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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 $\hat{\mathbf{A}}$ 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:

$$\hat{\mathbf{P}} = \mathsf{R}_3(\Omega)\,\mathsf{R}_1(-\chi)\,\mathsf{R}_2(\psi)\,\mathsf{R}_3(\phi)\,\mathsf{R}_2(90^\circ-\delta)\,\mathsf{R}_3(\alpha)\,\hat{\mathbf{A}}, \tag{1}$$

where α and δ are the right ascension and declination of the camera boresight; ϕ is the nominal twist angle of the camera; and ψ, χ, and Ω are misalignments in elevation, cross-elevation, and twist. We ignored the three misalignment angles in this analysis and took α, δ and ϕ from the picture headers.

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

$$\begin{pmatrix} x \\ y \end{pmatrix} = \frac{f}{P_3}\begin{pmatrix} P_1 \\ P_2 \end{pmatrix}; \tag{2}$$

$$r^2 \equiv x^2 + y^2; \tag{3}$$

$$\begin{pmatrix} \Delta x \\ \Delta y \end{pmatrix} = \begin{pmatrix} xr^2 & xy & x^2 \\ yr^2 & y^2 & xy \end{pmatrix} \begin{pmatrix} \epsilon_2 \\ \epsilon_5 \\ \epsilon_6 \end{pmatrix}; \tag{4}$$

$$\begin{pmatrix} s \\ l \end{pmatrix} = \begin{pmatrix} K_x & K_{xy} \\ K_{yx} & K_y \end{pmatrix} \begin{pmatrix} x + \Delta x \\ y + \Delta y \end{pmatrix} + \begin{pmatrix} s_0 \\ l_0 \end{pmatrix}; \tag{5}$$

where f is the camera focal length in mm; the ϵ's are coefficients of cubic radial distortion and detector misalignment; the matrix $\mathbf{K}$ 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}, ϵ_2, ϵ_5, and ϵ_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 $\sqrt{\chi^2_\nu}$), appear in Table 1 below.

The calibration results appear good. The postfit 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 ± 0.01 pixels in the corners of the field. Increasing f and increasing ϵ_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 ϵ_2 are strongly anticorrelated. Holding ϵ_2 fixed at zero causes f to increase from 2619.008 ± 0.021 mm to 2621.968 ± 0.014 mm. This latter result compares favorably to Rivkin's determination of 2622 mm.

We also find significant values for ϵ_5 and ϵ_6, the tip-tilt terms. The net effect of the three distortion terms is plotted in Fig. 2.

Table 1. LORRI 2006 Calibration Results

Parameter	Value	σ	Units
f	2619.008	0.021	mm
ϵ_2	$+2.696$	0.016	$\times 10^{-5}\,\mathrm{mm}^{-2}$
ϵ_5	$+1.988$	0.091	$\times 10^{-5}\,\mathrm{mm}^{-1}$
ϵ_6	-2.864	0.099	$\times 10^{-5}\,\mathrm{mm}^{-1}$
K_x	76.9231	—	samples/mm
K_{xy}	0.0	—	samples/mm
K_{yx}	0.0	—	lines/mm
K_y	-76.9231	—	lines/mm
s_0	512.5	—	samples
l_0	512.5	—	lines
# ref stars	242		
# field stars	909		
# data points	5349		
RMS resid	(0.116, 0.159)		(s, l)
Goodness of fit	1.17		

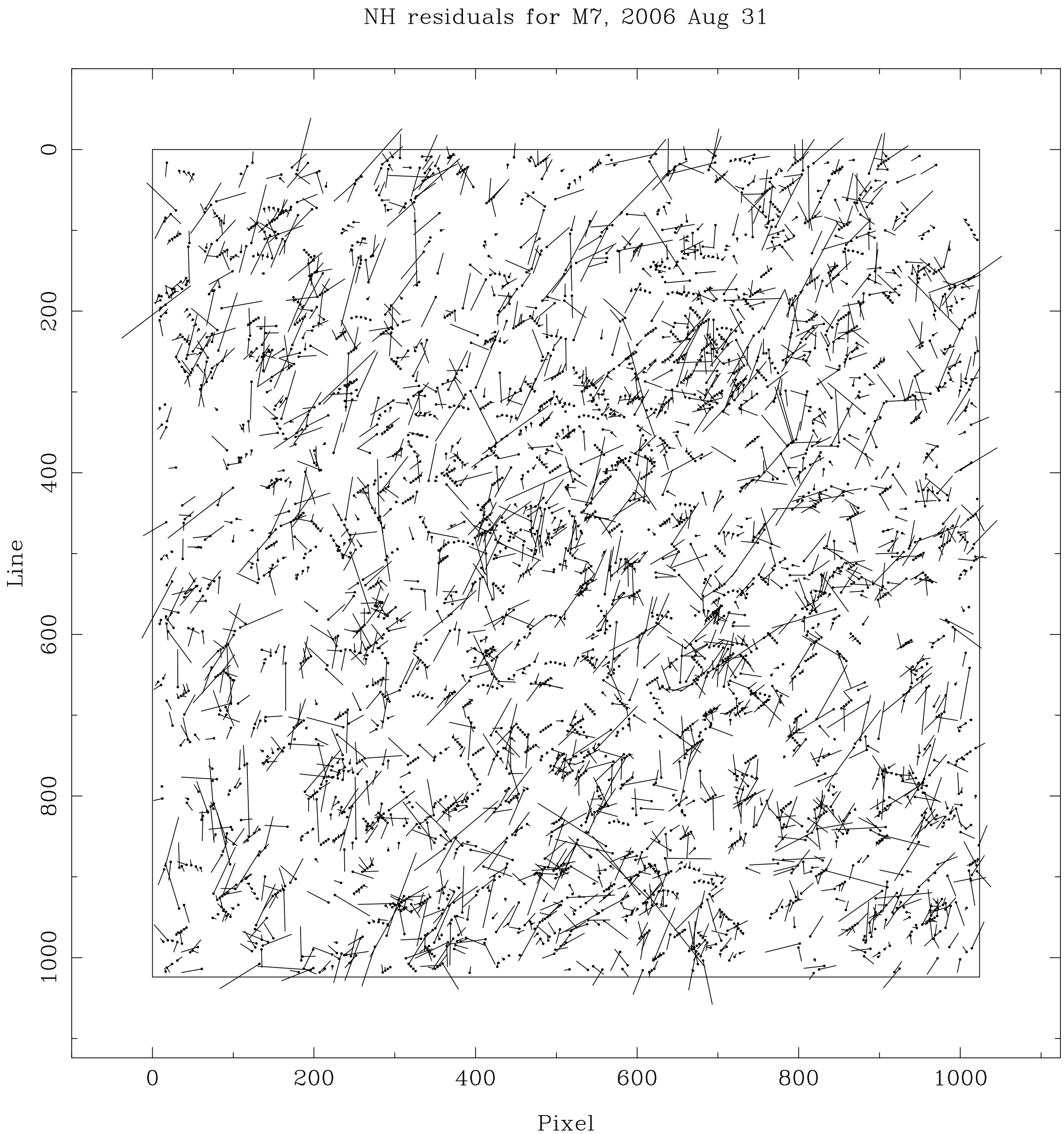

Figure 1. LORRI postfit residuals. These are scaled up by a factor of 100 and plotted at the location of the image.

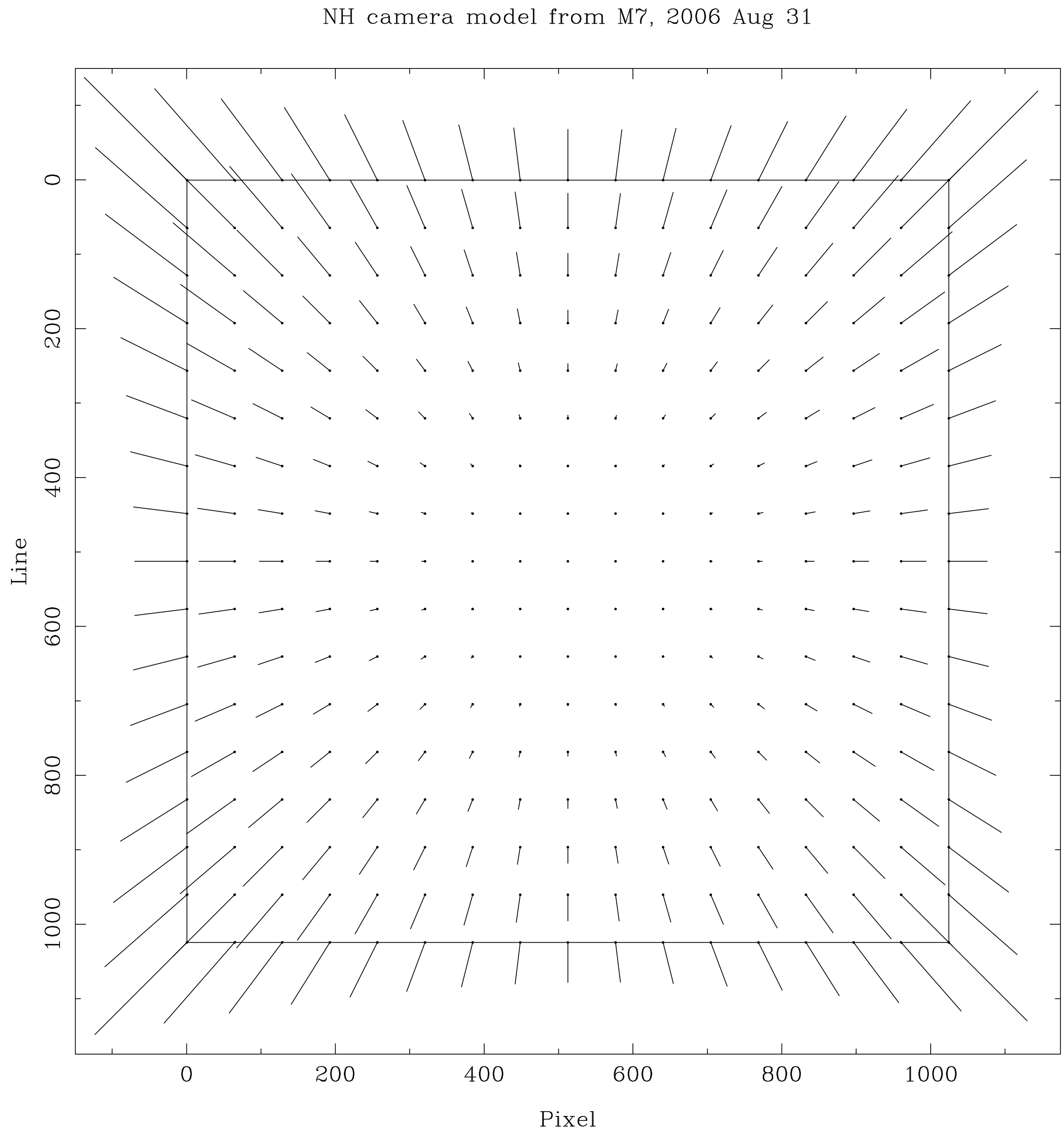

Figure 2. LORRI distortion model. The corrections are sampled every 64 pixels and scaled up by a factor of 100.

References:

1. Rivkin, A., Weaver., H., and the LORRI Team, "Plate Solutions for LORRI from images of M7," March 21, 2008.
2. Cheng, A., F. *et al.*, "Long-Range Reconnaissance Imager on New Horizons," *Space Science Reviews* **140**, 189–215, 2008.
3. Owen, W. M. Jr., and Vaughan, R. M., "Optical Navigation Program Mathematical Models," JPL Engineering Memorandum 314–513, August 9, 1991.
4. Owen, W. M. Jr., "Methods of Optical Navigation," AAS paper 11–215, AAS/AIAA Spaceflight Mechanics Conference, New Orleans, Feb. 2011.
5. Owen, W. M. Jr., "Automated Astrometric Data Analysis System User's Guide," JPL Interoffice Memorandum 312.8–96–013, November 7, 1996.
6. Eichhorn, H. K., *Astron. Nachr.* **285**, 233, 1960.

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