Phase shifts and astrometric biases due to relay optics focus errors

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Results of the CIP runs

This note summarises the results of several runs with the ‘CIP’ software, aimed at quantifying the possible astrometric implications of a large focus error of the IDT relay optics.

The main data are given in Table 1. The definition of the telescope defocus ($\Delta z$) and relay optics defocus ($\Delta z'$) is indicated in Fig. 1. For the IFOV profile (the IDT proper profile) I have used two different curves (Fig. 2) taken from various MATRA documents.

The calculations give, for a certain combination of telescope and relay optics defocus and a given IFOV profile, a two-dimensional map of the phase shift of the first harmonic, $\delta \eta$, as function of the IFOV detuning angles $\Delta \eta$ (longitudinal) and $\Delta \zeta$ (transverse). Figs. 3–4 are examples of such maps. However, the most interesting relation is the phase shift versus the longitudinal IFOV detuning, or a cut at $\Delta \zeta = 0$ through the maps; this relation is shown in Figs. 5–6.

For moderate defocussing of the relay optics (up to about 100 $\mu$m) the curves show a plateau around the origin, with small phase shifts up to at least 5 arcsec detuning. This is the expected behaviour when the defocussed star image fits well within the IFOV profile.

However, for a defocussing of 150–250 $\mu$m, the plateau is no longer present and we have an almost linear relation between the detuning and the phase shift. The constant of proportionality, calculated for the interval $|\Delta \eta| < 5$ arcsec, is given in Table 2.

Error propagation to the astrometric parameters

The IFOV detuning contains both systematic and random components. The form of error propagation used in MATRA’s accuracy analysis applies to random IFOV detuning errors. But the systematic component, caused by errors in the Input Catalogue, may be much more important in view of the direct proportionality found between the phase shift and the longitudinal IFOV detuning. In fact, if the telescope defocus would remain constant (at, say, 15 $\mu$m) throughout the mission, then the astrometric results would simply be biased towards the IC by the factor $q$. For instance, $q = 3$ milliarcsec/arcsec would mean that an IC error of 1 arcsec would result in a positional bias of 3 milliarcsec (towards the IC position) in the final Hipparcos catalogue.

Fortunately the telescope focus error ($\Delta z$) does not remain constant, and since $q$ is proportional to $\Delta z$ there is an ‘improvement factor’ for this bias, roughly equal to $n^{-1/2}$, if $n$ is the typical number of different focus positions in which a given star is observed throughout the mission. A reasonable estimate is perhaps $n \simeq 10$. In the example above, the bias is then reduced to the order of 1 milliarcsec. Even this is quite unacceptable, especially since the biases are still in some fashion related to the positional errors in the IC.

In conclusion, a relay optics focus error by 250 $\mu$m could result in a very serious degradation of the Hipparcos catalogue, especially in regard to systematic astrometric errors. Reducing the focus error to about 100 $\mu$m or less would reduce this problem by a factor of 5 to 10, and hence to an acceptable level. To further minimise the risk of introducing this kind of bias we should consider to update the IC at an early stage and more frequent and/or more accurate refocussing operations.
Table 1. Assumed data for the optical system.

Entrance pupil : half-circular, diameter $D = 0.290 \text{ m}$
  obscuration ratio = 0.38

Focal length : $f = 1.400 \text{ m}$

Grid geometry : period = 8.20 $\mu\text{m}$, slit width = 3.13 $\mu\text{m}$

Relay optics : magnification $m = 0.442$
  oversizing $\beta = 1.000$

IFOV profile : diameter $\Phi = 110 \mu\text{m}$
  IFOV$\alpha$ from E26-HIP-09497 (85/02/28), Fig. 3.3/4c
  IFOV$\beta$ from MAT-HIP-03425 (Iss 3.1), Table I

No aberrations were assumed, except for defocussing of the telescope by $\Delta x = 15 \mu\text{m}$ and of the relay optics by $\Delta x' = 50$, 150 and 250 $\mu\text{m}$.

Table 2. The factor $q = \Delta \eta / \Delta \eta$, in milliarcsec/arcsec, for different combinations of IFOV profile and relay optics defocussing. The telescope defocus is $\Delta x = 15 \mu\text{m}$ ($q$ is roughly proportional to $\Delta x$).

<table>
<thead>
<tr>
<th>Relay optics defocus $\Delta x' = \mu\text{m}$</th>
<th>50</th>
<th>150</th>
<th>250</th>
</tr>
</thead>
<tbody>
<tr>
<td>profile IFOV$\alpha$:</td>
<td>0.02</td>
<td>0.53</td>
<td>2.89 mas/arcsec</td>
</tr>
<tr>
<td>profile IFOV$\beta$:</td>
<td>0.29</td>
<td>0.81</td>
<td>1.95 mas/arcsec</td>
</tr>
</tbody>
</table>
**FIGURE 1.**

Hipparcos equivalent optics scheme

**FIGURE 2.**

IFOVa (solid line) and IFOVb (dashed)

('Bumps' are caused by interpolation problems in the calculation of the IFOV hankel transform. Should have very small effect on phase calculations.)
FIGURE 3. Sample output of CIP run: Phase error of first harmonic (left), diffraction image on photocathode (right).
FIGURE 4. Sample output of CIP run

Contour levels at 1 mas interval
Relay optics defocus - diffraction model (CIP)

Telescope defocus:
Δx = 15 μm (all curves)

IFOV model:
IFOVb

Relay optics defocus:
Δx' = 50 μm
Δx' = 150 μm
Δx' = 250 μm

Longitudinal IFOV depointing [arcsec]

Phase error [milli-arcsec]

(same as above but in a larger scale)

Δx' =
50 μm
150 μm
250 μm

Longitudinal IFOV depointing [arcsec]

FIGURE 6: Phase shift of first harmonic versus longitudinal IFOV depointing (profile IFOVb)