Overview of Chandra IRU Calibration History for 1999:241 to 2002:321

OUTLINE

- On-board rate computation
- IRU calibration concepts
- History of IRU calibration
- OAC IRU calibration
- Calibration uplinked July 2002
- Investigation of unexpected large update leads to additional calibration adjustments
- Components of difference matrix and observed time dependence
- 1-year calibration results
- 6-month calibration results
- Follow-up actions and comments

On-Board Rate Computation

$$\vec{\omega} = (I + M)\, G \begin{bmatrix} f_1^{(\pm)}\, \delta N_1 \\ f_2^{(\pm)}\, \delta N_2 \\ f_3^{(\pm)}\, \delta N_3 \\ f_4^{(\pm)}\, \delta N_4 \end{bmatrix} - \vec{b}$$

δN_n is change in count for channel n in time δt.
$\vec{b}$ is 3-vector bias.

Uplinkable k-constants are

- 9 components of 3×3 adjustment matrix M
- 12 components of 3×4 matrix G (pseudo-inverse matrix)
- 8 scale factors: $f_1^{(+)}, f_2^{(+)}, f_3^{(+)}, f_4^{(+)}$ for positive rates and $f_1^{(-)}, f_2^{(-)}, f_3^{(-)}, f_4^{(-)}$ for negative rates

Original IRU calibration scenario was to update M with OFLS and continue using prelaunch values for G and $f_n^{\pm}$.

IRU Calibration Concepts

If rate $\vec{\omega}$ is computed with misalignment M and rate $\vec{\omega}'$ is computed with with misalignment M', then the difference in rates can be related to a "difference matrix" D,

$$\Delta\vec{\omega} = \vec{\omega}' - \vec{\omega} = D\,\vec{\omega}$$

where $D = \left(I + M'\right)\left(I + M\right)^{-1}$. OFLS/IRUCAL and the one-shot calibration methods use star and gyro data to find the matrix D which minimizes the post-maneuver attitude error. Given D and M, the new misalignment matrix is

$$M' = D\left(I + M\right) - I$$

IRU Calibration Concepts (continued)

The difference matrix is 3x3, which is 9 parameters. It is convenient to express the difference matrix to arcsec, which then gives the rotation difference in arcsec per radian of rotation.

The total number of independent IRU calibration parameters is 16. The individual gyro-axis calibration method solves for 4 parameters per axis by solving for parameters "hidden" from the difference matrix and for plus and minus scale factors. This method uses the solved-for difference matrix and the difference in counts for each of the 4 gyro axes to determine the actual and observed rotation around each gyro axis.

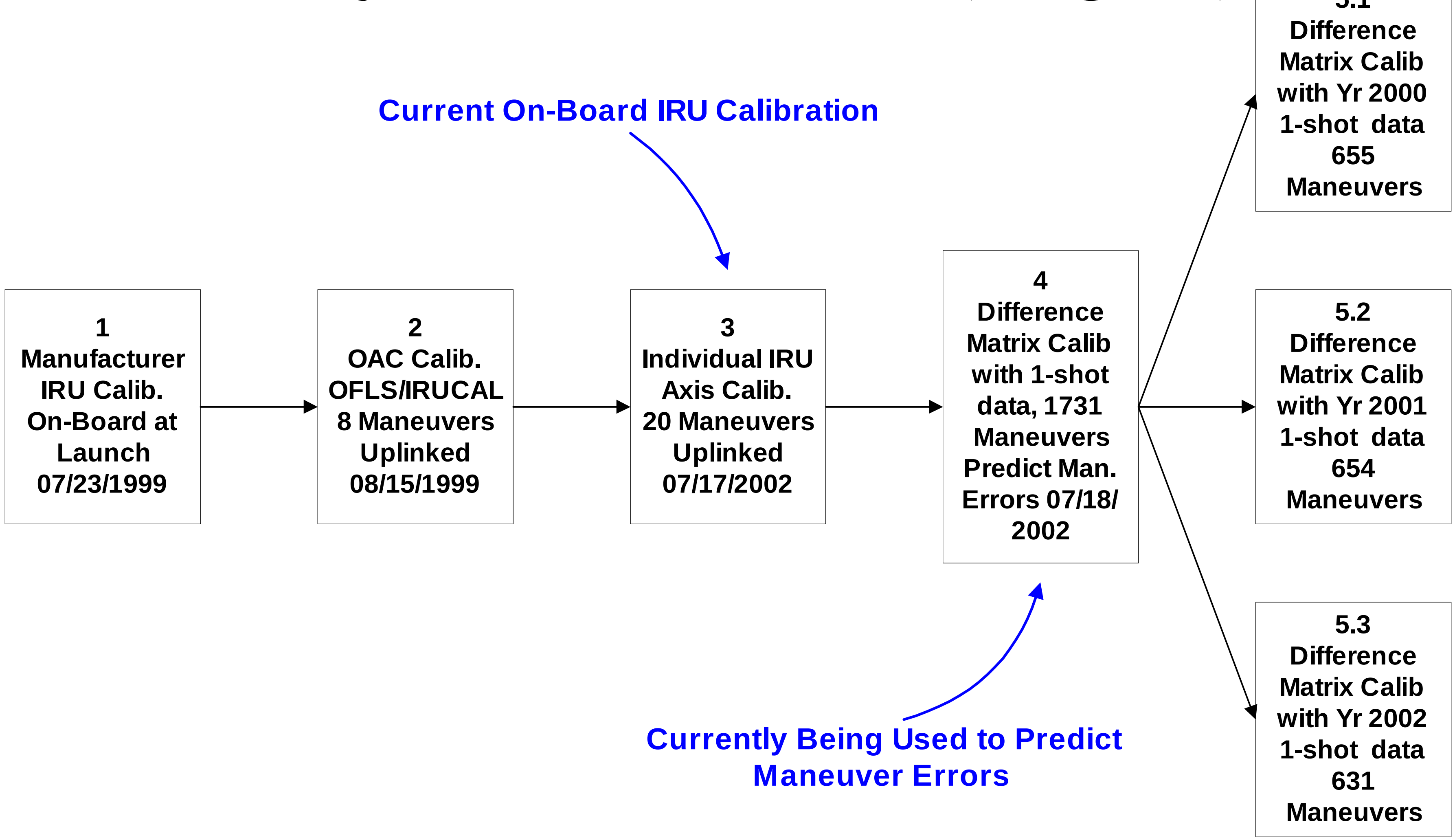
History of IRU Calibration

1. **Manufacturer Supplied Calibration**
   - **±Scale factors, G-matrix, M-matrix all zeros**
   - **On-board at launch 7/23/1999**
2. **OAC Calibration**
   - **OFLS/IRUCAL computed M-matrix**
   - **Data from 8 maneuvers**
   - **Calibration computed and uplinked 8/15/1999**
3. **Individual Gyro-Axis Calibration**
   - **OFLS/IRUCAL & Mathcad calibration of gyro-axes & ±scale factors**
   - **Data from 20 maneuvers (from second half of 2000)**
   - **Uplinked 7/17/2002, ±scale factors, G-matrix, M-matrix all zeros**
4. **One-Shot Error Minimization**
   - **Mathcad calibration of M-matrix with linearized method**
   - **Data from 1731 maneuvers > 30 deg (from 1999:241 to 2002:197)**
   - **On 7/18/2002, use updated M-matrix for maneuver error prediction**

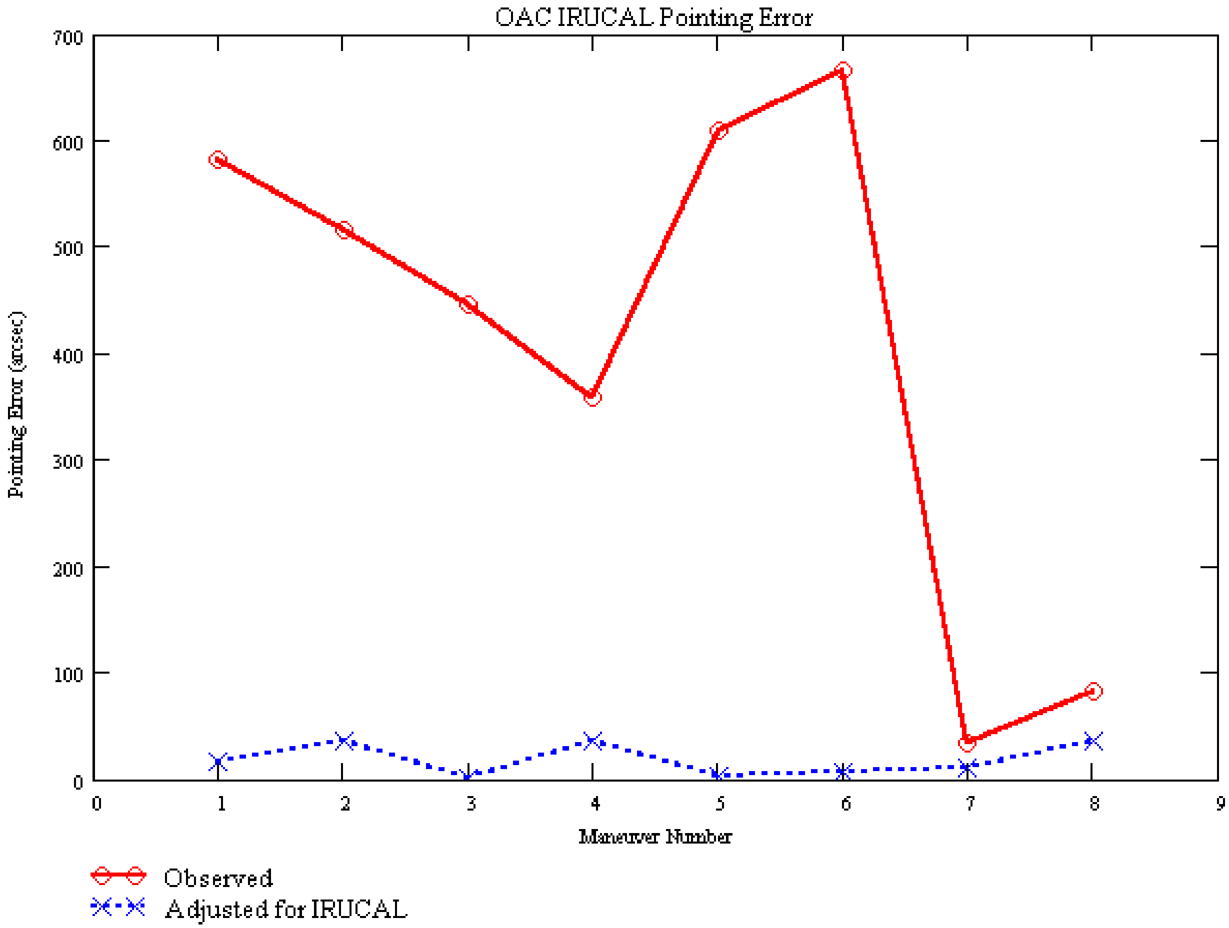
History of IRU Calibration (Continued)

5. **One-Shot Error Minimization**
   - **Mathcad calibration of M-matrix**
   - **Method provides sufficient statistics for yearly or 6-mo. calibrations**
   - **Data from maneuvers > 30 deg (from 2000:001 to 2002:197)**
   - **Years 2000, 2001, and 2002 separately calibrated**
   - **Also, six 6-month intervals separately calibrated**

History of IRU Calibration (Diagram)



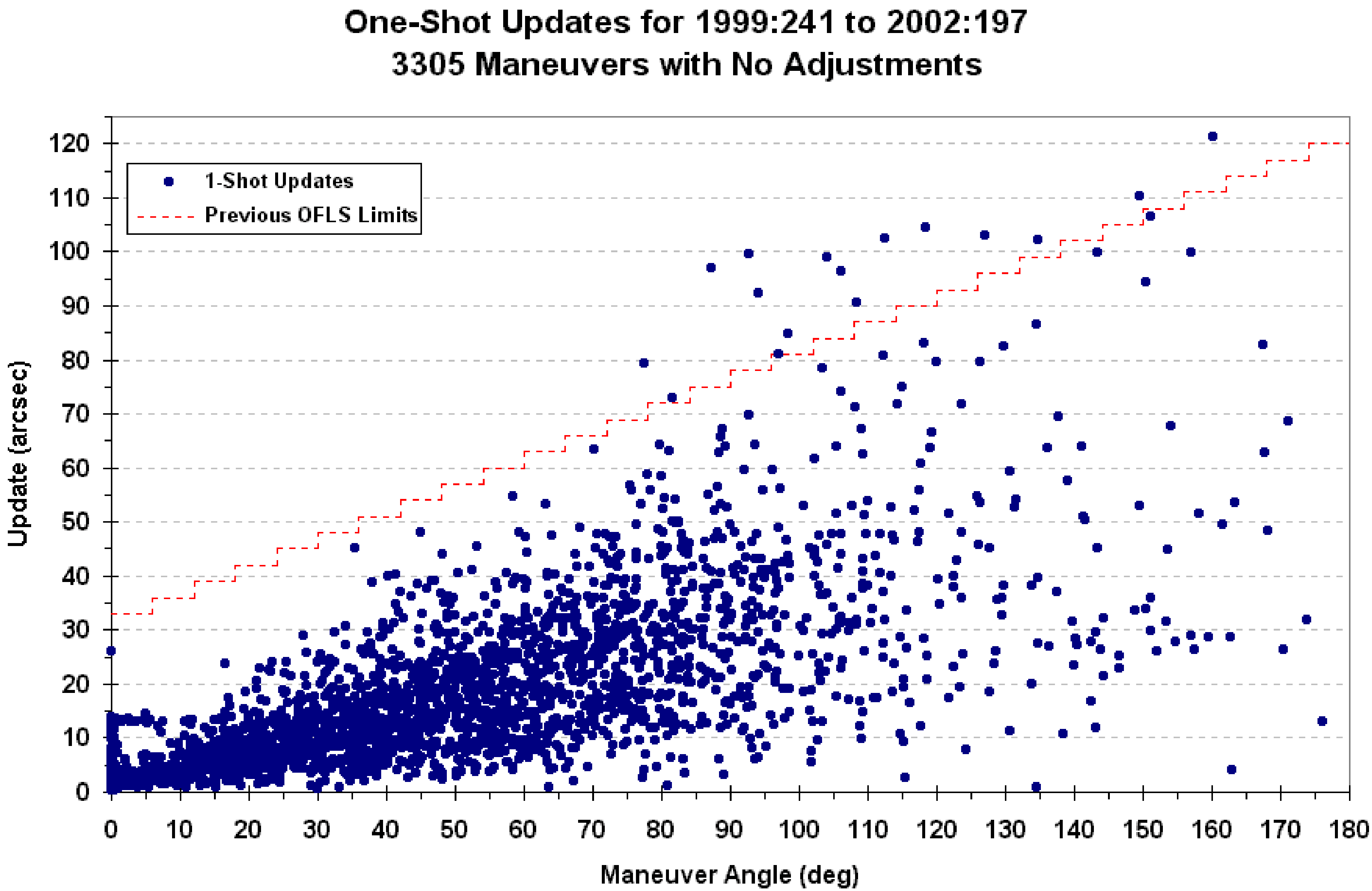
Post-Maneuver Pointing Errors for 8 Maneuvers of OAC IRU Calibration (Calib 2) and Adjusted Errors



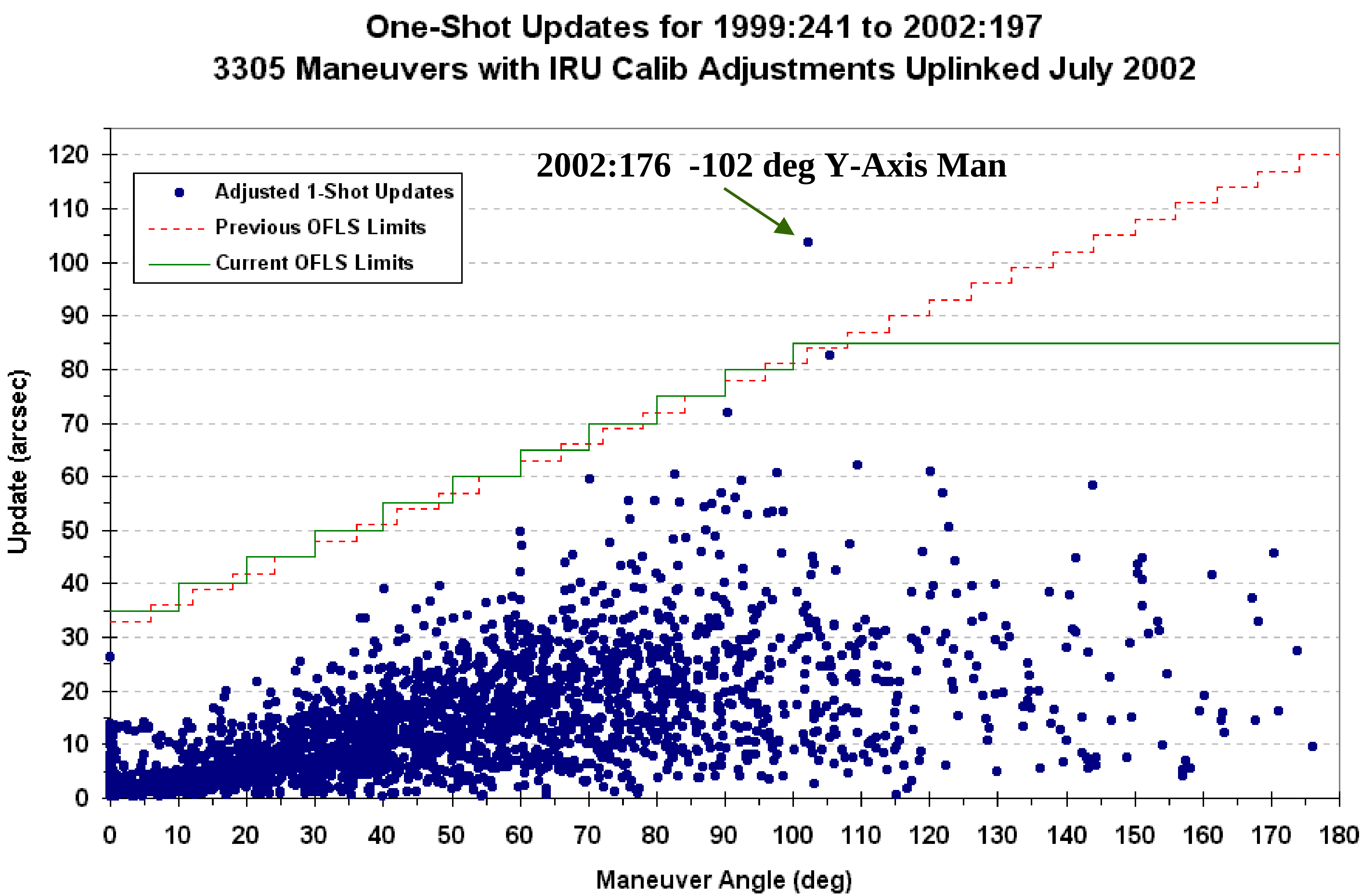
$D = M_{OAC} =$

$$\begin{bmatrix} -9.78 & 14.77 & -13.39 \\ -21.48 & 20.46 & -663.34 \\ 31.43 & 650.26 & 5.97 \end{bmatrix} \text{arcsec}$$

Calibration contains 657-arcsec rotation around X-axis.



In-Flight Results Using Calib 2

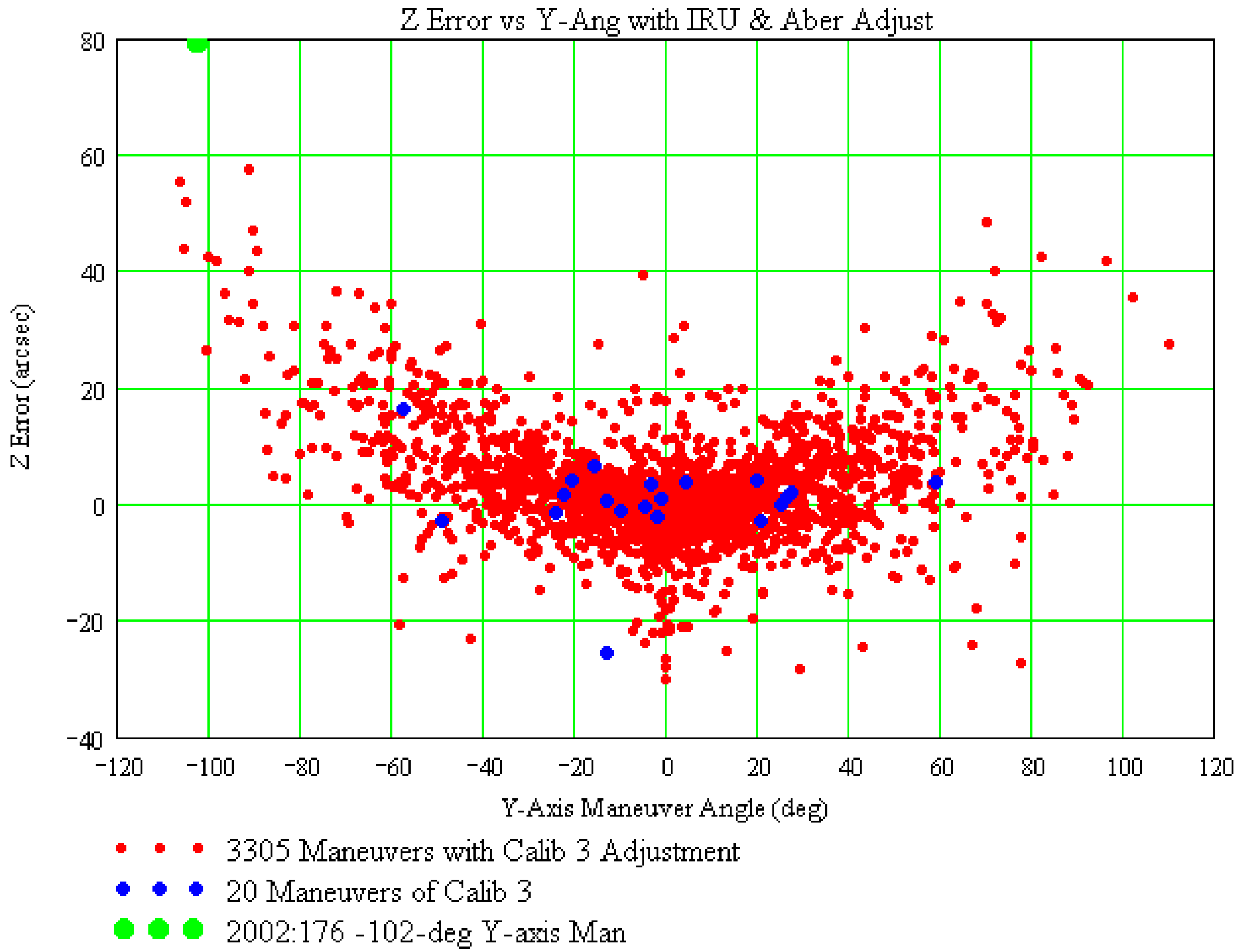


In-Flight Results Adjusted for Calib 3

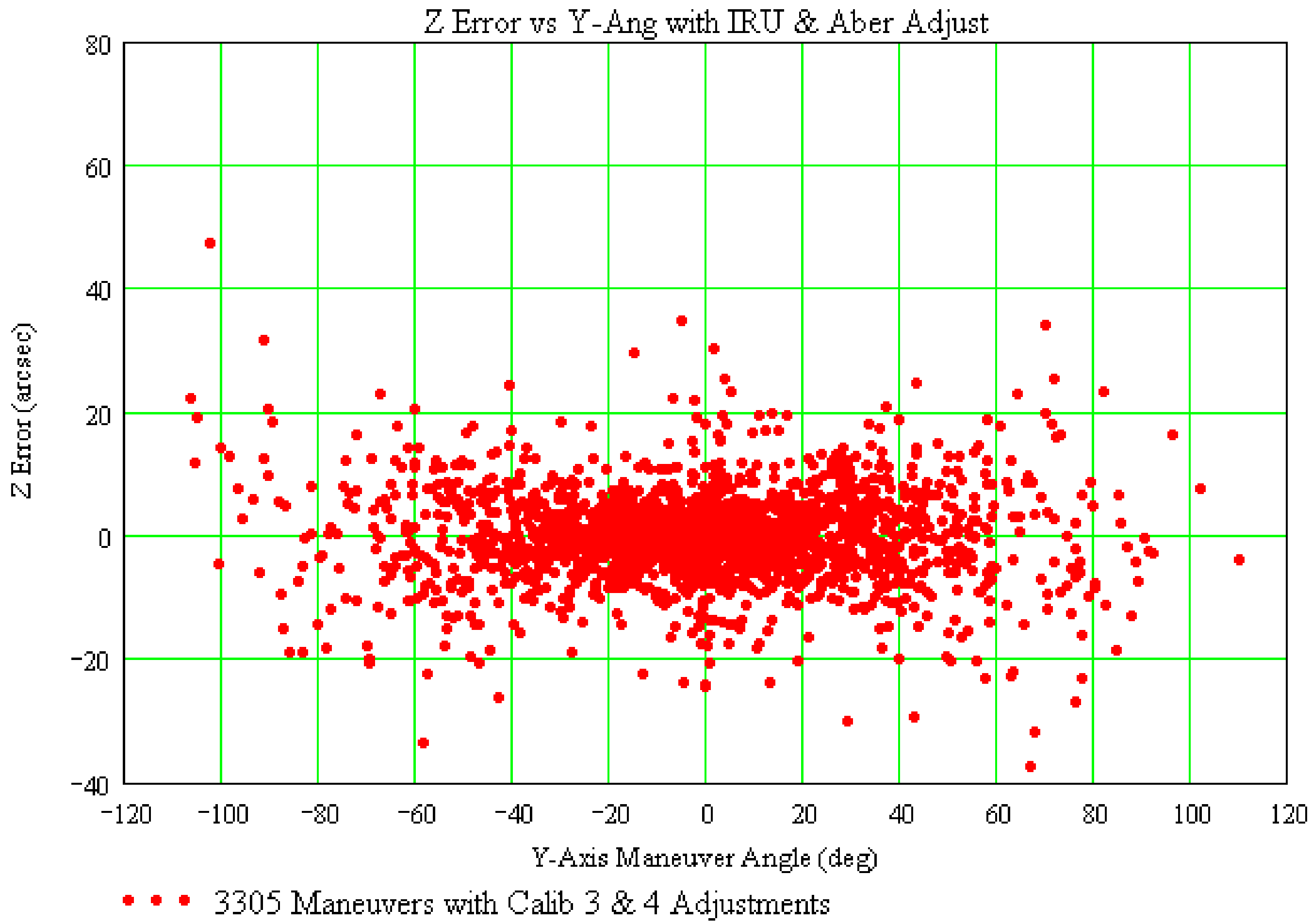
Investigation of 2002:176 Large Error

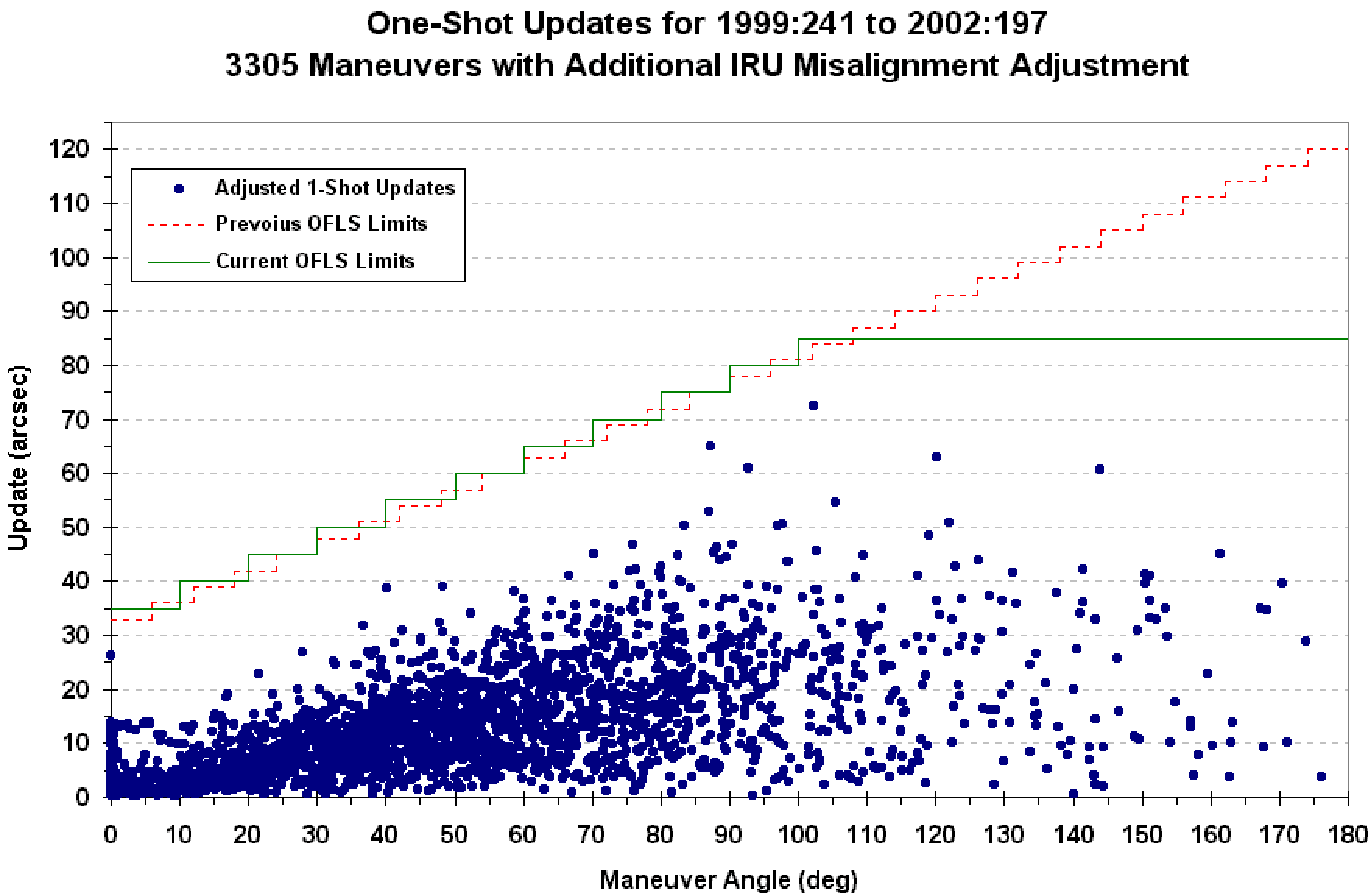
- Plot Y- and Z-errors vs components of rotation vector with adjustments for Calib 3 and aberration
- Graph on page 12 shows plot with largest systematic error, Z-error vs Y-axis maneuver angle
- Inspection of graph shows obvious systematic error not observed with 20 maneuvers of Calib 3 due to insufficient statistics and maneuver range
- Use 1731 one-shot errors (1999:241 to 2002:197) for maneuvers greater than 30 deg to compute new M-matrix, Calib 4
- Graph on page 13 shows plot of Z-error vs Y-axis maneuver angle with adjustments for Calib 3 & 4 and aberration
- Systematic error significantly reduced

Z-Error vs Y-Axis Maneuver Angle with Calib 3 Adj



Z-Error vs Y-Axis Maneuver Angle with Calib 3 & 4 Adj





In-Flight Results Adjusted for Calib 3 & 4

Components of Difference Matrix

The (j, k) component of the difference matrix gives the difference in the j-component of the rotation vector per rotation angle around the k-component of the eigen axis. Diagonal components of D indicate differences in scale factors. Off-diagonal components of D indicate differences in alignment.

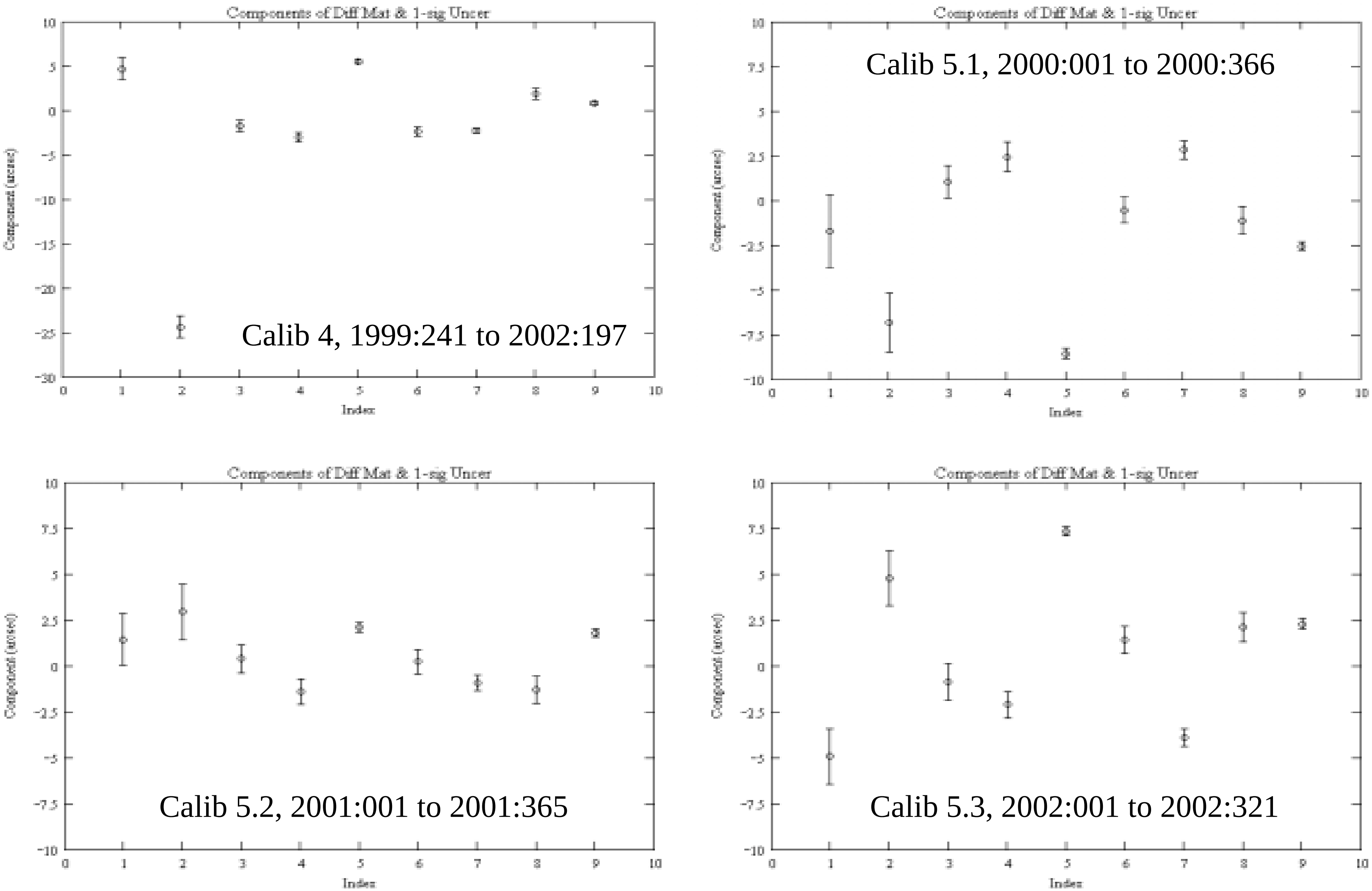
Indicate components of difference matrix with a single index,

$$D = \begin{bmatrix} D_{11} & D_{12} & D_{13} \\ D_{21} & D_{22} & D_{23} \\ D_{31} & D_{32} & D_{33} \end{bmatrix} = \begin{bmatrix} X_1 & X_2 & X_3 \\ X_4 & X_5 & X_6 \\ X_7 & X_8 & X_9 \end{bmatrix}$$

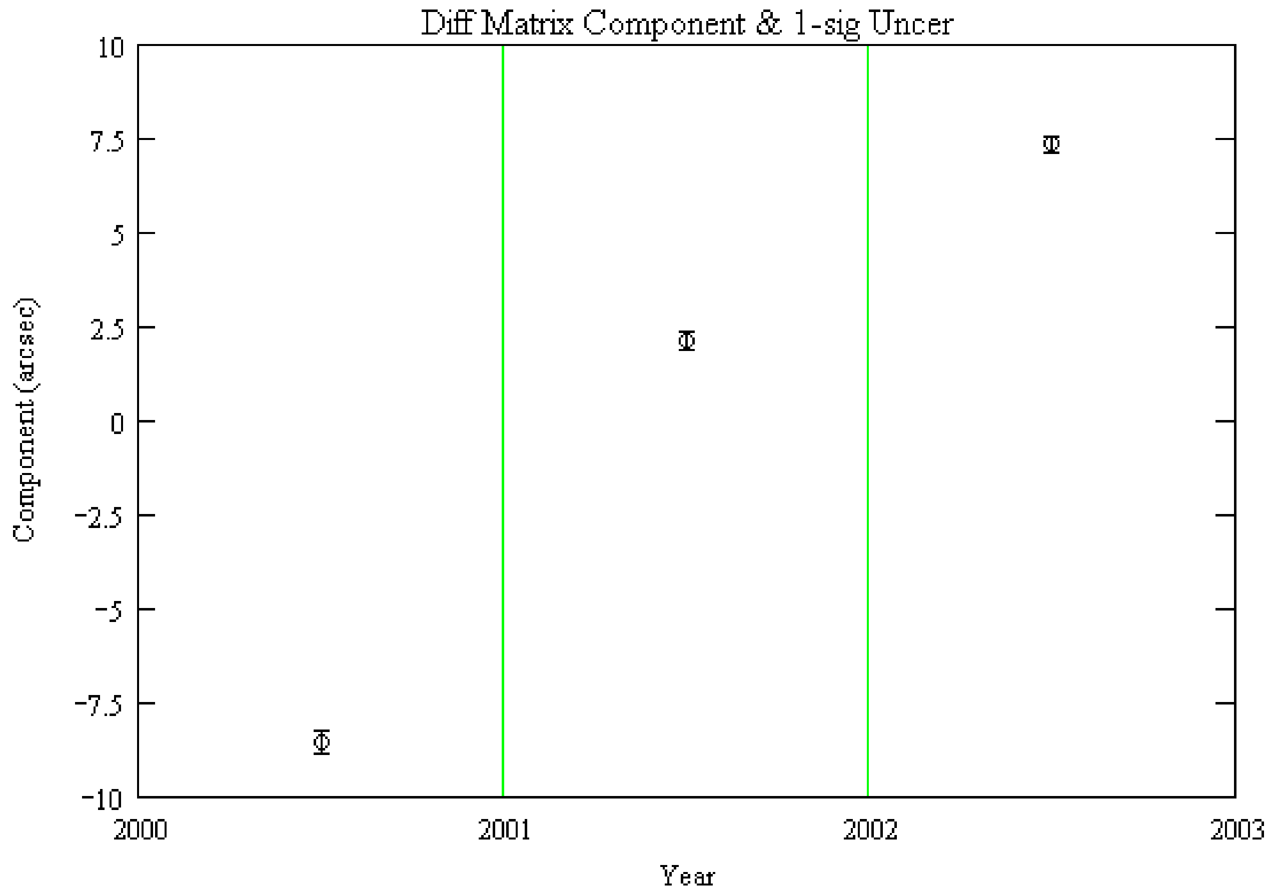
Components of Difference Matrix for Calib 4 & 5

- Graphs on page 17 show components of difference matrices for Calib 4 & 5
- The D(1,2) component of Calib 4 is about 25 arcsec and accounts for most of the systematic error seen in the graph on page 12
- Calib 5.1, 5.2, and 5.3 provide additional adjustments to Calib 4 for the years 2000, 2001, and 2002, respectively
- Graphs on pages 17, 18, and 21 show time-dependence of D(2,2) and D(3,3) components of Calib 5
- Graphs on pages 19 and 20 show Y-error vs Y-angle for Calib 4 and 5; we see improvement with time-dependent Y-axis scale adjustment D(2,2)
- Graphs on pages 22 and 23 show Z-error vs Z-angle for Calib 4 and 5; we see improvement with time-dependent Z-axis scale adjustment D(3,3)

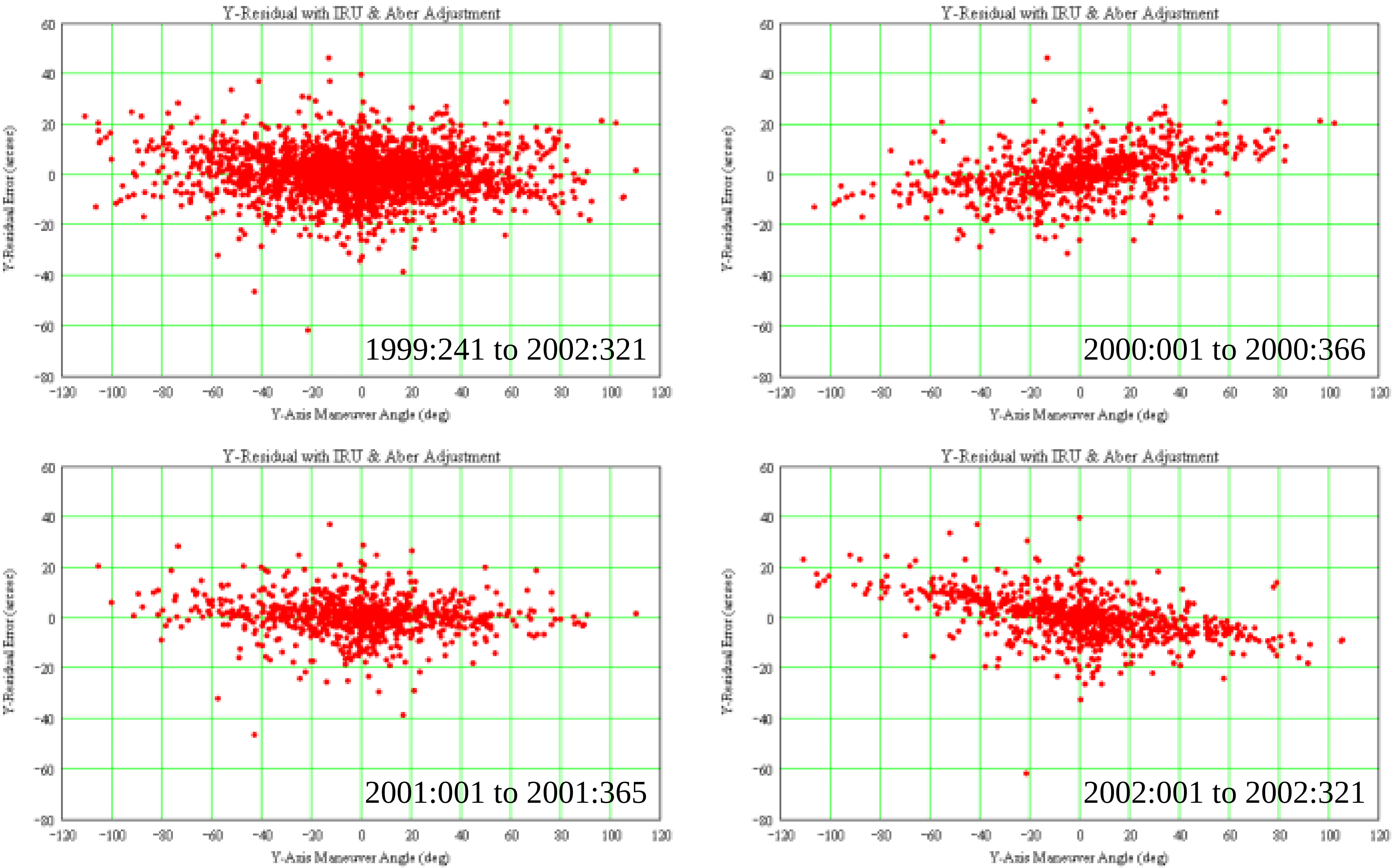
Components of Calibrated Rate Difference Matrix & 1-sig Uncertainty for Various Time Intervals



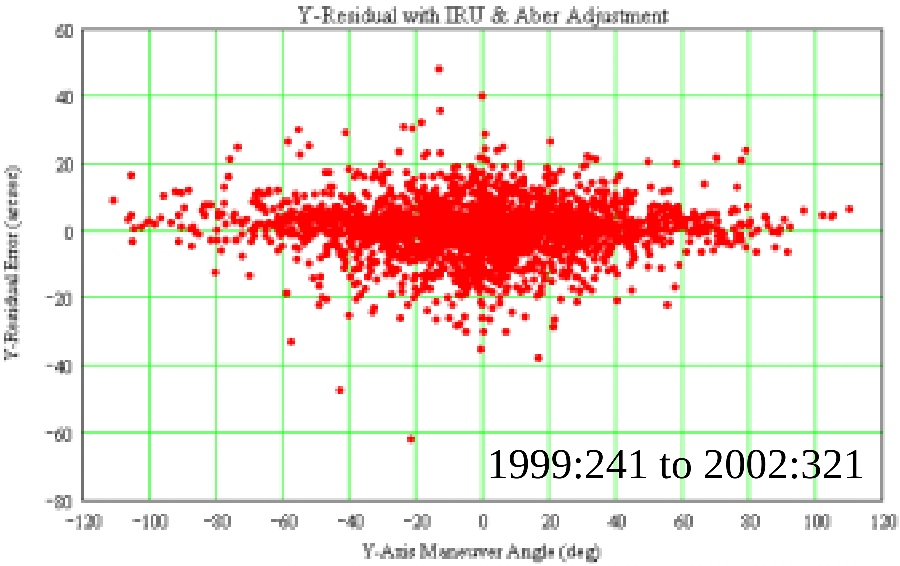
(2,2) Component of Difference Matrix from Calibration of 1-Shot Updates per Year

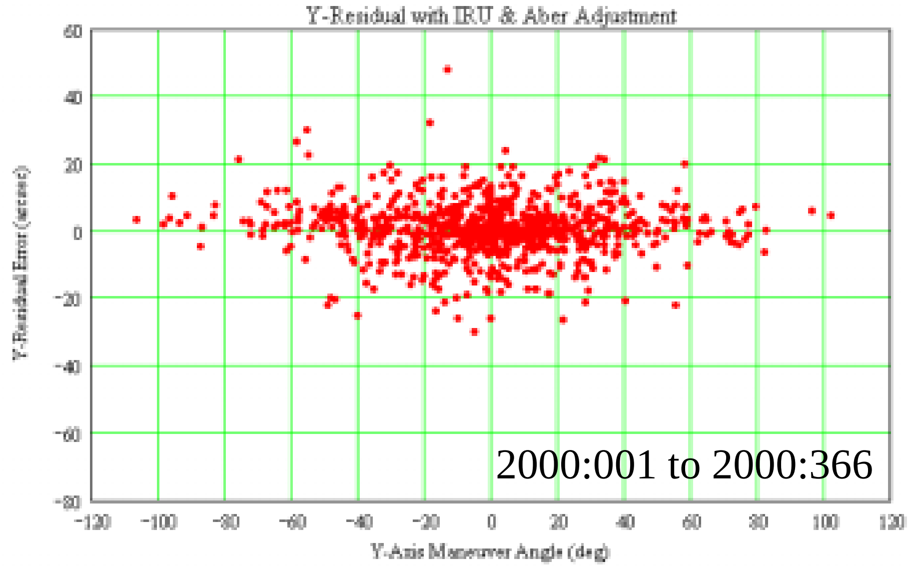


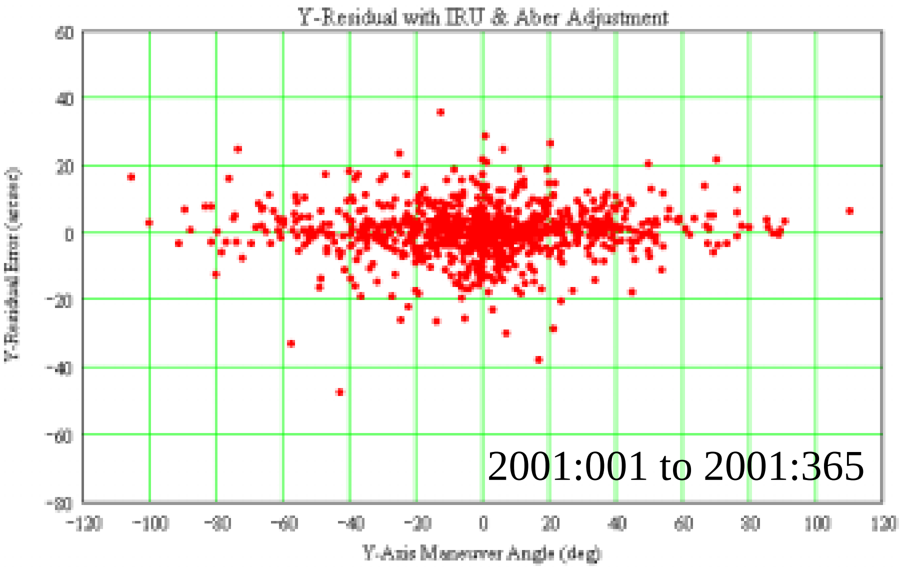
Y-Error Adjusted for IRU Calib 4 & Aberration vs Y-Axis Maneuver Angle

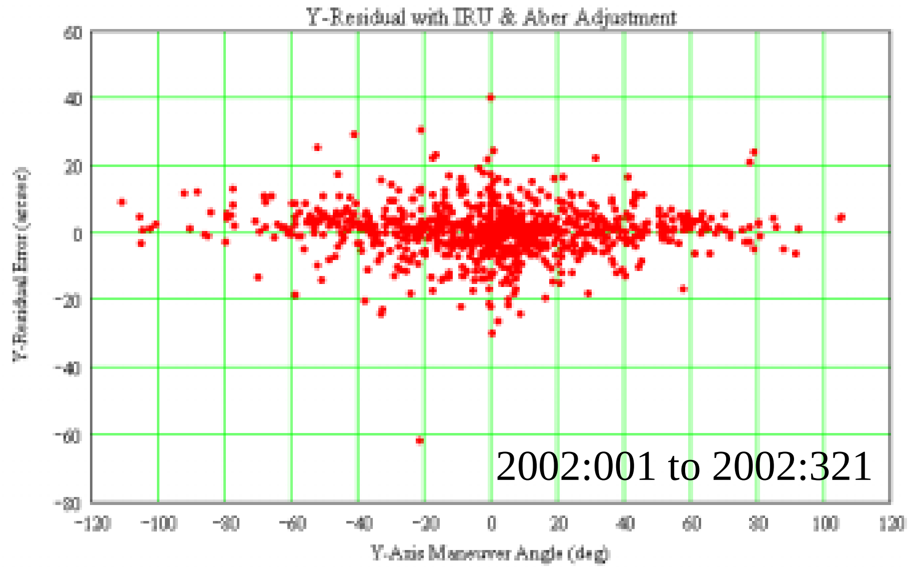


Y-Error Adjusted for IRU Calib 5.1, 5.2, 5.3, & Aberration vs Y-Axis Maneuver Angle

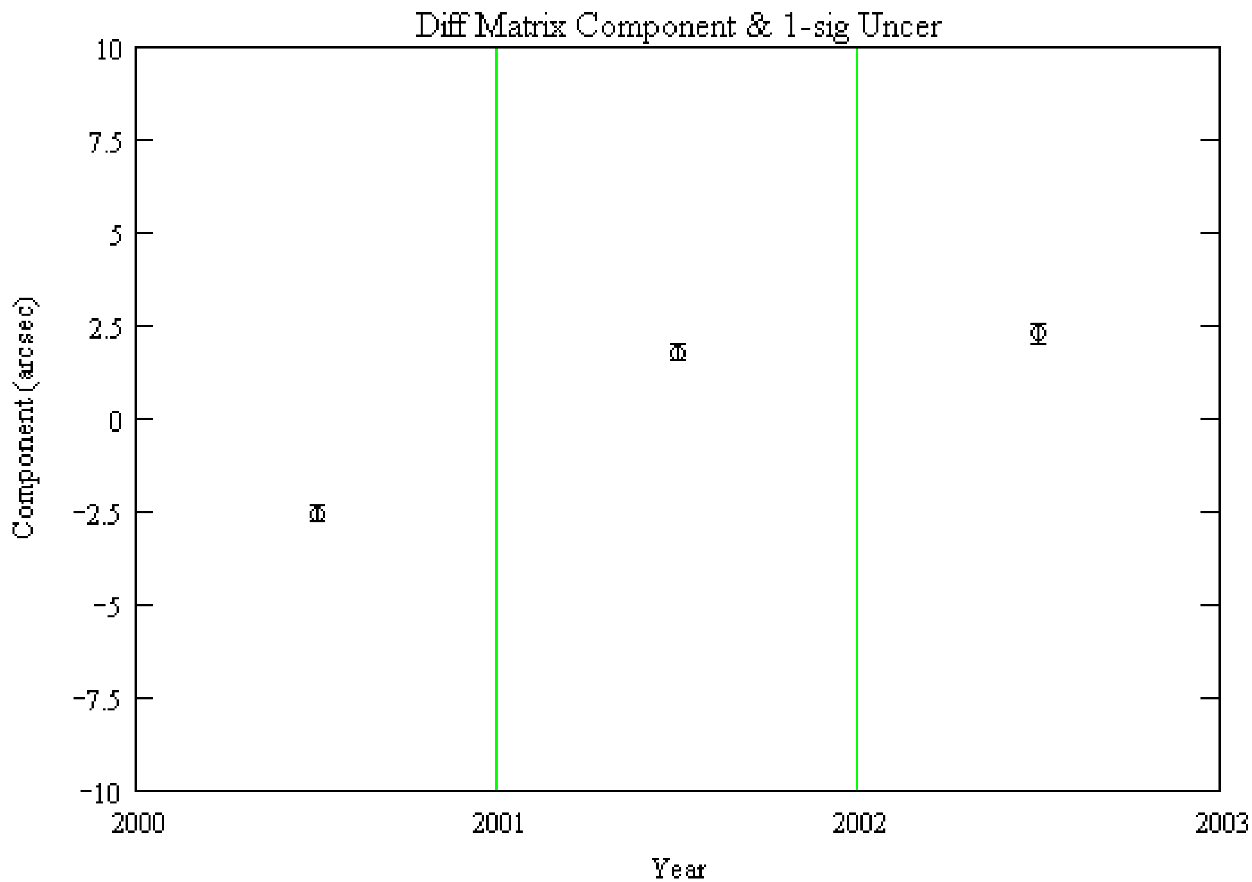




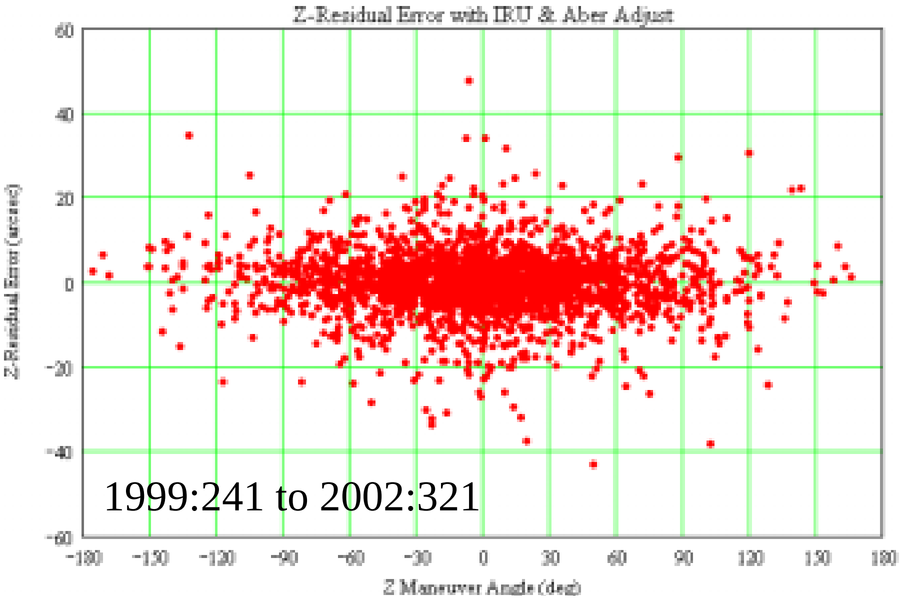


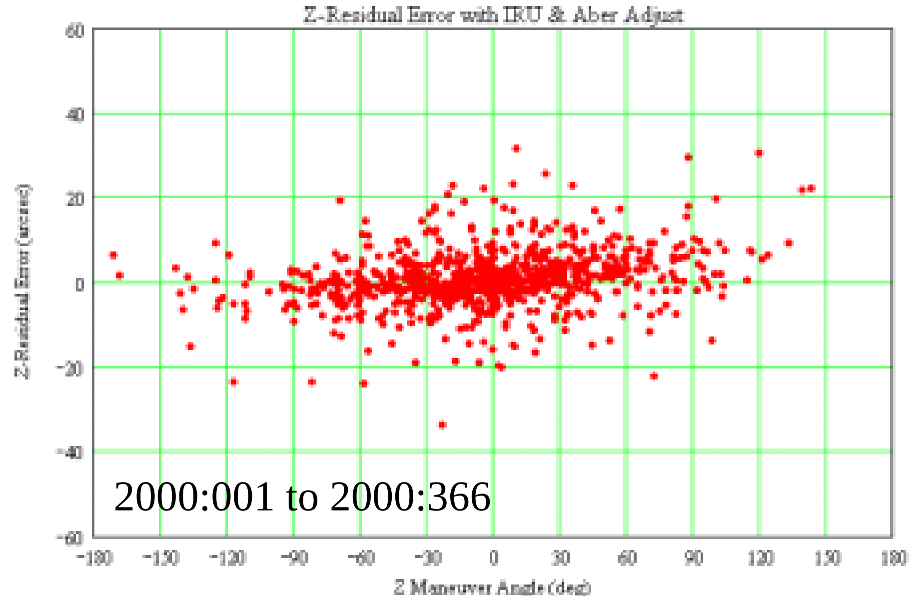


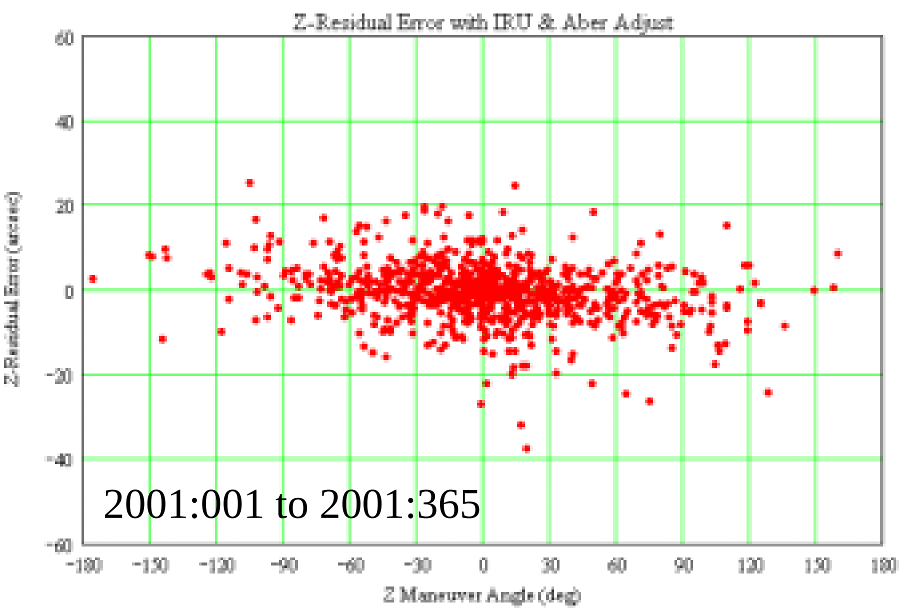
(3,3) Component of Difference Matrix from Calibration of 1-Shot Updates per Year

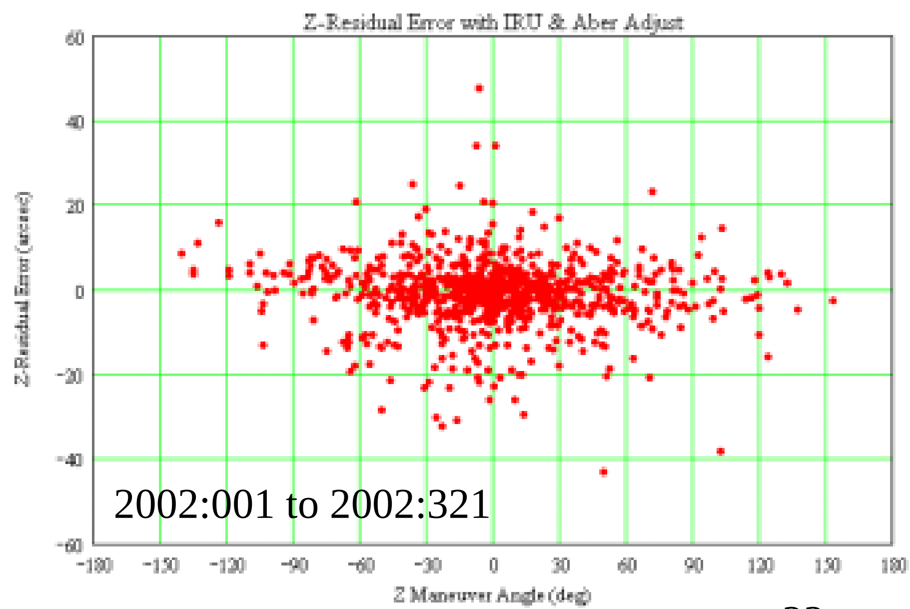


Z-Error Adjusted for IRU Calib 4 & Aberration vs Z-Axis Maneuver Angle

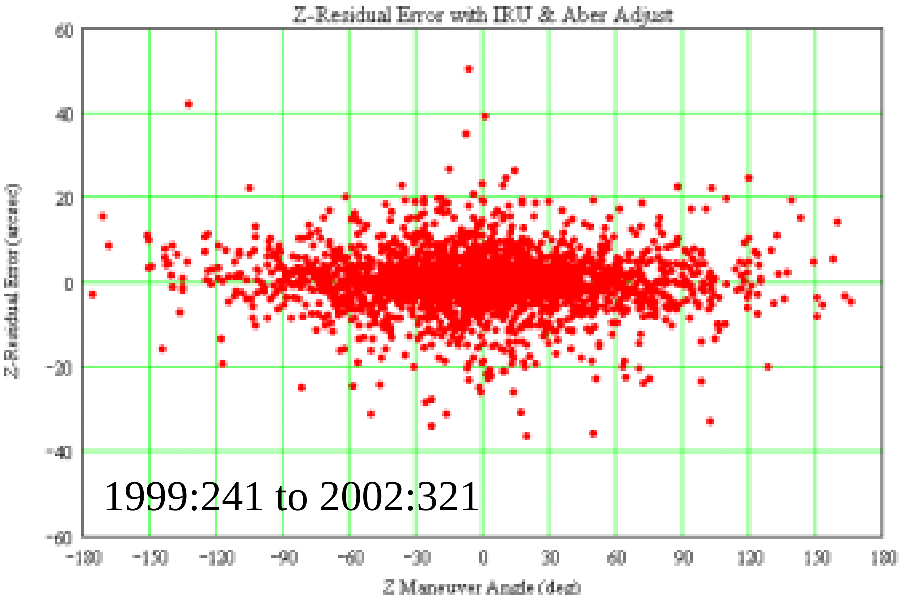


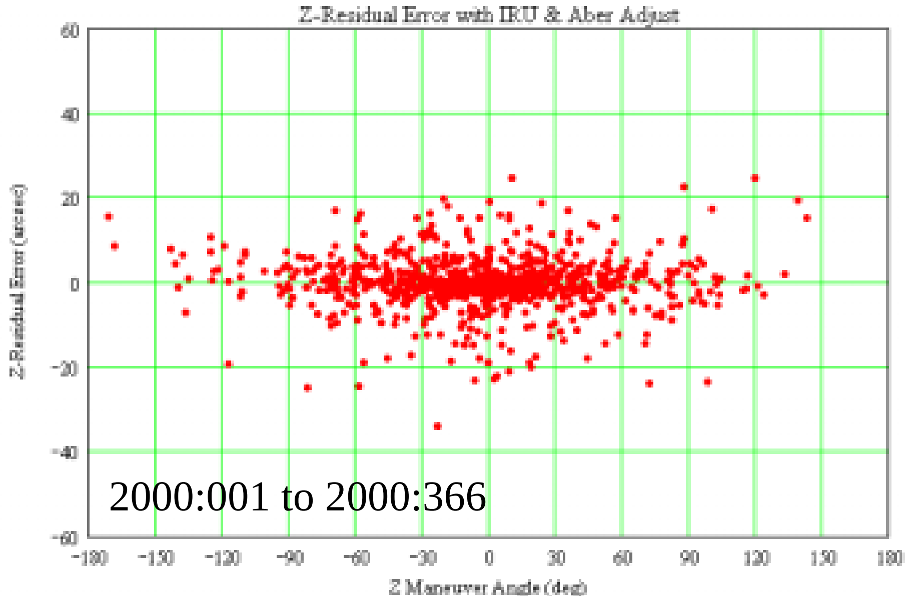


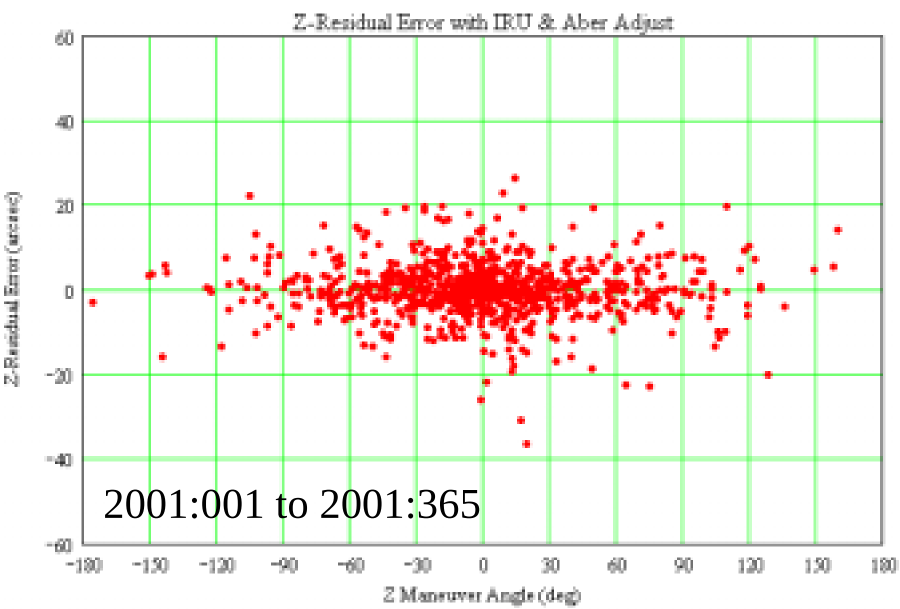


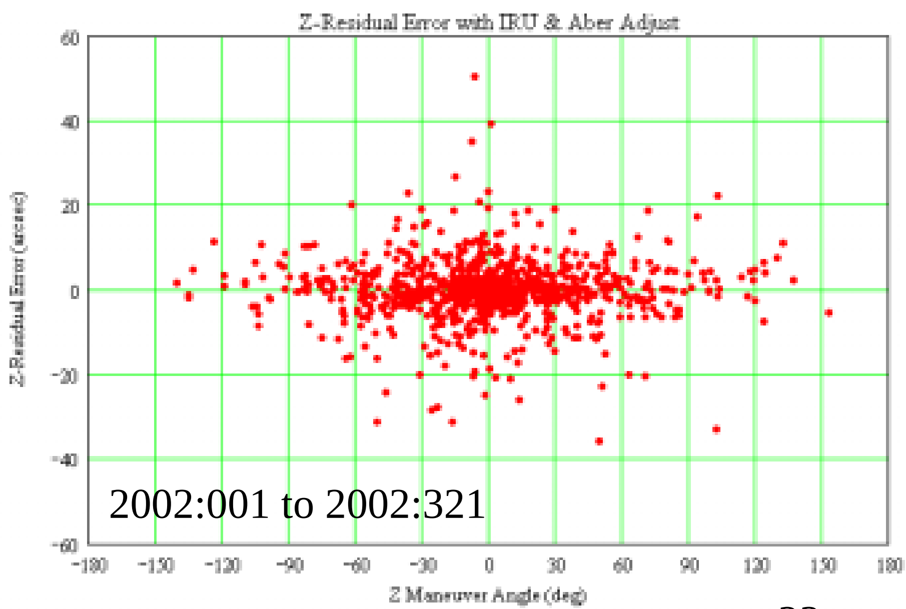


Z-Error Adjusted for IRU Calib 5.1, 5.2, 5.3, & Aberration vs Z-Axis Maneuver Angle





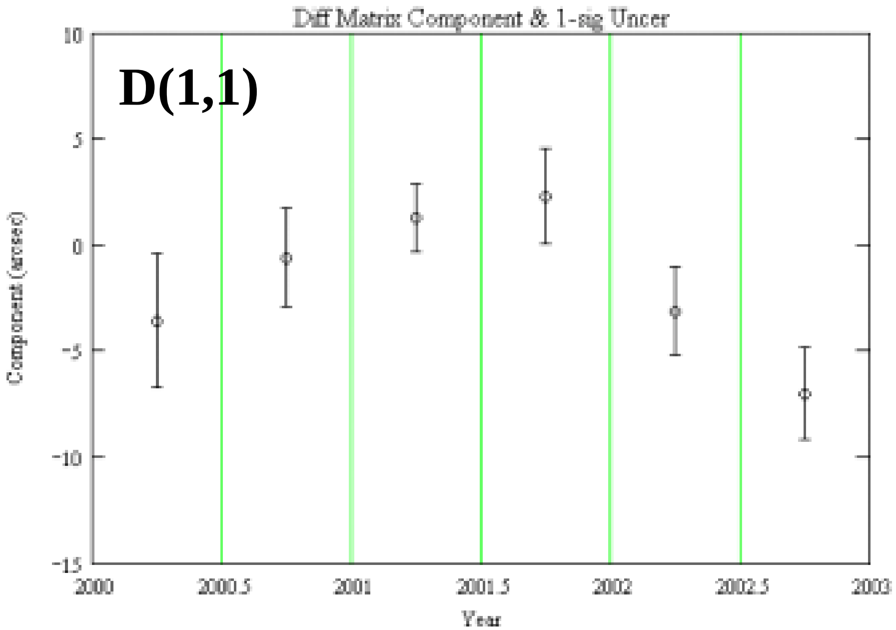


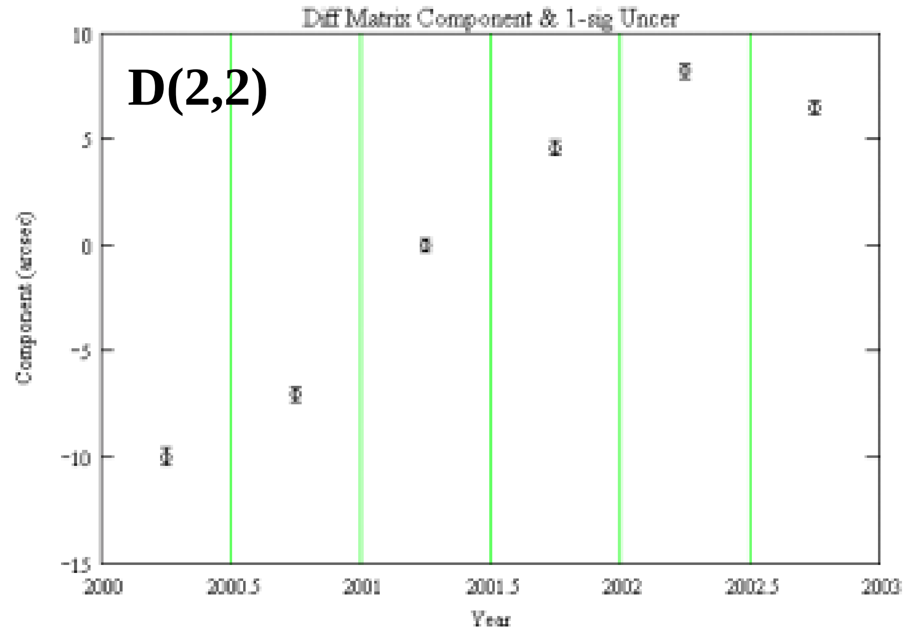


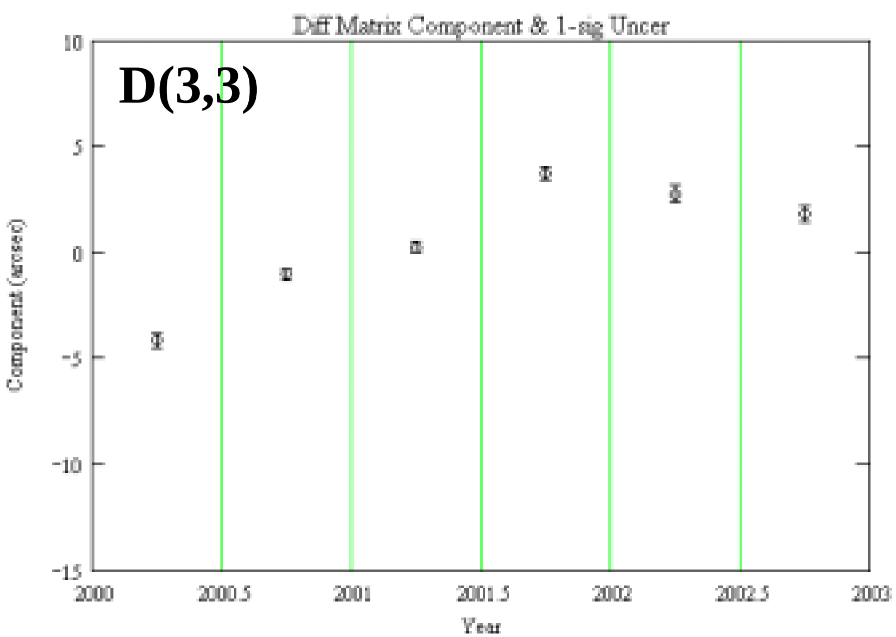
Calib 5 at 6-month Intervals

- Compute adjustments to Calib 4 at 6-month intervals, instead of 1 year to see finer time dependence
- Graphs on pages 25, 26, and 27 show plots of components of difference matrix vs time
- Time dependence is seen for diagonal components of difference matrix as well as D(3,1) and D(1,2)

Diagonal Components of Difference Matrix from 6-Month Calibrations



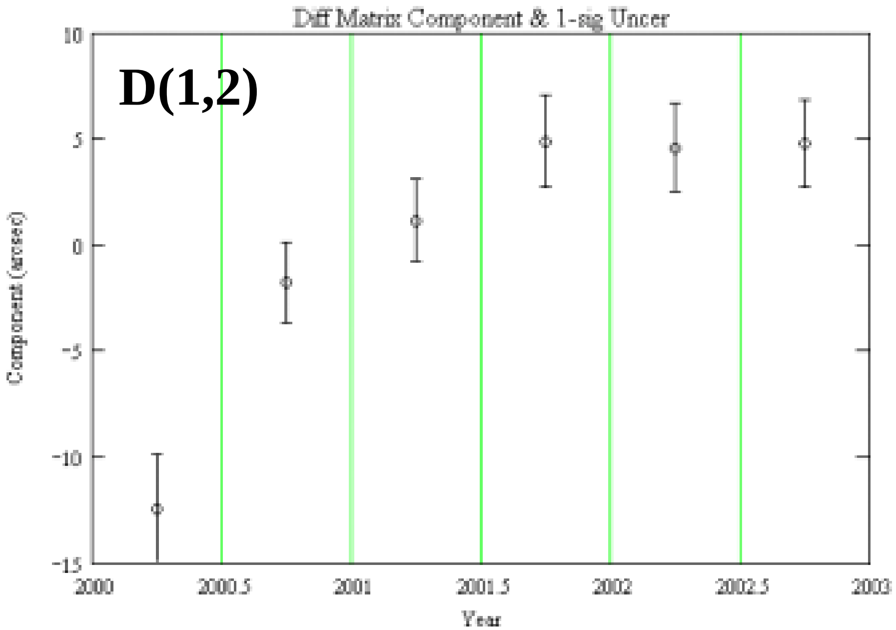


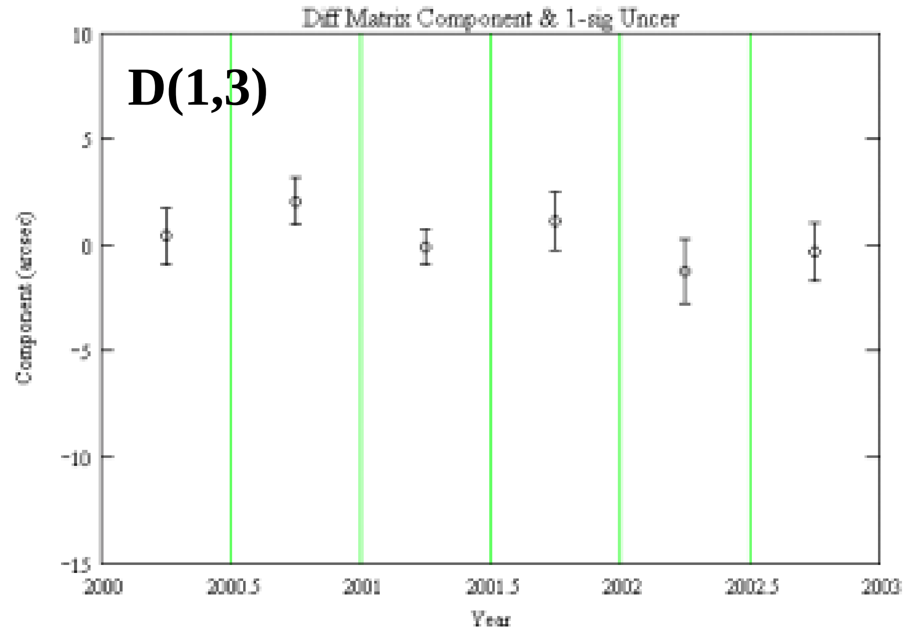


Diagonal components of difference matrix

$$\begin{bmatrix} D_{11} & \cdots & \cdots \\ \cdots & D_{22} & \cdots \\ \cdots & \cdots & D_{33} \end{bmatrix}$$

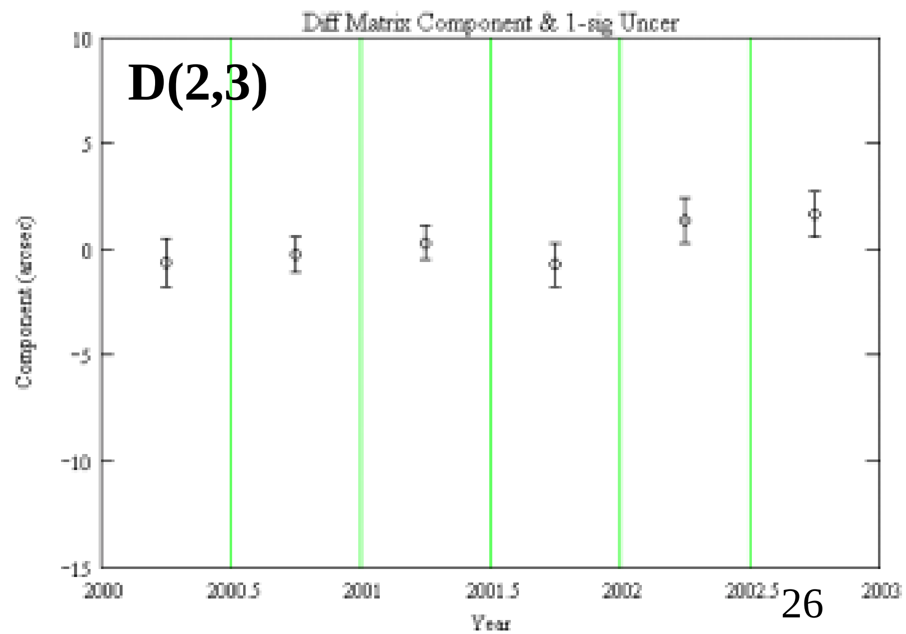
Upper Off-Diagonal Components of Difference Matrix from 6-Month Calibrations



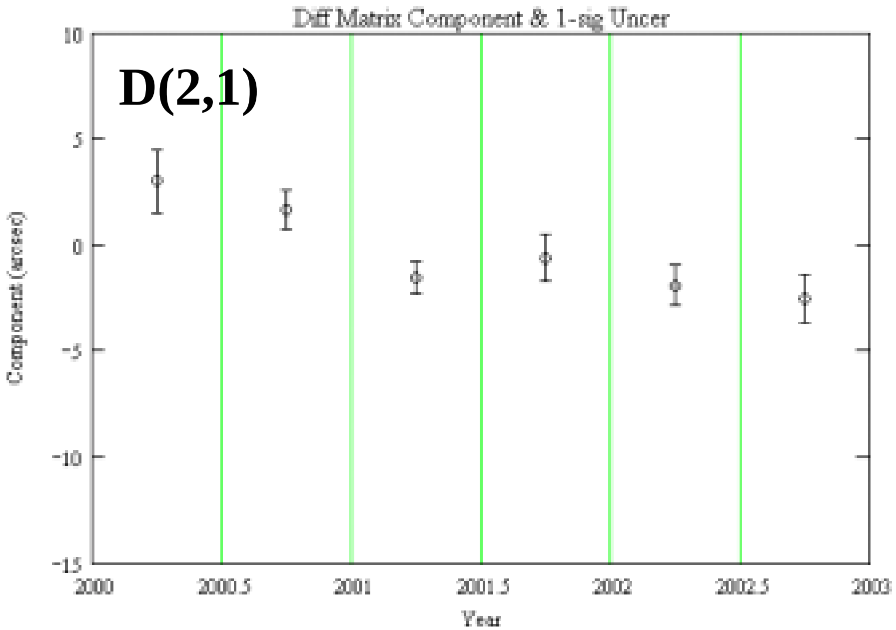


Upper triangle of difference matrix

$$\begin{bmatrix} \cdots & D_{12} & D_{13} \\ \cdots & \cdots & D_{23} \\ \cdots & \cdots & \cdots \end{bmatrix}$$

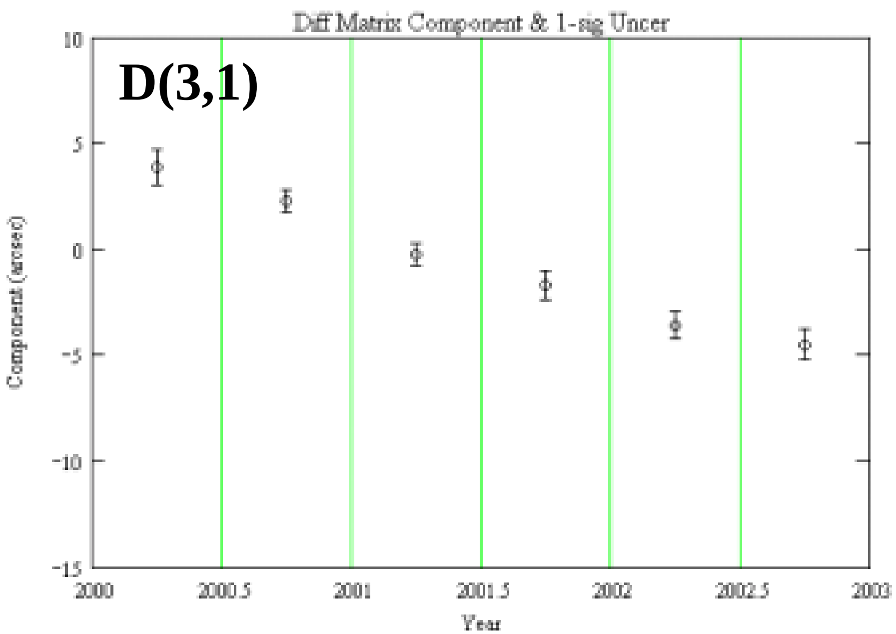


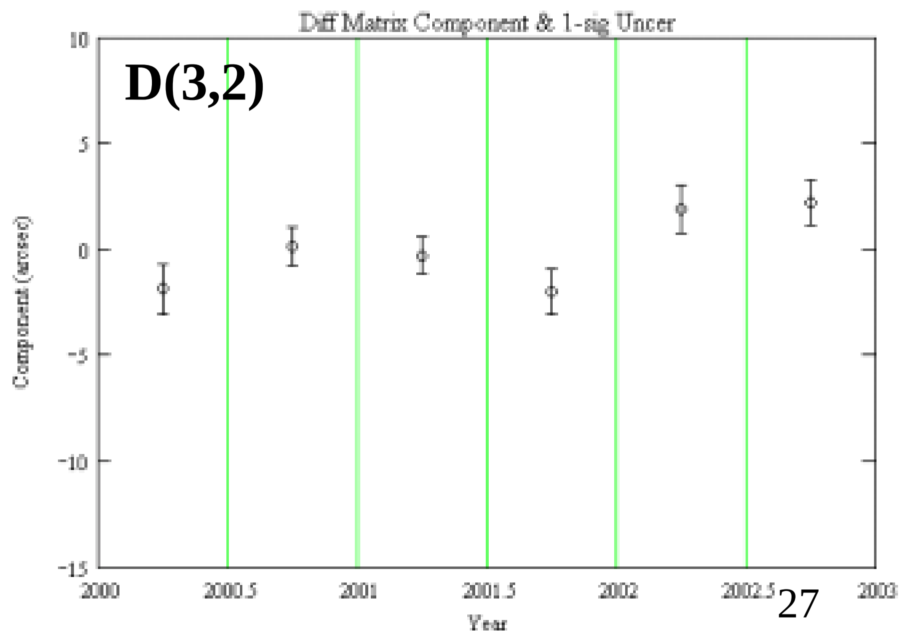
Lower Off-Diagonal Components of Difference Matrix from 6-Month Calibrations



Lower triangle of difference matrix

$$\begin{bmatrix} \cdots & \cdots & \cdots \\ D_{21} & \cdots & \cdots \\ D_{31} & D_{32} & \cdots \end{bmatrix}$$





Follow-up Actions and Comments

- 6-mo calibrations indicate changes slowing in 2002 (?)
- Provide details of algorithm to compute 3x3 IRU calibration with one-shot error data and computation of error bars
- Implement method for routine calibration with 1-shot update data
- Maintain SAUSAGE IRU calibration parameters
  – Review (and update as needed) every 6 months (?)
  – Make SAUSAGE IRU calibration parameters FDB controlled item
  – What should be the criteria for uplinking IRU calibration changes?