

Artemis I Flight Instrumentation Data Quality Assessment and Processing

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On November 16th, 2022, NASA launched the inaugural test flight of the Space Launch System (SLS) carrying the Orion capsule into a high orbit far beyond the Moon. The launch vehicle was instrumented with over three thousand flight instrumentation sensors, many of which monitored aerodynamic, acoustic, structural, and thermal environments. These data are intended contribute to the validation of experimental and numerical tools used to predict the design environments that the vehicle experiences during launch and ascent. Prior to launch, tests were performed at the SLS Systems Integration Laboratory (SIL) using flight-like avionics and on the integrated flight hardware of Artemis I at the Vehicle Assembly Building (VAB). The purpose of these tests was to characterize the data acquisition units (DAUs) used to record and telemeter flight data to ground stations in order to assure that flight test objectives can be achieved and to quantify the expected quality of the flight data. In addition, preflight assessment and development of tools and methods used to process and disseminate flight data at the Huntsville Operations Support Center (HOSC) were conducted and adjustments made with respect to DAU time synchronization prior to and after the flight. This paper summarizes these tests. Some aspects of the data postprocessing are discussed.

Notice to Readers

The Space Launch System, including its predicted performance and certain other features and characteristics, have been defined by the U.S. Government to be Controlled Unclassified Information (CUI). Information deemed to be CUI requires special protection and may not be disclosed to an international audience. To comply with CUI restrictions, details such as absolute values have been removed from some plots and figures in this paper. It is the opinion of the authors that despite these alterations, there is no loss of meaningful technical content. Analytical methodologies and

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capabilities are discussed, significant and interesting technical results are still present, and meaningful conclusions are presented.

I. Introduction

The flight of Artemis I carried over 3000 Operational Flight Instrumentation (OFI), Engineering Flight Instrumentation (EFI), and Developmental Flight Instrumentation (DFI) sensors to help validate vehicle design environments and system performance to assist with qualifying the vehicle as human rated. There are 24 Space Launch System (SLS) flight test objectives (FTOs) that require the OFI, EFI, and DFI flight data in support of 169 flight data analysis (FDA) tasks to satisfy the FTOs [1, 2]. It is therefore essential to fully characterize the flight avionics systems and methods used to acquire and telemeter these data to ground systems. Furthermore, accurate dissemination of these data via the Huntsville Operations and Support Center (HOSC) at Marshall Spaceflight Center (MSFC) requires post-flight processing to assure, for example, that all data measurements are time-synchronized across multiple data acquisition units (DAUs) on the vehicle. To this end, tests were conducted prior to flight at the SLS Systems Integration Laboratory (SIL) using flight-like avionics and on the integrated flight hardware of Artemis I at the Vehicle Assembly Building (VAB).

The FTOs and FDA tasks support a wide variety of launch vehicle disciplines and thus the DAUs have been designed to power, amplify, filter, and digitize data from a variety of sensors such as: pressure, temperature, strain, force, acceleration, heat flux, and many others. Each variety of flight instrumentation has a unique purpose in the life of the SLS vehicle. The OFI includes sensors collecting flight-critical data needed for real-time operation and monitoring. While both the EFI and DFI systems record data for post-flight analyses, the EFI system will be present on all SLS missions and consists of relatively few sensors that monitor fleet health and performance. In comparison, the DFI is designed to be temporary and separate from the OFI and EFI systems. It hosts numerous sensors to capture data at a relatively high sampling frequency (in comparison to EFI). DFI data are used for vehicle Design Math Model (DMM) validation and to satisfy FTOs and FDA tasks by comparing flight data to preflight predictions across many launch vehicle design disciplines.

The cross-channel time synchronization and sample rate requirements for the flight data depends on the various physical phenomena that is being captured, as summarized in Fig. 1. Among the more challenging launch vehicle environments to characterize and measure are those that are dominated by unsteady aerodynamic pressure due to transonic and supersonic flow on the vehicle geometry [3] and blast/shock pressure transients due to liftoff acoustics and ignition overpressure (IOP) [4]. These measurements require data sampled at high rates. For example, an unsteady pressure sensor for buffet or IOP environments was sampled at about 500 Hz, whereas a microphone used for aeroacoustic and launch acoustic measurements was sampled on the order of 10,000 Hz. Aside from high sample rates, the density of sensor spatial distribution is important. The analysis of buffet environments required several unsteady pressure sensors arranged in a ring-like configuration with sensors installed at different azimuthal locations for each longitudinal station. This configuration allowed for azimuthal integration of the pressure to obtain a sectional load. Integration of several such sensor rings along the length of the vehicle provided the longitudinal forcing distribution, known as buffet forcing functions (BFFs). These BFFs applied to the vehicle finite element model (FEM) would result in loads that could then be compared to the structural vibratory response of the vehicle measured by external and internal accelerometers. So, not only is the time accuracy of each measurement important, but the synchronization between measurements was also critical to allow for cross-channel data analysis.

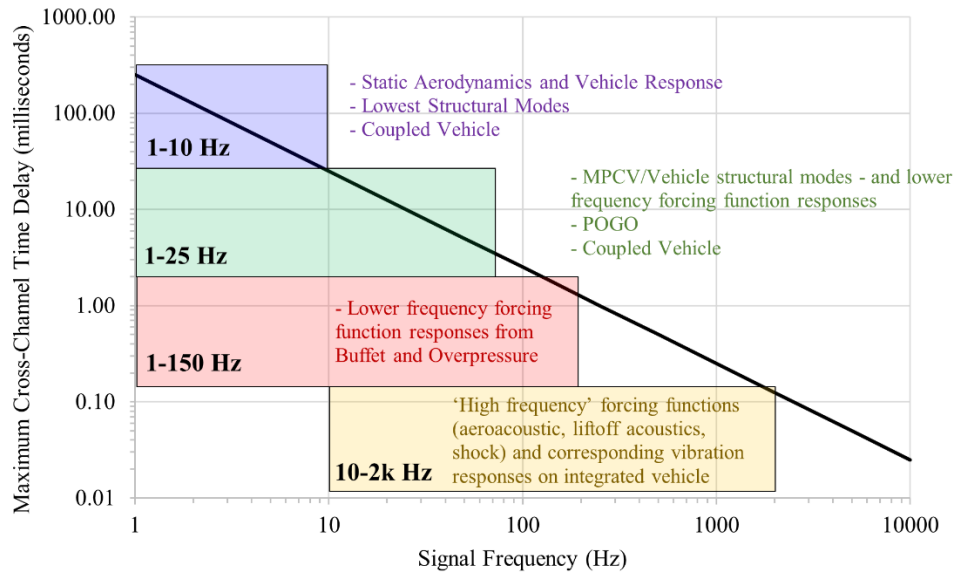


Figure 1: Cross-channel time delay allowable changes with frequency, which is related to various physical phenomena of interest.

The authors of this paper are concerned with 'Integrated Vehicle environments' such as pogo, aerodynamics, external acoustics, structural loads, and dynamics. Of the twenty-nine post-flight analyses that were developed by these disciplines following Artemis I flight, some relied on flight data from a single area or Element (such as base heating or plume impingement), while many analyses (such as liftoff acoustics) relied on data collected by five data acquisition systems (DAUs) across all vehicle components during liftoff. These included data from the SLS DFI and EFI sensors on the core stage and boosters, as well as from data systems on the upper stage (Interim Cryogenic Propulsion Stage - ICPS), Orion, and Exploration Ground Systems (EGS). The number of sensors and DAUs required the implementation of a strict time synchronization. Part of the motivation for flight data to have very accurate timestamps is found in the Lessons Learned from the Ares I-X flight test, flown in 2009. This vehicle had separate data acquisition units on the Upper Stage simulator, First Stage, and the ground system. Uncertainties in the data timestamp accuracies were responsible for months of delays in the IOP post-launch analysis.

SLS is largely an integration project with constraints to use existing or modified-off-the-shelf/commercial-off-the-shelf (MOTS/COTS) subsystems. As such, timing requirements were not specified for noncritical instrumentation systems. Timestamps are assigned to data by each individual DAU, and the relative time accuracy between data points gathered by each individual DAU is very high. Analyses of the pogo, acoustics, flex dynamics and buffet need a high level of time accuracy for data that are gathered by multiple DAU systems from sensors distributed across the vehicle. The results of analyses would be degraded if they had to rely solely on the time stamps assigned by the individual DAUs because of the uncertainty in the time synchronization between these various DAUs. Adding a requirement for these DAUs to be synchronized was not a realistic option because of schedule and cost impacts. The stakeholders realized that characterizing the response of the various DAUs through prelaunch testing could be as good as, if not better than, having the timing requirement. The testing in the SLS SIL and in the VAB were justified by the need to understand the timing characteristics of the SLS DAUs as well as the integrated stack (SLS with Orion, ICPS, and ground). Once the decision was made to do testing, the additional cost to include other objectives was insignificant. These add-on objectives included characterizing the linearity of the phase response, linearity of the amplitude response, and discovering the quiescent noise floor of the overall system. These could have been accomplished using bench testing of individual DAUs, or DAU cards, but integrated testing at the SIL and the flight hardware was ideal.

Characterizing the response of the various data acquisition systems can be achieved by the simultaneous injection of a test signal into several data channels so the input can be recorded and compared. In general, the individual data acquisition cards and boxes have very well understood timing characteristics, and additional testing was not required. Of concern was how the timing errors would propagate and accumulate once the data acquisition units were integrated into the SLS avionics system. An ideal situation would have been to test multiple channels on the flight hardware once the Artemis I stack was integrated at the launch pad (testing SLS DFI, SLS EFI, ICPS, Orion, and EGS altogether). However, such testing would have delayed launch. Also, the test data would be acquired too late to be useful. Instead, most of the desired test objectives could be accomplished over a year prior to launch using flight-like hardware at the MSFC SIL, which is a hardware-in-the-loop testing facility configured as a near-replica of the SLS avionics stack with very few emulated hardware components. The MSFC SIL testing provided an understanding of how the SLS DFI and EFI systems operated, but the Induced Environments (IE) and Loads Dynamics and Integrated Design (LDI) teams needed to understand the accuracy of data time stamps across the rocket – relative differences between SLS, ICPS, Orion, and EGS. This was accomplished using the SIL test data and also with the additional data from the DAU Time Correlation Test, which was performed on the integrated vehicle stack in the VAB on January 25th, 2022.

This paper presents the methods used to characterize the Artemis I flight instrumentation, especially in the context of time accuracy, through both the SIL testing and DAU Time Correlation Test at VAB. The architecture of the data acquisition system on the SLS will be summarized. A brief discussion of the postprocessing of the flight data is also included.

II. SLS Instrumentation Systems

The origins of the Space Launch System DFI data acquisition systems are found in the Ares I program and the Ares I-X flight test vehicle, which were part of the Constellation program and preceded the SLS and Artemis programs. The contracts for SLS data acquisition hardware and the program structure were inherited from the Constellation program. In general, the same is true for the Orion and ground data acquisition systems – the designs, contracts and plans carried over from the Constellation program to the new Exploration Systems Development Mission Directorate. Similarly, the ICPS was derived from the Delta IV Cryogenic Second Stage (DCSS) with a history of over 40 flights and was purchased as an off-the-shelf design, limiting the control over the ICPS DAU architecture.

The EFI system is controlled by three Data Acquisition and Control Units (DACUs): DACU-1, DACU-2, and DACU-3, which collect measurements from sensors across Core Stage and send data to a Command and Telemetry Controller (CTC-1) for further processing. The DFI System is controlled differently; by four Master Data Acquisition Units (MDAUs), each with a Remote Data Acquisition Unit (RDAU) used as an extension. Core Stage data were collected by two MDAUs: MDAU-1 and MDAU-2; and two RDAUs: RDAU-1 and RDAU-2. In addition, MDAU-L and RDAU-L collected data from the Left Booster and MDAU-R and RDAU-R from the Right Booster. The four MDAUs route data through another Command and Telemetry Controller (CTC-2) for subsequent processing. ICPS and Orion have separate EFI/DFI systems. This architecture is depicted in Fig. 2, which illustrates the relative positions of the main EFI and DFI components across the Artemis I stack. Core EFI components are shown in orange, and DFI are shown in blue. Individual sensors extend throughout the various structures but are not depicted. Also note the CTCs process commands and data from other systems.

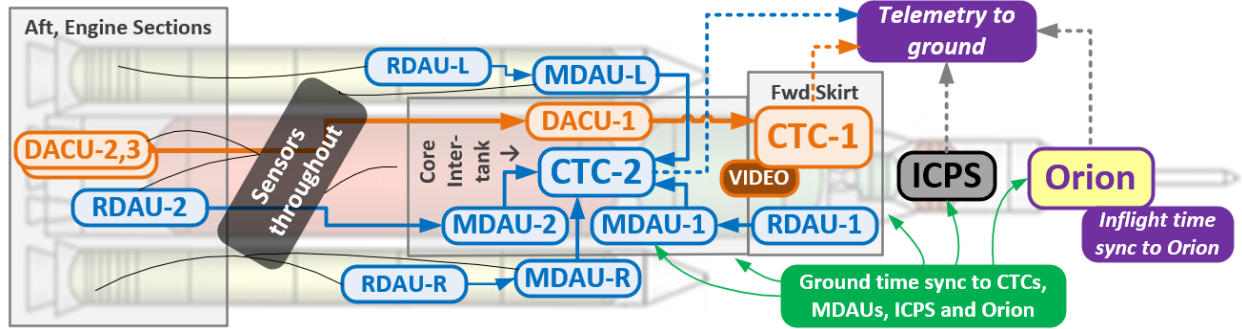


Figure 2: EFI and DFI Subsystem Across Artemis I

Each DACU and MDAU periodically collects thousands of samples from all its sensors, using a fixed cycle and sample schedule. They organize that data with housekeeping parameters into a “major frame”, which is comprised of several minor frames and each minor frame is sent to its CTC at fixed intervals. The major frame has one timestamp, which precisely corresponds to the beginning of each collection cycle.

Prior to liftoff, all vehicle data were streamed using Radio Frequency (RF) and also through the umbilical, which provides a physical connection between the vehicle and the Mobile Launcher (ML). The umbilical was disconnected at launch, and afterwards, all data were telemetered to three ground: Kennedy Uplink Station (KUS) - located about 6 miles south of the launch pad 39B, Ponce de Leon (PDL) - located 35 miles north of the launch pad, and NASA Wallops Range’s downrange Bermuda (BDA) station - located roughly 980 miles down range. The OFI data and EFI data were telemetered live, while DFI data were telemetered separately with a time delay [5, 6]. Streamed data from SLS, ICPS (only from Master/Remote Telemetry Unit DAU, also known as MRTU), and EGS were ultimately stored at the HOSC where it is available for download. The available data is stored in a raw form, with minimal processing.

III. Systems Integration Lab (SIL) Testing

The SIL, pictured in Fig. 3, is primarily used to test the response of the entire SLS avionics architecture to various simulated failures and error conditions, as well as nominal flight conditions considering expected trajectory and environment dispersions. The laboratory contains flight-representative avionics hardware, which includes a set of DAUs. All components are electrically connected using cables, which also are representative of the ones installed on the SLS vehicle. This allowed the ability to accurately capture any signal delay due to cable length. Individual DFI and EFI sensors were not installed at the SIL. Instead, a custom signal generator was used to simultaneously inject an artificial signal into 63 sensor channels. One more channel from the signal generator was sent to an oscilloscope with Inter-Range Instrumentation Group (IRIG) timecode synchronization to capture the raw generated signal. Similar to the SLS vehicle, data recorded by the DAU at SIL were sent to the HOSC for processing and storage. Any signal delays associated with the cable length and filter settings, as well as Element-provided delay corrections, were incorporated into the data processing algorithm at the HOSC called Time-of-Validity (TOV). The SIL architecture allowed for nearly end-to-end verification of the SLS DAU architecture with sensors themselves as the only component missing in the data capture chain.

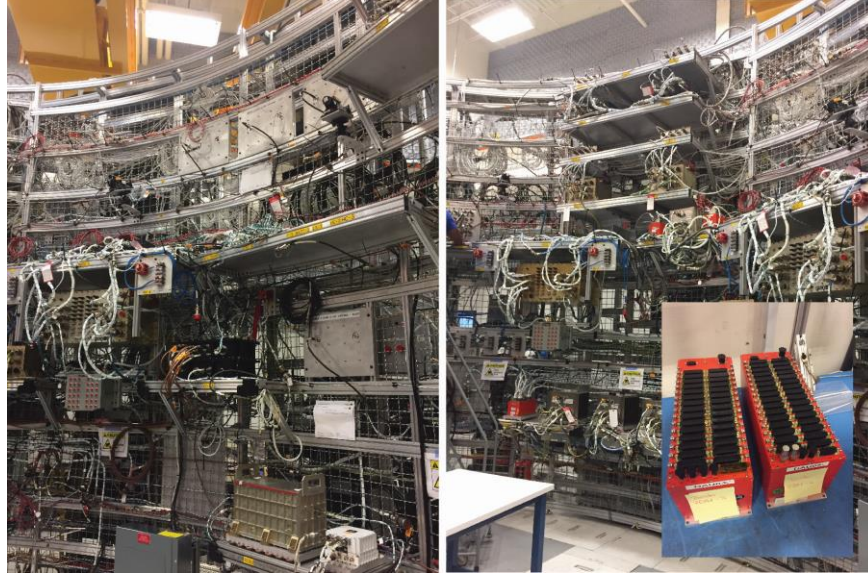


Figure 3: Two views of the SIL facility. DAU units shown in the inset on the right.

For the SIL DAU characterization tests, test signals were generated and sent to different channels across various DAU card types and channels with various sampling rates and filter settings to characterize their performance. The key parameters-of-interest were computed between channels, as well as between the DAUs and generated test signal. These parameters included the frequency response, which encompasses the relative gain and phase lag, as well as the linear coherence. Of particular interest to this paper was the SIL test sequence, which injected Gaussian white noise and a square wave pulse into the DAU test signal channels that helped determine time alignment and visually verify corrections, respectively. Processing time delays of the SLS DAUs were determined by computing the cross-correlation between the DAU recorded data and a simultaneous local recording of the test signal input. In theory, since all the cable length and filter delays were incorporated in the HOSC TOV postprocessing algorithm, a square wave signal measured by the DAU at SIL and downloaded from HOSC should have no time delay when compared to the signal recorded by the oscilloscope. This was true for the majority of the channels, and measured delays were negligible indicating that the theoretical delays programmed in the HOSC postprocessing algorithm were accurate. However, the characterization tests on some channels revealed a slight time offset between the measured and the generated test signal. In fact, as shown in Fig. 4(a), SIL-HOSC signal indicated the square wave arrived to the DAU before it did to the oscilloscope input signal, which is not physical and is indicative of delay values implemented in the HOSC algorithm overcorrecting for a time offset. The measured time offset between the DAU and input signal was recorded and HOSC delay values were further adjusted to provide an acceptable synchronization between the SIL DAU and oscilloscope input signals, as shown in Fig. 4(b).

It was impractical to individually characterize every EFI and DFI channel since building special cables to inject the test signals into all the channels would have been too costly. Instead, an artificially generated test signal was sent to a subset of DAU channels. Each selected channel in this subset was representative of the channels that share the same DAU card setting - filter and sampling rate. The goal was to test one channel per card on the DAU to determine a time delay value, or offset, and use this offset for all channels on that card having the same DAU settings. Further testing verified that a group of channels that all use the same DAU card type, sampling rate, and filter settings had the same offset values. So, grouping channels by their DAU settings was an appropriate approach for incorporating delay value corrections.

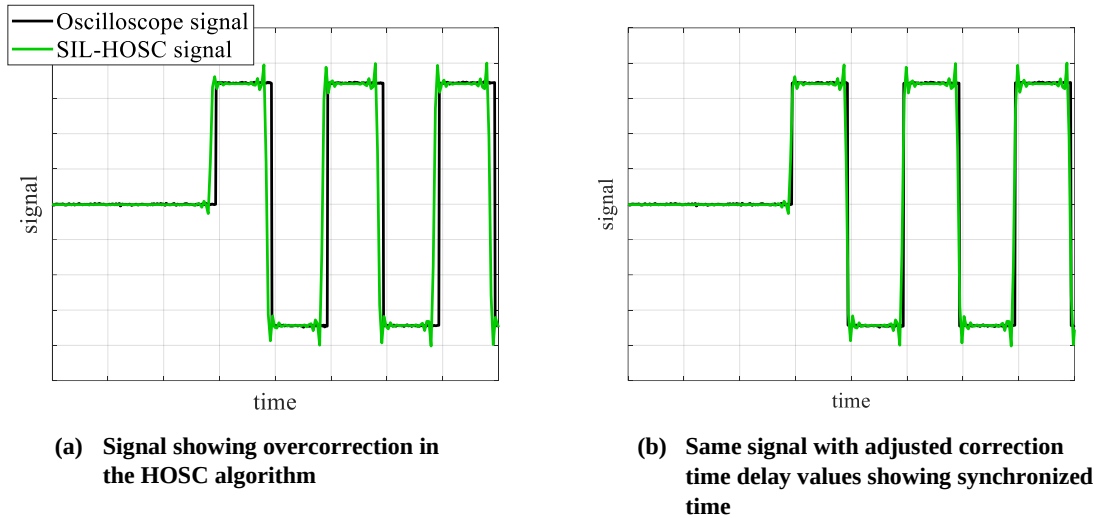


Figure 4: A typical square wave input signal captured by the oscilloscope and output signal captured by the HOSC.

Furthermore, cross-channel analysis of the SIL DAU characterization test data was used to determine group delays and phase delays for channels across various DAU cards and sampling rates. The delays were visualized versus frequency to determine whether the filters exhibited any frequency-dependent delays. The results indicated no frequency dependence in all instances.

The methods developed during the SIL characterization test will be used in future work. For SIL tests leading up to Artemis II, similar methods will be utilized to determine unknown delays and validate provided theoretical delay values.

IV. Data Acquisition Units Time Correlation Test

Artemis I was stacked at the Kennedy Space Center’s VAB in mid-2021, and for the first time, individual components were integrated into a single vehicle. A DAU Time Correlation Test was conducted in January of 2022 to measure the time drift of the SLS timing components and identify time offsets between the DAUs across all major components.

Two scenarios were tested. The first scenario resembled a time just after liftoff with minimum drift of the avionics clock. The second scenario resembled a time late in flight with maximum clock drift. In order to minimize the impact on the VAB processing schedule, the second scenario was tested first. The vehicle components were disconnected from the ground-based IRIG timecode signal a few hours prior to testing in order to simulate a worst-case clock drift. A pressure sensor on each of the subsystems was excited using an audio speaker assembly shown in Fig. 5. The assembly consisted of an audio speaker, electrically connected to an amplifier and an audio signal generator, and a sound tube. The speaker was placed at one end of the sound tube. A reference microphone was positioned at the other end of the tube to measure the actual audio signal used in the excitation. The open end of the tube was positioned in close proximity to pressure sensors on the vehicle or sensor on the ML using a scaffolding supporting structure. In total, six audio speakers were used at six different locations shown in Fig. 6. One sensor was excited on each of the following: left Booster, SLS ICPS, Orion capsule, and ML. The Core Stage had two sensors: one on an EFI sensor and one on a DFI sensor. All audio speakers were connected to a common amplifier and an audio signal generator to simultaneously deliver a sound signal to all sensors. After this first data capture, the time sync was briefly reestablished, and testing was repeated to capture the “just after liftoff” scenario.

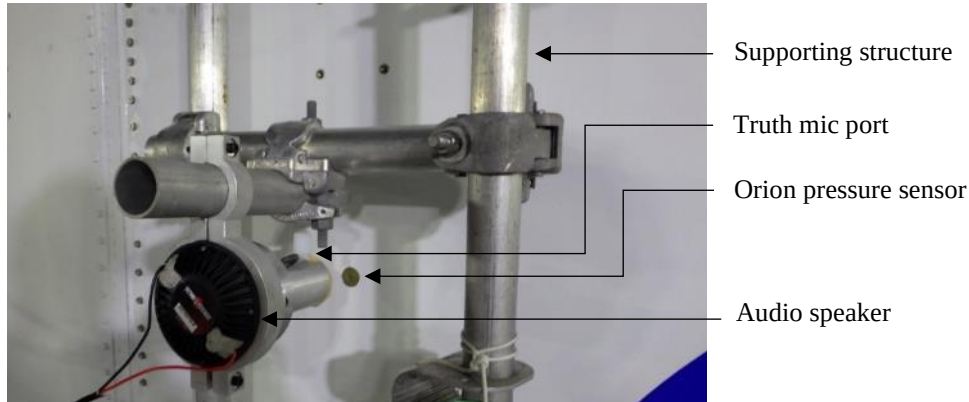


Figure 5: Audio speaker assembly used during the DAU Time Correlation Test [Photo: NASA]

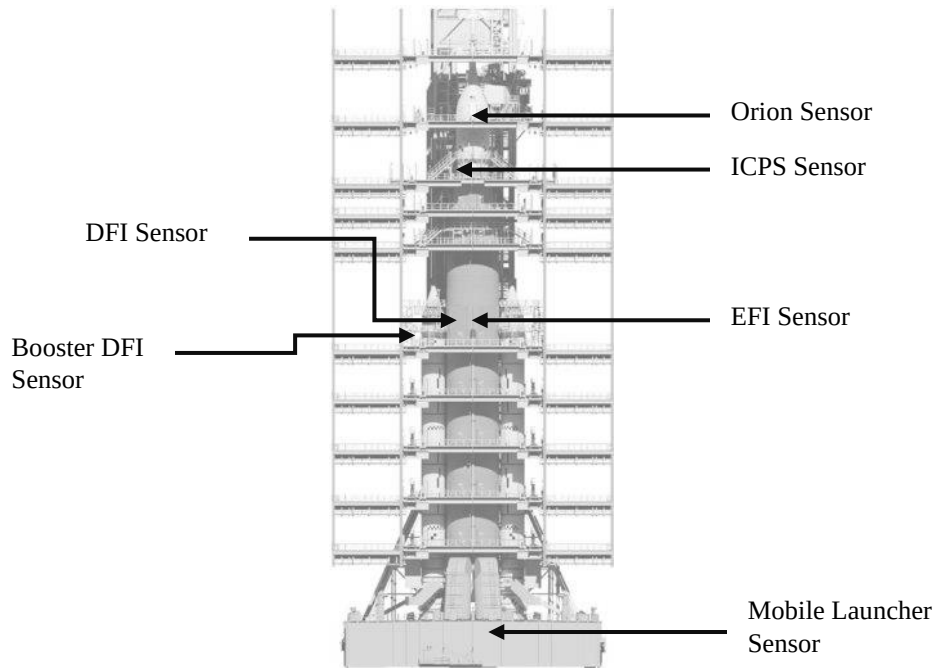


Figure 6: Audio speaker locations around the Artemis I components

During testing, the vehicle was powered on, and data were streamed through the umbilical and the radio frequency (RF) transmitters. Both the DAUs and the CTCs received the IRIG time signal through the umbilical. At a predefined time, T_1 , the IRIG time synchronization to CTC was disconnected and its internal clock was allowed to drift. Since the major frame data header contained both the CTC and MDAU timestamps, the drift rate for CTC clock could be measured by evaluating the difference between the CTC clock, which was drifting, and MDAU clock that was still syncing to the IRIG signal. At another time, T_2 , the IRIG time synchronization with MDAU was also disconnected and both the CTC and MDAU clocks were drifting. Again, the timestamps of the data were used to measure the drift of CTC and MDAU combined. Previously measured CTC drift was subtracted from the combined drift to evaluate the drift of the MDAU clock alone. The MDAU and CTC timestamp difference value plotted against the universal time is shown in Fig. 7. The time difference between the CTC and MDAU clocks is zero prior to T_1 as expected, since both were synced to the universal IRIG signal. In the time period between T_1 and T_2 , the CTC was drifting. The slope

of the resultant line is a measure of the CTC drift. Finally, the slope of the line after T_2 is a measure of the combined CTC and MDAU time drift.

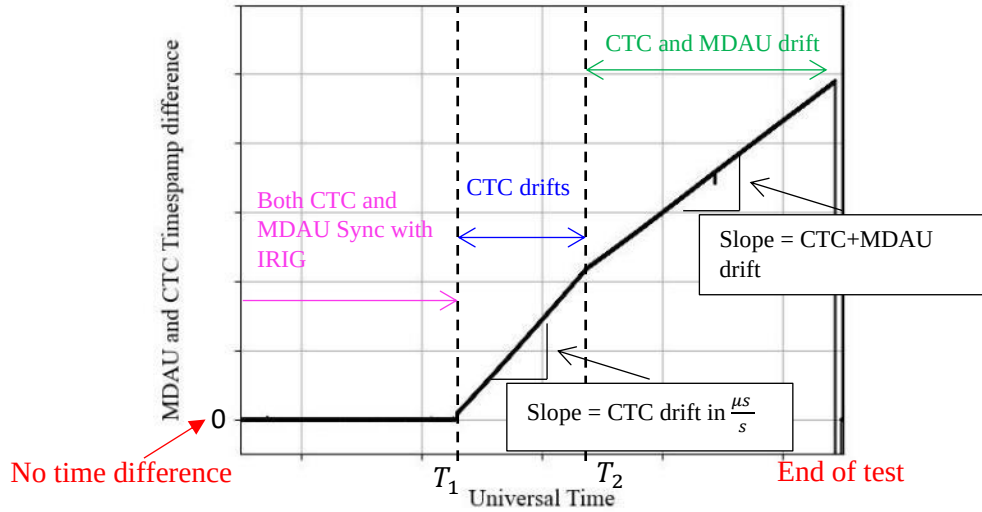


Figure 7: SLS DAU time drift analysis

A short pulse of sound waves, resembling a chirp, was sent to all the speakers at the end of the test, after the IRIG signal was disconnected and all internal clocks were drifting for several hours. The data from the reference mics (Fig. 8) show nearly no arrival time delay of the excitation signal to the sensors across the stack. Figure 9 shows the recorded data from sensors on five of the six components (ICPS sensor excluded) with and without time delay drift correction. Figure 9(a) plot clearly shows a fictitious offset in the time of arrival of the chirps, which were sent at the same time to all audio speakers. The correction for these offsets were calculated by multiplying the drift rate in Fig. 7 by the elapsed time from when the IRIG signal was disconnected. Figure 9(b) shows that the drift calculation synchronized the timing across all systems.

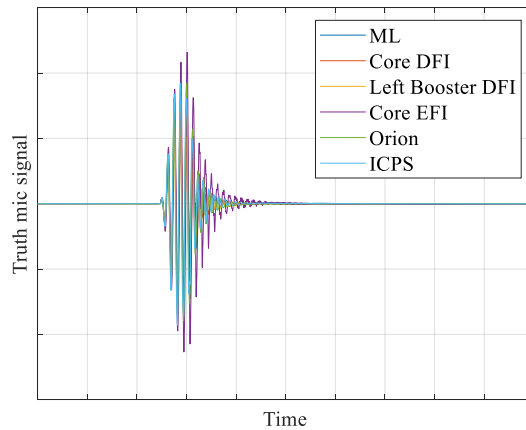


Figure 8: Reference mic signal on each DAU showing nearly-uniform arrival time of the chirp to all sensors.

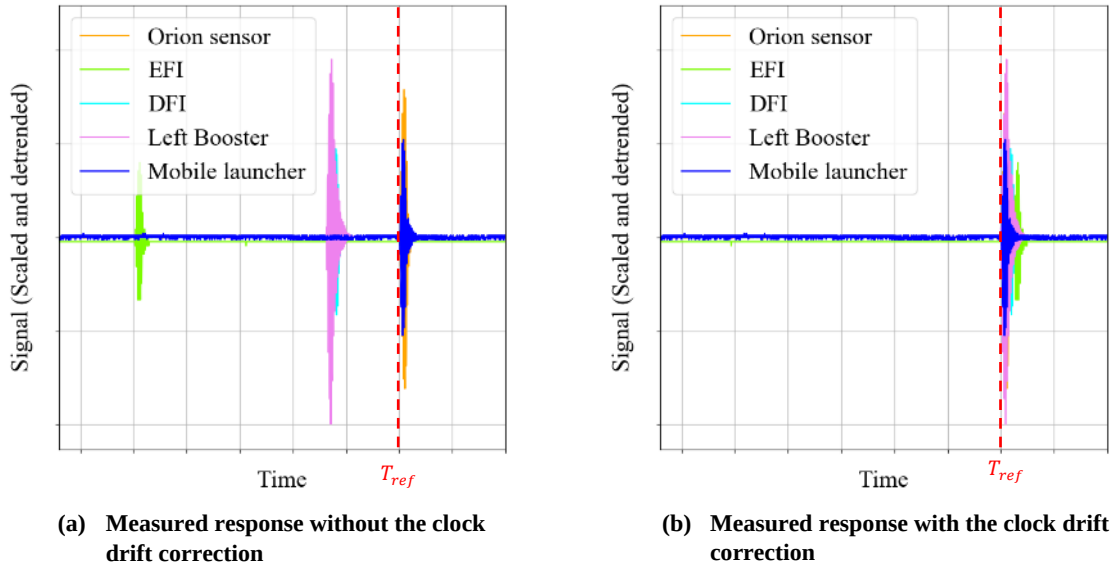


Figure 9: Chirp sound signal recorded on all Artemis I components.

An additional analytical technique was used to validate these results. Utilizing cross-correlation analysis, as discussed previously for the SIL characterization, the clock drift rate and bias were determined. By computing the lag time between channels at multiple times throughout the test data, a best fit line can be computed for which the slope is the clock drift rate, and the y-intercept is the clock bias. This method yielded similar results to the methods described above and is mathematically based and repeatable.

On April 22nd, 2022, an interesting and an unexpected time synchronization validation occurred prior to Artemis I launch while the SLS vehicle was on the launch pad. While vehicle data acquisition systems were activated, a lightning strike occurred. Figure 10 shows an image of this strike captured by a tower camera. This was a significant strike and turned out to be the most powerful one ever recorded at KSC. The lightning protection system ensured that there was no impact to avionics, or any other component such as SLS, Orion, or the ML. This event served as an unintended data acquisition architecture synchronization considering the event as an abrupt acoustic excitation of the pressure sensors and microphones.



Figure 10: Lightning striking the Lightning Protection System on April 2, 2022. [Photo: NASA]

The signals from DFI pressure sensors and microphones were examined in the time frame of the lightning strike. Figure 11(a) shows a signal from two sensors on the vehicle, which clearly show a response around the time the lightning strike occurred. The two sensors also exhibit a time delay in the response. This time delay was noted in the SIL testing described in the previous section and was not yet accounted for in the HOSC postprocessing algorithm. Figure 11(b) shows the same response with the adjusted delay applied manually, after data were downloaded from the HOSC. The manually-corrected data appears to be synced and confirmed the validity of the adjusted time delay values.

Some attention to the speed of sound needs to be taken into analyzing the lightning strike event data. A portion of the measured time delay can certainly be attributed to the distance between the two sensors and the propagation time of the lightning sound wave. Considering a speed of sound value in standard atmosphere, the time for a sound wave to travel between two sensors is smaller than the measured delay, but it is on the same order of magnitude. In reality, the sound most likely did not propagate directly from top to bottom of the vehicle since the strike occurred at the lightning protection system, which is located at the perimeter of the launch site. So, the actual value of the time delay due to sound propagation is probably smaller than the one estimated using the entire distance between two sensors. The exact contribution to the measured delay due to wave propagation cannot be determined, however, since the exact location of the sound wave origin from the lightning is unknown. Moreover, the lightning strike was not sensed by all DFI sensors due to insufficient sensor resolution for such an event. So, this event cannot be used as a validation test across the entire stack, but served as an unexpected, yet useful, verification of the time delay settings for a few sensors.

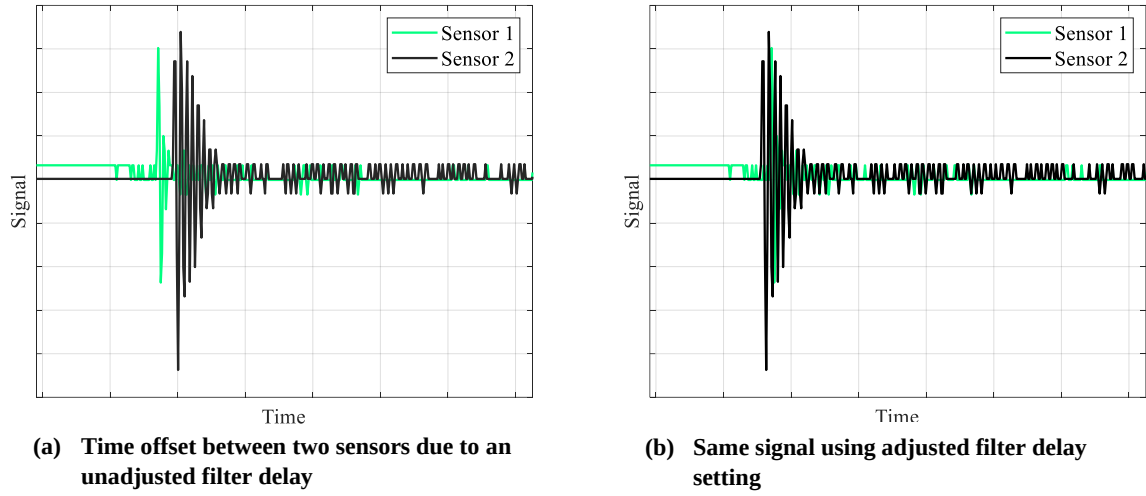


Figure 11: Signal measured by the DFI sensors capturing the lightning strike event.

V. Flight Data Postprocessing

The success of preflight testing on the vehicle DAUs was evident in the flight data, which exhibited an unparalleled level of accuracy in time alignment. Figure 12 presents a series of plotted curves representing pressure signals capturing the acoustic wave travelling along the length of the vehicle during liftoff. The pressure signals are plotted versus time, separated by vehicle elevation, across various Elements including the Core, Booster, Engine, and Orion. The plot shows data from all the SLS DAUs, and from separate DAUs for the Orion sensors. The final set of curves at the bottom of the plot corresponds to the Orion pressure sensors. The excellent alignment across the SLS DAUs was instrumental in deriving a correction for the Orion sensor data, which had been impacted by a filter delay. This comprehensive approach ensured a high degree of accuracy and consistency in the data collected, paving the way for successful future missions.

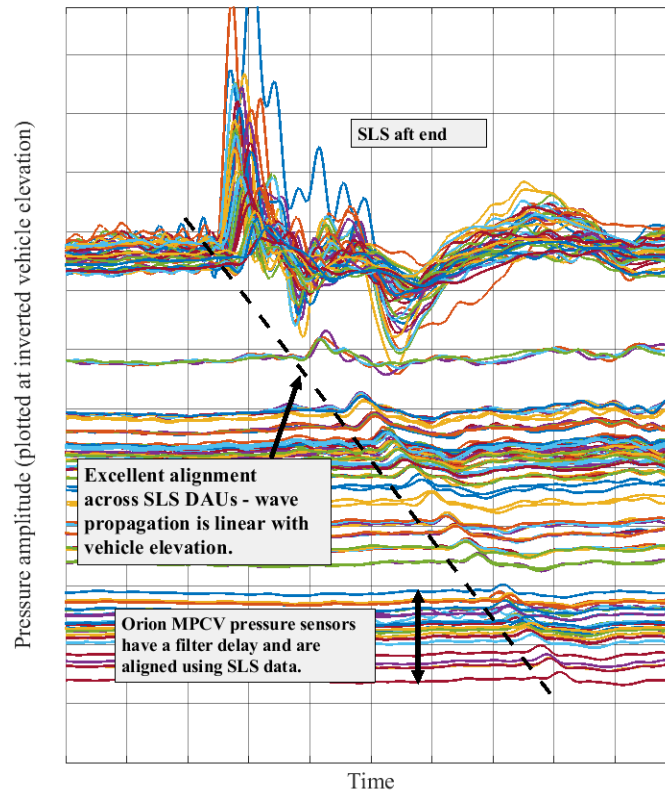


Figure 12: Sound pressure wave travelling along the vehicle during Artemis I launch showing excellent time alignment across SLS DAUs

The flight data at the HOSC is stored in its raw form, with minimal processing, and is available for download. Analysis of individual channels was readily possible using these raw data. For example, pressure signals plotted versus the mission elapsed time from several five sensors on booster station 3055 are easily visualized in Fig. 13. The detrended signal is shown in the set of plots on the right of Fig. 13. However, to perform cross-channel analysis, further postprocessing of data was required. In the raw form of the data, MDAUs assign a timestamp to a data frame rather than an individual data point. Each data frame may contain data from several sensors, and in the case of the high-frequency channels, each sensor may contain more than one data point within this frame. As described previously, a postprocessing calculation, called TOV, was applied to raw data to assign an individual unique timestamp to each data point within the data frame. This unique timestamp was based on the sampling rate of each data channel, the cable length between the sensor and the data acquisition units, and assigned filter delay values. Considering that the SLS stack measured 322-ft tall, the time delay due to cable length was not negligible and was evaluated in prior testing. The TOV calculation provided a unique timestamp for each measurement but made any cross-channel analysis, which required independent sensor measurements with a *commonly* aligned timestamp vector, impossible. Flight data postprocessing was further complicated by the minor data dropouts in RF signal, which resulted in missing or corrupt data. To perform the analysis on the flight measurements, further postprocessing of data was required.

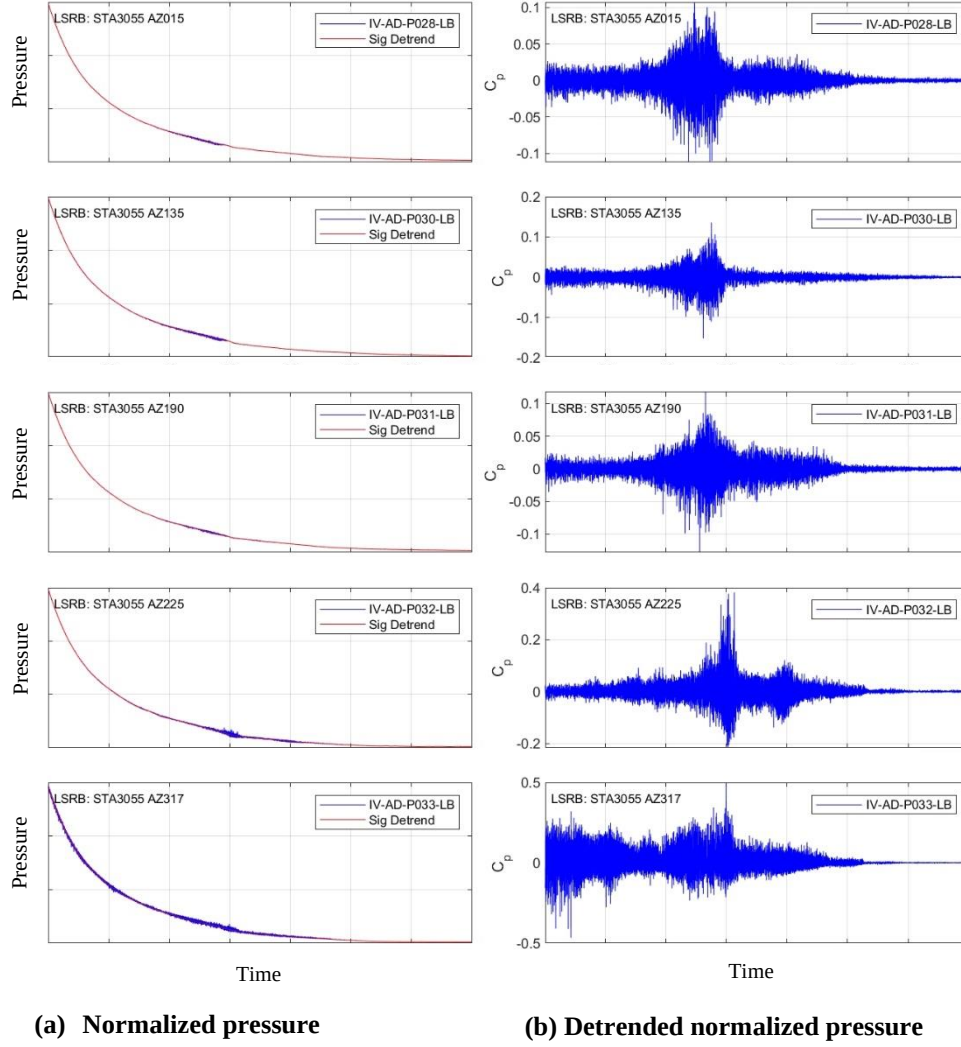


Figure 13: Normalized pressure signal captured by sensors located on a booster at station (STA) 3055 and various azimuthal (AZ) angles.

Resampling of flight data to a common time vector was achieved using a Fourier decomposition approach. A Fast Fourier Transform (FFT) calculation was performed on the original data to obtain Fourier coefficients, phase, and frequency values of each original signal channel. A new time vector was then constructed that all channels of interest could be resampled or down-sampled to. A reconstructed signal for each channel was then computed using the new time vector and the previously calculated coefficients. The process was applied to all channels of interest, resulting in a dataset based on a consistent time vector.

To perform the decomposition of the original signal using Fourier analysis, a dataset uniformly spaced in time was needed with no data dropouts. However, as previously mentioned, RF dropouts did occur in flight and slight variations in sampling rate were observed in otherwise clean data. It was determined that this small variation in sampling rate would create an insignificant time shift in the signal compared to one assuming a constant sample rate, over roughly a two-minute ascent time window of the vehicle and would have a trivial impact to spectral analysis. Therefore, the assumption of constant sample rate was made for the signal, excluding data gaps. This sampling rate value was

calculated by selecting the statistical mode of all instantaneous sampling rates for the data channel of interest. On the other hand, data dropouts could not be ignored in calculating the Fourier coefficients. The duration of the data dropouts was in some cases on the order of a tenth of a second. To address this, the original signal was divided into sections and the resampling algorithm was applied to each section separately. The first section spanned the time from the start of the dataset to the beginning of the first data gap. The second section started at the end first data gap and spanned until the beginning of the next data gap and so on. For each section, a Fourier analysis was performed separately, and a signal was reconstructed, filling in the data gap itself with a newly reconstructed signal based on the amplitude of the frequencies calculated in the Fourier transformation.

Several reconstructed datasets were produced for various FDA requirements. Figure 14 shows the resampling of a DC-coupled signal to a lower sampling frequency time vector. The plot on the left of the figure shows the time series of the original and the resampled signal. A gap in the original data is highlighted with a red-dashed ellipse. The resampling procedure allows for the reconstruction of the signal using a continuous time vector, which eliminates the data gap by padding it with predicted data valued based on the Fourier coefficients. This reconstruction does not alter the frequency domain as evident by the PSD plot on the right of the figure.

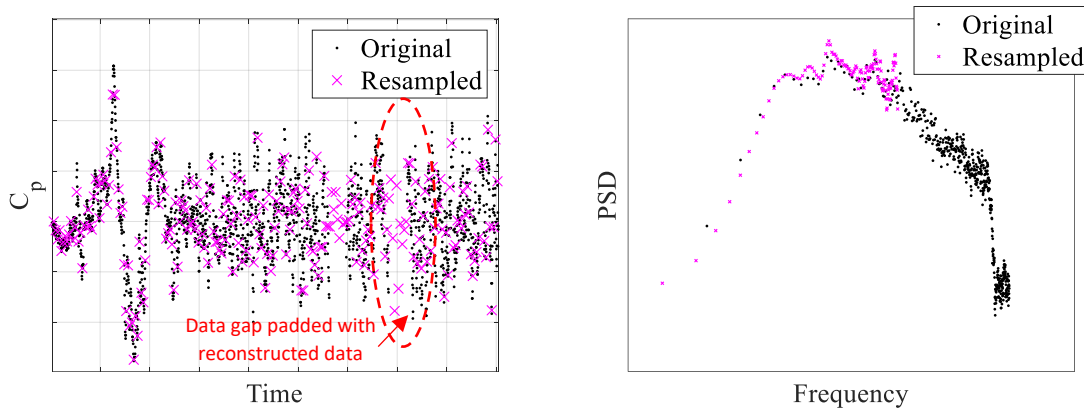


Figure 14: Down-sampling of a DC-coupled sensor to the lower sampling frequency time vector.

For liftoff environments, an alternative to the Fourier decomposition approach was to address the RF dropouts. Without elaborating on details, the RF dropouts were addressed by removing the data mean and filling the dropout with zeros. After these steps, a spectrum can be estimated and theoretically corrected based on the number of zeros present in the data block. This approach to handling the RF dropouts in the spectral domain was used for liftoff environment assessments.

For ascent analysis, another postprocessing step was performed to correct for the offset in the pressure readings of the DC-coupled sensors. This offset was observed between the DFI-measured pressure values and the ambient values provided by the meteorological instrumentation. The stack height was taken into account for this calculation to consider the barometric pressure change with altitude. The offset was attributed to the sensor calibration coefficients drifting slightly from the time DFI sensors were installed on the vehicle to the day of launch. A two-point correction approach was used. The method relied on proposing a pressure correction value that changes linearly between two points as a function of measured pressure. These two points are correction values at ambient pressure and at near-vacuum condition, at approximately 104 seconds into the flight. Both of these values were obtained by calculating the difference between the DFI-measured pressure and the one provided by best estimated trajectory. Using the two points, a linear equation was constructed that provided a pressure correction value based on the DFI-measured pressure value.

VI. Conclusion

The methods used to perform Flight Data Analysis (FDA) tasks on the Artemis I flight required high frequency data that was tightly synchronized across various data systems located on multiple components, such as boosters, core, Orion, and the Mobile Launcher (ML). To characterize the time accuracy across the entire stack, characterization tests were performed at the Systems Integration Laboratory (SIL) and on the vehicle at the Vehicle Assembly Building (VAB). The SIL tests validated the filter delays and delays associated with the instrumentation cable length for individual components and provided corrections where needed. The Data Acquisition Unit (DAU) Time Correlation test at the VAB was used to measure the time drift and offset of time signal on DAUs across the entire stack and mobile launcher. These offsets and drifts were used to adjust the HOSC postprocessing algorithm and provide a time-correlated data to the stakeholders. The resultant time-accuracy of the flight data was within the required threshold. The flight data, however, also suffered from irregularities associated with poor RF data transmission, which resulted in data gaps and prevented cross-channel analysis. To correct for this, a Fourier decomposition approach was used with some success to provide a continuous dataset at uniform sampling frequency. The efforts described here supported 169 FDA tasks and the completion of all 24 SLS Flight Test Objectives.

VII. Acknowledgments

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