Clock Correlation Contribution to Chandra Timing Accuracy

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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 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:

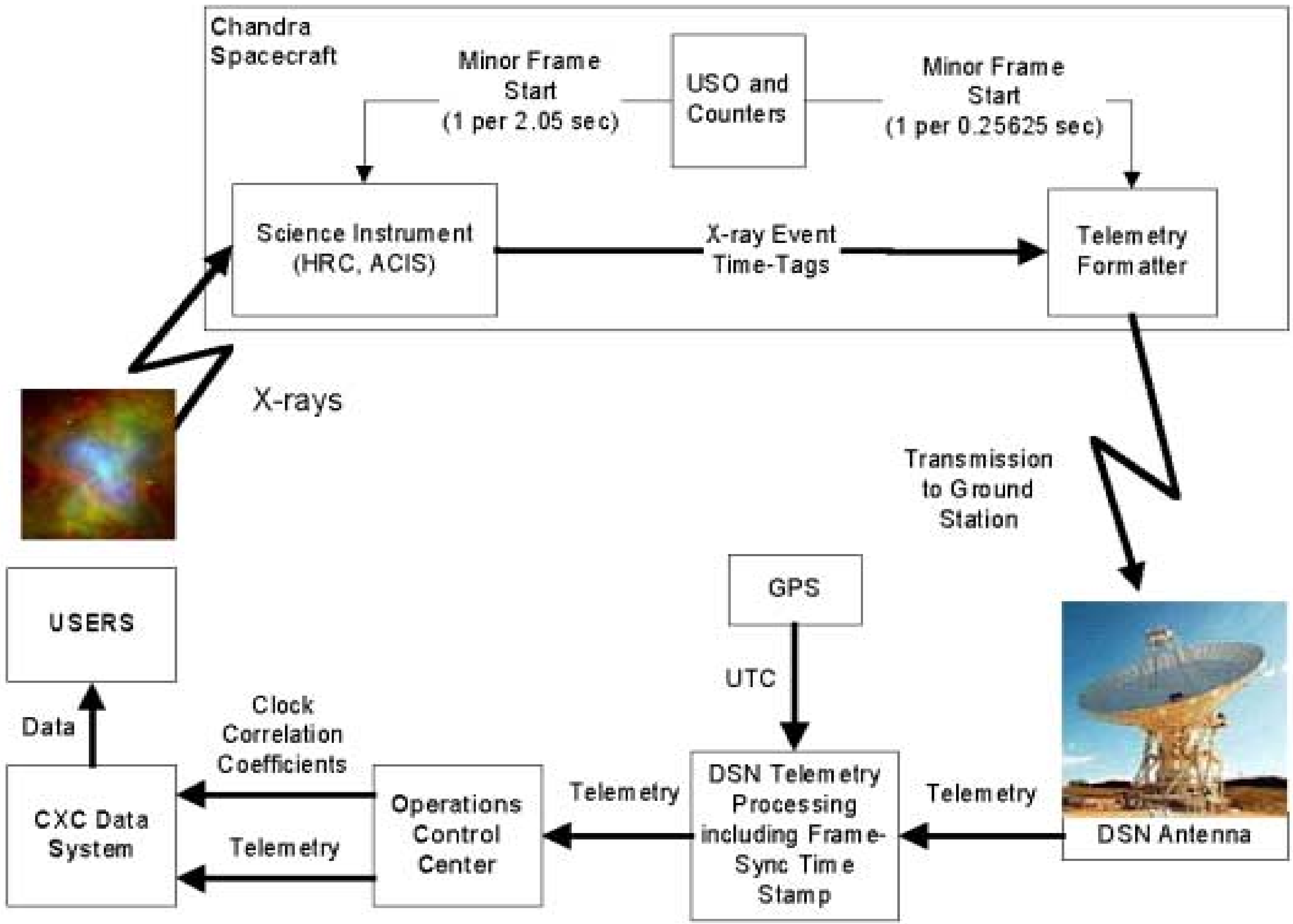
- An ultrastable quartz-crystal oscillator at 4,000,000 Hz (not adjustable in flight)
- A divide by 1,025,000 counter which counts intervals of 0.25625 sec and triggers the start of each minor frame (a.k.a. virtual channel data unit (VCDU))

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



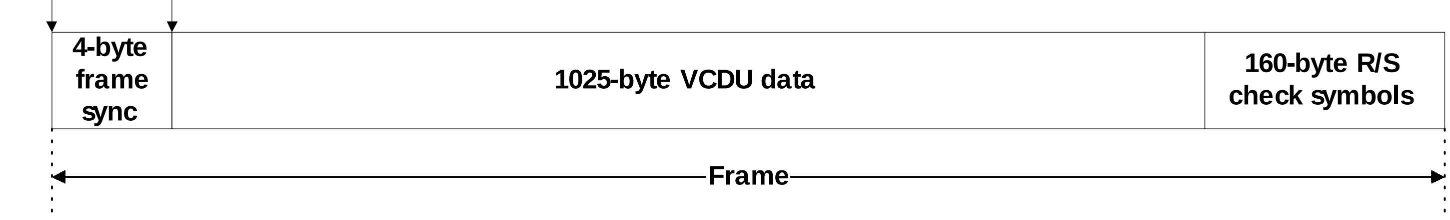
VCDU Data and Synchronization

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)

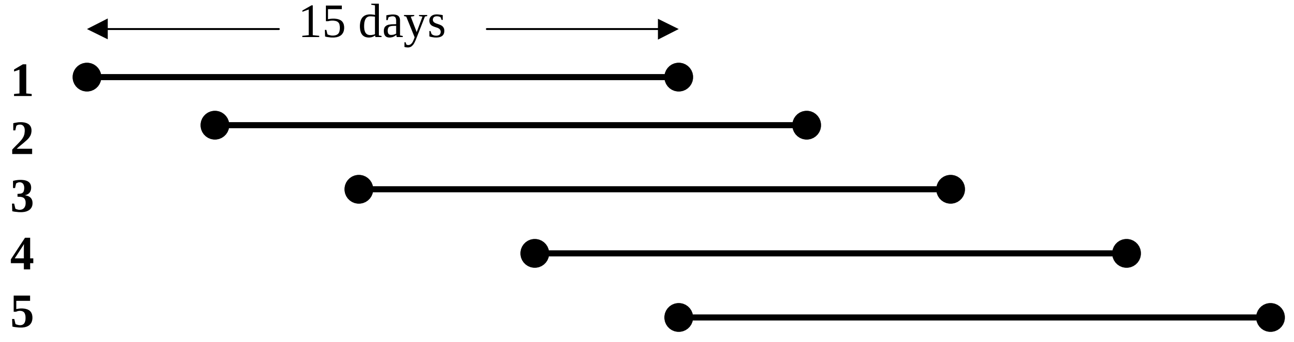
$$T_{VCDU}^{\text{"true"}} = T_{VCDU}^{clkcorr} + \Delta t_{OFFSET}$$

Error Source	Systematic Error (μsec)	Systematic Uncertainty (μsec)	Random Uncertainty (μsec)	Statistics
Spacecraft Delay Errors				
Spacecraft model includes a delay that does not apply to SI event time-tags	281.2	0.0	--	
Adjustment to 512 kbps (original telemetry rate)	10.2	0.1	--	1σ
Residual uncertainty over all data rates	0.0	1.0	--	1σ
DSN Timing Errors				
DSN time-tag calibration uncertainty (engineering estimate)	0.0	10.0	5.0	$3^{1/2}\sigma^*$
Adjustment to 34m stations	-6.2	0.5	--	1σ
Residual rate-dependent error (26m stations)	-0.5	0.1	1.0	$3^{1/2}\sigma^*$
Time-stamping jitter	0.0	--	0.5	$3^{1/2}\sigma^*$
Ground software uses UTC instead of UT1	0.0	--	0.8	$3^{1/2}\sigma^*$
Ephemeris error	0.0	--	0.8	1σ
Combined uncompensated relativistic effects and spacecraft motion during radio travel propagation delay	0.0	--	1.5	$3^{1/2}\sigma^*$
Systematic Error Δt_{OFFSET} (engineering estimate)	284.7	5.9		1σ RSS
Random Error of $T_{VCDU}^{clkcorr}$ (estimated)			3.2	1σ RSS

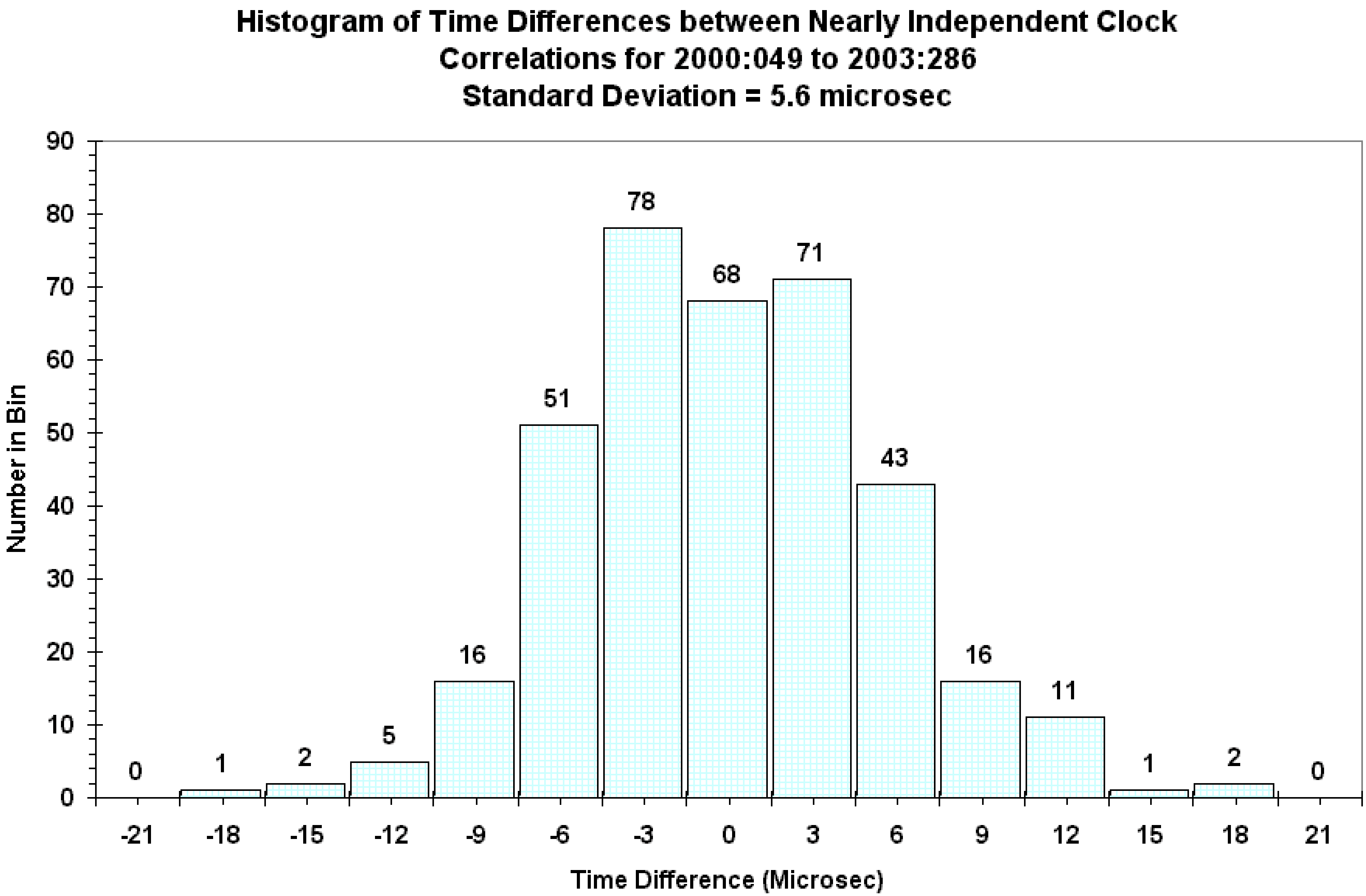
* Uniform distribution assumed, with ± limits given in uncertainty columns (see Misc. Math Comments)

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,

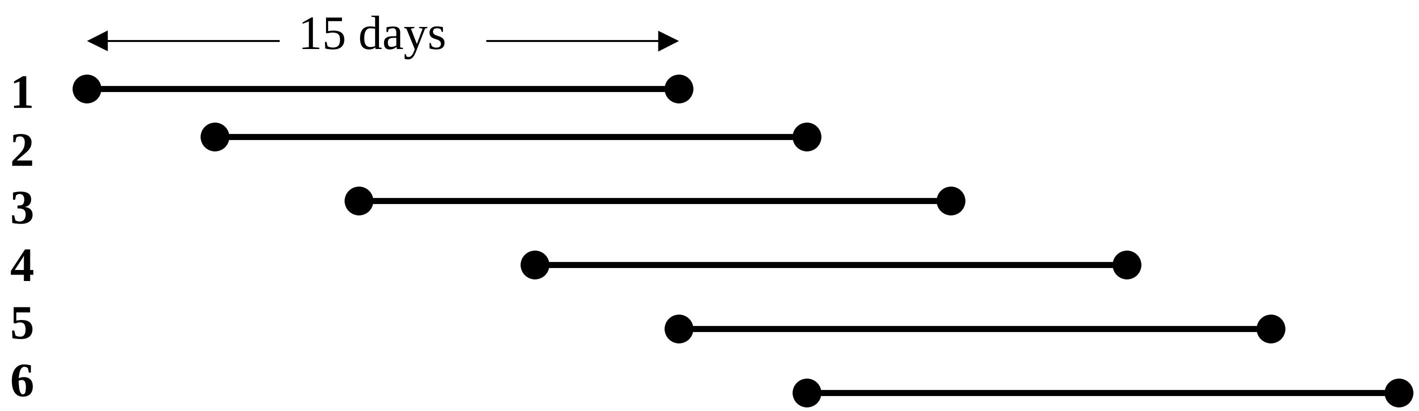


Correlations 1 and 5 overlap by just one day. Correlation 1 can be used to compute the time of the first VCDU count of correlation 5. Comparison of this computed time to the first time of correlation 5 provides nearly independent errors of correlation-computed times.


Histogram of Time Differences between Nearly Independent Clock
Correlations for 2000:049 to 2003:286
Standard Deviation = 5.6 microsec
Number in Bin
0
10
20
30
40
50
60
70
80
90
0
1
2
5
16
51
78
68
71
43
16
11
1
2
0
-21
-18
-15
-12
-9
-6
-3
0
3
6
9
12
15
18
21
Time Difference (Microsec)

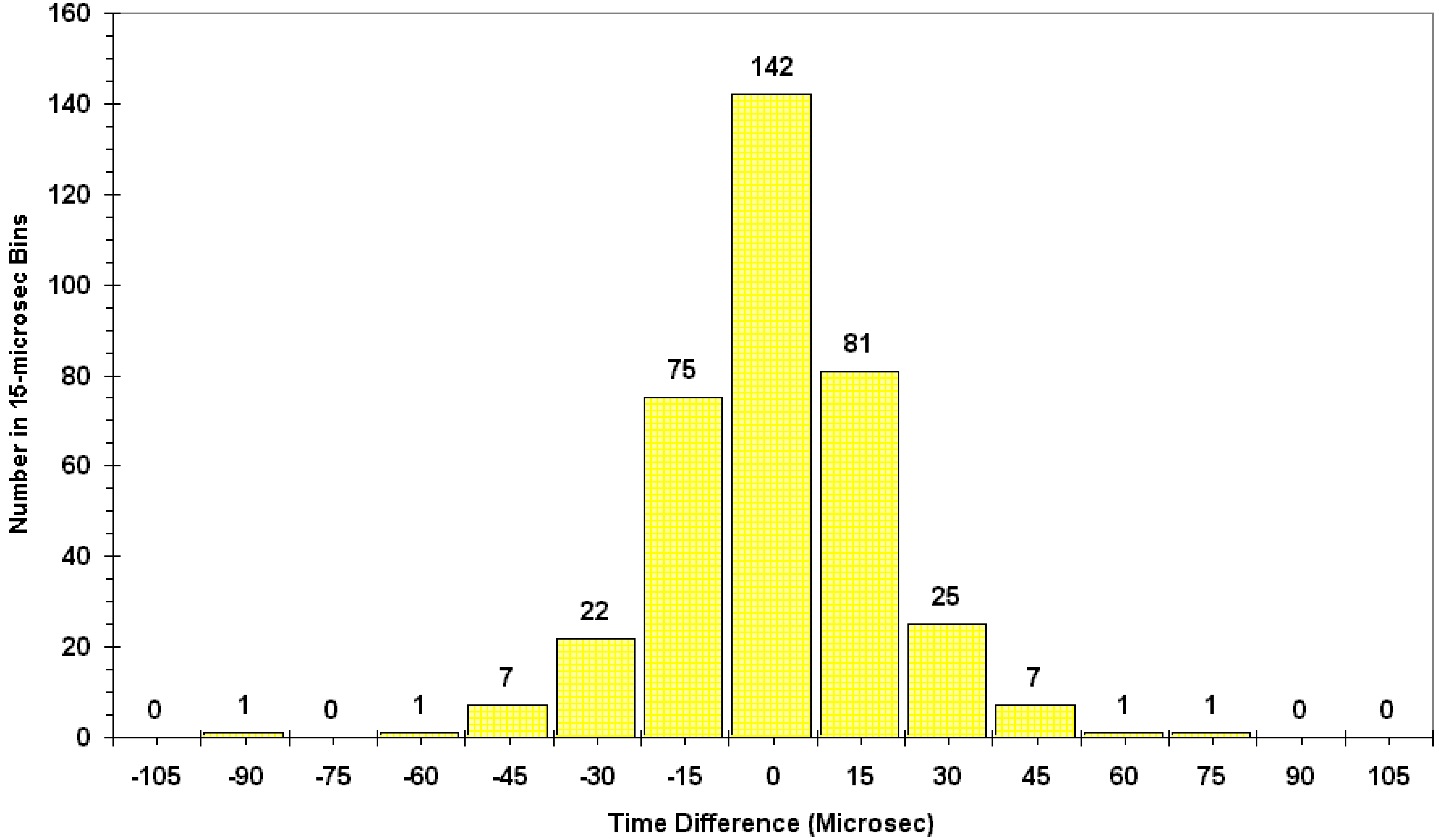
Observed Time Differences for 3 to 4 Day Extrapolations

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 μsec)/$2^{1/2}$ = 4.0 μsec, which is a measurement of the 1-σ random error.
- The distribution of time differences shows two peaks at ± 3 μsec indicating two "error states" of unknown origin.

Time differences from 3 to 4 day extrapolations,

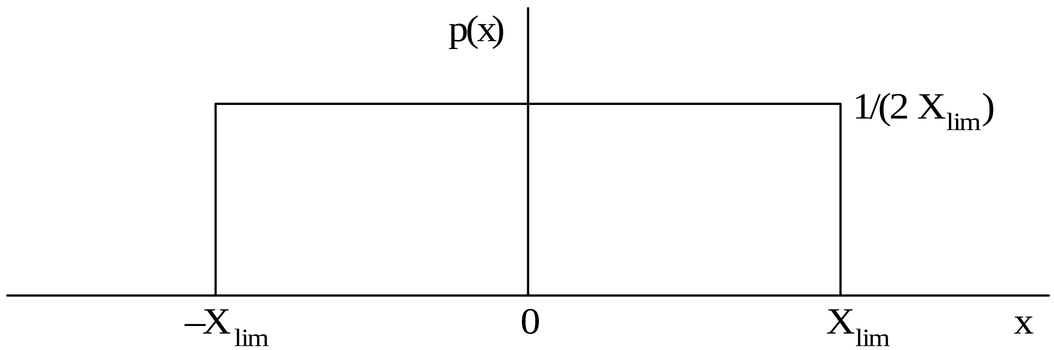
- Assume clock correlation which is not extrapolated has standard deviation 4.0 μsec.
- The standard deviation of the extrapolated correlation is then $((18.4\ \mu\text{sec})^2 - (4.0\ \mu\text{sec})^2)^{1/2}$ = 18.0 μsec, which is a measurement of the 1-σ random error of a 3 to 4 day extrapolated clock 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 μsec. 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 μsec ±6 μsec (1-σ), 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 μsec.**
- **The estimated standard deviation of the random error of the times computed with clock correlations is 3.2 μsec. 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 μsec to 18.0 μsec.**
- **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 $\pm X_{lim}$.



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

Error sources are assumed to be statistically independent. Thus, the standard deviations are root sum squared.

Misc. Math Comments (continued)

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)
- Δt_{SYNC} is the duration of the frame-sync
- δt_{DSN} are adjustments to the DSN internal delays
- Δt_{SC} is the spacecraft delay
- Δt_{LTT} is the light travel time delay

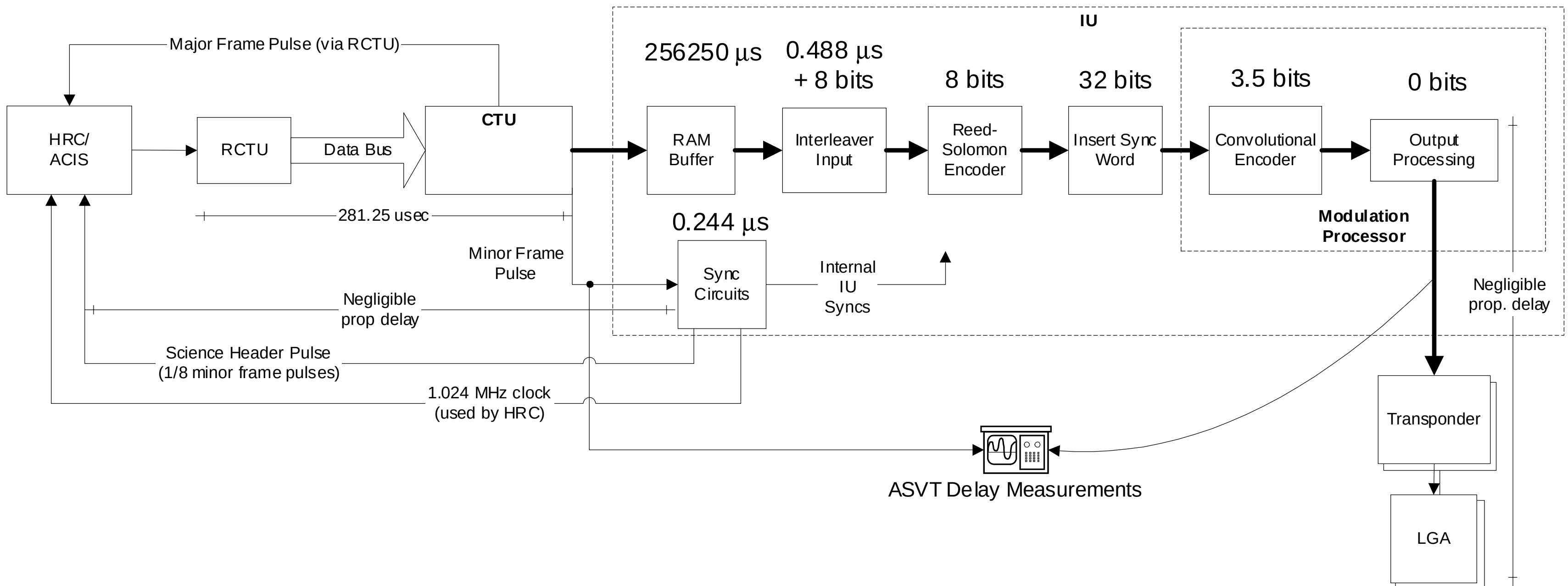
For the VCDU count N_{VCDU} and its start time T_{VCDU}, from real-time contacts, compute the start times of VCDUs outside real-time contacts from a quadratic fit of the observed N_{VCDU} to T_{VCDU},

$$T_{VCDU}^{clkcorr} = T_{REF} + R\,(N_{VCDU} - N_{REF}) + \tfrac{1}{2}\,D\,(N_{VCDU} - N_{REF})^2$$

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 3.45×10^{-18} sec/cnt^2)

Corrected Spacecraft Delay Model from Engineering Analysis & ASVT Tests



Δt_{SC} = Spacecraft Delay = 256.250732 ms + 51.5 bits/(1.16*IU_Rate) **coded & uncoded**

Note that the 281 µsec 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

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