1. INTRODUCTION

The title in the top margin of this document perhaps suggests that the 4-Bed Carbon Dioxide Removal equipment was only operating on the date shown, however, as life support equipment, this technology is used on and off around the clock on the International Space Station (ISS). It is a mainstay for metabolic carbon dioxide (CO_2) removal and crew life support. The previous generation was known as the Carbon Dioxide Removal Assembly (CDRA) with a long history of unplanned maintenance as well as obsolete core components. The 4-Bed CO_2 equipment was commissioned to operate with no unplanned maintenance for 3 years while removing 4 crew-equivalents of CO_2 at a target inlet concentration of 2 torr CO_2.

Transitions of 4BCO2 Equipment Time Correlated with SAMS Measurements

In this document, we focus on three things that happen during 4BCO2 half-cycle (HC) transition that affect vibration levels (note: **BLW** refers to the Blower, and **ASP** refers to the Air Save Pump):

1) BLW speed decreased from 130K to 80K RPM. *Could reduce vibration levels?*. Note: anecdotal hands-on experience tells us that the blower does not vibrate much (hard to tell it is running based on touch). However when run in open air (without beds attached) the air movement is notably energetic and we know that turbulent air flow generally results in broadband vibrations. See the white trace in the topmost subplot in Figure 6 in page 9. Compare the time transitions there as you flip back/forth with the SAMS measurement data on the page previous to that. Realize here that SAMS passband has an upper limit of 200 Hz, so we are not directly measuring the BLW speed, e.g. 80K RPM ≈ 1,333 Hz. Instead, we measure an harmonic alias of that frequency, which falls within the passband of SAMS.
2) Six valves rotate to new positions. Not particularly fast rotation, *would not expect much vibration to result?*. See the 6 traces in the middle subplot of Figure 6. We do not attempt to account for these brief open/close transitions here, but for those interested, we can take a closer look?
3) BLW speed increases from 80K to 130K. *Could marginally increase vibration levels?* The Quantify section attempts to address the impact of 4BCO2 equipment vibratory impact via one-third octave frequency band root-mean-square (RMS) acceleration levels.
4) ASP turns on for 10 minutes. *This pump is acoustically noisy, so prime suspect for high vibration levels?* We see a strong, narrowband signature we attribute to the ASP. Compare the purple trace in the top subplot of Figure 6 to what we see in the SAMS spectrogram of Figure 5 near 66.7 Hz, which is the ASP's fundamental frequency (≈ 4K RPM). We also see the ASP's 2^{nd} harmonic near 133 Hz. The magenta text and triangular annotations point out the narrowband spectral peaks in Figure 4, which align with the two distinct "ON" periods for the ASP shown in Figure 6.

During change from segment 1 to segment 2, at 10 minutes into HC:

1) One valve rotates to a new position.
2) The ASP turns off. This is clearly seen in the vibratory data with "turn off" of strong, narrowband vibrations at the 66.7 Hz fundamental and at the 2^{nd} harmonic near 133 Hz. Both turn off after 10 minutes as discussed above.

HC change occurs every 80 minutes. The Air Save Pump vibration should decrease as the pressure in the sorbent beds decrease and it is moving less mass; the ASP is loudest when it first turns on. We will examine this feature in the Quantify Section below.

Microgravity Measurement & Analysis

For the microgravity acceleration environment analysis in this document, we are using the Space Acceleration Measurement System (SAMS) data primarily based on a time frame from GMT 2023-01-06/13:15 to 15:30 for four SAMS sensor heads.

Those sensors are distributed throughout the space station as follows (see the topology/distribution in Figure 1 on page 4):

1) ES-20 at LAB1P4, near 4BCO2.
2) SE-F04 at LAB1P2, near Cold Atom Lab.
3) SE-F05 at JPM1F1, near Plant Habitat.
4) SE-F08 at COL1A3, near PK-4.

2. QUALIFY

Figure 2 on page 5 shows a color spectrogram computed from Space Acceleration Measurement System (SAMS) sensor es20 measurements. This sensor was mounted on the seat track of LAB1P4, and nearest to the 4BCO2 equipment. This first figure shows an overview (roadmap) plot span of just over 2 hours using a typical magnitude range for its color scale limits. However, we note clipping on the upper (red/magenta) end of the magnitude/color scale, so we replotted in Figure 3 on subsequent page to better show the high magnitude vibration signatures, however, now at the expense of clipping the low-magnitude vibrations at the dark blue end. Note the "yellow-to-red" areas, especially the mostly-horizontal-red streaks above 160 Hz, in this spectrogram of Figure 3. We associate these with the 4BCO2 Blower, albeit mostly likely aliasing of upper harmonics well above the SAMS passband.

Next, we zoom-in on a 15-minute period starting at about GMT 13:30 to get Figure 4 on page 7. The magenta annotations in this spectrogram are intended to identify the strong, narrowband spectral peaks associated with the Air Save Pump (ASP) at its fundamental frequency near 66.7 Hz and at its 2nd harmonic near 133 Hz. A strong vibration, but confined to narrow frequency bands for about a 10-minute duration.

Spectrogram color scales (i.e. power spectral density magnitudes) can only crudely quantify acceleration magnitudes and in units that are not that meaningful. The next section seeks to better quantify the vibratory impact of the 4BCO2 equipment.

3. QUANTIFY

In order to quantify the impact of the 4BCO2 equipment, we will first focus our attention on three one-third octave (OTO) frequency bands as shown in Figure 7 through Figure 9 starting on page 10.

The most distinctive feature in the first of those figures for OTO Band #1 is the two 10-minute periods when the Air Save Pump was ON. For those 2 periods, the root-mean-square (RMS) acceleration in that frequency band approximately doubled on each of the Y- and Z-axis. A planar disturbance suggesting rotational equipment operations.

Next, again consider the qualitative information shown in Figure 3 on page 6, but now focusing on the frequency range between 120 and 140 Hz as part of OTO Band #2. Comparing that spectrogram plot to what we see quantitied in Figure 8 on page 10, it's clear that: (1) when the Blower operational frequency dips down to near 120 Hz, we see a ten-fold increase in RMS acceleration on the XZ-plane (less so on the Y-axis) and interestingly, the Air Save Pump's 2nd harmonic near 133 Hz is strongest on the X-axis and much less noticeable on the YZ-plane.

Perhaps what might be considered the largest impact in terms of one-third octave frequency bands' RMS acceleration levels appears primarily from the Blower equipment and aligned mostly with the X-axis. This is seen in the RMS plot of Figure 9 on page 11. Here we see the X-axis RMS level doubling then tripling within that approximately 2-hour window with peak RMS levels extending above 12 mg_{RMS}.

A summary comparison of RMS acceleration levels versus one-third octave frequency bands is shown in Figure 11 on page 12. Note that the magenta numbering labels reference the 3 OTO bands discussed above, and the blue stairstep curve is the historic ISS microgravity requirements curve. The black trace was computed from SAMS measurements nearest the 4BCO2 equipment.

Propagation of 4BCO2 Equipment Vibrations

The four SAMS sensor heads listed above in the **Microgravity Measurement & Analysis** section were analyzed via color spectrogram and interval RMS acceleration versus time for the same frequency bands mentioned above. The results in Figure 12 and Figure 13 show the only indications of propagation of vibrations from 4BCO2 to other sensor locations for the time frame from GMT 13:15 to 15:30 were in the frequency range from 180 to 200 Hz.

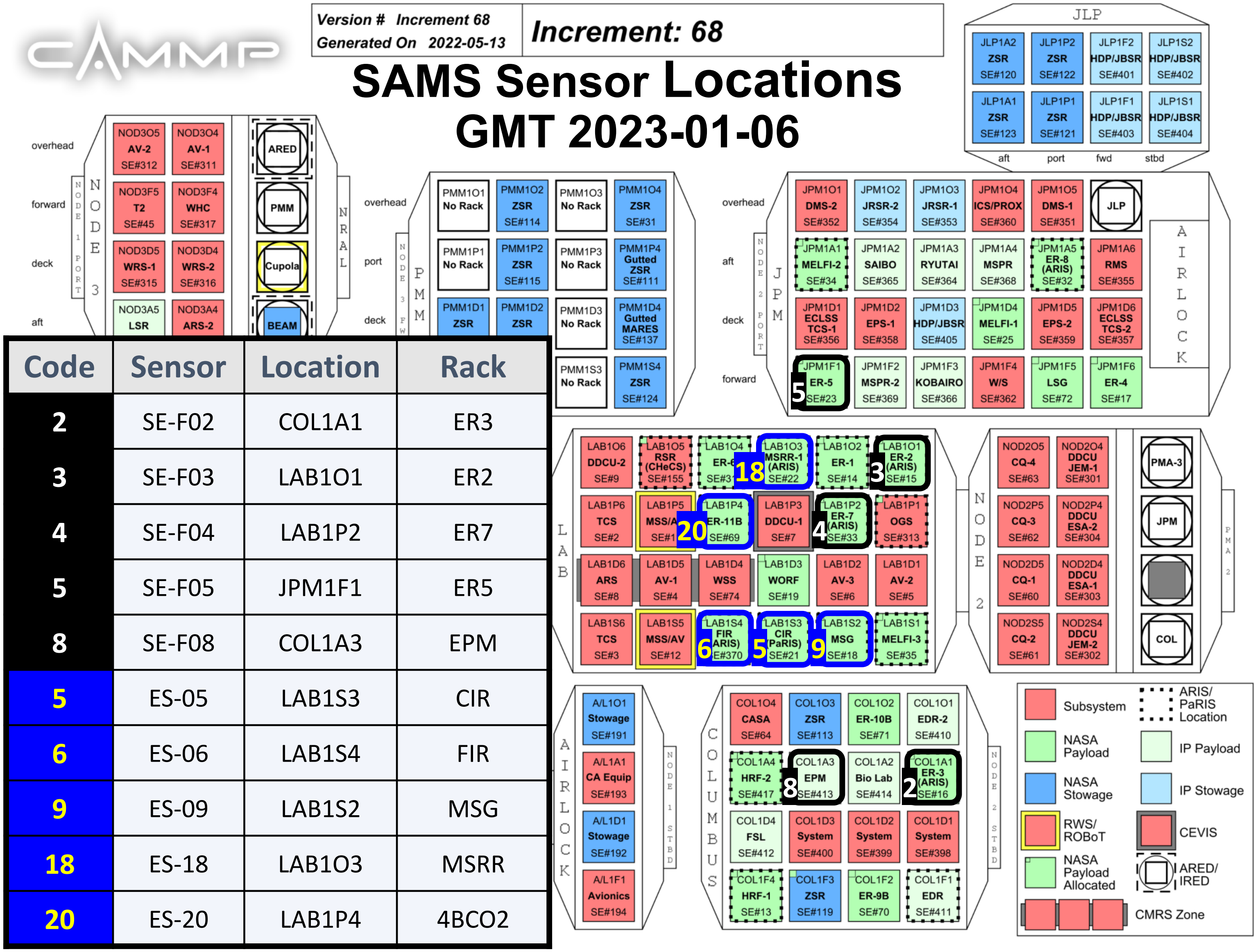
Figure 12 on page 13 shows large excursions from baseline when the 4BCO2 Blower was operating for the SAMS sensor nearest this equipment. The same 3 traces from this figure were copied (now as red traces) to Figure 13 on page 14, where the black traces are now for the SAMS sensor head mounted on the Cold Atom Lab in the LAB1P2 rack. Note that the red traces on this overlay set of plots are not scaled (or offset properly). They were just dropped in place to emphasize temporal correlation, i.e. these are 4BCO2 Blower vibrations propagating to this other (nearby) rack, "two racks over on the port side". Excursions above baseline for these 2 sensor locations (between 180 and 200 Hz) were:

1) **nearly 10 mg_{RMS}** nearest 4BCO2 (ES-20, LAB1P4)
2) **about 50 μg_{RMS}** near Cold Atom Lab (SE-F04, LAB1P2)

4. CONCLUSION

The analysis results from 4 SAMS sensor heads distributed across all 3 main labs of the ISS on GMT 2023-01-06 between about 13:15 and 15:30 during 4BCO2 operations, most notably the Blower and Air Save Pump, showed localized vibrations from both of those equipment sources:

- for spectrograms computed from the SAMS sensor nearest 4BCO2, we had to rescale the color/magnitude in order to **"pull the signal features out of saturation"**
- **the Air Save Pump signature had a fundamental frequency near 66.7 Hz and a 2nd harmonic near 133 Hz** – we saw that pump turn on/off twice, each time for a duration just a bit over 10 minutes within about a 2-hour span of time
- direct identification of the Blower signature was confounded by its higher-than-SAMS-passband operating frequency, but we clearly saw what we attribute as alias signals from its fundamental or upper harmonics – these Blower signatures drop into the frequency band measured by SAMS from about 100 to about 200 Hz
- comparing 4 SAMS sensor head locations distributed throughout the ISS showed only one indication of propagation of 4BCO2 vibrations – that was between 180 and 200 Hz (i.e. the Blower) and that was limited to propagation to "two racks over on the port side"



Code	Sensor	Location	Rack
2	SE-F02	COL1A1	ER3
3	SE-F03	LAB1O1	ER2
4	SE-F04	LAB1P2	ER7
5	SE-F05	JPM1F1	ER5
8	SE-F08	COL1A3	EPM
5	ES-05	LAB1S3	CIR
6	ES-06	LAB1S4	FIR
9	ES-09	LAB1S2	MSG
18	ES-18	LAB1O3	MSRR
20	ES-20	LAB1P4	4BCO2

Fig. 1: ISS Topology showing **SAMS Sensor Locations** on GMT 2023-01-06.

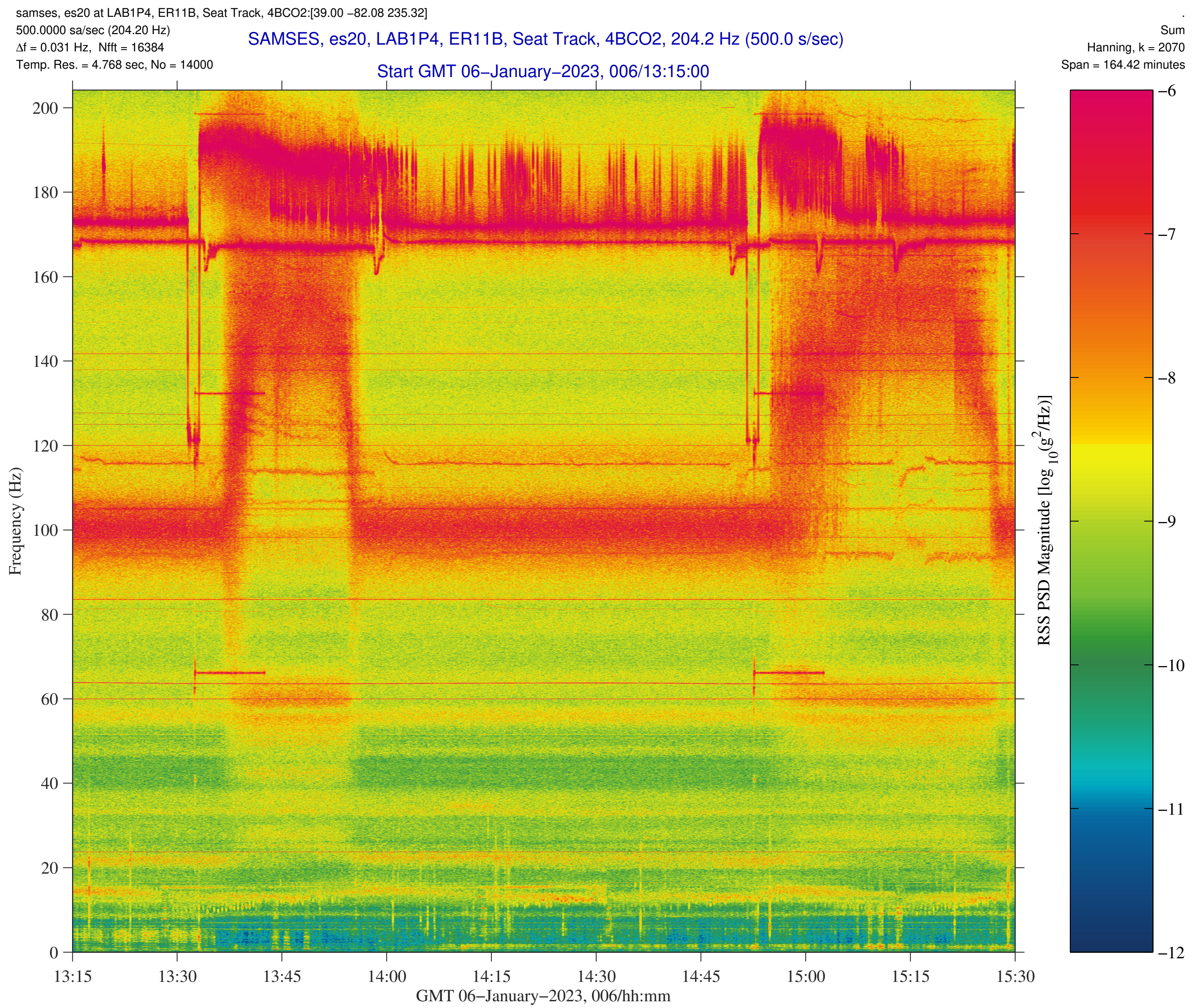


Fig. 2: ~Two-Hour Spectrogram (< 200 Hz) SAMS Sensor es20 on GMT 2023-01-06.

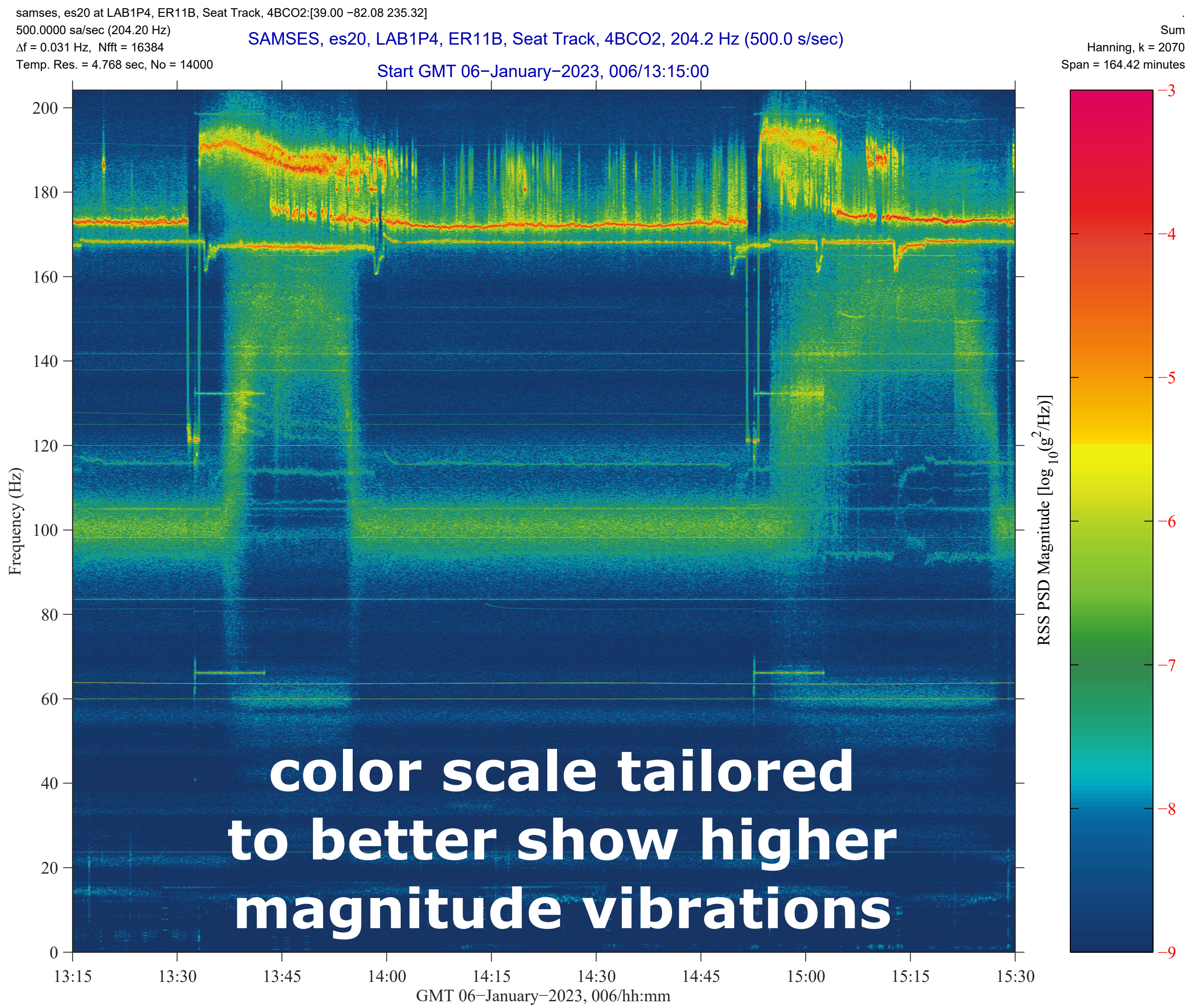


Fig. 3: Replotted Spectrogram with **Tailored Color Scale** to Better Show 4BCO2 “Yellow-to-Red” Signatures.

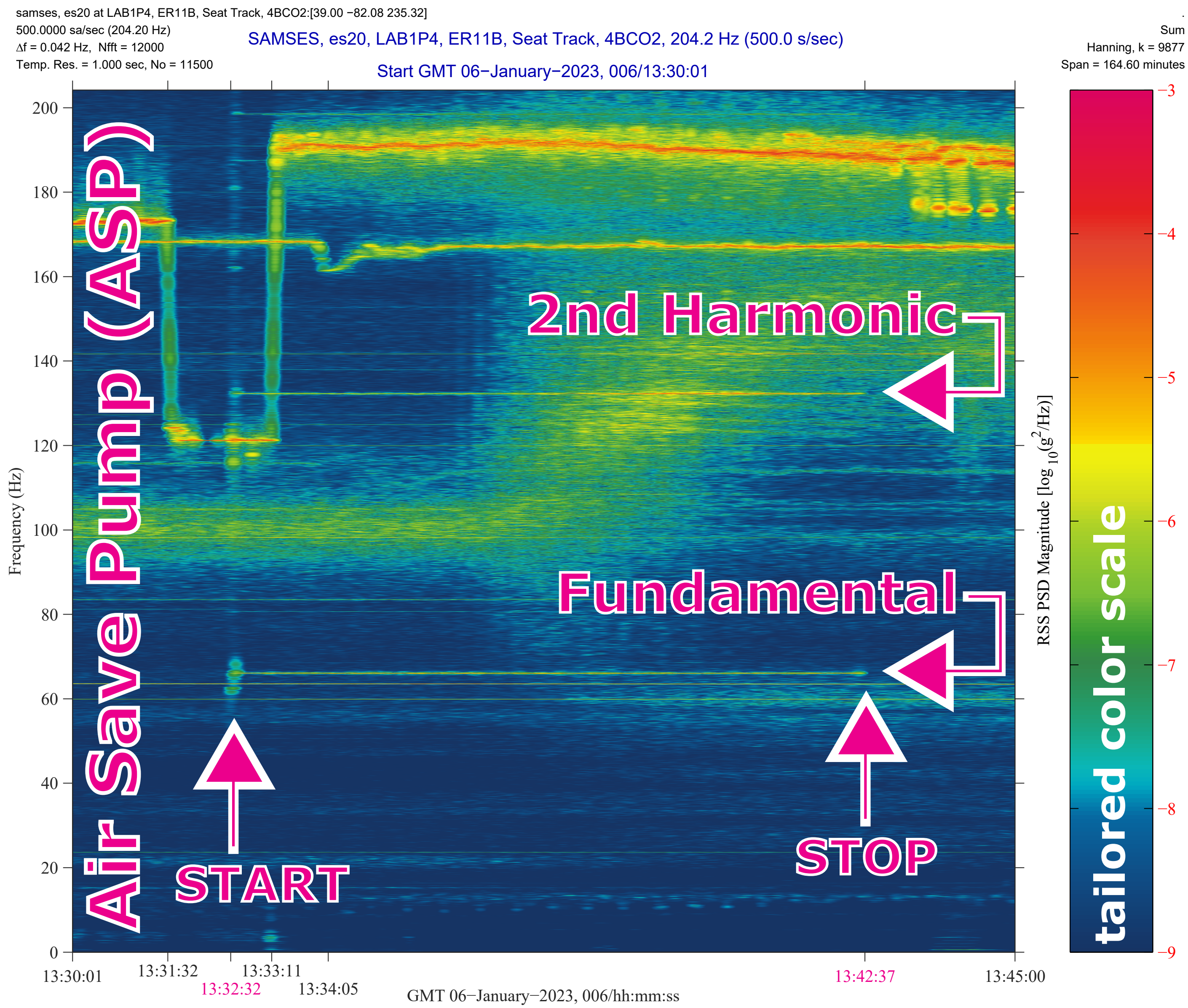


Fig. 4: **15-Minute Zoom-In** of Previous Spectrogram.

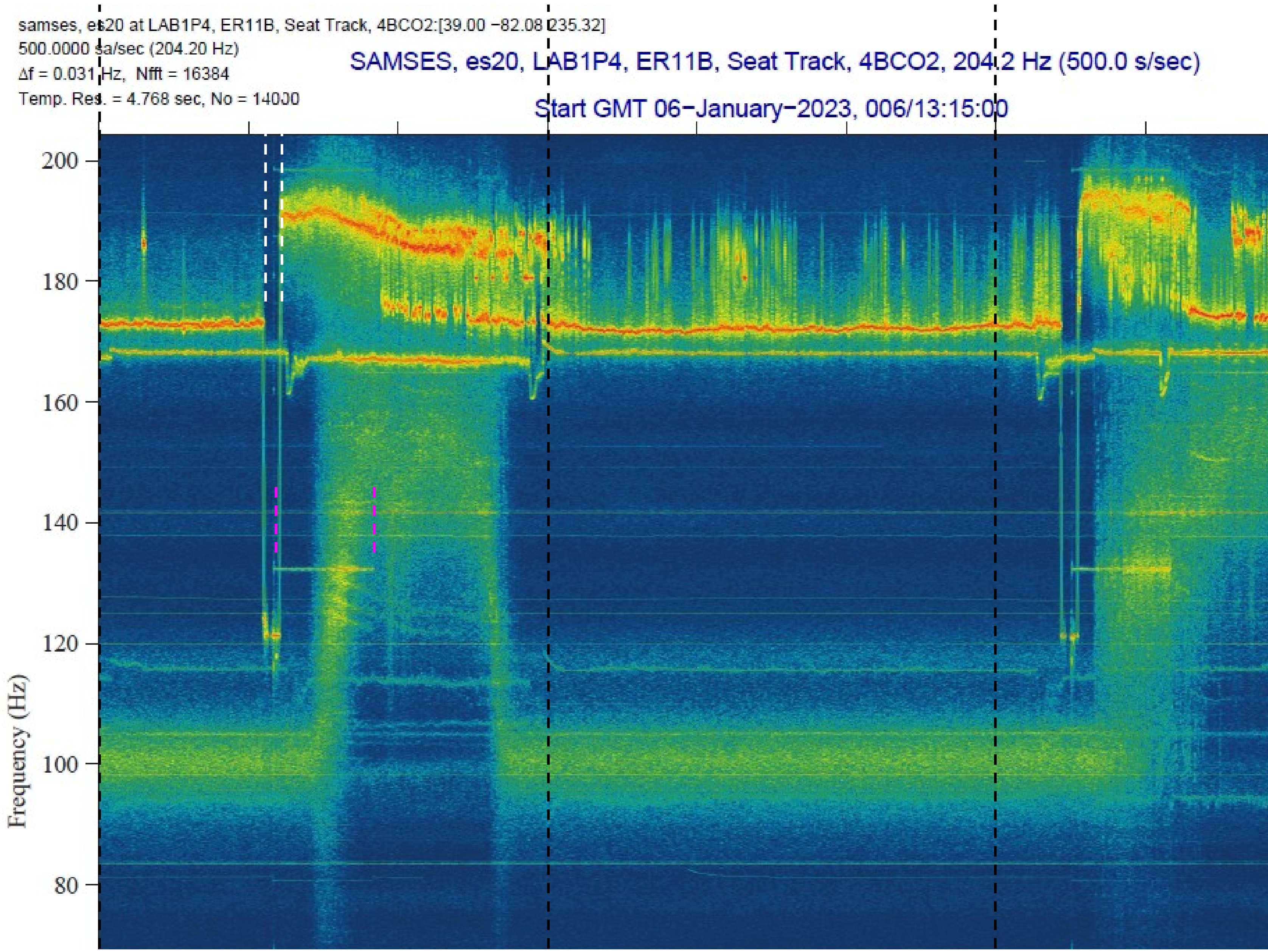


Fig. 5: Overlay #1 (*use your PDF viewer/alignment skills to toggle back/forth with next page*).

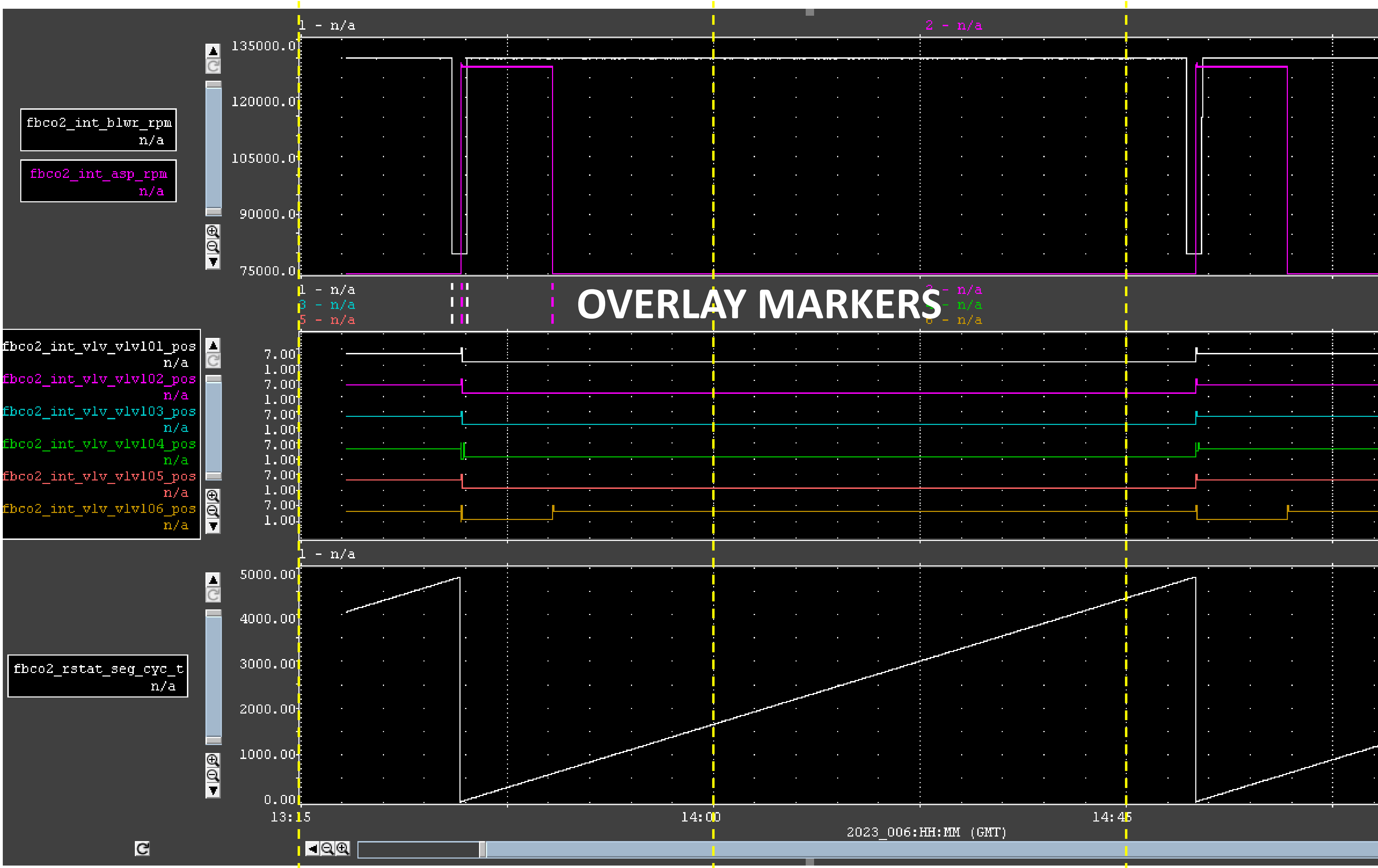


Fig. 6: Overlay #2 (*use your PDF viewer/alignment skills to toggle back/forth with previous page*).

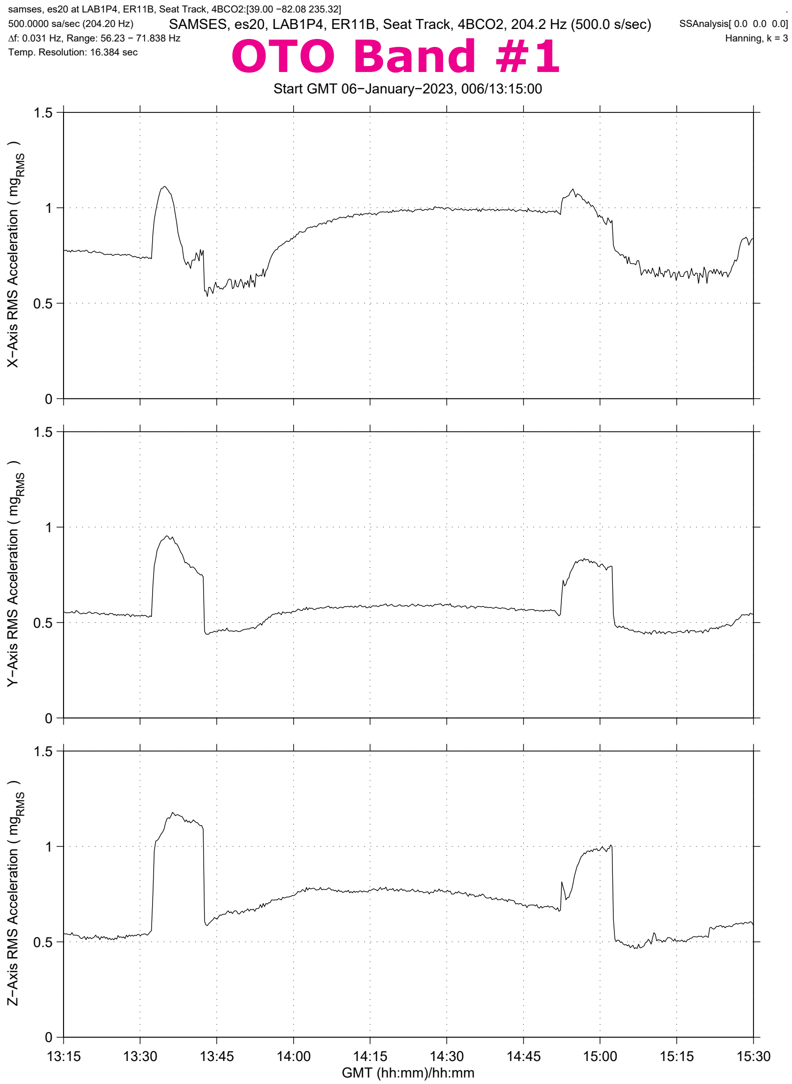


Fig. 7: 16-sec Interval RMS Acceleration **(56 < f < 72 Hz)**.

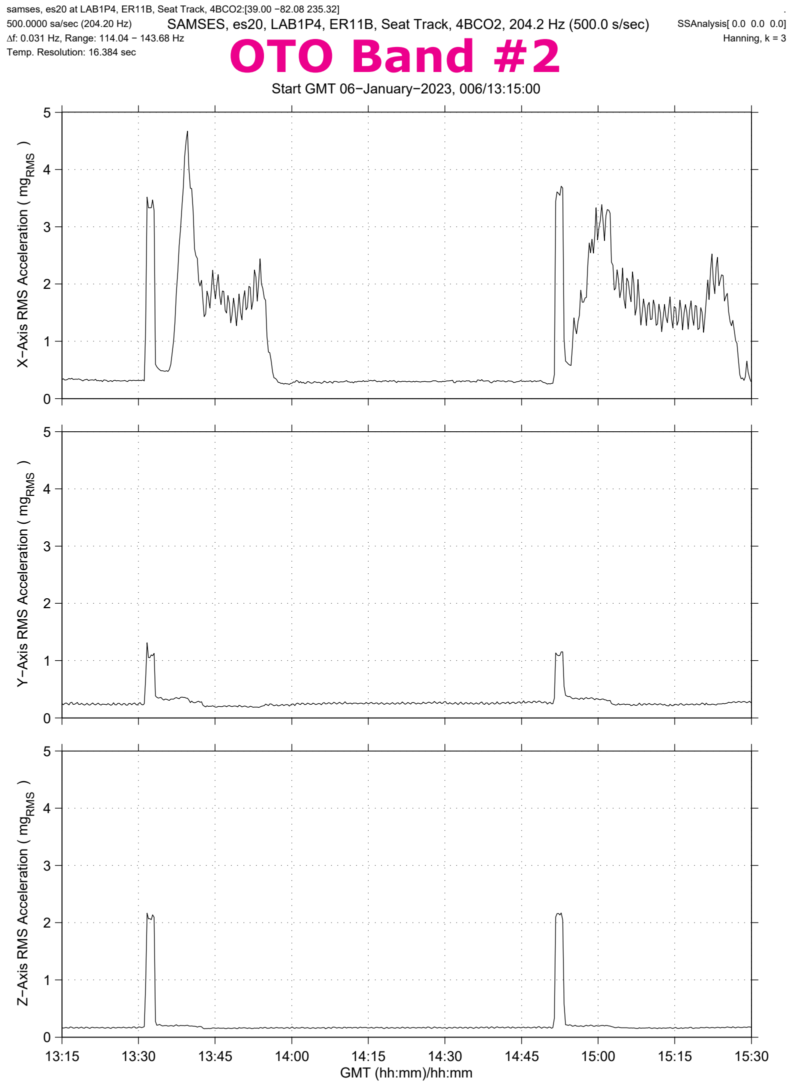


Fig. 8: 16-sec Interval RMS Acceleration **(114 < f < 144 Hz)**.

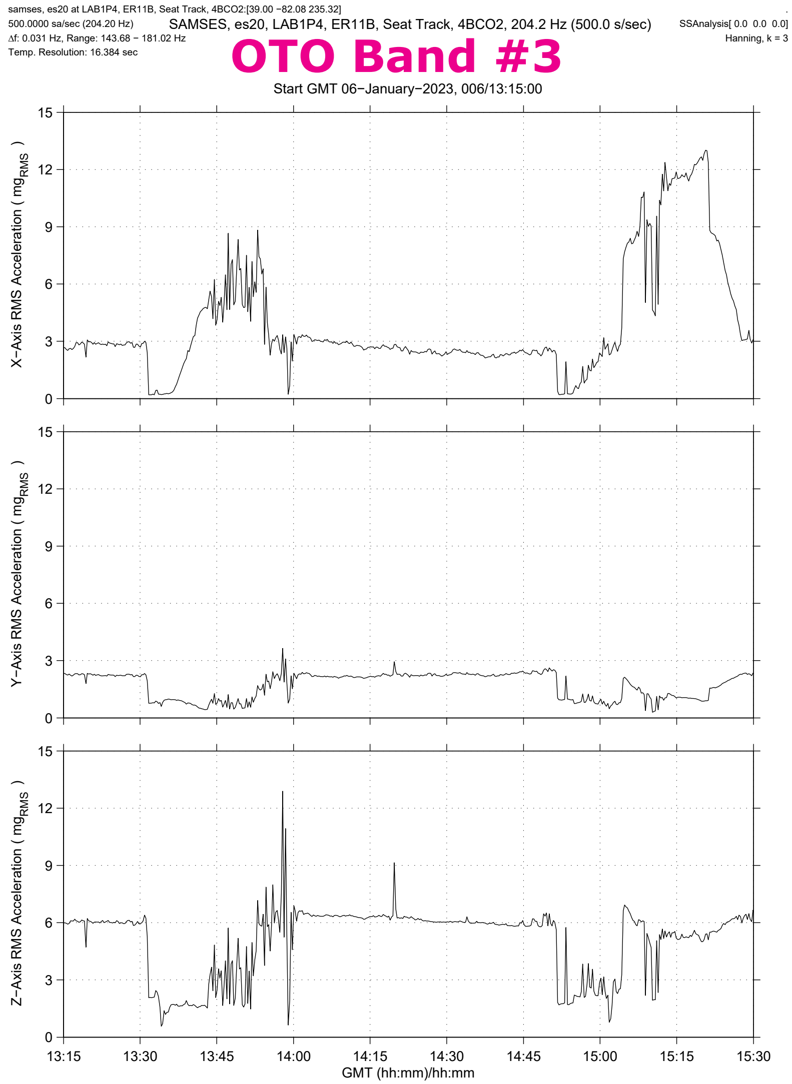


Fig. 9: 16-sec Interval RMS Acceleration **(144 < f < 181 Hz)**.

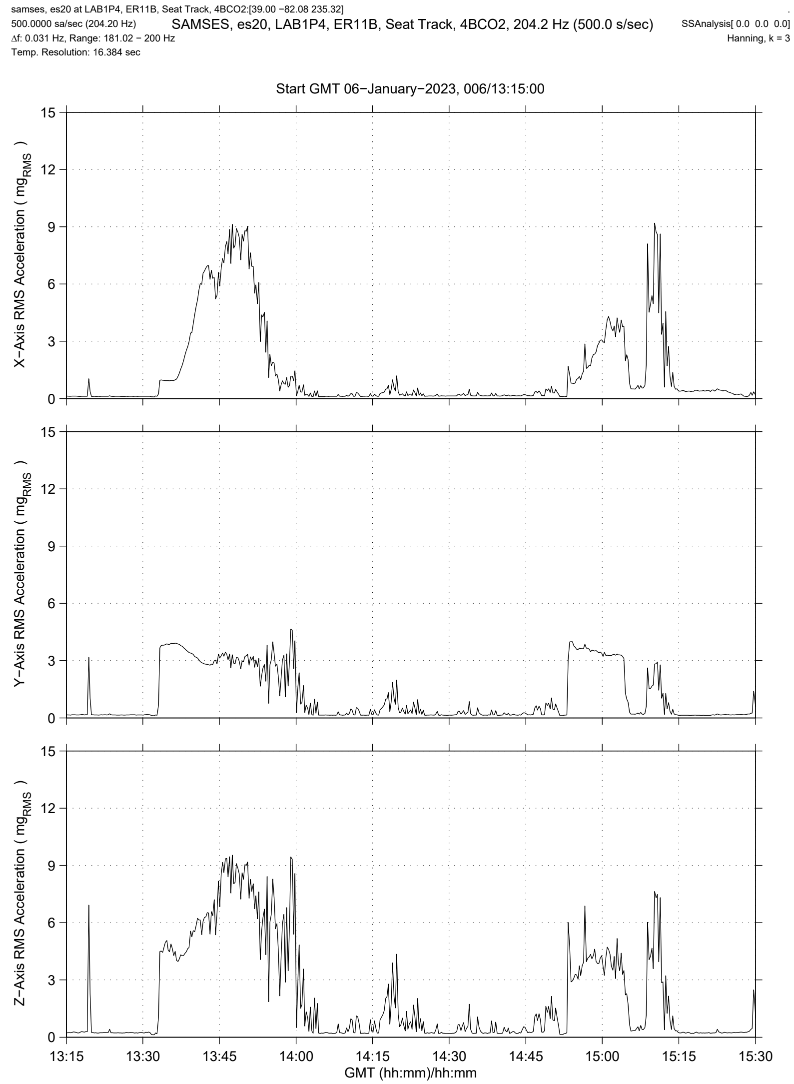


Fig. 10: 16-sec Interval RMS Acceleration **(181 < f < 200 Hz)**.

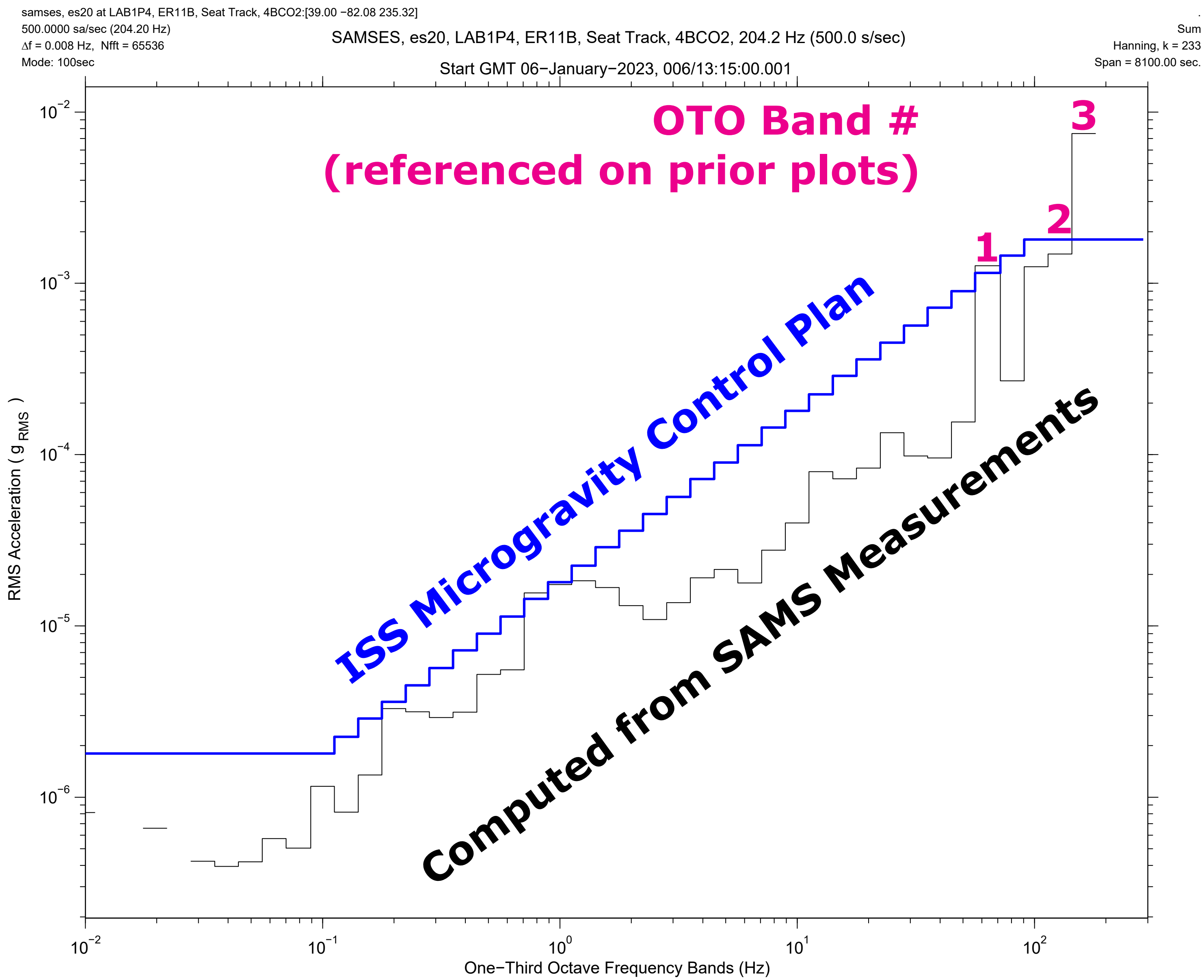


Fig. 11: RMS Acceleration versus One-Third Octave (OTO) Frequency Band.

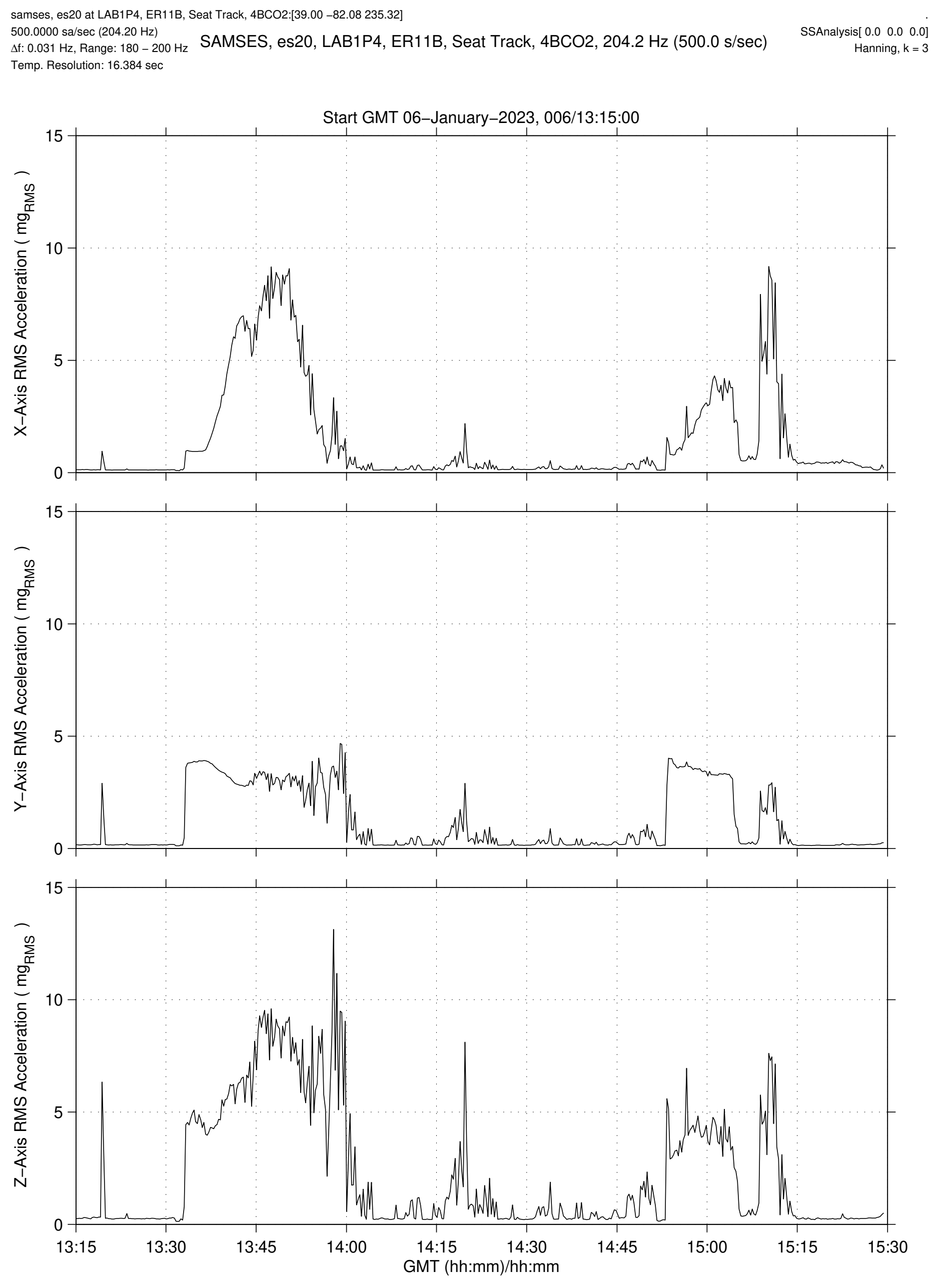


Fig. 12: 16-sec Interval RMS Acceleration **(180 < f < 200 Hz)** for Sensor Nearest 4BCO2.

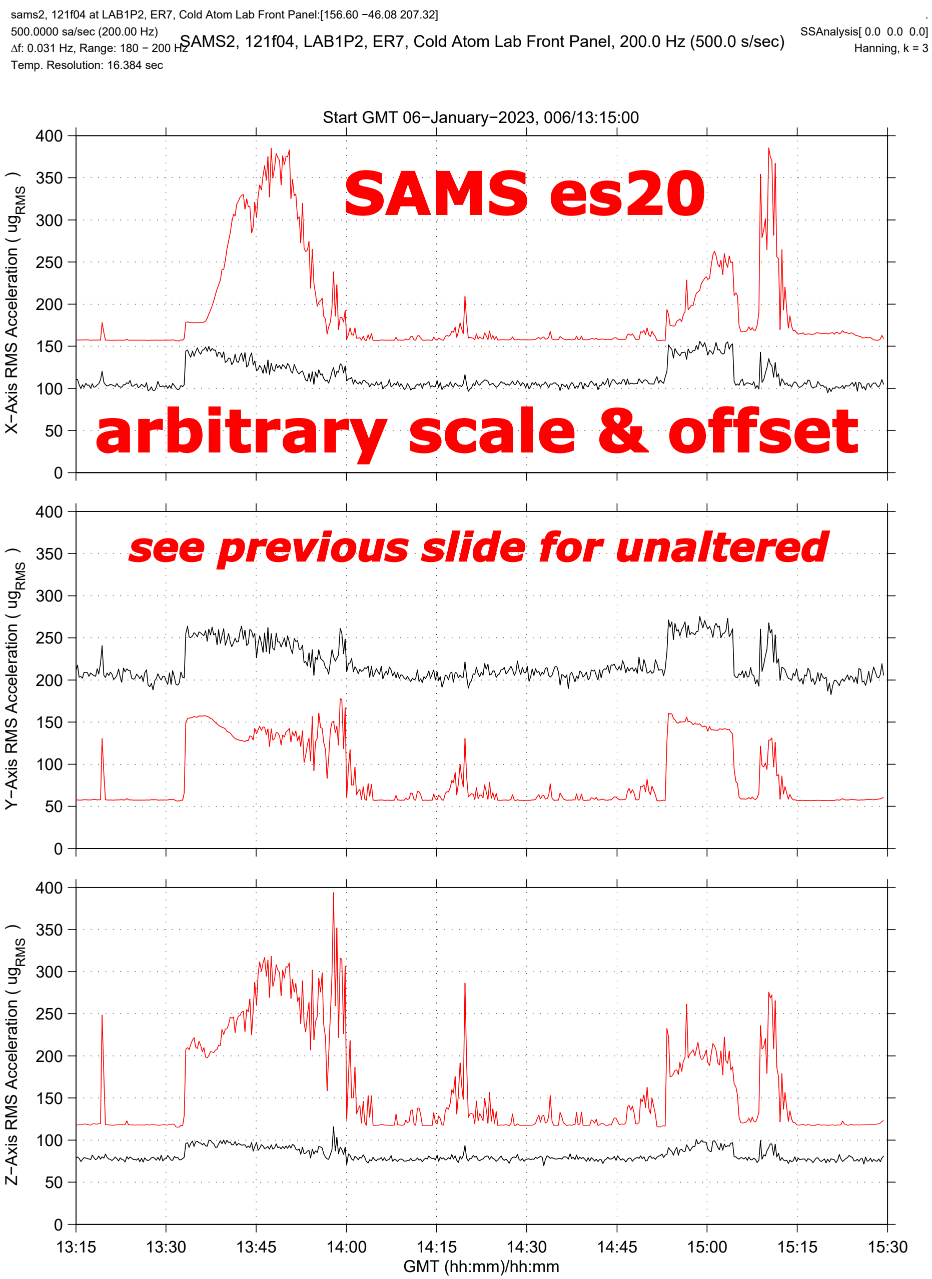


Fig. 13: 16-sec Interval RMS Acceleration **(180 < f < 200 Hz)** with 2 Sets of Sensor Traces Overlaid.