JET PROPULSION LABORATORY

INTEROFFICE MEMORANDUM

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9 May 2003

TO: Distribution

FROM: W. M. Owen, Jr. WMO

SUBJECT: Cassini ISS Geometric Calibration of April 2003

As part of the first onboard test of the Opnav block, Cassini's Imaging Science Subsystem (ISS) took a set of pictures of the open star cluster M35 in Gemini. These pictures fulfilled our expectations and were useful for determining the various geometric properties of both cameras. This memo presents the results of that analysis.

The Observations

We commanded a 3×3 mosaic of simultaneous narrow-angle (NAC) and wide-angle (WAC) pictures, with a shift of roughly $\frac{1}{4}$ of a NAC field of view, or 1.5 mrad, between pictures. We commanded each pointing individually, eschewing the onboard mosaic commands in order to place certain catalogued stars near the corners of the NAC. All exposures were 1.0 second through clear filters. Anti-blooming was disabled in order to maintain a stationary boundary between adjacent rows on the CCDs. The pictures used a gain of 29 electrons per DN, 12 bits per pixel, no binning, and lossless compression. The spacecraft was on reaction wheels, and the telemetry mode was S&ER-5, producing the fastest data transfer to the onboard recorder.

The pictures proved excellent. The actual pointing was within 50 μrad of the commanded pointing. The brightest stars (magnitude 3.4 in the WAC, 6.3 in the NAC) did not saturate, and the dimmest stars visible in the NAC were approximately 13th magnitude. The measured noise in the background was about 0.5 DN in the NAC and 0.8 DN in the WAC.

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 average Gaussian sigma of the fitted point-spread was 0.54 pixel in the NAC and 0.77 pixel in the WAC; the FWHM was therefore 1.3 and 1.8 pixels respectively. Our program attempts to find stars throughout each picture, whether catalogued or not. It detected an average of 243 stars in the NAC field and 332 stars in the WAC field. About 90 of these were catalogued for each camera; we used a brighter cutoff in the WAC predictions.

The camera model

The prediction of the location of a star image in (sample, line) coordinates uses a subset of the full model in Ref. 1. 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:

$$\hat{P} = R_3(\Omega)\, R_1(-\chi)\, R_2(\psi)\, R_3(\phi)\, R_2(90^\circ - \delta)\, R_3(\alpha)\, \hat{A}, \quad (1)$$

where α and δ are the right ascension and declination of the NAC boresight; ϕ is the nominal twist angle of the camera; and ψ, χ, and Ω are misalignments in elevation, cross-elevation, and twist.

Angles ψ and χ are zero by definition for the NAC. For these pictures, the commanded secondary axis was $-X$ to the North Ecliptic Pole, and ϕ is approximately $-90°$. The matrices $\mathbf{R}_i(\theta)$ rotate the coordinate system by angle θ about the ith axis.

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 0.012 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. 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.

Peter Thomas' calibration model (Ref. 2) is similar to the above. He adds the constraint $K_x = K_y$ ("pxl" in his notation). The undistorted positions are (x, y) in my notation and (xfp, yfp) in his. My ϵ_2 is his k. My ϵ_5 and ϵ_6 correspond loosely to changes in s_0 and l_0 coupled with compensating changes to the pointing of the optical axis.

The distortion analysis

We used the Automated Astrometric Data Reduction System (AADRS; Ref. 3) to perform most of the analysis. The algorithm is based on Heinz Eichhorn's overlapping plate technique (Ref. 4), 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}. The non-orthogonality component K_{yx} proved to be insignificant and was removed from the final solution.

The NAC and WAC frames were processed in separate AADRS runs. Then the final NAC pointing was compared to the nominal NAC pointing to determine Ω for the NAC, and the final WAC pointing was compared to the final NAC pointing to obtain ψ, χ, and Ω for the WAC. The results, with their actual uncertainties (the formal sigmas multiplied by the goodness of fit $\sqrt{\chi^2_\nu}$), appear in Table 1 below.

These results will be incorporated into all future opnav deliveries to the nav team (in particular, the OPTDAT file and picture sequence files).

Table 1. Cassini April 2003 Calibration Results

Parameter	NAC Value	NAC σ	WAC Value	WAC σ	Units
f	2002.703	0.065	200.7761	0.0021	mm
ϵ_2	+8.28	0.23	+60.89	0.29	$\times 10^{-6}\,\mathrm{mm}^{-2}$
ϵ_5	+5.45	1.30	+4.93	1.11	$\times 10^{-6}\,\mathrm{mm}^{-1}$
ϵ_6	−19.67	1.15	−72.28	1.11	$\times 10^{-6}\,\mathrm{mm}^{-1}$
K_x	83.33333	—	83.33333	—	samples/mm
K_{xy}	0.0	—	0.0	—	samples/mm
K_{yx}	0.0	—	0.0	—	lines/mm
K_y	83.3428	0.0041	83.34114	0.00057	lines/mm
s_0	512.5	—	512.5	—	samples
l_0	512.5	—	512.5	—	lines
ψ	0.0	—	+0.022924	0.000012	deg
χ	0.0	—	−0.038432	0.000019	deg
Ω	+0.095	0.002	−0.018	0.002	deg
# ref stars	144		99		
# field stars	442		650		
# data points	2188		3022		
RMS resid	(0.056, 0.055)		(0.059, 0.056)		(s, l)
Goodness of fit	3.82		1.82		

Discussion

The calibration results appear good. The postfit star residuals have an RMS scatter below 0.06 pixel, and there is no sign of an obvious trend in the residuals as a function of position on the chip (Figs. 1 and 2). The pixels are systematically rectangular, not square, at the 8-sigma level for the NAC and the 25-sigma level for the WAC. The aspect ratio is statistically the same for both cameras. This effect is probably the result of a step-and-repeat error in the fabrication of the CCDs.

There is, as expected in the optics, some pincushion distortion ($\epsilon_2 > 0$) in the corners of the field. This distortion amounts to 0.45 pixel diagonally in the corners of the NAC and 3.36 pixels in the corners of the WAC.

The most surprising result is the magnitude of ϵ_6. This term models a rotation of the detector about its horizontal axis, causing a square in the sky to project into a trapezoid on the detector. A displacement of the optical axis from the center of the chip will produce the same signature. And indeed, Peter Thomas (Ref. 2) has found that the optical axis of the WAC is located near sample 548.

These results agree well with those presented in Ref. 2. The values for the radial distortion coefficient (ϵ_2 or k) agree within their sigmas: 8.28 ± 0.23 *vs.* $8 \pm 2 \times 10^{-6}$ mm^{-2} for the NAC, 60.89 ± 0.29 *vs.* $62 \pm 3 \times 10^{-6}$ mm^{-2} for the WAC. The values for the focal length (through CL1/CL2 filters) are in reasonable agreement for the WAC but not as close for the NAC: 2002.703 ± 0.065 *vs.* 2002.88 ± 0.04 mm for the NAC, 200.7761 ± 0.0020 *vs.* 200.77 mm for the WAC. However, Thomas did not solve for separate scales in s and l. We found that the pixels are significantly smaller in the line direction. If we remove this parameter, our values of the focal length increase to 2002.82 and 200.785 mm, providing better agreement for the NAC and slightly worse agreement for the WAC.

The same calibration sequence will be repeated on October 10, 2003, in sequence C39. We hope to perform similar calibrations occasionally during the tour phase of the mission, in order to investigate any temporal changes in the model parameters.

References:

1. Owen, W. M. Jr., and R. M. Vaughan, "Optical Navigation Program Mathematical Models," JPL Engineering Memorandum 314–513, August 9, 1991.
2. Thomas, P., "Geometric Calibration of the ISS NAC and WAC," December 18, 2002.
3. Owen, W. M. Jr., "Automated Astrometric Data Analysis System User's Guide," JPL Interoffice Memorandum 312.8–96–013, November 7, 1996.
4. Eichhorn, H. K., *Astron. Nachr.* **285**, 233, 1960.

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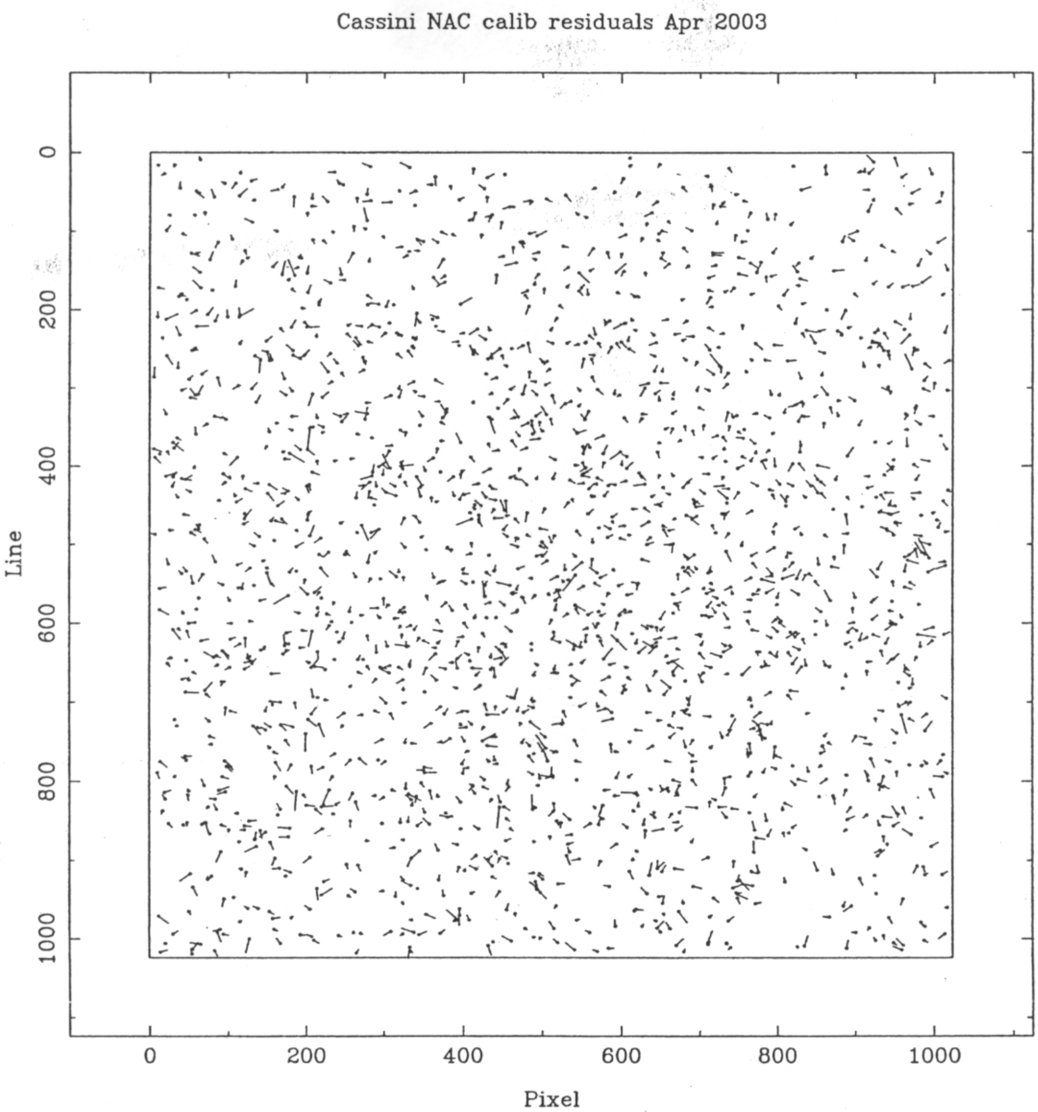

Figure 1. NAC postfit residuals. These are scaled up by a factor of 100 and plotted at the location of the image.

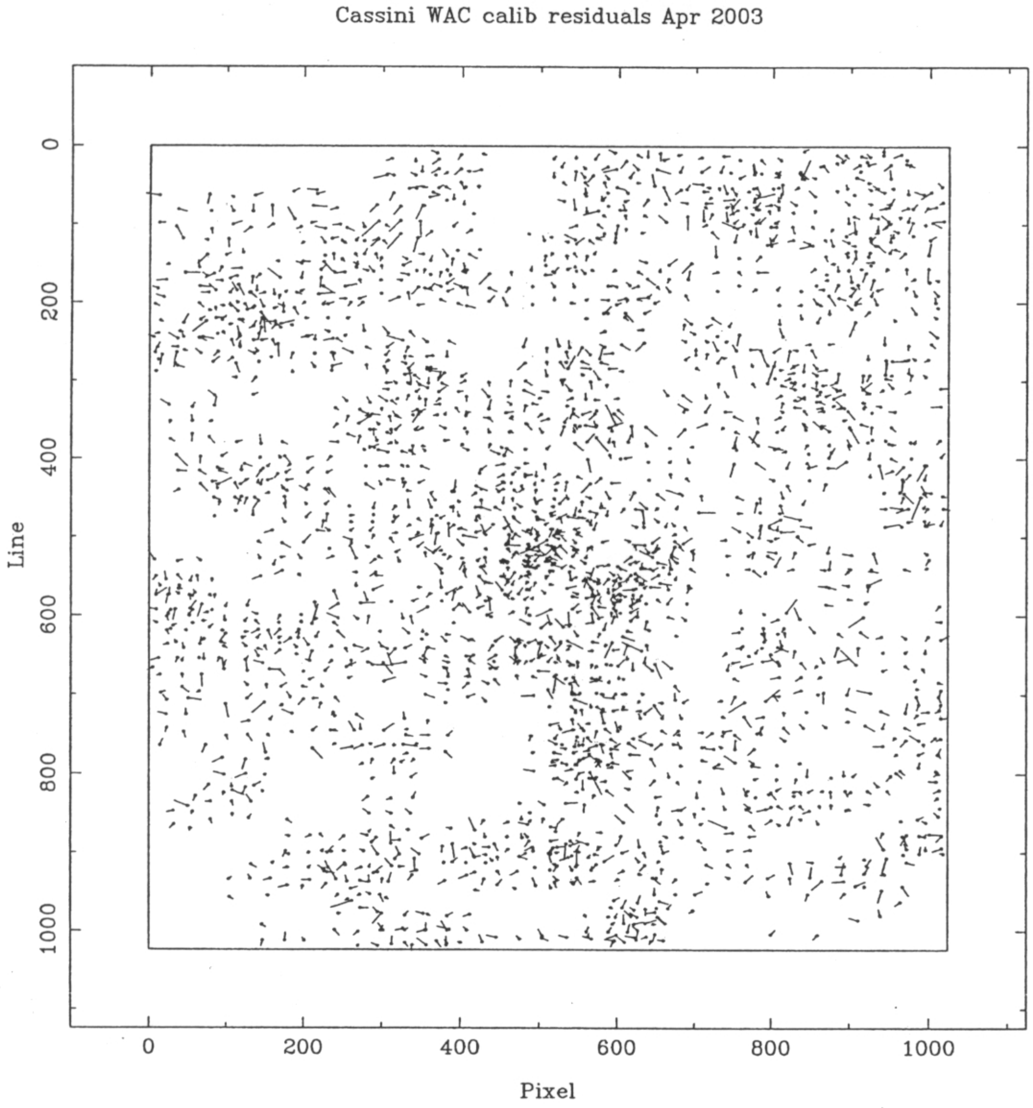

Figure 2. WAC postfit residuals. These are scaled up by a factor of 100 and plotted at the location of the image.

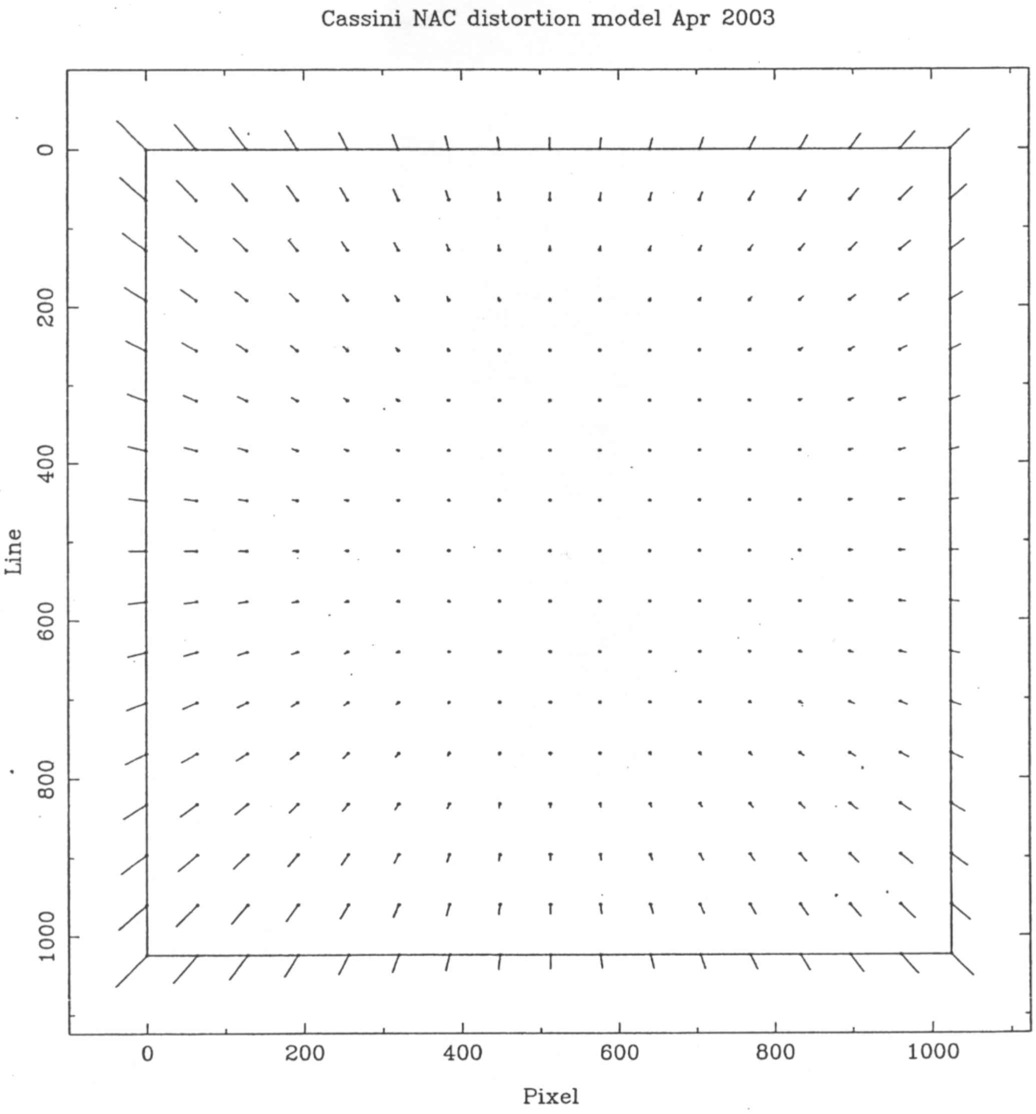

Figure 3. NAC distortion model. The corrections are sampled every 64 pixels and scaled up by a factor of 100.

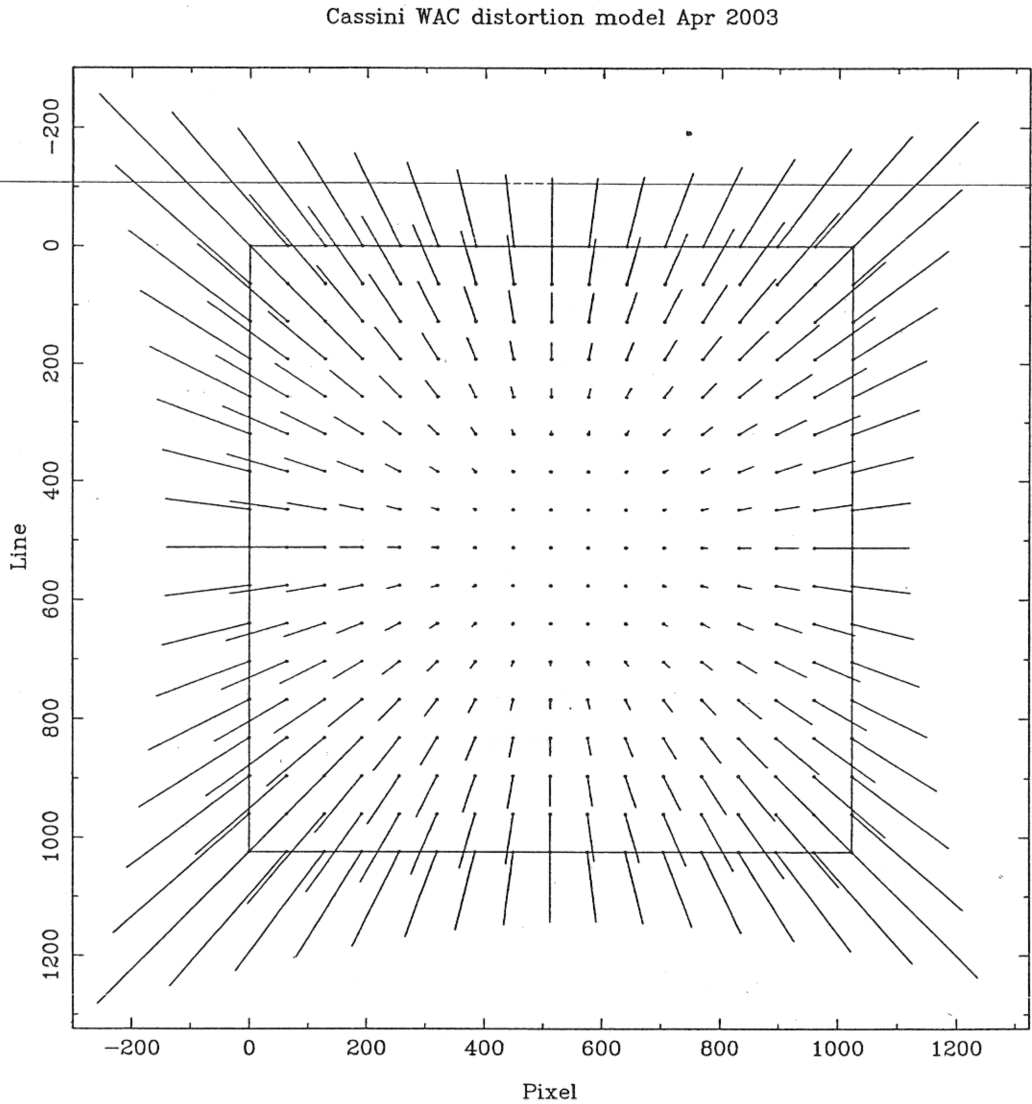

Figure 4. WAC distortion model. The corrections are sampled every 64 pixels and scaled up by a factor of 100. Note that the corrections in the corners are almost 3 pixels in each coordinate, and there is therefore more margin around the field of view in this figure.

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