PROSPECTS FOR SPACE STELLAR ASTROMETRY

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Abstract. Astrometry is the major astronomical technique to measure distances, masses and motions of stars. Dividing astrometric techniques into five types according to the size of the field in which a single instrument can produce measurements, the present achievements of the Earth-based astrometry are described. The astrometric activities such as measurements of star diameters, double star relative positioning or stellar parallaxes, search for invisible companions, photographic plate reduction, visual and photoelectric meridian and astrolable astrometry are reviewed. Then, the methods used to construct a quasi-inertial celestial reference frame and to materialize it by a fundamental catalogue are presented and discussed. A much better definition of an absolute reference frame is made possible by VLBI, but the problem of extending it to stellar positions is not yet satisfactorily resolved.

The limitations of the ground based astrometry are: the atmospheric turbulence and refraction, Earth's motions and the impossibility to view the entire sky with a single instrument. These limitations are discussed and it is shown how astrometry from space can overcome them. A priori, a gain of two orders of magnitudes in accuracy for all types of astrometry is expected, but at this new level of precision, new effects and limitations will appear, as already shown in the studies of the approved programs.

Then, the ESA astrometric satellite HIPPARCOS presently under development is presented. The satellite and the payload are described as well as the observing procedures. Several limitations, specific to space borne instrumentation and to the milliarc second accuracy expected have been identified. However the main limitation in precision remains the photon noise. The data reduction methods are sketched. The data downlinked at a rate of 20 kilobits per second have to be used with an equal weight all over the $2\frac{1}{2}$ years of observation. They are expected to yield a mean accuracy of 2 milliarc seconds in position and parallax and 2 m.a.s. per year in proper motion for most of the 100000 stars of the program ($M_B < 9$). Stars to be observed by HIPPARCOS have to be carefully selected. The main fields in which the results of HIPPARCOS will be used are listed from the proposals made by the scientific community. The task of constructing the 'HIPPARCOS input catalogue' from these proposals is presented.

Another feature of the ESA astrometric satellite is the use of the HIPPARCOS star-mapper as a photometric and position survey of the sky. This experiment, called TYCHO, should give at least 400000 star positions with accuracies of the order of $0''.03$ to $0''.15$ depending upon the magnitudes. Two colour instantaneous magnitudes should also be obtained to 0.1–0.4 mag. precision.

Several Space-Telescope on-board instruments are also capable to make small field astrometric observations. Accurate imaging is possible with the Wide Field and the Faint Object cameras. Lunar occultations will be performed with the High Speed photometer. But the main astrometric mode of the Space Telescope will be the use of the Fine Guidance Sensors to measure the relative positions of stars to $\pm 0''.002$. It is described together with its main scientific applications.

The establishment of an absolute reference frame is subsequently discussed. Plans using simultaneously VLBI, HIPPARCOS, and Space Telescope observations are described. They consist in linking the HIPPARCOS stellar system to quasars via radio-stars or stars in the vicinity of optical quasars.

Finally, several space astrometry proposals are described: long focus space astrometry and two versions of space interferometry.

1. Introduction

Astrometry is the part of Astronomy that is devoted to the measurement of the positions, motions, distances, dimensions, and geometry of celestial bodies. Until the advent of

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Astrophysics a century ago, Astronomy consisted only of what is now called Astrometry and its theoretical counterpart – Celestial Mechanics. Practically all that was known about the Universe at the turn of the present century was obtained uniquely by astrometric techniques.

Since then, various aspects of Astrophysics have developed so tremendously, that Astrometry appeared as a rather unrewarding field of Astronomy. The advent of space techniques has accentuated this trend, since only Astrophysics has, till now, benefited from observations made in space, opening new fields such as planetology, UV-, X-ray, and γ-ray Astronomy, etc. and developing all the other domains in solar, stellar, galactic and extragalactic research. However, some of the very fundamental bases of our knowledge of the Universe are obtained by astrometric measurements and there is no other way to determine them. This is the case, for instance, for stellar masses, the distance scale and the dimensions of stars or galaxies. This is also the case for the kinematics of our Galaxy and, to a large extent, of its dynamics. Even if there are many spectroscopic or photometric methods to extend the distance scale to the most remote objects of the Universe, the actual scaling is based strictly on the precise measurement of trigonometric parallaxes of nearby stars. Similarly the basic knowledge of masses of stars is obtained from the measured parallaxes and relative motions of a few selected double stars.

Classically, Astrometry includes also the study of the motions of the Earth. This is a necessity since, all the observations being made from the Earth, positions of celestial bodies are referred to it and the observed motions are combinations of their actual motions and the rotational and orbital movements of the Earth. A major difficulty of Astrometry is to separate these two components. For instance, any systematic component of the Earth rotation like an error in the precession will introduce in the system of stellar proper motions a systematic bias that will affect the determinations of the galactic rotation or of the motion of stellar groups. This is one of the many reasons for the never-ending search for a better 'reference system', a system of coordinates in which all terrestrial effects would have been removed and which would be truly non rotational: *absolute* or *inertial*. This search will be partly discussed in the present review, but we shall disconnect it from the study of the Earth's motions. This means that we consider the latter as a geophysical phenomenon to be studied for its own sake, completely independent from the celestial phenomena that are to be detected or measured by astrometry. In other terms, we reduce astrometry to the study of geometric and kinematic properties of celestial bodies, assuming that the Earth's components are separated. For a recent description of the major problems concerning the Earth rotation, we refer, for instance, to Kovalevsky and Yatskiv (1982) or, for a much more detailed study, to Lambeck (1980).

In this review, solar system astrometry will also be excluded. Earth based astrometry of solar system bodies includes classical techniques used also for stars such as meridian circles, astrolabes and photography. Specific methods are also used like star occultations or laser ranging for the Moon, radar ranging for planets and some natural satellites. The study of the motion of planets and satellites has gained very much from radar observations and tracking of space probes. This is a very specific and different set of methods that will not be described here.

Consequently, we shall only consider in this paper stellar Astrometry, giving first a broad outlook of the present state of Earth based Astrometry and describing afterwards programs and further possibilities of stellar Astrometry in space.

2. The Five Types of Astrometry

Evidently, the great variety of goals to be achieved by astrometric measurements implies a great variety of techniques that must be used. The main characteristic of any one of them can be described by the size of the field of view necessary to reach the desired result. It may vary from a few arc sec to the entire sky. Even if different methods can be used to obtain the same quantities, it is very convenient to present them in terms of the useful extension of the field θ (Kovalevsky, 1979). One may then distinguish

(1) Very narrow field astrometry: $\theta < 10''$.
(2) Narrow field astrometry: $\theta < 0^{\circ}.5$.
(3) Wide field astrometry: $\theta < 5^{\circ}$.
(4) Semi-global astrometry: a large part of the sky.
(5) Global astrometry: the entire sky.

Let us consider successively the applications and the ground based methods corresponding to each of these five cases.

2.1. VERY NARROW FIELD ASTROMETRY

This type of astrometry is devoted to the study of single or multiple stars without reference to the nearby stellar surroundings. The typical work in this domain is the study of the relative motion of the components of a double star. Visual observations using long focus telescopes or refractors are still the main technique. It applies to all systems with separations larger than $0''.2$. Systems with a separation of $0''.1$ are hardly recognizable by the most experienced observers and only if the components are equally bright. The more they differ in brightness, the larger is the minimum separation permitting their detection. Whenever measurements are possible, the accuracy is of the order of $0''.1$ (see for instance Heintz, 1978; or Couteau, 1971).

For systems with larger separations ($2''$ or more) photography is also applied and gives slightly better accuracy, typically $0''.07$ (see for instance, Jeffers and Vaselevskis, 1978) and possibly $0''.05$ (Strand, 1971b).

The main limitation of visual or photographic observations comes from the atmosphere. Whatever the resolving power of the telescope, star images have diameters between $0''.7$ in the best cases and $2''$ or $3''$. Visually, it is difficult to estimate the positions of the photocenters of star images to better than 10% of the image size and, consequently, the relative positions of the components of a binary stars. Using photographic plates and a gaussian fitting of the image, 1 to 2% are obtainable (Chiu, 1977), so that with many exposures of the same separated binary, an accuracy of a few milliarc seconds is possible.

However, it is possible to bring the resolving power to the theoretical diffraction limit by eliminating the effect of turbulence – the major cause of bad seeing. This is done by observing not be the full image, but speckles produced by interference through the inhomogeneities of the atmosphere and to observe if they are widened or divided. This is the principle of speckle interferometry introduced by Labeyrie (1970) and described for instance by Worden *et al.* (1976) or Labeyrie (1981a). This technique is now widely used and mean errors of the order of 0″.005 to 0″.002 are commonly reported in separation as well as in the transverse component (see McAlister, 1979; Bonneau and Foy, 1980; or McAlister and Fekel, 1980), including multiple systems (McAlister, 1976; or Bonneau, 1979). Furthermore, this technique also permits the determination of stellar diameters with similar accuracies (see Worden, 1976; Christou and Worden, 1980; or Bonneau *et al.*, 1982).

An even more powerful tool appears to be direct Michelson interferometry with two telescopes as introduced by Labeyrie (1975) and developed since then by his team in CERGA (Labeyrie, 1978). The results obtained by a prototype with two 25 cm telescopes on a north–south variable base-line permitting separations up to 67 m, show precisions of the order of 0″.01 to 0″.001 on diameter measurements (Faucherre and Bonneau, 1981; Bonneau *et al.*, 1981) as well as on the separation of binary stars (Vakili *et al.*, 1981).

This technique, presently limited to stars of magnitude less than 4 because of the small size of the telescopes will soon be extended in CERGA to several movable 150 cm telescopes (Labeyrie, 1981b) with an expected precision of the same order of magnitude as for the small interferometer.

To be complete, let us recall that the intensity interferometry technique was developed by Hanbury Brown *et al.* (1967) with a separation of telescopes up to 188 m. Accuracies of 0″.0001 or better have been reported (Hanbury Brown *et al.*, 1974) but this difficult technique needs a considerable amount of light and only stars of magnitudes less than 2.5 have been observed with 6 m collectors, so that significant extensions of this method are not expected.

Another – very specific – technique of determining the diameter of a star is the observation of its light curve when it is occulted by the Moon. The interpretation of the measurements in terms of stellar surface properties has progressed greatly in the last years (Barnes *et al.*, 1978) as well as the reduction techniques (Froeschlé and Meyer, 1983). Accuracies of the order of 0″.001 to 0″.003 are currently obtained. But the great disadvantage of this technique lies in the fact that only a very small fraction of the sky is scanned by the Moon every year. Consequently most of the interesting objects are not accessible to this method.

In conclusion, the expected precision of diameter and double star measurements should not be drastically changed in the years to come, so that the figure of one milli arc sec may be considered as representative of the present accuracy of occultations and different interferometric techniques applied to very narrow field astrometry, while the bulk of results on double stars is still obtained visually with a precision of the order of 0″.1, while photographic observations reach a much better precision on widely separated binaries.

2.2. NARROW FIELD ASTROMETRY

Narrow field astrometry is used when it is necessary to link the position of a star to a certain number of surrounding stars. It is typically the case for the determination of the parallax of a star relative to a few field stars that are usually supposed to be very remote or to have a statistically determined mean parallax. It is also used for the search of invisible companions of stars, inducing a non linearity in their proper motions. The technique used is long-focus photography and it has been extensively described by Van de Kamp (1967). On can reach magnitude 16–17 with the large astrometric telescope in Flagstaff.

The precision of a good single observation (two exposures) is of the order of $0\overset{''}{.}03$, but the final result in determining parallaxes depends essentially on the number of plates taken. For some stars studied over several decades, internal errors of the order of a milli-second of arc have been obtained by Van de Kamp (1981) and Lippincott (1978). But these are exceptionally precise results. Most of the 10000 parallaxes catalogued in the GCTP (Jenkins, 1952, 1963) have precisions of $0\overset{''}{.}005$ to $0\overset{''}{.}020$ with differences between individual observations ranging in the same intervals (Upgren, 1977, 1979; Schmidt-Kaler, 1979a, b). Systematic errors that are present in most of the determinations of parallaxes has been widely discussed by these authors and many others using in addition comparisons with spectroscopic parallaxes. A good summary is found in Lutz (1979). The errors are of the order of a few milli arc sec and affect differently various observatories with a possible time dependence (Van de Kamp, 1979). A definite northern to southern hemisphere difference also exists.

Good determinations of parallaxes are now systematically obtained with the US Naval Observatory 61-inch astrometric reflector in Flagstaff (Strand, 1971a). The internal error is of the order of $0\overset{''}{.}004$ for a parallax based upon 36 plates (Strand *et al.*, 1974) while the external errors seem to be of the same order of magnitude (Harrington and Kallarakal, 1978). However, only about 700 parallaxes have now been determined in Flagstaff and the number increases by about 50 per year, so that this is still a marginal result in comparison with the number of stars for which precise trigonometric parallaxes are needed.

No technique other than photography has been used for determining trigonometric parallaxes. Plans are being made to apply optical interferometry for simultaneous or quasi-simultaneous observations of several stars (Shao, 1983). First test results on such a two-color coherent interferometer have been reported (Shao, 1983). The fringe tracking is done to better than a quarter of a wavelength during more than an hour and the results are very promising. But the present situation for parallaxes can still be summarized as follows:

- Less than 100 parallaxes at the milli arc sec accuracy level with systematic errors of a few milli arc sec.
- About 1000 parallaxes with an accuracy of the order of $0\overset{''}{.}005$.
- Over 10000 parallaxes with accuracies ranging between $0\overset{''}{.}01$ and $0\overset{''}{.}02$.

2.3. WIDE FIELD ASTROMETRY

We refer here to photographic Astrometry using astrographs and Schmidt telescopes. It is essentially relative astrometry: star positions are determined with respect to some reference stars whose celestial coordinates must be known from other means. The observational techniques as well as the reduction procedures are described in detail by Eichhorn (1974). The internal measurement errors are of the order of 0″.2 for classical astrographs (type Carte du Ciel) and can be reduced to less than 0″.1 for the most modern Schmidt telescopes (Murray and Corben, 1979) and the A.G. astrographs.

Actually, the dominant error in determining positions by astrography comes from the uncertainties in the positions of the reference stars. It is usually necessary to have about 15 reference stars for reducing a plate of 2° × 2°. About 30–50 such stars are needed to reduce a large field Schmidt plate (5° × 5°). This represents a mean density of reference stars of 2 to 4 per square degree. Unless specially measured stars are used, the positions are taken from existing catalogues providing a sufficient density of stars such as the SAO catalogue or, for the northern hemisphere, the AGK3. As we shall see below, the errors for epoch 1980 may range between 0″.4 and more than 1″ in the southern hemisphere. So, in practice, these are the orders of magnitudes of actual errors in large field astrometry.

It is to be remarked, however, that in some cases the actual position of stars are not needed, but only their relative positions. This is the case, for instance, when one studies the internal motions of a cluster or the motion of an association. In these cases, of course, only the plate measurement errors are showing and one gets accuracies of the order of 0″.1 or better in the determination of the relative displacement of stars.

2.4. SEMI-GLOBAL ASTROMETRY

We designate under this name astrometric methods that allow the determination of position of stars that may be far apart from each other. However, direct connection can be made only within some well defined large portion of the sky. The best example is the work that can be done with the classical meridian circle which can determine right ascensions and declinations of all stars to a given magnitude situated within a certain range of declination, a function of the latitude of the instrument. It is also the case of astrolabes (see for instance, Eichhorn, 1974; or, for a detailed discussion, Podobed and Nesterov, 1975).

Classical visual meridian astrometry yields accuracies of the order of 0″.2 in each coordinate for a single star transit. This accuracy is transferred to the coordinates given in catalogues derived from the observations by a single instrument. The catalogues usually include several hundred stars in a given declination range for stars of magnitudes $m_v < 9$ with actual systematic errors of the order of 0″.01 to 0″.02 in each coordinate (see, for instance, Nowacki and Strobel, 1968; and Fricke, 1982). Similarly, astrolable catalogues contain about 100 to 200 stars of magnitude $m < 6.5$ with a precision of about 0″.1 in each coordinate (Billaud *et al.*, 1978).

A sizeable gain in precision and in the number of stars observed during a night is brought by the introduction of photoelectric instead of visual observations and by the subsequent automatization of the instrument (Fogh Olsen and Helmer, 1979; Requième, 1980). For instance, the Danish Brorfelde meridian circle presently tested (Høg, 1983) gives accuracies of $0''.2$ with a possibility of observing 50 000 stars per year at a good site. It has been transferred to La Palma in a joint Denmark–UK–Spain programme (Clauser *et al.*, 1982). The Bordeaux automatic meridian circle gives operationally $\varepsilon_\alpha = 0''.11$ and $\varepsilon_\delta = 0''.17$ accuracy on stars brighter than magnitude 11 and can reach magnitude 12 or 13. It has a capability of about 20 000 observations per year (Requième and Mazurier, 1983). Similarly, the photoelectric astrolabe now in operation in CERGA gives an internal precision of $0''.07$ per star passage up to magnitude 7.5 which is a factor of two better than visual astrolabes.

In conclusion, it is possible to state that the present semi-global astrometry is able to give stellar coordinates to better than $0''.10$ with a production rate significantly faster than the classical visual transit circles.

2.5. GLOBAL ASTROMETRY

The positions and the derived proper motions of stars have to be given in such a way that they are comparable whatever is the region of the sky where the star is. As we have already pointed out in the introduction, it is essential to refer all the results of semi-global astrometry (and consequently those of the wide field photographic astrometry referred to stars observed by semi-global methods) to a single consistent reference system, if possible inertial and with regional errors reduced to a minimum. To establish such a reference frame and to materialize it with star positions and proper motions is the object of global astrometry.

Conceptually, an ideal celestial reference frame is an inertial one (see Kovalevsky, 1975). In such a system, which is by essence non-rotating, the differential equations of motion must not include any rotational term. In principle it can only be constructed from the analysis of the motion of one or several celestial bodies (such as Moon and planets), but this implies that a detailed model of the dynamical system (e.g. planetary masses, initial conditions) be precisely evaluated. This is a major difficulty as has been shown by Duncombe *et al.* (1975) for planets or by Mulholland (1977) for the lunar motion. Another possibility of defining a non-rotating reference system is to consider that some observable celestial bodies are sufficiently remote so that they can be considered as apparently fixed or slowly moving in the sky in a modellable fashion (distant stars, galaxies, quasars).

In practice, once a reference system is defined, it must be materialized. This means to assign coordinates and eventually proper motions to a sufficient number of objects in such a way that it is possible by some interpolating methods such as photography or meridian observations to determine the coordinates of any point in the sky. This is done by a *Fundamental Catalogue* associated with a reference system.

The methods used to construct a fundamental star catalogue from the presently existing relevant data imply a complex discussion of observations of the Sun, Moon, and planets to determine the system, of the components of the Earth rotation in space (precession and nutation) and of star positions given in star catalogues obtained by semi-global methods. Some of these must be linked to the dynamical system (absolute catalogues), others are simply a collection of relative positions. Presently, a new fundamental catalogue, the FK5, is being constructed and is due to be completed for 1984. The methods used to construct it are described in the literature (Fricke, 1977, 1981). It is a rather pragmatic approach, where the results obtained from the dynamics of the solar system are corrected by a model of galactic rotation. This has led to a final accuracy of the FK5 system of the order of $0''.15$ per century instead of $1''$ per century for the present FK4 system.

The FK5 fundamental catalogue will be a significant improvement over the presently existing FK4, used since 1963. FK4 is defined by the positions and proper motions of 1535 stars brighter than magnitude $m_v = 7.5$. Systematic regional errors that can reach $0''.2$ in the southern hemisphere have been assessed by many authors. Furthermore the mean observing period being 1930, the errors in proper motions have increased the random uncertainties to $0''.12$ for each coordinate.

The construction of FK5 started in 1973 (Fricke, 1974). In addition to the improved global system, it will contain approximately 4500 stars of magnitude $m_v < 9$. The star positions are deduced from 150 new catalogues observed since the compilation of the FK4. It is expected that the random errors of the FK5 will be of the order of $0''.03$ in position and $0''.002$ per year in proper motion (see also, Fricke, 1980).

Evidently, FK4 or FK5 do not have a sufficient number of stars to be used as reference for photographic astrometry. It is necessary to extend the fundamental system by giving the positions and proper motions of many more stars, up to a density of several stars per square degree.

The first step to this densification is done essentially by meridian observations. There are about 38 000 such stars divided into AGK3R in the Northern hemisphere, observed around 1959 and the SRS in the southern hemisphere observed around 1968. Proper motions were computed using earlier observations and computed in the FK4 system. The mean errors of the AGK3R proper motions are of the order of $0''.4$ per century in each coordinate (Corbin, 1979). It is expected that the errors of the SRS, referred to the same FK4, are somewhat larger, because systematic biases of the FK4 may reach $0''.2$ to $0''.3$ for $-60° < \delta < -80°$ (Polozhentsev, 1979). However, applying systematic corrections FK5–FK4, one may consider that the positions of all these stars (also called IRS = International Reference Stars) have *positions* known to about $0''.3$ at our present epoch.

IRS stars represent a uniformly distributed density of one star per square degree with magnitudes $7.5 < m_v < 10.5$. This is still insufficient for photographic astrometry and further densification is needed. This has been done for the northern hemisphere. The AGK3 catalogue, including 180 000 stars with photographic magnitudes ranging from 5 to 12 is the best present reference. However, since its mean epochs of observation were 1930 and 1960, the effects of errors in proper motions are now building up, so that the mean errors are of the order of $0''.4$, and probably above $0''.5$ for faint stars. A project of reobservation of the AGK3 stars has been proposed (De Vegt, 1979) and some plates have been taken.

In the southern hemisphere, there is no photographic reference catalogue. A project of establishing one is being developed (Polozhenstev and Potter, 1979). Presently, the 130 000 southern stars of the SAO catalogue represent the only complete compilation of stellar positions and proper motions in that hemisphere. Unfortunately the data used was very inconsistent and often quite unaccurate, so that errors of more than 1″ are quite common in this catalogue, for the present epoch and is growing very rapidly with time.

An important consequence of this situation is that there does not exist a systematic survey of proper motions all over the sky. The data available for statistical kinematic studies is either scarce, or very inhomogeneous or covering only a part of the sky (AGK3). The largest set would be the 38 000 IRS stars corrected of FK4 systematic errors. The precision of proper motions is of the order of 0″.005 per year, in the northern hemisphere, worst in the southern, but the choice of stars (one per square degree) represents a biased observational selection and cannot be considered a significant sample of our galactic surroundings.

To complete this overview of the present state of global astrometry, let us note the tremendous breakthrough in the search for a quasi-inertial reference frame made possible by the VLBI technique. This technique is now currently applied for astrometric work (Counselman, 1976) and the positions of quasars are now determined to 0″.01 accuracy. Presently, the Jet Propulsion Laboratory VLBI reference frame is composed of more than 100 sources spread more or less uniformly over the celestial sphere at declinations larger than −40°. The estimated uncertainties of the positions of these sources range between 0″.003 and 0″.010 with a mean value of 0″.007 (Fanselow *et al.*, 1984). The accuracy is expected to approach 1 or 2 milli arc sec in a few years from now. Similar accuracies are reported also by MIT/Haystack group (Herring *et al.*, 1981; Rogers *et al.*, 1982).

The VLBI reference system is indeed the closest available approximation to an inertial reference frame. Even if quasars had transverse velocities of the order of their recession speed, this would produce proper motions of the order of 2×10^{-5} arc sec per year. The actual representation of a non-rotating system by quasars is probably much better. The problem with this system is its extension to stellar position: optical counterparts of bright radio quasars are generally fainter than magnitude 16 and are not accessible to semi global astrometrical techniques. In order to insure the link, the present method is to use large field photographic plates that give accuracies of the order of 0″.1. Several such programs are now in progress (e.g. Argue *et al.*, 1979; De Vegt and Gehlich, 1979; Wroblewski *et al.*, 1981). At JPL, direct connection of quasars to planets has been performed with an accuracy of 0″.03. A program of radiostar to quasar ties is presently under consideration (see also Section 8). However, if the individual connections are more precise, they can be done with a very limited sky density.

The use of small field photography may improve the internal accuracy of some links, but the probability of finding a bright enough star decreases. So, presently, it does not seem that linking the existing reference systems to VLBI could be made with sufficient accuracy to be really significant.

3. Limitations of Ground-Based Astrometry

In considering the present state of ground-based astrometry as outlined in the preceding section, we can identify several drastic limitations that tend to indicate that the accuracies already achieved cannot be improved by a large factor, probably not even by half an order of magnitude. These limitations are the following:

3.1. ATMOSPHERIC TURBULENCE

The wavefront from the stars is constantly distorted by the atmosphere. Turbulent cells are moving at various altitudes through the ray path and have two different effects on the theoretical position and shape of the diffraction pattern of the star through the instrument as compared with the results expected with a perfectly stable atmosphere: the position is changed randomly and the diffraction pattern is distorted. Turbulence does not affect the image sharpress if the aperture of the telescope is of the order of these cells: 10–20 cm in good astronomical sites at night (Roddier, 1979). Assuming winds of the order of 5 to 10 m s^{-1} for a good observing night, a given optical situation is stable during times of the order of a few hundredths of a second to half a second (atmospheric coherence time). If the aperture of the instrument is of the same size (10 cm), it is possible to make full use of a diffraction limited image of a star during such an interval of time. The astrometric use of an interferometer is hindered by these limitations (Shao, 1979). The two or more stars to be compared should be observed quasi-simultaneously within that interval of time; this drastically limits the possible observations to bright stars. When this is achieved, the turbulence error is no more of the order of magnitude of the image motion, but of the distortion of the diffraction pattern by the atmospheric cells, which moves the photocenter only by a few milli arc sec (at least if the stars are within an isoplanetic path, see Lindegren, 1980).

When the aperture of the instrument is larger than 10 cm, various atmospheric cells give different images: the speckles. Speckles are constantly and randomly moving in the field and it is not possible to follow the images for an astrometric use. Analogous features appear also in a two telescope interferometer, so that only the fringe contrast is measured at different separations and is used to study the star, limiting until now the interferometric technique to very narrow field astrometry.

If it is not possible to restrict the duration of an elementary measurement to the atmospheric coherence time, then the diffracted image moves in the focal plane and the cumulated image used in astrometry has a dimension of the order of $1''$ in good nights. The shape and the intensity profile of the image is the result of the statistics of turbulent motion of the diffracted image. The dispersion of the statistical noise as well as the detector noise (emultion grain, photoelectric noise) do not allow the determination of the photocenter to better than a few per cent of the resulting spot. This is the main cause of the $0\overset{''}{.}2$ to $0\overset{''}{.}05$ limitations found in non interferometric astrometry. Long focus large aperture telescopes like the USNO astrometric telescope improve the situation essentially by reducing the detector noise and enlarging the image, but a few hundredths of an arc-second is still a general limit of precision in a sufficiently large field of view. The most favourable and extreme cases described by King (1979) with 4 m telescopes would give $0\overset{''}{.}01$ to $0\overset{''}{.}005$, but in a field much smaller than the $0\overset{\circ}{.}5$ necessary for most of the applications of narrow field astrometry.

A theoretical study by Lindegren (1980) of the atmospheric limitations in narrow-field optical astronomy has concluded that the mean error of a measured angle θ (in radian) between two objects near zenith is:

$$\varepsilon = 1\overset{''}{.}3\theta^{1/4}\,T^{-1/2}\,,$$

where T is the integration time in seconds. This formula is consistent with observing precisions stated by various observers using a large range of techniques and allows for the degradation of the accuracy when the field increases.

In the case of semi-global astrometry, Høg (1968) finds an empirical limiting mean accuracy of:

$$\varepsilon' = 0\overset{''}{.}33T^{-1/4}\,.$$

The most remarkable feature of this last expression is that the accuracy of the semi-global astrometry increases so slowly with observing time. This is due to the increasing spectral power density of the image motion towards low frequencies (slow global variations of refraction).

3.2. ATMOSPHERIC REFRACTION

The atmospheric refraction is generally corrected using the values of temperature, pressure and also water vapour pressure at the site of observation and a standard model of atmospheric refraction as a function of the zenith distance. It is well known however that the models are not perfect and there exist systematic and random anomalies. At great zenith distances ($z = 80°$ or more) errors in models may exceed 1″, but even for higher elevations, errors of $0\overset{''}{.}1$ are common. Random (that is time dependent) errors may amount to a few hundredths of an arc second (see Brunner, 1982). The unmodelled part of the errors contribute to the total observing error. Even if unknown refraction parameters are determined at the same time as other observation reduction parameters, errors still exist. In the best ideal conditions, temperature, pressure and humidity being measured with the current accuracy (1°, 1 millibar, 1%), it is not possible to compute the normal (modelled) refraction to better than $\pm 0\overset{''}{.}02 \tan z$ (Teleki, 1982). Furthermore, even if a star is observed many times, the random errors being partly smoothed out, there still remains some constant part of the anomaly linked with the site (Sugawa and Kikuchi, 1979) and its immediate surroundings (Hughes, 1979). Such an error contributes to the systematic instrumental errors and, in particular, enter with its full size in the declination determination by meridian circles.

Another refraction effect is due to the colour dependance. For instance, at $z = 30°$ a difference of $0\overset{''}{.}005$ μm in wavelength, induces a difference of refraction of $0\overset{''}{.}026$ at $\lambda = 0.430$ μm and $0\overset{''}{.}010$ at $\lambda = 0.575$ μm (Danjon, 1980). So, if as is often the case, the colour of the stars are not known, errors in position up to $0\overset{''}{.}1$ or more may exist.

To correct this effect, Currie (1979) has proposed to use a two colour refractometer, but this is a complex procedure that is not yet in use in ground based astrometry.

In conclusion, errors exceeding $0''.02$ and reaching $0''.1$ due to refraction exist in semiglobal astrometric methods. Although they are reduced, some errors remain also in photographic astrometry (Dommanget, 1979). Significant parts of these errors are so well entangled with the unknown positions of stars that, as Teleki writes in his introductory lecture to a symposium devoted to refraction (Teleki, 1979): "It may be stated that the methods intended at the singling out of refractional influence from astrometric measurements are without prospects in the future". This does not exclude that efforts are being done and will continue in order to reduce this influence, but it is not possible to see how to eliminate it presently from ground-based astrometry.

3.3. EARTH MOTIONS

The apparent position of a star depends upon the motion of the Earth around the Sun (annual parallax) or its axis of rotation (diurnal parallax) and upon its velocity in space (aberration). Furthermore, the system of coordinates used (right ascensions and declinations) are defined from an origin involving the plane of the Earth's equator. This means that the celestial coordinate system depends upon the orientation of the Earth in space described by the precession and nutation or upon the position of the observer with respect to the intersection of these axes with the moving Earth reference system (polar motion and irregularities in Universal time). A descriptive definition of these various quantities is given in Kovalevsky and Yatskiv (1982) as well as is fundamental astronomy text books. Since most of these quantities are determined from the observations of apparent positions of stars, the separation of effects is not perfect, and the above-mentioned remark by Teleki can be strictly applied to the precession, nutation and Earth rotation influences on astrometric measurements. The effects is quite sizeable as far as proper motions are concerned (estimated as $0''.15$ per century for the best present value and a second of arc for old astrometric observations still used in determining proper motions).

3.4. INCONSISTENCY OF GLOBAL ASTROMETRY

No ground based instrument can observe the entire sky. Consequently, the construction of a system of star positions covering the sky can be achieved only by combining observations made by several instruments situated in different parts of the world. Each instrument has its own systematic errors, more or less function of the region of the sky (for instance, tube flexure and circle irregularities produce systematic errors in the determination of declinations by meridian circles). Constructing the resulting global catalogue, these errors are discussed and partly removed by comparing individual catalogues. However, some of them remain, and the compilation catalogues have regional errors of instrumental and possibly refraction origin that cannot be removed and this bias reaches, as we have already said, $0''.2$ in the FK4, the best presently available fundamental catalogue.

All these four effects are the causes of the major limitations that cannot be overcome from the ground. We shall see that they disappear if astrometry is done from space.

4. Astrometry from Space

An instrument in space will not be subject to the errors described in the preceding section and will be able to scan the whole sky. In particular, a star image will have a constant shape and dimension, so that it will be possible to analyse it without the drastic time limitation imposed on the Earth by atmospheric turbulence. The only colour effects will be those introduced by the instrument itself and there will not be any systematic regional defect due to refraction. The observation conditions may be isotropic directed towards any point in the sky. Finally, ever though parallax and aberration effects will remain, the direction observed will no more be referred to the Earth and will no more be subject to errors due to an insufficient knowledge of Earth rotation parameters. It is therefore to be expected *a priori* that space astrometry should reach a precision of the order of a fraction of the diffraction pattern of the instrument, the limitation being the instrumental imperfections distorting the expected image and the possibilities of the detector system to analyse the actual image. We shall see in the next sections that the present technology sets this limit to a few milliseconds of arc. However, at that level of accuracy, new effects appear that will have to be overcome or modelled; if not they will produce new limitations.

The fact that one may expect to gain a couple of orders of magnitude in accuracy for most of the astrometric measurements is not, by itself, a sufficient reason to do space astrometry, an undoubtedly very expensive venture. It is first necessary to see what our knowledge of the Universe will gain from this increase of accuracy in the determination of various astrometric parameters related to stars. This will be discussed in conjunction with the projects that will be described in the course of this review.

The technical difficulties that have to be overcome to ensure measurements at a few milliarc second accuracy are so high, that no space astrometry project was seriously taken into consideration for many years. The first space astrometry project to be studied was proposed by P. Lacroûte in 1966 and a feasibility study was performed in 1969–1970 by CNES (Husson, 1975). It was supposed to observe the positions of at least 700 FK4 stars distributed all over the sky with an accuracy of $0''.01$ by superposing two fields of view. The project was not retained, but its main ideas are at the origin of the first approved purely astrometric space mission: HIPPARCOS. At the same time, NASA started to study the project of the Large Space Telescope and among the six instrument definition teams, one was devoted to astrometry. The team showed that small field astrometry at the main focus of the Large Space Telescope could be achieved to a $0''.002$ accuracy (Van Altena *et al.*, 1974). This proposal developed into the astrometric use of the Fine Guidance Sensors of the Space Telescope. Both Hipparcos (and its joint experiment TYCHO) and Space Telescope will yield the first space astrometry results at the end of the 1980's. Several more sophisticated projects have been proposed and one of them – space interferometry – is being studied by the

European Space Agency, while others have undergone preliminary assessement studies. All of them claim a two orders of magnitude improvement in the accuracies of some kind of ground-based astrometry and/or a multiplication by a large factor of the number of bodies measured. In the following sections, we shall describe in detail the approved programs and give the main features of the others.

5. Hipparcos

5.1. PRINCIPLE

The principle of a space global astrometry satellite was imagined in 1966 by Lacroûte and presented to the IAU (Lacroûte, 1968). However, the details were given only a few years later in the open literature, already significantly improved (Bacchus and Lacroûte, 1974). A double rigid plane mirror reflects into a single telescope two fields of view separated by a constant angle (Figure 1). The images I_1, I_2 of stars S_1, S_2 are moving in the focal plane while the satellite rotates around an axis parallel to the mirror intersection. They cross a grid that modulates the light. From the dephasing of the modulated light of two stars, and the value of the constant basic angle γ, it is possible to determine the actual angle between stars S_1 and S_2 in projection on the plane perpendicular to the grid slits. This angle is not distorted by any kind of refraction and if the sky is properly scanned, a given star may be linked to several others in different directions (Figure 2). This is repeated for every star of the program, so that a tight net of angular distances between stars covering the whole sky is constructed. The net is very similar to a geodetic network except that it covers the whole sky, allowing closure equations that do not exist in the case of geodesy. Solving for the coordinates of stars, one gets a consistent catalogue of star positions – the main goal of global astrometry. If the observation can be extended sufficiently in time variations of apparent positions may be determined: the annual parallax and proper motions also become accessible.

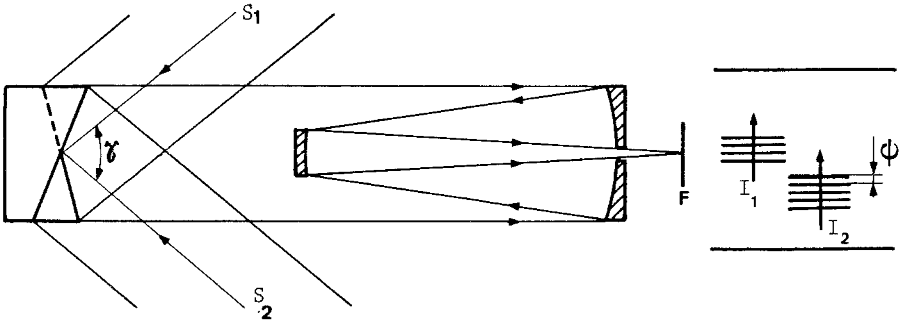

Fig. 1. Principle of Hipparcos telescope and view of two star-images crossing the grid.

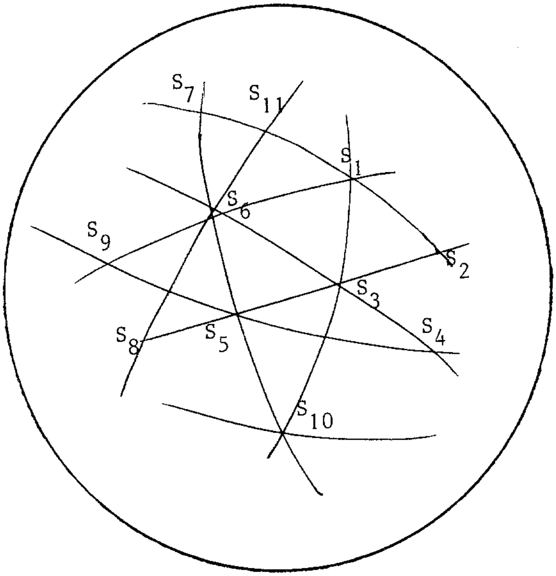

Fig. 2. Interconnection of stars by Hipparcos sky scanning.

5.2. EVOLUTION AND DESCRIPTION OF THE PROJECT

Between the time that the project was proposed to ESRO (now ESA) in 1974 and the definition of the satellite at the end of the industrial phase B in 1983, the satellite has greatly evolved. This evolution is marked by successive descriptions that can be found in the literature: Lacroûte (1975), Bernacca (1979), Høg (1980), Kovalevsky (1982b). A historical sketch of this evolution can be found in Lacroûte (1982). The most important new features added during this period are:

- The introduction of an image dissector that isolates the image of a single star in the focal plane proposed by E. Høg.

- The decision taken that the satellite should be geostationary, facilitating the implementation of an optimized sky-scanning law.

- The decision taken to use the data collected by the star-mapper, initially designed only for attitude control and reconstitution for a large all-sky survey, for positions and colour indices of stars (Program TYCHO proposed by E. Høg).

The project was first studied by ESA in 1975–1976 in the frame of a 'mission definition study' (ESA, 1977). Then a phase A study was decided and later supplemented by a more refined analysis of the technical system. These were carried out during the years 1977–1979 (ESA, 1979). The final name given to the project was HIPPARCOS, refering to the Greek astronomer (190–120 BC) who made the first accurate star map and discovered precession. But this name is also an acronym for 'HIgh Precision PARallax COllecting Satellite'. The decision to include Hipparcos in its mandatory scientific program was taken by ESA in 1980 and the phase B study was performed in

1982–1983 by an industrial consortium led by the French firm MATRA (MESH Consortium).

The program TYCHO was added to the main Hipparcos mission and the corresponding studies were successfully performed. The satellite and payload systems and subsystems are now totally defined and the expected accuracy has been assessed (Bouffard and Zeis, 1983). Nominally, the mission is expected to determine positions, parallaxes and proper motions of 100 000 stars with accuracies of $0''.002$ or $0''.002$ per year respectively for any star with blue magnitude smaller than 9, the precision being degraded for fainter stars. Four tasks are to be completed before the launch of the satellite, presently scheduled for the first part of 1988:

- Construction and test of the satellite by the industrial consortium MESH under the control of ESA (C/D phase starting January 1, 1984).
- Preparation of a catalogue of the 100 000 stars to be observed.
- Preparation of software that will be used to reduce the data and obtain the astrometric parameters.
- Preparation of the TYCHO data reduction software.

The last three tasks have been allocated to four scientific consortia and constitute major scientific endeavours that have to be successfully completed before any use of the data can be made for astrophysical purposes.

In the next sections, we shall first describe the satellite, then present the reduction schemes and accuracy assessments. The technical and computational constraints that will appear have a strong impact on the way that stars should be distributed throughout the sky and consequently on the possible scientific programs that will subsequently be described. Finally, an independent chapter will treat the TYCHO project.

5.3. THE SATELLITE AND THE PAYLOAD

(a) *The Optics*

The main core of the instrument is the beam combiner made of zerodur. It consists of two semi-circular mirrors making an angle $A = 29°$. This angle gives the superposition of two fields of view separated by $\gamma = 58°$. This is the basic angle that serves as the angular standard for the mission. Its value will be determined throughout the mission, but it must have a stability better than $0''.001$ maximum value during at least one rotation of the satellite, about 2 hr. The combined rays coming from the fields 1 and 2 (see Figure 3) are reflected by a flat folding mirror towards a spherical primary mirror. The images are formed at the prime focal surface of the mirror, just beyond the perforated folding mirror. The focal length is 1400 mm, the diameter of the entrance pupil is 290 mm with an oblong central obscuration (ratio: 0.39). The useful field, for which a perfect definition of the sky to focal surface transformation must be achieved, is a square of $0^\circ.9 \times 0^\circ.9$. This is not possible with a single spherical mirror, and a Schmidt-type correction must be applied. The idea of adding a classical lens corrector was rejected, since it would give rise to large chromatic effects that have to be minimized in order to avoid corrections the stellar light. In principle, an achromatic dioptric correction might

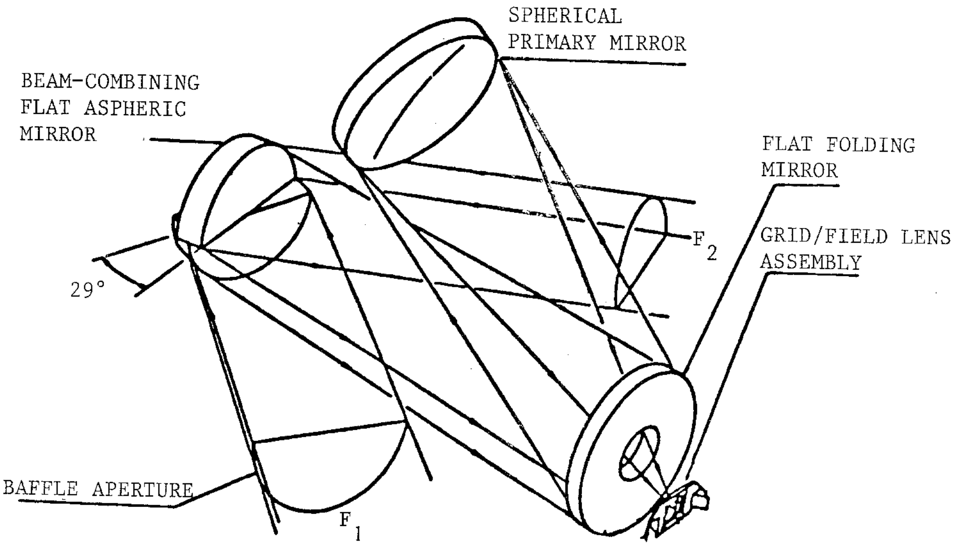

Fig. 3. Scheme of Hipparcos beam combiner and telescope.

have been designed, but would have meant more mass and more manufacturing and alignment difficulties. Consequently, the corresponding Schmidt correction will be applied on the mirrors of the beam combiner. This all-reflective Schmidt system works at a high incidence on the mirror (14°.5), the deformation will have a quasi elliptic profile to be manufactured with a tolerance of $\lambda/60$ r.m.s. on the wavefront. The optimized Schmidt mirror profile is now computed (Le Gall *et al.*, 1983) but undoubtedly the manufacturing will be one of the main difficulties in building the payload.

(b) *The Main Grid*

At the focal surface of the corrected telescope, the grid will be deposited by electron beam techniques on a curved substrate. The shape is as presented in Figure 4. It includes, in the center of the field, the main grid consisting of 2700 slits with a period $s = 1''.2$ and an obscuration ratio of 0.39. While the satellite rotates around an axis parallel to its image on the sky (the $Y'Y$ axis), the diffraction figure of a star moves on the grid and the light that is transmitted through the grid is modulated.

If we call D_x the signal so transmitted and x denotes the abcissa of the mean ray on the $X'X$ axis, one has (Le Gall *et al.*, 1983):

$$D_x = \int_{\lambda_1}^{\lambda_2} \int_{\text{grid}} T(\lambda, X - x)\, G(\lambda, X)\, \mathrm{d}X\, \mathrm{d}\lambda\,, \tag{1}$$

where T is the distribution of intensity on the grid for the given wavelength, $G(\lambda, X)$ is the grid transmittance and λ_1, λ_2 are the wavelength limits of the telescope transmission. Formula (1) representing a convolution, one can deduce that

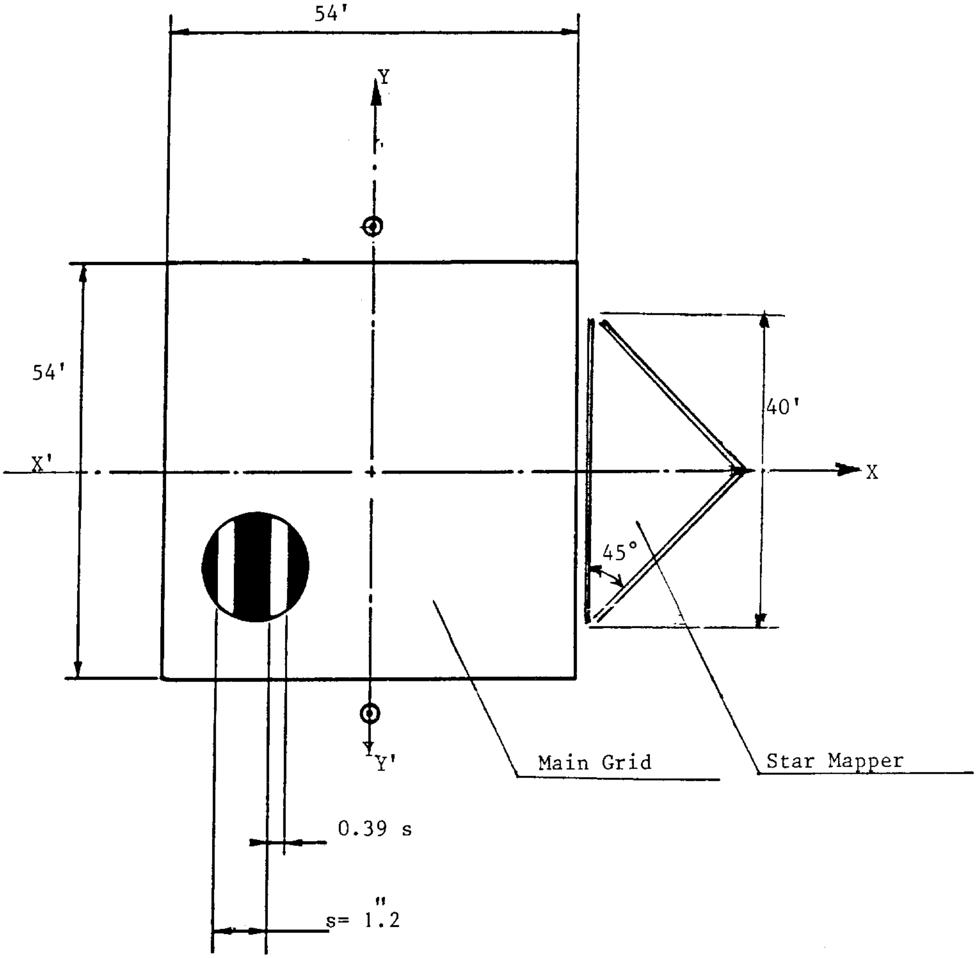

Fig. 4. The main grid and one of the star-mappers of Hipparcos.

$$F(D) = F(T)F(G)\,, \tag{2}$$

where F represents a Fourier transform. $F(T)$ is the telescope optical transfer function. Furthermore, $F(G)$ being the Fourier transform of a periodic grid, it is a sum of discrete terms of frequencies ν, 2ν, etc. The grid spatial frequency being $\nu = 125\ \text{mm}^{-1}$, the cut off frequency is 2ν or 3ν, depending upon λ. So if:

a_0, a_1, a_2 are the values of $F(G)$ for frequencies 0, ν, 2ν.

M_1, M_2 are the first coefficients of the telescope transfer function, one can show that:

$$D_x = a_0 + a_1 M_1 \cos(2\pi \nu x + v_1) + a_2 M_2 \cos(4\pi \nu x + v_2)\,. \tag{3}$$

The coefficient of the 3rd harmonic is negligible. As, *a priori*, the phase v_1 is different from $v_2/2$, the images corresponding to both harmonics do not coincide. The conventional position of the 'center' of the image used to define the position is a weighted mean, that has been optimized so that the abcissa retained for this point is characterized by the phase:

$$\phi = 0.56\nu_1 + 0.44\nu_2 . \tag{4}$$

Figure 5 gives the modulation for two stars of different colour indices, showing the dependence on colour.

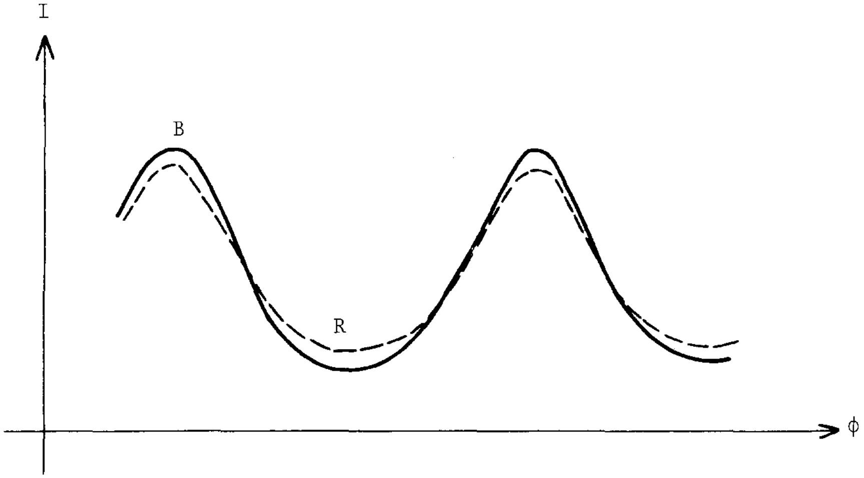

Fig. 5. Modulations curves of a blue star (B, Ic = −0.25) and a red star (R, Ic = 1.5).

(c) *The Detector*

The light is transmitted by relay optics to an image dissector tube (IDT) detecting only the photoelectrons produced by a small region of the focal surface. The diameter of the useful region on the grid (instantaneous field of view: IFOV) is 30″ so that stars that are present further away in the field do not interfere with the observed stars. In practice, however, the cut off is not sharp, and the response of the IDT has the shape given in Figure 6. So, some light of a bright star even rather remotely situated in the field of view, will contribute to the detected signal, causing what is called a *veiling glare* which we shall discuss later (see Section 5(f)).

(d) *Principle of Basic Measurement*

When the satellite rotates, the star images cross the grid and produce the light modulations described above. The period of the modulation depends on the rotational speed of the satellite. The latter has been optimized to be of the order of 2 hr (exactly 2^h8^m) per revolution so that a star can be observed for a sufficiently long time to permit an accurate determination of the phase of its light curve. In the present case, a star crosses the field of view in 19.2 s. If this time was much longer, it would have been difficult to scan the sky with sufficient density.

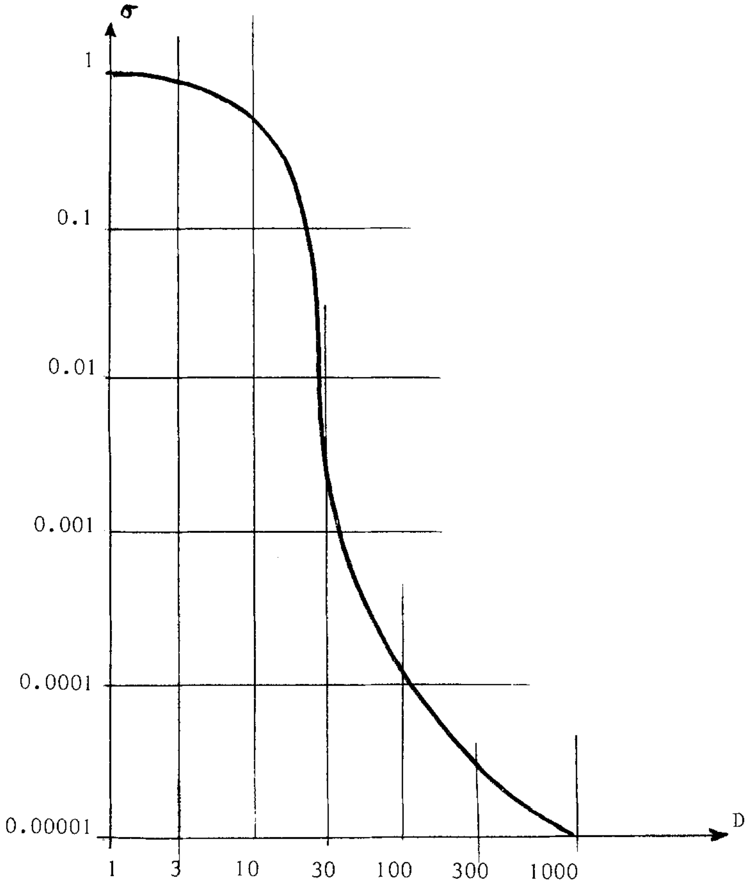

Fig. 6. IDT sensitivity profile in function of the distance D in arc sec to the center of the IFOV.

Let us assume that the pole is fixed, and that the satellite rotates uniformly. Let us observe two stars simultaneously present in the fields of view by setting the IFOV alternatively at each of the two images. Let us determine the phases ϕ_1 and ϕ_2 of formula (4) for each star. The measured quantity is the angle of the projection of the stars on the great circle perpendicular to the axis of rotation. It is given by:

$$\psi_{12} = \varepsilon\gamma + \lambda s + (\phi_1 - \phi_2)\frac{s}{2\pi}\,. \tag{5}$$

If both stars are in the same field of view, $\varepsilon = 0$; if not $\varepsilon = \pm 1$. At the same instant, star images are not on the same grid slit: λ is the integer number of slit periods that separate the stars. Finally, $\phi_1 - \phi_2$, the phase difference, is the measure of the fractional part of the angle $\psi_{12} - \varepsilon\gamma$ in terms of slit periods. If we assume that γ is accurately calibrated and that the actual positions of stars are sufficiently well known

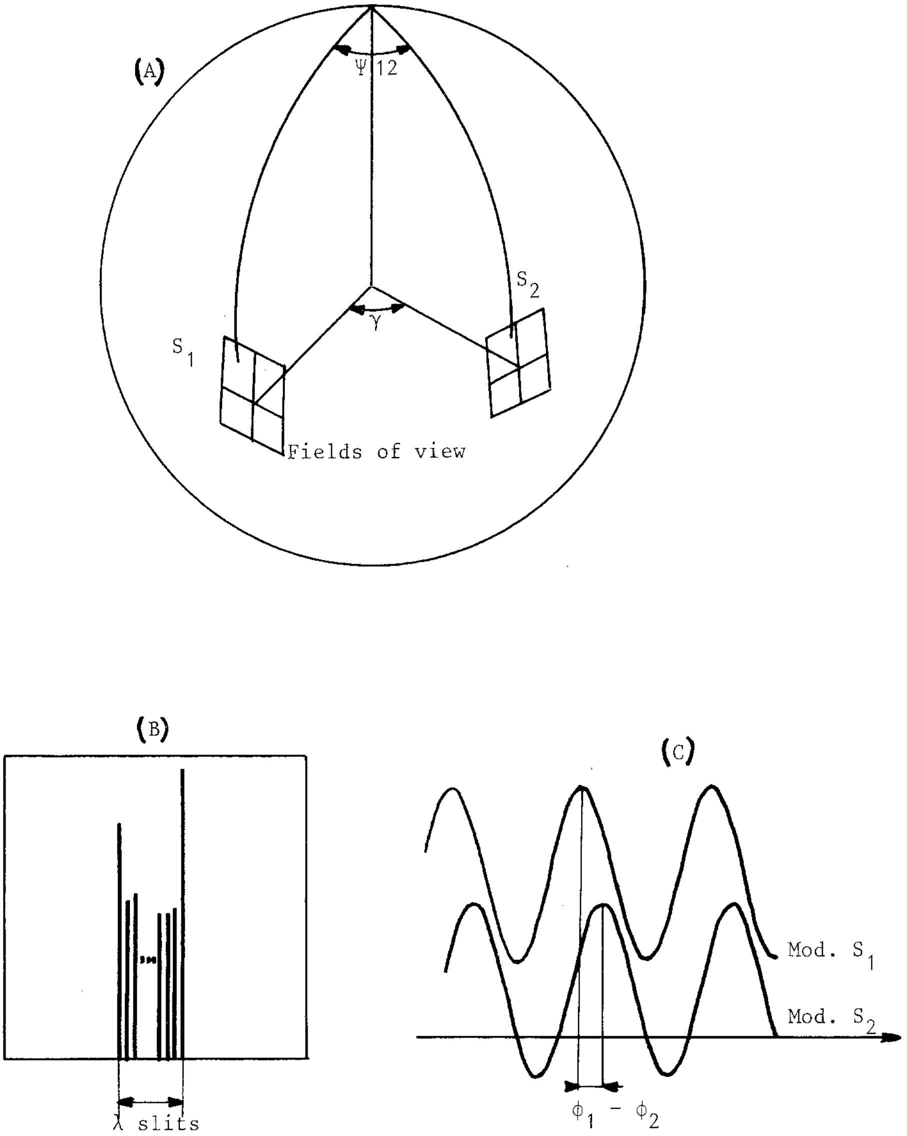

Fig. 7. The basic measurement of Hipparcos: (A) Separation of the fields of view. (B) Grid step reckoning. (C) Phase determination.

a priori, so that λ can be considered as known, then the basic HIPPARCOS measurement is just a vernier determination of the fraction of the grid period to be added to $\varepsilon\gamma + \lambda s$ in order to obtain ψ_{12} (Figure 7). Actually, the value of γ is one of the unknowns of the global data reduction procedure. Furthermore, the positions of some stars may not be as accurately known *a priori*. If they are a minority, there exist procedures to recover λ (see Section 5.6(e)).

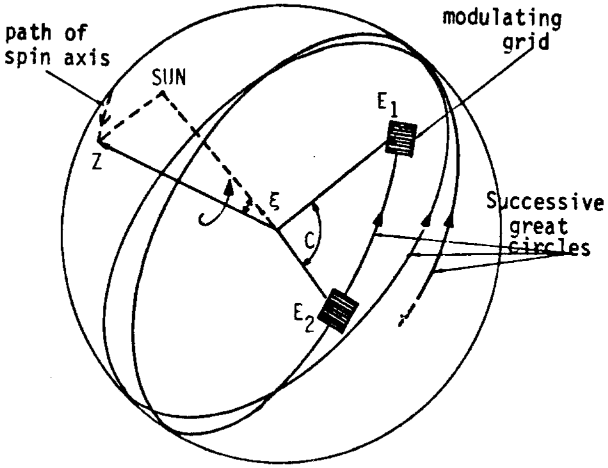

Fig. 8. Principle of the sky scanning by Hipparcos.

(e) *Scanning the Sky*

The satellite axis of rotation must move in such a way that all the sky is scanned by the satellite and that every star is chained to as many stars as possible by the procedure described in the preceding paragraph.

The ideal would be that at every point on the sky there exist observing great circles tangent to all directions. However, this is not the optimal solution. It has been attempted, in the choice of the scanning law, to optimize the accuracy of the parallax determination. And since the parallactic displacement of a star is perpendicular to the direction of the Sun, the observing great circles must be placed in such a way that the mean angle θ of the Sun direction with the great circle C be all the time as small as possible, so that the projection of the parallactic displacement on C be as large and as smoothly distributed over C as possible. This is achieved for an angle ξ between the spin axis and the direction of the Sun of the order of 45° (Figure 8). This angle should be constant throughout the mission. Hence, the nominal scanning law is obtained by slowly moving the axis of rotation around the Sun on a small circle of $\xi = 43°$. A rate of 6.4 revolutions per year has been adopted. While the Sun is moving on the ecliptic, the pole describes a curve shown in Figure 9. The actual scanning during $1\frac{1}{2}$ months is also shown in the same figure. The pattern is repeated by translating it along the ecliptic. The final position and the apparent movements of a star are reconstructed from the successive positions on different great circles at which it is observed (Figure 10). During the expected $2\frac{1}{2}$ year duration of the mission, every star will be observed on at least 30 different great circles.

Looking at Figure 9, it can be seen that high latitude stars can be observed in all directions, while low latitude stars cannot be observed along great circles with small inclinations to the ecliptic. Consequently, the final accuracy of the star positions is

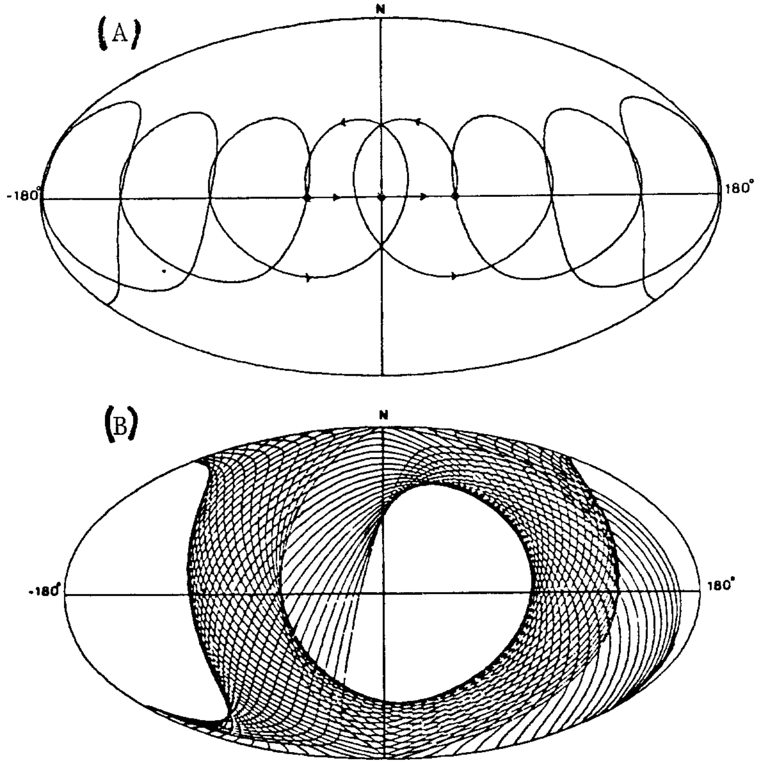

Fig. 9. The scanning law of Hipparcos: (A) Yearly motion of the spin axis in ecliptic coordinates. (B) Actual scanning during one rotation of the spin axis.

practically isotropic for high latitude stars. Around the ecliptic, latitude will be better determined than longitude.

In practice, the rotation axis of the satellite is supposed to move regularly in the sky. This motion is controlled by gas jets. It is expected that the nominal scan will be realized to an accuracy of ± 10 arc min by actuating the jets in the mean every five or ten minutes.

(f) *The Star-Mapper and the IDT Guiding System*

When a star crosses the field of view, it is necessary that its position be known with a sufficient accuracy so that the IDT can be centered at the star. Since the IDT transfer function (Figure 6) has a very sharp maximum, the errors should not exceed $5''$ so that the star light is not unnecessarily attenuated. Three major causes affect this error. The first is the error on the knowledge of the position of the star. In order to reduce it, most of the program stars will be reobserved from the ground so that about 60% of the positions should be in error of less than $1''$ and the others will have r.m.s. error of $1''\!.5$ at worst. This is a major ground based accompanying astrometric program.

The second cause of IDT mispositioning is the error in the real time knowledge of the attitude of the satellite. It is presently expected that it will be determined on board

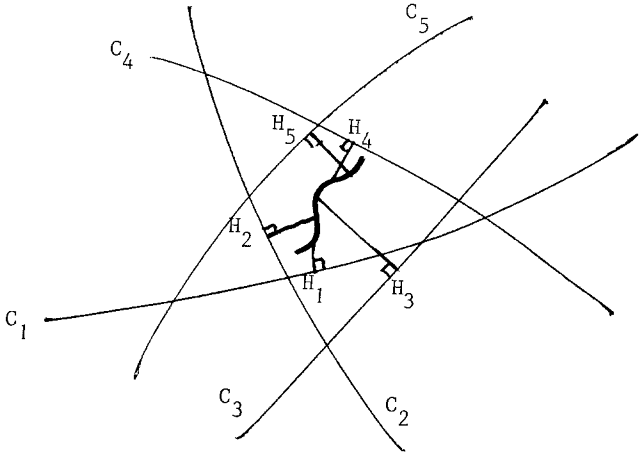

Fig. 10. The apparent path of a star is reconstructed from successive projections $H_1\ H_2\ H_3\ H_4\ H_5$ on great circles $C_1\ C_2\ C_3 \ldots$

with a 1″ r.m.s. error. The main instrument for this determination is the star-mapper. It consists of four vertical and four chevron slits placed on the edges of the main grid as shown in Figure 4. All the light passing through a star-mapper is collected and sensed by a photomultiplier. The times when a star image crosses the two groups of slits are recorded. This gives at these instants two points of information about the attitude of the satellite provided that the position of the star is known. After several such transits, a sufficient number of information is collected for the determination of the attitude if one uses in addition the readings of the 3 gyroscopes that are attached to the instrument. Using the positions of the 60% best determined program stars, it is expected that the attitude will be continuously determined in real time to an accuracy of about 1″ r.m.s.

The third error in the IDT positioning is the error in the relationship between the intensity of the deflecting currents in the tube and the position of the IFOV. It is expected that it may be calibrated to 1 or 2 arc sec, so that, in the whole, the resulting inaccuracy in the IDT positioning will remain within acceptable limits.

The star-mapper is also the main instrument for the TYCHO experiment (see Section 6).

(g) *On-Board Computer*

Several functions must be executed simultaneously: payload temperature and current controls, data exchange with the Earth based control station (a single one will suffice since the orbit is geostationary), securities from straylight when the Earth or the Moon approaches a field of view, formatting the outgoing data, etc. All these functions are controlled by an on-board computer as well as all the more specific tasks.

Every 10–15 min, the satellite receives the positions, magnitudes and other informations about stars that may be observable (that is within ± 37′ from the nominal scanning law). Recognizing the stars crossing the star-mapper, the computer reduces the corresponding data and uses it, together with previous data and gyroscope readings, to determine the attitude. Eventually, if the discrepancy with the nominal scanning law exceeds 10′, it computes and actuates the gas-jets in order to force the attitude back to the desired scanning.

From the knowledge of the attitude, the visibility and the time of entry of images in the main grid are computed for every uplinked star. It can then direct the IFOV successively on the images of all observable stars following an a priori procedure described as the 'observing strategy'.

5.4. OBSERVING PROCEDURE

Significant astrometric results on a given star can be obtained only if it is systematically observed during the entire mission. This is why it is necessary to select in advance those stars that will be observed. The list of these stars constitutes the 'Input Catalogue', the preparation of which will be described later (see Section 8). It will contain approximately 100000 stars well distributed all over the sky. The density achieved is 2 stars per field of view, so that, in the mean, 4 star images will be simultaneously present on the main grid. The role of the observing strategy is to distribute optimally the available observing time among the present stars. Three conditions are to be fulfilled.

(a) The main precision factor is the photon count. It is necessary to observe fain stars longer than the bright ones. A 'global strategy' giving the target observing time over a $2\frac{1}{2}$ year mission in function of magnitude will be given. Figure 11, taken from Kovalevsky and Dumoulin (1983), shows what could be such a time distribution for a probable distribution of magnitudes among the 100000 stars as given in Table I.

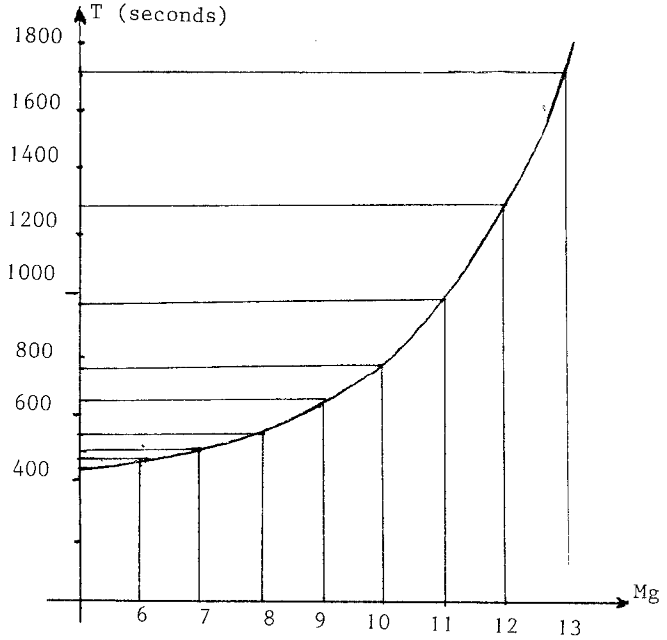

Fig. 11. Proposed global distribution of observing time in function of the magnitudes of stars.

TABLE I

Expected number of stars in the input catalogue

Magnitude (B)	Number of stars	Completeness
<6	3000	100%
6–7	5400	100%
7–8	14800	100%
8–9	40800	90%
9–10	16000	15%
10–11	12000	4%
11–12	6000	0.8%
12–13	2000	0.1%

(b) In order to have significant results in the determination of the phase, a minimum observing time will also have to be defined. This limits the number of stars that can be simultaneously observed and prevents the inclusion of a great number of cluster stars in the program.

(c) Although internally originated oscillations of the satellite have been minimized by rejecting inertial wheels as the attitude control system, gas jets and possibly other moving pieces like gyroscopes will produce mechanical jitter that will move the star images on the grid with total mean amplitudes estimated to less than 3 milli arc sec (except during the first 20 s after gas is ejected). The most important jitter components have frequencies of the order of 3–10 Hz. In order to avoid spurious terms in the evolution of the light modulations and consequently in the determination of the relative phases, the IFOV will have to be transferred at short intervals from one star to another, so that the jitter effect is the same on both stars and is subsequently eliminated.

From these three conditions and some other minor ones, an observing strategy has been devised, essentially based upon four major periods.

– The sampling period $T_1 = 1/1200$ s corresponds to the time of accumulation of photoelectrons and the elaboration of a single output count.

– The IFOV repositioning period $T_2 = 8T_1$. The duration of continuous observation of a given star is an integer number of T_2. Roughly this time represents one slit crossing.

– The interlacing period $T_3 = 20T_2$. It is the period of time during which all the stars selected for observation have to be observed. The instantaneous dwell time strategy performed by the on-board computer is the distribution of the 20 repositioning periods among the N stars to be observed proportionally to the global strategy table, account being taken of their minimum observing time.

– The frame period $T_4 = 16T_3 = 2^{\mathrm{s}}.133\ldots$ is a period during which the observing sequence defined in an interlacing period is identically repeated. In other words, the configuration of stars to be observed is frozen during a frame period. However, exceptions are accepted in favour of bright stars entering or leaving the field of view during the frame period. In this case 2 or 3 observing sequences may be programmed. Figure 12 shows an example of the observing sequences during one T_4 with 4 fully observable stars and a 5th star entering the field before the 11th interlacing period.

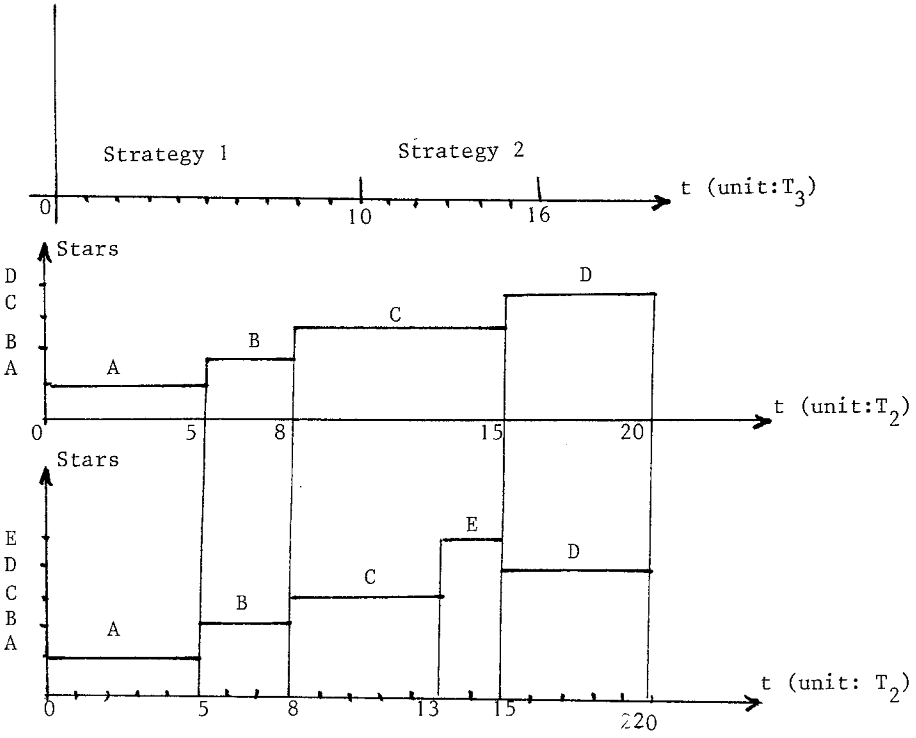

Fig. 12. Example of time distribution between 5 stars during one frame period. The star *E* entered the field of view before the 11th interlacing period.

During the mission, a systematic survey of the observations actually performed will be made. It will be possible to correct the deviations to the expected cumulated observations by modifying the target observing time of some stars.

5.5. LIMITATIONS

Earth based astrometry has a number of limitations that we have described Section 3. They are overcome by HIPPARCOS, but new problems have been identified, some times unexpectedly. Let us describe the most important which are probably not specific of HIPPARCOS, but would affect any space astrometric mission.

(a) *Jitter*

Under this general name, we designate all short periodic motions of the optical axes that cannot be taken into account by attitude reconstitution procedures. In the case of HIPPARCOS, it is essentially due to the oscillations induced by gas jet. The main jitter frequencies are due to the elasticity of solar panels. Computations have shown that the r.m.s. amplitude of jitter is of the order of 2 milli arc sec. Some of the oscillation modes have a very large damping factor (> 0.99) so that the mean jitter is practically the same all over the mission. Figure 13 shows the amplitude spectrum of jitter as presently

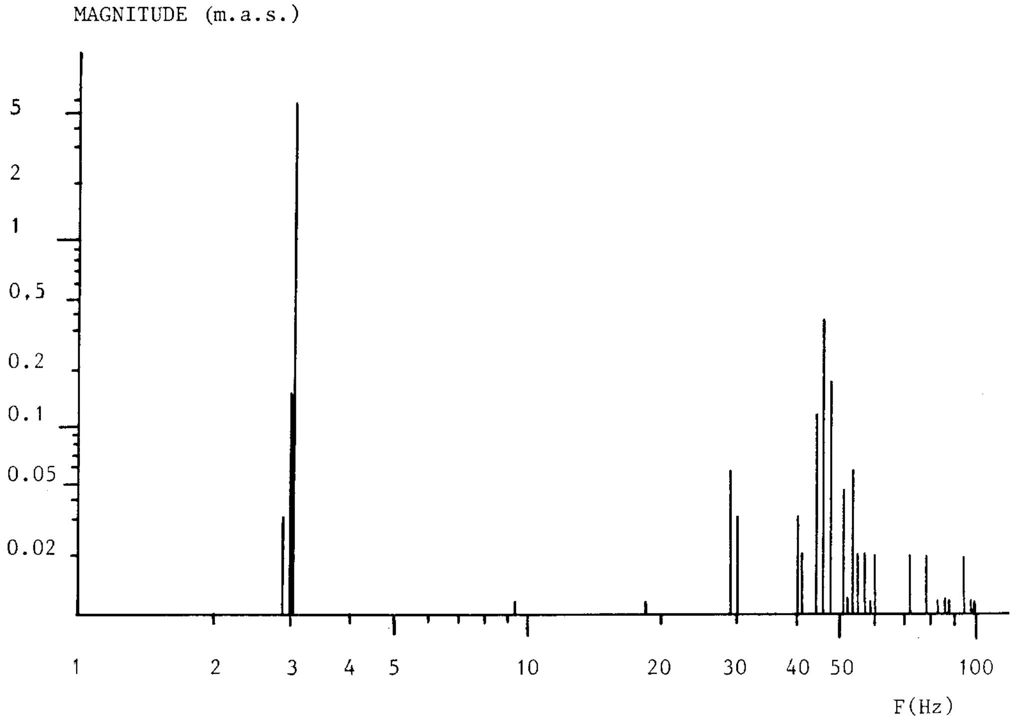

Fig. 13. Shape of the amplitude spectrum of the jitter in function of the frequency. The peaks correspond to the main proper frequencies of the satellite.

expected for HIPPARCOS. It has shown that if the attitude control was performed using inertial wheels the jitter would have been at least 5 times larger. It is practically impossible to eliminate the jitter from the measurements since it is only reduced proportionally to $\sqrt{T}$ by increasing the observing time T. So, in practice, the jitter mean amplitude is a measure of the limiting precision of an observation.

(b) *Stray Light*

Bright objects like the Sun, the Earth, or the Moon illuminate the tube of the telescope even if they are not in the field of view. The light is reflected or diffused by the tube and some of it reaches the detector, creating a background signal that adds to the noise of the measurement. The requirement put upon HIPPARCOS is that this stray light should be less than 10 times the dark sky background signal. The baffles have been designed in such a way that the solar stray light should never reach this limit. This condition was rather easy to comply with, since the scanning law does not permit the Sun to be at an angle smaller than 47° from the directions of the optical axes. But this is not the case for the Earth and Moon which may even cross the fields of view. The unprotected field of view extends to ± 12° along track and ± 7° in the perpendicular direction. Whenever a part of the Earth enters these unprotected regions, observations have to stop. The unprotected field of view for the Moon is somewhat smaller. But all together, the interruptions caused by stray light amount to 6% of the total observing time distributed in approximately 28% of the scans.

(c) *Thermal Effects*

The high accuracy requested from the definition of the positions of the star images imply a highly stable optical configuration. This means that, in addition to a great mechanical rigidity, thermal expansion should be reduced to a minimum. The use of material with zero thermal expansion coefficients for the structure is not sufficient and very accurate thermal control is a necessity in space astrometry. For instance, in the case of HIPPARCOS, it is requested that the basic angle defined by the complex mirror should be stable to 1 milli arc sec (3σ) during any time period $t_1 - t_2 < 2.8$ hr. This implies an active thermal control of the mirrors to better than $0\overset{\circ}{.}2$ all over the mission. Similar demands exist also on other parts of the optical system. It does not seem possible, with the present technology, to avoid errors of the order of 1 milli arc sec due to such thermo-mechanical effects.

(d) *Chromaticity*

This effect discovered in ESTEC during the precise study of the optical design was one of the main surprises of the study of HIPPARCOS (Vaghi, 1979). The name of chromaticity has been given to a phenomena which can be described as being a diffraction chromatism, in contrast with the normal chromatic effects present in all dioptric systems where the refractive indices vary with wavelength. In the case of mirror systems like HIPPARCOS, chromatism does not exist but, at the level of precision requested, the difference of shape and dimensions of diffraction patterns affected by aberration produces a displacement of the photocenter which is a function of the relative intensity of different parts of the spectrum of the source (see Le Gall, 1983a, b; Le Gall *et al.*, 1983). Figure 14 qualitatively illustrates this effect. Let us assume that at some given point of the field there exists a coma. This means that the monochromatic diffraction pattern is not symmetrical. Since the dimensions of the pattern is wavelength dependent, there is no reason that the photocenters of the spots coincide. If, now, the sources are real stars, the actual photocenter is the resulting photocenter over the whole spectrum of the star so that its position will depend upon the colour of the star. This displacement is the chromaticity.

Considering the modulation of this polychromatic diffraction pattern by the grid, this effect introduces a chromatic dependence into the phases v_1 and v_2 of formula (3). If we observe two stars A and B of different colours, the corresponding phases being v_{1A}, v_{1B}, v_{2A}, v_{2B}, the relative chromaticity of the first harmonic is defined by:

$$\chi_1 = \frac{1}{2\pi\nu}\,(v_{1A} - v_{1B})\,. \tag{6}$$

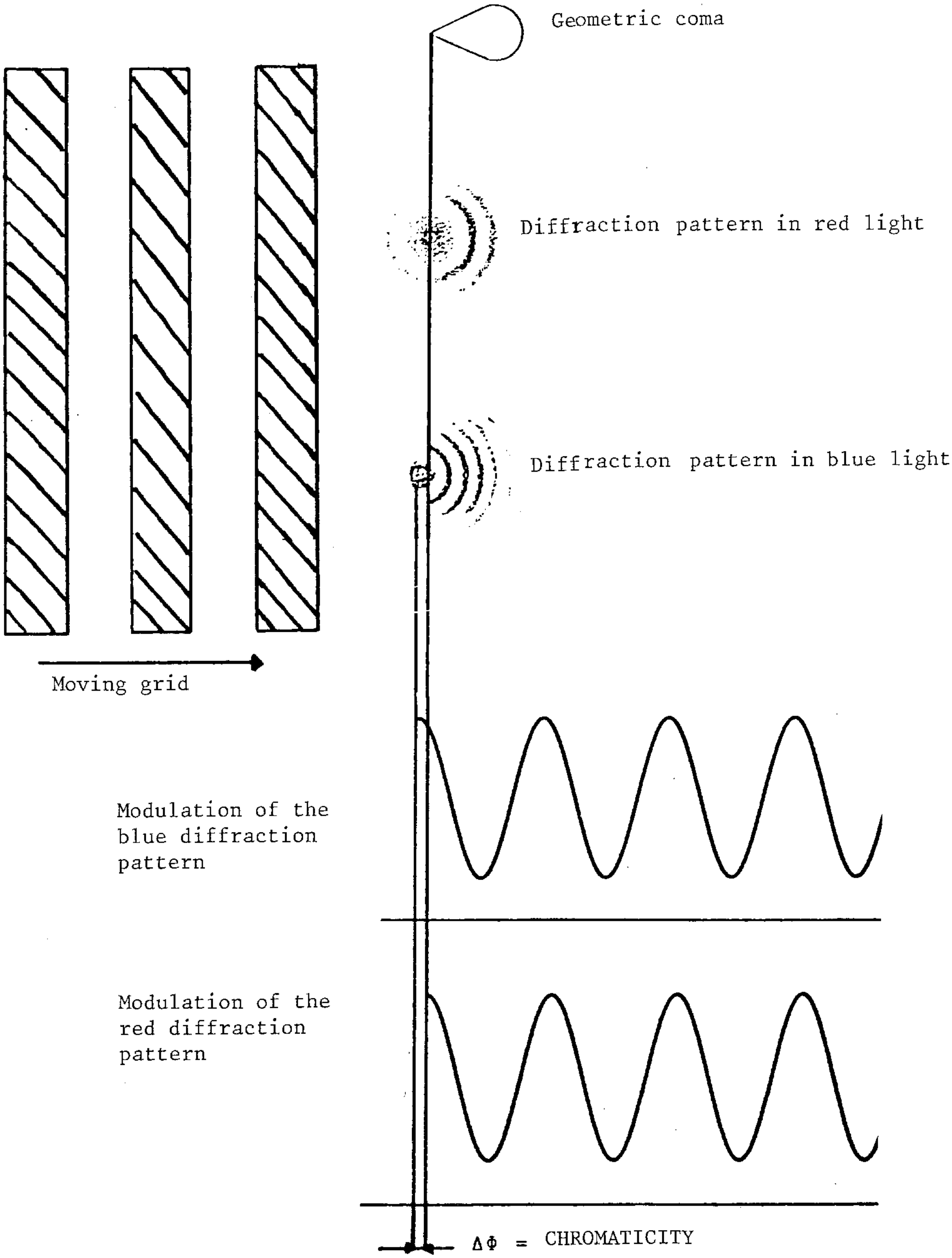

Fig. 14. Schematic description of the chromaticity effect (Le Gall, 1983a).

A similar definition describes the second harmonic chromaticity. Assuming that A is a blue star (color index $c = -0.25$), and B is a red star ($c = 1.25$), Le Gall *et al.* (1983) have computed the chromaticity for the nominal HIPPARCOS telescope. It is found that it depends only on the ordinate of the star along the slits and does not vary along a parallel to the main OX axis of the grid (Figure 4). The results are represented by the formula:

$$v_{1A} - v_{1B} = 0\overset{\circ}{.}0155\eta' ,$$

where η' is the ordinate of the star expressed in minutes of arc. The corresponding error in the positioning of the star is:

$$\Delta\psi = 0.052\eta' \text{ milli arc sec} \tag{7}$$

since $-27' < \eta' < +27'$, the effect may amount to $0\overset{''}{.}0014$.

But the actual telescope will not be perfect and misalignments will occur. It is easy to show that they will greatly increase the effect. Presently, the requirements set up by ESA are that the constant chromaticity (constant all over the field of view and throughout the mission) will not exceed $0\overset{''}{.}0025$. The same limit is allocated to the variable part. This means that the chromaticity error may exceed $0\overset{''}{.}005$ in extreme cases. This is not a tolerable error and it will be necessary to calibrate the instrument for chromaticity and correct all measurements for it. This implies that one shall have to know the color indices of stars to about 0.2 magnitude for the brightest.

(e) *Grid Irregularities*

The accuracy of the grid profile should be compatible with the required observing precision of a few milliarc seconds. The construction of the grid is one of the major technical difficulties in the HIPPARCOS project. The main grid will have to be etched on a curved surface whose dimensions are 22 × 22 mm. One micrometer on the grid represents $0\overset{''}{.}15$ in the sky. Precisions of a few tens of nanometers will have to be realized in manufacturing the grid.

This appears to be feasable with the present electron beam techniques. The major difficulty lies in the fact that the desired accuracies are attained only on very small pieces. The presently proposed method consists in etching a patchwork of quasi-identical squares of 16 grid periods. There would be about 170 × 46 such elementary grids covering the useful area but some uncertainty will remain in their relative positioning. This 'stitching error', which may be of the order of $0\overset{''}{.}01$ will have to be calibrated and corrections to the phases should be applied in every elementary square. First studies have shown that such a procedure would work and that the overall effect on the measurement of the residual stitching error could be of the order of $0\overset{''}{.}001$ provided that about 4% of the observations are rejected. However, studies are still in progress to increase the dimensions of the elementary grids and hopes exist that this problem might prove to be less dramatic than presently feared.

(f) *Veiling Glare*

As we have already seen, the IDT transfer function as shown in Figure 6 does not fall sharply to zero, so that stars even quite distant from the observed object contribute at least slightly to the signal. This is well known and is usually a minor nuisance, since it amounts to increasing the background noise. But in the case of HIPPARCOS, the problem is that the light of the parasitic star is modulated by the same grid as the star being observed. So what is obtained is the composition of the main modulation with the spurious modulation having the same period and the same form (3) except for the global intensity factor and for the phase v which depends of course of the relative position of the parasitic star. The resulting modulation curve has still the same form (3), but the actual phase of the observed star is shifted by some quantity Δv. To correct for this phase error, it is necessary to know the distance D between both stars as projected perpendicularly to the grid slits. Figure 15 shows the distance r of the disturbing star and the magnitude difference for which the veiling glare is smaller than a given value. Although this error can be considered as random for all the great circles involving a given disturbed star, this effect may still in some cases limit the final accuracy. If only one or even two parasitic stars exist in the vicinity of a program star, the veiling glare may be corrected for if they are also program stars so that their positions will be improved by HIPPARCOS itself. But in some regions like in clusters such as Pleiades, this will not be possible and a significant degradation of accuracy may result from this effect.

Concluding this section on limitations, we may say that several factors (general or specific to HIPPARCOS) contribute equally to observing errors of the order of one or

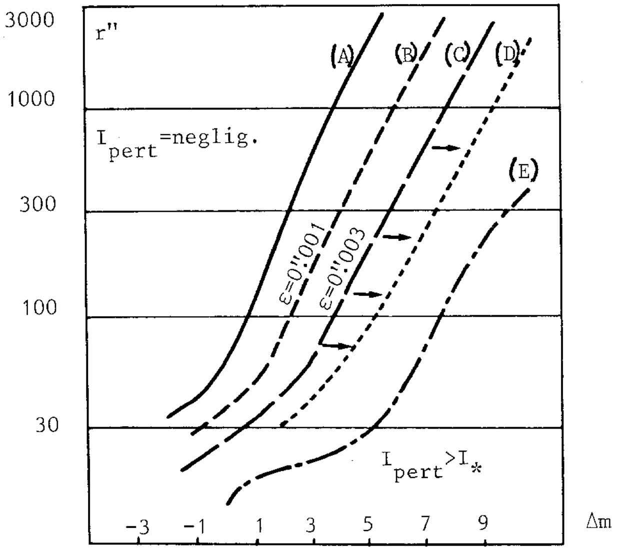

Fig. 15. The veiling glare disturbing effect due to a star of magnitude Δm brighter than the observed star: (A) On the left of this curve, the effect is negligigle. (B, C, D) The perturbation of the position may reach 0''.001, 0''.003, 0''.01. (E) On the right of E, the modulation of the disturbing star is preponderant.

a few milliarc seconds. This is the order of magnitude of the precision to be presently expected from space astrometric missions.

5.6. DATA REDUCTION

HIPPARCOS will generate about 20000 bits of data every second. But unlike other space missions, every second of observations has the same weight. No choice has to be made among the data and all the 1.5×10^{12} bits collected during the $2\frac{1}{2}$ years of the mission will have to be processed in order to contribute to the final solution: 100000 stellar positions, proper motions and parallaxes. It is only when these astrometric parameters will be calculated that it will be possible to do astronomy or astrophysics with HIPPARCOS. One may say that the data reduction task is just as important as the satellite construction and data recovery. This is why, ESA has appointed two (friendly!) concurrent scientific consortia to prepare the data reduction and later treat it. One of these consortia called NDAC (for Northern Data Analysis Consortium) is headed by E. Høg and includes scientific teams from Denmark, Sweden, and U.K. Their answer to the ESA invitation to tender describes their plans as they were viewed in 1981 (Høg and Cruise, 1981). The second consortium is FAST (for Fundamental Astronomy by Space Techniques) is headed by the author of this review and includes 17 scientific groups from France, F.R.G., Italy, Netherlands, and U.S.A. Their plans for data reduction as in 1981 are also described in their answer to ESA invitation (FAST Consortium, 1981). Actually both approaches have great similarities and we shall describe the present lines of thought of FAST consortium, but indicating on what points other options have been or may have been taken.

The general approach is to handle the data reduction in three quasi independent steps. This three step procedure has been first proposed by Lindegren (unpublished, 1976) and is constantly used for accuracy assessments.

1st step: Reduction of all the data collected during several successive rotations of the satellite and determination of the abcissae of the projection of observed stars on a *fixed* 'reference great circle' (or R.G.C.) approximating the mean path of the fields of view.

2nd step: The sphere reference system is constructed from the results of all the R.G.C.'s. Some star positions or fiducial points on the R.G.C.'s being considered as primary unknowns, they are globally determined using the fact that stars will have been observed in the mean on at least 30 different R.G.C.'s, generally more. This provides a consistent reference on all great circles in form of origins to, and possibly scale variations along, reference great circles.

3rd step: Back substitution of these results into the abcissae on R.G.C.'s gives the actual consistent abcissae of stars on every R.G.C. on which they have been observed. Grouping the results for a given star, one solves for the position, proper motion and parallax.

This very rough sketch of the reduction procedure is not sufficient to give an idea of the complexity and the heaviness of the actual work. This difficulty is illustrated by the fact that only the preparation of the reduction represents between one and three hundred man years of work in which are involved many scientists (astronomers, geodesists, applied mathematicians, system control specialists, etc.) as well as engineers and technicians. This is why we shall give a somewhat more detailed picture of the HIPPARCOS data reduction method, including two other steps that are to be executed before starting the actual ‘3 steps’ procedure or that are intermingled in various iterations.

(a) *A Posteriori Attitude Reconstitution*

During the 5 to 10 hr of the duration of the observations relative to one R.G.C., the instantaneous observing plane may depart from the reference circle Σ by about two degrees. The geometry between the positions of simultaneously observed stars E_i and E_j and their projections K_i, K_j on Σ and on the instantaneous scanning circle $C_T(H_i, H_j)$ is given in Figure 16. The transformation between the angles ψ_i, ψ_j and ϕ_i, ϕ_j (representing respectively the projection on the R.G.C. and the measurable abcissae) implies the knowledge of the actual position of C_T with respect to Σ. In order that no error larger than 0″.001 be introduced in the transformation $(\phi) \rightarrow (\psi)$, it is necessary to know the parameters $I \cos \Omega$ and $I \sin \Omega$ to at least 0″.1 accuracy. This is the goal of the *a posteriori* attitude reconstitution.

The basis of this attitude determination are the star-mapper observations and the gyroscope readings. We have seen that these data are already used for the on-board attitude reconstitution and that a 1″ r.m.s. accuracy is expected. In order to achieve the necessary 0″.1 r.m.s. accuracy, one must remove the main source of error: the star positions. This means that the attitude determination will be part of a general iterative

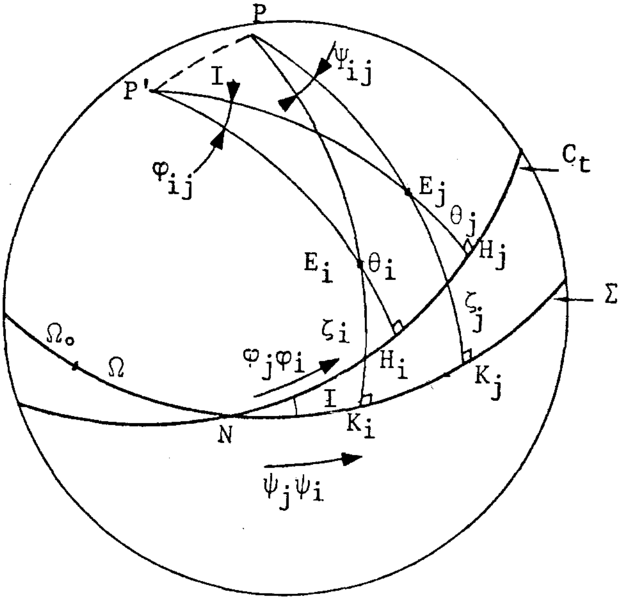

Fig. 16. Geometry of the great circle reduction. Stars E_i and E_j are observed in projection on the instantaneous great circle C and reduced on the Reference Great Circle (RGC) Σ. The attitude of the satellite provides I and Ω.

scheme. The 1″ attitude will be used to determine the star positions to a few hundredths of an arc second in a first round of the reduction. These positions will make it possible to get the attitude to the desired accuracy for the final reduction.

The star-mapper data processing uses the aperiodic structure of the two grids. The transit time estimation is based on a maximum likehood criterion applied to find the maximum of the convolution of the photon count by a suitable finite length filter characterizing the grid structure (Canuto *et al.*, 1983a).

The attitude determination is based on some kind of model of the time evolution of the satellite parameters. It has been shown by Van der Marel (1983) that three or four degree polynomials can represent the evolution of the parameters during 300 s with a precision of 0″.01, except at the times of attitude control. Such a model is the simplest that can be used for the *a posteriori* attitude reconstitution. Considering the band width of the external disturbing torques (solar radiation pressure, gravity gradient torque, and gyroscope reaction) and the presence of about one star-mapper observation every 10–30 s, its has been shown that gyroscope readings bring no information at the required level of precision (Belforte *et al.*, 1983) and that the Gauss–Markov estimation (Rao and Mitra, 1971) of the attitude should provide a final accuracy of 0″.1, possibly 0″.05.

(b) *Grid Coordinate Determination*

As we have seen in describing the observing strategy, observations are divided into frames of $T_4 = 2.133$ s. During this time several stars are observed. The role of the grid coordinate determination is to evaluate the parameters of the formula (3) describing the evolution of the photon counts:

$$I = A_0 + A_1 \cos(2\pi \nu x + v_1) + A_2 \cos(4\pi \nu x + v_2)\,. \tag{8}$$

In applying this formula, one has to interpret νx as the grid coordinate displacement from a given origin at the time t of observation. It is a function of the actual rotational speed of the satellite. Its value will be sufficiently well determined even at the first iteration of the attitude and it can be considered as constant. It has also been shown (Canuto *et al.*, 1983b), that the variance of the grid phase is uncorrelated with the grid phase estimate. The estimation may be done in two steps: a first approximation is obtained by a Fourier analysis of the photon count records, then a Gauss–Markov estimation driven by the first approximation is used (rather that the classical least squares solution that was proved to be less powerful).

At this point, several corrections are to be introduced in the solution: calibrated grid irregularities as a function of the position of the image in the field of view, the chromaticity as a function of the hopefully known colour of the star and possibly others. Furthermore, the estimated values of the parameters of (8) will be tested in order to detect if, eventually, it is a double star. In the positive case, special algorithms may be used to determine some of its characteristics (see, for instance, Delaney, 1983).

(c) *Great Circle Reduction*

This is the first step in Lindegren's procedure. The main inputs to this task are the grid coordinates and their variances frame by frame of all stars observed (currently between 30000 and 100000 quantities) and the best available attitude data. Instantaneous positions of stars corrected for aberration computed from the satellite orbital data and the ephemerides of the motion of the Earth around the barycenter of the Solar System and taken from the comparison (input) catalogue will also be provided so that only corrections to positions will be determined.

From the attitude data and the grid coordinates, the sky coordinates of every star observation will be computed, using a nominal grid to sky transformation and the corresponding 'nominal' abcissae on the R.G.C. will be deduced by simple formulae resulting from the geometric situation describe in Figure 16. Theoretically, the error in the transformation should be smaller than $0''.001$. This necessitates not only the attitude to be known to $0''.1$, but also the star position itself. This will not be available at first and it is only after a complete reduction of the data that sufficiently precise star positions can be used to eliminate the geometric transformation errors (Kovalevsky, 1980).

For every grid coordinate, one observational equation will be written. It will express that the difference of the R.G.C. abcissa ψ_0 deduced from the grid coordinate measurement and the known attitude parameters and the R.G.C. abcissa ψ_c deduced from the reference star catalogue is due to the sum of the following effects:

– The inadequacy of the grid to sky transformation. A twelve parameter formula per field of view will take case of the mechanical, thermal and other distortions of the optics. They represent the large scale field distortions that are expected to be stable to $0''.001$ in 24 hr.

– Other displacements of the images due to thermo-mechanical effects modelled as a function of on-board measurements transmitted by telemetry.

– Errors in the along-track attitude.

– Corrections to the reference position of the star, that are the actual useful results for the next phase of the reduction. Let us write symbolically the equation as:

$$\psi_0 - \psi_c = \sum A_i \alpha_i + \sum B_i \beta_i + \sum C_i \gamma_i + \sum D_i \delta_i \tag{9}$$

where the roman letters represent computed coefficients and the greek letters, the unknowns corresponding to the four types of effects.

Several methods have been proposed that differ in the way that attitude unknowns γ_i are treated.

– The purely geometrical method, equations corresponding to identical times (same frames) are associated and the attitudes are eliminated by subtraction (Lindegren, 1981). This amounts to use only angles between stars.

– Another approach to the geometrical mode is to take as independent unknowns the values of the attitude at every frame and solve for all unknowns simultaneously.

– The last approach, elaborated by FAST, is to represent the attitude by analytic formulae. The presently preferred representations are cubic spline function (Van der Marel, 1983). This approach, called Dynamical or Numerical smoothing, is based on the fact that the satellite rotation parameters are deterministic solutions of dynamical equation of motions (Pinard *et al.*, 1983) and consequently permit to link observations

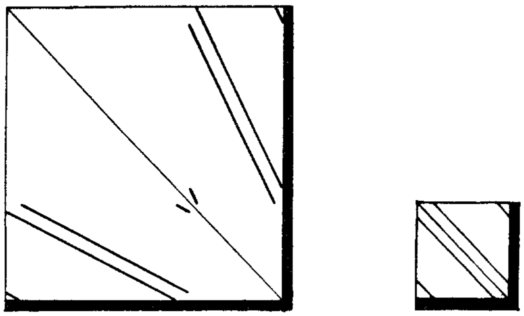

Fig. 17. Great circle reduction: structure of the normal matrix with all the unknowns (left) and after the elimination of the attitude unknowns (right).

separated by several minutes, so that they link stars not simultaneously visible in the field of view (Lacroûte, 1979, 1983). This is equivalent to a drastic increase of the width of the grid from $0\overset{\circ}{.}9$ to several degrees.

Methods of solution of the system of equation with 3000–4000 unknowns after the formation of normal equations are being studied in both data reduction Consortia (for FAST, see Van Daalen, 1983). The normal matrix is a very sparse banded matrix (see Figure 17) that can be solved by iterative methods or various decomposition methods which have been compared (Tommasini-Montareni, 1983). In particular, Cholesky decomposition (Lawson and Hanson, 1974) seems to be quite advantageous.

(d) *Sphere Reconstruction*

For every star k observed on a reference great circle Σ_i, one has obtained a longitude ψ_i^k, refered to an arbitrary origin Ω_i. The basic equation for this observation relates ψ_i^k to the value ψ_{0i}^k derived from the reference catalogue instantaneous position of the same star. The difference $\psi_i^k - \psi_{0i}^k$ is a function of the following unknown small quantities:

- error in the position at epoch, λ and β;
- error in the assumed proper motion μ_λ and μ_β;
- error in the assumed parallax ω;
- a displacement of the photocenter if the star is double;
- an error in the assumed magnitude of the forshortening effect;
- a chromaticity displacement for a star of unknown colour;
- errors in some general quantities adopted for the reduction, such as the constant of aberration;
- a displacement c_i of the origin of Σ_i.

Symbolically, let us write the equation as:

$$\psi_i^k - \psi_{0i}^k = a\delta\lambda + b\delta\beta + c(t - t0)\,\delta\mu_\lambda + d(t - t0)\,\delta\mu_\beta + e(t)\,\delta\omega + \\ + \sum_j f_j\,\delta\varepsilon_j + c_i\,. \qquad (10)$$

The first five unknowns are always present as well as general quantity errors and c_i. Those stars that are suspected to have some supplementary unknowns are called *secondary stars* and are not suitable to be used during this step. Among other stars, those for which no problem of precision has been detected in any part of the reduction, are ranked as *primary stars* and play a particular role in this stage of the reduction. Actually various proposed schemes of sphere reconstitution differ by the number and the use made of primary stars.

In the original formulation of the problem, (Lindegren, 1979), about 1000 stars are chosen as primary stars. In the corresponding equations, at a first stage all but the astrometric unknowns are eliminated, and the astrometric parameters of the primary stars are obtained. Then, after back-substitution in the complete equations, one obtains easily the corrections c_i. This approach has been extensively tested on simulated data with up to 450 stars (Hoyer *et al.*, 1981) and it was shown that the accuracy of the results obtained agrees with theoretical estimates and permits the extrapolation of the method to the full sphere.

In the FAST proposal (FAST Consortium, 1981) it was proposed to adopt a much larger number of primary stars (30000 to 40000). This approach is now also followed by NDAC. This makes it more difficult to have an a priori selection of such stars. They should all be sufficiently bright for a good signal to noise ratio ($m < 9$), they should not be double so that the photocenter be well defined in all directions nor should they be variable. A good distribution all over the sky and a good *a priori* knowledge of their position to avoid one grid step ambiguity error are also criteria for their selection. A larger list will be prepared beforehand and unsuitable or badly observed stars will be eliminated during the first iteration. In solving the equations, one would first eliminate the astrometric parameters of stars, and then compute the corrections c_i and other global unknowns.

More recently a new method has been proposed by Sansó and studied by his team (Betti *et al.*, 1983). In this approach, not only the great circles, but also their origins are fixed *a priori*. What is interpreted in the preceding methods as a shift of an origin, is considered here as a rotation of the system of stars. Consequently, the coordinate system is actually defined by the positions of stars themselves as it is the case actually in star catalogues or geodetic networks. The greater the number of stars participating in the definition, the stronger is the final solution. The main difficulty of this approach is that it leads to the solution of a normal matrix of dimensions $5N$ where N is the number of stars. Rigidity studies have shown that one should have $N > 2800$. A choice of $N = 5000$ to 6000 seems to be a reasonable compromise without coming up against unmanageable matrix inversions, the limit of which is presently set to 30000 or 40000. However, it appears that even $N = 6000$ is not sufficient to permit an optimal distribution of stars throughout the sky. This is why it is proposed to divide the primary stars into 6 to 8 groups of some 5000 stars and then to make an adjustment between the solutions using some common stars and the numerous observational equations linking stars belonging to different groups.

Finally, it must be remarked that, whatever is the chosen method, the problem has a rank deficiency of order 6. Physically, it can be represented by an arbitrary rotation $\mathbf{R}$ of the coordinate system and an uniform time dependent rotation $\dot{\mathbf{R}}$. The determination of these quantities will be discussed in Section 8.

(e) *Astrometric Parameter Determination*

In two of the three methods described above, the astrometric parameters of primary stars are determined during the sphere reconstitution process. For the other stars (or for all of them), this determination passes through the computation of new star abcissae on great circles using the parameters (origins or positions of reference stars) determined during the sphere reconstitution task. For every star, as many equations (10) as there are R.G.C.'s on which it has been observed are written and solved by least squares method. It would be a very straight-forward computation if errors of an integer number of grid steps did not occur in some observations, introduced by a poor *a priori* knowledge of the star position during the grid coordinate determination. Special algorithms to detect and correct this error at this stage have been set up (Walter, 1983). Also at this stage, the results of the examination of double star observations selected at the grid coordinate determination level will be introduced to constrain the corresponding unknowns in (10).

However, the most delicate and time-consuming task in this step will be the examination and the evaluation of the results. From various independent data (best ground based parallaxes, statistical behaviour of stellar groups, VLBI observations of radio-stars, etc.) the credibility of the results should be assessed and, possibly, some blunders discovered.

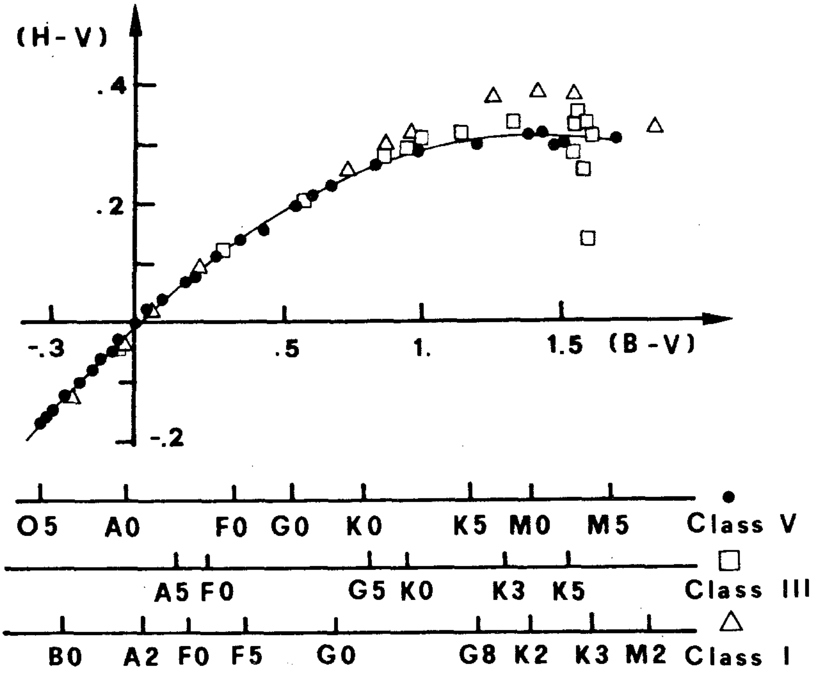

Fig. 18. Relation between the Hipparcos magnitudes and B and V magnitudes for various types of stars (Granès and Mignard, 1983).

(f) *Magnitudes*

In addition to the phase information, the modulation curve has also an intensity information that can be interpreted in terms of magnitudes. The spectral transmission of HIPPARCOS is a wide band ranging from 390 to 750 nm centered at approximately 530 nm. It is therefore wider that the B and V filters of UBV photometry. It defines a 'Hipparcos magnitude scale' that will be the result of the photometric reduction of HIPPARCOS. From spectral distribution of theoretical models of stellar atmospheres (Kurucz, 1979) or the observed fluxes of late type stars (Straizys and Sviderskine, 1972), the relationship between B, V, and H shown in Figure 18 has been obtained by Granès and Mignard (1983). It is expected that the accuracy of a mean magnitude determination from a single crossing of the field of view could be of the order of 1% of the total flux up to magnitude 9, provided that accurate calibration could be periodically made on stars of well known spectral distribution of fluxes. Variability should also be detected since every star will be observed in about 200 fields of view separated by at least 20 min. The results for variable stars will be given at each epoch of observation in the final catalogue.

(g) *Iterations*

As we have seen, several iterations will be needed in order to update the star positions in the first steps of the reduction. Furthermore, intermediate results will be very useful for discovering possible flaws in the reduction (even if, as it is the foreseen by FAST, a year of mission should be simulated before the launch). A logical design of the iterations and data complementations leading to 7 successive catalogues has been adopted for FAST (Kovalevsky, 1983).

5.7. ERROR BUDGET

The expected errors of the HIPPARCOS catalogue result from the following System Requirements (ESA, 1982a):

(a) For stars of magnitudes $B = 9$, color index $B - V = 0.5$, r.m.s. errors over the whole sky shall be less than:

- 0.″002 for the parallaxes and each component of the positions,
- 0.″002/year for each component of the proper motion.

This assumes a total observing time of 600 s per star and a $2\frac{1}{2}$ year mission.

(b) For the whole range of colour indices $-0.25 < B - V < 1.25$, the r.m.s. errors shall not be more than 30% larger than the ones quoted in (a) for the same magnitude $B = 9$.

(c) For stars of magnitude $B = 12$, the r.m.s. errors as a function of $B - V$ shall not be more than a factor of 2 larger than those quoted above assuming a total observing time of 1500 s.

A large number of simulations and accuracy analyses have been performed by ESA, by MESH (Bouffard and Zeis, 1983) or the scientific consortia. They tend to agree that the present design of the satellite and its payload do permit the above mentioned accuracies to be reached using a straightforward (geometric) reduction procedure, independent of possible improvements introduced in the computations by the scientific consortia (such as dynamical smoothing). This leaves a good margin for the above requirements to be met.

In the error assessment the first and most important factor is the estimation of the precision with which the RCC abcissae are determined in the great circle reduction.

The main cause of error is the photon noise. For a $B = 9$ star with $B - V = 0.5$, the Cramer–Rao bound is 0″.0075 for an observation during a frame of 2.13 s. The r.m.s. error due to jitter is estimated to be 0″.002 and the field to grid transformation, including the grid irregularities and the uncertainties in the stability of the correction has an r.m.s. error of 0″.0028 to which one has to add the chromaticity error if the color of the star is not known. Table II, taken from Bouffard and Zeis (1983), gives the star abcissa expected error ε on a great circle with a mean observing time corresponding to the conditions stated in the requirements.

TABLE II

Star abcissa expected r.m.s. error

	$B = 9$	$B = 12$
$B - V = -0.25$	0″.0063	0″.0115
$B - V = +0.5$	0″.0060	0″.0100
$B - V = +1.25$	0″.0058	0″.0085

Taking the mean value $B - V = 0.5$, this table can be extended to all magnitudes using the global observing time given in Figure 11. It is given in Figure 19, assuming known the colour of the star (the contribution of chromaticity to the error budget is significant only for bright stars, the colour of which will be known).

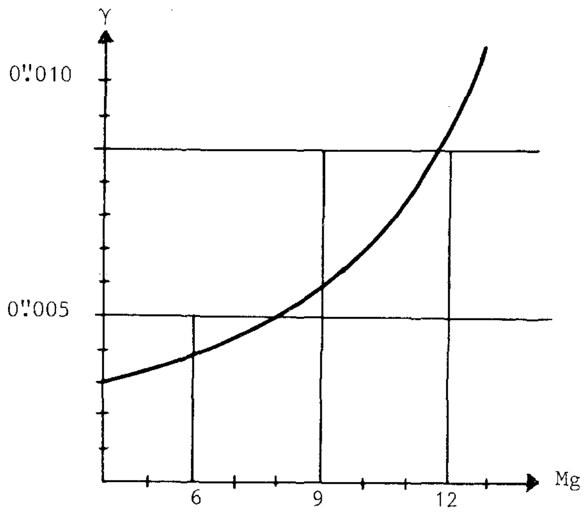

Fig. 19. Mean estimated error γ on the abcissae on a reference great circle in function of magnitude.

In order to assess the final precision of the astrometric parameters, it is necessary to simulate the mean number of observations during the mission and the direction of all great circles passing through a given star, taking into account dead time. Some algorithm giving the transformation of the variances through the sphere reconstitution procedure has to be also assumed. Results obtained by various people being quite analogous, we present the results obtained in CERGA. Figure 20 gives the coefficients of improvement k for the final position in ecliptic coordinates (β, $\lambda \cos \beta$) and parallax. The effect of the anisotropy of the scanning law clearly appears in this figure. The actual expected r.m.s. error η for a given type of star is given by

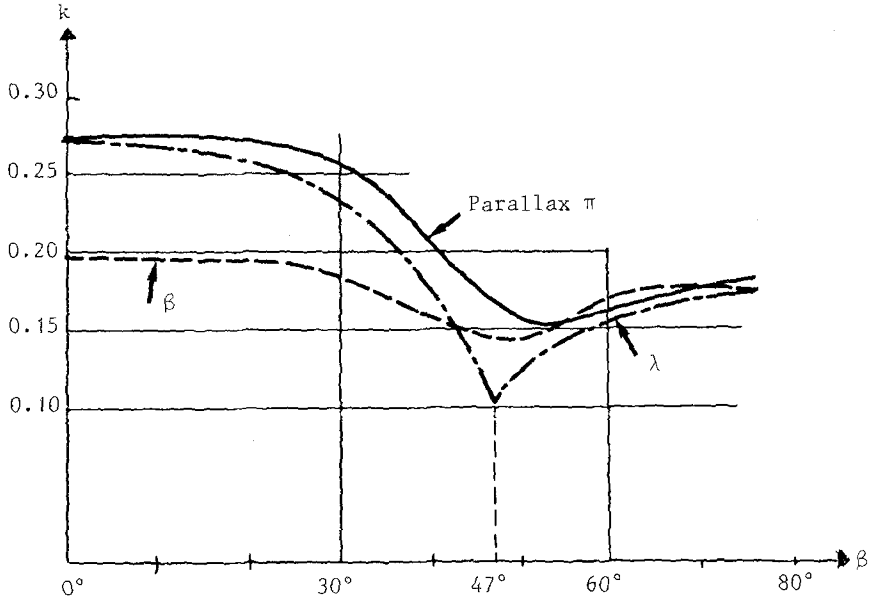

Fig. 20. Coefficients of improvement k deduced from the nominal scanning law in parallax and the position of stars in function of their ecliptic latitude.

$$\eta = \gamma k ,$$

where γ is taken in Figure 19 and k in Figure 20. To assess the precision in proper motion, one may use

$$k(\mu_{\lambda \cos \beta}) = 1.23 k(\lambda \cos \beta) ,$$

$$k(\mu_\beta) = 1.35 k(\beta) .$$

In particular, for $B = 9$ the specifications are met with a margin of at least 10%, the worst case being the proper motion in ecliptic longitude. The specifications are met with even greater margin for fainter stars.

5.8. THE INPUT CATALOGUE

The choice of stars to be included in the HIPPARCOS program is a very delicate task since it has to comply with several sometimes contradictory requirements dictated by the reduction procedures and the 2 milli arc sec overall accuracy objective. The basic constraints can be summarized as follows:

– The number of stars should be of the order of 100 000, the accuracy assessment being based on a mean number of two stars per instantaneous field of view ($0\overset{\circ}{.}9 \times 0\overset{\circ}{.}9$).

– The proportion of faint stars should not be significantly larger than the one given in Table I. Otherwise the observing time allocated to brighter stars would be severely reduced at the sacrifice of the accuracy and the rigidity of the great circle solution.

– The repartition of stars should be the closest possible to a regular distribution over the sky.

In addition, since for the first time we shall have a fully consistent global system of proper motions, it would be a serious error to introduce statistical biases in the distribution of stars. This means that a very clear definition should exist of the completeness limits of the catalogue, for instance the limiting magnitude as a function of galactic latitude.

Last, but not least, it should include a maximum number of stars of astrophysical interest for which the accurate determination of at least one of the astrometric parameters would have a significant scientific value. ESA has issued in 1981 a call for all astronomers to propose lists of stars to be included in the program. A scientific committee, under the leadership of A. Blaauw, has rated more than 200 proposals received from the worldwide scientific community and has often opened a dialogue with proposers for improvements or reductions of the lists. About 770 000 stars were at first proposed. Although many of them are redundant requests, there are more than 200 000 different stars among them.

The task to choose among them the program stars and to complete the retained stars by supplementary ones in order to comply with the constraints is only a part of the job to be completed to constitute the so-called 'input catalogue'. An approximate position must be given with a maximum error of $0\overset{''}{.}4$ for as many stars as possible to avoid the grid step errors. At least 56 000 star-mapper stars must have positions accurate to $1''$ and for others, an r.m.s. position of $1\overset{''}{.}5$ is required. For all the chosen stars, the present knowledge about duplicity and variability must be collected. Magnitudes of all stars should be given and colour indices to about 0.2 magnitude are requested for as many stars as possible for which the chromaticity error is a significant part of the error budget (mag. < 10). A large part of the requested data already exists in particular in the 'Centre de données stellaires' in Strasbourg. It is still necessary to compile and cross-check it. But still quite a sizeable quantity of data does not exist and a large number of ground based observations have to be performed before 1987.

All these tasks have been entrusted by ESA to the scientific consortium INCA (Input Catalogue) led by Catherine Turon (Meudon Observatory) and including 26 teams of the following countries: Argentina, Austria, Belgium, France, Germany (Federal

Republic), Netherlands, Spain, Switzerland, United Kingdom, and U.S.A. The description of the work to be done by INCA can be found in Turon (1981, 1982a, and b).

Most of the teams involved the INCA will dedicate themselves to the acquisition of new data and the compilation of the existing ones. In addition, the specific task to compile the catalogue itself necessitates a complete simulation of the mission. Its aim is, given a tentative Input Catalogue and local and global observing strategies, to check that the scientific objectives can actually be reached or to measure its degree of fulfilment as well as the compliance with the basic constraints. The evaluation of successive versions of the Input Catalogue will guide optimal integration of candidate stars and a progressive improvement of the global strategy.

5.9. SCIENTIFIC OBJECTIVES

The main a priori scientific objectives have been globally described in the phase A study (ESA, 1979) and a list of possible studies can be found in Kovalevsky (1979). Now that more than 200 proposals for observation have been received, it is possible to have a more exact view about how astronomers expect to use HIPPARCOS data in the light of the present state of the art. They are all based on the use of the major improvement of parallaxes and proper motions in comparison with the present situation described in Section 2: 100 times more significant parallaxes at the 0″.002 level accuracy and extension of the 4000 stars of the FK5 in a consistent system of 100000 stars.

Dividing rather arbitrarily the domains of research using HIPPAROS into ten categories, all proposals received fall into one or several of them. Let us list them with a selection of the proposed objectives.

(a) *Solar System*

- New reduction of fundamental observations (Earth rotation, lunar occultation, etc.) using better star positions and their use for future ground based observations.
- Positions of reference stars for improving the knowledge of the motion of asteroids, of Pluto, etc., in particular for a dynamical reference system (see Section 8).
- Preparation or reduction of stellar occultations by asteroids, planets or satellites.

(b) *Stellar Absolute Luminosities*

- Absolute luminosities of different types of stars (e.g. carbon stars, binaries, subdwarfs, T Tauri, RR Lyrae, and Cepheids, faint early type stars, Wolf–Rayet, etc.).
- Fine structure of the HR diagram for F, G, and K stars.
- Luminosity function.
- Study of subdwarfs.
- etc.

(c) *Stellar Masses*

It is expected that the number of stellar masses from binaries might be increased by at least a factor of 10. This will be achieved by improving the parallaxes of visual or spectroscopic binaries with well determined orbital elements.

(d) *Stellar Evolution*

- Study of types of stars that may have a key position in the evolutionary path (hot subdwarfs, δ Scuti variables, Wolf–Rayet, T Tauri, close binaries, Mira, white dwarfs, carbon stars, etc.).
- Stars with chemical peculiarities.
- Evolution of late type dwarfs.
- Evolution of pre-Main Sequence stars.
- Young stars.
- Population II dwarf stars.
- Subgiant stars.
- 'Normal stars' of various types and classes.
- etc.

(e) *Double and Multiple Stars*

- Physical structure of eclipsing binaries.
- Trapezium type stars.
- Cataclysmic variables.
- Symbiotic stars.
- Statistical studies on binary systems.
- etc.

(f) *Variability*

- Search for new variables from the magnitude observations.
- Physical conditions in various types of variable stars (δ Scuti, flare stars, cataclysmic variables, pulsating variable stars, etc.).

(g) *Clusters*

- Dynamic study of the Haydes for which a 3-dimensional view may be obtained.
- Kinematics and distance of open clusters (Pleiades, Coma Berenices, etc.).
- Structure and evolution of stellar associations.

(h) *Galactic Structure*

Most of the proposed studies have a statistical character and request the inclusion of a large number of stars in the catalogue.

- Oort constants and the rotation of the Galaxy.
- Proper motions in the Magellanic clouds.
- Halo stars and stars of intermediate class.
- High galactic latitude stars.
- High velocity stars.
- Local Gould's belt system.
- Kinematic properties of metal deficient stars.
- Eggen's moving groups.

- Ealry type stars for galactic structure.
- Birth places of stars.
- Stellar velocity distribution.
- Kinematics of stars and chemical composition.
- Local density in the Galaxy.

(i) *Distance Scale*

The cosmic distance scale will be re-calibrated from the HIPPARCOS accurate parallaxes.

- Calibration of Cepheids and RR Lyrae.
- Comparison of HIPPARCOS and ground based parallaxes.
- Distances to planetary nebulae.
- Calibration of several typical types of stars.
- Calibration of Hyades stars.

(j) *Reference Frames*

Establising links of HIPPARCOS reference frame with other systems (see also Section 8).

- FK5 stars.
- Radio-stars.
- Observation of minor planets.
- Stars near quasars.

This selection of objectives does not pretend to be exhaustive nor to show some indication of relative importance. It is only a sample of the multiple applications of HIPPARCOS catalogue to Astronomy and Astrophysics.

6. TYCHO

A very fruitful addition to the original HIPPARCOS design was made at the suggestion of E. Høg when ESA accepted to record systematically all the star-mapper data, introducing a possibility of a survey type of observation in addition to the active astrometric measurements of the main mission. This proposal involved some modifications to the original structure of the relay optics permitting the observation in two colors. They are now part of the HIPPARCOS payload.

6.1. DESCRIPTION

The aim of TYCHO is to measure the positions and magnitudes in two colors of at least 400000 stars brighter than the 11th magnitude (Høg *et al.*, 1982). For this, the light outgoing from the star-mapper grid is directed towards a dichroic filter centered approximately at 520 nm. The blue reflected and the red transmitted beams are sent to two photomultipliers (Figure 21). The spectral distribution of light in each channel is not yet completely defined, but they will be rather close to the B and V filters of the UBV system.

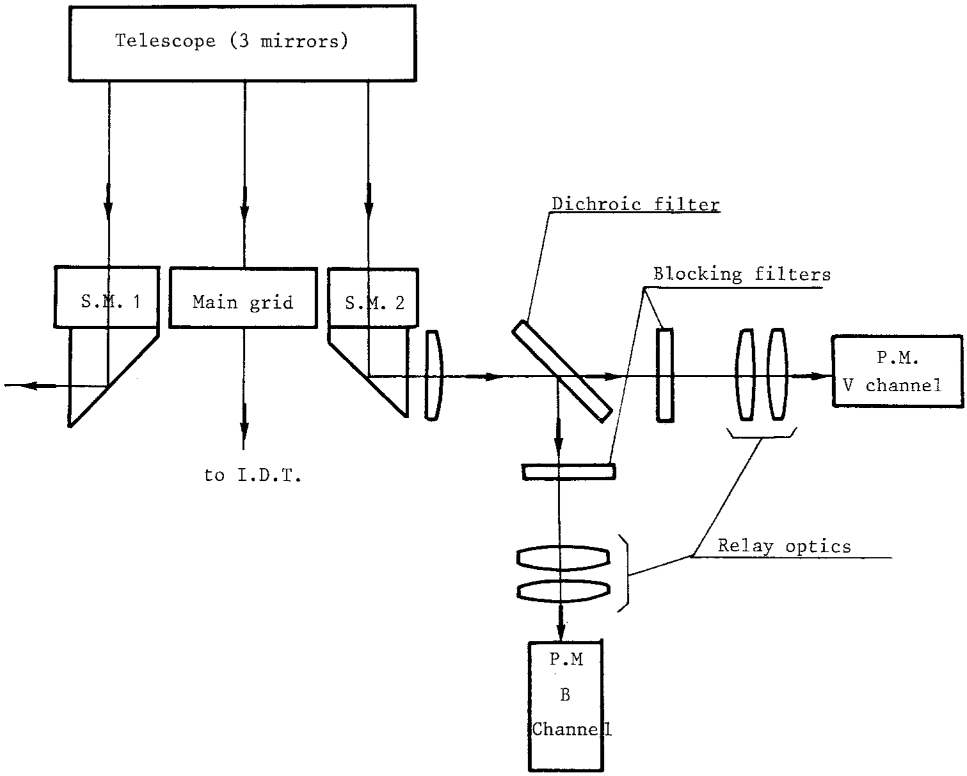

Fig. 21. Star-mapper optical diagram.

The sampling rate is 600 Hz in each colour. The combined counts will be used for the determination of the time of crossing of the grids by a star, while, for the magnitude determinations, they will be used separately.

6.2. OBSERVATIONS AND DATA REDUCTION

The photomultipliers will remain open during the entire mission except during the dead time due to illumination by the Earth and the Moon. Consequently all stars scanned by the 40′ wide grids will provide photometric signals. It is estimated that possibly 1500000 to 2000000 stars will produce detectable signals.

The reduction of the TYCHO data has been entrusted by ESA to a consortium headed by M. Grewing (Tübingen) including several teams already belonging to one or other consortia (NDAC, FAST, INCA) and some other Institutes, including the Space Telescope Science Institute in the U.S.A.

The complete analysis of the entire TYCHO data appears to be very problematical: it would be necessary to relate signals produced by the same star all over the duration of the mission and this would mean a considerable amount of computing time to make the cross-correlations if the positions of the stars are not known *a priori*. This is why it is currently foreesen to reduce only the data on stars for which an input catalogue will be provided. The Space Telescope Science Institute being involved in constructing a very dense catalogue of star positions for the guiding system of Space Telescope, TYCHO will benefit from this all-sky survey and the TYCHO input catalogue will then be constructed in cooperation with the Space Telescope Guide Star selection team in Baltimore and the Centre de Données Stellaires in Strasbourg. It will contain at least 400 000 stars, hopefully significantly more.

The astrometric reduction follows the same scheme as the star-mapper reduction for HIPPARCOS except that the accurate attitude of the satellite will be provided by the HIPPARCOS data reduction consortia and the unknown will be the position of the star on the sky. The methods to be used are described in the proposal of the TYCHO Consortium to ESA (Høg and Mauder, 1982). Pieces of the star-mapper records are picked out from the data flow using the Input Catalogue and the attitude. The selected records are filtered as described for HIPPARCOS (Section 5.6(a)) and this gives the desired positional information. All the information collected on a given star is then treated globally in order to determine the position of the star.

The two colour records are also treated for the magnitude of the signal in order to deduce – using the results of calibration like in the photometric reduction of HIPPARCOS – the instantaneous magnitudes in each of the two colours. Let us remark, in addition, that this photometric reduction, if made in time, could help the main mission in reducing the chromaticity error, and this has been included in both data reduction consortia plans.

6.3. EXPECTED PRECISION AND SCIENTIFIC OBJECTIVES

The accuracy of the final positions deduced from all the star-mapper crossings should be of the order of (Bouffard and Zeis, 1983):

$$0''.03 \text{ for stars of } \frac{B+V}{2} = 8.7,$$

$$0''.06 \text{ for stars of } \frac{B+V}{2} = 9.7,$$

$$0''.15 \text{ for stars of } \frac{B+V}{2} = 10.7,$$

The magnitude accuracy for non variable stars are given in Table III for a single star-mapper crossing.

On can see that, even for magnitudes up to 10.7, the astrometric accuracies compete favourably with Earth based astrometry and will constitute a remarkable first (or second) epoch observation for a very large general catalogue covering the sky. As for HIPPARCOS, it is expected that these positions will be consistent and free of regional errors. They will actually be in the HIPPARCOS system. Combined with the existing AGK2 and Cape Catalogues made in 1930 a system of proper motion of about 300 000 stars may be constructed with accuracies of about 0''.003 per year that would

TABLE III

Errors in magnitude for a single star-mapper crossing

$\frac{B+V}{2}$	8.7			9.7			10.7		
$B-V$	0	0.7	1.5	0	0.7	1.5	0	0.7	1.5
Error on B_{TYCHO}	0.07	0.08	0.10	0.12	0.15	0.18	0.24	0.30	0.37
Error on V_{TYCHO}	0.12	0.10	0.08	0.25	0.21	0.14	0.5	0.4	0.3

be a very good complement to HIPPARCOS even if the regional errors of the first epoch catalogues will not be removed.

The photometric results for the 400 000 stars will also constitute a remarkable capital of observations since presently no more that 70 000 stars have *UBV* photometry which is not fully consistent. A great number of variable stars will also be detected and measured at many times. So the photometric expectations of what was essentially devised as an astrometric mission are quite considerable and have enhanced the overall importance of the TYCHO addition to the HIPPARCOS satellite.

7. Space Telescope

7.1. ASTROMETRY WITH SPACE TELESCOPE

Space Telescope is the most powerful, but also the most versatile instrument for astronomy. So, among its great variety of possible functions, astrometry has not been neglected. It is actually a very powerful instrument for narrow field astrometry and it will also contribute to very narrow field astrometry. Four out of its six on-board instruments may use for astrometric purposes the excellent Ritchey–Chrétien optical design of the 2.4 m telescope.

Astrometric properties of the Space Telescope follow from the properties of the Ritchey–Chrétien configuration. At 6.33 nm, 70% of the total image energy is encircled within $0\overset{''}{.}1$ (O'Dell, 1982). It is coma free all over the 14′ radius useful field, but has significant astigmatism in its outer portions (O'Dell, 1981): the diameter of the circle of least confusion increases from $0\overset{''}{.}08$ to $0\overset{''}{.}32$ at 10′. However, the image remains centered, so that this is not a major nuisance for astrometric use of the outer parts of the focal surface. The focal plane is divided into sections dedicated to different instruments as shown in Figure 22.

Some of the limitations described in detail for HIPPARCOS are also present in the Space Telescope. Straylight control is more stringent because very faint objects are to be observed. It is limited to an illumination equivalent to the darkest part of the zodiacal cloud. No observations will be made at less than 50° from the Sun, 15° from the Moon and 70° from the bright limb of the Earth. This, together with the low orbit of the satellite, may limit drastically the continuous exposure times over a given region.

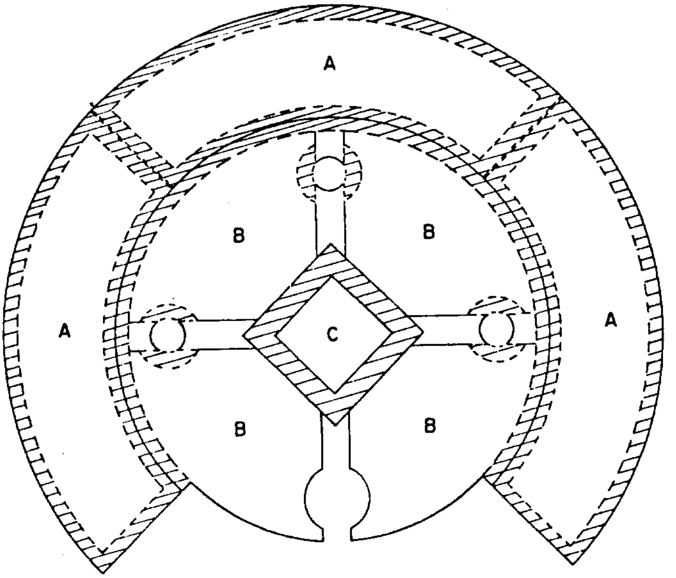

Fig. 22. Focal plane of the Space Telescope: (A) FGS field of view. (B) Axial Scientific Instrument fields. (C) Wide Field Camera field.

The other important limitation for astrometry is jitter. Spece Telescope attitude has to be controlled by inertial wheels and the jet gas solution retained for HIPPARCOS could not be adapted for 0″.01 or better pointing accuracy. Consequently, and despite the large inertia of the satellite, the mean jitter is estimated to 0″.007 and certainly represents the ultimate limiting factor for astrometric accuracy.

Three types of astrometric activities will exist in Space Telescope. Let us describe them.

(a) *Imaging*

The two cameras of the Space Telescope are capable of doing same kind of small field astrometry as the long focus photography on the ground.

The Wide Field/Planetary Camera uses the central part of the field of view, the part that has no astigmatism. The most favourable mode for astrometry is the *f*/30 imaging on the four planetary 800 × 800 pixel CCD outputs covering a field of 68″ × 68″ (Westphal, 1982). The corresponding resolving power is 0″.05. This leads to a possible precision of the order of 0″.02 in determining relative positions. This is comparable with the best Earth based photographs, but of course with a gain of at least 10 mag.

The Faint Object Camera is one of the axial instruments. The imaging at *f*/96 can exploit the diffraction limited angular resolution of 0″.066 at 633 nm and 0″.013 at 125 nm. There exists also an imaging capability at *f*/288 giving a pixel size of 0″.007 (corresponding to the jitter r.m.s. errors) in a field of 7″.5 × 7″.5 (Macchetto, 1982). This is already what we called very narrow field astrometry, but in a domain of magnitudes and separations that is not accessible to Earth based techniques. Using the coronograph occulting mask, the Faint Object Camera can for instance make important contributions in the direct search for stellar planetary companions of very faint magnitudes.

Actually both cameras are in some respect complementary. When they will be used for relative positioning of faint stars, they will bring significant contribution to faint object astrometry that is impossible to do from the ground.

(b) *Lunar Occultations*

We have seen that, from the ground, photometric observations of occultations of stars by the Moon provide very accurate determinations of stellar diameters. Similar possibility is offered in the Space Telescope by the High Speed Photometer. The relative motion of the satellite and the Moon is such that, twice during each orbit, the Moon appears to be nearly stationary with respect to the celestial sphere. At that times, objects will be occulted much more slowly than if they were viewed from the ground (Bless, 1982) enabling them to be observed at a higher signal-to-noise ratio.

(c) *Use of Fine Guidance Sensors*

Three Fine Guidance Sensors (FGS) are placed on the Space Telescope and each of them uses a 90° sector of the outer portion of the focal plane (Figure 22) representing about 70 square arc-minute field of view. During every observing sequence, two of the three systems are used to control the pointing of telescope, while the third is available for operation in the astrometric mode.

The design of a FGS is given in Figure 23. The descriptions published in the open

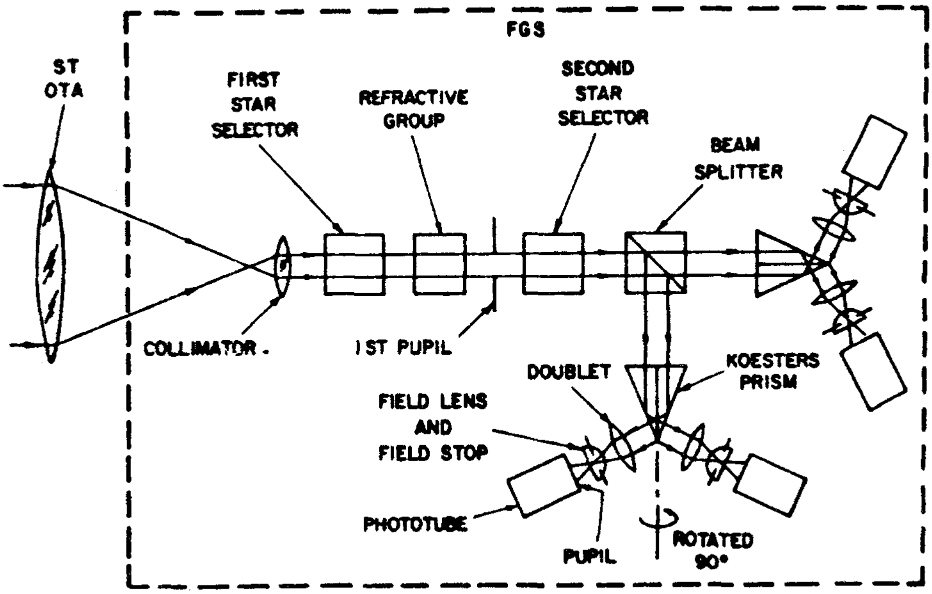

Fig. 23. Schematic design of a Fine Guidance Sensor.

litterature are rather succint (see Jeffreys, 1978, 1980; Van Altena, 1979; Duncombe *et al.*, 1982). The light coming from the telescope and the relay optics crosses two star selectors, one along each axis. A star selector is composed of a system of rotating mirrors that can bring the image of any star in the field of view of the detectors. A refractive group, placed between the star selectors corrects the image for off-axis aberrations. A beam splitter directs the light into two Koester's prism interferometers, one for each coordinate.

If an object is exactly on the axis of an interferometer, the signal from each of the two photomultipliers will be equal. If the object is off-axis, the signals are not equal and the difference creates a non-zero error signal that is used to measure how far the object is from the axis and to reposition the star selectors bringing the image of the object back onto the interferometer axis and the procedure is repeated until a zero signal is recorded on both interferometers. Let us call θ_A and θ_B the angular displacements measured by the encoders of the star selectors when the star is brought approximately in the 3 arc sec square aperture of the interferometers. Let $\Delta\theta_A$ and $\Delta\theta_B$ be the rotations of the star-selectors recorded during the final repositioning phase. The actual positioning defined by $\theta_A + \Delta\theta_A$ and $\theta_B + \Delta\theta_B$ gives the position of the star with respect to the origin of the field defined by the zero markings of the star selector encoders. Several objects may be measured similarly while the telescope is directed towards the same point.

The specifications are that the relative positions of two stars of magnitudes between 10 and 17 will be measured with a precision of $\pm 0\overset{''}{.}002$ at a rate of about one star per minute. Filters will actually permit the magnitude range to be extended by another 4 magnitudes. But the actual accuracy of the astrometric results will depend upon at least two other factors:

– The stability of the telescope pointing during the observing session. While the other two FGS ensure the stability of the position of two stars within their respective fields to $\pm 0\overset{''}{.}002$, the jitter amplitude of $0\overset{''}{.}007$ introduces a positional noise of the same order of magnitude, the effect of which on the astrometric measurement will have to be assessed.

– The whole three fields of the FGS's must be calibrated: the relationship between the measurements of the angles θ and the actual position of a star image should be determined thoughout the 18′ fields to better than $0\overset{''}{.}002$. The main difficulty of this calibration is that no stellar field is actually known with such a precision. The technique presently envisaged (Duncombe *et al.*, 1982) is to determine the field distortions using the same stellar configuration observed in various parts of the field. Overlapping field astrometric techniques will provide the field distortions within a scale factor. The later may be determined with the $0\overset{''}{.}002$ accuracy using an asteroid (Hemenway, 1978).

So, presently, it is difficult to assess very precisely what will be the accuracy of the astrometric measurements by the FGS. It seems reasonable to estimate it to lie between $0\overset{''}{.}002$ and $0\overset{''}{.}004$.

It is important to note, that FGS can also be used in two other modes:

– In the *moving target mode*, the interferometers lock the FGS on the objects, while the readings of the encoders are periodically sampled, providing the data for recovering the path of the object through the field of view.

– In the *multiple star mode*, the target object is moved across the aperture of the interferometers, and the error signal is sampled. The analysis of the instrumental transfer function so obtained will permit duplicity of stars to be detected and the separation between the companions to be measured to a few milliarc second accuracy.

7.2. SCIENTIFIC POSSIBILITIES

The scientific objectives of the astrometric measurements by various instruments on board of Space Telescope cover practically all the goals of the narrow and very narrow field astrometry.

As far as the second type of astrometry is concerned, the observations of stellar diameters by occultations using the High Speed Photometer or of double stars by the multiple star mode of FGS will yield results of the same order of magnitude of precision as the ground based interferometry and stellar occultations by the Moon. But the gain in magnitude is considerable: 5 to 10 at least. This will permit a larger number of new objects and new types of objects to be measured. More specifically, double stars in the range of 0″.03–0″.2 separation are difficult to observe from the ground, so that selected objects important for mass determinations, will constitute objectives of primary importance for Space Telescope. Actually, if a double star is in the field of view of the free FGS when the telescope is pointed to a region to be studied by other instruments, it would be possible to measure it independently of any specific program, only for statistical purposes.

The main results to be expected from Space Telescope are, however, in the domain of narrow field astrometry. Relative parallaxes of stars will become measurable to a precision of about 0″.001 for stars of magnitude 10 to 17. This is a domain of magnitudes that is essentially complementary to the domain of HIPPARCOS, so that stars of different types – and especially faint stars such as M dwarfs or white dwarfs and other sub Main-Sequence objects will be particularly important to observe with the FGS. Also, since the observations can be extended over many years, this will be the ideal instrument in the search for unseen companions of nearby stars.

The fact that parallaxes will be relative is less of a problem than in the case of ground based parallax research, since one may choose much fainter – and consequently, in the mean, farther – reference stars. The correction needed to get absolute parallaxes will be smaller. It is also to be noted that HIPPARCOS will hopefully provide a better photometric and spectroscopic mean parallax system to compute this correction.

Another application of Space Telescope (and probably more the Wide Field Camera than FGS) is a detailed kinematic study of open clusters. The precision achieved will be better than from ground based photography and, overall, faint stars will be included in the observations, permitting much more realistic dynamical studies of the clusters.

Finally any astronomical objective, where very accurate relative positions and proper motions are required in a given small field, will gain enormously from observations by Space Telescope. A striking example of such a possibility will be described in the next chapter.

8. Establishment of an Absolute Reference Frame

As we have seen, the fundamental objective of global Astrometry is to construct an absolute – or fixed – reference system. We have described the flaws of the present systems derived from ground based observations. We have also seen that HIPPARCOS will provide a very consistent system of star coordinates, essentially without regional errors, but a residual rotation may remain undetected. Fortunately, the combination of several space and ground based observations will permit this problem to be solved.

Several methods can be proposed to link the HIPPARCOS system to an absolute reference frame (Kovelevsky, 1981) and actually there are plans to use the following four.

8.1. DYNAMICAL METHOD

The bodies proposed for the method are asteroids. The small bodies of the solar system have an almost point-like image and their observation gives an accuracy equivalent of that of stellar observations. About 20 to 30 asteroids of magnitudes 8 to 12 will be observed by HIPPARCOS. Simulations made by Söderhjelm and Lindegren (1982) have shown that the $2\frac{1}{2}$ years of observations may be sufficient to find the necessary rotation of the HIPPARCOS system to an accuracy of $0\overset{''}{.}001$ per year around axes in the ecliptic plane and $0\overset{''}{.}004$ per year around the poles of the ecliptic.

This would be a satisfactory but not quite sufficient result. Actually, rather discouraging results of many attempts made earlier in this direction (see Kovalevsky, 1982a) throw some doubts on this method applied on such a short interval of time. This drawback is eliminated by the proposal by Hemenway (1980), where HIPPARCOS stars are used only as references near crossing points of asteroidal apparent paths. The relative positions of the minor planet and the star being observed by long focus astrometry, the HIPPARCOS accuracy can then be spread over a much longer time.

8.2. LINK TO THE FK5 SYSTEM

This link will be made by both HIPPARCOS data reduction consortia. A possible method is the one already used in synthesizing a catalogue from several others (Röser, 1983), while the comparison of FK5 with HIPPARCOS will show the regional errors of the FK5 by a method devised by Bien *et al.* (1978).

8.3. LINK TO THE VLBI SYSTEM

We have seen (Section 2.5) that the VLBI reference system will soon become the best realization of an absolute system. The most direct way of linking with HIPPARCOS is to use objects common to VLBI and HIPPARCOS systems. Since quasars are too faint to be observed by HIPPARCOS (with the only exception of 3C–273), only radio emitting bright stars can be used. Several lists of such stars have been set up for observation by HIPPARCOS. The best candidates seem to be non thermal emittors, especially RS CVn binaries (see Hall, 1975). Important radio emissions occur in RS CVn systems which probably originate from a gyro-synchrotron mechanism (cyclotron radiation from mildly relativistic electrons). The size of their radio-source is smaller than 2 milli arc sec as measured with VLBI for HR 5110 (Lestrade *et al.*, 1984). Stars with thermal emission seem to be insufficiently point-like for milliarc second VLBI observations.

The main difficulty in the observation of RS CVn's by VLBI is that radio-emission is weak and sporadic. However, at least 11 such radio-stars have already been detected by VLBI (Preston *et al.*, 1983; and Preston, private comm.) and it is expected that 20 or 30 should eventually be detected. Froeschlé and Kovalevsky (1982) have shown by simulation that, if ε is the angular error of VLBI observations, the r.m.s. error in the link would be of the order of:

$$\sigma = 2.5\varepsilon/\sqrt{N} \text{ per year,}$$

where N is the number of stars used. So with 15 stars or more, it is reasonable to expect to determine the rotation of the system with an error of the order of 0.″001 or better per year, at least if the present trend in the improvement of VLBI observations is confirmed.

8.4. LINK WITH QUASARS

Quasi-stellar objects that are part of the VLBI system or other point-like extragalactic objects can be linked to HIPPARCOS stars using the Space Telescope FGS described in Section 7. The relative positions of stars and quasars can be measured by ST and, after 4 or 5 years, the variations of the distance between the two objects can be determined to an accuracy of about 0.″001/year. Simulations made by Froeschlé and Kovalevsky (1982) have shown that this procedure is less efficient than the direct use of radio stars. Five such connections star-quasar yield comparable information as one radio star observed in the VLBI system. But since the number of possible radio stars is very small, the Space Telescope observations may bring a very important contribution to the final link.

Actually, since all the methods will be applied, there is a good chance that the final HIPPARCOS system will be quasi-inertial possibly to better than 0.″0005 per year.

9. Proposed Space Astrometry Projects

In addition to the already approved space astrometry missions, several other proposals have been made by various scientists. All of them refer to narrow field or very narrow field astrometry: no alternative space global astrometry project to HIPPARCOS has been proposed.

9.1. SCIENTIFIC OBJECTIVES

As for HIPPARCOS, for which a gross gain of a factor 100 in accuracy or number of stars has been the driving factor for the acceptance of the mission, the proposed local astrometry projects aim at giving at least the same factor over ground based techniques. But, since we have seen that ground based very narrow field astrometry is capable of the milliarc second accuracy if not better and that long focus astrometry precision is within 0″.01 to 0″.03, the objectives of these projects are in the 10^{-6} to 10^{-4} arc second range. The typical goals for such precise astrometric measurements are the following:

– *Search for unvisible planetary system.* A 10^{-6} arc sec detected motion would correspond to the displacement of a solar type star situated at 10 parsecs, due to a planet like the Earth at three astronomical units from its mother star. It is 500 times larger for Jupiter and 100 to 300 for other giant planets.

– *Parallaxes of very distant objects.* The trigonometric parallax of M31 is 10^{-6} arc sec. The Magellanic clouds have annual parallaxes of 10^{-5} arc sec. All detectable stars in our Galaxy have much larger parallaxes, and all these would become accessible. However, the parallaxes obtained are relative and the calibration of reference stars will be a difficult task.

– *Cluster kinematics.* Internal motions of distant clusters and some globular clusters will become accessible. In a 10 kpc distant globular cluster observed at 10^{-5} arc sec accuracy, relative proper motions may be detected with a 0.1 km s^{-1} precision.

– *Resolution of stars.* Images of stars will be attainable to the same order of resolution. A 10^{-5} resolution means the possibility to produce images with 100 × 100 pixels of a solar type star at 10 parsecs. But for most objects, the determination of the diameter with such accuracies represents already a considerable improvement with respect to the present situation.

– *Multiple stars.* The resolution increase will allow the observation of very close binary or multiple stars. The periods of such stars being short, one will be able to obtain good orbits in a few weeks or months, allowing a great number of new mass determinations. If, per chance, the pair of stars is not physically connected, the Einsteinian deflection will become measurable with an accuracy of the order of the resolution achieved.

– *Quasi stellar objects and galaxy nuclei.* With the stated resolution, it is to be expected that some quasars, galaxy nuclei or BL Lacertae objects may be resolved and possibly mapped.

Another exciting prospect is that in Space, all these measurements might be made in a much larger spectral range than from Earth (e.g. 120 nm to 10 μm in one of the proposed missions).

9.2. LONG FOCUS TELESCOPE IN SPACE

A proposal of a 16.5 m focal length 1 m aperture astrometric telescope in Space was made by G. Gatewood and a feasibility study was performed (LMSC, 1982). The focal plane would involve a split field of view, with a guiding detector for a bright central star and four quadrants each with a large CCD. The star image is formed on a moving grid that modulates the star light. The star position is retreived from the modulated signal in a similar manner as in HIPPARCOS, but all stars are modulated in the same time so that the detector must resolve the stars in the field of view. The final precision is obtained by observing a long time the same stellar field. The expected precision of 10^{-6} arc sec on position with respect to 25 field stars could be achieved in about 10 hr observation. Such an instrument would be essentially dedicated to the search of planetary systems, each of the candidate stars being observed at least 20 times.

The nominal accuracy goal is probably optimistic because of all the limitations already described for HIPPARCOS (V.5) some of which will have to be calibrated to the expected accuracy and some others to be considered as white noise and smoothed out during the long observation. And, between 10^{-3} and 10^{-6} accuracy limit, other unexpected effects may take place! In any case it is a very interesting project that should gain in taking into account the present and future experience from HIPPARCOS.

9.3. SPACE INTERFEROMETRY

The concept of Michelson interferometry is very simple to extend to Space as discussed for instance by Knowles and Thaker (1980). Two proposals have been submitted and some assessment have been made. A proposal by Shao based on Shao and Staelin (1977) has been studied for the California Space Institute (LMSC, 1982) while a proposal by Labeyrie, 1980b; Labeyrie *et al.*, 1980) has had a preliminary assessment by ESA (1982b) after a new concept of 3 independent satellites was added.

The original design proposed by Labeyrie under the name FLUTE and by Shao is a rigid structure of about 15 m with a fringe spacing of 0".007 in yellow light.

The Shao concept is essentially directed towards the search for planetary systems. Its pupil plane interferometer would have the capability of observing 4 stars simultaneously by 4 independent interferometers. The Labeyrie poject FLUTE includes only one interferometer, but other channels are associated with the field of view: the guiding system reimaging the field into a CCD sensor, a spectrograph (so that fringes appear as horizontal lines along the spectrum and permit the wavelength-dependent morphology of the star to be studied) and an infrared channel.

Both projects also greatly differ on the fringe recovery procedures. In the Shao concept some areas of the mirrors are overlaid with weak ion etched gratings used in the optical path difference measurement. In Labeyrie's concept, the guider reimages the field onto a CCD sensor through an adjustable optical delay line. The optical path difference may be zeroed on the guide star as well as on the observed object. The delay line setting is adjusted and encoded with 0.5 nm accuracy giving 0.1% of the fringe accuracy when measuring star separations.

Both projects have a 10^{-4} to 10^{-5} arc sec resolution limit. But with a very long integration time (10 min for 4 reference 15 th magnitude stars) the Shao project might reach 10^{-6} arc sec resolution.

As presented, the Shao design is much more complex and difficult than the FLUTE. But in order to achieve the 10^{-6} arc sec resolution, Labeyrie also complicates the design by allowing long variable baselines. He proposes to separate completely the two mirrors and the central fringe detector, placing them in three independent satellites (project TRIO, ESA, 1982b), In this technologically very advanced project, the attitude and the relative positions of the satellites would be controlled by radiation pressure forces and torques on a satellite surface with controllable surface properties (like liquid crystal elements). In such a concept, the baseline could be as large as several kilometers giving a basic precision of the order of 10^{-5} to 10^{-6} arc sec. Very preliminary studies of this system are being pursued in ESA.

9.4. A SECOND HIPPARCOS

The idea to launch a second HIPPARCOS 10 years after the first was in the minds of all the promoters of this project. Assuming that it would not include any improvement over the first mission, it would allow to divide by 10 the errors in proper motions: at the 10^{-4} arc sec per year level of accuracy, they would indeed represent a gain of one order of magnitude over a situation already greatly improved by HIPPARCOS I. It would mean a new considerable advance in the kinematic and dynamical environment of the Sun, of the Galaxy and of some clusters and associations.

10. Conclusions

The end of the eighties will witness the first major break through of astrometry into space. A gain of two orders of magnitude in accuracy and/or number of stars will give a completely new basis for stellar astrophysics and stellar kinematics. This new milliarc second global astrometry will be accompanied by the development of narrow and very narrow field strometry in the same accuracy brackets by space as well as ground based techniques. Later, possibly at the turn of the century, some new gain may be expected in global astrometry if a new mission is decided. But, more probably, the very narrow and the narrow field astrometry will also enter space and reach the 10^{-5} or 10^{-6} arc sec precision. This will be a new considerable input to the astrophysics of stars and other apparently point-like objects.

In any case the late entry of Astrometry in the Space club will replace this old but fundamental science in a leading situation that is justified by the great number of applications is most of the aspects of Astronomy.

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