ABSTRACT

Radio interferometry using multiple small satellites will enable measurements with high angular resolution for remote sensing and astronomy. The NASA sponsored Auroral Emissions Radio Explorer (AERO) and Vector Interferometry Space Technology using AERO (VISTA) CubeSats will demonstrate orbital interferometry from 0.1 MHz to 15 MHz, frequencies which are largely blocked by the ionosphere. We report on the design and testing of a clock system for radio interferometry between these orbital receivers. We discuss the clock system design up to PCB fabrication, including requirements flow and major hardware trades. The performance of the timing components has been verified using a phase noise test set with a high-quality benchtop crystal. While these results are presented for the AERO-VISTA mission payload, they are more generally applicable to any orbital interferometry platform with multiple satellites.

BACKGROUND

AERO and VISTA Architecture

AERO and VISTA are a pair of identical 6U spacecraft that will measure the radio emissions from Earth’s aurora from low earth orbit. The AERO and VISTA spacecraft will operate cooperatively as a pair of interferometric receivers in the HF band by accurately timestamping RF sample data and then downlinking the raw RF data and/or a compressed data product for correlation on the ground. This is conceptually similar to the method by which ground based Very Long Baseline Interferometric (VLBI) arrays operate, whereby the data from multiple receivers can be stored and shipped to a different location for correlation and other processing.

The primary payload of each spacecraft is a six-element vector sensor, consisting of three orthogonal loop antennae and two orthogonal dipole antennae, both of which are orthogonal to a monopole. These antennae are deployed from the CubeSat bus on five different booms each about 2 meters in length. These antennae completely sample the electric and magnetic field vector of a propagating RF signal. Despite being electrically small compared to the wavelengths of interest, the phase relationships of the signals on these six elements can be combined to determine polarization and direction of propagation of RF signals that pass over the spacecraft.
Each spacecraft also includes a highly stable reference clock that allows maximization search algorithms to correlate the signals from the two spacecraft on the ground. The correlation of data from multiple receivers increases the vector sensor’s ability to resolve multiple sources by increasing the number of independent measurements, and also decreases the angular resolution by increasing the effectivereceive aperture in one dimension through use of the baseline or separation of the spacecraft.\(^{(1,3)}\) This is analogous to how ground based interferometric arrays are resolution limited not by the size of any one receiving antenna, but by the maximum separation of two antennae.\(^{(9)}\)

**AERO and VISTA Objectives**

While AERO and VISTA are identical spacecraft with a strongly overlapping development team, the two spacecraft represent different sets of measurement goals. The objectives of the single AERO spacecraft are closely tied to the space physics of auroral radio emission. The direction-finding and polarimetry capabilities of the vector sensor on AERO allow the spacecraft to measure the radio aurora to answer questions in Space Science. Several primary radio emission targets exist for AERO, including Auroral Kilometric Radiation (AKR), a strong radio source at frequencies up to 750 kHz that is associated with auroral events. AERO will additionally be able to measure and analyze radio emission due to auroral hiss, auroral roar, and medium frequency burst. All of these emission mechanisms are located in the HF bands \(\leq 15\) MHz and are spatially complex.\(^{(4,5)}\)

The timing requirements for radio interferometry increase with increasing RF frequency, so HF band observations impose a tractable set of requirements. Combined with radio aurora emission qualities of relatively low emission frequencies and spatial complexity, these form an alluring target for measurement by an interferometric array. This match led to the addition of VISTA to the AERO program and its associated interferometric timing questions. VISTA, together with AERO, will validate vector sensor interferometry in space and will enable vector sensing interferometry of space physics radio emissions that fall below the ionospheric cutoff frequency of about 10 MHz.\(^{(1)}\)

**INTERFEROMETRIC TIMING**

Radio interferometry requires separation in space and synchronization in time. In ground-based interferometry, synchronization is achieved with Hydrogen MASERs, but CubeSats like AERO and VISTA are too small to house Hydrogen MASERs, at least with current technology. Instead a trade is needed between timing requirements and other requirements such as size, weight, and power (SWaP). To intelligently conduct this trade, we analyze here the impacts of timing error on the performance of our interferometric system and further describe how clock source options are characterized.

**Characterizing Clock Sources**

The two most common methods by which high quality clock sources are characterized are Allan Deviation and the power spectrum of the fractional frequency deviation. The Allan Deviation (\(\sigma_f\)) is a statistical measure which can be understood as the expectation value of the fractional drift of a clock frequency over a given amount of time. The power spectrum of the fractional frequency deviation measures the frequency distribution of phase noise from the oscillator. This measure is given in dBc/Hz at a given frequency and is typically represented as \(S_f(f)\), the power at a frequency offset \(f\).\(^{(6)}\)

The underlying sources of noise in an oscillator often appear as power law dependencies \(\sigma_f^2(\tau) \propto \tau^{\mu}\) where \(\mu\) is a constant. These dependencies create linear regions when the Allan deviation or spectral power density are plotted on a log-log plot as shown in Figure 2.\(^{(6-8)}\)

![Figure 2: Power Law Linear Regions](image)
The underlying noise processes and scaling relationships are summarized in Table 1.

### Table 1: Oscillator Noise Sources

<table>
<thead>
<tr>
<th>Region</th>
<th>Noise Name</th>
<th>$S_v(f)$ Scaling</th>
<th>$\sigma_v(\tau)$ Scaling</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>White Phase</td>
<td>$\propto f^2$</td>
<td>$\propto \tau^{-2}$</td>
</tr>
<tr>
<td>II</td>
<td>Flicker Phase</td>
<td>$\propto f^1$</td>
<td>$\propto \ln(\tau)\tau^{-2}$</td>
</tr>
<tr>
<td>III</td>
<td>White Frequency</td>
<td>$\propto$ const.</td>
<td>$\propto \tau^{-2}$</td>
</tr>
<tr>
<td>IV</td>
<td>Flicker Frequency</td>
<td>$\propto f^{-1}$</td>
<td>$\propto$ const.</td>
</tr>
<tr>
<td>V</td>
<td>Random Walk of Frequency</td>
<td>$\propto f^{-2}$</td>
<td>$\propto \tau^3$</td>
</tr>
</tbody>
</table>

### Deriving AERO-VISTA Timing Requirements

The AERO-VISTA science team has established high-level requirements that flow into timing system requirements and inform timing system design. The science measurement requires a maximum coherence loss of less than 15%. The worst-case coherence loss occurs for the longest integration time and the highest frequency, defined to be 100 seconds and 15 MHz for AERO-VISTA.

As a zeroth order estimate of the necessary timing requirement we require that the rms phase error be less than one radian of RF phase. This requirement is captured in Equation 1,

$$\sigma_v(\tau) < \frac{1}{2\pi v_0 T}$$  \hspace{1cm} (1)

where $v_0$ = receive frequency, and $T$ = integration time.

For AERO-VISTA, this expression provides an estimate of $1.06 \times 10^{-10}$ for the required Allan Deviation at 100 s.

This scaling relationship was used to first estimate the level of effort necessary for the timing system and is a good match to more exhaustive calculations of correlation loss as further described below.

To analyze the impact of the timing source on coherence loss we first must define a model of the clock source. The characterization of frequency stability that follows is defined and well discussed by Barnes et al. (1971);6 here we only highlight some of the important relationships necessary to estimate timing requirements. Underpinning the entire analysis of frequency stability is the model of an oscillator by

$$V(t) = [V_0 + \epsilon(t)]\sin[2\pi v_0 t + \varphi(t)]$$  \hspace{1cm} (2)

where $V_0$ and $v_0$ are the nominal amplitude and frequency, and $\epsilon(t)$ and $\varphi(t)$ are time dependent amplitude and phase noise sources. When the noise sources are small, the fractional instantaneous frequency deviation from normal is given by:

$$y(t) = \frac{\dot{\varphi}(t)}{2\pi v_0}$$  \hspace{1cm} (3)

The impact of timing error on correlator performance can be analyzed more precisely by introducing the coherence function defined by Rogers and Moran (1981)\footnote{Rogers, F. T.: and Moran, C.:} as:

$$C(T) = \left| \frac{1}{T} \int_0^T e^{i\varphi(t)} dt \right|$$  \hspace{1cm} (4)

Here, $\varphi(t)$ is a characteristic signal of instrument origin caused by the timing error, and is not known a-priori. Accordingly, we will work with the RMS value of this coherence function, which can be calculated from the Allan deviation with the below relation

$$\langle C^2(T) \rangle \approx \frac{2}{T} \int_0^T \frac{\omega^2 \tau^2}{4} \left( I^2(\tau) \right) \left( 1 - \frac{\tau}{T} \right) d\tau$$  \hspace{1cm} (5)

$$I^2(\tau) = \sigma_v^2(\tau) + \sigma_v^2(2\tau) + \sigma_v^2(4\tau) + \ldots$$  \hspace{1cm} (6)

We define the infinite Allan variance series with a function $I^2(\tau)$, the “true variance.” Ultimately, the RMS of the correlation function is related to the correlation loss by Equation 7

$$L_c = 1 - \sqrt{\langle C^2(T) \rangle}$$  \hspace{1cm} (7)

The Allan variance infinite series in $I^2(\tau)$ converges for the special cases of white phase noise and white frequency noise, and analytic expressions can be used. When the series does not converge, Equation 6 can still be used with a correction to account for post processing of the data products.

In VLBI processing, it is typical to perform a search for maximum correlation, thereby removing static offsets and linear frequency drift from the correlation loss function. The equivalent Allan variation can be approximated as being equal to the real Allan variation up to the averaging time $T$, with further multiplication of the intrinsic Allan variation by a $\tau^{-2}$ high-pass roll-off factor.\footnote{Barnes, T. J.: et al.:} With this piecewise representation, the infinite series can be evaluated in a tractable manner through numerical integration up to the integration time $T$, and with analytic evaluation when the series begins to converge at integration times beyond $T$. This method is limited to cases in which the Allan deviation proportionality is at most linearly increasing with $T$, but this covers all the major noise sources presented. These
equations and resulting possible requirements are shown in Table 2 and the correlation loss functions are plotted in Figure 3.

Table 2: Correlation Loss Analysis

<table>
<thead>
<tr>
<th>Noise Source</th>
<th>Analysis Type</th>
<th>Analytic Expression for $\langle C^2(T) \rangle$ or $\sigma_x^2(\tau)$</th>
<th>Piecewise Approximation</th>
</tr>
</thead>
<tbody>
<tr>
<td>White Phase</td>
<td>Analytic</td>
<td>$a = 2\pi^2 \nu^2 K^2_e$</td>
<td>(8)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\langle C^2(T) \rangle = \frac{2(e^{-aT} + aT - 1)}{aT^2}$</td>
<td>(9)</td>
</tr>
<tr>
<td>Flicker Phase</td>
<td>1^NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>White Freq.</td>
<td>Analytic</td>
<td>$\langle C^2(T) \rangle = \exp \left(-\frac{4\pi^2 \nu^2 K^2_e}{3} \right)$</td>
<td>(10)</td>
</tr>
<tr>
<td>Flicker Freq.</td>
<td>Numerical</td>
<td>$\sigma_x^2(\tau) = \begin{cases} \alpha \tau &amp; \tau &lt; T \ \frac{\alpha \tau^2 + 1}{T} &amp; \tau \geq T \end{cases}$</td>
<td>(11)</td>
</tr>
<tr>
<td>Random Walk of Freq.</td>
<td>Numerical</td>
<td>$\sigma_x^2(\tau) = \begin{cases} \alpha \tau &amp; \tau &lt; T \ \frac{\alpha \tau^2 + 1}{T} &amp; \tau \geq T \end{cases}$</td>
<td>(12)</td>
</tr>
</tbody>
</table>

*Flicker phase differs from white phase only by an log(τ) term and the two are analyzed together.

Figure 3: Coherence Loss Allan Deviation Dependence

The exact spectral nature of the oscillator noise among the choices in Table 2 can create up to a factor of 3 deviation in the resulting Allan deviation requirement, from roughly $1 \times 10^{-10}$ for white phase noise, to roughly $3 \times 10^{-10}$ for random walk of frequency noise. This does not necessarily mean that a phase noise dominated oscillator is a better oscillator than a frequency walk dominated oscillator, because they are likely to have very different Allan deviations at the integration time of interest. The measured Allan deviations of reference oscillators can vary in practice by many orders of magnitude so the factor of three modification for spectral type is not that significant, and therefore the zeroth order model from earlier is adequate for clock selection in many applications. This analysis together with some input from the AERO-VISTA signal processing team on the impact of the correlation maximization search led to the slightly more relaxed requirement of $\sigma_y(100s) < 5 \times 10^{-10}$.

Table 3: Requirements from Correlation Loss

<table>
<thead>
<tr>
<th>Noise Source</th>
<th>Resultant Requirement 100 s Allan Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>White Phase</td>
<td>$\sigma_y(100s) &lt; 1.06 \times 10^{-10}$</td>
</tr>
<tr>
<td>White Frequency</td>
<td>$\sigma_y(100s) &lt; 1.55 \times 10^{-10}$</td>
</tr>
<tr>
<td>Flicker Frequency</td>
<td>$\sigma_y(100s) &lt; 2.75 \times 10^{-10}$</td>
</tr>
<tr>
<td>Random Walk of Freq.</td>
<td>$\sigma_y(100s) &lt; 3.21 \times 10^{-10}$</td>
</tr>
</tbody>
</table>

Temperature Variation

Most clock sources are measured in a laboratory environment far different than that of a small satellite in low Earth orbit. In particular, the fast temperature variations encountered by the oscillator can add frequency drift that may not be able to be removed by the correlation maximization search. Additionally, the exact frequency dependence of thermally introduced timing error is not characterized in datasheet parameters. To estimate a requirement on the temperature coefficient of the clock source, we can require that the spectral drift caused by temperature variation be less than that of our general clock noise analysis above.

An initial thermal analysis of AERO and VISTA has indicated that a maximum temperature variation over a 100 seconds collection time will be about 1.3 °C. This temperature difference corresponds to moving from eclipse to sun just as a high-power data collection mode is entered. If the resultant frequency drift from thermal variation is to be less than the $5 \times 10^{-10}$ requirement for oscillator noise, this leads to a required temperature coefficient of $< 6 \times 10^{-10}$ °C⁻¹.

Jitter and Receiver Noise

In addition to long-term stability requirements, the clock system must exhibit good short-term stability. The clock system is used to discipline an RF analog-to-digital converter (ADC) on each of the antenna channels, and short-term timing error can couple into the signal chain and reduce SNR. The short-term error is frequently represented as either phase noise at a frequency offset, or in an integrated time-domain form as jitter. The phase noise plot over offset frequency is a more complete
representation of short-term stability as the jitter can be derived from the phase noise, but the opposite is not true.\textsuperscript{10}

The requirement for phase noise has been derived from the ADC’s SNR degradation with jitter as presented in Figure 4.

Figure 4: ADC Clock Jitter Impact on SNR\textsuperscript{11}

A RF system trade was conducted to determine how much SNR degradation would be acceptable to the signal processing chain at the worst-case frequency of 15 MHz, and the jitter requirement was subsequently set at <1 ps.

Phase noise can also cause problems in Fourier analysis of the incoming signal by causing an otherwise monochromatic source to spread into adjacent frequency bins during the FFT processing. To minimize this effect, an additional requirement of < -110 dBc/Hz at 100 Hz offset was established.

The high-level timing system requirements are summarized in Table 4 for reference in subsequent hardware trade discussions.

Table 4: Clock System Requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allan Deviation</td>
<td>$\sigma^2(100s) &lt; 5 \times 10^{-10}$</td>
</tr>
<tr>
<td>Temperature Coefficient</td>
<td>$&lt; 6 \times 10^{-10} \circ C^{-1}$</td>
</tr>
<tr>
<td>Integrated Jitter (12 kHz - 20 MHz)</td>
<td>&lt;1 ps</td>
</tr>
<tr>
<td>Phase Noise</td>
<td>$&lt; -110$ dBc/Hz at 100 Hz offset</td>
</tr>
</tbody>
</table>

CLOCK SYSTEM DESIGN FOR AERO-VISTA

This section details the major development phases in the hardware design of the clock system, including the supporting electronics comprising a vector sensor subsystem known as the Clock Board. The system and board design are broken into the following steps:

1) Selection Trade for major clock system components
2) Supporting Electronics
3) PCB Considerations for High Quality Clocking
4) Expected System Performance

Selection Trade for major clock system components

The major clock system components are a stable reference source and a clock multiplication/distribution device. In very high-performance clock systems, the reference clock source may be directly connected to the sink device to preserve optimal phase noise performance. For AERO-VISTA the phase noise requirements are more modest and multiple clock signals of different frequencies are needed. Therefore, a clock multiplication and distribution component is used to create the system clock from the reference source.

The primary clock reference must meet the timing requirements as well as SWaP constraints typical of Cube Satellites. We start our clock selection processes by looking at some typical Allan Deviation curves for high quality reference clocks.

Figure 5: Typical Reference Clock Sources\textsuperscript{9}

Here the Allan deviation requirement has been called out with the purple diamond symbol. It is immediately apparent from this plot that all of the high-quality reference clocks presented here could easily meet our Allan Deviation requirement. However, these clocks represent high-quality laboratory reference systems that are generally far too large and power hungry to fly in a small satellite. Additionally, these specifications are collected without regard to temperature variation. Ovenized quartz oscillators can be found in relatively...
small and low-power packages, but can exhibit adverse
temperature coefficients orders of magnitude higher than
that of the CSAC.

To meet our temperature stability requirements and fly
on a small satellite, two devices were traded early in the
design process, the Chip Scale Atomic Clock (CSAC)
from MicroSemi1,2, and a low-power ovenized oscillator
(OCXO) manufactured by Bliley14.

The critical oscillator parameters based on the datasheets
are shown in Table 5: Reference Oscillator Comparison
for comparison.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CSAC</th>
<th>OCXO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adev at 100 s</td>
<td>$3 \times 10^{-11}$</td>
<td>$\sim 8 \times 10^{-12}$ – $8 \times 10^{-11}$</td>
</tr>
<tr>
<td>Temperature Coefficient</td>
<td>$6 \times 10^{-12}$</td>
<td>$6 \times 10^{-10}$</td>
</tr>
<tr>
<td>Power</td>
<td>120 mW – 140 mW</td>
<td>135 mW – 350 mW</td>
</tr>
<tr>
<td>Volume</td>
<td>16 cm$^3$</td>
<td>5.9 cm$^3$</td>
</tr>
</tbody>
</table>

*Extrapolated with flicker frequency and random walk frequency
noise from Adev at 1s

*Corresponds to tightest tolerance available of ±50 ppb

*Dependent on device configuration and output frequency

Both devices meet the necessary Allan deviation at 100 s,
but the temperature coefficient of the OCXO only
marginally meets the derived requirement. The CSAC
consumes slightly less power but both devices are
comparable in power draw after warmup. The CSAC is
significantly larger than the OCXO but slightly shorter
in height off the PCB, so may be easier to integrate into
a standard payload stack as long as the other components
can fit in the remaining PCB area. The CSAC was
ultimately selected primarily for its improved stability to
temperature variation. The CSAC has the added benefit
of being space qualified with flight heritage on a similar
CubeSat, the CubeSat Handling of Multisystem
Precision Time Transfer (CHOMPTT) mission by the
University of Florida in 2018.15

The next major component selection involved the clock
generation and distribution component. Multiplication of
the reference clock signal for the ADC reference
frequency requires a PLL with significant programmable
controllability since the ADC frequency is not
necessarily a multiple of the reference frequency.
Additionally, it is desirable to integrate multiple
independently programmable output frequencies that are
locked to each other with a fixed phase relationship. This
is needed to drive the multiple spacecraft clock
frequencies in a phase coherent manner to reduce EMI.
Finally, the device must achieve low integrated jitter and
phase noise. The clock distribution component that
meets these requirements is the Analog Devices
AD9545. The selection criteria and device parameters
are summarized in Table 6: PLL Selection Criteria.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Desired Feature</th>
<th>AD9545</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Outputs</td>
<td>&gt;2</td>
<td>5 differential or 10 single-ended</td>
</tr>
<tr>
<td>Output Configuration</td>
<td>Differential and Single Ended capability</td>
<td>Both Differential and Single Ended capability</td>
</tr>
<tr>
<td>Integrated Jitter</td>
<td>&lt;1 ps</td>
<td>&lt; 0.3 ps*</td>
</tr>
<tr>
<td>Reference Signal Range</td>
<td>Must be driven by 10 MHz, ability to synchronize to 1 PPS desirable</td>
<td>Synchronization to 1 Hz to 750 MHz (including 1 PPS)</td>
</tr>
<tr>
<td>Power</td>
<td>Low Power, preferably &lt; 1 W</td>
<td>800 mW*</td>
</tr>
</tbody>
</table>

*Dependent on device configuration and output frequency

*Measured with the development kit in the anticipated operating mode

Supporting Electronics

The Clock Board integrates supporting electronics for
the control, power, and communication with the major
clock system components. Control of the Clock Board is
primarily accomplished with a “backplane” SPI bus
shared with the rest of the payload electronics. This
shared SPI bus is used for low data rate configuration,
communication of health and status monitoring data,
and power supply domain control. The CSAC uses a UART
protocol for configuration so is separate from the
backplane SPI.

The Clock Board has three power domains: a block that
is always on, a CSAC block, and a PLL block. When not
being used as a primary clock source, the PLL block can
be turned off to conserve power, and the CSAC can be
left on to keep warmed up and keep lock to the GPS
reference Pulse Per Second (PPS). Alternatively, the
Clock Board can be powered down to all but the health
and status electronics by powering down both the PLL
and CSAC power domains. This flexibility allows the
high-performance clock system to consume less average
power but does require careful design and protection of
inputs that may be damaged if driven while the
component is off. This protection is provided by a simple
and low power analog MUX with built-in circuitry to
exhibit high input impedance when powered off.

The Clock Board collects health and status monitoring
data using circuitry and communications protocols that
are standard to all of the AERO-VISTA payload
electronics. This data includes voltage of all power
domains, current consumption of each independently switchable power domain, and temperature. This data is read over the backplane SPI bus at 10 Hz.

![Figure 6: Clock Board Block Diagram](image)

All serial communication with the Clock Board and all transmission of clock signals occurs over a differential pair. Routing serial lines by differential pair reduces EMI from the payload electronics to avoid interference with the primary vector sensor payload. Routing the clock lines as a differential pair helps reduce interference on the vector sensor and also protects the clock lines from noise that may couple from adjacent digital electronics.

**PCB Considerations for High Quality Clocking**

Once the low jitter and low phase noise clock signal is generated by the AD9545 PLL, it must be protected from degradation by noise and reflections. The clock signal is directly generated by the PLL as a differential pair to eliminate the need for an extra buffer. The clock signal is buffered only once, for distribution at the ADC by a buffer selected specifically for its ultra-low additive clock jitter. In accordance with good mixed-signal practice, the clock signals are routed for maximum signal integrity. The layout of the Clock Board has been specifically optimized for minimum routing length of the clock signals, particularly when single-ended between the CSAC and the PLL.

![Figure 7: Single Ended Clock Route](image)

In Figure 7 the critical CSAC RF signal is highlighted, before and after the input protection MUX. The total routed electrical length of this signal is 0.8”.

Similarly, the PLL has been placed so that the clock signal is as close as possible to the backplane connector so that the differential route length can be as short as possible as shown in Figure 8.

![Figure 8: ADC Reference Clock Route](image)

This total electrical length is 1.9” and the differential pair path lengths are matched to within 5 mil or about 0.8 ps.

All mixed-signal routes are placed between two unbroken ground planes with ground plane via stitching and a copper flood fill on the signal layer to shield the clock signals from external interference.
Finally, all serial communication signals were routed with minimum plane breaks and always sandwiched between two planes to minimize propagation of electrical noise between board regions.

**Expected System Performance**

Based on our careful treatment of the clock lines, we can estimate the total system specifications based on the data sheet parameters, and these values are summarized in Table 7. Some of these parameters were estimated with simplifying assumptions or extrapolation of data and will need to be verified with testing.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Board Area</td>
<td>50 cm$^2$</td>
</tr>
<tr>
<td>Total Power</td>
<td>1.5 W</td>
</tr>
<tr>
<td>Adev (100s)</td>
<td>$3 \times 10^{-11}$</td>
</tr>
<tr>
<td>Tempco</td>
<td>$6 \times 10^{-12}$</td>
</tr>
<tr>
<td>Clock Jitter</td>
<td>0.3 ps</td>
</tr>
<tr>
<td>Phase noise at 100 Hz separation</td>
<td>$\sim \sim 110 , dBc/Hz$ at 100 Hz offset</td>
</tr>
</tbody>
</table>

**VERIFYING CLOCK SYSTEM PERFORMANCE**

Preliminary testing of the major clock system components has been conducted using the CSAC and AD9545 on their respective evaluation boards. The output of the simulated clock system was compared to an ovenized benchtop crystal with a Symmetricom 5115A phase noise measurement test set. This test system is summarized in Figure 10.

**Figure 10: Measurement Block Diagram**

To verify the datasheet-advertised long-term stability, Figure 11 plots the observed Allan deviation out to 100 s.

**Figure 11: CSAC with PLL Allan Deviation**

The plot indicates that the intercept for the white phase noise portion of the Allan deviation plot is nearly two orders of magnitude better than advertised on the datasheet. However, the corner point from white phase noise to random frequency walk occurs at about 1 s integration time (0 on the log-scale independent axis), not beyond 1000 s as expected.

This behavior is ascribed to the longer time stability of the benchtop crystal, since this test’s setup inherently compared one oscillator to another. In particular, as was shown in Figure 5, benchtop crystals can have very low Allan deviations at short integration times but may begin to increase with integration time at about 1 s, similar to the observed test data. Interestingly, despite this inherent reference limitation, we were still able to prove that the Allan deviation at 100 s is better than the required $\sigma_y(100\, \text{s}) < 5 \times 10^{-10}$.

Following the analysis used to derive the timing requirement and using white phase noise for power-law fitting, the expected coherence loss with integration time is plotted in Figure 12. This analysis assumes that the entire frequency spectrum is white noise, which was shown earlier to create the strictest requirements for integration times less than the Allan Deviation measurement period. Conversely, white phase noise is the most best-case assumption for coherence loss at
integrations times beyond the Allan Deviation measurement period. Therefore, interpolation beyond 100 s in Figure 12 may be inaccurate, but these results accurately show that the CSAC meets coherence limit requirements up to 100 seconds integration time.

Future tests will improve on this measurement using the Hydrogen MASER at MIT Haystack Observatory as a frequency reference. Hydrogen MASERs are typically capable of achieving $\sigma_y(100s) < 1 \times 10^{-14}$. This will ultimately allow measurement of the CSAC inherent drift even if our CSAC is operating 100 times more stable than advertised.

The short-term jitter and phase noise at the output of the AD9545 PLL were measured with the same measurement setup in Figure 10, but with the Symmetricom phase noise test set configured to capture phase noise instead of Allan deviation. These results are presented in Figure 13.

If the Clock Board meets all system requirements, it will be integrated into the rest of the payload for interface testing and full system characterization. If the Clock Board does not meet all timing system requirements, some edits can be made to the PLL configuration for improved phase noise without redesigning the entire system. This is evidenced in the wide range of phase noise plots provided on the AD9545 datasheet for different operating configurations.

**CONCLUSION**

The timing system for AERO and VISTA will enable a unique demonstration of orbital interferometry with vector sensors. The correlation of data from these spacecraft will enable greater angular resolution measurements for enhanced imaging of the radio aurora.

The timing system requirements have been derived from the science and observation requirements and the selected clock system components are expected to meet these requirements. The unavailability of laboratory equipment in 2020 has prevented full testing of the Clock Board components on the development kits as planned, but data from earlier tests has shown that the Clock Board will likely meet all timing system requirements. Fabrication and full testing of the Clock Board is expected to conclude by the end of Summer 2020, and integration with the rest of the payload and spacecraft bus is expected by the end of calendar year 2020.
The Clock Board is a capable timing system that is stable over both short and long time-scales, and offers a high degree of configurability due to the flexibility of the AD9545. A system similar to the Clock Board could enable other Small Satellite payloads such as Bistatic Radar or precision ranging payloads. Additionally, the lessons learned and design procedure followed for the AERO-VISTA Clock Board will continue to be relevant as higher quality CSACs and PLLs are developed. The development of ever better oscillators in small SWaP payloads will make cooperative swarms of small coherently synchronized satellites an affordable and attractive option for remote sensing and astronomy applications.

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