5. Geometrical stability and evolution of the Hipparcos telescope

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Received July 17, accepted January 27, 1991

Abstract. A simple geometrical model of the Hipparcos telescope is described whereby the relative positions and orientations of critical optical elements can be derived from the field-to-grid transformation determined as part of the normal data processing. The instrument is very stable on time scales of hours, but secular drifts of the order of 0.1 $\mu$m day\textsuperscript{-1} are observed and there is evidence for a progressive deformation of the mirrors which may eventually also affect the image quality.

Key words: Hipparcos – astrometry – data analysis – instruments – optics – space vehicles

1. Introduction

The Hipparcos project aims at determining the astrometric parameters of stars (their positions, parallaxes and annual proper motions) to milli-arcsec accuracy. The instrument was consequently designed and built to meet very strict requirements especially in terms of the short-term opto-mechanical stability (Burrows et al. 1989). Preliminary assessments of the in-orbit performance and instrument stability (Perryman et al. 1992, Schrijver & van der Marel 1992) show that these requirements are essentially met during the periods when scientific data are collected.

Long-term instrument stability is rather less critical to the scientific goals, as the data reductions can be made to incorporate the slowly changing instrument parameters in a self-consistent manner. This applies for instance to the so-called field-to-grid transformation, which describes the relation between, on one hand, the angular coordinates (or direction cosines) of stars in the two fields of view, and, on the other, the positions of their optical images on the modulating grid. This transformation, which includes the nominal transformation as well as optical distortion and large-scale imperfections of the grid pattern, is determined approximately once per orbital period (10.67 hours) by means of the great-circle reduction process (van der Marel & Petersen 1992). Schrijver & van der Marel (1992) describes the evolution of some of the transformation coefficients determined by means of the ‘first-look’ facility implemented within the FAST data reduction consortium (Kovalevsky et al. 1992).

In this paper we examine the extent to which the observed transformation and its variation in time can be attributed to simple geometrical effects, such as displacements and rotations of the optical elements. In order not to obscure the basic problem, we adopt the simplest possible model in which for instance only one ray is traced to each point in the field. We believe the resulting model gives some physical insight into the development of the Hipparcos telescope which may help to optimize the reduction software. In the NDAC Consortium the model is also used to extrapolate the main field geometry to the star-mapper grid (Lindegren et al. 1992).

2. The model

We consider a model of the Hipparcos telescope in which all optical surfaces are perfect in shape but possibly displaced or tilted. Moreover, only the rays passing through the centre of curvature of the spherical mirror are traced. Since the aperture of the telescope is thus infinitely small, one can assume that the two segments of the beam combiner mirror are flat. (In the real instrument these surfaces act as a Schmidt corrector by their aspheric figuring.) The imaging properties of this system is invariant to a parallel shift of the beam combiner surfaces, and we may choose to position both at the centre of curvature of the spherical mirror. Clearly the flat folding mirror can be disregarded under the present assumptions (cf. Fig. 1 in Perryman et al. 1992). Figure 1 illustrates the present model.

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{hipparcos_model.png}
\caption{Layout of the simplified geometrical model}
\end{figure}

\textsuperscript{*} Based on observations made with the ESA Hipparcos satellite

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2.1. Model parameters

The position and orientation of optical elements are specified in a laboratory frame \([X \ Y \ Z]\) with origin at the centre of curvature of the spherical mirror. The \(Z\) axis coincides with the intersection of the beam combiner surfaces, while \(X\) is the bisector of the mirror normals \(n_\theta\) (preceding) and \(n_t\) (following). With \(\Gamma\) denoting twice the angle between the two normals, we have:

\[
\begin{align*}
n_\theta &= X \cos(\Gamma/4) + Y \sin(\Gamma/4) \\
n_t &= X \cos(\Gamma/4) - Y \sin(\Gamma/4)
\end{align*}
\tag{1}
\]

Note that \([X \ Y \ Z]\) is not quite the same as the instrument frame \([x \ y \ z]\) implicitly used in the data reductions (Sect. 3.1 in Lindgren et al. 1992), although they would coincide for a perfectly aligned instrument; nor is \(\Gamma\) quite equal to the 'basic angle' \(\gamma\). The laboratory frame is completely defined by the two beam combiner mirror normals, which are not directly accessible by observation, whereas the observable frame is determined with reference to the modulating grid. The relation between the two frames is discussed in Sect. 2.3.

The grid frame \([F \ G \ H]\) is physically attached to the grid and measured in mm. \((G, H)\) are measured in the plane tangent to the grid at the nominal centre. \(F\) is measured positive on the convex side of the grid. The slits of the main grid are nominally parallel to the \(H\) axis. The curvature radius of the grid, \(R\), is formally a model parameter. However, since one would need drastic changes in the curvature to produce a measurable distortion (some 2% for 1 milli-arcsec distortion) it is better to consider \(R = 1400\) mm as a fixed parameter. The coordinate \(F\) is then a known function of \((G, H)\) which we write as:

\[
F = \frac{-\left(G^2 + H^2\right)}{R + \sqrt{R^2 - (G^2 + H^2)}} \equiv F(G, H) \tag{2}
\]

The relation between laboratory coordinates and grid coordinates is defined by six parameters which specify the displacement and rotation bringing a coordinate system initially aligned with \([X \ Y \ Z]\) into coincidence with \([F \ G \ H]\):

1. displace the origin to \((X_0, Y_0, Z_0)\);
2. rotate an angle \(\psi\) about the 3rd axis;
3. rotate an angle \(\theta\) about the 2nd axis;
4. rotate an angle \(\phi\) about the 1st axis.

The resulting transformation is:

\[
\begin{pmatrix} X \\
Y \\
Z
\end{pmatrix} = \begin{pmatrix} X_0 \\
Y_0 \\
Z_0
\end{pmatrix} + \begin{pmatrix} F \\
G \\
H
\end{pmatrix} \cdot \begin{pmatrix} c_\psi & s_\psi & 0 \\
s_\psi & c_\psi & 0 \\
0 & 0 & 1
\end{pmatrix} \begin{pmatrix} c_\theta & s_\theta & 0 \\
-s_\theta & c_\theta & 0 \\
0 & 0 & 1
\end{pmatrix} \begin{pmatrix} c_\phi & s_\phi & 0 \\
-s_\phi & c_\phi & 0 \\
0 & 0 & 1
\end{pmatrix} \tag{3}
\]

Nominally the slit centres of the main grid should be straight and equidistant lines in the \((G, H)\) plane. Due to imperfections of the electron beam pattern generator used to produce the grid, this is not strictly true for the actual grid (Rafter & Batut 1989). Conceptually we may introduce a system of 'electronic' coordinates \((g, h)\) in which the slits occupy strictly their nominal positions; the irregularities of the real grid are then accounted for in the transformation from the electronic coordinates to the geometrical coordinates \((G, H)\). In the present context it is interesting to consider the effects of a tilt between the grid and the electron beam used to generate the slit pattern. The tilt of the electronic frame \([f \ g \ h]\) with respect to the grid frame may be described by two rotations bringing \([F \ G \ H]\) into coincidence with \([f \ g \ h]\):

1. a rotation by the angle \(\alpha\) about the 3rd axis;
2. a rotation by the angle \(\beta\) about the 2nd axis.

This gives the transformation:

\[
\begin{pmatrix} F' \\
G \\
H
\end{pmatrix} = \begin{pmatrix} c_\beta c_\alpha & -s_\beta & s_\alpha \\
c_\beta s_\alpha & c_\alpha & s_\beta s_\alpha \\
-s_\beta & 0 & c_\beta
\end{pmatrix} \begin{pmatrix} f \\
g \\
h
\end{pmatrix} \tag{4}
\]

The calculation of \((G, H)\) from \((g, h)\) is most conveniently done by iterating the equations:

\[
G = g \sec \alpha + F \tan \alpha \\
H = h \sec \beta - F \sec \alpha \tan \beta - g \tan \alpha \tan \beta \tag{5}
\]

\[
F = F(G, H)
\]

starting from \(F = 0\). The transformation from \((G, H)\) to \((g, h)\) is obtained directly from Eq. (2) and the inverse of Eq. (4).

This completes the specification of the instrument model. The model parameters are: \(\Gamma, \ R, \ X_0, \ Y_0, \ Z_0, \ \phi, \ \theta, \ \psi, \ \alpha\) and \(\beta\). We have already noted that \(R\) should not be considered a free parameter. Also, it can be seen that \(Y_0\) and \(\psi\) are coupled in the sense that displacing the grid along the \(Y\) axis is equivalent to a simultaneous rotation of the grid and beam combiner, each about its own \(Z\) axis, plus some second-order adjustment of the distance between the two elements. Since rotating the beam combiner about \(Z\) does not change the field-to-grid transformation we conclude that \(Y_0\) and \(\psi\) are, in effect, indistinguishable. Without loss of generality we can therefore set \(\psi = 0\). Inspection of Eq. (4) shows, furthermore, that the electronic tilt angle \(\beta\) does not enter the expression for \(g\) as a function of \((F, G, H)\). Hence it cannot be determined from the observed distortion of the main field, and we are forced to assume \(\beta = 0\). The remaining seven parameters \((\Gamma, \ X_0, \ Y_0, \ Z_0, \ \phi, \ \theta, \ \alpha)\) can be adjusted freely to represent the observed field-to-grid transformation as closely as possible.

The curvature radius of the spherical mirror does not enter as a model parameter because the ray tracing through the centre of curvature is independent of that radius.

2.2. Ray tracing

The field-to-grid transformation according to the model is obtained by tracing a number of rays from different directions in either field of view through the origin \(X = Y = Z = 0\) and up to its intersection with the grid surface. Given the instrument parameters and the unit vector \(u\) towards a star, the direction of the ray after reflection in the beam combiner is given by:

\[
v = 2nn' - u \tag{6}
\]

where \(n\) is the mirror normal from Eq. (1). After reflection in the spherical mirror, the ray returns to the origin in direction \(-v\). Its intercept with the grid is computed from the parametric equation \([vt - c] = R\) where \(c\), the position of the centre of curvature of the grid, is obtained by setting \(F = -R\) and \(G = H = 0\) in Eq. (3).

Solving for \(t\) we find:

\[
t = v'c + \sqrt{R^2 + (v'c)^2 - c^2} \tag{7}
\]
The point of interception is \(r_t\) in the laboratory system; by means of Eqs. (3) and (4) it can be transformed to the grid frame and then to the electronic frame, yielding the \((g, h)\) coordinates of the ray.

Raytracing in the opposite direction, starting from a point \((g, h)\) in the electronic frame, is done by successively applying Eqs. (5), (3) and (6).

2.3. Relation to field coordinates

The laboratory system \([X Y Z]\) is not directly accessible to measurements. Instead we define also an \(instrument\ frame\ [x y z]\) and associated \(field\ coordinates\ \((w, z)\), to which the in-orbit calibrations can be related. These are defined by the optics together with a reference value \(\gamma_0\) of the basic angle and two specific features on the grid:

1. the chevron apex of the active star mapper, which defines the origin of the transverse field coordinate \(z\);
2. the centre line of the main field, halfway between the 1344th and 1345th slits, which defines the origin of the longitudinal coordinate \(w\).

In electronic coordinates the star-mapper apex is \((g_A, 0)\) with \(g_A = -21.63385\) mm; the centre line of the main field is defined by \(g = 0\).

In the instrument system the two directions in space corresponding to the field point \((w, z)\):

\[
\begin{align*}
\mathbf{u} = [x \ y \ z] \\
&= \left(\begin{array}{c}
\mp w \sin(\gamma_0/2) + \sqrt{1 - w^2 - z^2} \cos(\gamma_0/2) \\
+ w \cos(\gamma_0/2) \pm \sqrt{1 - w^2 - z^2} \sin(\gamma_0/2)
\end{array}\right) \\
z
\end{align*}
\]

(8)

where upper/lower sign refers to the preceding/following field. The following procedure is used to calculate \([x \ y \ z]\) in the laboratory system. A ray from \((g_A, 0)\) is traced through the preceding field. Let \(\mathbf{a}_0\) be the resulting unit vector towards the point on the sky that is imaged on the star-mapper apex. Similarly the corresponding direction \(\mathbf{a}_1\) through the following field is traced. Then:

\[
z = \left(\mathbf{a}_1 \times \mathbf{a}_0\right)
\]

(9)

with \(\times\) denoting vector normalization. Next we must find the two viewing directions \(\mathbf{b}_0\) and \(\mathbf{b}_1\), perpendicular to \(z\), which are imaged onto the main field centre line, \(g = 0\). This may be done by writing, e.g., \(\mathbf{b}_0 = (\mathbf{a}_0 + z \times \mathbf{a}_0)\) where \(z\) is a scalar to be found by inverse linear interpolation. The remaining instrument axes are then obtained as:

\[
x = (\mathbf{b}_0 + \mathbf{b}_1) \\
y = z \times x.
\]

(10)

The basic angle is \(\gamma = \arccos(\mathbf{b}_0 \cdot \mathbf{b}_0)\).

3. Observations

Stellar observations on the main grid provide a determination of the longitudinal electronic coordinate \(g\) as function of time. The basic assumption is that \(g\) increments by exactly 8.2 \(\mu m\) for each light modulation period. In the great-circle reductions (van der Marel & Petersen 1992) such elementary observations are combined to establish an empirical relation between \(g\) and the field coordinates \((w, z)\).

The relation may be expressed in the form of polynomial coefficients \(g_{ij}, h_{ij}\) in the (simplified) field-to-grid transformation formula:

\[
g = -F_0 w + \sum_{i,j} (g_{ij} \pm h_{ij}) w^i z^j.
\]

(11)

[ Cf. Eq. (15) in Lindegren et al. (1992).] \(F_0\) is a reference value for the equivalent focal length. Usually terms up to 4th order \((i + j < 4)\) are included. The complete field-to-grid transformation contains also colour-dependent terms, but they are not considered here.

The transformation coefficients analysed below consist of two largely independent data sets. The first set contains data from 67 great-circle reductions from the ‘first-look’ evaluation performed by the FAST Consortium at SRON Space Research Utrecht (Kovalovsky et al. 1992). This is basically a subset of the data described by Schrijver & van der Marel (1992); in the following they are labelled ‘SRU’. The second set (labelled ‘CUO’) represent 169 great-circle reductions made at Copenhagen University Observatory as part of the ‘provisional’ processing performed by the NDAC Consortium (Lindegren et al. 1992). Since the reduction consortia use slightly different representations of the transformation the SRU values were first converted to NDAC conventions. This involved reversing the signs of all coefficients of even degree \((i + j)\) and adding the nominal transformation.

4. Model fitting

Given the coefficients \(g_{ij}, h_{ij}\) from the great-circle reduction and the corresponding reference values \(\gamma_0, F_0\) the ‘observed’ electronic coordinate \(g_0\) is obtained for the arbitrary position \((w, z)\) in either field of view. The geometrical instrument model yields, on the other hand, the ‘calculated’ coordinate \(g_c\) by means of Eq. (8) and a tracing from \(w\) to the electronic frame. The calculated value depends on the model parameters, which are now adjusted to minimize the mean square deviation in both fields of view (FOV):

\[
\text{RMS}^2 = \frac{1}{2n^2} \sum_{\text{FOVs}} \sum_{k=1}^{n} \sum_{z=1}^{n} \left[ g_0(w_k, z_k) - g_c(w_k, z_k) \right]^2
\]

(12)

For the present analysis a total of 98 rays \((n = 7)\) were used with a discretization step of 0.0022 in \(w\) and \(z\). The adjustment of the model parameters was made with a standard library minimization routine which does not require the calculation of derivatives.

5. Results

Figures 2a–d and 3a–c show the results for the parameters \(\Gamma, X_0, Y_0, Z_0, \phi, \theta, \alpha\) as functions of time. For \(X_0, Y_0, \phi, \theta\) and \(\alpha\) systematic differences were noted between the SRU and CUO reductions. In the figures these differences have been removed by adding \(-1.3\ \mu m, -3.3\ \mu m, -1.5\ \arcsec, -6\ \arcsec\) and \(-19\ \arcsec\), respectively, to the SRU results. Figure 3d shows the rms residual [Eq. (12)] as a function of time. It can be noted first that the residuals are consistently larger for the CUO data (crosses) than for the SRU data, secondly, that the rms residual in both data sets increases steadily with time. Tables 1–2 show the residuals of the fits to the first and last CUO transformations. The residuals of the fits to the SRU data look similar.

The systematic differences between the SRU and CUO data are probably mainly due to the different definitions of the light modulation phase. In the CUO data only the phase of the first (fundamental) harmonic is used, while a weighted mean of the first and second harmonics is used for the SRU data. The observed differences are of the expected order of magnitude, given that the phase difference between the two harmonics is some 10–20 milli-arcsec and variable over the fields and in time (Schrijver & van der Marel 1992).
Fig. 2. Temporal evolution of the model parameters $\Gamma$, $X_0$, $Y_0$ and $Z_0$, using data from SRU (circles and lines) and CUO (crosses).

Fig. 3. Temporal evolution of the model parameters $\phi$, $\theta$ and $\alpha$, and of the rms residual of the model fits, using data from SRU (circles and lines) and CUO (crosses).
It is instructive to see which terms $g_2$, $h_2$ the model can adjust to. A closer examination of the residuals shows that the only terms that attain significant values in the model are: $h_0$ (related to the basic angle), $g_0$ (scale value), $g_0$ (grid rotation about the optical axis), $h_0$ (grid displacement along the Z axis), and the tilt terms $g_{2n}$, $g_{1n}$, $g_2$. The model cannot reproduce the remaining terms, in particular $h_0$ (scale difference between the fields of view) and the cubic terms ($i+j=3$), which largely explain the pattern of residuals in Tables 1–2.

The steadily growing rms residual seen in Fig. 3d is mainly due to the increasing difference in scale between the preceding and following field of view (cf. Schrijver & van der Marel 1992), and to a smaller extent to the increasing magnitudes of the cubic coefficients $g_{1n}$, $g_{2n}$ and $g_2$.

The evolution of all model parameters except $X_0$ appears to be generally rather smooth. However, there are a few significant jumps especially in $\Gamma$ and $\phi$, e.g., around day 88, 180 and 247. Some of them can be related to incidents in the thermal control system of the satellite (Schrijver & van der Marel 1992). The evolution of $X_0$ is characterized by the sudden changes effected by refocussing operations (Perryman et al. 1992), usually by +2 steps or 2.76 $\mu$m. Recalling that $X_0$ is actually the optical distance between the grid and the curvature centre of the spherical mirror, we conclude that the mechanical structure connecting the spherical mirror and the flat folding mirror is steadily shrinking; this is compensated by the periodic refocussing moving the grid away from the flat mirror.

It is gratifying to note that the parameter $\alpha$ is constant to within the measurement errors. This is of course to be expected if this particular distortion pattern was generated during the manufacturing of the grid.

The long-term drifts in $X_0$, $Y_0$ and $Z_0$ are all of the order of 0.1 $\mu$m day$^{-1}$. Also the mean drift in $\theta$, when converted to a linear rate at a distance of 50–100 mm (the size of the grid assembly) is of similar size, while it is 30 times less in $\phi$. The drift in $\Gamma$ corresponds to only 10$^{-3}$ $\mu$m day$^{-1}$ at the edges of the beam combiner. With the possible exception of $Z_0$ all drift rates are decreasing with time.

### Table 1. Residuals $g_0 - g_c$ (in milli-arcsec) versus position in field $(u, z)$ (in milli-rad) from the model fit to the CUO transformation data for 1989 Nov 5

<table>
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<th>$z \div w$</th>
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### Table 2. Residuals $g_0 - g_c$ (in milli-arcsec) versus position in field $(u, z)$ (in milli-rad) from the model fit to the CUO transformation data for 1991 Feb 5

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The evolution of the differential scale and cubic terms can only be understood in terms of deformations of one or several of the mirror surfaces. The scale difference between the preceding and following field of view is perhaps most likely caused by the two halves of the beam combiner having slightly different paraxial curvatures. It would then seem that the curvatures of the two fields evolve at different rates (from a nearly common curvature at launch), possibly depending on the different mechanical suspension geometries of the two mirror halves. This would also cause the ‘best focus’ position to diverge between the two fields of view, resulting in a gradually degrading compromise focus. To produce a cubic distortion seems to require a quartic deformation of a mirror which is nor in the plane of the entrance pupil, i.e., of the folding or spherical mirror. The required deformation is of the order of 50 nm peak value. The corresponding rms wavefront error would be of the order of $\lambda/30$, hardly enough to decrease the light modulation by a significant amount. If the mirror deformations continues to grow with time, as suggested by Fig. 3d, then the effect on the image quality and light modulation could eventually become important.

### 6. Conclusions

The present model is not intended to ‘explain’ the many different observed characteristics of the real instrument. On the contrary the aim has been to set up a minimal model to account for those characteristics of the field-to-grid transformation that can be attributed to simple geometrical effects. Clearly the model is a useful tool to follow the temporal evolution of the mechanical structure connecting the optical elements. But perhaps a more important result is the evidence that certain components of the transformation cannot be explained by such structural variations. A closer examination of these effects is however beyond the scope of this paper.

### Acknowledgements

We wish to thank Dr. H. Schrijver and the FAST Consortium for providing ‘first look’ results for the field-to-grid transformation. The Copenhagen great-circle results were based on reductions performed by the Hipparcos team at the Royal Greenwich

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Observatory, led by Dr. F. van Leeuwen. The work performed at the observatories in Copenhagen and Lund is supported by the Danish Space Board and the Swedish National Space Board.

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