1. INTRODUCTION

New air filtration technology was installed on the International Space Station (ISS), where it is demonstrating advanced life support system capabilities that could help future explorers on the Moon and Mars breathe easier. The new hardware, known as the 4-Bed Carbon Dioxide Scrubber, was manifested aboard the Cygnus NG-16 commercial resupply mission. The scrubber is one of two next-generation Environmental Control and Life Support System (ECLSS) technologies set to be tested on the space station for one year, helping recycle and regenerate most of the air and water necessary to sustain its crew – and proving advanced regenerative technology solutions for upcoming Artemis missions to the Moon and eventual human excursions to Mars. The Thermal Amine Scrubber (TAS), was delivered to the station in early 2021, uses actively heated and cooled amine beds – water purification technology used around the world – to remove carbon dioxide from the air. Once installed, the new carbon dioxide scrubber will use commercial adsorbent materials to retain water vapor while filtering carbon dioxide out of the space station's airflow. Adsorption is the use of beaded porous materials (molecular sieves) to separate metabolic carbon dioxide to be discarded or recycled. The space station's current Carbon Dioxide Removal Assembly (CDRA) has conducted this task since early 2001. The 4-Bed Carbon Dioxide Scrubber is a design iteration of the current assembly, incorporating numerous engineering and technology changes to improve durability and maintainability. These upgrades and refinements are crucial for future exploration missions beyond Earth orbit. Once its year of technology demonstration is over and the system proves its capabilities, the new scrubber unit will be integrated into the station's closed-loop recycling system for a minimum of three years to further demonstrate its viability for long-duration exploration missions and to contribute to station crew life support capabilities. The new scrubber unit will enable testing of a first-of-its-kind, magnetic bearing air blower developed by a commercial provider to replace an obsolete blower technology. The new hardware is roughly the size of a small refrigerator and weighs approximately 450 pounds and is installed in EXpedite the PRocessing of Experiments to the Space Station (EXPRESS) Rack (ER) ER2 at rack location LAB1O1. See Figure 1 on page 4 for a depiction of TAS equipment in ER2.

2. QUALIFY

Figure 2 on page 5 is a color spectrogram computed from Space Acceleration Measurement System (SAMS) sensor 121f03 measurements. This sensor was mounted on the lower Z-panel of ER2 at rack location LAB1O1, in the US Lab Module, nearby to the TAS equipment. This spectrogram plot shows a 55-minute span centered roughly in time on when the TAS was put into two bed mode.

SAMS Time Correlation with Reported Operations Notes

As we see on page 5 in Figure 2 as indicated by the upward-pointing dark arrow, there is a notable horizontal, red streak (a strong, narrowband disturbance) that starts at GMT 12:23:18, and this time we know corresponds to the start of scrubber operation, or at least the time it was put into two bed mode. This strong, narrowband fan disturbance starts operating at about 105 Hz and then slowly falls to settle at about 102 Hz.

There are other, brief TAS operational changes as indicated by the rightward-pointing, white arrow. This white arrow is pointing to start of the 2nd harmonic with a much stronger fundamental frequency, but harder to make out at about 41 Hz as it is obscured by broadband vibrations from another source. This fundamental peak at **about 41 Hz is the strong, narrowband signature of the air save pump**. Also, as expected with turbulent airflow from the TAS blower, we observe indications of broadband excitation in the vibratory measurements – note the general "yellowing", i.e. heightening vibrations that start with activation in two bed mode at about GMT 12:23:18 in Figure 2.

Figure 3 again shows close correlation in time between SAMS measurements and activation of the TAS, now in four bed mode at GMT 04:52:27 on the following day. The arrow annotations in this figure are analogous to those noted above for the previous day's two bed mode activation, however, now the strong, narrowband disturbance starts at about 103 Hz and settles to 101 Hz.

One last note on Figure 3 as indicated by the hollow, blue, upward-pointing arrow is what appears presumably to be the end of TAS operations in two bed mode at GMT 04:30:39.

3. QUANTIFY

Figure 4 on page 7 shows a 3-minute interval root-mean-square (RMS) acceleration versus time plot calculated from the SAMS 121f03 sensor measurements. The time axis of this plot spans 2 days starting at GMT 2021-09-23/00:00:00 and covers the two bed mode activation and the four bed mode activation on those 2 consecutive days, respectively. The RMS levels here were computed via Parseval's theorem and only intend to capture the strong, narrowband disturbance just above 100 Hz or so, that is, we consider only...

RMS Acceleration Levels for 99.2 < f < 103.8 Hz

TAS NOT ACTIVE ~ 200 µg

The green portion of the RMS results are for a 6-hour span when we presume the TAS was off and the median RMS value during that span was 210 µg.

TAS ACTIVE IN TWO BED MODE ~ 700 µg

The red portion of the RMS results in Figure 4 represents a 6-hour span when we know the TAS was active in two bed mode and the median RMS value during that span was 691 µg.

TAS ACTIVE IN FOUR BED MODE ~ 500 µg

The blue portion of the RMS results in Figure 4 represents a 6-hour span when we know the TAS was active in four bed mode and the median RMS value during that span was 533 µg.

The information shown in Table 1 breaks out the per-axis and total RMS values for various operating conditions. Note the disturbance near 100 Hz was primarily aligned with X-axis.

	6-Hour Span	RMS (micro-g)			
TAS	Start GMT	X-Axis	Y-Axis	Z-Axis	RSS
OFF	23-Sep-2021/00:00	182	85	61	210
TWO BED	23-Sep-2021/18:00	494	365	316	691
FOUR BED	24-Sep-2021/06:00	372	295	242	533

Table 1. Sensor SE-F03 RMS Acceleration Levels for 99.2 < f < 103.8 Hz for Various TAS Operating Conditions.

TAS Vibratory Per-Axis Alignment

Figure 5 on page 8 shows a per-axis plot of acceleration versus time. This rendering clearly shows that the TAS equipment has an impact on all 3 acceleration measurement axes, but mostly so on the YZ-plane. This plot considers the entire measurement bandwidth (up to 200 Hz) for a sensor located quite close to the source, within the same rack. We see during this 2-hour span there is a signal feature that pops up above the baseline vibrations every 15 minutes and for 2 minutes in duration. This is the air save pump turning ON for 2 minutes in 2 crew mode, then OFF for 13 minutes and the cycle repeats (1 minute ON in 4 crew mode). See Figure 6 for a spectrogram of the same 2-hour period that clearly shows the feature that pops up above baseline is the air save pump's strong, narrowband fundamental frequency at 41.5 Hz along with 2nd through 4th harmonics at 83, 124.5, and 166 Hz, respectively. Note in this figure that we changed from our typical colormap to one called "jet", which better shows the air save pump's fundamental at 41.5 Hz.

The values tabulated in Table 2 show further that the air save pump at 41.5 Hz plus harmonics can get to very high RMS levels near the source and furthermore, these vibrations propagate to other laboratory modules on the space station, notably so in the Columbus module and to lesser extent, not shown in this table, in the Japanese module too.

		RMS (micro-g)	
Rack	SAMS Sensor	TAS OFF	TAS ON
ER2, LAB1O1	121f03	761	**23,749**
ER7, LAB1P2	121f04	77	559
ER3, COL1A1	121f02	31	84

Table 2. RMS Acceleration Levels for 39.5 < f < 42.5 Hz for 2-Day Span Starting on GMT 23-Sep-2021 (TAS OFF vs. ON).

GMT 2022-02-04 Follow-Up One-Third Octave Analysis

On GMT 2022-02-04, the Thermal Amine System was known to have been powered off. We used this opportunity to quantify and compare OFF versus ON primarily via RMS acceleration levels versus one-third octave frequency bands. Figure 10 on page 13 shows a spectrogram computed from the SAMS sensor mounted on the same rack that contains the TAS. The black text annotation near the top shows when the TAS was turned OFF and the annotations along the left side (frequency) axis show the fundamental and harmonics of the air save pump as it cycles ON for 2 minutes at a time and we see a train of 3 such ON periods of that pump before GMT 14:30.

The per-axis power spectral density plots in Figure 11 on page 14 gives a crude quantitative comparison of TAS air save pump ON (red traces) versus OFF (black traces). The spectral peaks marked with annotations show the pump's fundamental and harmonic frequencies. Note in particular from the fundamental just under 42 Hz that the pump's reciprocating motion appears mostly aligned with the YZ-plane and to a lesser extent on the X-axis.

Another quantitative comparison can be seen in Figure 12 on page 15. This figure shows a 35-minute period starting at GMT 2022-02-04/13:45 when the air save pump was ON in the red trace along with a 35-minute period starting at GMT 2022-02-04/14:35 when the air save pump was OFF in the black trace. As a backdrop, the gray stairstep curve shows the ISS Microgravity Control Plan curve. The red annotation that shows the RMS acceleration level as the "pump PARTIALLY* ON" is because during that 35-minute period, the air save pump was only on for 6 minutes in that span, so the RMS value gets averaged down to a lower value of about 7.53 mg whereas when we use Parseval's theorem to extract the RMS level when the air save pump was "FULLY ON" for the entire time span of the calculation, then we see RMS levels closer to about 23.58 mg.

4. CONCLUSION

We have shown that SAMS vibratory sensor measurements in the US Lab module correlated closely in time with activation of the TAS in two bed and four bed modes on GMT 2021-09-23 and GMT 2021-09-24. For calculations based on SAMS measurements, we see that a strong disturbance aligned mainly with the YZ-plane propagates throughout the space station and comes from TAS operation of the air save pump. This strong, narrowband disturbance at 41.5 Hz (with multiple harmonics) produces RMS levels ranging from micro-g to tens of milli-g depending on distance from source to sensor. We also noted and quantified a lesser narrowband disturbance just above 100 Hz.

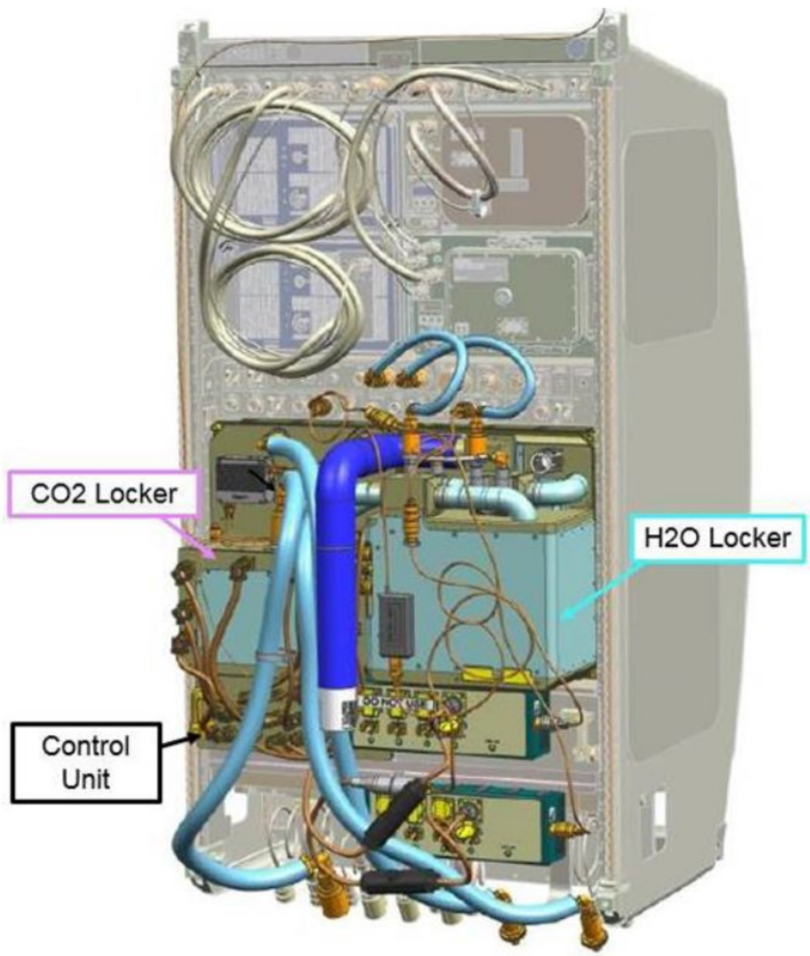

Fig. 1: Depiction of Thermal Amine Scrubber equipment in ER2.

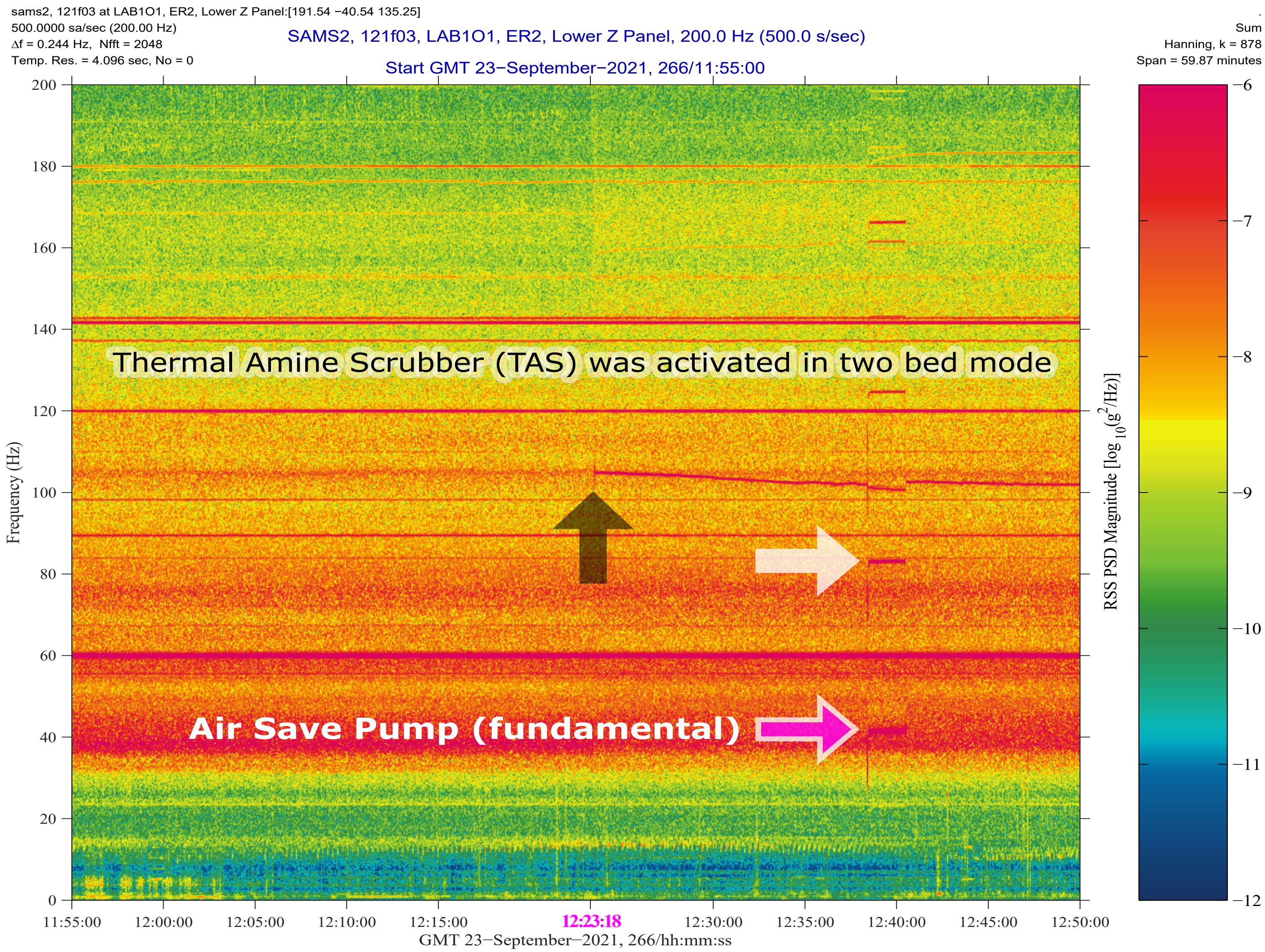

Fig. 2: Spectrogram showing TAS activation in two bed mode on GMT 2021-09-23.

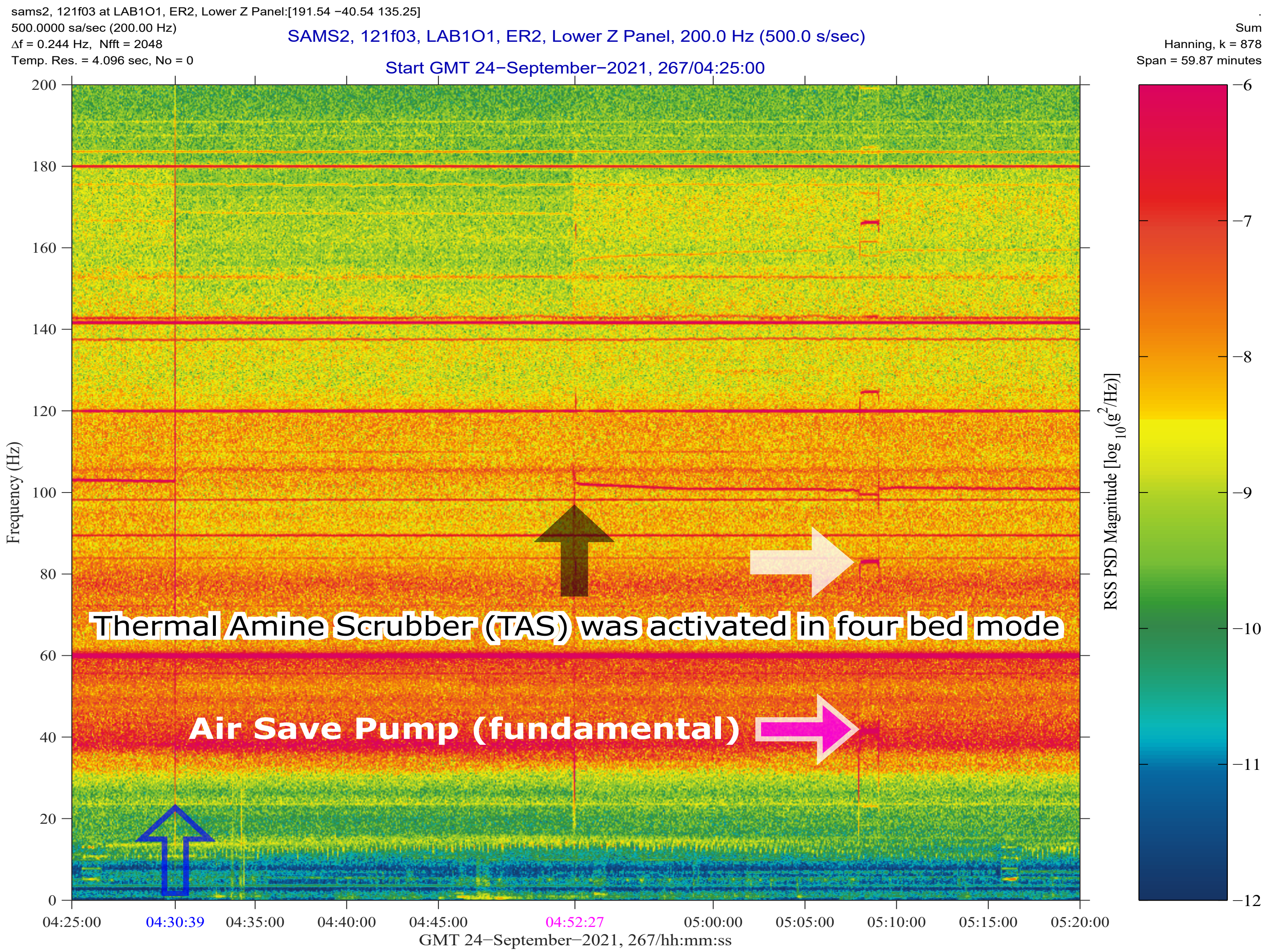

Fig. 3: Spectrogram showing TAS activation in four bed mode on GMT 2021-09-24.

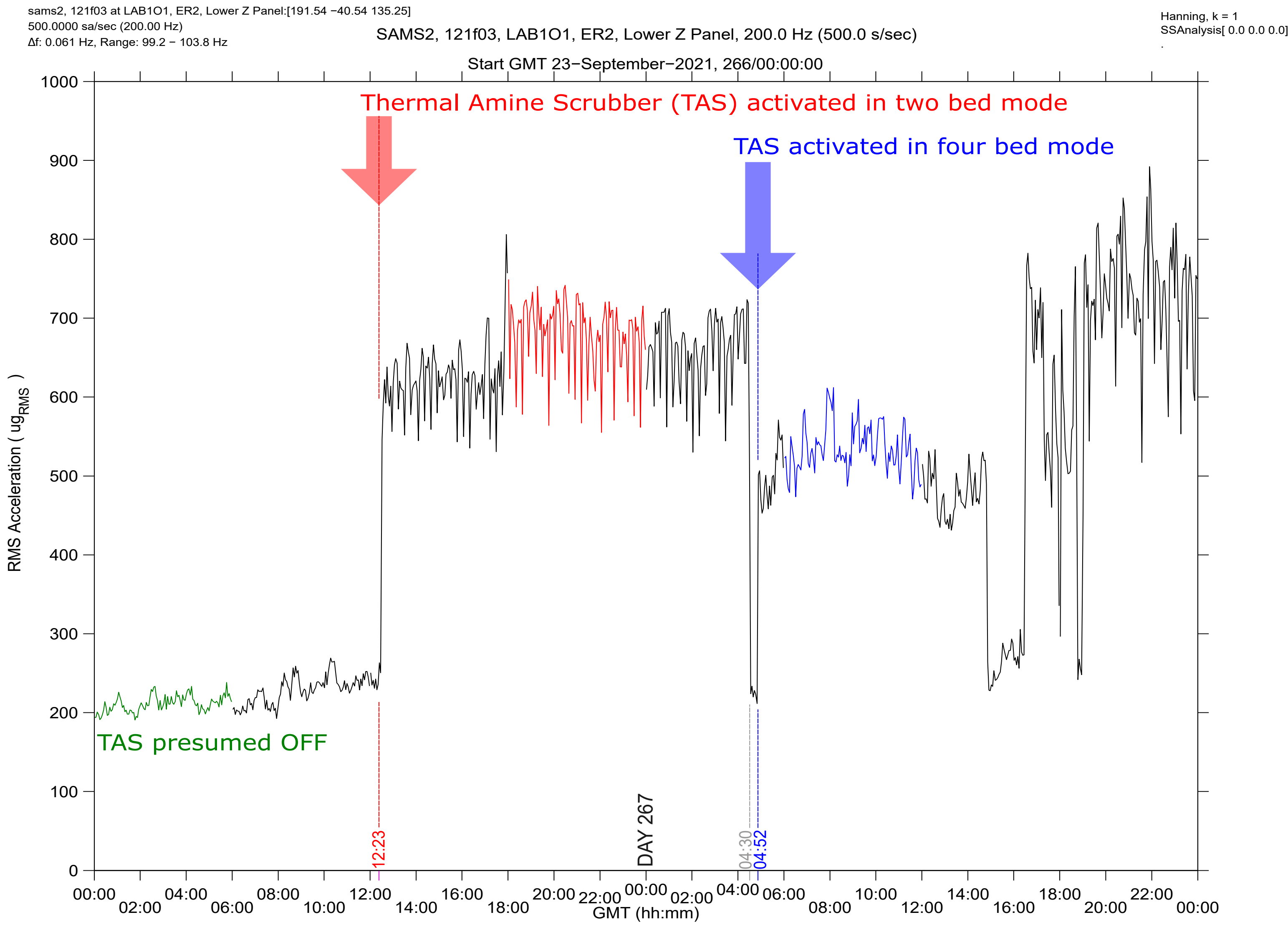

Fig. 4: Interval RMS Accel. (99.2 < f < 103.8 Hz) shows TAS activations on GMT 2021-09-23 & 2021-09-24.

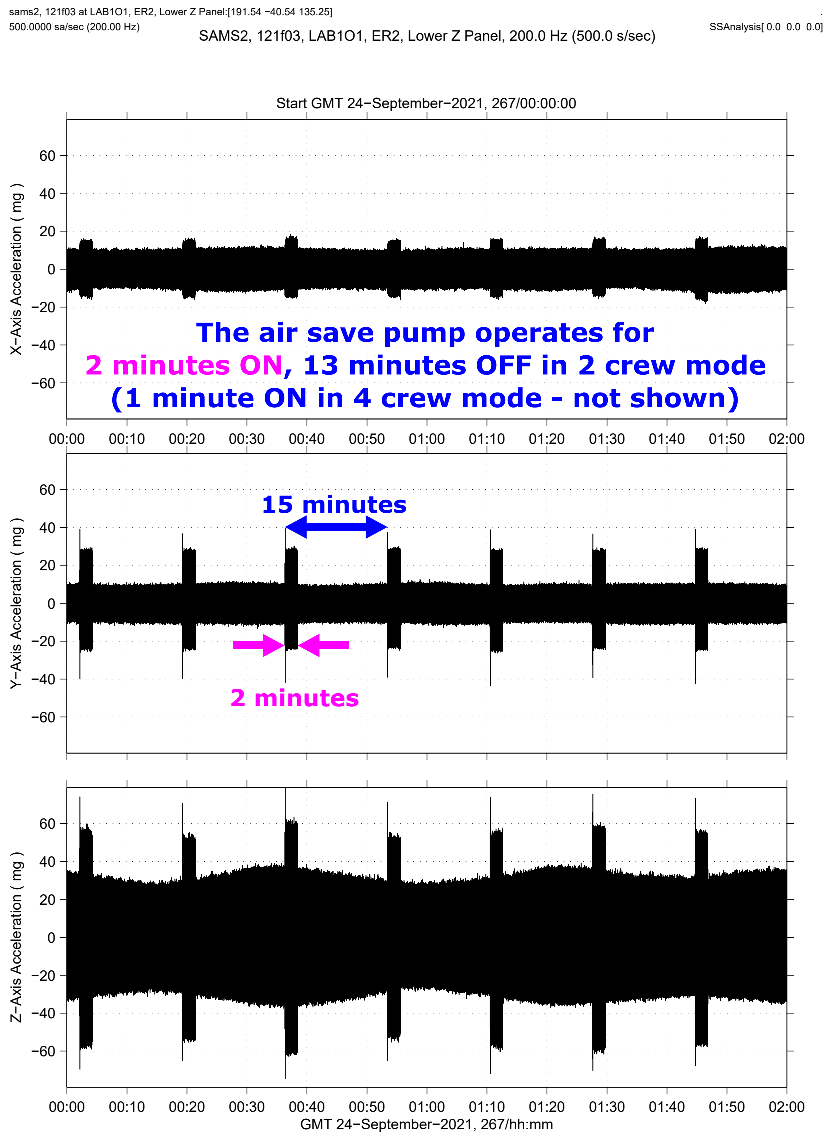

Fig. 5: Acceleration vs. time shows per-axis components of TAS Air Save Pump on GMT 2021-09-24.

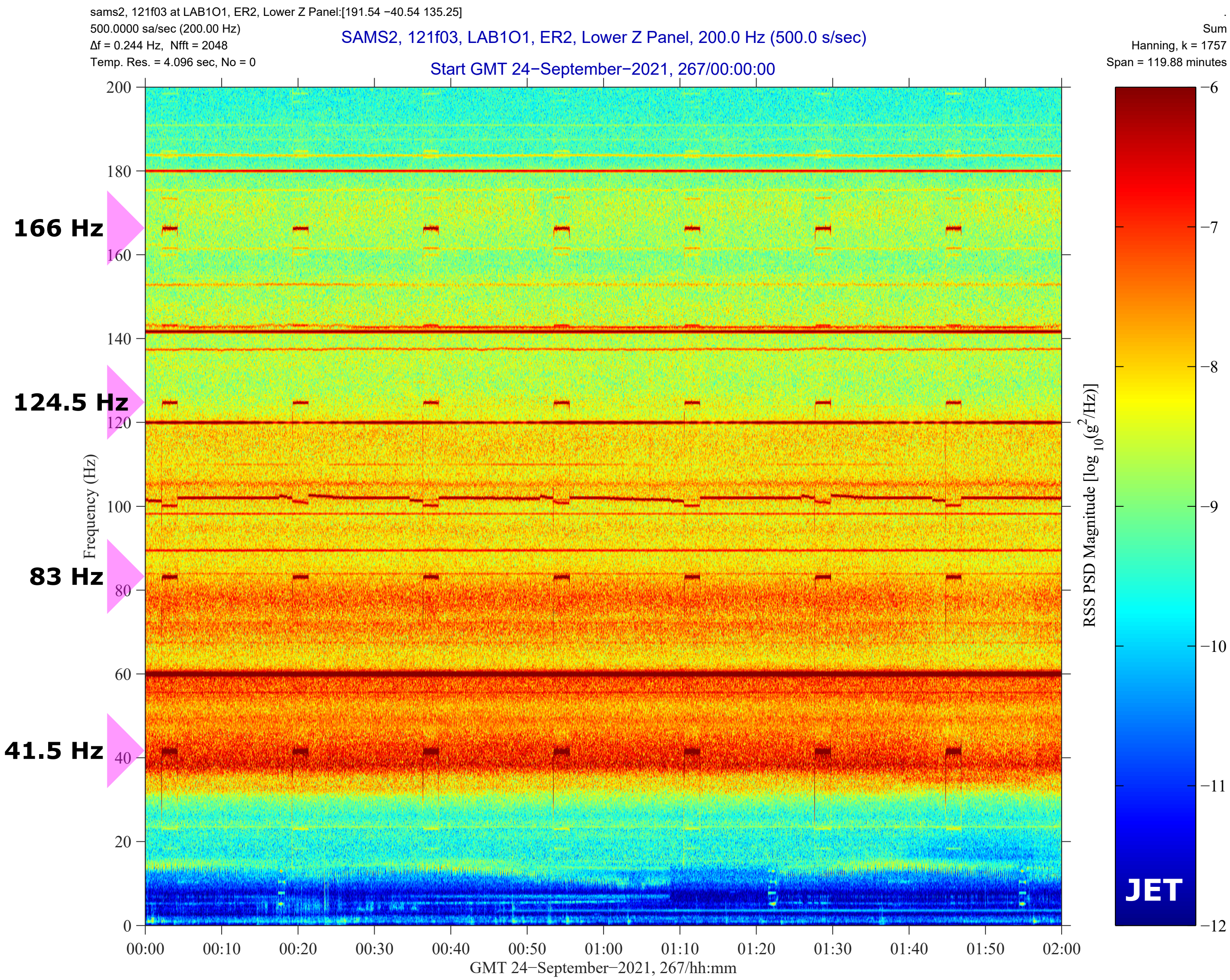

Fig. 6: Alternative "JET" Color Scale to Better Show Air Save Pump signature on GMT 2021-09-24.

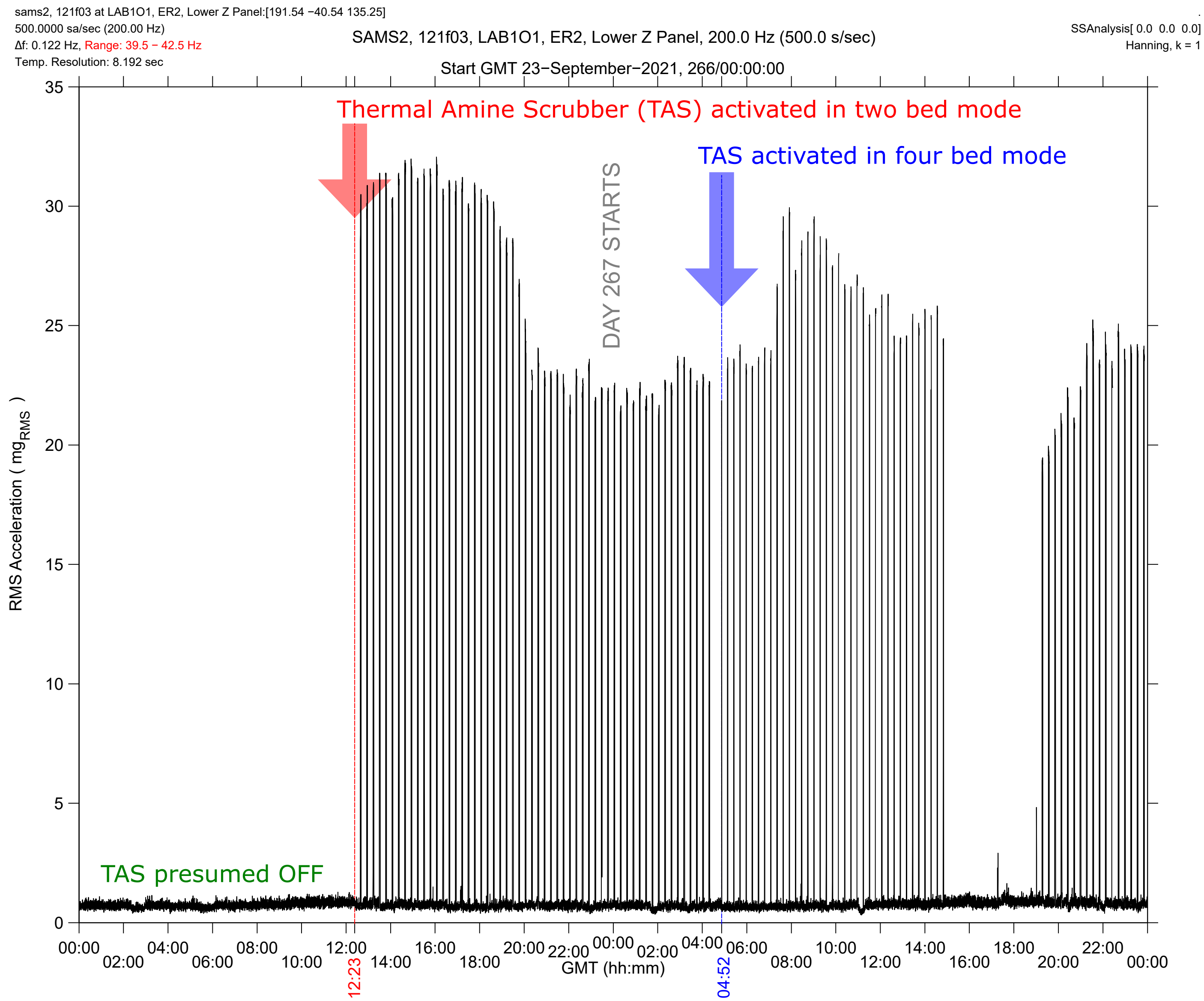

Fig. 7: Narrowband Interval RMS Accel. to Quantify Air Save Pump at ER2 in LAB on GMT 2021-09-23.

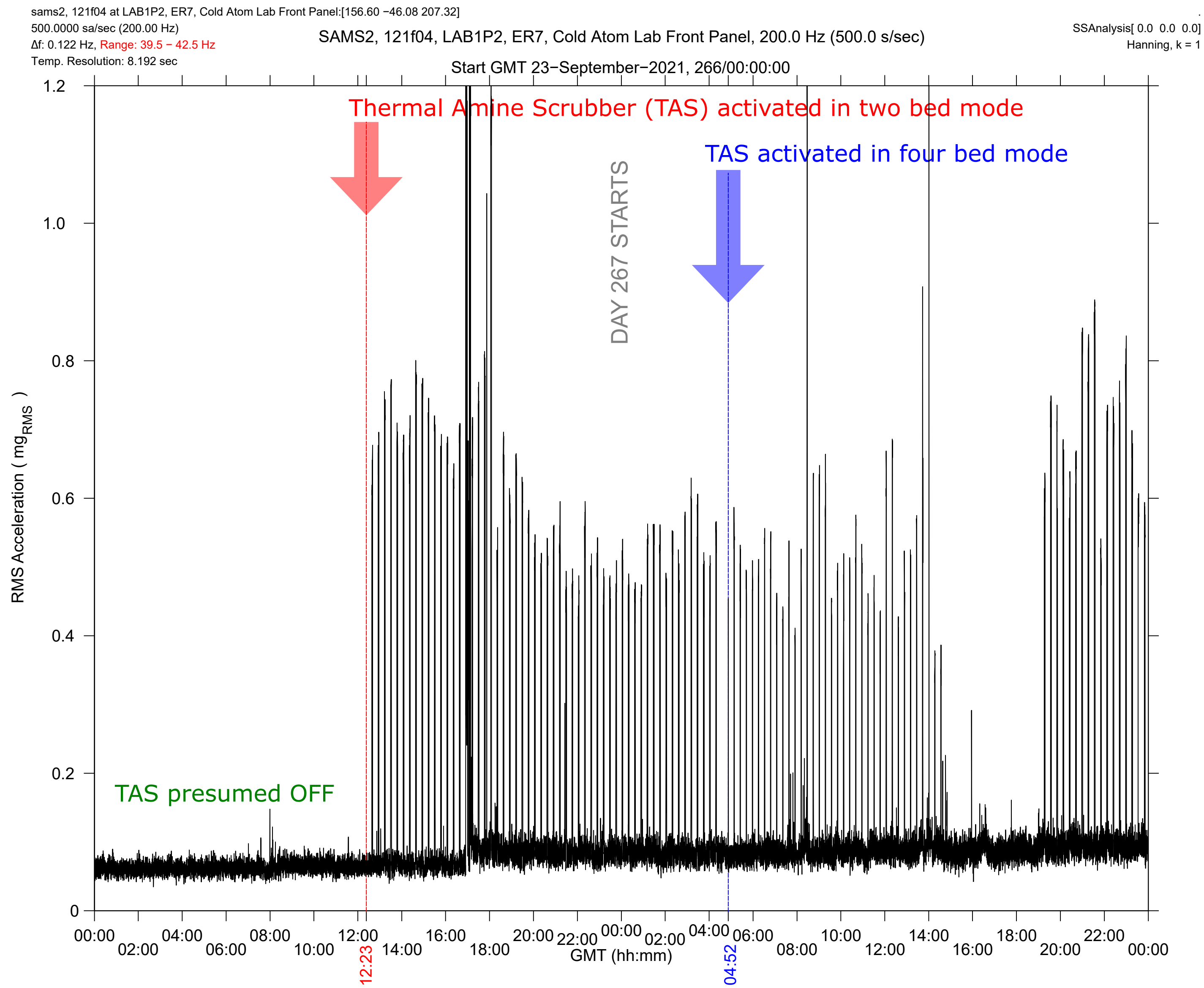

Fig. 8: Narrowband Interval RMS Accel. to Quantify Air Save Pump at Cold Atom Lab on GMT 2021-09-23.

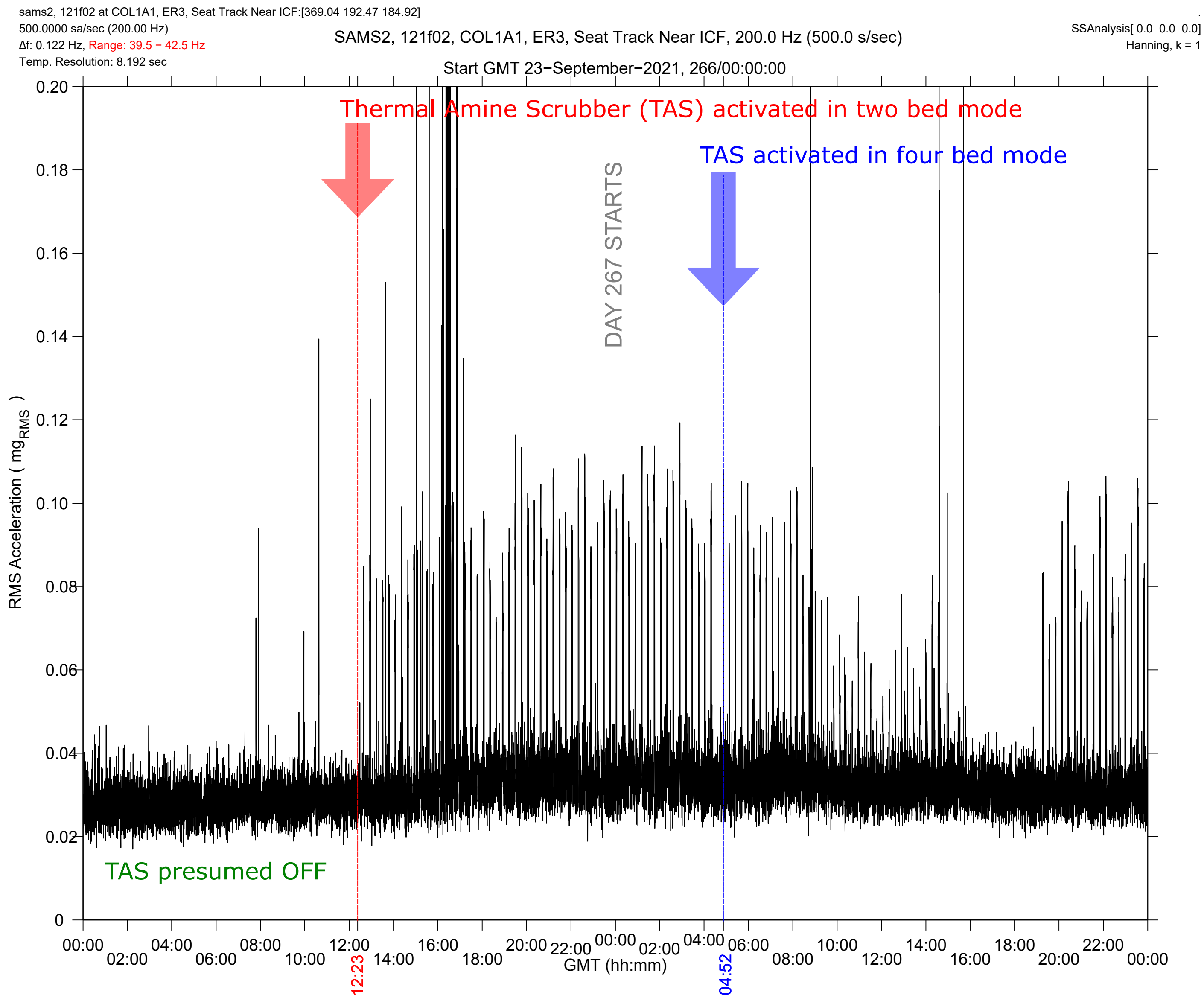

Fig. 9: Narrowband Interval RMS Accel. to Quantify Air Save Pump at ER3 in COL on GMT 2021-09-23.

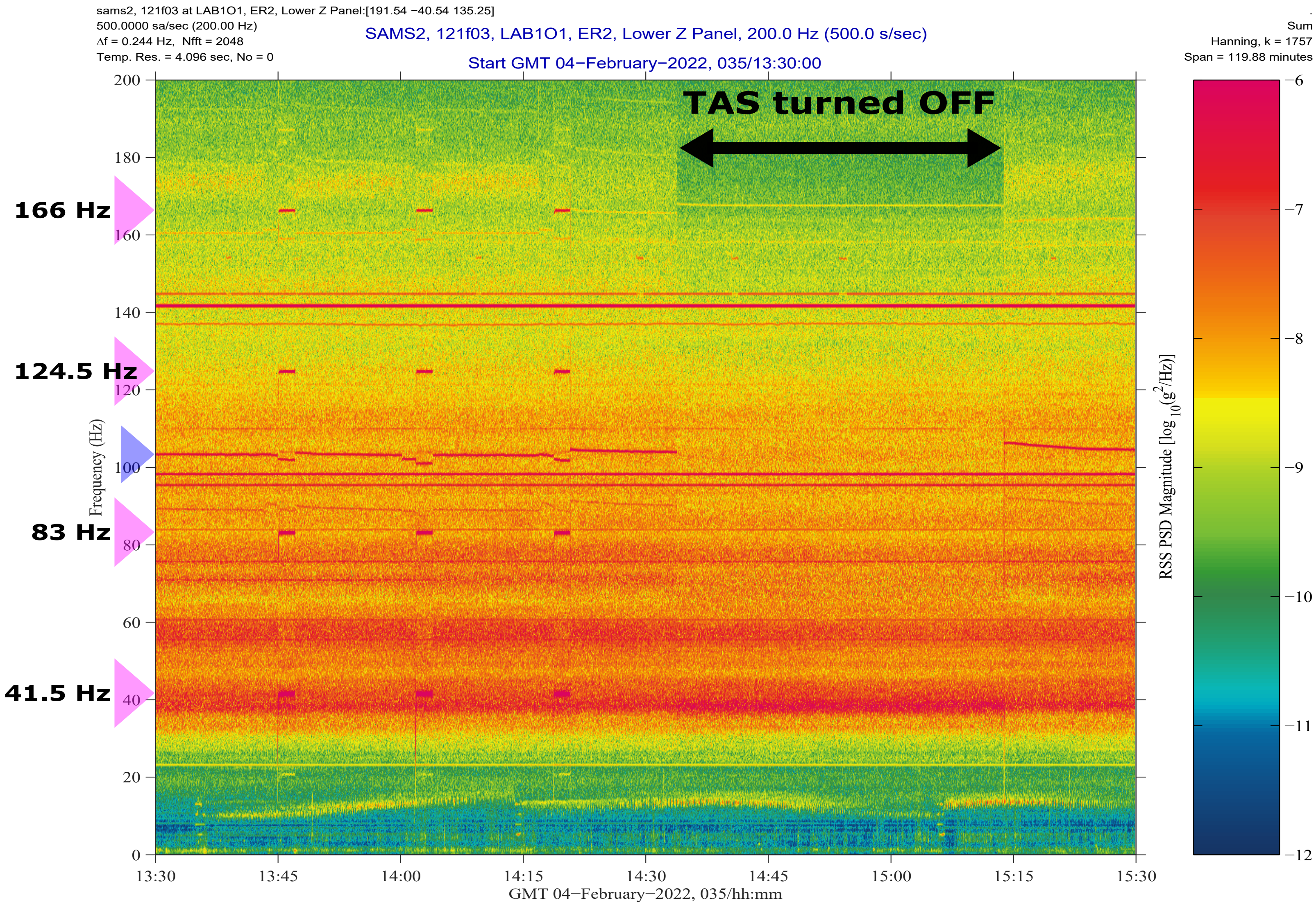

Fig. 10: Spectrogram showing TAS deactivation on GMT 2022-02-04.

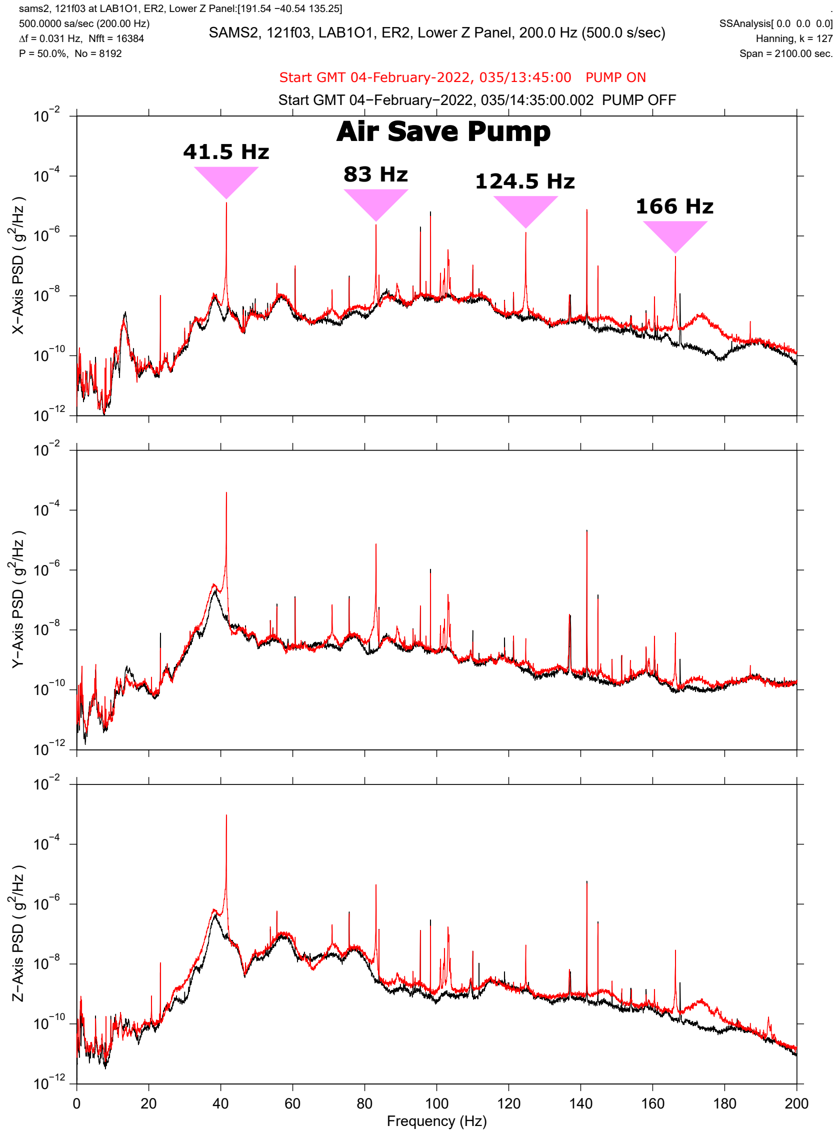

Fig. 11: Power spectral density plots per-axis components of TAS Air Save Pump ON vs. OFF on GMT 2022-02-04.

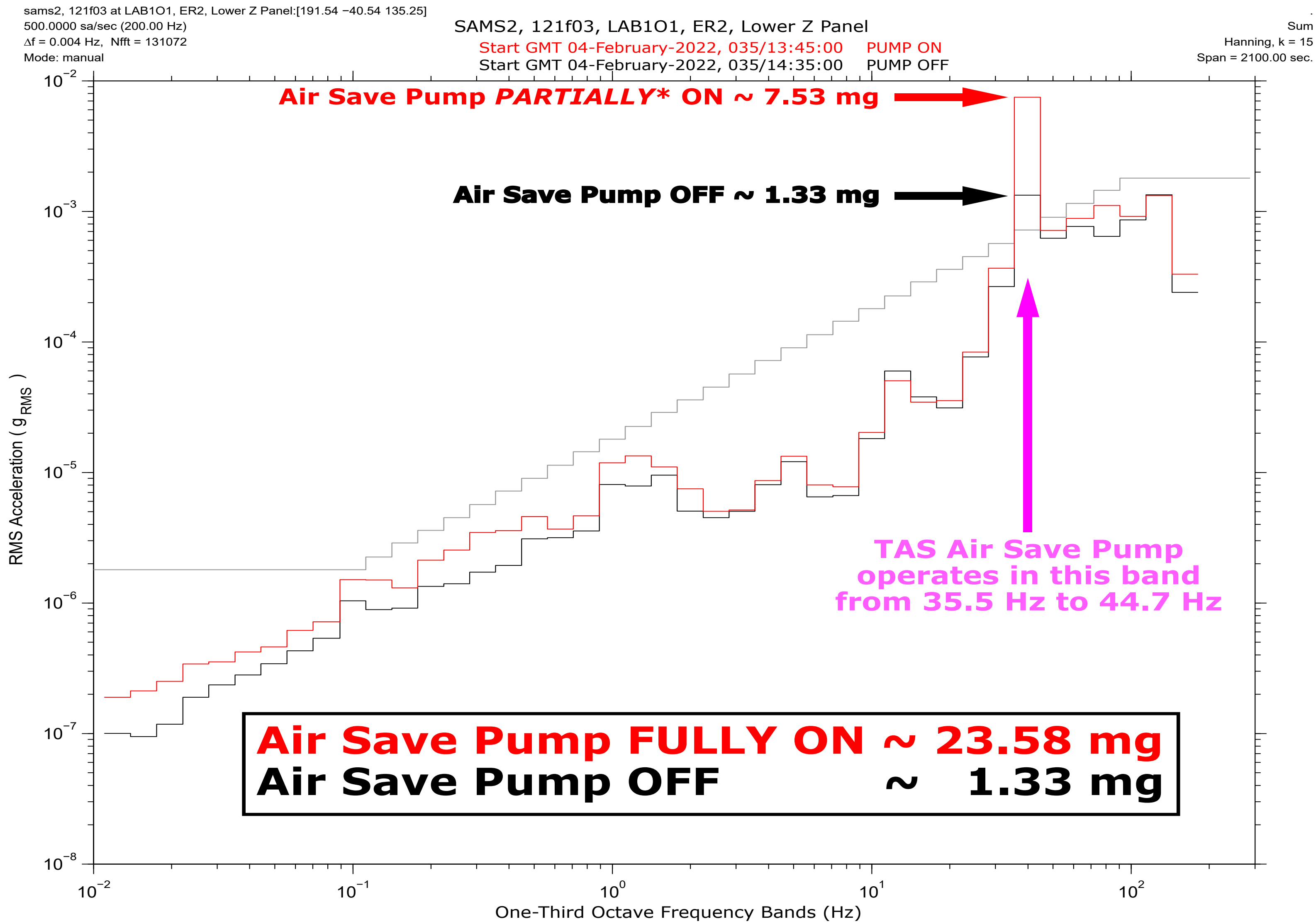

Fig. 12: Spectrogram showing TAS deactivation on GMT 2022-02-04.