15-Apr-26

Doppler Tracking of Orion at DSES

For the Artemis-II Mission

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Deep Space Exploration Society (DSES), https://dses.science/

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EXECUTIVE SUMMARY

The Deep Space Exploration Society (DSES) participated in the Artemis II tracking campaign using the 60-foot Plishner Radio Telescope. While full mission data capture objectives were not achieved due to a combination of hardware, software, and operational challenges, several successful reception intervals enabled detailed Doppler analysis of the Orion spacecraft signal.

The analysis demonstrates:

- Strong agreement between measured and modeled Doppler signatures using a one-way light-time geometric model
- Residual errors on the order of **4.65 Hz RMS (~0.6 m/s)**
- Identification of a **~1.3 ppm frequency bias**, consistent with receiver reference uncertainty or signal processing configuration

In addition, the campaign yielded critical insights into:

- Feed system optimization and pointing strategy
- SDR signal chain configuration and Doppler extraction methodology
- Operational coordination and software integration challenges

These results validate the fundamental capability of the DSES system for deep-space Doppler tracking while identifying key areas for improvement in future campaigns.

INTRODUCTION

The Deep Space Exploration Society (DSES) was selected by NASA to participate in a volunteer ground-station network supporting the Artemis II mission. As part of this effort, the 60-foot radio telescope at the Plishner Radio Telescope site was configured to receive S-band transmissions from the Orion spacecraft.

Artemis II launched on April 1, 2026, at 22:35 UTC. Initial observation opportunities were missed due to a misunderstanding of the tracking schedule. Subsequent efforts focused on preparing the antenna system, validating polarization alignment, and resolving feed and reference clock issues.

Over the following days, multiple teams worked to:

- Optimize feed positioning and focus
- Correct a failure in the 10 MHz reference distribution system
- Diagnose azimuth control issues and work around them to continue the mission
- Conduct manual tracking in the absence of full automation

Despite these challenges, several successful reception intervals were achieved, providing data suitable for Doppler analysis. These measurements form the basis of the technical results presented in this report.

VOLUNTEERS

This dedicated and hard working group of volunteers made this project possible.

The system 1 team; Glenn Davis W0OFZ, Lewis Putman, Phil Gage KI0NY.

The tracking teams: Bill Miller KC0FHN, Roger Oakey W3MIX, Mario Biendarra, Travis Lightsey, Richie Lary, Larry Stewart N7LWS, Anne Haney W0ZDW, and Tom Eggers. The dedication of this team was evident especially considering that all the periods when the Orion capsule was in view were “third shift”, approximately midnight until a couple hours after sunrise.

Preparation and maintenance: Pat McDevitt KE0CQE, Myron Babcock KL7YY, Anne Haney W0ZDW, Ray Uberecken AA0L, Paul Sobon NO0T and Jeff Fladung KC0ZJY.

Remote operators and engineering: Richard Hambly K0GD, Alex Nersesian K6VHF. During the mission, this team worked on improving the data collection software, upgrading it from software revision 1.6 to 1.13, constantly improving the software capabilities and resolving issues.

DAY-TO-DAY DETAILS

Artemis-II launched April 1, 2026, at 4:35 p.m. MDT (22:35 GMT). Due to a mix-up in our understanding, DSES did not record data during the first opportunity in the late evening of April 1st and early morning of April 2nd.

On April 2nd Roger Oakey and Lewis Putnam headed down to the site for the April 3rd morning observation. They spent the day working on the feed. They were only able to see a carrier from the Orion spacecraft at the start and end of the transmission period. They were able to verify that we were using the correct circular polarization at the feed - Orion transmits right hand circular polarization [RHCP] and because of the one reflection off the dish, we were correctly receiving on the feed's left hand circular polarization [LHCP] port.

On April 3rd Bill Miller, Mario Biendarra and Travis Lightsey took over. They resolved the feed's focus problem. In the early morning hours of the 4th a problem with the 10MHz reference distribution amplifier was discovered and rectified. Data from the Orion spacecraft was collected, some of which is shown in this document.

On April 4th Bill, Mario and Travis stayed on. Just after midnight on the 5th while slewing the dish to Orion's rising azimuth, the computer's azimuth control for the dish failed, allowing the azimuth to only move in one direction. Glenn Davis called in from Hawaii. Bill and Glenn worked to troubleshoot the problem. On the afternoon of the 5th Lewis Putman, Paul Sobon and Jeff Fladung went to the site with replacement parts to effect repairs.

On April 5th no data was collected in the morning. During the day Paul Sobon and Lewis Putnam worked to diagnose the problem. The tests ruled out problems with the Labjack LJTick-DAC device, the Labjack U3 device, and the cable between DAC and motor controller. The conclusion was that the motor controller may have an issue.

On April 6th: no data was collected in the morning.

On April 7th no data was collected in the morning. Larry Stewart, Anne Haney, Richie Lary and Roger Oakey arrived on site.

On April 8th data collection was started soon after midnight. The dish was pointed by using manual controls, using the Artemis tracking software developed by Lewis Putman, Glenn Davis and Phil Gage, though we were unable to allow the computer to control the dish. Instead, using the manual dish controls we pointed the dish at approximately two-minute intervals. An hour or two in the primary computer and/or software appeared to freeze. Maintaining the spacecraft within the antenna beamwidth required continuous manual adjustments, highlighting the need for reliable automated tracking.

We did shifts of two people for two hours each, trading off between the two "on shift" as fatigue and/or boredom became an issue. This was Anne's suggestion and worked quite well. Richie Lary good-naturedly described keeping Artemis within the 3dB circle as "The world's most boring video game."

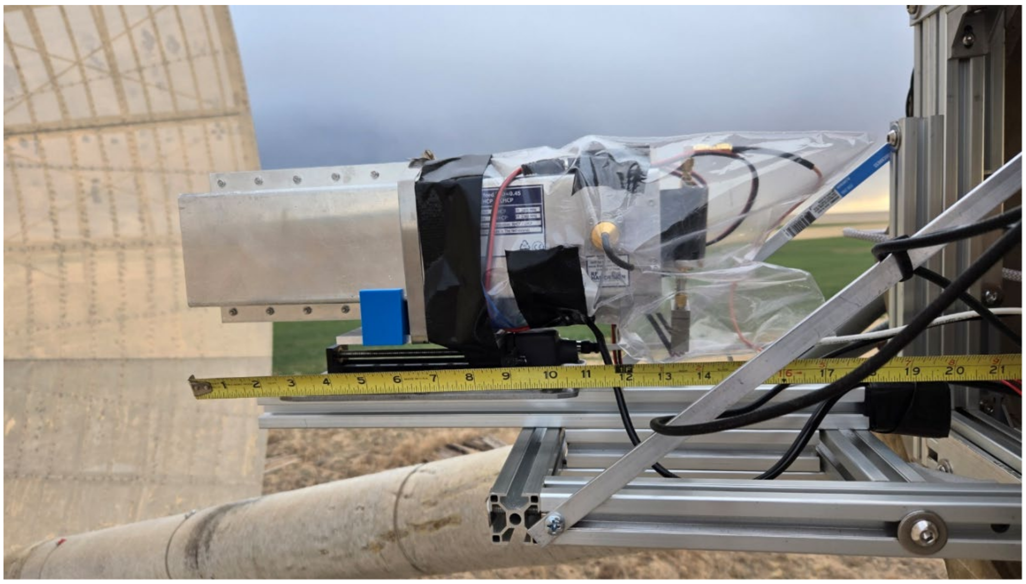
April 8th Richie Lary departed for a group lunch back in the 'springs and attending that lunch was Tom Eggers. Tom became interested enough in what we were doing to drive down that afternoon and join us. So, the group going into the next morning's data gathering was Larry Stewart, Anne Haney, Tom Eggers and Roger Oakey.

The morning of April 9th was like the morning of the 8th with two shifts of two people. This time the primary computer's software ran all night but an hour or two in it appeared that the signal from Orion was lost. Because of not having any visibility into what was happening with the secondary computer, the dish was kept on Artemis all night until there was an indication that the Azimuth drive had failed - about 7am in the morning. Turns out it was user error combined with a misdiagnosis on my part and the AZ drive is just fine (at least under manual control). So, the morning of the 9th we cleaned up, packed up, pulled the hardware out of the hub and headed home.

There was no data gathered the morning of the 10th.

ANTENNA AND CONTROL CONSOLE

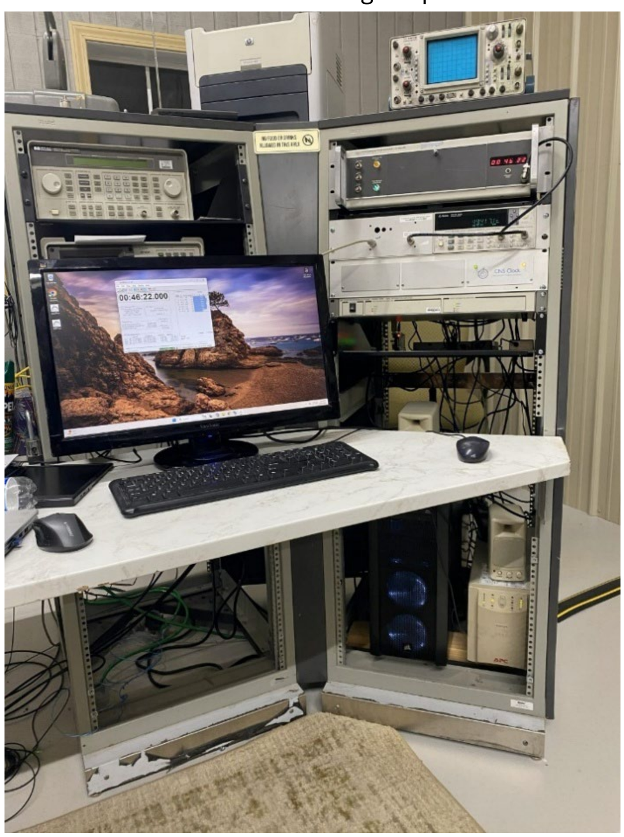
This is the feed and custom electronics that was designed specifically for the Artemis-II mission mounted in the 60' dish's antenna's hub. For more information about the antenna feed design, see *DSES Antenna Study for the Artemis-II Mission* by Richard M Hambly, K0GD, 12-Apr-2026 at https://dses.science/wp-content/uploads/Projects/Artemis-II/DSES-60-Foot_Antenna_Study_for_Artemis-II_RevA.pdf.



Below is the left section of the control console that contains the System 1 dish steering and secondary receiver and recording hardware.

Below is the center section of the control console showing the display for the primary receiver and recording system.

Below is the rightmost section of the control console showing the precision time and frequency system.

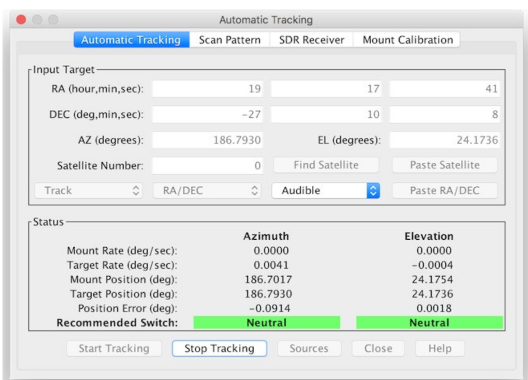


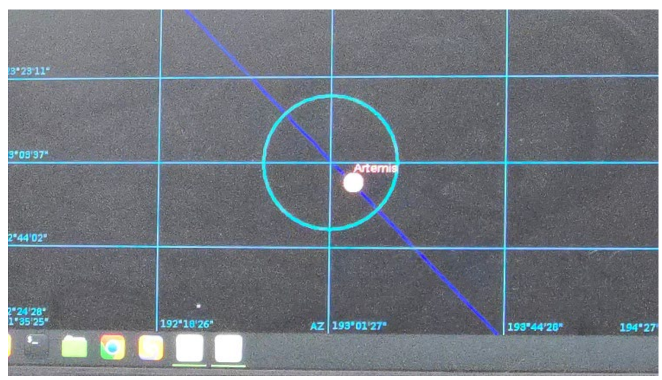
THE SYSTEM 1 UPGRADE

System 1 is the system that is responsible for steering the DSES 60’ dish. It has both manual and automatic controllers and both high and a low resolution sensors. The team responsible for the maintenance and software development of System 1 are Glenn Davis (W0OFZ), Lewis Putman, Phil Gage (KI0NY). In January 2026 the team began investigation ways to upgrade System 1 to use the Artemis-II data available on the Horizons web site. This was necessary as tracking data for the Orion capsule changes whenever there is a thruster burn. They considered “manual Ra/Dec pointing with sidereal track, Az/El Pointing (not great), or a valid 2 or 3 line element set (which provides automatic tracking).”

By late March the System 1 (dish positioning software) team rolled out a version of software which will track the capsule without human intervention, with a manual fallback in case of loss if internet connectivity which is required for automated tracking. This software regularly gathers new tracking data from the Horizons web site (https://ssd.jpl.nasa.gov/horizons/app.html#/) to keep our pointing system up to date.

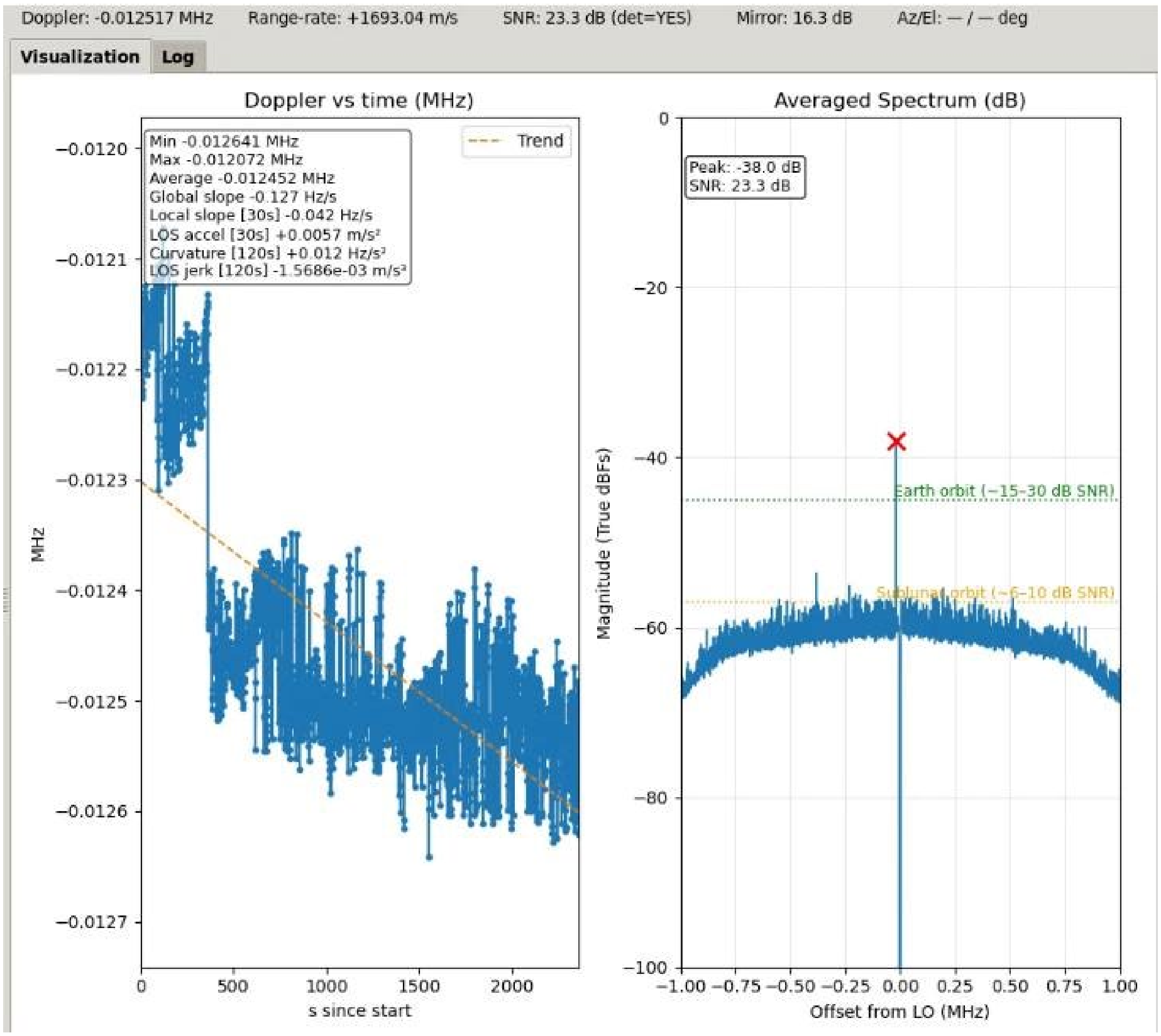
For more information, see *System 1 Ephemeris Tool Operation for Artemis II Tracking at the DSES Plishner Site* by Glenn Davis, Lewis Putnam, and Phil Gage, 18-March-2026 available at https://dses.science/wp-content/uploads/Projects/Artemis-II/Ephemeris_Tool_Operation-v3.pdf





TIME-REFERENCED DOPPLER COMPARISON AND RESIDUAL ANALYSIS

This section looks at the first solid data collected by DSES of the Orion spacecraft. It is analyzed carefully to verify that the data is indeed the Orion spacecraft and that the DSES hardware and data collection software is working as expected. The picture below represents a partial screen capture of the first successfully acquires signal from the Orion Capsule "Integrity" on April 4, 2026.



DOPPLER COMPARISON IN ABSOLUTE TIME

The figure *Artemis II / Orion Doppler Comparison at DSES* below presents the measured and modeled Doppler time histories plotted against absolute UTC time (HH:MM). The date of observation is indicated in the lower-left corner of the figure.

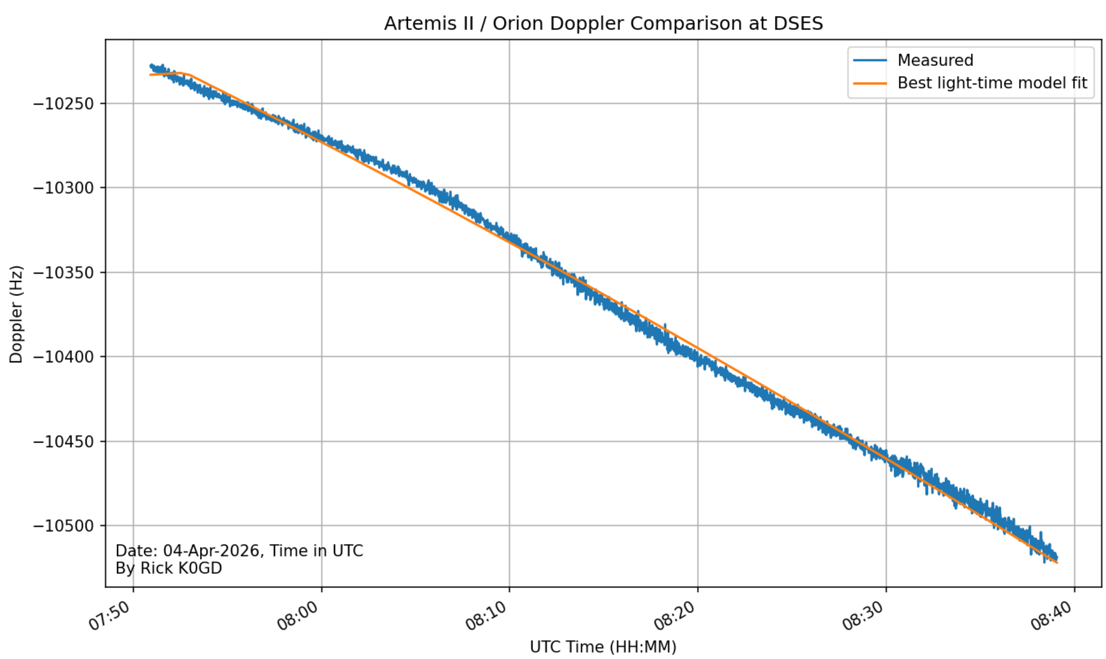
In this plot:

- The **measured Doppler** represents the frequency offset derived from the SDR signal processing chain.
- The **modeled Doppler** corresponds to the one-way light-time corrected geometric prediction, including bias and linear drift terms obtained through least-squares fitting.

Displaying the data in absolute time provides several advantages:

- It enables direct correlation with external datasets such as antenna pointing logs, SDR configuration events, and mission timelines.
- It allows verification of acquisition and loss-of-signal timing relative to predicted spacecraft visibility.
- It facilitates identification of any time-dependent anomalies that may be associated with station operations or environmental effects.

The close agreement between the measured and modeled curves over the full observation interval demonstrates that the dominant Doppler behavior is accurately captured by the light-time geometric model. Any remaining discrepancies are small compared to the total Doppler excursion and are further examined in the residual analysis.



RESIDUAL DOPPLER IN ABSOLUTE TIME

The figure *Residual Doppler (Measured - Best Light-Time Model)* shows the post-fit Doppler residuals as a function of absolute UTC time, again with the observation date annotated in the lower-left corner.

The residual is defined as:

$$\epsilon(t) = f_{meas}(t) - f_{fit}(t)$$

where $f_{fit}(t)$ includes the geometric modeled Doppler along with fitted bias and drift terms.

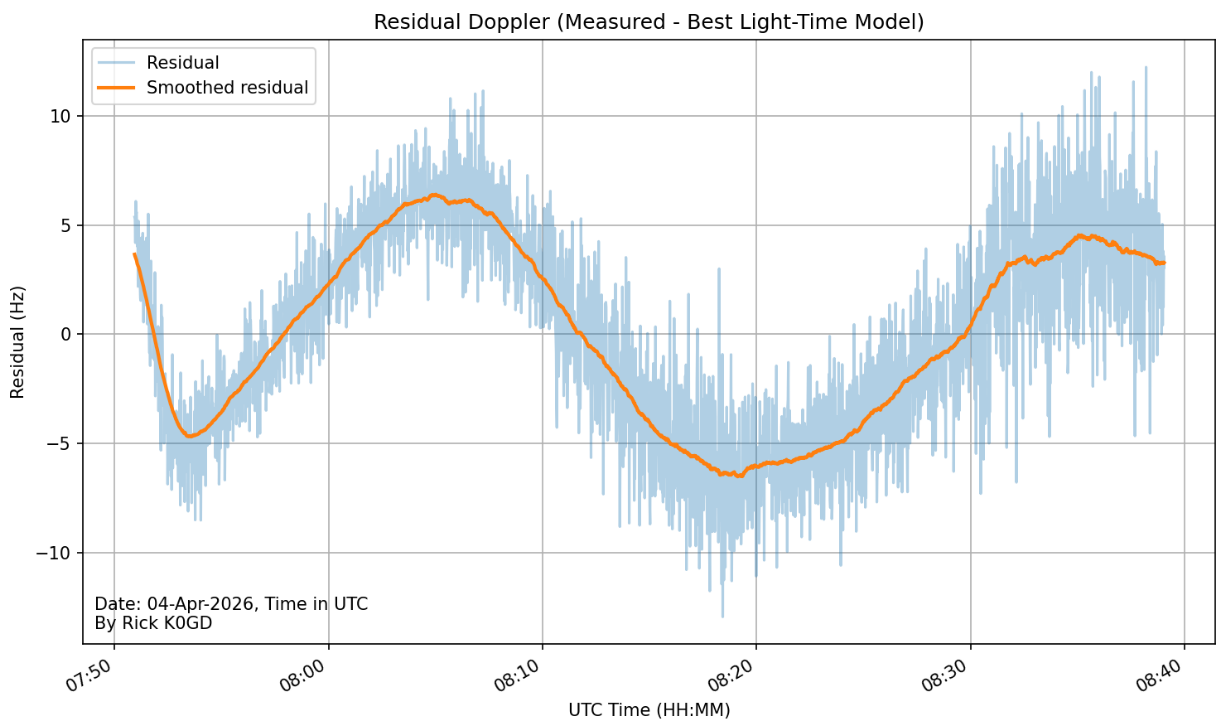
Two curves are shown:

- The **raw residual**, which reflects the instantaneous difference between measurement and model.
- A **smoothed residual**, obtained via moving-average filtering, which highlights systematic trends by suppressing short-term noise.

Key observations from this figure include:

- The residual is bounded within a few Hz over the entire pass, with an RMS value of approximately 4.65 Hz.
- The residual exhibits a smooth, slowly varying structure rather than random noise, indicating that it arises from systematic effects not included in the current model.
- The absence of abrupt discontinuities or large excursions confirms the stability of both the measurement system and the time/frequency references during the observation.

Expressed in terms of equivalent line-of-sight velocity, the residual corresponds to approximately 0.6 m/s RMS, demonstrating a high level of agreement between measurement and prediction for an SDR-based receiving system.



INTERPRETATION

Together, these two figures above provide a comprehensive time-domain validation of the Doppler model:

- The comparison plot confirms that the primary Doppler signature of the spacecraft is accurately reproduced in both magnitude and temporal evolution.
- The residual plot isolates the remaining discrepancies, which are small and exhibit structured behavior consistent with higher-order effects such as measurement averaging, oscillator characteristics, or differences in observable definition.

BIAS TERM AND ITS SIGNIFICANCE

A constant frequency offset (bias) is included in the Doppler model to account for systematic differences between the measured signal and the assumed nominal carrier frequency. The fitted model is expressed as:

$$f_{fit}(t) = f_{pred}(t) + b + (d \times t)$$

where:

- b is the **bias** (constant frequency offset)
- d is the linear drift term
- t is time

For the dataset analyzed, the estimated bias is:

$$b \approx -2935\ Hz$$

Physical Interpretation

The bias represents a **constant frequency offset** between the assumed nominal carrier frequency and the effective frequency reference of the measurement system.

Rearranging the model:

$$f_{0,eff} = f_0 - b$$

gives an implied effective carrier frequency of: $\boldsymbol{f_{0,eff} \approx 2216502935\ Hz}$

This indicates that the measurement system behaved as though the carrier frequency were approximately **2.935 kHz higher** than the nominal value used in the model.

Fractional Frequency Error

The magnitude of this offset can be expressed as a fractional frequency error:

$$\frac{\Delta f}{f0} \approx \frac{2935}{2.2165 \times 10^9} \approx 1.3 \times 10^{-6}$$

This corresponds to approximately: **~1.3 parts per million (ppm)**

Such an error is consistent with:

- an SDR local oscillator not fully locked to an external reference
- a misconfiguration of the reference clock input
- or a difference between the assumed and actual nominal carrier frequency

Impact on Doppler Analysis

The bias term has the following implications:

1. It does not affect Doppler shape

The bias is a **constant offset**, so it does not alter:

- the curvature of the Doppler profile

- the time evolution of the signal
- the comparison of measured versus predicted dynamics

Thus, the **agreement in Doppler shape remains valid** even in the presence of a large bias.

2. It must be removed for accurate comparison

Without removing the bias:

- the measured and predicted curves would be separated by several kHz
- the comparison would be dominated by a constant offset rather than dynamic agreement

Fitting and removing the bias allows the analysis to focus on the **true Doppler behavior**.

3. It is largely instrumental, not physical

The magnitude and constancy of the bias strongly indicate that it arises from the **receiver system**, rather than the spacecraft or propagation effects.

Specifically, the observed offset is consistent with:

- a small fractional frequency error in the SDR reference
- equivalent to approximately 13 Hz error at a 10 MHz reference

This is typical of an SDR operating without a properly locked external frequency standard.

Relationship to Residual Error

After removal of the bias (and drift), the remaining Doppler residual is approximately: **RMS ≈ 4.65 Hz**

This demonstrates that:

- the **bias accounts for the dominant systematic offset (~2935 Hz)**
- the remaining error is **three orders of magnitude smaller** and reflects higher-order effects

Summary

The fitted bias term represents a constant frequency offset of approximately **-2935 Hz**, corresponding to a fractional error of **~1.3 ppm**. This offset is consistent with receiver frequency reference uncertainty and does not affect the validity of the Doppler shape comparison. Removal of the bias enables accurate evaluation of the Doppler model, revealing a much smaller residual error that reflects second-order effects rather than fundamental modeling or measurement errors.

IMPACT OF SIGNAL PROCESSING CONFIGURATION ON BIAS

Relationship to SDR Processing Logic

The observed bias of approximately **-2935 Hz** must be interpreted in the context of the Doppler extraction equation implemented in the data collection software:

$$doppler = (f_{center} + f_{FFT}) - f_0 - f_{dc_{offset}}$$

This formulation requires that all frequency offsets applied within the SDR signal chain (e.g., LO shifts, DC avoidance offsets, or digital frequency translations) are **accounted for exactly once** in the Doppler computation.

Any mismatch between:

- how offsets are applied in the signal chain, and
- how they are removed in the Doppler equation

will introduce a **constant frequency bias**.

Potential Source of Bias in Previous Configuration

In the configuration used for this measurement:

- $f_{center} = 2216.505\ MHz$
- $f_{dc_{offset}} = 5\ kHz$

the intended behavior was:

$(f_{center} - f_0) = +5\ kHz$ and $f_{dc\_offset} = 5\ kHz$

so that the offsets cancel.

However, this approach depends critically on:

- the SDR applying the LO/DC offset exactly as assumed
- the FFT frequency axis being referenced consistently
- the software subtracting the correct offset value

If any of these conditions are not met, the result is a **systematic frequency error on the order of the offset itself (kHz-scale)**.

Revised Configuration and Its Advantages

The software was updated by Alex Nersesian and will be used in the next data collection session. It simplifies the processing chain:

- $f_{center} = 2216.520\ MHz$
- $f_0 = 2216.500\ MHz$
- $f_{dc\_offset} = 0$
- DC avoidance handled via spectral placement rather than explicit correction resulting in:

$$doppler = (f_{center} + f_{FFT}) - f_0$$

or equivalently:

$$doppler = f_{FFT} + 20\ kHz$$

This approach has several advantages:

- It removes the need for an explicit offset subtraction term.
- It avoids ambiguity regarding whether a frequency shift has already been applied.
- It reduces the risk of double-counting or omitting offsets.

Expected Impact on Bias

By eliminating the explicit f_{dc_offset} correction term, the revised configuration:

- reduces the number of parameters that must be kept consistent across the signal chain
- minimizes the possibility of bookkeeping errors
- ensures that any constant offset observed in the data is more directly attributable to:
  - receiver frequency reference error, or
  - nominal carrier uncertainty

As a result, the large bias observed in the current dataset (≈2935 Hz) is less likely to arise from software misinterpretation of offsets in future observations.

Residual Bias Considerations

Even with the improved configuration, a residual bias may still be present due to:

- imperfect locking of the SDR to the external 10 MHz reference
- small discrepancies between the assumed and actual spacecraft carrier frequency

However, these effects are expected to be:

- smaller in magnitude
- more stable
- and easier to interpret

compared to biases introduced by offset-handling inconsistencies.

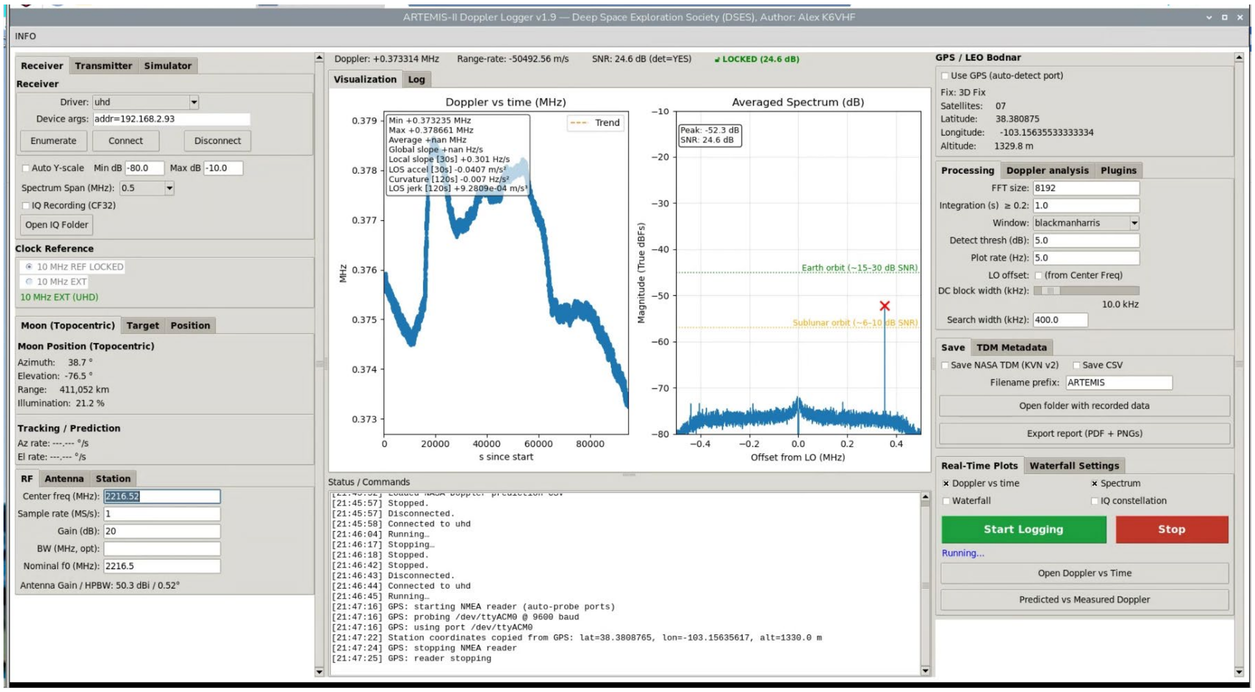
Summary

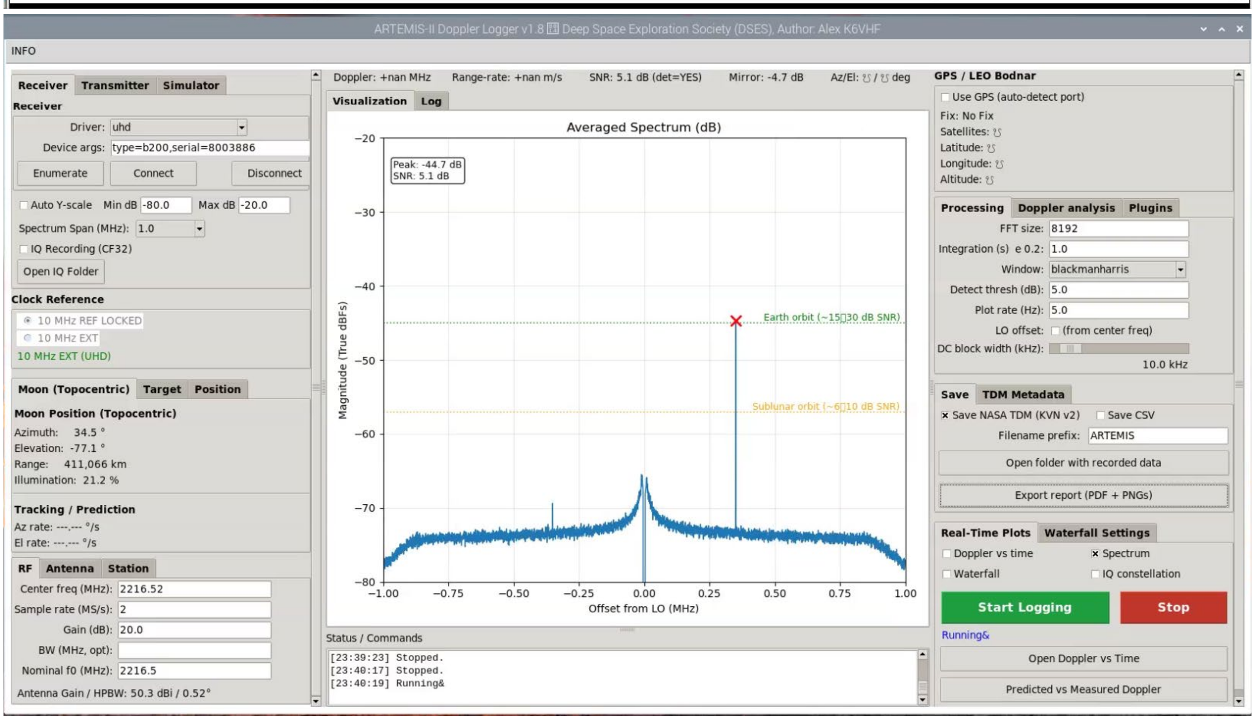
The revised Doppler extraction method simplifies the signal processing chain and removes a potential source of systematic error. By avoiding explicit offset compensation terms, it improves the robustness of the measurement and increases confidence that any remaining bias reflects true hardware or reference effects rather than software bookkeeping artifacts.

DSES

RECEIVING THE TEST BEACON

The figures below show a snapshot of the primary and backup SDR receivers while connected to the 60’ dish antenna while receiveing a test beacon signal. The beacon frequency is sensitive to temperature and so produces a pseudo-Dioppler effect that is useful in receiver comparisons and software developmennt.





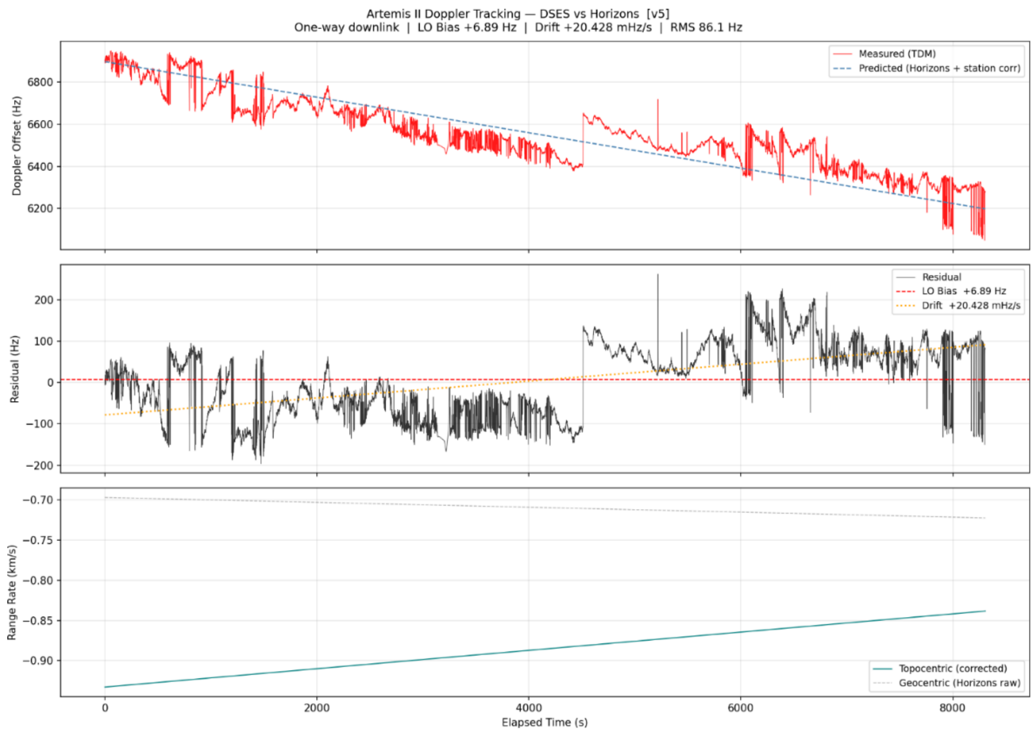
ADDITIONAL RECORDING SESSIONS

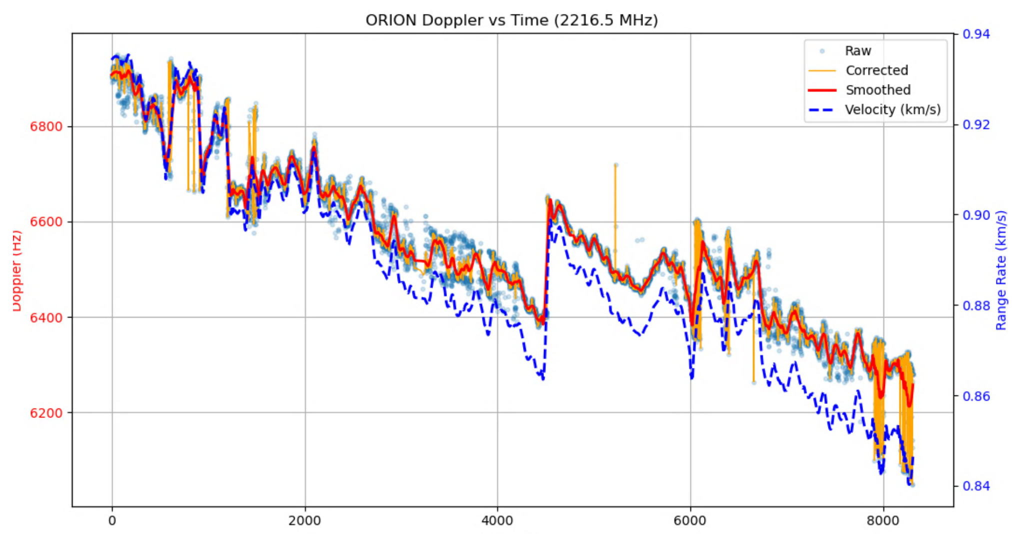
DATA COLLECTED 4/7/2026 BY THE PRIMARY SYSTEM

Data collected 4/7/2026 by the primary system showing DSES raw data compared to the JPL Horizons data. Few things obvious here.

- frequency drift was identified 20.4mHz/sec
- strong phase fluctuations

Other than that, we are on the right slope for Doppler.





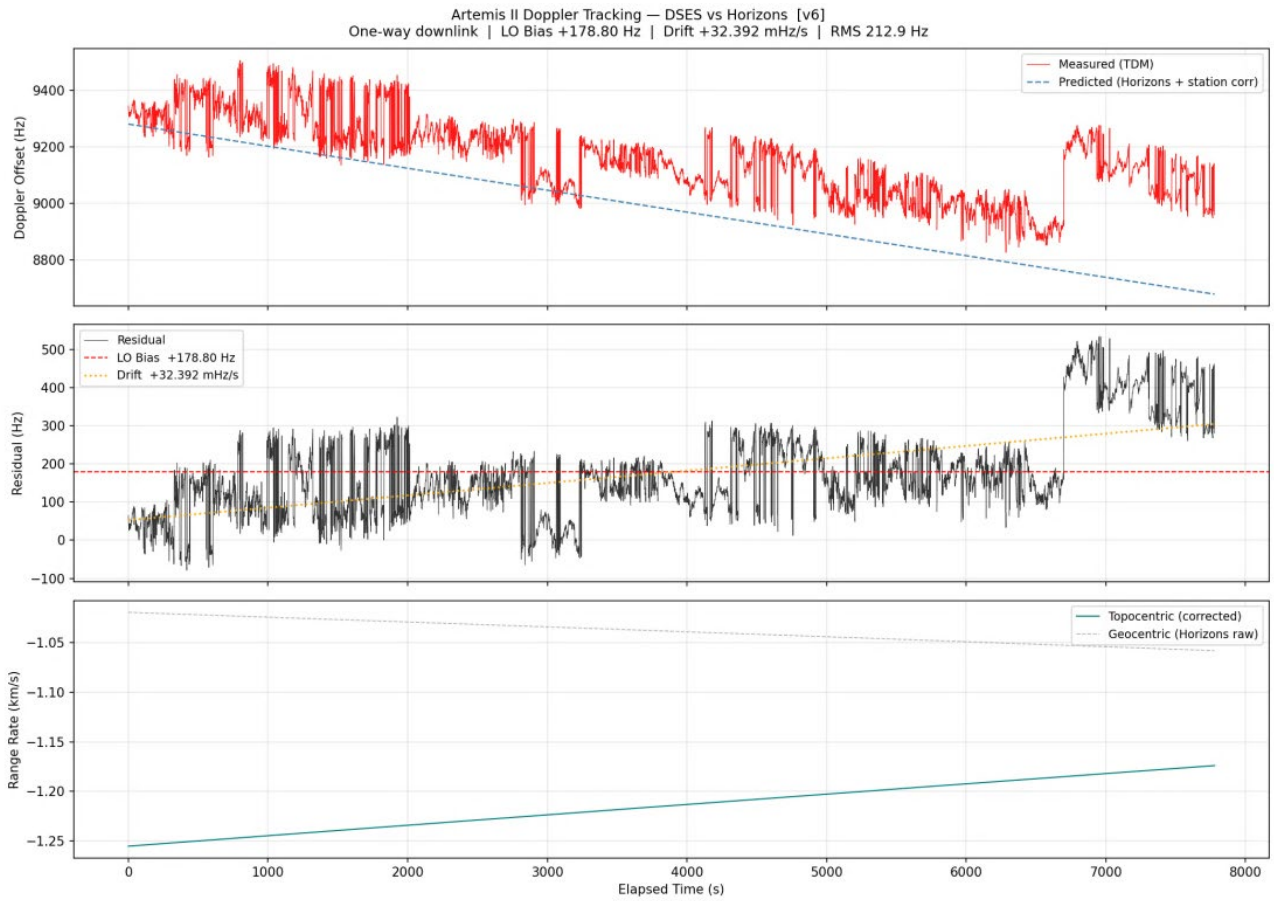
DATA COLLECTED 4/8/2026 BY THE PRIMARY SYSTEM:

Out of entire night we only detected two clear ORION transmissions.

First one:

START_TIME = 2026-04-09T06:39:23.990Z - AOS at Haswell

STOP_TIME = 2026-04-09T08:49:02.530Z - signal disappeared



RESULTS

The primary goal of each of the 34 volunteer ground stations was to track the entire Artemis-II mission whenever in view and upload the resulting TDM files to the NASA data collection site for later postprocessing. DSES will only a few valid TDM files to send to NASA because of formatting and scheduling issues, so the primary goal was not met.

Although the primary objective of continuous tracking and submission of TDM files to NASA was not achieved the campaign successfully demonstrated:

- Verified reception of Orion spacecraft signals
- High-fidelity Doppler tracking with strong agreement to predictive models
- Identification and quantification of system-level biases
- Validation of SDR-based deep-space tracking capability

Equally important, the campaign exposed critical system limitations and operational gaps, providing a clear roadmap for improvement. These lessons significantly enhance DSES readiness for future coordinated tracking efforts.

The DSES mission, as stated on our web site, is: “DSES is a not-for-profit organization and a recognized Colorado charity whose primary purposes are research and education. We exist to foster the exploration and understanding of space by encouraging students, society members, and the general public to participate in that exploration. We facilitate experiments designed to expand our knowledge of space, and to execute ground-based missions designed to support those experiments.” In this regard I believe we have succeeded quite well. Feedback from members is generally positive in this respect and is a primary motivator for most members to continue their involvement with DSES and its programs.

LESSONS LEARNED

Antenna Feed Optimization
Proper matching of feed illumination to dish geometry is essential. Future designs should ensure that the -10 dB illumination edge aligns with the reflector boundary to maximize efficiency and minimize spillover.

RF Chain Design
A clearer understanding of the relationship between overall antenna performance (G/T), system noise figure, gain distribution, and SDR dynamic range is required. Future designs should be based on quantitative system modeling rather than heuristic approaches.

The secondary system was plagued by the presence of a phantom signal that apparently overwhelmed the Orion spacecraft data and ruined the last two days of our recording sessions. The cause is under investigation. It may be related to the gain settings on the SDR (a B210 clone). The B210 has a very different front end than the SDR in the primary system. The following guideline didn't seem to work well with our RF path planning.

- **Receive (RX) Gain:**
  - **Range:** 0 to 76 dB.
  - **Dynamic Range:** Use at least **half the available gain** (38 dB+) to maintain a reasonable dynamic range.
  - **Max Input Power:** The absolute maximum input for the B210 is **0 dBm**.

Data Acquisition Strategy
Late-stage changes to recording formats introduced significant risk. Future campaigns should:

- Freeze data formats prior to operations
- Validate compatibility with external requirements (e.g., NASA TDM)
- Conduct end-to-end testing well in advance
- Choosing to record I/Q data, while advantageous in many respects, requires advanced planning on how to manage high bandwidth data and large files effectively.

Software Integration and Testing
Software development is often the weakest link in a project. For example, a critical error in the TDM file formats was not found until the mission was nearly complete. This resulted in DSES lacking much if any data to send NASA as they specifically asked that we not modify the TDM files after the mission. Future efforts should include:

- A clearly understood statement of purpose and requirements
- A change control discipline
- Version control discipline
- Formal code reviews
- Quality control authority

System Architecture
Relocating SDR hardware to the antenna hub did not produce measurable performance benefits and increased operational complexity. Future designs should favor maintainability unless clear advantages are demonstrated.

Teamwork
Most of the DSES's teams came together with remarkable effectiveness and dedication. Where teamwork was strongest the mission processes worked best.

We had the opportunity to cooperate with outside organizations including ORI, Dwingeloo Radio Observatory, Bochum Observatory, and Astropeiler Stockert (Stockert Radio Telescope). For a variety of reasons DSES has not pursued these potential partnerships, but we have lost opportunities as a result.

APPENDIX A: LIGHT-TIME DOPPLER MODEL DESCRIPTION

The Doppler analysis presented in this work is based on a **one-way light-time corrected geometric model**, augmented with empirical bias and drift estimation to account for instrumental and reference uncertainties.

MEASUREMENT DEFINITION

The measured Doppler observable is derived from the SDR processing chain as:

$$f_{meas(t)} = \left(f_{center} + f_{FFT}(t)\right) - f_0$$

Where:

- $fcenter$ is the SDR tuning frequency,
- $f_{FFT}(t)$ is the spectral offset, and
- f_0 is the nominal carrier.

This produces a Doppler estimate in Hz relative to the assumed nominal carrier.

ONE-WAY LIGHT-TIME GEOMETRY

The model accounts for the finite propagation time of the signal between spacecraft and ground station.

The receive time t_{rx} and transmit time t_{tx} are related by:

$$\mathrm{t_{tx}} = \mathrm{t_{rx}} - \frac{\mathrm{R(t_{tx})}}{\mathrm{c}}$$

where:

- $R(t)$ is the geometric range between spacecraft and station
- c is the speed of light

This equation is solved iteratively to obtain the correct transmit epoch.

STATE VECTORS

Spacecraft position and velocity are obtained from JPL Horizons in an Earth-centered inertial (ECI) frame:

$$r_{sc}(t), v_{sc}(t)$$

The ground station state is computed from geodetic coordinates using Earth rotation:

$$r_{st}(t), v_{st}(t)$$

LINE-OF-SIGHT KINEMATICS

The instantaneous line-of-sight unit vector is:

$$\hat{\rho} = \frac{r_{sc}(t_{tx}) - r_{st}(t_{rx})}{\left|\left|\mathrm{r_{sc}(t_{tx})} - \mathrm{r}_{st}(t_{rx})\right|\right|}$$

The relative radial velocity is:

$$\dot{R}(t) = \left(v_{sc}(t_{tx}) - v_{st}(t_{rx})\right) \cdot \hat{\rho}(t)$$

PREDICTED DOPPLER

The predicted one-way Doppler shift is given by:

$$f_{pred}(t) = -f_0 \frac{\dot{R}(t)}{c}$$

where the negative sign follows the convention that positive radial velocity (receding) produces a negative frequency shift.

TIME AVERAGING

To account for finite integration time in the receiver, the predicted Doppler is optionally averaged over a time window Δt:

$$\bar{f}_{pred}(t) = \left(\frac{1}{\Delta t}\right) \int_{t-\Delta t/2}^{t+\Delta t/2} f_{pred}(\tau) d\tau$$

This models the effective measurement bandwidth and spectral estimation process.

BIAS AND DRIFT MODEL

Residual differences between measurement and model are represented by a linear correction:

$$f_{fit}(t) = f_{pred}(t) + b + dt$$

where:

- b is a constant frequency bias
- d is a linear frequency drift term

These parameters are estimated via least-squares fitting.

RESIDUALS AND PERFORMANCE

The post-fit residual is:

$$\varepsilon(t) = f_{meas}(t) - f_{fit}(t)$$

The model performance is quantified using the root-mean-square (RMS) residual:

$$\sigma_f = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \epsilon_i^2}$$

The model performance is quantified using the root-mean-square (RMS) residual:

$$\sigma_v = \frac{c}{f_0} \sigma_f$$

IMPLIED CARRIER FREQUENCY

The fitted bias term provides an estimate of the effective carrier frequency:

$$f_{0,eff} = f_0 - b$$

This value reflects the combined effects of:

- receiver frequency reference error

- nominal carrier uncertainty
- constant offsets in the measurement definition

SUMMARY

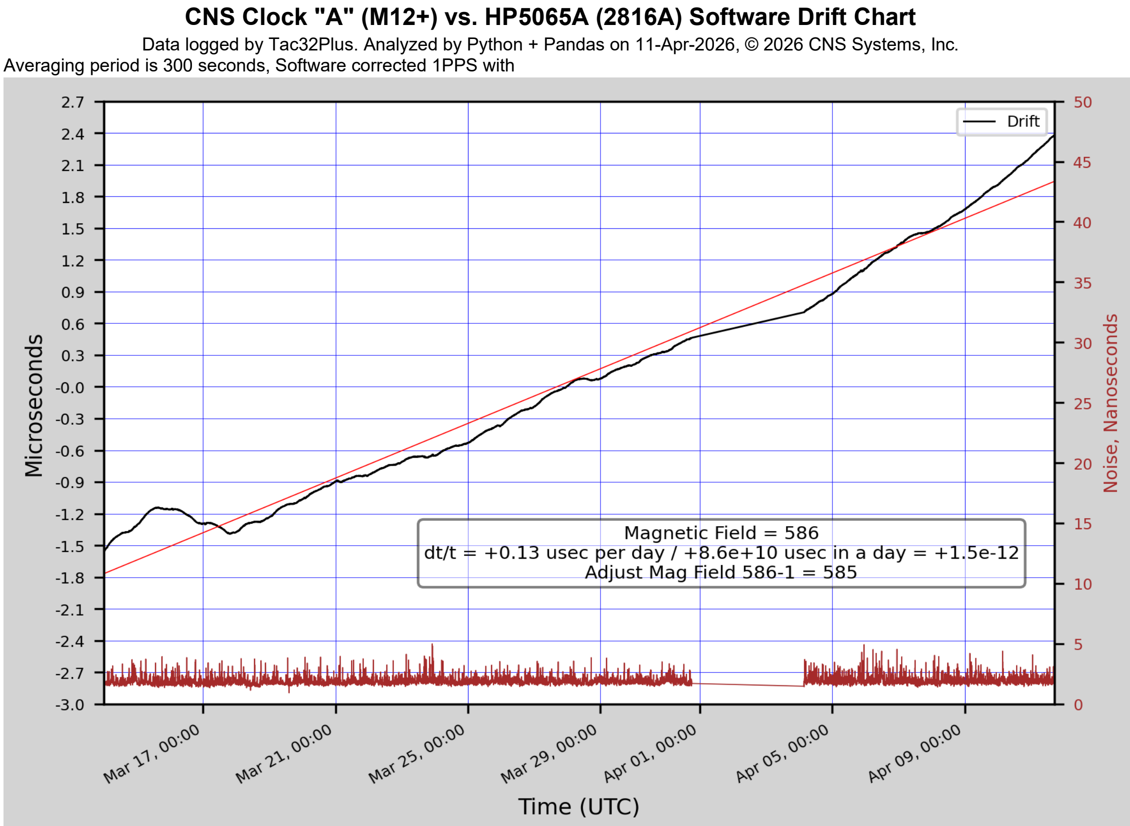
The light-time carrier model incorporates:

- full geometric spacecraft motion from JPL Horizons
- Earth rotation and station motion
- one-way signal propagation delay
- optional measurement time averaging
- empirical bias and drift correction

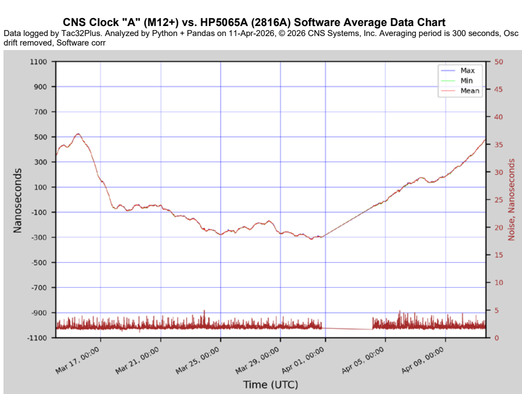
This framework enables high-fidelity comparison between measured and predicted Doppler and supports quantitative assessment of system performance.

APPENDIX B: 10MHZ REFERENCE CALIBRATION RUN

The attached slides represent the calibration run for the period including the Artemis mission. The first slide shows the drift of the HP5065A Rubidium oscillator over a period that includes the Artimus mission. It shows that the reference 10MHz signal that was used to drive our SDR receivers had a frequency error of approximately 1.5 parts in 10^{-12} as compared to GPS. This data shows that the precision 10MHz reference is more than good enough for the requirements of this mission and is unlikely to be responsible for any data irregularities.



Below is data with the drift removed and the raw and quantized corrected GPS pulse-per-second (PPS) data.



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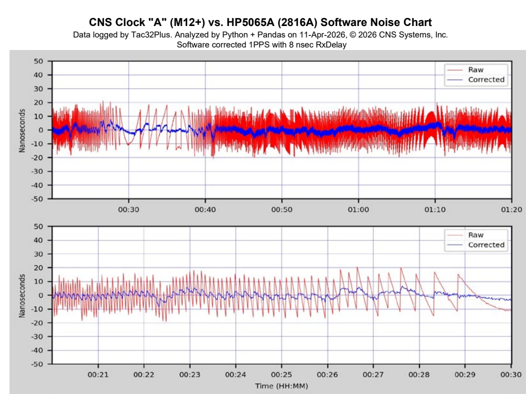


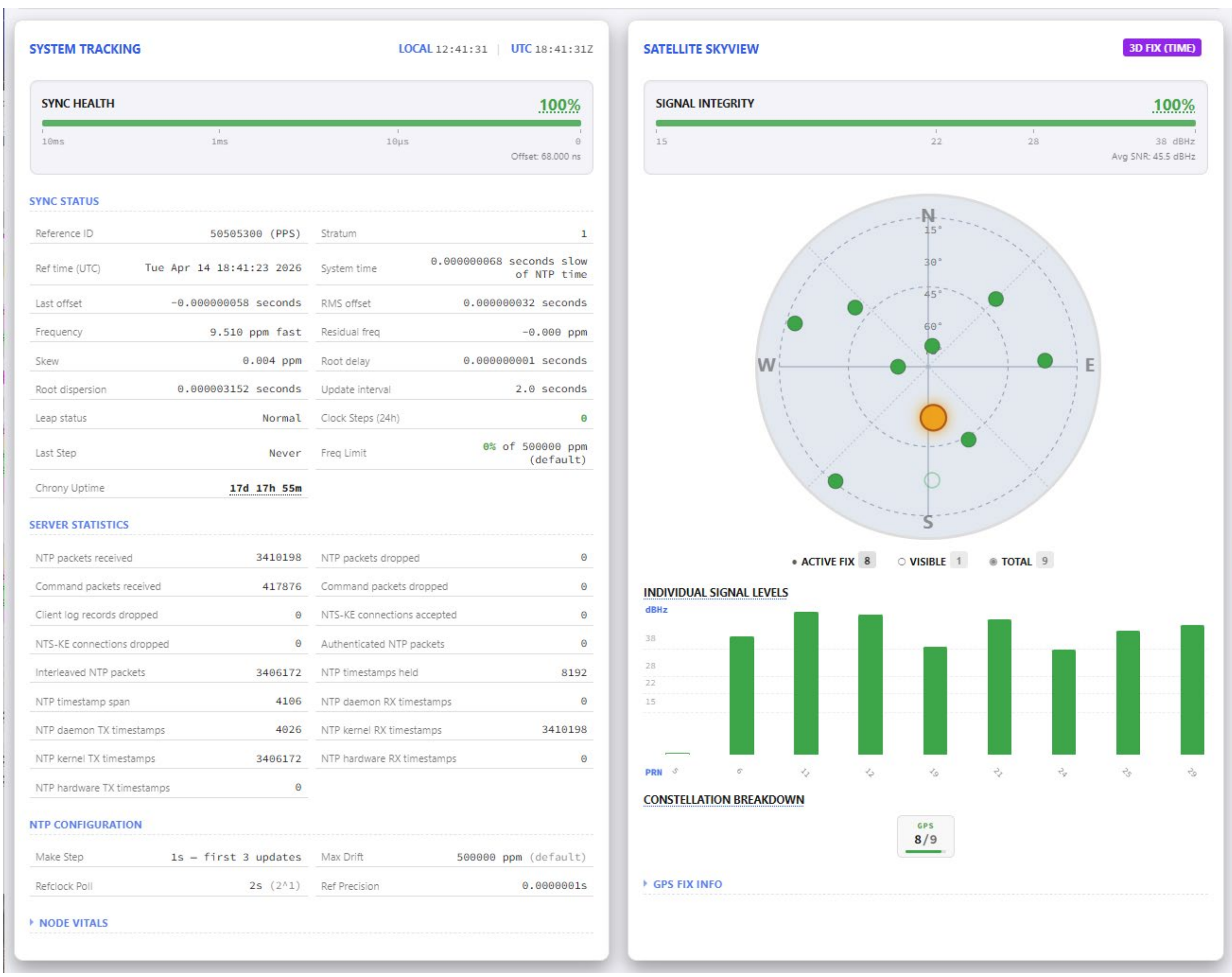
APPENDIX C: PRECISION NTP SOURCE

The DSES precision NTP time source is a part of the new Precision Time and Frequency rack. It is driven directly by a GPS receiver that had been calibrated at USNO and can deliver about 100 microsecond accuracy to any client on the DSES local area network (LAN).

The ChroGPS dashboard for the "DSES Time & Frequency" node provides a comprehensive real-time view of system timing performance and GPS receiver status. The system is shown in a **GPS LOCKED** condition, confirming that the local timebase is actively disciplined by a calibrated GPS reference.

The **System Tracking** panel indicates excellent synchronization health at **100%**, with a reported timing offset on the order of tens of nanoseconds. The node is operating as a **Stratum-1 NTP server**, using a direct **PPS (Pulse Per Second)** reference from the GPS receiver. Measured performance metrics include negligible last offset, very low RMS timing error (~10^{-7} seconds), and stable frequency control with minimal residual drift.

The **server statistics** confirm sustained operation, with millions of NTP packets processed and zero packet loss, indicating reliable time distribution across the DSES local network.



The **Satellite Skyview** panel shows the spatial distribution of GPS satellites currently in view, with **8 satellites contributing to the active timing solution**. Signal integrity is reported at **100%**, and the average signal-to-noise ratio (~47 dB-Hz) indicates strong, high-quality reception. The polar sky plot demonstrates good geometric diversity, which is essential for maintaining timing accuracy and robustness.

The **individual signal level chart** further confirms consistent satellite signal strength across the tracked constellation, supporting stable GPS lock and precise time transfer.

Overall, this display demonstrates that the DSES precision timing system is operating nominally, delivering high-stability, GPS-disciplined time with performance consistent with the expected ~100 microsecond (or better) network distribution accuracy described for the DSES NTP service.

This ChroGPS view presents the **Chrony source selection status** alongside detailed **GPS satellite signal data**, providing insight into both time reference hierarchy and signal quality.

The **Chrony Sources** panel shows that the system is primarily disciplined by the **GPS receiver** and, more importantly, the **PPS (Pulse Per Second) reference**, which provides the highest precision. The PPS source exhibits a timing offset on the order of **hundreds of nanoseconds**, confirming that it is the dominant reference used to achieve stratum-1 performance.

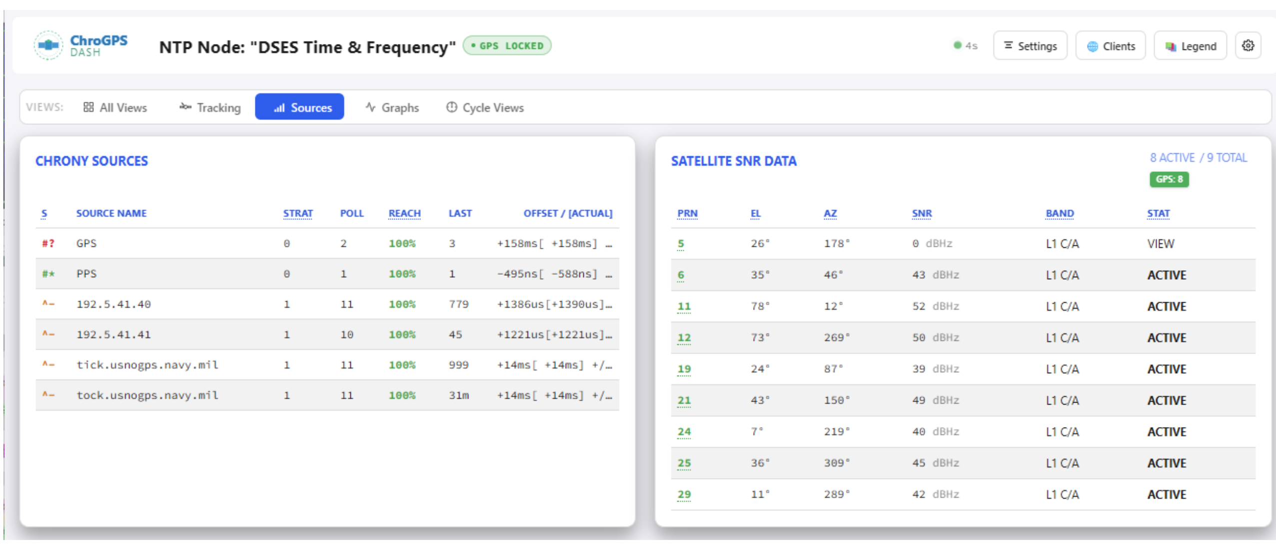
Several external NTP servers, including **USNO hosts (e.g., tick.usno.navy.mil and tock.usno.navy.mil)**, are also configured as secondary references. These sources show offsets in the **millisecond range**, which is expected due to network latency, and serve as validation and backup rather than primary timing inputs.

The **polling intervals and reach values (100%)** indicate stable and continuous communication with all configured sources, with no loss of synchronization.

The **Satellite SNR Data** panel lists individual GPS satellites contributing to the solution, including their **PRN identifiers, elevation and azimuth angles, and signal-to-noise ratios (SNR)**. A total of **8 satellites are active out of 9 visible**, all operating on the **L1 C/A band**.

Reported SNR values (typically **~40–52 dB-Hz**) indicate strong, reliable signal reception across the constellation. The distribution of satellites across different azimuth and elevation angles provides good geometric diversity, which enhances timing accuracy and robustness.

Overall, this display confirms that the DSES timing system is correctly prioritizing the **high-precision PPS reference**, while maintaining healthy satellite tracking and redundant network time sources, ensuring both **accuracy and resilience** in the NTP service.



S	SOURCE NAME	STRAT	POLL	REACH	LAST	OFFSET / [ACTUAL]
#?	GPS	0	2	100%	3	+158ms[+158ms] …
#*	PPS	0	1	100%	1	-495ns[-588ns] …
^-	192.5.41.40	1	11	100%	779	+1386us[+1390us]…
^-	192.5.41.41	1	10	100%	45	+1221us[+1221us]…
^-	tick.usnogps.navy.mil	1	11	100%	999	+14ms[+14ms] +/…
^-	tock.usnogps.navy.mil	1	11	100%	31m	+14ms[+14ms] +/…

PRN	EL	AZ	SNR	BAND	STAT
5	26°	178°	0 dBHz	L1 C/A	VIEW
6	35°	46°	43 dBHz	L1 C/A	ACTIVE
11	78°	12°	52 dBHz	L1 C/A	ACTIVE
12	73°	269°	50 dBHz	L1 C/A	ACTIVE
19	24°	87°	39 dBHz	L1 C/A	ACTIVE
21	43°	150°	49 dBHz	L1 C/A	ACTIVE
24	7°	219°	40 dBHz	L1 C/A	ACTIVE
25	36°	309°	45 dBHz	L1 C/A	ACTIVE
29	11°	289°	42 dBHz	L1 C/A	ACTIVE

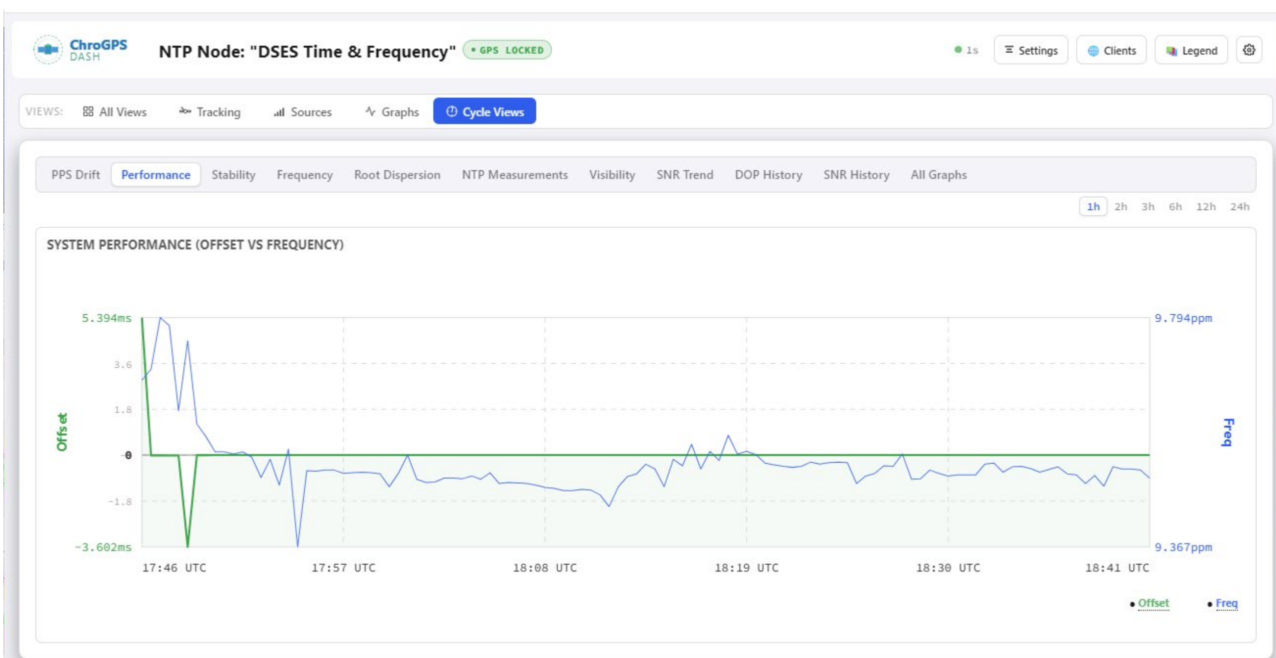
This ChroGPS **Cycle View** presents system performance over a defined observation interval, showing the relationship between **timing offset** (green trace) and **frequency deviation** (blue trace) as the NTP server's GPS-disciplined oscillator progresses through acquisition and steady-state operation.

The initial portion of the plot captures a **repeatable acquisition transient**, where the timing offset briefly reaches millisecond-level excursions before rapidly converging toward zero. This behavior reflects the control loop's response when aligning the local oscillator with the GPS PPS reference.

Following acquisition, the system enters a stable regime in which the **timing offset remains effectively zero** while the **frequency correction settles into a narrow operating band (~9.37–9.79 ppm)**. The small, continuous adjustments in frequency demonstrate normal disciplining activity as the system compensates for oscillator drift and environmental influences.

The Cycle View is particularly useful for verifying **consistency and repeatability** of the synchronization process. The absence of sustained offset excursions and the smooth, bounded frequency behavior indicate a well-tuned control loop with stable long-term performance.

Overall, this figure confirms that the DSES timing system not only achieves rapid synchronization but does so in a **predictable and repeatable manner**, reinforcing confidence in its use as a reliable, GPS-disciplined **stratum-1 NTP reference**.



There are a variety of other graphical views that can be useful in evaluating the NTP server's performance.