TO: Distribution
FROM: W. M. Owen, Jr. and D. O’Connell
SUBJECT: New Horizons LORRI Geometric Calibration of August 2006

The LORRI camera on New Horizons took 48 pictures of the open cluster Messier 7 on August 31, 2006, and 18 more pictures of the same cluster on September 24, 2006. Rivkin, Weaver et al. (2008) have analyzed these pictures. The analysis presented here uses more catalogued stars (UCAC2 instead of Tycho-2) and adds a significant cubic radial distortion term to the camera model.

The observations

Rivkin et al. discuss the observations. The first five pictures on August 31 used 3 ms exposures and captured too few stars to be useful. The 35th picture, at MET 19314898, was missing all but the first 20 lines. We used the remaining 58 pictures in our analysis.

Centers of the star images were determined by fitting a two-dimensional Gaussian point-spread to the data, with the height and width as adjustable parameters. The median Gaussian sigma of the fitted point-spread was 0.98 pixel; the FWHM was therefore 2.31 pixels. Note that we used the Level 1 images, in which the readout smear (Cheng et al. 2008) had not been removed.

Our program attempts to find all stars throughout each picture, whether catalogued or not. It detected an average of 92 stars (about half of them catalogued) per picture, but this average is deceptive. The long exposures included about 70 catalogued stars and 400 field stars; the 10 ms exposures had about 15 catalogued stars and only a handful of field stars.

The camera model

The prediction of the location of a star image in (sample, line) coordinates uses a subset of the full model in Owen & Vaughan (1991) or Owen (2011). Given a unit vector \( \hat{A} \) representing the apparent position of a star (with proper motion, parallax, and stellar aberration included), the direction to the star in camera body coordinates is given by:

\[
\hat{P} = R_3(\Omega) R_1(-\chi) R_2(\psi) R_3(\phi) R_2(90^\circ - \delta) R_3(\alpha) \hat{A},
\]

where \( \alpha \) and \( \delta \) are the right ascension and declination of the camera boresight; \( \phi \) is the nominal twist angle of the camera; and \( \psi, \chi, \text{ and } \Omega \) are misalignments in elevation, cross-elevation, and twist. We ignored the three misalignment angles in this analysis and took \( \alpha, \delta \text{ and } \phi \) from the picture headers.

Then \( \hat{P} \) is mapped into \((s,l)\) coordinates by:

\[
\begin{pmatrix} x \\ y \end{pmatrix} = \frac{f}{P_3} \begin{pmatrix} P_1 \\ P_2 \end{pmatrix};
\]

1
\[ r^2 \equiv x^2 + y^2; \]
\[
\begin{pmatrix}
\Delta x \\
\Delta y
\end{pmatrix} = \begin{pmatrix}
x r^2 \\
y r^2
\end{pmatrix}
\begin{pmatrix}
x^2 & x y \\
y^2 & x y
\end{pmatrix}
\begin{pmatrix}
\epsilon_2 \\
\epsilon_5 \\
\epsilon_6
\end{pmatrix};
\]
\[
\begin{pmatrix}
s \\
l
\end{pmatrix} = \begin{pmatrix}
K_x \\
K_{xy}
\end{pmatrix}
\begin{pmatrix}
x + \Delta x \\
y + \Delta y
\end{pmatrix} + \begin{pmatrix}
s_0 \\
l_0
\end{pmatrix};
\]

where \( f \) is the camera focal length in mm; the \( \epsilon \)'s are coefficients of cubic radial distortion and detector misalignment; the matrix \( K \) maps from millimeters to pixels in the focal plane; and \((s_0, l_0)\) are the focal plane coordinates of the optical axis. We hold \( K_x \) fixed at 1 pixel per 0.013 mm; \( K_{xy} \) is set to zero, since it can be absorbed in the camera twist angle; and \((s_0, l_0)\) are fixed at \((512.5, 512.5)\) pixels. With these constraints, \( f \) measures the scale of the camera in the sample direction, \( K_y \) allows pixels to be rectangles instead of squares, and \( K_{yx} \) allows pixels to be parallelograms instead of rectangles. Our measuring scheme puts \((1, 1)\) in the center of the top left pixel and \((1024, 1024)\) in the center of the bottom right pixel. The field of view thus runs from 0.5 to 1024.5 in each coordinate. Furthermore, we display the first pixel in a picture in the top left corner. For LORRI this convention produces a mirror image of the sky, and we set \( K_y < 0 \) accordingly.

The distortion analysis

We used the Automated Astrometric Data Reduction System (AADRS; Owen 1996) to perform most of the analysis. The algorithm is based on Heinz Eichhorn’s (1960) overlapping plate technique, in which all stars that are imaged more than once contribute to the determination of the calibration parameters. The solution parameters include the right ascension and declination of every star, with known stars constrained by the catalogued uncertainty in their coordinates at the epoch of observation; three correction angles to the camera pointing for each picture; and the model parameters \( f, K_y, K_{yx}, \epsilon_2, \epsilon_5, \) and \( \epsilon_6 \). The catalogued stars provide the information for determining \( f, K_y, \) and \( K_{yx} \). Changes to the parameters \( K_y \) and \( K_{yx} \) proved to be insignificant, so we retained their nominal values in the final solution.

The 58 viable pictures were processed in one AADRS run. The results, with their actual uncertainties (the formal sigmas multiplied by the goodness of fit \( \sqrt{\chi^2} \)), appear in Table 1 below.

The calibration results appear good. The post-fit star residuals have an RMS scatter of about 0.14 pixel, which is understandable given that many of the exposures were short. There is no sign of an obvious trend in the residuals as a function of position on the chip (Fig. 1). The pixels appear square.

We find a significant pincushion distortion (\( \epsilon_2 > 0 \)) in the camera, amounting to \( 1.73 \pm 0.01 \) pixels in the corners of the field. Increasing \( f \) and increasing \( \epsilon_2 \) both cause images to move radially away from the center of the field—in one case linearly, in the other as \( r^3 \)—and thus \( f \) and \( \epsilon_2 \) are strongly anticorrelated. Holding \( \epsilon_2 \) fixed at zero causes \( f \) to increase from \( 2619.008 \pm 0.021 \) mm to \( 2621.968 \pm 0.014 \) mm. This latter result compares favorably to Rivkin’s determination of 2622 mm.

We also find significant values for \( \epsilon_5 \) and \( \epsilon_6 \), the tip-tilt terms. The net effect of the three distortion terms is plotted in Fig. 2.


<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>$\sigma$</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f$</td>
<td>2619.008</td>
<td>0.021</td>
<td>mm</td>
</tr>
<tr>
<td>$\epsilon_2$</td>
<td>+2.696</td>
<td>0.016</td>
<td>$\times 10^{-5}$ mm$^{-2}$</td>
</tr>
<tr>
<td>$\epsilon_5$</td>
<td>+1.988</td>
<td>0.091</td>
<td>$\times 10^{-5}$ mm$^{-1}$</td>
</tr>
<tr>
<td>$\epsilon_6$</td>
<td>−2.864</td>
<td>0.099</td>
<td>$\times 10^{-5}$ mm$^{-1}$</td>
</tr>
<tr>
<td>$K_x$</td>
<td>76.9231</td>
<td>—</td>
<td>samples/mm</td>
</tr>
<tr>
<td>$K_{xy}$</td>
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<td>—</td>
<td>samples/mm</td>
</tr>
<tr>
<td>$K_{yx}$</td>
<td>0.0</td>
<td>—</td>
<td>lines/mm</td>
</tr>
<tr>
<td>$K_y$</td>
<td>−76.9231</td>
<td>—</td>
<td>lines/mm</td>
</tr>
<tr>
<td>$s_0$</td>
<td>512.5</td>
<td>—</td>
<td>samples</td>
</tr>
<tr>
<td>$l_0$</td>
<td>512.5</td>
<td>—</td>
<td>lines</td>
</tr>
</tbody>
</table>

# ref stars 242
# field stars 909
# data points 5349
RMS resid (0.116, 0.159) $(s,l)$
Goodness of fit 1.17
Figure 1. LORRI postfit residuals. These are scaled up by a factor of 100 and plotted at the location of the image.
Figure 2. LORRI distortion model. The corrections are sampled every 64 pixels and scaled up by a factor of 100.
References:


Distribution:

S. Bhaskaran
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