dimensional MK spectral types will be available for some 60 000 of the 120 000 programme stars; while radial velocities will only be available for some 20 000 of the programme stars (although many others have meanwhile been acquired by associated principal investigators).

The absence of radial velocities for the majority of the Hipparcos objects (let alone for the one million Tycho objects) is quite unfortunate—radial velocities provide the third space velocity component of the star, and high velocity accuracy can be achieved—very important supplementary information for any kinematical or dynamical interpretation of the proper motion data. At the same time, repeated radial velocity measurements provide a powerful method of inferring and characterising double or multiple systems (and consequently, for mass determinations). And finally, radial velocities will be of significance in the assessment of secular (perspective) acceleration, the contribution to the apparent photocentric motion due to the (apparent) time-dependent proper motion, an effect which will attain increasing significance with improved astrometric measurements.

All of these considerations imply that very careful thought will have to be given to the large-scale acquisition of complementary astrophysical data necessary for a complete astrophysical exploitation of the resulting astrometric data. The questions to be asked are the following: whether, and to what accuracy (depending on scientific aim), parameters such as radial velocity, spectral type, and metallicity are demanded, and on what time-scale? Can the acquisition of such data wait until the astrometric measurements have been acquired? Is a specific dedicated ground-based observational programme required in advance of launch? What parameters can be estimated through appropriate payload design? Can a spectroscopic facility on-board simply provide radial velocities to some useful accuracy? Would the use of an energy-sensitive detector on board, or appropriate photometric filter selection, provide spectral classification material to an adequate accuracy?

## 4.5 Data Rights and Related Issues

The question of data rights, publication policies, early release of data, etc, are complex issues which face the conduct of any space mission and, of course, all scientific experiments conducted as large collaborations. Much energy is devoted to these issues, for which there is rarely a clear-cut right or wrong answer.

Perhaps, more than other astronomical disciplines, astrometry has a rather altruistic tradition: catalogue construction is perceived as a service provided to users. To a large extent, such an approach offers great advantages; the scientists skilled and motivated by the problems of instrumental design and data reduction may work unencumbered by problems of data rights; certainly, those who have devoted many years to the production of such final products may not necessarily be those well placed to exploit the resulting data scientifically.

Consideration might therefore be given, during any assessment phase of the GAIA concept, to partitioning responsibilities even more clearly: with no scientific proposals needed to drive the observing programme, no associated data rights would be needed or allocated. Only those motivated by the desire to create a final product of the highest possible accuracy and fidelity, a task at times inconsistent with data exploitation, would become involved. Consortia members would be free to publish material illustrating the statistical progress of the data analysis tasks. Once the final catalogue is compiled, it would be available to all, without delay.

These ideas are not considered as intending to establish the rules under which scientific participation in a future astrometric mission would be governed; rather they are presented to illustrate questions of deontology that must be faced early on in such a complex and unusual programme.

# 5 Comparison With Other Missions

The success of Hipparcos, and the resulting resurgence of interest in the astrophysical capabilities of astrometry, has led to a variety of recent proposals for space missions dedicated to astrometry. These missions are divided into two categories: those that aim for Hipparcos-type accuracy on a comparable number of stars (i.e., some one hundred thousand objects); and those that aim for a significantly higher astrometric accuracy.

In the former category are three proposed missions from scientists and agencies within the former Soviet Union (Lomonosov, Regatta-Astron, and AIST). These have been under consideration for several years, are still in the study phase, and all face uncertain financial support. The objectives of all three missions was to achieve Hipparcos-type (milli-arcsec) accuracy on up to a few hundred thousand stars, taking the Hipparcos goals as roughly indicative of the state of the art. Their scientific importance was based on maintaining the reference frame established by the Hipparcos mission throughout the coming decades—the optical reference frame defined by Hipparcos will degrade with time as a result of the uncertainties on the individual proper motions, such that a mission in 10-20 years from now, with individual accuracies in the range 1-2 mas will still have a useful and important, if not fundamentally new, scientific value.

Very recently, a Japanese Astrometric Satellite has been mentioned (Yoshizawa, private communication). This is at an early study phase only, no details have been made available, but it is considered to lie within the same type of mission concept as those described in the previous paragraph.

Significantly higher astrometric accuracy is the goal of the proposed POINTS mission (Reasenberg *et al.* 1994a), and a recently proposed low-cost alternative NEWCOMB (Reasenberg *et al.* 1994b), both being proposed as part of NASA's future scientific programme. These programmes aim to reach accuracies at the level of a few microarcsec or better, by means of *pointed*, rather than scanning, satellites. Although they are able to contain only a relatively small target observing list, of say several hundred, or several thousand, pre-selected programme stars, their intended accuracy makes these programmes highly interesting for specific scientific goals (such as the detection of sub-solar mass planetary companions around selected nearby stars); however, the relatively few objects which can be observed, and their relatively bright limiting magnitude, means that these missions do not significantly overlap with, and therefore do not duplicate, the majority of the scientific goals attainable by GAIA.

For completeness, we note that there is a continuing effort to develop ground-based optical interferometers, especially in the USA, building on the success of the Mk III optical interferometer (see, e.g., Hummel *et al.* 1994). These instruments should ultimately provide very high relative astrometric accuracy on bright double or multiple systems; they are not seriously being considered as tools for large-angle (positional) astrometry, which is now considered to be mandatory for the large-scale determination of parallaxes and proper motions.

In summary, the proposers are not aware of any planned or proposed space astrometry missions which enter the parameter space defined by the GAIA concept—this conclusion was also presented by the ESA AWG in its preparatory report for the Horizon 2000+ discussion meetings.

# 6 Conclusions

The scientific goals of a future astrometric mission are clearly defined, and tremendously extensive. A mission following the GAIA principles would be expected to advance many of the major problems which face astrophysical research in many areas of stellar structure and evolution, and galactic structure and dynamics. There are numerous spin-offs, in areas such as stellar angular diameters, stellar multi-colour photometry and variability studies, the search for sub-solar mass stellar companions, metric determination, etc.

The results of Hipparcos have demonstrated that astrometry has entered a new chapter in its history, and will become deeply tied up with astrophysical research in the coming years. This development would be further accelerated and strengthened by the GAIA mission.

GAIA seems achievable within the ESA cornerstone mission envelope, as a dual Ariane 5 launch, as a purely European mission, and within the indicated cost envelope (even with the payload being provided by ESA). Some technological development, in particular in the area of payload element stabilization and alignment at the levels necessary for interferometric operations, is necessary, but not at a level which brings into serious doubt the programme's feasibility.

A large scientific community exists which is strongly supporting the continuing development of the astrometric initiatives pioneered by ESA, and which would be in a position to undertake the scientific aspects necessary to bring this challenging programme to a successful conclusion.

# Acknowledgements

We acknowledge the ideas provided by the original proposers of the Roemer and GAIA missions. We acknowledge specific inputs for this document provided by Drs S. Loiseau and S. Shacklan at JPL, and M. Lattanzi and S. Casertano at the STScI, who all provided valuable assistance with the optical design presented here; and by Dr E. Høg for accuracy estimates for the incoherent operational mode. Many of the scientific goals presented in this document have been researched and written up in the published or unpublished literature, and we acknowledge in particular the contributions by Kovalevsky & Turon (1991), by the ESA Interferometry Review Panel under the chairmanship of Prof C. Dainty, and from the NASA report on the capabilities of an Astrometric Interferometry Mission, prepared by the Space Interferometry Science Working Group under the chairmanship of Dr. S. Ridgway. On other aspects of the scientific and instrumental capabilities we are pleased to acknowledge useful discussions with Drs R.D. Reasenberg and J. Phillips (CfA, Harvard), and Dr M. Shao (JPL). We thank the many colleagues who have indicated their interest in, and support for, a future astrometric mission; we note that a resolution to this effect was passed at the recent IAU General Assembly meeting in The Hague (August 1994).

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Further individuals have expressed their explicit (written and documented) support for a future astrometry mission within the ESA Horizon 2000+ framework. No concerted effort has been made to make this list in any way exhaustive. The list of people having explicitly expressed an interest in such an initiative is:

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# Appendix B:
# Topics addressable by a future astrometry mission

In outlining possible interest in a future astrometric programme, the following topics of interest were cited. In view of the great diversity of programmes and scientific objectives, and the considerable overlap between them, no attempt has been made here to order these by topic, or remove redundancies. The list is included simply to illustrate the breadth of scientific interest which underlies such a future astrometric mission:

Link of optical star and extragalactic frames
Star formation in the Mon R2 cloud
Accurate registration of optical and radio images
Absolute luminosities of radio and infrared stars
Possible past stellar interactions with the Oort Cloud

Hubble Space Telescope Astrometry
Space Interferometry
Large astrometric catalogues of high precision
Luminosity of RS CVn binaries
Galactic structure
Galactic evolution
Galactic dynamics
Galactic astronomy
Cosmic distance scale
Solar system ephemeric improvement
Stellar populations
Motion of Uranus and Neptune
Galactic kinematics and evolution
Masses of horizontal branch stars
Single-lined spectrospcopic binaries
Atmospheres of white dwarfs
Photographic astrometry
Global radio-optical reference frame
Investigations of the metric
Detection of extra-solar planetary systems
RR Lyrae proper motions
Open clusters and young associations
Wilson-Bappu relation
Kinematics and dynamics of the galactic disk
Kinematics of the Local Group of galaxies
Stellar mass scale
Nearby AGB stars
Kinematics in the solar neighbourhood
Calibration of physical parameters of pulsating variables
Calibration of physical parameters of pre-main-sequence stars
Dynamics of galactic disks: dynamical stability, merger and formation history
Galactic rotation curve and dark matter distribution in the galaxy
Binary statistics and binary formation
Galactic merger history and the suspected thick disk
The space velocity and future fate of the Magellanic Clouds
Gravitational micro-lensing by stars and diverse dark matter candidates
Eclipsing binaries
Star formation
Search for high velocity stars
Evolution of galaxies
Ageing of galactic disks
Luminosity and masses of Orion supergiants
OB stars and the extragalactic distance scale
Local interstellar medium
Relaxation of the galactic globular-cluster system
Galactic dark matter
Cataclysmic variables
Absolute sizes of cool stars
Metal abundances
Primordial helium
Galactic chemical evolution
Extension of the celestial reference frame for geodynamic applications
Minor planets
Use of VLBI for geodesy and astrometry

Determination of space motions
Kinematics of star clusters and halo objects
Geometrical properties of radio stars
Asteroid astrometry
Evolved massive runaway stars
Global and narrow nield astrometry
Galactic structure and kinematics
Stellar luminosity function
White dwarfs
Brown dwarfs
Astrometry (Schmidt, satellite and transit circle)
Galactic rotation parameters
Symbiotic stars as supernova precursors
Six-dimensional (position and velocity) structure of star clusters
Cosmic distance scale
Galactic structure and kinematics
Hertsprung-Russell diagram of the Hyades
Kinematic signatures of spiral structure
Stellar moving groups
Kinematics of RR Lyraes and Cepheids
Gould's belt
Spatial distribution, luminosity function, and kinematics of nearby stars
Calibration of absolute stellar parameters, especially pre-main-sequence objects
Kinematics of star-forming regions
Structure and history of T-Tauri associations
Kinematics and dynamics of the galactic disk and halo
Halo/corona mass distribution from globular cluster kinematics
Masses of minor planets
Kinematic signatures of spiral structure in the galactic disk
Extrasolar planetary systems
Origin and meaning of Gould's belt
Kinematics of the Local Group
Structure of nearby star-forming regions and of the Orion complex
Close approaches of asteroids and stars
Low-mass companions to pre-main-sequence stars
Dynamics and structure of open clusters
Distances of A-type stars
Luminosities and masses of pre-main-sequence stars
Duplicity statistics of young stars
Physical parameters of young stellar objects (from parallaxes and photometry)
3-dimensional motions of bipolar outflow material and Herbig-Haro knots
Space velocities of stellar objects in dark cloud complexes
Calibration of luminosities and diameters for young stellar objects
Distribution of dust in the Galaxy
Expansion of OB associations
Microvariability of B stars
Gravitational stability in binary systems
Galaxy rotation curve
Internal kinematics of spiral arms
Luminosity of bright stars, halo, Kz-relation
Galactic Structure (Kz, halo structure, age-metallicity, galaxy rotation curve)
Old open clusters (the halo - thick disk connection)
Galactic and extragalactic distance scale
Tests of General Relativity

Variability of B and Be stars
Solar Sytem minor bodies
Inertial reference frame
Radio-optical link
Evolution of star clusters and galaxies
Double and multiple stars
Radio/optical frame tie
Galactic structure and kinematics
The statistics of binary systems
Astrometric techniques
Reference frames
Galactic structure and kinematics
Basic stellar parameters
Stellar evolution
Peculiar objects (cataclismic variables, collapsed objects)
Faint end of the luminosity functions of stellar populations in the Galaxy
Tracing precisely at all scales the gravitational potential
Gravitational light bending
Kinematics of Barium stars
Missing mass
Existence and distribution of non-baryonic matter
Extra solar system planets
High velocity stars
Late stages of stellar evolution
White dwarf atmosphere modelling
Multicolor photometry of stars
Interstellar extinction and polarization
Distribution of dust particles in the space between stars
Characteristics of interstellar dust clouds
Properties of interstellar and circumstellar dust
Red variables
Galactic structure and kinematics
Determination of physical parameters from photometry
Extension of the Hipparcos-Tycho reference frame to fainter stars up to V=16
Astrometric effects of General Relativity
Meridian circle and astrolabe reduction methods
Radial velocities
Kinematics of the Galaxy
Young stellar groups
Fundamentals of the Hertzsprung Russell diagram
Distances, luminosities, evolutionary status of Pop II stars
Lithium, beryllium, boron abundances (constraints on primordial nucleosynthesis)
Stellar structure and evolution, with special emphasis on the transport
Mechanisms (of matter and angular momentum)
Relativity
Extra-solar planet search
Realization of a quasi-inertial reference frame
Galactic structure
Stellar dynamics
Stellar classification
Galactic structure
Statistical astronomy
Double and multiple stars
Galactic Dynamics

Stellar cluster Dynamics
Binaries as tracers of stellar formation processes
Space astrometry
Photometry
Binary formation, their evolution and disruption scenarios
Galactic structure and dynamics
Stellar kinematics
Stellar evolution
Interstellar matter
Open Clusters
Stellar evolution
Stellar Physics
Stellar Pulsation and Variability
Stellar Evolution
Stellar Dynamics
Galaxies
Kinematic of galactic O- and B-stars
Analysis of double star motions