ngVLA Electronics Memo # 15

Timing Requirements & Considerations

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Abstract

We provide a summary of current considerations for timing reference signal distribution to the antennas and central signal processor to support the system-level timing requirements. We consider a design with separate antenna clock domains that are synchronized to within ±2.5 μsec, with stable offsets maintained by a round-trip phase correction system. The time differences between the antenna clock domain and a system clock domain are monitored and corrected retroactively, or alternatively in real time as part of the delay and phase model. Differences between the system clock and the GPS time reference are tracked so that the system retroactively refers the recorded data products timestamps to GPS time with an accuracy better than 10 nsec.

1 Introduction

The ngVLA project is developing a functional model of the system architecture and establishing sub-system requirements in advance of a Local Oscillator Reference & Timing System Conceptual Design Review. As part of the functional architecture development, we consider the flow down of the system-level timing requirements and considerations for the distribution or generation of timing references at the antenna and central signal processor (CSP), as well as the application of timestamps in the system. Permissible time differences between clock domains, the requisite precision with which these differences must be tracked, and the functional relationships between the various references in the system are considered.

2 System Requirements

Some of the driving timing requirements that are included in the System Requirements [1] are:

- Temporal Accuracy (SYS2002): "Data Product timestamps must be referred to an absolute time standard (e.g., GPS or TAI) with an error of less than 10 ns (goal of 1 ns)."

- Timestamp Corrections (SYS2003): "Timestamps may be applied or corrected retroactively (i.e., it is not necessary for it to be known in real time.) Any timestamp corrections shall be made through a metadata table that is incorporated into the data model."

- Subarray Composition (SYS0603): "The composition of a sub-array shall be configurable to any arbitrary combination of antennas from a single antenna to the full array."

- Subarray Modification (SYS0607): "The system shall permit an Array Operator to add or remove antennas in a sub-array without interrupting an in-progress observation."

Based on a more detailed consideration of the timing requirements for all operating modes, SYS2002 should be clarified. Importantly, this is indicative of the *precision* and *stability* required in timestamps applied by the online system. It is not indicative of permissible offsets, i.e., the *accuracy* of the timestamps relative to the GPS time reference, given the ability to measure and retroactively correct for offsets in subsequent observations.

Consistent with SYS2003, a convention must be selected for the clock domain that is used as the basis of time in the recorded observation. This could be either a reference antenna clock domain or the system clock domain depending on design choices. Any corrections to refer this clock domain to the GPS time reference will be appended to the science data model, ensuring that this correction may be improved with additional knowledge of the observation, consistent with how calibration tables are recorded and applied.

The desired flexibility in subarray composition also has implications for the timing system. SYS0603 is considered self-explanatory, but SYS0607 may need to be clarified with some exceptions. In particular, we assume that the use of reference antennas for delay calibration is acceptable, and that the selected reference antenna in a subarray would need to be present for the duration of the observation (i.e., they are not readily added or subtracted from the subarray).

Other requirements that drive functional timing needs include permissible antenna tracking errors, the amplitude stability required in noise diode calibration, and practical lengths of fringe search windows. We consider each of these factors in Section 4.

3 System Design Assumptions

The ngVLA System will have multiple clock domains. The most relevant to the scope of this work are:

1. A central System Clock domain, generated by the Reference LO & Timing Generation (RTG) subsystem in the Central Electronics Building (CEB).
2. A Central Signal Processor (CSP) Clock domain, unique to each subarray, which is a "virtual timescale" generated by the CSP based on received data timestamps and delay models.
3. An Antenna Clock domain, unique to each antenna, generated locally from a reference clock which may be distributed from the CEB or independently generated at the antenna site (e.g., antennas in the Long Baseline Array).
4. Station Clock domains, unique to long-baseline and mid-baseline sites with their own reference LO and timing generation subsystem hardware.

Relative differences in time between each clock domain are expected, but the stability of these differences and their precise measurement is necessary to support the system-level requirements. We make the following assumptions about the system design in considering the functional requirements related to each clock domain:

The system will include a local realization of GPS time, provided by a receiver collocated with the primary frequency reference (an active hydrogen maser) and the reference frequency distribution system. This GPS receiver may be single-band, dual-band, or triple-band (L1C, L2C, and L5) depending on commercial-grade receiver options and the deployed GPS constellation status. GNSS support is not being actively considered.

The system will generate a central system clock that runs open loop on the primary frequency reference. For the sake of this memo, we will assume that the central system clock consists of two signals: a 1 PPS signal and 500 MHz reference. These are diagrammatic only, and other solutions are feasible.

Periodically when commanded, the system clock 1 PPS will be synchronized to a time code from the GPS time reference, and thereafter resume open loop operation.

Differences between the GPS time reference and the central system clock 1 PPS signal can be monitored and logged w/o resynchronizing the system clock to the GPS time standard. This difference is measured once in every second period and averaged over a 1 to 24 hr. periods to reduce the noise in the measurement.

The central system clock, both the 500 MHz reference and 1 PPS, may be distributed directly to the CSP. Importantly, these references would be used for functional operation and monitor and control applications only, and have no direct bearing on the clock domain of the data products. The CSP data products exist in a virtual clock domain dictated by the data time stamps (in the antenna clock domains) and the distributed and applied delay models.

Frequency references (and possibly a timecode or 1 PPS) will be distributed to all nearby antennas where coherent frequency reference distribution is feasible. The frequency distribution system will include round-trip phase correction, but may not include a direct measurement of the cable delay. The digitizer clock and any local oscillators for down-conversion will be phase-locked to the distributed frequency reference, ensuring relative stability between the LO signals and the digitizer clock within each antenna.

Additional remote station clocks will be generated at the remote antenna stations that are too distant for coherent frequency reference distribution. For these remote stations, the antenna station clock will likely be a duplicate of the central system clock hardware, with its own GPS time reference and primary frequency reference. Digitizer clocks and any local oscillators for down-conversion will be locked to the station clock.

The astronomical data streams (time-voltage data streams) from each antenna will be timestamped with the local antenna time, and must be aligned to a common time domain (the CSP clock domain) before correlation or beamforming based on a per-antenna delay model for the observation. This delay model will be integrated with a phase model will be generated and distributed per sub-band, in practice.

The simplest implementation would use a reference antenna's clock domain, as provided by its data timestamps, for the reference in the CSP clock domain, with the delay models synchronizing all antennas to the reference antenna. If a real-time measure of the difference between the reference antenna clock domain and the system clock domain can be provided, this information could also be included in the delay and phase model, tightly coupling the CSP clock domain to the system clock domain. In this scenario, the delay model could depend on a priori accurately measured and recorded antenna positions and cable delays, as well as recent astronomical calibrations to determine time-varying atmospheric propagation delays and antenna clock drift. The use of a reference antenna's clock domain will be selected as the default for the recorded visibility and beamformed data products, with computed or measured corrections to the system clock domain appended to the science data model. This will ensure data provenance and enable improved post observation calibration when desired.

The remote antennas where the central frequency reference is not distributed must monitor the time difference between the generated station clock (free-running on the station maser) and its local realization of GPS time, as is the case with the system clock. When using a remote site for the reference antenna, the CSP clock domain must be coupled to the reference antenna clock domain, and retroactively referred to the local realization of GPS time. Astronomical calibrations may be periodically required to reference the station realizations of GPS time to each other and to the central GPS time reference at the CEB.

The implementation of the antenna clocks and relevant performance requirements for managing (correcting or measuring) delays between clock domains will be considered in the following subsections.

4 Functional Requirements

4.1 Antenna Time

Timing differences between antenna clock domains, and between the antenna clocks and the system clock domain, must be constrained in support of various functional and performance specifications. Specifications must be derived for both permissible differences between domains, and the precision with which these differences are measured. We first consider the following known needs for position tracking, switched power gain calibration, and the fringe search window size.

Antenna tracking: at 10x sidereal rates, the antenna can track over 150" on sky per second of time. 1 msec of timing error in the execution of antenna control unit (ACU) commands would equate to 0.15" of tracking error added to error budget. Limiting timing contributions to the error budget to less than 0.01" would constrain us to 66 μsec of relative error, or less, across the antenna clock domains. We assume that the ACU commands are distributed in advance with a time-tag for execution, so relative differences in antenna time matter in this case more so than differences between the antenna and system clock. As described in the preceding section, CSP time will be tied to a reference antenna's time for a given subarray, so phase centers will in practice be shifted relative to the reference antenna time, not the system time, ensuring that antenna primary beam centers and phase centers remain the same (when desired) regardless of any offsets between system time and reference antenna time (which should be orders of magnitude smaller than this requirement, regardless).

Switched power: We will assume the system cycles the noise diode at 100 Hz, with a 50% duty cycle, representing rates that may be suitable for total power observations (the limiting case). 1% noise power drift is permitted on monthly timescales (CAL0401), and this noise reference is used in support of relative amplitude calibration (CAL0405), which assumes comparable accuracy of the injected noise power signal across observations [2]. This requirement is the permissible change in noise power after measurement at the CSP, so an uncorrected difference between antenna time and CSP time would lead to leakage of power from the 'on' and 'off' state bins. Limiting this timing-based amplitude error to 0.1%, an order of magnitude less than the long-term noise diode stability requirement, would constrain uncorrected antenna relative timing errors to less than 5 μsec.

Fringe search: It is desirable to limit the size of a fringe search window to ensure that delays from an uncalibrated antenna can be readily determined and the antenna easily added back to the array after maintenance. A calibrator observation should exhibit strong correlation as long as the delay difference between stations is much smaller than the signal's coherence time, or the inverse of its bandwidth. Since cross-correlations are computed per frequency channel pairs, for the native CSP frequency resolution of approximately 15 kHz [3] a total uncorrected delay error of ~6.7 μsec should still preserve at least 90% of the correlation amplitude. Larger search windows should be possible through narrower channelization, if required. Note that this is total error, so ionospheric, atmospheric and instrumental delay contributions along with position and geometry errors must be considered in addition to errors in the antenna time.

The three needs considered here, inclusive of some design margin, lead to a requirement for the antenna clock domains to not deviate from the system clock by more than about 5 μsec. I.e., **the relative difference between local antenna time and the system clock shall not exceed ±2.5 μsec**. This requirement must be met by the hardware alone, before the application of time corrections (online or offline) derived from astronomical calibration or other sources. We note that this is within the capabilities of the IEEE 1588 Precision Time Protocol and other available commercial services (White Rabbit, GNSS Receivers, etc.)

An additional constraint on the antenna clock design can be traced to the need to ensure that the number of samples comprised in the time interval between consecutive timestamps is consistent with the interval duration. This is necessary to avoid gaps (or overlaps) in the digital data stream. As noted previously, the distributed frequency reference is used to generate the sampler clocks. In order to maintain the correct number of samples in each time interval, **the antenna clock must be phase-locked to the distributed coherent frequency reference distributed to each antenna, or the antenna station frequency reference in the case of remote antennas**. The stability of the antenna time relative to the central system clock will then be determined by the stability or drift in this antenna frequency reference relative to the central frequency standard (which in turn is the primary reference for the system clock).

With these requirements satisfied, the antenna will operate within specification and produce useful time stamps for conversion to the CSP clock domain, and ultimately, to the system clock and/or GPS time. We consider the measurement of the difference between clock domains in Section 4.3.

4.2 CSP Time Distribution & Data Timestamps

The central system clock may need to be distributed to each of the elements of the CSP for internal synchronization of the CSP. The copy of the system clock is purely functional and does not contribute to the CSP time domain in this architecture. In the ngVLA correlator implementation, the antenna timestamp is carried forward with the data stream, and the CSP data products will have a timestamp that is synchronized to a reference antenna clock domain via delay model correction.

This calibration scheme effectively aligns the time at all antennas in a subarray to a reference antenna time domain. The reference antenna time is referred to the system clock domain based on either a measured or indirectly estimated (e.g., based on fiber path length) time difference between the reference antenna clock and central system clock. This offset is computed and carried forward with the data as part of the science data model.

In order to maintain a characterized and correctible time difference between the reference antenna clock and the system clock, drift in the antenna frequency reference will need to be constrained. However, other delay/phase stability requirements (derived in support of imaging dynamic range) are appreciably tighter and expected to drive the design of the reference distribution system, inclusive of the round-trip phase correction. Stability better than 0.1 nsec per hour can be expected without any additional constraints.

When deciding where to apply this correction between reference antenna clock domain and system clock domain, a related consideration is the reference point in the signal path for the application of data timestamps. It is **desirable that the data timestamp in the system clock domain and GPS time standard represent the time of arrival at the common delay center for the subarray**. This should be captured as a functional requirement for the post-facto corrections generated by the Online System and applied by the Offline System.

4.3 Difference between Antenna Time and System Time

As described in the preceding section, relative electronic and atmospheric propagation delays between antennas can be determined astronomically, but all measurements are relative and reported as offsets to an arbitrary reference antenna. In order to reference the time of arrival of the signal to the system time, the difference between the system time and the reference antenna time must be established.

A minimal implementation might rely on the stability of the propagation delay from the reference antenna, as is the case in the VLA today. The central clock is distributed to the reference antenna and the propagation delay is estimated based on previously measured cable lengths – there is no active measurement of the propagation delay in this scenario. As described in Section 4.1, the antenna clock from which timestamps are generated must be locked to the frequency reference distributed to each antenna to ensure there are no gaps/overlaps in the output data streams. The antenna time can be synchronized to the distributed central clock (with propagation delay) on command, and should thereafter exhibit minimal drift (since both are phase-locked to the same central frequency reference) which can be monitored.

Such an approach may be viable for reference antennas near the center of the array, and for remote antennas served by a nearby maser (LBA site and remote mid-baseline sites). Optical time domain reflectometers exhibit 0.5m uncertainty in the fiber length measurement at short distances, resulting in 1.7 nsec time uncertainty, though this measurement error increases with fiber length. A 2km fiber path length to a reference antenna, with a fiber length stability of 10E-6/C and a seasonal 30C change in temperature, results in approximately 2 nsec uncertainty due to seasonal variation, though this can be approximated based on soil temperature. At these short distances these errors are tolerable, but such an approach does not scale effectively to 100km-scale baselines. A passive system would require bootstrapping astronomical delay solutions from the array core to reference antennas in remote subarrays. This may be feasible but adds risk and operational complexity, so a more robust solution is preferred for the extent of the connected elements in the main array. The passive fiber length approach could be acceptable for the long-baseline and mid-baseline antennas with nearby station references.

Alternatively, the time difference between antenna and system clocks could be measured as part of a timing signal distribution system. The proposed LO reference and timing distribution system can incorporate a measurement of this difference that is accurate to nsec-scale by measuring round-trip travel time for all antennas that receive coherent frequency references. [4] Incorporating such a system on a subset of antennas, representative of reference antennas for all planned science subarrays could suffice in practice but would violate the spirit of the subarray flexibility requirement (SYS0603). Given the flexibility desired, the round-trip travel time measurement system should be deployed on all antennas where references are distributed, which would provide full operational flexibility and provide a high value system monitor for engineering diagnostics and maintenance activities. We will adopt this as the best-value conformant design implementation. The precision with which the difference between the antenna clock domain and system clock domain must be measured is considered as part of a broader error budget in support of the system requirement.

5 Error Budget

A preliminary error budget for the system timing precision requirement is shown in Table 1. The intent of this table is to provide a preliminary distribution of errors for incorporation in a system-level error budget, and to demonstrate that supporting the system-level requirements appears to be feasible with ample margin. The proposed error allocations are larger than the 'goal' target for timestamp precision (1 nsec), but present a best-value solution.

Table 1 - Timing Precision Error Budget

Sub-System Timing Precision Allocation	Error (nsec)	Notes
GPS Time Measurement Error	1.67	Conservative 100 nsec rms measurement noise, 1 measurement every second, integrated over 1 hr with no significant residual drift. Could be extended to 24 hrs. if necessary.
Unaccounted Time Delay between System Clock and Time Distribution System	0.3	Assume CEB thermally regulated to 1C on diurnal scales and cable lengths measured to better than 10cm precision. Pessimistic.
Reference Antenna Clock offset w.r.t. System Clock Measurement Error	2.00	Error of the round-trip measurement of timing signal, compared to local time. Allocation based on feasibility and stated goal; could be relaxed.
Antenna Structural & Electronic Delay Drift	0.05	Unaccounted time delay between reference antenna clock received at the FE and applied at the DBE. Max of 48 psec./hr drift in support of other requirements. [4 psec over 300 sec, combined across all systems in an antenna, between astronomical calibrations.]
DBE Timestamping Error	1.00	Worst case scenario. Assumes no aid from the digitizer (e.g., unformatted data) as opposed to digitizer-aided timestamping (e.g., JESD204B/C Subclass 1). Depends on implementation, could be 0.13nsec scale (1/8 GSPS).
Other Delay Model Errors	1.00	0.1 psec drift permissible in CAL requirements, but we assume other sources of uncorrected error (e.g. uncorrected antenna position errors, uncorrected tropospheric delay errors).
Sub-System Error Sub-total	**2.98** ***±6.02***	**RSS Combination of Errors** ***Linear Sum of Correlated Errors***
System-level Total Error Budget	**10.00**	**RSS Combination of Errors**

6 Conclusions

It is feasible to achieve the relevant system-level requirements for timing-sensitive events and data timestamp accuracy if we ensure the following sub-system requirements are met:

- The relative difference between local antenna clocks and the system clock shall not exceed ±2.5 μsec across all antennas in the array.
- The antenna clock shall be phase-locked to the frequency reference distributed to each antenna, either from the central building or the standalone frequency reference in the case of remote antenna stations.
- The difference between GPS time and the system clock time shall be averaged for variable sliding periods (1hr to 12hr) and recorded in the system configuration database.
- The difference between the antenna clock time and system clock time (or station clock time for remote antennas) shall be measured for each antenna in the array to a precision of better than 2 nsec on time scales of 1hr or faster. This requirement can be relaxed (there is available

error budget margin) if necessary for technical feasibility.

- The DBE shall apply timestamps to the time-voltage data stream with an error less than 1 nsec relative to the antenna clock. Error of less than 0.2nsec appears feasible and is desirable, but not required.

7 Acronyms & Definitions

ACU	Antenna Control Unit
CEB	Central Electronics Building
CSP	Central Signal Processor
DBE	Digital Back End
GPS	Global Positioning System
LO	Local Oscillator
PPS	Pulse Per Second
RSS	Residual Sum of Squares
RTG	Reference Timing Generation
TAI	International Atomic Time

8 References

[1] Selina, R., et al. "System Requirements" ngVLA Document 020.10.15.10.00-0003-REQ, rev C, March 2021.

[2] Hales, C., "Calibration Requirements" ngVLA Document 020.22.00.00.00-0001-REQ, rev C, Nov 2020.

[3] Yeste Ojeda, O., "Central Signal Processor Design Description" ngVLA Document 020.40.00.00.00-0005-DSN, rev A, 2022.

[4] Shillue, Bill. "LO Reference and Timing Design Description" ngVLA Document 020.35.00.00.00-0002-DSN , rev B, May 2022.