Calibration of the Actuator Test Stand

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The calibration of the test stand produces a laboratory reference to which all of the pneumatic mirror support actuators for the 6.5m honeycomb mirror can be aligned and calibrated. The intent is to calibrate the mirror support actuators so that they apply the same force vector relative to their mounting surfaces (within tolerances). Therefore the exchange of two actuators in the telescope cell should not disrupt the active optics calibrations of the mirror support forces as a function of zenith angle, temperature, and other parameters. Besides knowing that any two actuators produce the same force vector relative to each other with high precision, we prefer to know the absolute force vector as accurately as the test stand allows. The first requirement is necessary to avoid re-optimization of support forces upon the exchange of two actuators and separates the task of maintaining the support actuators from the task of actively optimizing the figure of the mirror. The second is required to make the absolute force vector as close to the theoretically optimized vector as possible so that initial force optimization is facilitated.

The test stand consists of a work-plate suspended by 6 load cells with in-series flexures (see Figure 1). The 6 cells are arranged in 3 pairs with 2 cells parallel to each of the x, y, and z axes. This test stand was constructed at the UA in 1991/1992 for the purpose of calibrating the actuators for the Air Force 3.5m mirror. It has been used to test prototype actuators for larger mirrors and is now being used to calibrate the actuators for the MMT 6.5m mirror.

The calibration of the test stand is accomplished by applying a series of known forces and moments (load vectors) to the work-plate. Each load vector produces a set of load cell voltages which are converted to forces (force vector). Given a minimum of 6 load and corresponding force vectors, a matrix is determined that will convert an arbitrary force vector into a load vector. In this way, the telescope actuator can be mounted to the stand and its action can be precisely converted into forces and moments.

Load vectors are applied in each of the x,y, and z directions by rotating and leveling the stand. A precision reference block with accurately positioned fiducials at the load application points (15 in all) was attached to the work-plate. A calibrated weight was hung from each application point at the end of a near frictionless pivot.

This is a MathCad document with comments.

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$\mathrm{ORIGIN} \equiv 1$ Change all array origins to 1.

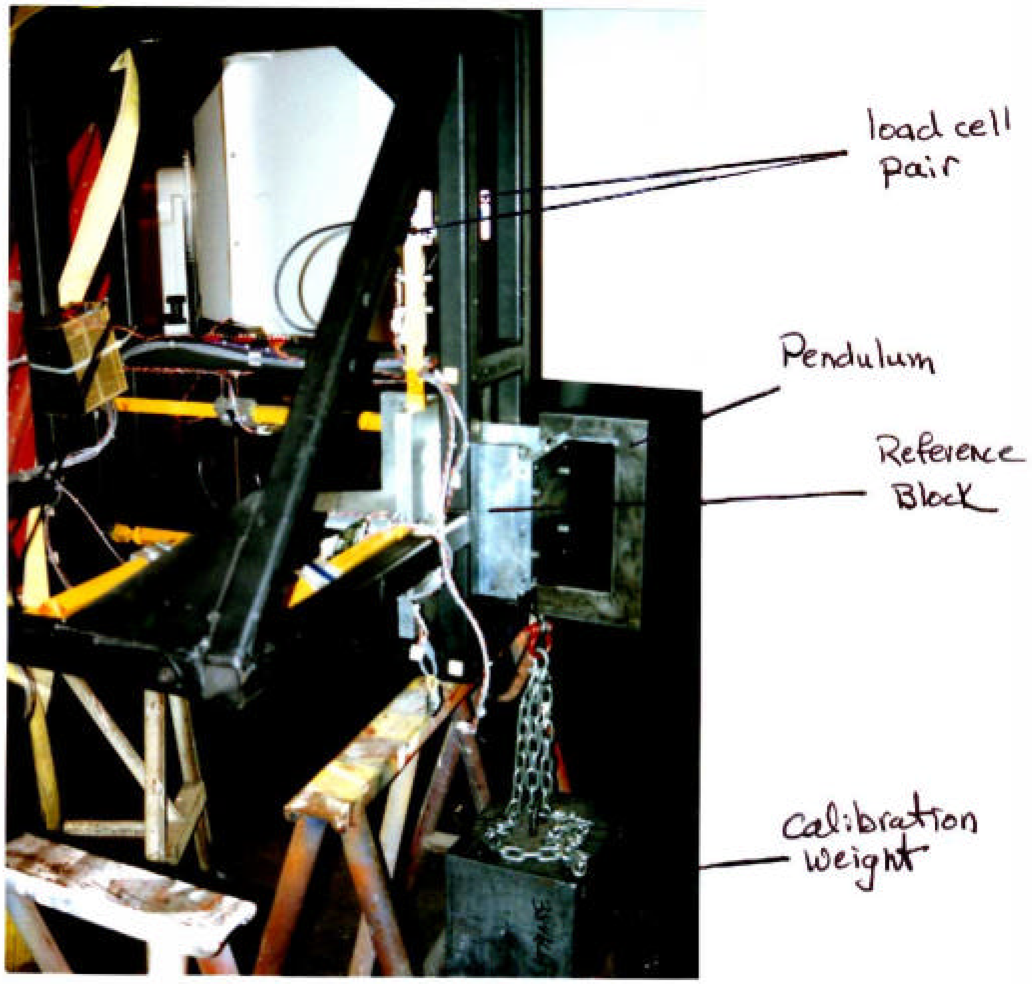

Figure 1: Photograph of the actuator test stand (in one of three orientations) being calibrated. Shown is the frame, 3 load cell pairs, reference block, near-frictionless pendulum, and lead weight.

1. Force Vectors:

$volts := READPRN("tstand.prn")$

Read in voltage vectors. Each row corresponds to a set of load cell voltages produced by applying a load vector. The columns (0-5) correspond to load cells 3, 4,5,6,7,and 8 as marked on the test stand (don't know the history of this numbering scheme!). Each row corresponds to the notch number written on the block.

$$force := \overrightarrow{\frac{-volts}{0.013216}}$$

Element-wise conversion to force (lbs). Note that the conversion is the same for all load cells despite their gain differences. The gain differences will come out in the conversion matrix element slopes. If one of these load cells is replaced, the reading from that channel must be ratioed by the gain of new cell compared to the old (reading = output *(oldgain/newgain)). Columns 1 and 2 are z, 3 and 4 are x, 5 and 6 are y.

Axis sums are obtained by adding the load cell pairs in the x, y, and z directions:

$i := 1 .. rows(force)$

Z

X

Y

$f_{i,1} := force_{i,1} + force_{i,2}$

Z

$f_{i,2} := force_{i,3} + force_{i,4}$

X

$f_{i,3} := force_{i,5} + force_{i,6}$

Y

Each force vector is decomposed into the sum along x, y, and z.

f =

	1	2	3
1	402.077	-1.043	0.789
2	402.145	-0.79	-1.09
3	402.377	-0.531	-2.73
4	400.862	-0.86	1.469
5	400.963	-0.577	-0.222
6	401.125	-0.517	-2.064
7	399.481	-0.633	2.148
8	399.587	-0.286	0.277
9	399.74	-0.384	-1.353
10	1.833	-7.62	408.316
11	1.662	-1.404	408.482
12	1.22	4.115	408.838
13	2.088	397.634	$9.08 \cdot 10^{-3}$
14	1.866	400.456	0.143
15	1.783	403.217	0.263

Note that the variations in the summed axis data for a single stand orientation are real. Measurements made by independently leveling and loading the reference block typically repeated to 0.2 lbs. Under these circumstances the stand repeats to ~0.13%, but in one constant orientation with a fixed support and nearly constant loading point, the stand will perform differential measurements near the 0.05% level. The absolute accuracy of these differential measurements will be determined below.

Load Vectors:

Attached to the stand work-plate is a reference plate which has 15 precision notches drilled into its surface (Figure 2). A weight is hung from each of the notches with the stand in different orientations (with a watch pivot pendulum). Depending on which notches are being used, the stand is rotated in x, y, and z and leveled to less than 1 arcminute. The notches are laid in with a milling machine measured to within 0.0002-in from one of the reference block corners.

By noting the orientation of the stand and the coordinates of the notch with respect to some reference (*e.g.* the work-plate center), the load vector is derived.

The reference block and notches are shown in the figure below. Notches 1-9 are loaded in the +z direction, 10-12 in the +y direction, and 13-15 in the +x direction. (+) loading puts load cells in tension.

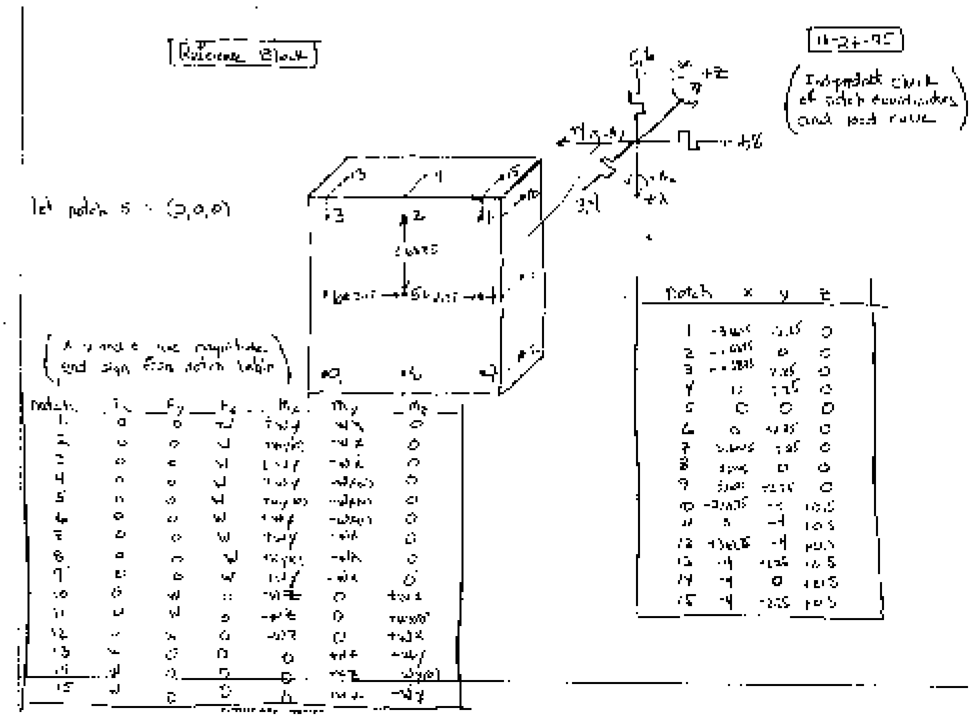

Figure 2: Reference block schematic showing the 15 load application points, their coordinates, and the corresponding load vectors produced.

Weight of hung mass:

The weight consists of a steel c-shaped pivot, 2 shackles, 3 washers, 2 bolts, a chain, and a lead block. The total weight is:

$wt := 388.5 + \frac{154.5}{453.6} + \frac{2950.4}{453.6}$ $wt = 395.345$ Weight (lbs).

Geometry of the reference block notches:

$notch := READPRN("notches.prn")$ Each row gives x,y, and z (i) for each notch as measured from notch 5 of the reference block.

$xoff := -0.07$ $yoff := -0.02$ $zoff := -5.086$ Offset of coordinate origin (i) from point 5 of the reference block. Designating the origin to be at the center top surface of the "T" gives off=(0,0,-5.5). The cross point is 10.950-10.536-5.5 = -5.086-in away from notch 5.

$x := notch^{\langle 1 \rangle} - xoff$ $y := notch^{\langle 2 \rangle} - yoff$ Load notch coordinates into vectors.

$z := notch^{\langle 3 \rangle} - zoff$

$x_7 := x_7 + .007$ $y_7 := y_7 + .011$

$x_9 := x_9 - .012$ $y_9 := y_9 - .009$ $y_4 := y_4 + 0.013$

Upon inspection of the block, the pendulum did not quite seat in the notch centers for these points.

$i := 1 .. 9$ Do all the z loadings (along cells 3 and 4).

$L1_{i,1} := 0$ $L1_{i,2} := 0$ $L1_{i,3} := wt$ Force applied along x, y, and z (lb).

$L1_{i,4} := wt \cdot y_i$ $L1_{i,5} := -wt \cdot x_i$ $L1_{i,6} := 0$ Moments around the x, y, and z axes (i-lbs). Positive moments obey the right hand rule.

$i := 10 .. 12$ Load cases along y (cells 7 and 8).

$L1_{i,1} := 0$ $L1_{i,2} := wt$ $L1_{i,3} := 0$ Forces in x,y, and z.

$L1_{i,4} := -wt \cdot z_i$ $L1_{i,5} := 0$ $L1_{i,6} := wt \cdot x_i$ Moments about x,y, and z.

$i := 13 .. 15$ Loads along x (cells 5 and 6).

$L1_{i,1} := wt$ $L1_{i,2} := 0$ $L1_{i,3} := 0$ Forces along x,y, and z.

$L1_{i,4} := 0$ $L1_{i,5} := wt \cdot z_i$ $L1_{i,6} := -wt \cdot y_i$ Moments about x,y, and z.

Here are the load cases for each notch number. Each row corresponds to a notch with Fx, Fy, Fz, Mx, My, and Mz. Forces in lbs and moments in lb-i.

Fx Fy Fz Mx My Mz

$L1 =$

	1	2	3	4	5	6
1	0	0	395.345	-881.619	$1.43\cdot10^{3}$	0
2	0	0	395.345	7.907	$1.43\cdot10^{3}$	0
3	0	0	395.345	897.433	$1.43\cdot10^{3}$	0
4	0	0	395.345	-876.48	-27.674	0
5	0	0	395.345	7.907	-27.674	0
6	0	0	395.345	897.433	-27.674	0
7	0	0	395.345	-877.271	$-1.488\cdot10^{3}$	0
8	0	0	395.345	7.907	$-1.486\cdot10^{3}$	0
9	0	0	395.345	893.875	$-1.481\cdot10^{3}$	0
10	0	395.345	0	$-2.208\cdot10^{3}$	0	$-1.43\cdot10^{3}$
11	0	395.345	0	$-2.208\cdot10^{3}$	0	27.674
12	0	395.345	0	$-2.208\cdot10^{3}$	0	$1.486\cdot10^{3}$
13	395.345	0	0	0	$2.208\cdot10^{3}$	-897.433
14	395.345	0	0	0	$2.208\cdot10^{3}$	-7.907
15	395.345	0	0	0	$2.208\cdot10^{3}$	881.619

Now grab a subset of load cell forces F and corresponding load cases L with which to solve for the transformation matrices.

$i := 1..6$

$F_{1,i} := force_{1,i}$ $F_{2,i} := force_{3,i}$ $F_{3,i} := force_{8,i}$ $F_{4,i} := force_{10,i}$ Load cell forces.

$F_{5,i} := force_{12,i}$ $F_{6,i} := force_{14,i}$

$L_{1,i} := L1_{1,i}$ $L_{2,i} := L1_{3,i}$ $L_{3,i} := L1_{8,i}$ $L_{4,i} := L1_{10,i}$ Load cases.

$L_{5,i} := L1_{12,i}$ $L_{6,i} := L1_{14,i}$

Solving for the matrices that convert to/from load and force vectors.

Each column of the above force matrix F contains 6 readings for an individual load cell (force). Each force column is related to the load matrix L by:

$F_{i,j} = A\cdot L_{i,1} + B\cdot L_{i,2} + C\cdot L_{i,3} + D\cdot L_{i,4} + E\cdot L_{i,5} + G\cdot L_{i,6}$. where A,B,...G are the row terms for the transformation matrix corresponding to force vector j. So a least squares solution for each row of the transformation matrix looks like:

$SSR(j) = \sum_i \left[F_{i,j} - \left(A\cdot L_{i,1} + B\cdot L_{i,2} + C\cdot L_{i,3} + D\cdot L_{i,4} + E\cdot L_{i,5} + G\cdot L_{i,6}\right)\right]^2$, where j is force vector column. This could be solved six times to get each row of the transformation matrix.

Put in vector form, this is **F** = L * **R**, where **R** is the matrix row corresponding to force column **F**, and L contains the matrix of the selected load cases. Mathcad provides lsolve() to find **R**.

$i := 1..6$

$R^{\langle i\rangle} := \mathrm{lsolve}\left(L, F^{\langle i\rangle}\right)$

Solve for each row of the transformation matrix and stuff each into a column of the matrix R.

$L2F := \mathrm{Re}(R)^T$

Transpose to produce a matrix that converts a load column vector into a force column vector. lsolve returns complex numbers -- just use real part.

$$L2F = \begin{pmatrix} -0.091 & 4.016\times10^{-3} & 0.498 & 2.722\times10^{-4} & -0.1 & 3.184\times10^{-4} \\ 0.09 & 8.009\times10^{-4} & 0.516 & -1.038\times10^{-4} & 0.101 & -5.289\times10^{-4} \\ 0.503 & 3.259\times10^{-3} & -1.351\times10^{-3} & -2.552\times10^{-6} & -3.223\times10^{-4} & -0.098 \\ 0.511 & -6.366\times10^{-3} & -2.447\times10^{-5} & 2.905\times10^{-4} & 1.504\times10^{-4} & 0.102 \\ 3.858\times10^{-3} & 1.114 & -2.544\times10^{-3} & -0.101 & -6.747\times10^{-5} & -3.659\times10^{-5} \\ -1.103\times10^{-3} & -0.092 & 1.677\times10^{-3} & 0.099 & -3.603\times10^{-4} & 2.157\times10^{-4} \end{pmatrix}$$

Test on load case j, and print residuals:

$j := 3$

Residual (lbs)

Measured (lbs)

$$L2F\cdot\left(L1^T\right)^{\langle j\rangle} - \left(force^T\right)^{\langle j\rangle} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \qquad \left(force^T\right)^{\langle j\rangle} = \begin{pmatrix} 53.826 \\ 348.551 \\ -0.997 \\ 0.466 \\ -91.71 \\ 88.98 \end{pmatrix}$$

Inversion gives a matrix that converts a force vector into a corresponding load vector.

$\mathrm{F2L} := \mathrm{L2F}^{-1}$

$$\begin{array}{lcccccccc}
\text{Cell \# -->} & 3 & 4 & 5 & 6 & 7 & 8 & & \text{Nagel's convention} \\
 & 4.702\times10^{-4} & 2.238\times10^{-3} & 1.006 & 0.966 & 2.558\times10^{-3} & -1.998\times10^{-4} & \text{<-- Fx} & \text{Fy} \\
 & -1.35\times10^{-3} & 2.879\times10^{-3} & -2.18\times10^{-3} & -3.842\times10^{-3} & 0.98 & 0.999 & \text{<-- Fy} & \text{Fx} \\
\mathrm{F2L} = & 0.991 & 0.982 & 1.243\times10^{-4} & 2.136\times10^{-3} & -4.809\times10^{-3} & -6.606\times10^{-3} & \text{<-- Fz} & \text{Fz} \\
 & -0.036 & 3.864\times10^{-3} & 0.017 & -6.777\times10^{-3} & 0.91 & 11.031 & & \\
 & -5.061 & 4.878 & -0.925 & -0.847 & 0.016 & 0.038 & & \\
 & 5.381\times10^{-3} & -0.018 & -5.054 & 4.98 & 0.046 & 0.032 & &
\end{array}$$

Nagel's coord convention has x and y swapped from this convention, but the signs are the same.
So when giving the matrix to Trebisky, swap the Fx and Fy and swap Mx and My rows.

Note: My coord convention is written onto the test stand!

Precision with which the derived matrix predicts the load vectors from the force vectors:

$j := 1 .. \mathrm{rows(force)}$

$\mathrm{Resid}^{\langle j\rangle} := \mathrm{F2L}\cdot\left(\mathrm{force}^{T}\right)^{\langle j\rangle} - \left(\mathrm{L1}^{T}\right)^{\langle j\rangle}$

$\mathrm{Resid}^{T} =$

	dFx	dFy	dFz	dMx	dMy	dMz
	1	2	3	4	5	6
1	0	$4.353\cdot10^{-14}$	$-5.684\cdot10^{-14}$	$1.137\cdot10^{-13}$	0	$3.316\cdot10^{-15}$
2	$-2.989\cdot10^{-3}$	-0.118	-0.083	-1.56	3.436	0.234
3	0	$-1.635\cdot10^{-14}$	$-5.684\cdot10^{-14}$	$-1.137\cdot10^{-13}$	0	0
4	-0.07	0.062	0.101	-1.565	1.887	0.951
5	-0.04	0.118	0.054	-2.971	2.318	0.508
6	-0.231	0.044	0.065	0.479	1.925	-0.496
7	-0.1	0.129	0.044	6.469	0.192	2.029
8	0	$6.569\cdot10^{-15}$	$-1.137\cdot10^{-13}$	$6.04\cdot10^{-14}$	$4.547\cdot10^{-13}$	0
9	-0.34	0.119	$-6.507\cdot10^{-3}$	-3.589	6.18	-1.186
10	$-4.725\cdot10^{-14}$	$1.137\cdot10^{-13}$	$9.653\cdot10^{-15}$	$4.547\cdot10^{-13}$	$3.202\cdot10^{-14}$	$2.274\cdot10^{-13}$
11	0.349	-0.09	0.134	1.37	0.138	-1.42
12	$-1.505\cdot10^{-14}$	$1.137\cdot10^{-13}$	$-1.094\cdot10^{-14}$	$4.547\cdot10^{-13}$	$3.168\cdot10^{-14}$	0
13	0.759	0.021	0.035	-0.925	-1.784	-2.619
14	0	0	$1.673\cdot10^{-14}$	$1.538\cdot10^{-15}$	0	$-5.151\cdot10^{-14}$
15	-0.836	-0.032	0.1	1.523	4.521	7.312

$j := 1 .. 6$

$sd_j := \mathrm{stdev}\left[\left(Resid^T\right)^{\langle j\rangle}\right]$ $\qquad$ $pv_j := \max\left[\left(Resid^T\right)^{\langle j\rangle}\right] - \min\left[\left(Resid^T\right)^{\langle j\rangle}\right]$

Standard deviations and peak to valley results.

$$sd = \begin{pmatrix} 0.323 \\ 0.068 \\ 0.053 \\ 2.216 \\ 2.045 \\ 2.12 \end{pmatrix} \qquad pv = \begin{pmatrix} 1.595 \\ 0.247 \\ 0.217 \\ 10.058 \\ 7.965 \\ 9.931 \end{pmatrix}$$

	Nagel's convention
<-- Fx (lb)	Fy
<-- Fy	Fx
<-- Fz	Fz
<-- Mx (lb-i)	My
<-- My	Mx
<-- Mz	Mz

Conclusions:

The precision application of calibrating forces is readily accomplished with precise leveling of the stand and loading of the weight with a near frictionless pivot at known application points.

If the stand is leveled to 1 arcminute and the 3-point support positions change slightly, the stand appears capable of reproducibility near 0.15%. If the stand is held in one orientation with its 3-point support fixed throughout the testing of all telescope actuators and the actuators mounted in nearly the exact same position wrt to the stand, it should be reasonable to expect reproducibility at 1/2 of this value (~0.07%).

Although this allows the actuators to be compared differentially at high accuracy, the absolute determination of forces and moments can only be accomplished with an accuracy of 0.25 to 0.5% per the statistics in the last section of this report. This is likely due to non-reproducible flexing of the stand when changing the position of the load points, incomplete cancellation of spurious effects by the flexures on the load cell arms, some sensitivity to local moments by the load cells, and uncertainties in the force application positions.

The data were obtained by averaging 20 samples from the A/D board. The resulting noise is about 0.1mV p-v (~0.008 lb). Longer term statistics showed a slow electronic drift of about 1mV/hr.

The efforts of Rich Cordova, Warren Davison, Ken Duffek, Patty Esterline, Bob Nagel, John Ray, Rick Teachout, Tom Trebisky, and Jeff Urban made this calibration possible.