Clock Correlation Contribution to Chandra Timing Accuracy

Authors
William Davis (Computer Sciences Corporation)
Jeffrey Holmes (Northrop Grumman Corporation)
Richard Myers (Northrop Grumman Corporation)

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Abstract
The clock correlation process synchronizes Chandra on-board timing events with a ground-based time. Specifically, quadratic coefficients are computed which provide the UTC time of the start of each minor frame as a function of minor frame count. A signal synchronized to the first of every 8 minor frames is sent to the science instruments to provide the time reference for the observed X-ray events. The clock correlation process is done entirely on the ground through time-stamping of frames by the DSN network, as the frames are received in real-time, and through computations and curve fits by the OCC which compensate for delays on the ground and on the spacecraft as well as light travel time. This presentation summarizes the clock correlation process and its contribution to the accuracy of the timing of the observed X-ray events. Engineering analysis of spacecraft time delays shows a 285 µsec absolute time offset.
Chandra VCDU Clock

Consider a clock as a system with the following three elements:

- Precision oscillator
- Counter of oscillations
- Synchronization process (to specific events or time systems)

The following two elements are on board the Chandra spacecraft:

- An ultrastable quartz-crystal oscillator at 4,000,000 Hz (not adjustable in flight)
- A divide by 1,025,000 counter which counts intervals of 0.25625 sec and triggers the start of each minor frame (a.k.a. virtual channel data unit (VCDU))

The synchronization process is performed on the ground as follows:

- DSN ground station determines the UTC time that the leading of the edge frame-sync arrives at the antenna for each VCDU transmitted in real-time
- OCC computes VCDU start of real-time data by adding the time interval of frame-sync and subtracting residual DSN delays, light-travel time, and on-board spacecraft delays
- OCC computes 15-day quadratic fit of VCDU UTC time to VCDU count

The start time of a VCDU is then computed from a quadratic equation of the VCDU count with the fitted coefficients.
Chandra Data Flow
VCDU Data and Synchronization

On-board, the telemetry formatter does the following processes:

- Creates 1025-byte minor frame (VCDU) once every 0.25625 seconds containing science and engineering data
- Computes 160-byte Reed-Solomon check symbols and appends to VCDU
- Prepends 4-byte frame-sync to VCDU, used by DSN site for time and frame synchronization

On the ground, time synchronization is done by,

- DSN site determines the time (UTC) that each leading-edge frame-sync arrives at the antenna
- OCC computes the time (UTC) that each VCDU starts on the spacecraft from frame-sync time, frame-sync duration, and known delays
Clock Correlation Strategy and Absolute Time Offset

Because only start times of VCDUs relative to the DSN frame-sync time can be observed with data available in the OCC, the OCC does not independently observe absolute time. The strategy to date for maintaining timing delays has been to minimize the dispersion of the clock correlation residuals while not disturbing any overall absolute time offset.

Early in the mission, only contacts at one telemetry rate were used. The relative timing of Goldstone stations was observed to be offset from Canberra and Madrid stations. This offset was later identified as an uncompensated ground propagation delay. So, the Goldstone station timings were compensated to be consistent with Canberra and Madrid stations.

Later in the mission, when the relative timing of contacts at different telemetry rates was compared, a discrepancy proportional to the bit rate was observed. To maintain consistency with previous clock correlations which used only the original telemetry rate, delays at other rates were adjusted to match.
Clock Correlation Strategy and Absolute Time Offset (continued)

A subsequent engineering reevaluation of on-board spacecraft delays revealed a "six-bit error" which explains the observed rate-dependent delay discrepancies. In the past year, the ground station electronics of the DSN antennas have been upgraded. The observed changes in relative timing with respect to the previous (legacy) equipment are applied to preserve the relative timing with respect to the legacy equipment.

Although the absolute time offset is unobservable from observations at the OCC, it can be estimated by engineering analyses and tests and observed by astronomical observations. The determination of the absolute time offset via multi-wavelength/multi-spacecraft astronomical observations of pulsars is in progress (See poster presentation by Arnold Rots). The best current value of the absolute time offset based on engineering analyses and observed relative time offsets is presented in the table on page 8.
Clock Correlation Error Sources

- Time interval of the frame-sync equals 32 bits times the bit rate, which is well known
- Residual DSN ground station timing delays
  - Observed station-to-station timing errors less than 3 µsec are not compensated
  - Individual station delays not the same from contact to contact
  - Frame-sync time resolution of integer µsec
- Light-travel time (radio propagation delay)
  - Error in Chandra orbit vectors
  - OCC software uses UTC instead of UT1 to compute station position
  - OCC software ignores spacecraft motion during radio propagation delay
  - Uncompensated relativistic effects
- On-board spacecraft delays
  - Reevaluated spacecraft delays show an excess delay in all clock correlations to date caused by an erroneously included 281 µsec delay
  - Residual error in spacecraft delay model
Clock Correlation Error Sources (continued)

\[ T_{VCDU}^{\text{true}} = T_{VCDU}^{\text{clkcorr}} + \Delta t_{OFFSET} \]

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Systematic Error ((\mu\text{sec}))</th>
<th>Systematic Uncertainty ((\mu\text{sec}))</th>
<th>Random Uncertainty ((\mu\text{sec}))</th>
<th>Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spacecraft Delay Errors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spacecraft model includes a delay that does not apply to SI event time-tags</td>
<td>281.2</td>
<td>0.0</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Adjustment to 512 kbps (original telemetry rate)</td>
<td>10.2</td>
<td>0.1</td>
<td>--</td>
<td>1(\sigma)</td>
</tr>
<tr>
<td>Residual uncertainty over all data rates</td>
<td>0.0</td>
<td>1.0</td>
<td>--</td>
<td>1(\sigma)</td>
</tr>
<tr>
<td>DSN Timing Errors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DSN time-tag calibration uncertainty (engineering estimate)</td>
<td>0.0</td>
<td>10.0</td>
<td>5.0</td>
<td>3(\frac{1}{2}) (\sigma) *</td>
</tr>
<tr>
<td>Adjustment to 34m stations</td>
<td>-6.2</td>
<td>0.5</td>
<td>--</td>
<td>1(\sigma)</td>
</tr>
<tr>
<td>Residual rate-dependent error (26m stations)</td>
<td>-0.5</td>
<td>0.1</td>
<td>1.0</td>
<td>3(\frac{1}{2}) (\sigma) *</td>
</tr>
<tr>
<td>Time-stamping jitter</td>
<td>0.0</td>
<td>--</td>
<td>0.5</td>
<td>3(\frac{1}{2}) (\sigma) *</td>
</tr>
<tr>
<td>Ground software uses UTC instead of UT1</td>
<td>0.0</td>
<td>--</td>
<td>0.8</td>
<td>3(\frac{1}{2}) (\sigma) *</td>
</tr>
<tr>
<td>Ephemeris error</td>
<td>0.0</td>
<td>--</td>
<td>0.8</td>
<td>1(\sigma)</td>
</tr>
<tr>
<td>Combined uncompensated relativistic effects and spacecraft motion during radio travel propagation delay</td>
<td>0.0</td>
<td>--</td>
<td>1.5</td>
<td>3(\frac{1}{2}) (\sigma) *</td>
</tr>
</tbody>
</table>

**Systematic Error** \(\Delta t_{OFFSET}\) (engineering estimate) 284.7 5.9 1\(\sigma\) RSS

**Random Error** of \(T_{VCDU}^{\text{clkcorr}}\) (estimated) 3.2 1\(\sigma\) RSS

* Uniform distribution assumed, with ± limits given in uncertainty columns (see Misc. Math Comments)
Observed Time Differences between Nearly Independent Clock Correlations

Routine clock correlations are done twice weekly with 15 days of data, successive correlations overlap in the telemetry data and definitive ephemeris data. Consider the time intervals of five overlapping correlations as follows,

Correlations 1 and 5 overlap by just one day. Correlation 1 can be used to compute the time of the first VCDU count of correlation 5. Comparison of this computed time to the first time of correlation 5 provides nearly independent errors of correlation-computed times.
Histogram of Time Differences between Nearly Independent Clock Correlations for 2000:049 to 2003:286
Standard Deviation = 5.6 microsec
Observed Time Differences for 3 to 4 Day Extrapolations

In the initial stages of science data processing, most of the time-tags applied to the events use extrapolated clock correlation values. To quantify the additional error of this extrapolation, compare correlations 1 and 6 as shown,

The end of correlation 1 and the beginning of correlation 6 differ by 3 to 4 days. It is within this time interval that extrapolations are done. To consider the worst case, use correlation 1 to compute the time of the first VCDU count of correlation 6. Compare this result to the first VCDU time of correlation 6 computed with correlation 6.
Histogram of Time Differences for 3 to 4 Day Extrapolations for 2000:049 to 2003:286, Standard Deviation = 18.4 microsec
Interpretation of Observed Time Differences as Random Error

Time differences between nearly independent clock correlations,

- Assume each clock correlation contributes equally to the statistics.
- The standard deviation of the times computed with each correlation is then \( (5.6 \ \mu\text{sec})/2^{1/2} = 4.0 \ \mu\text{sec} \), which is a measurement of the 1-\(\sigma\) random error.
- The distribution of time differences shows two peaks at \(\pm 3 \ \mu\text{sec}\) indicating two "error states" of unknown origin.

Time differences from 3 to 4 day extrapolations,

- Assume clock correlation which is not extrapolated has standard deviation 4.0 \(\mu\text{sec}\).
- The standard deviation of the extrapolated correlation is then \( ((18.4 \ \mu\text{sec})^2 - (4.0 \ \mu\text{sec})^2)^{1/2} = 18.0 \ \mu\text{sec} \), which is a measurement of the 1-\(\sigma\) random error of a 3 to 4 day extrapolated clock correlation.
- Typically X-ray events are time-tagged with the last day of a clock correlation or an extrapolation of up to 3 to 4 days. So, the timing standard deviation of the random error is 4 to 18 \(\mu\text{sec}\). Extrapolation is not done for science reprocessing.
Summary of Results

- From engineering analyses and tests, the absolute time offset of all clock correlations to date is $285 \mu\text{sec} \pm 6 \mu\text{sec (1-\sigma)}$, to be added to the times computed with the clock correlations.
- The observed standard deviation of the random error of the times computed with the clock correlations is $4.0 \mu\text{sec}$.
- The estimated standard deviation of the random error of the times computed with clock correlations is $3.2 \mu\text{sec}$. The major term in this standard deviation is an "engineering estimate".
- If the clock correlation is extrapolated past the end of the time of the data used in its computation, then by 3 to 4 days into the extrapolation, the standard deviation of the random error is observed to grow from $4.0 \mu\text{sec}$ to $18.0 \mu\text{sec}$.
- The clock correlation contribution to Chandra timing accuracy of X-ray events does not include delays in the science instruments or time adjustments by the CXC Data System.
Misc. Math Comments

Some error sources are modeled as a uniform distribution between the limits $\pm X_{\text{lim}}$.

The standard deviation of this distribution is $X_{\text{lim}}/3^{1/2}$.

Error sources are assumed to be statistically independent. Thus, the standard deviations are root sum squared.
The start time of a given VCDU during a real-time contact is obtained from the following calculation,

\[
T_{VCDU} = T_{ATT} + \Delta t_{SYNC} - \Delta t_{SC} - \Delta t_{LTT} - \delta t_{DSN}
\]

where

- \( T_{ATT} \) is DSN-attached time (frame-sync)
- \( \Delta t_{SYNC} \) is the duration of the frame-sync
- \( \Delta t_{SC} \) is the spacecraft delay
- \( \Delta t_{LTT} \) is the light travel time delay
- \( \delta t_{DSN} \) are adjustments to the DSN internal delays

For the VCDU count \( N_{VCDU} \) and its start time \( T_{VCDU} \), from real-time contacts, compute the start times of VCDUs outside real-time contacts from a quadratic fit of the observed \( N_{VCDU} \) to \( T_{VCDU} \),

\[
T_{VCDU}^{clkcorr} = T_{REF} + R (N_{VCDU} - N_{REF}) + \frac{1}{2} D (N_{VCDU} - N_{REF})^2
\]

where

- \( T_{REF} \) and \( N_{REF} \) are the time and count of the first VCDU of the fit interval
- \( R \) is the VCDU rate (actually period, nominally 0.25625 sec/cnt)
- \( D \) is the drift of the rate (derivative of \( R \), 1-yr value \( 3.45 \times 10^{-18} \) sec/cnt\(^2\))
Corrected Spacecraft Delay Model from Engineering Analysis & ASVT Tests

\[ \Delta t_{SC} = \text{Spacecraft Delay} = 256.250732 \text{ ms} + 51.5 \text{ bits}/(1.16 \times \text{IU_Rate}) \text{ coded & uncoded} \]

Note that the 281 \( \mu \text{sec} \) delay from RCTU input to CTU output is not and should not be included in VCDU start time as was originally done.
# Acronyms and Abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ASVT</td>
<td>Avionics and Software Validation Test</td>
</tr>
<tr>
<td>CCDM</td>
<td>Communications, Command, and Data Management</td>
</tr>
<tr>
<td>CTU</td>
<td>Command and Telemetry Unit</td>
</tr>
<tr>
<td>DSN</td>
<td>Deep Space Network</td>
</tr>
<tr>
<td>DSS</td>
<td>Deep Space Station</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>IU</td>
<td>Interface Unit</td>
</tr>
<tr>
<td>JPL</td>
<td>Jet Propulsion Laboratory</td>
</tr>
<tr>
<td>LGA</td>
<td>Low-Gain Antenna</td>
</tr>
<tr>
<td>OCC</td>
<td>Operations Control Center</td>
</tr>
<tr>
<td>RCTU</td>
<td>Remote Command and Telemetry Unit</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Squared</td>
</tr>
<tr>
<td>RSS</td>
<td>Root Sum Squared</td>
</tr>
<tr>
<td>SCS</td>
<td>Stored Command Sequence</td>
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<tr>
<td>SFDU</td>
<td>Standard Formatted Data Unit</td>
</tr>
<tr>
<td>USO</td>
<td>Ultra-Stable Oscillator</td>
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<tr>
<td>UT1</td>
<td>Universal Time 1 (from Earth's rotation angle)</td>
</tr>
<tr>
<td>UTC</td>
<td>Universal Time Coordinated</td>
</tr>
<tr>
<td>VCDU</td>
<td>Virtual Channel Data Unit ( = minor frame)</td>
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