Kiersten Lyde-Stad 42381061

Olivia Wankling 35824176

Mentor: Chris Waltham

Title: Modelling the Effect of Temperature on Resonant Frequencies with a Standard Trumpet

Abstract:

The objective was to experimentally confirm a relationship between increased temperature and frequency output of brass instruments. We hypothesised that the resonant frequencies of a trumpet will experience a shift upwards when exposed to temperatures higher than the standard ambient value of 25 °C due to the increasing kinetic energy of air molecules accelerating the velocity of the sound waves. To measure this, we projected a full range of frequencies, commonly referred to as white noise, through a silver-plated brass trumpet. It was then exposed to temperatures significantly above and below the standard ambient value. Using a spectrum reader (Spectrum Lab), we recorded the range of frequencies at a low temperature, then analysed phase shifts between the two graphs after the temperature was increased. It is accepted in the musical community that keeping an instrument's output in tune while performing in non-ambient temperatures is much more difficult. Since the speed of sound is heavily dependent on heat, instruments are calibrated to play set frequencies at approximately room temperature. Our results showed consistent increases in resonant frequencies as air temperature rises, supporting the hypothesis that higher temperature should result in the sharpness of trumpet pitches.

Introduction:

Professional musical wind instrument performers commonly agree upon the difficulty of producing an instrumental pitch that is in tune before a sufficient warm-up. A full range of frequencies is played through a silver-plated brass trumpet to see if this commonly accepted "fact" in the music community can be experimentally determined. The pitch of a musical tone is determined by the frequency of the sound waves creating the tone. Frequency, commonly measured in Hertz (Hz), directly affects how our brain's ability to process sound. The lower the frequency of the wave, the lower the pitch sounds to us, and vice versa ("The Audible Spectrum" 2001). A "flat" pitch occurs when the frequency of a musical sound wave shifts below that of a perfectly tuned tone. The pitch that results from the frequency shifting upwards is referred to as "sharp". Sound wave frequencies produced by wind instruments are directly proportional to the speed of the sound waves in question (Young 1946). The relation between the speed of sound and frequency can be modelled by the equation $v = f\lambda$, where v is the velocity of sound, f is the frequency of the wave, and λ is the wavelength. A positive correlation between ambient temperature and sound wave frequency can be inferred due to the positive correlation between temperature and kinetic energy. At higher temperatures, the kinetic energy of air molecules rises, causing them to move faster. This increased movement of air particles speeds up the velocity of sound waves travelling through, which in turn raises the frequency of the sound waves. Our goal was to experimentally determine if this change in frequency due to temperature is significant enough to be observed quantitatively and whether the common assumption that differing ambient temperatures can truly be blamed for the difficulty that wind instrument performers face.

Methods:

Setup:

- Laptop running a frequency spectrum recorder, Spectrum Lab on FFT size 65536
- Connected wire microphone
- Silver-plated brass trumpet, without the buzzer mouthpiece inserted
- Bluetooth speaker
- White noise (amplitude of 0.8) from audacity
- Misc equipment to stabilize the microphone

- Access to a cold ambient temperature
- Hairdryer

The experiment was performed using a single trumpet to reduce the capacity for error associated with differences in instruments. A small Bluetooth speaker playing white noise was placed at an angle into the bell end of the trumpet. The purpose of this was to provide the source of frequencies to resonate within the trumpet. These resonance frequencies were picked up by placing a small microphone into the mouthpiece end of the trumpet opposite to the bell, in place of a buzzer. The microphone was connected to a laptop running Spectrum Lab, which allowed the spectrums of the output resonance to be displayed quantitatively.

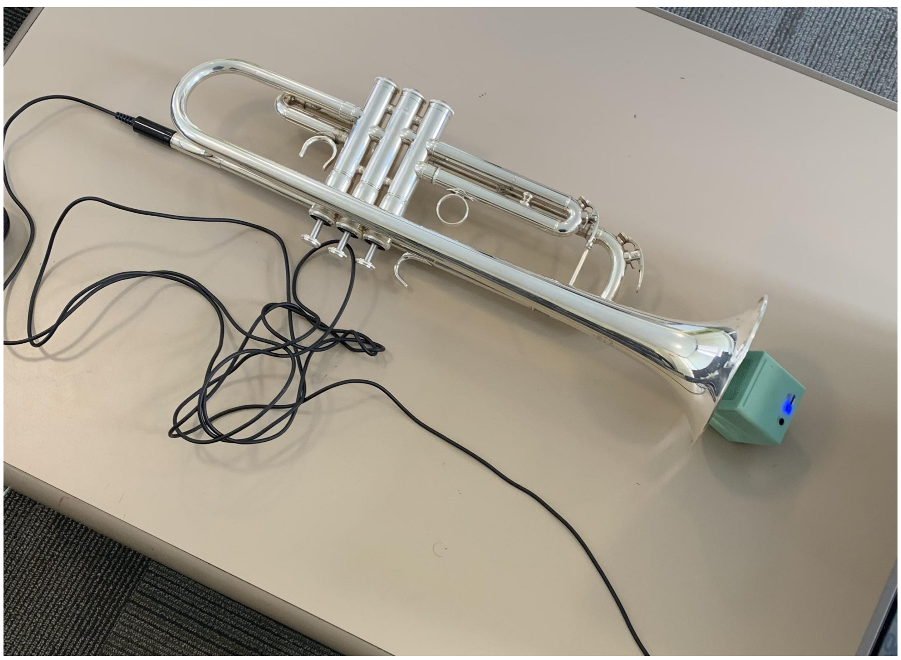

Fig 1. Experimental setup- Bluetooth speaker plays white noise into trumpet bell, and the frequencies resonate accordingly. A microphone located at the opposite end of the trumpet picks up this output and sends it to Spectrum Lab to be recorded as a quantitative frequency spectrum.

Experimental Procedure:

A heating model was chosen for the experiment rather than a cooling model, as the trumpet could be heated up without needing to be moved to a new location. This was necessary because a change in ambient environmental noise would interfere with the resulting frequencies recorded. During the point at which the recording equipment was set up and the resonance frequencies were recorded for 3 minutes in a room at ambient temperature. After 3 minutes, Spectrum Lab was paused, and the trumpet was directly heated with a hairdryer on a high setting for 2 minutes. Once a hand placed near the trumpet could feel the surrounding heat given off, Spectrum Lab was unpaused, and the resonance was recorded for another 3 minutes. As the data-taking was merely paused, the new heated resonance frequencies were recorded directly above the previous output. This allowed any differences between the frequency outputs of the treatments to be easily observed. The resulting Spectrum Lab graph for the experiment round was analysed for clear pattern differences. This process was repeated to gather sufficient amounts of data to confirm or reject any possible patterns.

Data Recording:

The axes of the Spectrum Lab graphs are frequency as a function of time, with the horizontal axis showing frequency and the vertical axis showing the passage of time. Areas of concentration at specific frequencies ranged from dark blue to bright orange, with brighter colours indicating where areas of the highest frequency concentration were located. The vertical axis for the time was from past to present from bottom to top, so the most recent data is at the top of the graph. The horizontal frequency axis was oriented from 0 Hz to 5000 Hz, left to right. This meant that frequencies further right were higher in pitch, or “sharper”. Similarly, frequencies further left were lower in pitch, or “flatter”.

Several Spectrum Lab graphs for each experiment round were analyzed. The appearance of the graph of the resonant frequencies due to white noise with no temperature effect was a black background with areas of concentration.

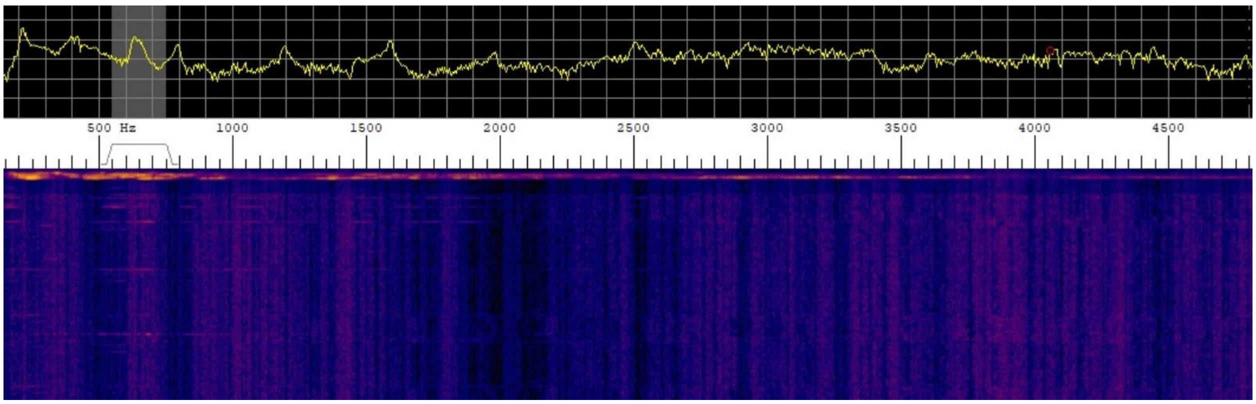

Fig 2. A Spectrum Lab frequency (horizontal axis, Hz) vs time (vertical axis) graph of white noise played into a room temperature trumpet. Brighter, warmer colours indicated more concentration at the frequency in question, while darker blue to black represented less to no sound. The bright orange line is from vocal noises being picked up immediately before the program was paused.

Results:

When white noise was played into the bell, the resonant frequencies were concentrated at specific locations. These clear areas of concentration were visibly differentiable due to being separated by black areas of no frequency concentration.

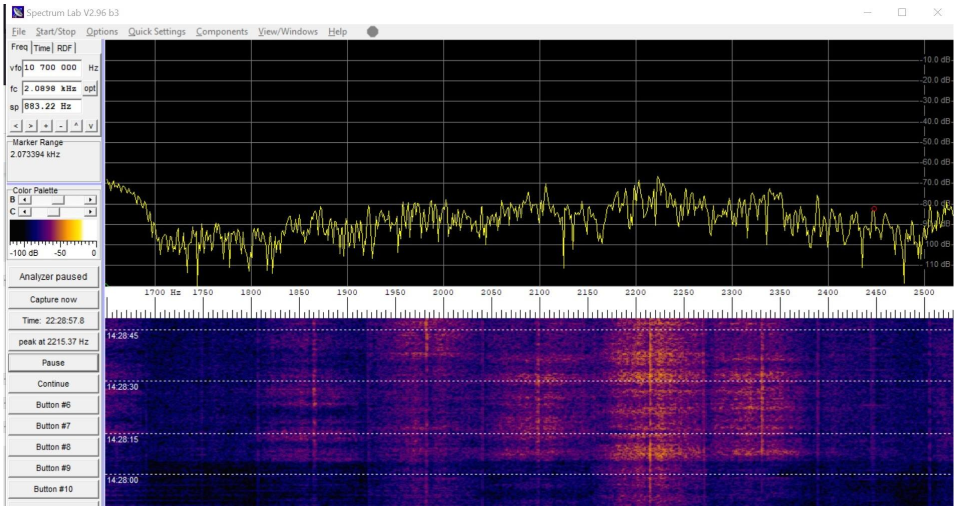

Fig 4. Control graph: A microphone was placed directly next to a Bb audio drone. The Spectrum Lab data recording was repeatedly unpaused and paused, as shown by the dotted white lines. There was no visible phase shift pattern during this process.

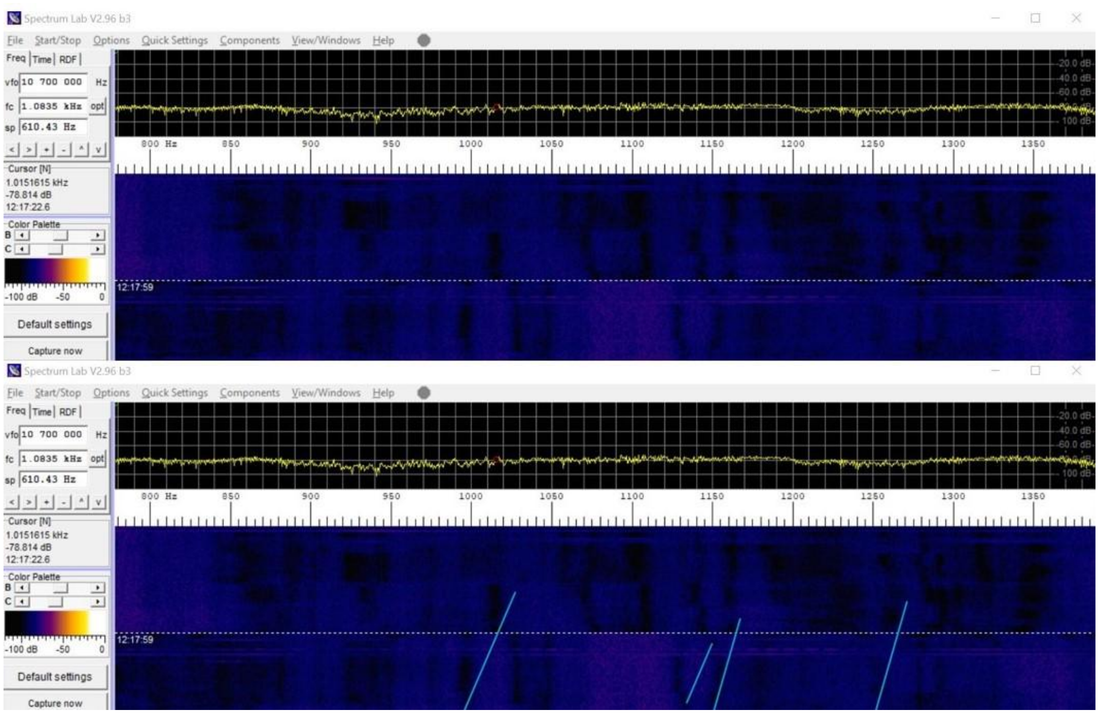

Fig 6. Above is one example of graphed results. The dotted white line is the divider between the lower data taken at a lower temperature, and the more recent, upper data taken at a higher temperature. The top

image is the untouched graph, and the bottom graph has blue lines showing the direction and location of some clear phase shifts occurring after the pause in recording between the two temperature conditions.

Once the heating process of the experiment had been performed, the data consistently showed a clear phase shift to the right. This phase shift right was relative to the pattern recorded during the initial cooler data taking. This phase shift to the right was confirmed by observing how the shape of the clearly defined dark spot shapes has all been shifted to the right by a constant amount. Consequently, this showed that the areas of frequency concentration were now at a higher pitch, and the overall output had become sharper post-heating. This pattern was observed throughout the entire process of data collection. A shift lower was never observed after heating. It was confirmed that a phase shift right that did occur would be negligible when the trumpet was insufficiently heated or cooled during the experiment.

Tabulated results:

Δf #	Δf (Hz)	Scale (Hz)	u[f] (Hz)
2A	20.0	5.0	1.3
2B	15.0	5.0	1.3
2C	15.0	5.0	1.3
3A	20.0	2.0	0.5
3B	12.0	2.0	0.5
3C	12.0	2.0	0.5
4A	20.0	5.0	1.3
4B	20.0	5.0	1.3
4C	13.0	5.0	1.3
4D	13.0	5.0	1.3
5A	25.0	50.0	12.5
5B	20.0	50.0	12.5
Δfw	15.2		
u[Δfw] (Hz)	0.2		

Table 1. Table of recorded frequency differences between hot and cold conditions collected across trials, showing magnitude (in Hz) and direction (positive signage denotes a shift upwards/right in frequency). The data is labelled from left to right, in columns: phase shift label, the magnitude of phase shift right, the scale of graph analysed, and uncertainty of measurement. Below the table, the weighted mean and weighted mean uncertainty are also calculated.

Discussion:

The common trend amongst the frequency measurements as the temperature changes is a consistent and observable phase shift in fig. 6. The frequencies between the pitch of semitones grow logarithmically with the frequency, as the differences in the magnitude of low-frequency semitone intervals are very small in comparison to those of their high-frequency counterparts. For example, the frequency difference between semitones C1 and C#1 is only 1.94463 Hz, while the difference in frequency between semitones E7 and F7 is 156.806 Hz. Semitones increase exponentially to the 12th root of 2, and so using this, we can mathematically calculate this through the formula $n=\Delta f$ ^ ($\sqrt[12]{2}$) where n is the number of semitones in cents, and Δf is the magnitude of phase shift between frequencies. The conversion factor between cents and semitones is 100 cents to 1 semitone and since in this experiment we should be observing a frequency shift of less than one full semitone, the units of cents can be used as a percentage of a true semitone.

Using the weighted mean of Δf tabulated in Table 1, we can calculate a weighted mean of the n between similar frequencies at cold vs different temperatures, and the uncertainty of n. By doing this, we get an n value of 17.87 cents, so 17.87% of a full semitone. The uncertainty of n calculated is 0.18174 cents, which is 0.0018 semitones.

The weighted average that the frequencies played through the trumpet shift between temperatures is 17.87% of a full semitone, which is a reasonable and predictable value. While playing wind instruments at the correct pitch in temperatures reasonably below or above the standard ambient value is difficult, the tune does not shift so drastically that the perceived note changes. The frequencies shifting upwards of approximately 17.87% of a semitone reasonably reflects the common consensus of wind instrument performers that musical pitch in colder and warmer temperatures varies enough that the tune is off, but not so drastically that the note itself shifts to a different pitch altogether.

Conclusion:

The full range of frequencies played through the trumpet was consistently observed to be higher when the trumpet was heated, resulting in sharp pitches. The frequencies observed after cooling were significantly lower, resulting in a flat pitch. We can thus conclude that the ambient temperature surrounding a trumpet does play a considerable role in its ability to play the correct pitch. From our experimental results, we recommend that musicians playing in warmer temperatures should tune to a slightly lower frequency, and vice versa in cool temperatures.

While results consistently aligned with our hypothesis, a more comprehensive experimental investigation into how frequencies differ between shorter ranges of specific temperatures could have provided us with the ability to better estimate the temperatures at which the trumpet begins to sound off-pitch.

Future research could focus on analysing how the frequencies change gradually as the trumpet cools or warms. An Arduino DHT11 sensor and a Python code could be utilised to examine the temperature in detail and plot the changes in temperature and frequencies as functions of time. It might also be beneficial to use this same equipment to analyse the possible effects of humidity on the magnitude of the sound wave frequencies, and consequently our resulting data.

Bibliography:

“The Audible Spectrum.” Neuroscience. 2nd edition., Sinauer Associates, Inc, 2001.

Velasco, S., et al. “A computer-assisted experiment for the measurement of the temperature dependence of the speed of sound in air.” American Journal of Physics, 2004. https://doi.org/10.1119/1.1611479.

Young, Robert W. “Dependence of Tuning of Wind Instruments on Temperature.” The Journal of the Acoustical Society of America, 1946. https://doi.org/10.1121/1.1916314.

Appendix:

Shown below is an example of a full data range, taken from our 11th experiment round. Phase shifts right are present across the full range of frequencies detected.

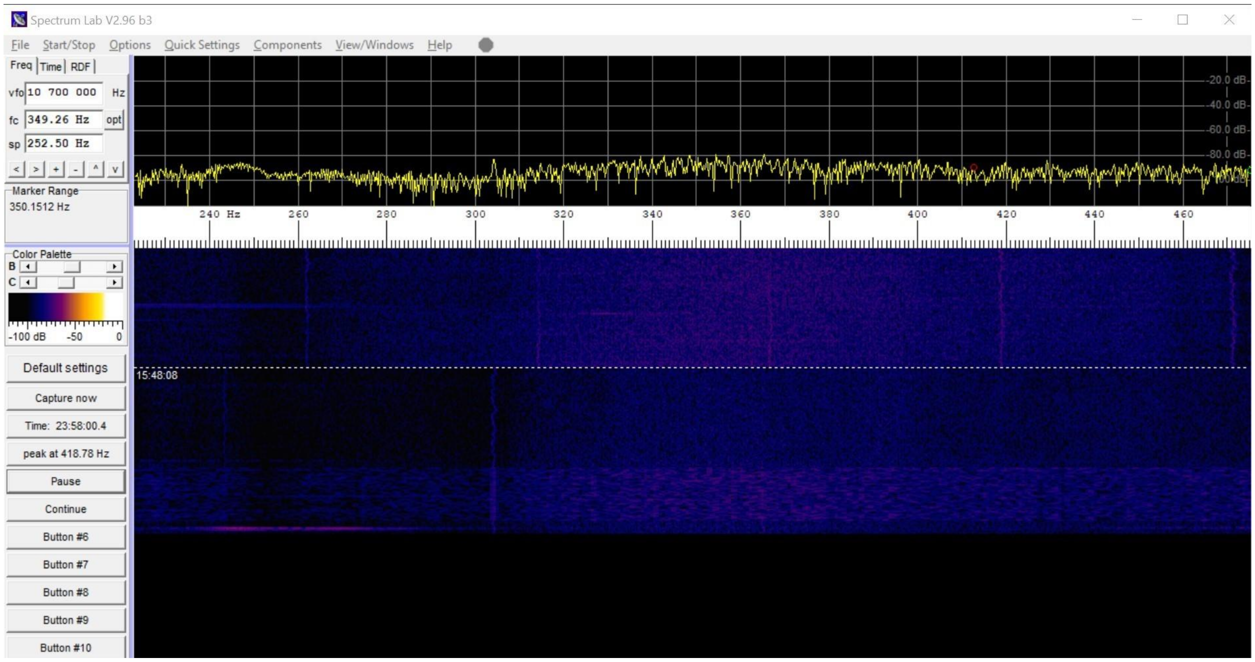

Fig. 1556-28-02

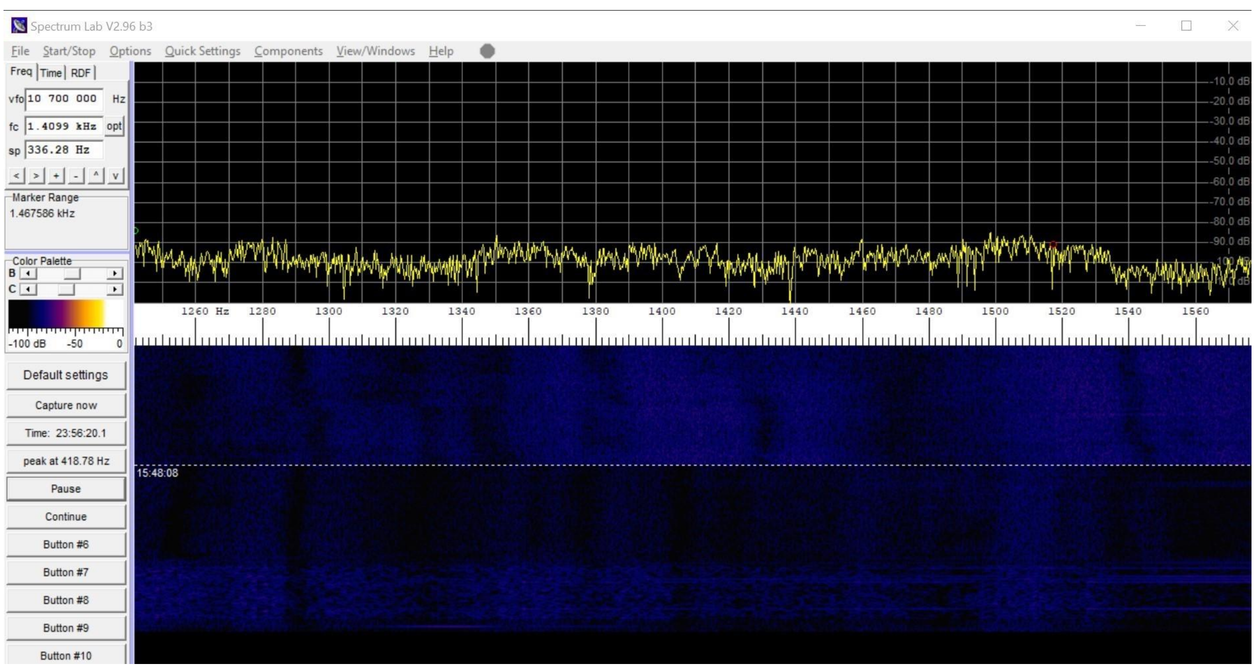

Fig. 1557-28-02

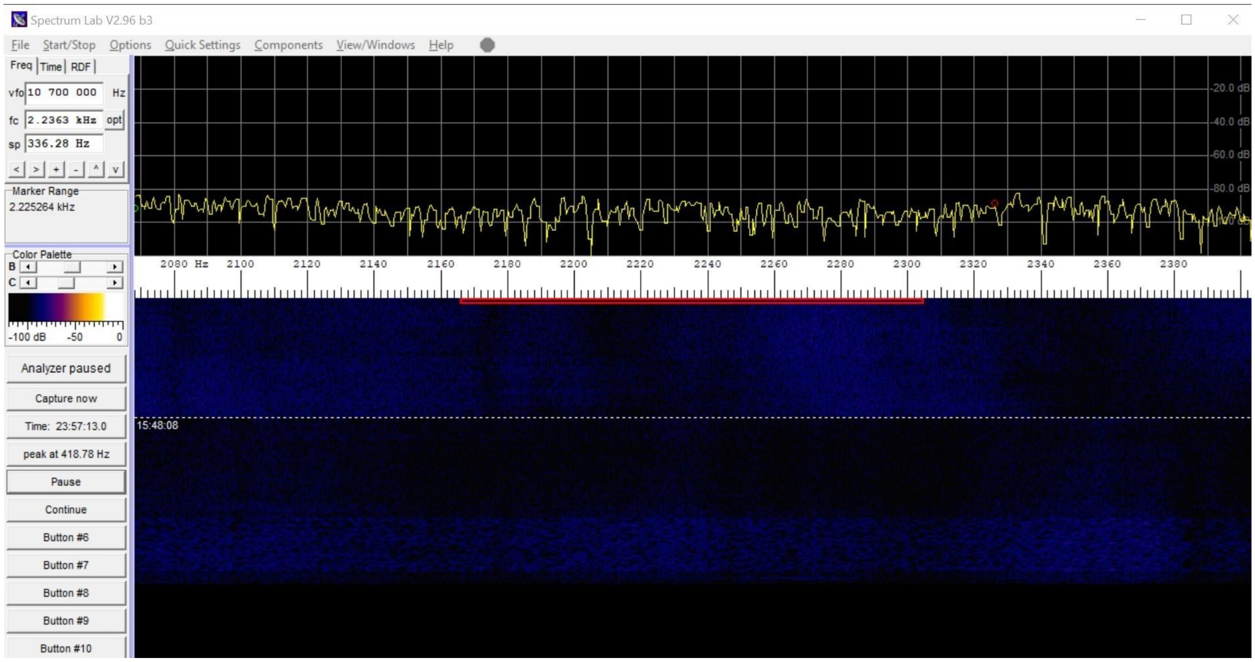

Fig. 1559-28-02 (note: the red outline box present is from the cursor select function, and not a part of the graph)