THE STELLAR REFERENCE FRAME FROM SPACE OBSERVATIONS

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ABSTRACT: The HIPPARCOS Satellite, to be launched by the European Space Agency, will provide a stellar reference frame over the whole celestial sphere with an average accuracy of ± 0".002 in each coordinate and component of annual proper motion, for some 100,000 stars.

The origin of coordinates will be arbitrary. Absolute rotation of the system of proper motions can be obtained by measuring quasars relative to stars in the HIPPARCOS catalogue, either with the NASA Space Telescope or by conventional ground based astrometric observations.

1. INTRODUCTION

In March 1980, the European Space Agency selected the astrometric satellite, HIPPARCOS, to be the next scientific mission. This satellite will produce astrometric data on some 10^5 stars which will be far superior in accuracy and homogeneity to those generally available from ground based observations.

The satellite will probably be launched in 1986 and the mission duration is to be about 2.5 years. The final results could be available by 1991.

The likely impact of the HIPPARCOS project in many fields of astronomy and astrophysics has been described in the ESA Phase A Study report (ESA 1979) and in numerous papers published in recent years, for example in the proceedings of the Colloquium on European Satellite Astrometry held in Padua in 1978.

A major feature of the scientific case for this mission has been the determination of absolute trigonometric parallaxes and also annual proper motions, with average accuracy of ± 0".002, for many thousands of stars which are of astrophysical interest. However, in this paper I want to confine attention to the implications of the HIPPARCOS project on the stellar reference frame which is used in dynamical and geodetic astronomy.

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Astrometric observations will also be made with the Space Telescope; these however will be confined to accurate relative measurements in small fields and are therefore complementary to data from HIPPARCOS. The various possibilities have been discussed by van Altena (1979). For the present discussion we need only consider the use of the fine guidance sensors (FGS) which, at any one time, will give a field of about 70 square arc minutes available for astrometry; an accuracy of ± 0".002 is expected.

2. HIPPARCOS OBSERVATIONS

The essential feature of HIPPARCOS is simultaneous observation in two directions, of the order of 70° apart, by means of a beam splitting mirror, known as the "complex mirror", which is placed in front of the main telescope. A schematic layout is shown in Fig 1.

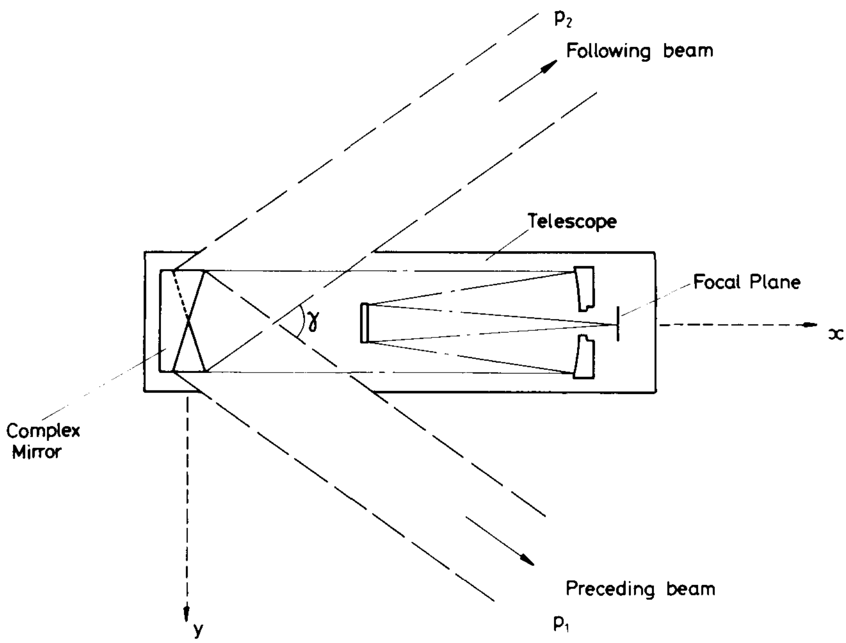

Fig 1

The sky is scanned by rotating the telescope at a rate of ten revolutions per day about an axis which is nominally perpendicular to the two beams. As the instrument rotates, star images from either beam will transit across the focal plane, and, if the rotation axis remains fixed, both beams will scan along approximately the same great circle. The angle between the centres of the two beams is known as the "basic angle"; its stability during a complete scan through 360° is crucial to the success of the mission.

Only preselected stars will be observed. The instantaneous field of view (IFOV) is defined by an image dissector tube (IDT) which

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can be switched rapidly from one location to another in the focal plane. The elementary observation consists of the detection of a signal from a star within the IFOV, which is modulated by a grid with parallel slits $0''.275$ wide and $1''.1$ apart, oriented perpendicular to the direction of image transit. The total area covered by the modulating grid is to be about $0^\circ.9 \times 0^\circ.9$, and the IFOV has a diameter of 30". Details of the observing technique are given in the Phase A Study report. For the purpose of the present discussion it is sufficient to regard an observation as being the time of transit across some fiducial mark, for example the central slit of the grid.

2.1 Geometry of the instrument

The plane parallel to the normals to the two faces of the complex mirror is known as the principal plane. The instrument can be represented by a triad of unit vectors $Z \equiv [\underline{x}\ \underline{y}\ \underline{z}]$ such that $\underline{z}$ is normal to the principal plane, $\underline{x}$ is along the internal bisector of the angle between the normals and $\underline{y} = \underline{z} \times \underline{x}$.

In Fig 1, $\underline{p}_i$ (i = 1,2) denotes the unit vector parallel to the centre of beam i. We can write

$$\underline{p}_i = \cos\tfrac{1}{2}\gamma\ \underline{x} - (-1)^i \sin\tfrac{1}{2}\gamma\ \underline{y} \tag{1}$$

where γ is the basic angle. If the sense of rotation is positive about $\underline{z}$, then $\underline{p}_1$ is known as the "preceding" direction and $\underline{p}_2$ the "following" direction.

Let $\underline{r}$ denote the unit vector in the direction to a star. This can be expressed symbolically as

$$\underline{r} = \underset{\sim}{Z} \begin{bmatrix} \underline{x}'\underline{r} \\ \underline{y}'\underline{r} \\ \underline{Z}'\underline{r} \end{bmatrix} \tag{2}$$

where the prime denotes scalar multiplication.

Now let $\underline{\varepsilon}$ be a small rotation of the triad $\underset{\sim}{Z}$. The corresponding small changes in the directions of $\underline{x}$, $\underline{y}$, $\underline{z}$ can be expressed as $\Delta\underset{\sim}{Z} = \underline{\varepsilon} \times \underset{\sim}{Z}$ and a general small change in $\underline{r}$ can be written

$$\Delta\,\underline{r} = \underline{\varepsilon} \times \underline{r} + \underset{\sim}{Z} \begin{bmatrix} \Delta\,(\underline{x}'\underline{r}) \\ \Delta\,(\underline{y}'\underline{r}) \\ \Delta\,(\underline{z}'\underline{r}) \end{bmatrix} \tag{3}$$

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Multiplying this equation scalarly by $\underline{z} \times \underline{r}$ and rearranging we obtain

$$(\underline{x}'\underline{r})\Delta(\underline{y}'\underline{r})-(\underline{y}'\underline{r})\Delta(\underline{x}'\underline{r})+|\underline{z}\times\underline{r}|^2\ \underline{z}'\underline{\varepsilon} = (\underline{z}\times\underline{r})'\Delta\underline{r}-(\underline{z}'\underline{r})(\underline{z}\times\underline{r})'\Delta\underline{z} \qquad (4)$$

where we have put $\Delta\ \underline{z} = \underline{\varepsilon} \times \underline{z}$

For a star in beam i we can express $\underline{r}$ in the form

$$\underline{r} = \cos\zeta\ \cos\eta\ \underline{p}_i + \cos\zeta\ \sin\eta\ \underline{z} \times \underline{p}_i + \sin\zeta\ \underline{z} \qquad (5)$$

where η, ζ are small angular displacements parallel and perpendicular to the principal plane; these correspond to coordinates of the reflected image in the focal plane of the main telescope. Combining (5) with (1) we derive

$$\begin{aligned}\underline{x}'\underline{r} &= \cos\zeta\ \cos(\eta \pm \tfrac{1}{2}\gamma)\\ \underline{y}'\underline{r} &= \cos\zeta\ \sin(\eta \pm \tfrac{1}{2}\gamma) \qquad (6)\\ \underline{z}'\underline{r} &= \sin\zeta\end{aligned}$$

where the upper and lower signs refer to the preceding and following field respectively. Differentiating the first two of (6) and using (4) we obtain

$$\Delta\eta \pm \tfrac{1}{2}\Delta\gamma + \underline{z}'\underline{\varepsilon} - \tan\zeta\ \underline{s}'\Delta\underline{z} = \sec\zeta\ \underline{s}'\Delta\underline{r} \qquad (7)$$

where $\underline{s}$ is the unit vector along $\underline{z} \times \underline{r}$. Equation (7) is the fundamental equation for HIPPARCOS data reduction. The displacement $\Delta\underline{z}$ of the $\underline{z}$ axis is multiplied by the small factor $\tan\zeta$ and therefore need not be known with extreme accuracy. The quantity $\underline{z}'\underline{\varepsilon}$ enters as an arbitrary zero point of the "abscissa" coordinate η; errors in $\underline{z}'\underline{\varepsilon}$ are virtually eliminated by making quasi-simultaneous observations of stars in both beams of the instrument. The correction $\Delta\gamma$ to the nominal basic angle can be obtained from each complete scan since all stars will be observed in both beams.

2.2 Attitude determination

The orientation of $\underset{\sim}{Z}$ can be determined from observations of transits of selected bright stars across an auxiliary grid near the edge of the field, which is known as the "star mapper". This grid, which is much coarser than the main modulating grid has some slits parallel to those of the main grid and some inclined at 45°; thus both coordinates can be measured.

Differentiating the third of equations (6) we obtain

$$\Delta\zeta = (\underline{z}'\Delta\underline{r} + \underline{r}'\Delta\underline{z})\sec\zeta \qquad (8)$$

Provided that $\Delta \underline{r}$ is small, (as it certainly will be after a first iteration of the data), equations (7) and (8) can be used to determine Δz and $\underline{z}'\varepsilon$ with sufficient accuracy. This can be done in principle from simultaneous observations of a star in each beam, but in practice the change in attitude will be monitored continuously by readings of three, or possibly four, gyros.

2.3 Scanning geometry

Complete sky coverage will be achieved by changing the direction of the axis of rotation. Let $\underline{c}$ be the unit vector along this axis, and $\underline{h}$ the unit vector toward the mean position of the Sun in the ecliptic. If $\underline{k}$ is the ecliptic pole we have

$$\underline{c} = \sin\xi \sin\nu \, \underline{k} + \sin\xi \cos\nu \, \underline{k} \times \underline{h} + \cos\xi \, \underline{h} \quad (9)$$

where ξ, the "revolving angle", is the angle between $\underline{c}$ and $\underline{h}$, and ν is the phase of revolution. The provisional scheme is for ξ to remain constant over extended periods and the rate of revolution of $\underline{c}$ about $\underline{h}$ will be chosen so that the locus of $\underline{c}$ is a series of overlapping loops.

When $\underline{c}$ crosses the ecliptic, $\underline{c}'\underline{k} = 0$ and $\nu = n\pi$ (n integer). In this case $\underline{h} \times \underline{c} = (-1)^n \sin\xi \, \underline{k}$. Now if the longitude of $\underline{h}$ is $2\pi\,(t-t_o)$ where t is the time measured in years, and $\underline{c}$ revolves about $\underline{h}$ K times per year, the longitude of $\underline{c}$ at the n^{th} crossing of the ecliptic is given by

$$\lambda_n = \frac{n\pi}{K} - 2\pi t_o + (-1)^n \xi \quad (10)$$

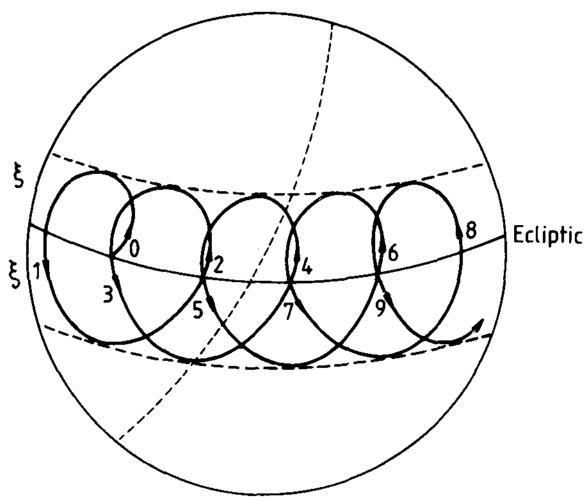

Fig 2

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As is shown in Fig 2, a sufficient condition for successive loops to overlap is $\lambda_{2m} \geq \lambda_{2m+3}$ which is equivalent to

$$K \geq \frac{3\pi}{2\xi} \tag{11}$$

The revolving angle is also the angle of incidence of sunlight on to the solar panels, and therefore cannot be too large. On the other hand, stellar parallactic displacement is proportional to sin ξ, and should be maximised. The constants provisionally chosen are $\xi = 36^o$, K = 7.5. With this pattern, it is seen from Fig 2 that any great circle will intersect the locus of c in at least six points so any point in the sky will be scanned at least six times per year.

2.4 Data reduction

The initial stages in processing the data will be to determine the attitude parameters as functions of the time, from the star mapper and gyro readings, and then to derive for each star, the angular coordinate along the scanning direction from the IDT photon counts obtained during a single great circle scan.

The procedure proposed in the Phase A Study report for deriving the final catalogue of astrometric parameters follows a so-called "three step" method. The first step is to combine all data from a "set" of five consecutive scans to provide abscissae for all stars projected on to a common reference great circle; these abscissae would be referred to an arbitrary zero point. In the second step, all abscissae for some 500-1000 primary stars obtained throughout the mission, will be analysed to determine the zero points for each "set". The third and final step will be to apply the zero point corrections to the abscissae for all programme stars and thence calculate the astrometric parameters. It is envisaged that several iterations of this procedure will be needed.

2.5 Observational programme

Taking into account the mission duration (assumed to be 2.5 years) and the need to have sufficient integration time on each star, the main features of a possible observing programme have been given in the Phase A Study report. In this programme the total number of stars would be 10^5; all 6 x 10^4 stars brighter than m_{pg} = 9 would be included and the remainder would be selected from stars with $9 \leq m_{pg} \leq 13$.

The mean errors of the final astrometric parameters will vary with magnitude and ecliptic latitude. The all sky average error in position for a star brighter than m_{pg} = 10 should not exceed ±0.″0022 in ecliptic longitude and ±0.″0010 in latitude. At m_{pg} = 13 the errors will increase by a factor of between two and three. The errors in annual proper motion components will be approximately fifty per cent larger than in the corresponding position coordinates.

3. ABSOLUTE REFERENCE FRAME

The final output from HIPPARCOS will be a fully coherent catalogue of relative positions and proper motions, and absolute parallaxes.

The method of measurement, with the modulating grid, precludes the observation of objects with non-stellar images; it will therefore not be possible to include solar system objects, except perhaps for a few bright minor planets. But it is not expected that any of these will be observed sufficiently frequently during the 2.5 year mission, to derive good orbits or to define a dynamical reference frame independent of ground based work. It will therefore be necessary to relate the HIPPARCOS system empirically to the fundamental system, FK5.

Any residual rotation of the HIPPARCOS proper motion system could also be determined from observations of extra galactic objects. Unfortunately only one quasar, 3C 273, is likely to be bright enough for direct observation. It is just possible that a few bright Seyfert galaxy nuclei could also be observed, but these would be very close to the faint limit for HIPPARCOS; nevertheless they should be observed at least once in order to assess their usefulness.

During the last decade, astrometric observations of extragalactic sources in both radio and optical wavebands have been used for referring the position system of the radio interferometric observations to the optical fundamental system FK4.

Because many radio sources have significant angular structure even though their optical counterparts appear to be quasi-stellar, it is necessary to select for this purpose only those sources which have small structure at radio frequencies. Accordingly at the IAU Colloquium No 48 on "Modern Astrometry" which was hald in Vienna in 1978, Commission 24 set up a working group of radio and optical astrometrists which was charged with the task of drawing up a list of suitable "bench mark" sources. This working group, under the chairmanship of K. J. Johnston, reporting to the Commission at Montreal, presented a list of 81 primary candidates and a further list of 32 possible candidates; nearly all these sources are quasars. Since these sources are all optically too faint for HIPPARCOS it is necessary that at least one bright star, close to each source should be included in the HIPPARCOS programme. Measurement of the angular separation between each source and its "associate" star, and its rate of change, would be sufficient to refer radio positions to the HIPPARCOS system and to determine the rotation of the HIPPARCOS proper motions relative to an extra-galactic frame.

Initially this might be feasible from ground based photographic astrometry since there is already a considerable body of optical astrometric data on many of the sources extending over a decade or more. A much better alternative would be to use the fine guidance

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sensors of the Space Telescope. For this to be feasible, the angular separation between a source and its associate star must be less than about 15'. From examination of a sample of northern radio source fields which have been observed in recent years at the Royal Greenwich Observatory, it is found that all have associate stars bright enough to be observed with HIPPARCOS and close enough to be measured with the Space Telescope; eighty per cent have AGK3 stars satisfying both these criteria. After one year a single relative displacement between quasar and star could be measured with the Space Telescope with a mean error of about ±"004; combining this with ±"002 for the HIPPARCOS proper motions and averaging over fifty well distributed fields, the mean error of one component of the rotation of the system would be only about ±"001.

4. ACKNOWLEDGEMENTS

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I am also grateful to Mr E D Clements who has identified possible associate stars in many of the radio source fields and also examined photographs of several bright Seyfert galaxies obtained with the 26 inch refractor at Herstmonceux.

1980 July 25

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