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

OUTLINE

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On-Board Rate Computation

\[ \bar{\omega} = (I + M) G \begin{bmatrix} f_1^{(\pm)} & \delta N_1 \\ f_2^{(\pm)} & \delta N_2 \\ f_3^{(\pm)} & \delta N_3 \\ f_4^{(\pm)} & \delta N_4 \end{bmatrix} - \bar{b} \]

- \( \delta N_n \) is change in count for channel \( n \) in time \( \delta t \).
- \( \bar{b} \) 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 $\ddot{\omega}$ is computed with misalignment $M$ and rate $\ddot{\omega}'$ is computed with misalignment $M'$, then the difference in rates can be related to a "difference matrix" $D$, 

$\Delta \ddot{\omega} = \ddot{\omega}' - \ddot{\omega} = D \ddot{\omega}$

where $D = (I + M')(I + M)^{-1}$. 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 

$M' = D (I + M) - I$
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)

1. Manufacturer IRU Calib. On-Board at Launch 07/23/1999
2. OAC Calib. OFLS/IRUCAL 8 Maneuvers Uplinked 08/15/1999
3. Individual IRU Axis Calib. 20 Maneuvers Uplinked 07/17/2002
5.1 Difference Matrix Calib with Yr 2000 1-shot data 655 Maneuvers
5.2 Difference Matrix Calib with Yr 2001 1-shot data 654 Maneuvers
5.3 Difference Matrix Calib with Yr 2002 1-shot data 631 Maneuvers

Current On-Board IRU Calibration Currently Being Used to Predict Maneuver Errors
Post-Maneuver Pointing Errors for 8 Maneuvers of OAC IRU Calibration (Calib 2) and Adjusted Errors

\[
D = M_{OAC} = \begin{bmatrix}
-21.48 & 20.46 & -663.34 \\
31.43 & 650.26 & 5.97
\end{bmatrix} \text{ arcsec}
\]

Calibration contains 657-arcsec rotation around X-axis.
One-Shot Updates for 1999:241 to 2002:197
3305 Maneuvers with IRU Calib Adjustments Uplinked July 2002

2002:176  -102 deg Y-Axis Man

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

![Graph showing Z-Error vs Y-Axis Maneuver Angle with Calib 3 Adj]

- Red dots: 3305 Maneuvers with Calib 3 Adjustment
- Blue dots: 20 Maneuvers of Calib 3

12/10/2002
Z-Error vs Y-Axis Maneuver Angle with Calib 3 & 4 Adj
One-Shot Updates for 1999:241 to 2002:197
3305 Maneuvers with Additional IRU Misalignment Adjustment

In-Flight Results Adjusted for Calib 3 & 4

12/10/2002
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

Calib 5.1, 2000:001 to 2000:366
Calib 5.2, 2001:001 to 2001:365
Calib 5.3, 2002:001 to 2002:321
Calib 4, 1999:241 to 2002:197
(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

1999:241 to 2002:321

2000:001 to 2000:366

2001:001 to 2001:365

2002:001 to 2002:321

12/10/2002
Y-Error Adjusted for IRU Calib 5.1, 5.2, 5.3, & Aberration vs Y-Axis Maneuver Angle

1999:241 to 2002:321

2000:001 to 2000:366

2001:001 to 2001:365

2002:001 to 2002:321

12/10/2002
(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

1999:241 to 2002:321
2000:001 to 2000:366
2001:001 to 2001:365
2002:001 to 2002:321
Z-Error Adjusted for IRU Calib 5.1, 5.2, 5.3, & Aberration vs Z-Axis Maneuver Angle

1999:241 to 2002:321

2000:001 to 2000:366

2001:001 to 2001:365

2002:001 to 2002:321
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

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

D(1,2)  
D(1,3)  
D(2,3)

12/10/2002
Lower Off-Diagonal Components of Difference Matrix from 6-Month Calibrations

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

Lower triangle of difference matrix
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?