SPACE ASTROMETRY MISSIONS : PRINCIPLES AND OBJECTIVES

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ABSTRACT. The objectives of space astrometry are the same as those of ground-based astrometry: to measure relative positions in a small field of view or/and to determine positions in a consistent full-sky reference frame (global astrometry). Three space techniques exist, and we present the principles of each, with a description of one realisation :

- The spaceborne classical small field imaging (HST);
- Michelson interferometry (SIM), optimised for small field astrometry, but which can also be used to build a global reference frame;
- Hipparcos type, two fields of view astrometry (GAIA, and DIVA and FAME, if they are re-endorsed). Specifically designed for global astrometry, but can also obtain good results within small fields.

In conclusion, a selection among the very large number of astronomical and astrophysical objectives of SIM and GAIA is presented.

1. INTRODUCTION

The objectives of space astrometry are, in principle, the same as those of ground based astrometry: to determine the apparent positions of celestial bodies and derive from them astrophysically important parameters such as distances, proper motions, movements within double and multiple star systems. There is no universal ground-based astrometric instrument. Different types are built and used for specific objectives: transit instruments and Schmidt telescopes for star position catalogues (global astrometry), long focus telescopes for parallaxes and double stars (small field astrometry), speckle and Michelson interferometry for stellar diameters and close binaries (analysis of structures). A description of these instruments can be found in Kovalevsky (2002). The final objective of all the observations collected by these instruments is to contribute essentially to stellar and galactic physics, planetary detection and fundamental physics, the latter including the realisation of a non-rotating kinematical frame.

So while highly specialised instruments are possible on the ground, where the cost of building and operating is reasonable, this is not possible in the case of the expensive space research where one must design more versatile instruments. In the latter case, one has an additional incentive, which is a dramatic increase of precision. But even this is not sufficient and it is necessary, in order to convince the space organisations, to devise a multi-purpose satellite. Three solutions are possible:

1. To give some astrometric capabilities to a general purpose satellite. This is the case of the Hubble Space Telescope (HST);
2. To design a mission capable to obtain results in all the fields mentioned above. The example is the Space Interferometry Mission (SIM);
3. To add to a satellite dedicated primarily to astrometry as many other functions as possible that enhance the astrophysical value of the observations. This is the policy underlying the design of GAIA.

We shall present, in the following sections these three missions. They illustrate the principles on which space astrometry is based, and why, considering their respective limitations, they are complementary rather than competing.

2. THE HUBBLE SPACE TELESCOPE

The HST is a multi-purpose pointing telescope in optical wavelengths. The $14'$ circular field of view is divided into eight segments, each dedicated to a specific scientific instrument (Hall, 1991). Among these, the three outer ones constitute the Fine Guidance Sensors (FGS), two of which are used to guide the telescope. The third is available for astrometry (Fig. 1). The position of a point in the field of view makes use of two star selectors which are actually two beam deflectors of fixed lengths a and b rotating in order to bring the light from an object anywhere in the FGS field of view into the $3''$ square aperture of the detector assembly. The star selector positions are referred to a fixed direction ZX by angles θ_A and θ_B so that, in the focal plane of the instrument, the coordinates of the center of the detected field S are given by

$$\begin{aligned} x &= a\cos\theta_A + b\cos\theta_B, \\ y &= a\sin\theta_A + b\sin\theta_B. \end{aligned}$$

The relative position of S' is then defined by $\Delta\theta_A$ and $\Delta\theta_B$. The image around S is sent through transmitting optics to a beam splitter towards two Koester interferometric prisms controlling the motion of the image until it is centered. The precision in position for 4 or 5 stars observed during 20 minutes is of the order 4 mas. It is also possible to measure double stars through the analysis of the transfer function. The general design, the modes of operation and calibration are described in Duncombe et al., (1991).

There is another small field astrometric capability of the HST. The central $2.'7 \times 2.'7$ field of view is reflected and sent to the Wide-Field / Planetary Camera ensemble (WC/PC). The beam can be folded into two systems of four 800×800 CCDs. The Wide-Field configuration provides a view of the full field, while the Planetary Camera configuration registers a $1.'1 \times 1.'1$ field of view. More details are given in Seidelmann (1991).

3. THE SPACE INTERFEROMETRY MISSION

The Space Interferometry Mission (SIM) will be the first space-based interferometer designed for precision astrometry, operating in the optical band with a 10-m baseline. SIM is an approved NASA project, which should be launched around 2009 on a trailing solar orbit slowly drifting at about 0.1 AU per year. SIM will serve also as a technology precursor for future missions such as the Terrestrial Planet Finder. The stellar interferometer comprises two siderostats with

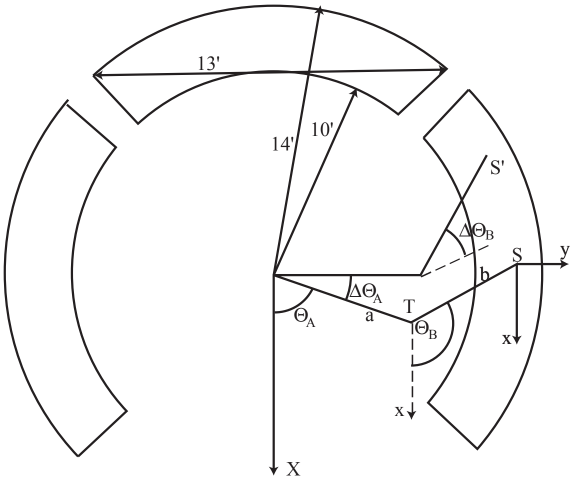

Figure 1: HST: the three segments of the FGS and the positioning of the star selectors .

equal apertures of 30 cm collecting the light with a separation of 10 meters. Each pod has two steerable mirrors which are the collectors of two guide interferometers directed towards bright stars and are used to determine the orientation in space of the baseline during the observation period. This allows measuring the relative positions of sources separated in the sky by 15°. The collected light is directed towards delay lines and a beam combiner. The principle is illustrated in Figure 2.

The basic measurement consists in adjusting the delay line so that the resulting optical path delay is closest to zero. In this configuration the instrument observes the white-light fringe. Therefore the observation equation for a single star is given by,

$$d = \mathbf{B} \cdot \mathbf{s} + \mathbf{C} \tag{1}$$

where $\mathbf{B}$ is the baseline vector and $\mathbf{s}$ the unit vector in the stellar direction. The constant delay C is a fixed instrument offset which must be calibrated to carry out absolute astrometry. On the other hand relative positions of stars are obtained from the change in the internal delay between the two sources as,

$$\delta d = \mathbf{B} \cdot (\mathbf{s_2} - \mathbf{s_1}) \tag{2}$$

which is independent of the instrument constant bias to first order. One must note that the instrument is sensitive only to the component of the relative displacement parallel to the baseline, hence several baselines have to be used. The microarcsecond accuracy translates immediately into a requirement in the fringe delay sensor $\sigma_d \simeq B\sigma_\theta \simeq 50$pm, or equivalently better than 10^{-4} in phase, imposing very severe constraints on the internal metrology, stability and calibration.

The accurate positioning of the collecting mirrors with respect to the beam combiner will be performed by infrared stabilised interferometers with an absolute accuracy of 1 μm per meter and the nulling technology is demonstrated to have a sensitivity of 10^{-4} in 5 minutes.

During its five years of operation SIM will cover the sky in a series of overlapping 'tiles', each 15 degress in diameter, with an average of 6 stars per tile. In total, the grid will comprise approximately 1300 metal-poor K-giant stars at R = 12 which should be observed with an uncertainty of $4\,\mu$as in wide angle astrometry ($3\,\mu$as for parallaxes and $2\,\mu$as/yr for proper motions). Fainter objects, down to magnitude $\sim$ 20, like extragalactic sources to tie the grid

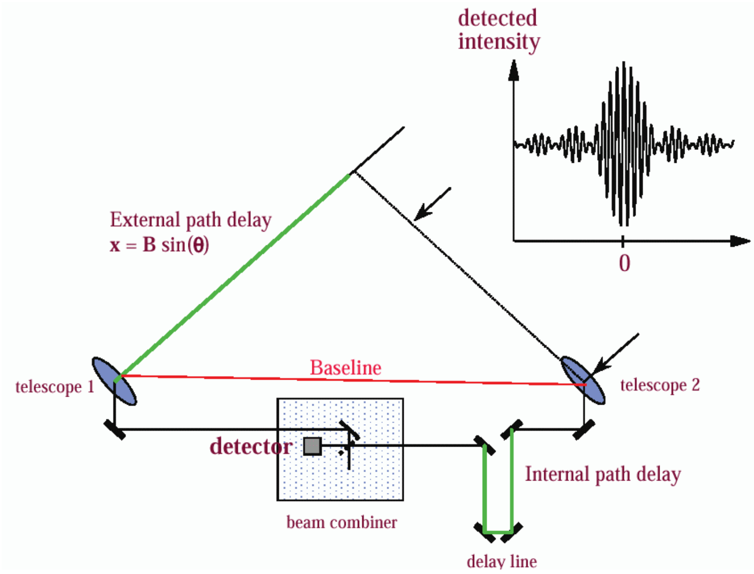

Figure 2: Principle of SIM astrometric measurements

to the ICRF, will also be included in this reference grid. This will need an integration time of 1 second for stars of magnitude smaller than 10, 200 s at magnitude 15, and more than four hours for the faintest objects, which will be observed only in exceptional circumstances.

SIM will have a single-measurement precision of 1 microarcsecond in a frame defined by nearby reference stars (field $< 1°$), enabling searches for planets with masses as small as a few earth masses around the nearest stars (typically 250 F, G, K stars within 10 pc). This will be complemented by a broad survey of planetary systems over a sample of $\sim$ 2000 stars within 25 pc. In addition, the interferometer can be used in amplitude mode, providing imaging potentiality with a uniform $u - v$ coverage. This will allow measuring diameters and shapes of stars and imaging symbiotic stars. More information can be found at http://sim.jpl.nasa.gov.

4. GAIA

4.1 Overall principles

Following the success of Hipparcos, the GAIA project has been approved in October 2000 as an ambitious experiment to probe with accurate astrometry and photometry a very large numbers of stars of our Galaxy. GAIA, which could be understood as an acronym for *Global Astrometric Instrument for Astrophysics*, is an ESA mission to be launched around 2010 as a cornerstone of the next generation in the science program. In opposition to HST and SIM, which are pointing instruments observing a preselected list of objects, GAIA is a scanning satellite that surveys in a systematic way, and repeatedly, the whole sky, linking together without regional errors widely separated sources. This has also the advantage of minimising the dead time and making use of almost all photons reaching the instrument. The disadvantage is, of course, that it cannot observe an interesting object when it is not coincident in time with the scanning law or to adapt the time allocation to the source brightness or astrophysics interest. The two principles are really complementary and do not compete with each other.

The principle is the one of Hipparcos, which has been described in many occasions. The

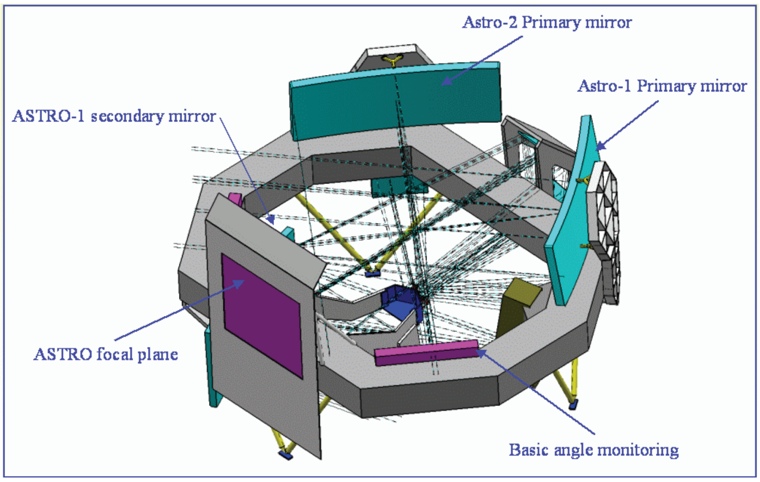

Figure 3: The GAIA payload with its two astrometric instruments separated by the 106° basic angle.

most detailed one can be found in Perryman et al. (1989). The reduction procedure was also described in many places. See, for instance, Kovalevsky et al. (1992) and Lindegren et al. (1992). The same principle was adopted for two other space missions: DIVA (Germany) and FAME (United States). Unfortunately both missions have stopped and it is not clear whether there is a chance for them to be re-activated.

4.2 The GAIA Payload

GAIA scans the sky according to a predefined pattern in which the axis of rotation (perpendicular to the two viewing directions) is kept at fixed angle from the Sun, describing a precessional motion about the Solar direction at a slightly variable rate so modulated as to ensure a constant motion of the rotation axis on the sky. The choice of the angle is a trade-off between the size of the Sun-shield, the parallax accuracy and its variation with ecliptic latitude, the interest of observing at small angle from the Sun for the space curvature determination and for the discovery of minor planet orbiting inside the orbit of the Earth.

In the case of GAIA, the two fields of view are separated by 106° with a Sun aspect angle of 50° (Hipparcos had 43°). The satellite rotates around an axis perpendicular to the plane of the two optical axes in 6 hours (Hipparcos, 2.2 hours). A description of the first design of the satellite is given in ESA (2000). Since then, the size was somewhat reduced so that, now, the astrometric instrumentation consists of two telescopes with a rectangular entrance pupil whose dimensions are 1.4×0.5 m^2 with a 46.7 meter equivalent focal length. The common focal plane covers two fields of view of $0^\circ\!.66 \times 0^\circ\!.66$ filled with some 180 CCDs operating in drift scanning mode. The pixel size will be $10 \times 30\,\mu$m^2 or equivalently 44×133 mas^2, allowing a good sampling of the diffraction pattern of about 100 mas along-scan.

The first two columns of the mosaic are sky-mappers which detect images above some given threshold and determine their positions and speeds in the focal plane. Then the image crosses the astrometric CCDs and the five broad bands photometers, but only small pixel windows around the predicted path are read and transmitted to the ground after some on-board treatment. The size of this widow is enlarged if an extended source or a multiple star system is recognised as such by the sky mappers.

A third instrument is placed midway between the two astrometric telescopes and dedicated

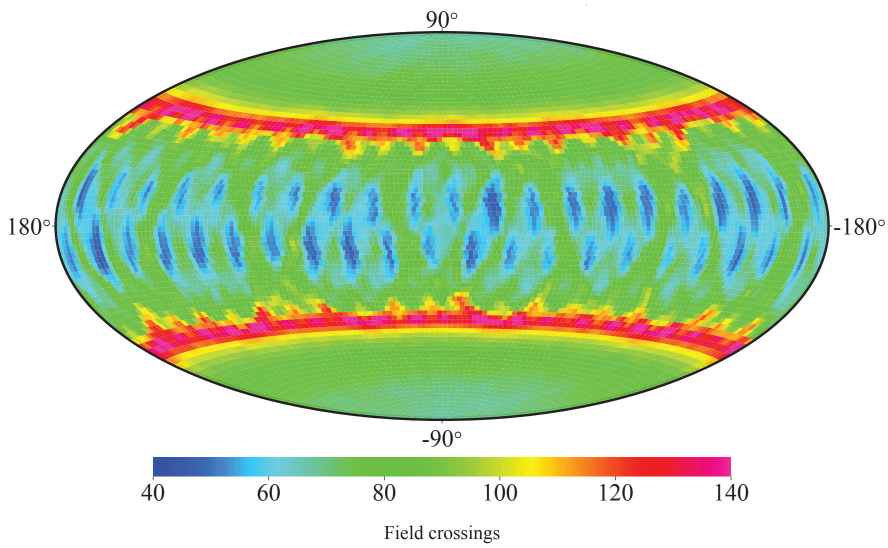

Figure 4: Number of observations in the astrometric fields of GAIA for a 5-year mission. Diagram plotted in ecliptic coordinates for the new design.

to the spectroscopy and the measurement of radial velocities, together with medium-band photometry over 11 bands of about 20-30 nm of width. The telescope is of smaller size (0.5×0.5 m^2) with a focal length of 2.1 m and a total field of view (spectroscopy + photometry) of $2\overset{\circ}{.}0 \times 4\overset{\circ}{.}8$. The image quality allows the use of 10μm^2 pixels within the photometric field corresponding to a spatial resolution of 1 arcsec.

The spectrometer is based on a slitless spectrograph whose resolution should be $R = 12\,000$, or equivalently 0.036 nm/pixel in the spectro CCD. GAIA spectra will cover the range 849 – 875 nm, centered on the near-IR Ca II triplet. This is the strongest spectral feature in the red/near-IR spectrum of the cool stars, visible even in the very metal-poor stars of the Halo. This will enable GAIA to measure radial velocities on virtually all GAIA targets. The main limitation will come from the sensitivity (not many photons are expected in each pixel with the dispersed light for stars fainter than V = 17) and from the crowding leading to overlapping spectra. In total the number of spectral targets should be around 10^8 implying, as in astrometry and photometry, a fully automatic data treatment.

4.3 Orbit and operation

GAIA is intended to be placed on a Lissajous orbit around the Lagrange point $L2$ of the Earth-Sun system in such a way that it avoids eclipses of the Sun by the Earth and can be operated in a very stable thermal and radiative environment. After the launch it will take five months to reach $L2$ when the observations will start, in principle for five years in the nominal mission. The sustained science data rate is about 1 Mbit per second which should be returned to the single ground station with a high gain antenna in daily 8-hour transmission sessions (meaning a data rate transmission of at least 3 Mbit/s and an on-board storage capacity for a few days).

The number of observations and their time distribution are two essential factors to achieve the scientific objectives. A large number of field crossings increases the photon statistics and the astrometric accuracy. But the distribution of these observations during the mission is just as important (i) to obtain a smooth sampling of the parallactic ellipse over the years, (ii) to be sensitive to the tiniest proper motion displacement, (iii) to study the orbit of astrometric binaries or (iv) to investigate the periodic output of variable stars of every type. A scanning mission like GAIA has a strong dependance of the total number of observations with the ecliptic latitude as illustrated in Fig.4. On the average, the number of crossings of the two astrometric fields is ~ 80, while it is 100 for the spectro field and 150 for the medium band photometer. The ecliptic region is under-observed compared to the average, while the number of field crossings is larger by a factor two at the ecliptic latitude 40°. A typical sequence of astrometric observations is a crossing in the first field, followed by a crossing of the second field 106 minutes later, and possibly a second pair five hours later. Then one must wait between 2 to 6 weeks for a new sequence of observations to happen. Over five years the number of different epochs at which observations are carried out is between 25 and 45, for all the fields, with a very distinctive pattern showing two well delimited region : below 30 degrees of ecliptic latitude with the smaller number and above 40 degrees for the larger. The transition is very steep.

4.4 Astrometric Accuracy

Compared to Hipparcos there are several components that account for the improved performance :

- The much larger optics provide a smaller diffraction pattern, so a better astrometric definition of the image center.
- This larger collecting area yields many more photon per unit of time.
- Going from a photoelectric detector to a CCD has a major impact on the detection efficiency and sensitivity.
- Detector arrays replacing a single sensitive surface permits to record many stars at a time.

A straight combination of these factors indicates an overall efficiency factor as large as 1400 relative to Hipparcos, yielding an accuracy of about 11 μas at $V = 15$.

A much more refined approach during study phase has confirmed this simple-minded estimate. The expected accuracies of positions and parallaxes for a 5 year mission, range from 4 μas for stars up to magnitude 12, degrading to 11 μas at magnitude 15, 27 μas at magnitude 17, and 160 μas for magnitude 20. The accuracy of yearly proper motions should be about three quarters of these numbers in $\mu\mathrm{as\,yr}^{-1}$. As for Hipparcos, GAIA will also provide relative positions and magnitudes of the components of double stars.

The numbers quoted above were recently confirmed by a laboratory experiment simulating the observations at the CCD pixel level. It was shown that the centroid of the image of a point-like object could be determined with an accuracy of one hundredth of a pixel, that is 0.3 mas at the CCD level. This is, in a much more disturbed environment, 1.2 times the theoretical estimate computed in exactly the same way as for the evaluation of the mission performances.

5. ASTROPHYSICAL OBJECTIVES

As stressed in the Sect.1 all these space missions have a wide range observing capabilities beyond the primary purpose. The true objectives of astrometric missions is to provide data for the description and the understanding of various features in our Galaxy, as well as in the extragalactic neighbourhood. In the case of GAIA, they are described in a very detailed manner in ESA (2000). The headlines can be summarised as follows:

- Recalibrate the galactic and extragalactic distance scale (Cepheides, RR Lyrae);

- Define and build an optical inertial reference frame;
- Determine absolute luminosities of a wide range of spectral types;
- Detailed structure of an extended to more dimensions HR diagram;
- Study in details the structure, content and kinematics of the Galaxy;
- Determine the age of globular clusters;
- Detect companion stars, brown dwarfs and giant planets;
- Determine stellar masses;
- Map the interstellar matter;
- Contribute to fundamental physics (General Relativity tests);
- Determine orbits, masses and taxonomy of asteroids.

SIM will be able to perform, but only by sampling the objects, some of the above tasks that GAIA will do over a very large number of stars. For instance, it is contemplated to construct a reference frame with few tens or hundreds extragalactic objects with an accuracy of $4\,\mu$as instead of two tenths of a μas with hundreds of thousands objects expected from GAIA (Mignard, 1998, 2002). But there are a series of specific objectives of SIM that are not accessible to GAIA, particularly, but not only, in the extragalactic environment. Among them, one can mention:

- Distance of nearby galaxies using rotational parallaxes;
- Detection of motions of active galactic nuclei (AGN) and bright knots in galaxies;
- Kinematics and dynamics of nearby galaxies;
- Structure of the central parts of some galaxies;
- Search for terrestrial type planets around neighbouring solar type stars;
- Structure of spectroscopic binaries and particularly of symbiotic stars;
- Search for microlensing effects.

So, in conclusion, SIM and GAIA have essentially different objectives and are therefore remarkably complementary. Their launch dates are now very similar and both are planned for a 5-year mission and they need to process all astrometric observations to draw the full benefit of their capabilities.

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